Czech Technical University in Prague

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Doctoral Thesis

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Czech Technical University in Prague

Faculty of Electrical Engineering
Department of Electrical Power Engineering

Reactive Power Compensation in Modern Electricity Grid Architecture with the Synchronous Condenser

Doctoral Thesis

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Ph.D. Programme: Electrical Engineering and Information Technology
Branch of study: Electrical Power Engineering

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Declaration

I hereby declare that this thesis is a record of my original work and that where any material could be construed as the work of others, it is fully cited and referenced, and/or with appropriate acknowledgement given. I have clearly stated the contribution of others to jointly-authored works that I have included in this thesis. These are including statistical assistance, survey design, data analysis, significant technical procedures, professional editorial advice, and any other original research work used or reported in this thesis. The content of this thesis is the result of work I have carried out since the commencement of my research for a higher degree candidature and does not include a substantial part of work that has been submitted to qualify for the award of any degree or diploma in any university or tertiary institution.

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Abstrakt

Klesající zdroje fosilních paliv, rostoucí ceny pohonných hmot a liberalizace elektroenergetických systémů mění kontext, ve kterém jsou provozovány a regulovány architektury elektrické sítě. Obavy týkající se bezpečnosti dodávek elektřiny a spolehlivosti spolu s integrací obnovitelných zdrojů energie představují pro provozovatele soustavy několik nových výzev. Jednou z hlavních změn, která je vidět, je připojení technologie jalového napájení k architektuře elektrické sítě pro výrobu jalového výkonu. To nutí znovu přezkoumat způsob, jakým je plánováno a provozováno reaktivní napájení dnešního energetického systému. Architektury elektrické sítě jsou vybaveny sofistikovanými zařízeními, která jí umožňují splňovat různé požadavky na kód sítě. Patří sem opatření k řízení reaktivního a aktivního výkonu k zajištění robustního fungování elektrické sítě. Robustní provoz síťové architektury znamená příznivé přizpůsobení profilů ztrát napětí a výkonu, čehož lze dosáhnout pomocí reaktivního a aktivního řízení výkonu.

Tato práce představuje technologii synchronního kondenzátoru pro usnadnění dodávky jalového výkonu do architektury elektrické sítě. Instalace synchronního kondenzátoru (SC) do elektrické sítě pomáhá v oblasti potřeb jalového výkonu, síly zkratu a následně setrvačnosti systému a zaručuje lepší dynamické obnovení napětí. Byla zkoumána schopnost synchronního kondenzátoru zajišťovat regulaci napětí a výstup jalového výkonu a cesta možnosti aktivního výkonu větrných turbín typu 3 pro dynamické stavové podmínky a problémy se stabilitou napětí. Tato práce přispívá k pochopení regulace napětí a minimalizace energetických ztrát v architektuře elektrické sítě s pronikáním obnovitelných zdrojů energie. Zdůrazňuje použití nových a / nebo dodatečně vybavených synchronních kondenzátorů pro výrobu jalového výkonu a větrných turbín typu 3 pro aktivní výrobu energie na architektuře radiální elektrické sítě.

Pro přizpůsobení schopnosti výroby synchronního kondenzátoru produkci jalového výkonu. Optimálně byly studovány režimy architektury elektrické sítě 33 kV (režim jedna a režim dva). Byla vyvinuta metodika pro určení optimálního umístění synchronního kondenzátoru koordinovaného v navrhovaném elektrickém systému se zúčastněnými větrnými elektrárnami pro dodávku kompenzace jalového výkonu a vstřikování činného výkonu v místě společného vazby (PCC) větrnými elektrárnami. Metodika je implementována a testována na standardní architektuře elektrické sítě. Prezentované výsledky ukazují, že účinek adoptovaného modelu synchronního kondenzátoru v prostředí MATLAB/Simulink poskytuje jalový výkon, zvyšuje stabilitu napětí a minimalizuje energetické ztráty, zatímco větrné elektrárny poskytují aktivní podporu energie s danými praktickými pravidly sítě.

Klíčová slova: činný výkon, jalový výkon, kompenzace jalového výkonu, synchronní kondenzátory, větrné elektrárny, architektura elektrické sítě, stabilita napětí, energetické ztráty.

Abstract

Dwindling fossil fuel resources, increasing fuel prices and the liberalization of electricity systems are changing the context in which electricity grid architectures are operated and regulated. Concerns about security of electricity supply and reliability along with the integration of renewable energy resources are presenting several new challenges to system operators. One of the major changes that is being seen is the connection of reactive power supply technology to the electricity grid architecture for reactive power production. This is forcing a reexamination of the way reactive power supply to present day power system is planned and operated. Electricity grid architectures are equipped with sophisticated devices that allows it to meet various grid code requirements. These include reactive and active power control measures to ensure robust functioning of the electricity grid. Robust operation of the grid architecture entails favorable voltage and power losses profile adjustments that can be achieved through reactive and active power controls.

This thesis presents the synchronous condenser technology for facilitating reactive power supply to the electricity grid architecture. Installing the Synchronous Condenser (SC) onto the electricity grid assists in the area of reactive power needs, short-circuit strength and consequently system inertia, and guarantees better dynamic voltage recovery. The synchronous condenser capability of providing voltage regulation and reactive power output, and the active power possibility path of Type-3 wind turbines for dynamic state conditions and voltage stability issues were investigated. This work adds to the insight of voltage control and power losses minimization in electricity grid architecture with penetration of renewable energy resources. It emphasizes the usage of new and/or retrofitted synchronous condensers for reactive power production and Type-3 wind turbines for active power production on a radial electricity grid architecture.

To accommodate the reactive power production ability of the synchronous condenser. A 33kV electricity grid architecture modes (Mode One and Mode Two) was optimally studied. A methodology was developed to determine the optimal location of the synchronous condenser coordinated in the proposed electricity system with participating wind plants to supply reactive power compensation and the injection of active power at the Point of Common Coupling (PCC) by the wind plants. The methodology is implemented and tested on a standard electricity grid architecture. Results presented demonstrates that the effect of the synchronous condenser solution adopted model in MATLAB/Simulink environment provides reactive power, enhances voltage stability and minimizes power losses, while the wind power plants provides active power support with given practical grid rules.

Keywords: Active power, reactive power, reactive power compensation, synchronous condensers, wind plants, electricity grid architecture, voltage stability, power losses.

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List of Abbreviations

AC	Alternating Current
APF	Active Power Filter
AS	Ancillary Service
ASSC	Adjustable Speed Synchronous Condenser
AVR	Automatic Voltage Regulator
CHP	Combined Heat and Power
CSC	Current Source Converter
DC	Direct Current
DFIG	Doubly Fed Induction Generator
DG	Distributed Generation
DSO	Distribution System Operator
DSP	Digital Signal Processor
EAF	Electric Arc Furnace
EHV	Extra High Voltage
FACTS	Flexible Alternating Current Transmission System
FRT	Fault Ride-Through
GCT	Gate Commutated Turn-off
GSC	Grid-Side Converter
GTO	Gate Turn-Off
GW	Giga-Watt
HPFC	Hybrid Power Flow Controller
HTS	High Temperature Superconductor
HVDC	High Voltage Direct Current
IEEE	Institute of Electrical and Electronics Engineers
IF	Impact Factor
IGCT	Integrated Gate-Commutated Thyristor
IGBT	Insulated-Gate Bipolar Transistor
IPFC	Interline Power Flow Controller
ISO	Independent System Operator
kVA	kilovolt-ampere
kW	kilowatt
LCC	Line Commutated Converter
LV	Low Voltage
LVRT	Low-Voltage Ride Through
MLI	Multilevel Inverter
MPP	Maximum Power Point
MPPT	Maximum Power Point Tracking
MSC	Mechanically Switched Capacitor
MSCDN	Mechanically Switched Capacitive Damping Network
MSR	Mechanically Switched Reactor
MV	Medium Voltage
MVA	Mega Volt-Amperes
MW	Mega-Watt

OLTCs	On Load Tap Changers
PAF	Parallel Active Filter
PCC	Point of Common Coupling
PF	Power Factor
PFC	Power Factor Correction
PI	Proportional–Integral
PLC	Power Line Carrier
PMSG	Permanent Magnet Synchronous Generator
POC	Point of Connection
POI	Point of Interconnection
PSS	Power System Stabilizer
PWM	Pulse Width Modulation
pu	Per Unit
PV	Photo Voltaic
RI	Radio Interference
RTDS	Real Time Digital Simulator
rms	Root-Mean-Square
RPC	Reactive Power Compensation
RPS	Reactive Power Support
RSC	Rotor-Side Converter
SAF	Series Active Filter
SC	Synchronous Condenser
SCIG	Squirrel Cage Induction Generator
SFIG	Singly Fed Induction Generator
SIL	Switching Impulse Level
SSSC	Static Synchronous Series Compensator
STATCOM	Static Synchronous Compensator
SVC	Static VAR Compensator
SVS	Static Var System
SWC	Surge Withstand Capability
TBS	Thyristor Bypass Switch
TCR	Thyristor-Controlled Reactor
TCSC	Thyristor Controlled Series Capacitor
TSC	Thyristor Switched Capacitor
TSO	Transmission System Operator
TSR	Thyristor-Switched Reactor
TSSC	Thyristor Switched Series Capacitor
UPFC	Unified Power Flow Controller
UPQC	Unified Power Quality Conditioner
VA	Volt-Ampere
VAR	Volt-Amperes Reactive
VRT	Variable Ratio Transmission
VSC	Voltage Source Converter
VSIG	Variable-Speed Induction Generator
WECS	Wind Energy Conversion System
WoS	Web of Science

WRIG	Wound Rotor Induction Generator
WRSG	Wound Rotor Synchronous Generator

List of Symbols

B	Susceptance
C	Capacitance
F	Farad
I	Current
L	Inductors
P	Active power
Q	Reactive power
R	Resistance
S	Apparent power
V	Voltage
X	Reactance
Z	Impedance
U_r	Receiving voltage
U_s	Sending voltage
U_s-U_r	Voltage difference between sending and receiving terminals
Q_C	Capacitive Reactive Power
Q_L	Inductive Reactive Power
Cp	Aerodynamic efficiency
ΔP	Power losses
ΔV	Voltage drop
f	Frequency
Ω	Ohm
$\cos\varphi$	Power factor
δ	Voltage phase difference

Chapter 1

1.0 Introduction

In modern electricity grid architecture with renewable energy penetration such as wind plants. Attention needs to be drawn to the importance of reactive power provision for the stability of the grid. Since electricity grid blackouts in many nations were as a result of the shortage of reactive power. One technology electricity utility managers and power system engineers can rely on for the provision of reactive power in the modern grid is the Synchronous Condenser (SC). Hence, the need for this research. This chapter is organized as follows: Section 1.1 provides the motivation for investigating reactive power compensation in modern electricity grid architecture with the synchronous condenser technology. General research background is given in Section 1.2. While the current state of reactive power provision in modern electricity grid architecture is discussed in Section1.3. This is followed by a statement of the considered research objectives in Section 1.4. Finally, an overview of the scientific contributions of this thesis is presented in Section 1.5.

1.1 Motivation

The motivation for this research is as follows:

1. Traditional generators can be retrofitted to synchronous condensers for them to serve a better purpose of voltage stabilization.
2. New synchronous condensers can be installed by electricity utility managers to serve same purpose of voltage stabilization.
3. The possibility of using existing electricity utility assets, like generators and buildings, with optimized investment costs.
4. Possibility of reusing existing power plant units at the end of their lifecycle. Instead of closing these units, they can be retrofitted to synchronous condensers and thus contribute to the stability of electricity grid architecture.
5. Retrofitting of conventional generators to synchronous condensers allow other generators on an electricity transmission network to provide more active power by removing the burden of reactive power support at wind farms. This can raise rated plant capacity.
6. Synchronous condensers provides smooth, step-less, and highly responsive voltage regulation with no switching required.
7. Electricity grid reliability is increased due to the ease of voltage adjustment with the synchronous condenser technology. It is possible to avoid a series of other operations necessary to achieve the same effect which requires more time, more equipment, more communication devices, and consequently, more risk.
8. Synchronous condensers increases flexibility of electricity grid operation in all load conditions. This is achieved by providing fast injection of reactive power to limit voltage drops and fast absorption of reactive power to limit any rise in the level of voltage.
9. SCs increases network inertia. Thereby helping to limit network’s rate of change of frequency and supports low-voltage ride through requirements of electricity grid architecture.

10. The utilization of the synchronous condenser technology assists in avoiding constant variation in the taps of elevating transformers.
11. SCs compensates for voltage drops over long transmission lines, resulting in improved transmission capacity and efficiency of electricity grid networks.
12. SCs provides reactive power compensation without the introduction of significant transients, resonances, or harmonics to the grid.
13. Different sizes of synchronous condensers available from various manufacturers, allow the optimal use of physical installation space for the equipment.

1.2 Background

Reactive power is the resultant power in watts of an Alternating Current (AC) circuit when the current waveform is out of phase with the waveform of the voltage. It is usually by 90 degrees if the load is purely reactive and is the result of either capacitive or inductive loads. Note here that only when current is in phase with voltage, that work is done, such as in resistive loads. A very good instance is the powering of an incandescent light bulb. In a reactive load power flows toward the load half the time, whereas in the other half power flows from it. This gives rise to the illusion that the load is not dissipating or consuming power [1]. There are three types of power present in loaded electricity circuits. These are true or active power, reactive power and apparent power. True or Active power—This is the actual amount of power in watts dissipated by an electricity grid circuit. Reactive power—This is the dissipated power resulting from inductive and capacitive loads. It is measured in volt-amperes reactive (VAR). Apparent power — This is the combination of reactive and true power. It is measured in volt-ampere (VA). Active, apparent and real power is only induced in an electricity circuit when current lags applied voltage by an angle, say Φ [1] – [2]. The right-angled triangle shown below in figure 1.1, illustrates the relation between active, reactive and apparent power. Electricity transmission lines need enough reactive power to satisfy the limits of power flow and to keep voltage limits. A very good demonstration of the significance of this electricity ancillary service is the fact that the electricity grid blackouts in many countries were mainly caused by the shortage of reactive power. The specific loss caused by reactive power flow on inductive transmission lines is approximately ten times more than the specific loss caused by active power flow. Furthermore, it is higher at significant load situations and not only in relative cases. For this reason, reactive power should not be transmitted over long distances. It should be generated at locations close to where it is needed [3]. Using a reliable and efficient reactive power compensation technology such as the synchronous condenser.

Reactive power exists in AC grid circuits when voltage and current are not in phase, due to inductive or capacitive effects. These effects can be on generation, transmission, and distribution sides of electricity grid architecture. Considering inductors, voltage leads current, but the reverse is true for capacitor. Thus, the direction of power is reverse for both. As a convention, it is considered that capacitors produce reactive power, while inductors consume it. For voltage stability, reactive power generation should be equal to reactive power consumption. Reactive power imbalance can have adverse effects on electricity grids. Take for instance, a decrease in the reactive power of a load causes voltage drop. For real power, voltage drop causes load current to increase. This endangers grid loads owing to the possibility of causing damage to these loads. If voltage further drops, generators are tripped to ensure safety. Thus, making electricity grid architecture condition becoming worse with further voltage drop [4].

1.3 Current State of Reactive Power Provision in Modern Electricity Grid Architecture

Electricity transmission lines are the main cause of reactive power mismatch. It has both inductive and capacitive effects. Therefore, it can create both increase and decrease in reactive power, while real power is being transmitted along power lines. An increase in reactive power causes voltage rise, while a decrease causes voltage drop along an electricity transmission line. At the distribution level, reactive power imbalance occurs owing to the inductive nature of most electricity distribution loads. Variation in demand at load side is another reason for reactive power effect on power lines. An increase in demand brings about increase in inductive reactive power at power distribution end. Resulting in additional reactive power being consumed at the transmission level. A decrease in demand causes an increase in capacitive reactive power at distribution end. Which equally results in additional reactive power to be generated at the transmission level. Thus, making voltage stability at stake at the distribution end too. Failure of generators and transmission lines can further increase reactive power demand. Thereby bring about the afore mentioned effects taking place again. Transmission System Operators (TSOs) and Distribution System Operators (DSOs) play their roles in controlling reactive power mismatch. TSO remunerates generators for reactive power. Besides, there may be some penalty charges for DSO or electricity consumers for creating additional reactive power mismatch [4].

Electricity product end users reactive power compensation inverter-based technology is a technology used for compensating reactive power at the consumer end of power lines. This technology is efficient, flexible, scalable and reliable. Efficiency; consumers reactive power compensation inverter-based technology helps to compensate reactive power in a location where power line current flow ability tends to increase and minimize heat losses in a specified location. Also, it helps to compensate the right amount of reactive power, thereby avoiding over or under compensation of reactive power. Flexibility; this technology is flexible as it allows multiple users to contribute their part in solving the problem of reactive power compensation in differs ways. Scalability; unlike capacitor banks, inverter-based consumers reactive power compensation technology expands with distribution system expansion. Just as the number of electricity consumers increases, the number of inverter-based compensation technology in the same vein increases as well. Reliability; since there are many capacitors in conventional compensator in distribution power lines. So, the inverter-based compensation technology is more vulnerable to failure. Considering cybersecurity point of view, local compensation is more resilient than centralized compensation [5] – [9]. Figure 1.1 represents a power triangle.

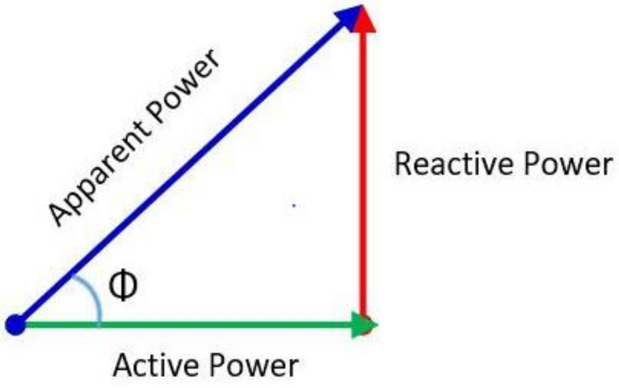

Fig. 1.1: Power Triangle [2].

The power which is dissipated and does useful work in an electricity circuit is known as active power. It is measured in watts or megawatts. The active power is denoted by the capital alphabet P. The apparent power considering Fig. 1.1 is given by the expression [2].

$$S = P + JQ \tag{1.1}$$
$$S = \sqrt{(S^2 + P^2)} \tag{1.2}$$

Where, S – apparent power
Q – reactive power
P – Active power

Therefore:

$$P = VI\cos\phi \tag{1.3}$$
$$= I^2R \text{ Watts} \tag{1.4}$$

The reactive power moves between source and load. This power is not doing any useful work on the load. Reactive power is measured in VAR. It is stored in a circuit and discharged by induction motor, transformer or solenoids [2].

Similarly, from Fig. 1.1;

$$Q = VI\sin\phi \tag{1.5}$$
$$= I^2 * VAR \tag{1.6}$$

Reactive power is equally called Phantom Power. Since it is not apparent wherever it goes or flows. It is common knowledge that reactive loads such as capacitors and inductors do not actually dissipate power. Reactive power in a sense is not used to power loads. But it is utilized for measuring the voltage and current around loads. Indicating the fact that reactive power drops voltage and draws current. Reactive power is dissipated through voltage drop and current drawn in the form of heat or waste energy. This is not done as actual work; hence power engineers have sought ways to lessen or rather minimize reactive power. Due to the presence of reactive power, conductors and generators are rated and sized accordingly. This enable generators and conductors to carry the total current in a network. Which is including not just the current that does the actual work, but also the wasted current. Active power does the useful work in a grid network. And the reactive power merely flows in a network without doing any useful work. Capacitors are considered to generate reactive power, whereas inductors consume it. So, when both are placed in parallel connection, the current flowing through them cancels out. This is essential when controlling the power factor of an electricity circuit and has become a fundamental mechanism in the transmission of electricity. Adding both capacitors and inductors in an electricity grid architecture helps partially to compensate for the reactive power consumed by the network loads [1] – [2].

Reactive power is a basic requirement for maintaining the voltage stability of an electricity grid architecture. As a well-established ancillary service, reactive power support and voltage control plays a vital role in the operation of electricity grids [10]. Solving reactive power flow problem is fundamental to the reduction of electricity transmission costs and is of increasing importance in grid operation [11]. The voltage level and economic operation of electricity grids has a close relationship with the reactive power levels of a grid architecture. Reactive power compensation in several nodes of electricity grid does not only reduce the active and reactive power losses. But this equally helps to maintain voltage levels and improve the stability of grids, in order to ensure safe and economic operation of electricity grid architecture. Implying that the choice of nodes for reactive power compensation is important for stability and economic operation of electricity grids [12]. The modern electricity grid architecture is facing significant changes. Conventional power plants are being shut down as they are becoming more and more unprofitable due to the continuous growing number of renewable electricity resources [13]. It is expected that electricity supply schemes will change fundamentally. Owing to environmental reasons and shortage of conventional electricity resources, electricity supply will be increasingly satisfied by renewables [14].

Penetration of renewables such as photovoltaic (PV) and wind power schemes is increasing for reducing carbon dioxide (CO_2) emission and energy independency [15]. With the rapid advancement of wind power plants, its negative influence of its integration on the electricity grid architecture is getting much serious. Large scale wind plant penetration inevitably consumes a huge amount of reactive power in grid networks. Thereby bringing about lack of reactive power and voltage drops issues. Furthermore, the inherent characteristic of wind power such as volatility and intermittent nature requires continuous and frequent regulation of reactive power sources. Thus, it is sufficiently important to optimally manage the reactive power sources in wind farms [16]. As one of the most feasible renewable resource, wind power will be developed more widely owing to its sustained developing strategy. Thus, its impact on electricity grid architecture, operation characteristic and control method in different functioning modes needs to be paid more attention. Wind generating plants can be divided into two types, namely, fixed speed and variable speed. Fixed speed wind generators have been used in earlier wind farms. Wind plants inability to regulate voltage makes it to absorb reactive power from the grid, but it injects active power into the grid. With global wind power installations increasing. Electricity grid voltage issues will become more serious. The Doubly Fed Induction Generator (DFIG) has become the mainstream in many wind farms. DFIG can realize variable-speed, constant-frequency control and decoupling of active and reactive power with its stator interconnected onto the electricity grid and the AC excitation controlled by the rotor side converter. DFIG can take part in voltage control by absorbing or generating reactive power according to grid operation mode and control strategy [17]. However, DFIG is now a more mature technology. The most typical control strategy is to ensure that the fans operates in a constant power factor mode. But in such situation, the reactive power exchange between the doubly fed wind turbine and the grid is insufficient, which is far from satisfying grid-connection requirements. The variable-speed constant-frequency wind generator operates in constant power factor mode. Hence, it cannot make full use of its reactive power regulating ability. So, for a large-scale wind farm with dynamic reactive power regulating ability. Compensating reactive power efficiently according to grid voltage fluctuation is required [17] – [18]. Hence, the necessity for the utilization of the synchronous condenser technology for reactive power compensation in modern grid architecture.

In the same vein, operation of large-scale grid-connected solar photovoltaic (PV) plants equally brings about voltage fluctuation. This affects the stable operation of electricity grids. To reduce this adverse effect of grid network loss brought about by PV plants, a novel coordination control strategy of reactive power control of PV plant is equally required. PV renewable plants can provide active power, thereby bringing about security of electricity grid architectures. Considering the fast advancement of centralized large-scale PV plants, reactive power control performance directly affects voltage security stability of grids. Hence, reactive power and voltage control are essential ingredient of electricity grid architectures. This should be given much attention as regards to research in electric power engineering [19]. A Synchronous Condenser (SC) can be installed in the low voltage side of PV plants to improve the dynamic reactive power compensation performance of electricity grid architecture.

The procurement and remuneration of Ancillary Service (AS) plays an important role in grid operation. AS is essential for the proper operation of electricity grid architecture. As part of AS policies, it is desirable to find a mechanism to motivate electricity utility companies to contribute to voltage control. Which ensures adequate supply of electricity product to consumers. Electricity grid voltage support as ancillary service, further buttress the need to give reactive power dispatch and assess to reactive power generation its due attention [20]. In the past, ancillary services such as reactive power compensation have been provided mostly by conventional power plants connected to the electricity grid. Owing to the changing conditions and composition of today’s electricity grid architecture. Innovative ways of reactive power provision are being investigated. One of such innovative ways to deal with reactive power provision in modern electricity grid architecture is the use of the synchronous condenser technology.

1.4 Research Objectives

The overall objective of the work presented in this thesis is the utilization of the synchronous condenser technology in the control of reactive power for wind integrated electricity grid architecture, which makes it possible for grid operators to manage voltage stability and power losses. To attain these goals, this research has been conducted by both theoretical analysis and simulations in MATLAB/Simulink environment.

1.5 Overview of Contributions

The contributions of this thesis are devoted to voltage control and reduction of power losses using the synchronous condenser technology through a developed MATLAB electricity grid architectures simulation toolbox. Papers addressing these issues have been published in journals and presented in conferences. Here, a brief overview of each paper is given which summaries the contribution. Thereafter, details of each paper are presented in the contributions section of this thesis.

PAPER ONE

Title: Utilizing the Synchronous Condenser for Robust Functioning of Wind Farm Implanted Electric Grid
Authors: Famous Oghomwen Igbinovia, Ghaeth Fandi, Juraj Kubica, Zdenek Muller, Frantisek Janicek, and Josef Tlusty
Published in: Journal of Electrical Engineering, The Journal of Slovak University of Technology, Volume 70: Issue 2, 2019, pp. 152 – 158.

Paper one presents the synchronous condenser capability of providing voltage regulation and reactive power output, and the active power possibility path of a Type-3 wind machine for dynamic state conditions and voltage stability issues carried out in MATLAB/Simulink environment. The simulation results prove the efficiency of the proposed methodology.

PAPER TWO

Title: Modeling and Simulation of the Anticipated Effects of the Synchronous Condenser on an Electric-Power Network with Participating Wind Plants
Authors: Famous O. Igbinovia, Ghaeth Fandi, Ibrahim Ahmad, Zdenek Muller and Josef Tlusty
Published in: Sustainability, MDPI, Open Access Journal, 2018, Vol. 10(12), 4834.

Paper two summarizes the practical potential of the synchronous condenser coordinated in an electric-power network with participating wind plants to supply reactive power compensation and injection of active power at their point of common coupling; it provides a systematic assessment method for simulating and analyzing the anticipated effects of the synchronous condenser on a power network with participating wind plants. A 33-kV power line has been used as a case study. The results indicate that the effect of the adopted synchronous condenser solution model in the MATLAB/Simulink environment provides reactive power, enhances voltage stability, and minimizes power losses, while the wind power plants provide active power support with given practical grid rules.

PAPER THREE

Title: Reputation of the Synchronous Condenser Technology in Modern Power Grid
Authors: Famous O. Igbinovia, Ghaeth Fandi, Zdenek Müller, Josef Tlusty
Published in: Proceedings of the 11th International Conference on Power System Technology (POWERCON), Guangzhou, China, 6–8 November 2018, pp. 2108 - 2115. Publisher: IEEE.

Paper three presents the synchronous condenser technology. It discusses the experience and lessons learnt from the use of the synchronous condenser in real projects. It also provides an outlook on the development of the use of the technology in modern power grid using two simulation study scenarios. These developments include Scenario One: utilizing only the synchronous condenser for voltage regulation on a power grid. And Scenario Two: Installing the synchronous condensers with Type-3 wind farm for voltage support on an electricity network, such contextualization is towards voltage stability in modern power grids.

PAPER FOUR

Title: Progressive Usage of the Synchronous Machine in Electrical Power Systems
Authors: Famous O. Igbinovia, Ghaeth Fandi, Zdenek Muller, Josef Tlusty
Published in: Indian Journal of Engineering, April 2018, Vol. 15, pp. 117-126.

Paper four presents a brief assessment of the synchronous machine and the motivation for the research work. It discusses the importance of the synchronous machine in electrical power systems, and the progressive trend in the use of the synchronous machine in electric-power networks. It stresses the need for the use of the synchronous machine for reactive power compensation purposes, with a vivid description given with MATLAB/Simulink simulation model. When the synchronous condenser is connected to the power system model at the terminating end of the network and switched ON, the medium voltage (MV) electrical power network simulation model effectively allows the control of reactive power, which improves voltage stability and power flow control of the proposed network.

PAPER FIVE

Title: Cost Implication and Reactive Power Generating Potential of the Synchronous Condenser
Authors: Famous O. Igbinovia, Ghaeth Fandi, Zdenek Müller, Jan Švec, Josef Tlusty,
Published in: Proceedings of the 2nd International Conference on Intelligent Green Building and Smart Grid (IGBSG 2016), 27-29 June 2016, pp. 1 – 6. Prague, Czech Republic, Publisher: IEEE.

Paper five x-rays the cost implication of the synchronous condenser in today's challenging environment. A vivid description of the reactive power generating potential of the synchronous condenser is shown in MATLAB/Simulink environment simulation of a medium voltage (MV) power system network. It is observed that the synchronous condenser is cost-effective as compared to other reactive power generating equipment's and sources. Furthermore, MATLAB/Simulink simulation results of the MV electric-power network shows an effective scheme for reactive power generation.

PAPER SIX

Title: Optimal Location of the Synchronous Condenser in Electric-Power System Networks
Authors: Famous O. Igbinovia, Ghaeth Fandi, Zdeněk Müller, Jan Švec, Josef Tlustý
*Published in:*17th International Scientific Conference on Electric Power Engineering (EPE), 16-18 May 2016, Prague, Czech Republic, pp. 1 – 6. Publisher: IEEE.

Paper six focuses on the use of the synchronous condenser device for voltage stability and power flow control on a three-phase 33 kV Medium Voltage (MV) electric-power system network. MATLAB/Simulink is used for the simulation of the proposed system model. To test the validity of the system, measured and calculated power factor values were obtained. Two scenarios were studied; Firstly, is the scenario with the synchronous condenser located at the terminal end of the 33 kV MV network (position 1). And secondly, is the scenario with the synchronous condenser placed at the beginning of the 33 kV MV power Line (position 2). Simulation results obtained from the study are compared in order to determine the most appropriate location for situating the synchronous condenser device. It is observed that the locations of the synchronous condenser equipment have different impacts on the electric-power system network. However, the proposed study of the simulation model base on the location of the synchronous condenser at the terminal end of the 33 kV MV electric-power system network (position 1) demonstrate a more effective and suitable scheme of the electric-power network concerning issues of voltage stability and power flow control.

PAPER SEVEN

Title: Comparative Review of Reactive Power Compensation Technologies
Authors: Famous. O. Igbinovia, Ghaeth Fandi, Jan Švec, Zdenek Müller, Josef Tlusty

Published in: IEEE16th International Scientific Conference on Electric Power Engineering (EPE), 20-22 May 2015, Kouty nad Desnou, Czech Republic, pp. 2 – 7. Publisher: IEEE.

Paper seven made a comparative review of reactive power compensation technologies; the devices reviewed include Synchronous Condenser, Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM). These technologies were defined, critically examined and compared, the most promising technology was recommended for the realization of an effective, efficient, sustainable, qualitative and reliable electrical power network.

Chapter 2

2.0 General Literature Review: Importance of Reactive Power and State of the Art Reactive Power Compensation Equipment’s in Modern Electricity Grid Architecture

In deregulated electricity business environment, financial and market forces demand a more optimal and profitable operation of electricity grid architecture with respect to the generation, transmission, and distribution of electricity product. Therefore, electricity utility authorities have found solutions in the form of reactive power compensation devices to enhance grid stability and improve the quality of electricity product supply. Electrical practices for the entire electricity industry are tremendously changing and these progressions mark an evolution of new concepts and strategies in the future. Particularly concerning the planning and operation of modern electricity grid architecture. The detrimental effects such as aging, hazardous atmospheric changes associated with conventional electricity sources has made renewable energy generation to take a lead in future electricity generation methodology. However, the integration of renewables has created many power quality problems such as voltage harmonics, voltage sags, voltage swells, voltage imbalance, current harmonics, Reactive Power Compensation (RPC), current imbalance and circulation of neutral currents, impulse transients, and interruptions. Among these, reactive power compensation is considered as a major concern in electricity grid architectures. The electricity grid operates on alternating current and most of the loads used in our daily life demand reactive power. Thus, reactive power (VAR) compensation is characterized as the administration of reactive power to enhance the performance of an alternating current grid architecture. The issue of reactive power compensation is seen from two directions: That is load and voltage support. The aim is to achieve an improved power factor and real power balance from the load point of view. While voltage support is primarily necessary to reduce voltage fluctuations at given terminals of power lines. In both situations, the reactive power that flows through power lines should be effectively controlled and compensated [21] – [33].

2.1 Importance of Reactive Power Compensation in Modern Electricity Grid Architecture

Importance of reactive power in electricity grid architecture is increasing with growing demand for electricity product by domestic and industrial electricity consumers. The stability and reliability of an electrical power system depends on reactive power management. Reactive power is required to supply electricity in a more efficient, reliable and cost-effective way. Effective delivering of electricity product requires the utilization of technologies like Flexible AC Transmission System (FACTS) devices, SCs and so on. This is to maintain voltage stability, high power factor and minimize power losses. Reactive power plays a crucial role in AC electricity grid architecture. Alternating current has alternating voltage characteristics that makes it beneficial for use in electricity grid architecture. In AC network, energy storage elements like inductance and capacitance may result in periodic reversals of the direction of energy flow. This direction of energy flow produces active power, that is the portion of AC network that is averaged over a complete cycle of an AC waveform. Reactive Power is produced due to stored energy and returns to the source of generation and not to the load in each cycle. Despite the non-usefulness of reactive power in transferring energy to load in electricity grid architecture. Voltage control is dependent on it, in order to drive adequate active power. Alternating current electricity grid architectures produces and consumes two types of power; active and reactive power. Real power or active power is the true power given to electrical load. It is used to accomplish useful work like lighting lamps, powering rotating motors, etc. On the other hand, reactive power is regarded as imaginary power or apparent power. It does not do any useful work but simply moves back and forth in an electricity grid. Reactive power is a by-product of alternating current electricity systems. It is produced from inductive and capacitive loads. It exists when there is phase displacement between voltage and current, and it is measured in units of volt-ampere reactive (VAR). Reactive power is both a problem and solution to electricity grid architectures for several reasons. It plays an important role in electricity systems, owing to its various functions such as satisfying reactive power requirement, improving voltage profiles, decreasing electricity grid power loss, providing enough reserves to ensure electricity grid security in emergencies and so on. Reactive power importance as it relates to modern electricity grid architecture is further discussed below [34] – [36].

Reactive power helps in voltage control: Electricity grid architecture equipment’s are designed to operate within ±5% of nominal voltages. That is within specified limits of rated voltage at electricity consumer terminals. Fluctuations in voltage levels lead to malfunctioning of appliances. High voltage damages the insulation of windings. Whereas low voltage causes poor performance of equipment’s like low illumination of electric lightening bulbs, overheating of induction motors, etc. Voltage variations are mainly caused due to variation in load on electricity grid generation sources. If the load on an electricity grid source increases, the voltage drop in the grid components increases too. Hence, the voltage at the consumer terminals decreases, and vice-versa. These voltage changes on the electricity supply grid is undesirable as it aids in the deviation of the actual performance of equipment’s at consumer end such as lamps, motors and other equipment’s sensitive to voltage variations. An electricity grid architecture, therefore, should be designed to maintain voltage variations by providing voltage-control equipment at suitable locations on an electricity grid. The most common method of maintaining voltage profile in electricity grids is through the injection and absorption of reactive power. In general, an increase in reactive power causes grid voltage to rise while a decrease in reactive power causes grid voltage to fall [34], [36]. In electricity grid architectures, voltage control equipment’s are placed in two or more places. This assists in avoiding long distance transmission of reactive power and reduces excessive reactive power losses in grid networks. As there will be different voltage drops in different sections of electricity grid systems. Also, load characteristics will be different at various circuits of electricity grid. Most commonly voltage control equipment’s are placed at power generating stations, transmission substations and feeders. These equipment’s are employed for controlling the receiving-end voltage. In case of highly loaded electricity grid, the reactive power demand is more than that supplied. Hence, more current is drawn from the supply grid. This leads the receiving-end voltage to fall drastically. If the voltage drop further increases, it causes tripping of the generating units, equipment failures and overheating of motors. Under such situation, automatic operating mechanism or relays activates reactive power equipment's, such that reactive power is increased. Generator excitation terminal voltage is usually increased to provide more alternating current to alternators, this brings back an electricity grid voltage to rated value. This can equally be achieved with series reactors and series capacitors. In case of light loaded electricity grid scheme, power demand is less than the supply of reactive power. The receiving-end voltage rises to a greater value. This causes insulation damage to machines, lower power factor and automatic tripping of equipment's [34], [36].

Reactive power is used to reduce blackout in electricity grid architectures: Inadequate reactive power in electricity grid architectures has been a major reason for power outages in the globe. Insufficient quantity of reactive power on an electricity grid architecture causes voltage collapse. This ultimately leads to the shutdown of generating stations and equipment's. Several electricity blackouts so far experienced is due to insufficient reactive power on the electrical power system. This is on a higher scale since demand for apparent power is unusually high due to long distance transmission of electricity product. This ultimately leads to shut down of equipment's and generation units due to low voltages. So, to ensure proper working of the electricity grid architecture, enough reactive power must be present in it [34], [36].

Electricity grid architectures need to satisfy reactive power demand: Some loads such as transformers and HVDC converters need reactive power for their proper functioning. When the loads have large reactive power demand, voltage drop will take place. As voltage drops, more current will be drawn from the electricity supply source to maintain adequate power supply to consumers. This causes power lines to consume more reactive power and hence voltage drop further. Thereby leading to voltage collapse if voltage drops too low. Voltage collapse causes the tripping of generators, instability of electricity grid and tripping of equipment's connected to a grid network. This voltage collapse is as a result of the grid network unable to supply reactive power demand of load which is not being met due to shortage of reactive power generation and transmission. In order to overcome this, reactive power sources like series capacitors are connected to the loads locally where reactive power is required by the loads. The synchronous condenser technology can be utilized for same purpose. However, utility companies charge consumers as a penalty for reactive power demand if the loads draw excessive reactive power over allowable reactive power demand [34], [36].

Machines/Equipment's requires reactive power to produce magnetic flux for proper functioning: Most inductive loads such as motors, transformers, ballasts and induction heating equipment's require reactive power in order to produce magnetic field. In every electrical machine, reactive power is consumed for creating and maintaining magnetic flux. However, this leads to lower power factor. In order to achieve a higher power factor, capacitors are generally connected across these devices to supply reactive power. Transformers, motors, generators and other electrical devices require reactive power to produce magnetic flux. This is so, since generation of magnetic flux is necessary for these devices to do useful work. Reactive power helps to create magnetic field in motor, but it leads to a decrease in the power factor. Therefore, capacitors are placed to compensate inductive reactive power by supplying capacitive reactive power [34], [36].

2.2 Reactive Power Compensation Equipment’s in Modern Electricity Grid Architecture

Existing research work suggests the application of different compensation devices as a solution to reactive power compensation. Usage of capacitor banks, application of TSC and TCR devices of classic technology mitigates issues of power quality as it relates to reactive power compensation. Power electronics based Flexible Alternating Current Transmission Systems (FACTS) devices [Conventional thyristor base FACTS devices--- Static Var Compensator/Shunt Type Compensator, Thyristor Controlled Series Capacitor (TCSC), and Thyristor Switched Series Capacitor (TSSC); Converter based FACTS devices--- Static Synchronous Shunt Compensator (STATCOM), Static Synchronous Series Compensator (SSSC), and Unified Power Flow Controllers (UPFC)], have been developed and seemingly provide a powerful solution to reactive power compensation. Different techniques for controlling voltage in electricity transmission lines are including of: excitation control, tap-changing transformers, shunt capacitors, series capacitors, synchronous condensers, and boosters. Each method has its own advantages and disadvantages. Depending on suitability, availability and cost, these methods are employed for controlling the receiving-end voltage electricity grid architectures. Basically, there are two types of reactive power sources namely dynamic and static reactive power sources. Dynamic reactive power sources include transmission equipment’s and devices, which can respond to reactive power changes by quickly injecting or providing enough reactive power into the electricity grid. These equipment’s are of high cost. These include; Synchronous generators - Depending on the excitation voltage, active and reactive power generated is varied in synchronous machines. Automatic Voltage Regulators (AVRs) are used to control the reactive power over an operating range in these machines. Synchronous condensers - These are types of small generators, used to produce the reactive power without producing real power. Solid state devices - These include power electronic converters and devices such as FACTS devices [21] – [36].

Static reactive power sources are low cost devices. Their response to reactive power variation is somewhat less than the dynamic reactive power devices. These equipment’s are including of: Capacitive and inductive compensators - These consist of some shunt capacitors and inductors connected to the system to adjust the system voltages. Capacitor generates apparent power whereas inductor absorbs reactive power. Underground cables and overhead lines - Current flowing through cables and overhead lines produces net magnetic flux which generates reactive power. A lightly loaded line acts as reactive power generator while heavily loaded line acts as absorber of reactive power. Photo Voltaic (PV) systems - These are used for active power injection as well as harmonic and reactive power compensation in electricity grid architectures [22] – [25].

At the distribution level, minor variations in voltage are dealt with using VOLT/VAR control, that is Distribution System Voltage Control. These minor voltage changes during daily operations may cause both under and over voltage violations. On Load Tap Changers (OLTCs) and capacitor banks are technologies usually used for dealing with reactive power compensation at the electricity distribution level. The controller manages the taps of both and checks for voltage limits at nodes. The reactive power provided here is not at the expense of real power, and the only capital cost is the installation of controllers, capacitors, and OLTC. At the generation level, the primary voltage control is provided by Automatic Voltage Regulator (AVR). A controller regulates the terminal voltage of synchronous generator. Even so, Power System Stabilizer (PSS) is equally used for further improving stability. These controls are enough for reactive power and voltage control at the generating end electricity grid architectures. Therefore, the main stability issue arises at the electricity transmission level. Thus, requiring reactive power compensation techniques. The conventional method is the use of synchronous generators at generation side for reactive power compensation resulting from reactive power imbalance at transmission level. Conventional power plants have synchronous generators to supply/absorb reactive power. Synchronous generator can produce reactive power in an over-excitation state. It can as well consume reactive power in an under-excitation state. All these are at the expense of real power [4].

Diverse sinks of reactive power do exist. Reactive power generated by generators and other sources is absorbed by loads, which are including of; Induction motor such as Pumps and Fans, Transformers, Under excited synchronous machines, and Heavily loaded electricity transmission lines. Transformers--- In order to produce magnetic field, transformers need reactive power, therefore it absorbs reactive power. The reactive power consumption of a transformer depends on the rating and current loading. Loads--- There are many reactive power consuming loads that have great impact on bus or power system voltage and stability. Some of these loads include induction motors, induction generators, arc furnaces, discharged lighting, constant loads such as induction heating, space heating, water heating, and air conditioning. Electricity Transmission Lines and Underground Cables--- Both transmission lines and cables absorb and generate reactive power. A heavily loaded electricity transmission line consumes reactive power. Thus, decreasing the voltage of the line whilst a lightly loaded electricity transmission line generates reactive power. Hence, increasing the voltage of the line. Solid State Converters--- There are several solid-state converters in-use in electricity grid operation, an example is the HVDC converters. These converters always consume reactive power when they are in operation. For this reason, most of the converters use reactive power compensation devices to control reactive power requirement of the converters. These equipment’s do experience losses; therefore, compensation devices are necessary to be placed at these loads [34], [36]. Some reactive power compensation equipment’s are discussed in detail in this chapter.

2.2.1 Capacitor Banks

A Capacitor Bank is a group of several capacitors of the same rating that are connected in series or parallel with each other to store electrical energy. The resulting bank is then used to counteract or correct a power factor lag or phase shift in an alternating current power supply. They can also be used in a direct current power supply scheme to increase the ripple current capacity of the power supply or to increase the overall amount of stored energy [37]. Connecting caps usually in parallel or unusually in series banks, still results in a capacitor. It is just one capacitor comprising of many caps. So, the functionality remains the same. But in the case of parallel connection, the capacitance increases. This is used to smoothen the output of huge rectified direct current supply. Most commonly utilized for power factor correction. For best efficiency, current and voltage must be in phase. In alternating circuits, this is only the case in purely resistive circuits. Inductance causes current to lag voltage. Capacitance causes current to lead voltage. In both cases, the greater the lag or lead angle, the greater the power losses. Realistically, most domestic, commercial and industrial loads are overall inductive, take for example transformers, motors, and generators. Inductance and capacitance have opposite effect. Capacitance causes current to lead voltage, while inductance causes current to lag voltage. The capacitive effect of capacitors is used to offset the inductance of combined inductive loads. This reduces voltage/current angle, thereby decreasing power losses [38]. In large electricity distribution systems such as are found in factories and other industrial settings, there are sometimes lots of motors and transformers. Both types of devices use magnetic fields and have inductive reactance. Inductive reactance as well as capacitive reactance both causes electricity system power factor to shift away from the desirable state of unity or 1. What this means is that there is power being consumed by the system. But this power is not useful, and it is not doing work. This power is called apparent power. The plant, factory, or whatever usually still must pay for this power. So, it is literally throwing money away. Capacitor banks are used to correct inductive reactance, by adding capacitive reactance to the electricity grid architecture. This helps to get grids network power factor closer to unity. A unity power factor means that a plant is only paying for real power, or power doing useful work [39]. A capacitor represents energy stored in the electric field of any dielectric material. This energy is termed reactive energy and is required to support the maintenance of electromagnetic fields for the transmission of power through and throughout an electricity grid architecture via the propagation of power stored within electromagnetic fields. Without enough capacitive reactance or reactive power, grid voltage may collapse. Capacitors can be used for power factor correction and power transmission improvement. It does this by making reactive energy stored within dielectric material available to load in an electricity grid architecture [40].

Inductors, which are present in motors and transformers draw power from the electricity networks. But after a little while they give it back to the network as reactive power. This power is not consumed, but it must travel all the way from the generation plant to end users like industries, and then the way back. Although this power is not consumed, electricity supplier charges for it since electricity grid networks has been designed to handle it. This is in addition to active power, which is consumed by electricity end users. When a capacitor is put near an inductor, reactive power is exchanged between the inductor and the capacitor. Energy is passed from the capacitor to the inductor, then from the inductor to the capacitor and so on. By this way, reactive power does not have to be supplied all the way from the electricity generation plant [41]. Heavy loads are inductive in nature. Implying that current lags voltage, power factor is therefore less. This condition makes power losses to increase. Warranting the reduction of the inductive nature of loads. Which can be achieved with capacitor banks. These capacitors just cancel the effect of increases in inductance and power factor. Thus, power losses are reduced [42].

In electricity grid architecture, most appliances used have inductive components. Therefore, they draw lagging reactive power from the grid. To balance or cancel out this effect, capacitors are connected in parallel with power system supply to draw leading reactive power. Leading reactive power is in the opposite direction of lagging reactive power. This methodology of connecting capacitors in parallel is to allow capacitance bank to maintain a voltage rating that is same or a little higher than system voltage [35]. The power consumed in a grid network is a combination of two types of powers, Active power (P) and Reactive power (Q). Take for instance, when running an electrical fan both active as well as reactive power is needed. The active power is responsible for the rotation of the fan and the reactive power is responsible for the magnetization of the field. But there are sometimes situations, when load consumes more reactive power than the desired value. Here, the reactive power demand increases beyond the desired value. There is a chance of voltage drop at the load end of the grid network. The generating side of the grid, at this instance cannot supply much amount of reactive power. If the voltage drops below a certain specified level, then there is chance of electric power failure. leading to electricity black out. To prevent issues like this, extra reactive power is supplied to loads with the help of capacitor bank. This VAR compensation technique helps to reduce the load on the generating station. The main purpose of

providing capacitor bank in case of electricity grid architecture is to supply reactive power to the power system. Capacitor banks are installed at the receiver end of grid networks [43].
Capacitor bank is used along with electricity transmission line system. It can supply reactive power mainly required by generators used in electricity power plants [44]. It can be star or delta connected. Delta-connected capacitor banks are generally used only in Medium Voltage (MV) distribution electricity systems and in Low Voltage (LV) installations. Capacitor banks may have built-in discharge resistors to dissipate stored energy to a safe level within a few seconds after power is removed. Capacitor banks are stored with the terminals shorted, as protection from potentially dangerous voltages due to dielectric absorption. High Voltage (HV) Capacitor banks are installed outdoors, surrounded by a fence, and LV Capacitor banks are installed indoors, in metallic enclosures such as switchboards. In MV installations Capacitor banks may be installed either outdoors, surrounded by a fence or in the pole of a MV overhead line, or indoors in metallic enclosures like switchgears. The fence has a lock with a delayed opening to assure the time requested for the complete discharge of the capacitors [45]. A shunt Capacitor bank or simply Capacitor banks is a set of capacitor units, arranged in parallel/series association within a steel enclosure. Series capacitor compensation is generally applied for electricity transmission lines to generate reactive power when it is most needed while shunt capacitors are installed at substations in load areas to generate reactive power and for keeping voltage within limits [36], [45]. In order to properly compensate reactive power changes that occur in an electricity grid system, shunt capacitor may need to be switched on or switched off at load maximum or minimum. This switching is apparently important to the success of this methodology, since load will always vary. Different conventional methods can be used to control switched capacitors, such as time, voltage and reactive power [35]. Capacitor banks for both HV and LV power systems operations are shown in Fig. 2.1 and 2.2 respectively.

Combination of switched capacitors is the less expensive amongst reactive power compensation methods, and there is no loss of real power due to reactive power. Although, reactive power varies with voltage in a square relation, according to capacitor equation. Thus, this methodology is only suited for LVs and MVs applications. Considering HV applications and applications where voltage is a critical phenomenon, such as the tripping of voltage relays in power system protection domain, switched capacitor is not a proper option [4]. Capacitor banks must be implemented in proper location in an electricity grid architecture. But the drawback of this technique appears when the capacitors turns on and off, which may cause disturbance in an electricity distribution network. A fixed Capacitor bank may often lead to either over or under compensation. Other issues associated with Capacitor bank are the generation of high frequency harmonic and the Resistor, Inductor, and Capacitor (RLC) circuit created by Capacitor bank may lead to resonance at some frequencies [5], [28].

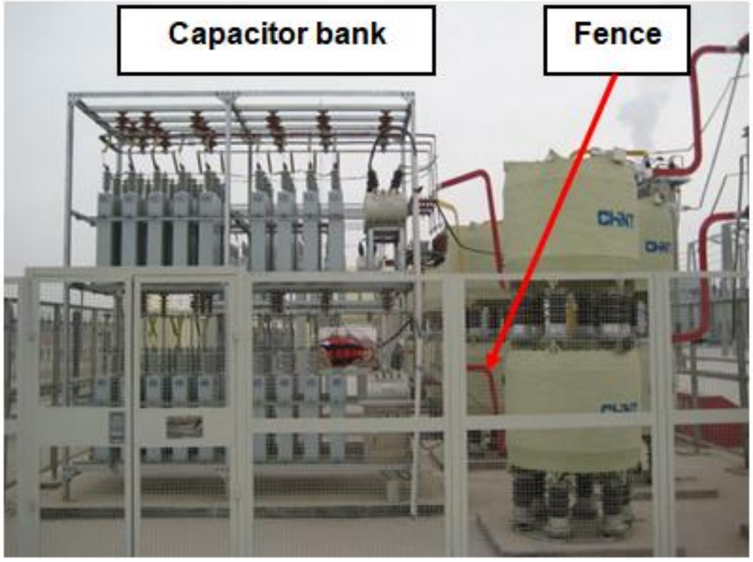

Fig. 2.1: High Voltage Capacitor bank [45].

Fig. 2.2: Low Voltage Capacitor bank [45].

2.2.1.1 Capacitor Unit

A capacitor is equally known as a condenser. It is an electrical element with two electrical conductors separated by an insulator material, in this case a dielectric. The most common used dielectrics are Ceramics; Plastic films; Oxide layer on metal such as Aluminum; Tantalum; and Niobium; Mica, glass, paper, air and other similar natural materials; and Vacuum. The electric parameter that defines a capacitor is the capacitance (C). The unit is the farad (F). Capacitors may retain a charge long after power is removed from a circuit; this charge can cause dangerous or even potentially fatal shocks or damage connected equipment's [45]. A simplified scheme of a capacitor is shown in figure 2.3.

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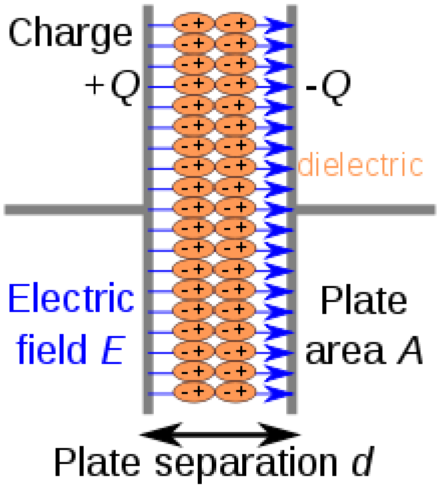


Fig. 2.3: A simplified scheme of a capacitor [45].

The capacitor unit is the building block of a series capacitor bank. The capacitor unit is made up of individual capacitor elements, arranged in parallel-connected or series-connected groups, within a stainless-steel enclosure as shown in Fig. 2.4. The internal discharge device is a resistor that reduces the unit residual voltage to 50 V or less in 5 minutes. Capacitor units are available in a variety of voltage ratings from 240 V to 24 940 V, and in sizes of 2.5 kvar to about 1000 kvar. Capacitors are designed to withstand higher currents such as those experienced during emergency loadings (which are typically 30 minutes rating), system swings, and during faults as specified by the purchaser. Capacitor bank rating are designed to operate continuously according to IEEE Std 1726™-2013.4. Capacitor units are designed to withstand specified continuous rated current, emergency loading, swing current, and power system faults, within a maximum allowable capacitor unbalance condition as determined by the control and protection system [46] – [48].

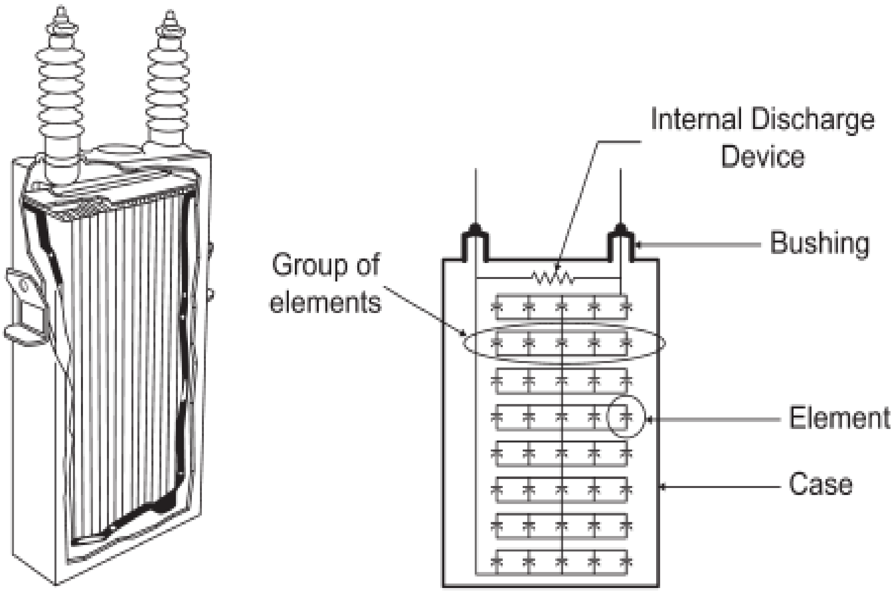


Fig. 2.4: The Capacitor Unit [46].

The capacitance of a capacitor bank is accomplished by connecting capacitor units in series and parallel to provide a required capacitive reactance with a continuous current rating. Three different types of fusing arrangements are applied on series capacitor banks. These are Externally fused capacitor bank, Internally fused capacitor bank, and Fuse-less capacitor bank [46] – [48].

The externally fused capacitors involve the connection of groups of fused capacitors in parallel, as necessary to meet the current rating of the bank. These groups are connected in series to realize the voltage and impedance ratings of the bank. Dual-element fuses consisting of two fuses in series are typically applied to each capacitor unit. One of these fuses is a current-limiting type, it is used owing to the high stored energy in the parallel capacitors group. The second fuse is an expulsion type, it operates for lower current conditions and provides visible break. A failure of a capacitor element welds the foils together and short-circuits the other capacitor elements connected in parallel in the same group. The remaining capacitor elements in the unit remain in service with a higher voltage across them than before the failure and an increase in capacitor unit current. If a second element fails, the process repeats itself resulting in an even higher voltage for the remaining elements. Successive failures within the same unit will cause the fuse to operate, disconnecting the capacitor unit and indicating which one failed. This results in increased voltage on the parallel units. The magnitude of this voltage increase is dependent on the number of units in parallel in a manufacturer's design. The available unbalance signal level decreases as the number of series groups of capacitors is increased or as the number of capacitor units in parallel per series group is increased. The capacitor units can have only one insulated terminal with uninsulated terminal connected to the rack or two insulated terminal bushings [46] – [48]. An Externally fused capacitor bank is shown in Fig. 2.5.

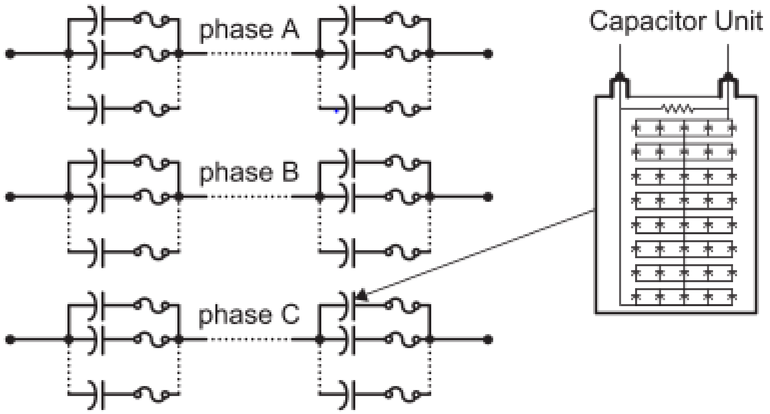


Fig. 2.5: An Externally fused capacitor bank [46].

The internally fused capacitor units equally involve groups of fused elements connected in parallel. These groups are then connected in series to realize the rating for the unit. The units are connected in series and parallel as necessary to meet the overall ratings of the bank. The failure of a capacitor element results in a discharge current from the parallel elements through the associated internal fuse, which blows the fuse. This results in increased voltage on the parallel elements within the unit and a much smaller increase in the voltage across the associated unit. The magnitudes of these voltage increases are highly dependent on the number of elements in parallel in a manufacturer's design. The capacitor units may have one or two insulated bushings [46] – [48]. A typical illustration of internally fused capacitor units is shown in Fig. 2.6.

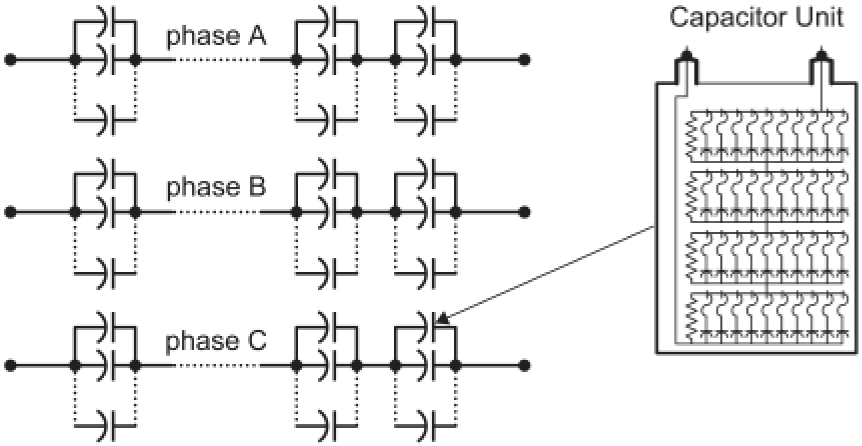


Fig. 2.6: Internally fused capacitor bank [46].

The capacitor units for fuse-less capacitor banks are identical to those for externally fused, or elements inside the unit may equally be series elements in a string that are in parallel. A bank is made of strings of series-connected capacitor units between phase and neutral. These strings of capacitors are connected in parallel as necessary to attain the current and impedance ratings of the bank. The number of units connected in series is as required to achieve the necessary voltage capability. For capacitor units designed like externally fused banks the failure of a capacitor element results in a short circuit of the associated group of elements within the capacitor unit. This results in an increase in current through, and increased voltage on, the remaining elements within that capacitor unit and the other capacitor units in the associated string. The degree of this increase is dependent on the total number of elements in series in the string. The capacitor unit with the shorted element remains in continuous operation. Modern capacitor units used in fuse-less applications have an all-film dielectric system [46] – [48]. A fuse-less capacitor banks is vividly presented in Fig. 2.7.

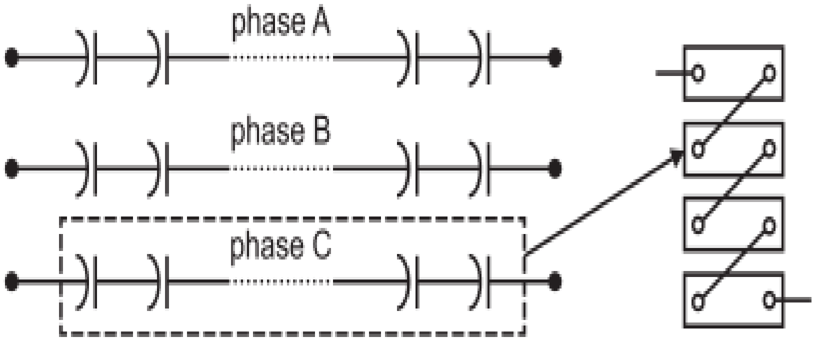


Fig. 2.7: Fuse-less capacitor bank [46].

2.2.2 Conventional Generators

There is scarcity of reactive power, when power system engineers fail to supply the required reactive power from generators at different electricity grid conditions. Scarcity of reactive power in an electricity grid architecture is due to the variation in generation and transmission capacity. Thus, power system engineers always ensure qualitative and reliable electricity product supply to customers. Despite efforts towards quality electricity product, overloading in existing power transmission systems, voltage collapse, voltage stability and power loss are still issues of major concerns. At grid conditions, the capability of a generator supplying reactive power can be increased by decreasing the requirements of the generator output. Also, voltage stability can be maintained with reallocation of reactive power production [49].

Very large industrial electricity generation facilities use sets of synchronous generators coupled to prime mover elements, such as gas or steam turbines to produce electricity. The system dispatcher provides each power plant in the grid with both active and reactive power. Consequently, each power plant distributes active power among available generators based on generators size and limitations. However, despite correctly distributing active load among generators of a power plant feeding the same transmission line. Reactive load might not be properly shared among generators. The unbalance in distribution of reactive power among different generators may lead to issues such as --- Some generators producing significantly more reactive power than others in relation to their size; Overloading has a negative effect on power generators life span. It leads to higher maintenance costs of generators. --- Overloaded generators are more likely to reach their own production limit which is set by the manufacturer; When that happens, increase in active load forces operators to manually intervene in order to properly distribute reactive load among generators.--- Reactive power unbalance among generators connected in parallel might cause voltage stability issues; Voltage stability is the ability of an electricity grid architecture to maintain a steady voltage in the presence of disturbances. In situations when load increases drastically, and an immediate increase of reactive power is needed to maintain voltage stability. Generators that has already reached their reactive power limits might not be able to contribute reactive power. Thus, providing a de-stabilizing action to the voltage control system of the grid. --- Unbalanced distribution of reactive load might cause the generation of circulating currents, due to the phase shifts among different generator outputs. Such circulating currents results in waste of fuel and possible overheating of generator coils, thereby lowering the efficiency of generators. These problems are very common in electricity generation plants. Therefore, there is a need for a control system that can prevent any unbalanced distribution of reactive power among generators within the same power plant. Since generators connected to the same power transmission line could be of different sizes, a mechanism to determine the amount of unbalance in the reactive load distribution is equally needed for feedback control purposes [50].

2.2.2.1 Reactive Power Capability of a Generator

Synchronous machines can generate or absorb reactive power depending on the Direct Current (DC) excitation to its field winding. It generates reactive power when over-excited and absorbs reactive power when under-excited. It is the most commonly used source of reactive power for voltage control [36]. The picture of a synchronous machine is shown in Fig. 2.8 below. It is very important to consider the reactive capability limits of synchronous machines particularly in voltage stability and long-term stability studies. The output power of synchronous generators is specified based on maximum MVA at rated voltage and power factor, which is to be carried out continuously without generator over-heating. The active output power is limited by the capability of prime mover. The continuous reactive output power limit of synchronous generator is mainly limited by armature current limit, field current limit, mechanical power limit and end region heating limit [51]. However, there are some limitations for synchronous generators provision of reactive power. Synchronous generators are designed to produce real power, and not reactive power. Therefore, the main issue is the loss of real power due to reactive power provision. The synchronous generator utilizes a significant portion of real power capability. It is thus clear that it is not very efficient utilizing it for the purpose of reactive power provision. The real power is limited by the size of turbine, and the reactive power has the limitation of the size of synchronous generator. Therefore, increase in reactive power means more investment in terms of increase in ratings of turbine and synchronous generator. There are equally limitations of rotor winding, stator winding, over-excitation, under-excitation etc. [4]. Reactive power compensation using the synchronous generators is efficient in stabilizing high voltage part of electricity distribution grid. Electricity grid system is limited geographically to the entry point of distribution network. Therefore, the reactive power supplied by synchronous generators has limited effect on Reactive Power (Q) and Voltage (V) in distribution networks. This reactive power compensation technique is fast enough to compensate for rapid load changes. But additional compensator is required to ensure that the quality of power delivered to electricity product consumers in remote parts of distribution systems is satisfied [5], [28].

Fig. 2.8: Synchronous Machine [36].

Reactive Power Support (RPS) is the capability of a generating unit to supply reactive power to or absorb reactive power from the electricity grid architecture. This is done to maintain bus voltage within five percent (5%) of nominal voltage. A generator is providing RPS, if it operates outside the range of 0.85 lagging and 0.90 leading power factor but within its reactive capability curve. [52]. An illustration of generator capability curve is presented in Fig. 2.9 and 2.10 respectively. Traditional synchronous generator reactive power capability is typically described by a “D curve”, covering the range from zero to rated output. But it should be noted that synchronous generators are limited by the minimum load capability of generating plant. Some traditional generators are designed to operate as synchronous condensers. Thereby allowing them to provide reactive power at zero load. Although these generators still cannot operate between zero and minimum load. The ability of traditional generators to provide reactive power at zero load should be a prerequisite in the design of power plant. Though this is not possible with many larger power plant designs. From the foregoing, it is vividly clear that the practical reactive power capability of a typical synchronous generator is more limited than the typical “D curve” as can be seen in Fig. 2.9 and 2.10. Taking into consideration negligible auxiliary load, corresponding power factor at the electricity transmission line interface is easily determined given generators power factor at terminal ends and reactance of generators step-up transformer. Generally, a generator with a reactive capability of 0.9 lag and 0.983 lead as calculated at generator terminals. When connected to electricity transmission grid through a transformer with a leakage reactance of 14% on a generators MVA base, can provide 0.95 lag to lead at the electricity transmission line interface. This is possible if the electricity transmission system is at nominal voltage, that is 100%. Typical specifications for synchronous generators require 0.90 lagging and 0.95 leading at the machine terminals. Allowing voltage regulation at an electricity transmission voltage range of 90% to 110%. Synchronous generators have maximum continuous voltages of 105%, and minimum voltage of 95%. Depending on power system voltage and generator output level, these limits may come into play. In such situation, reactive power capability is reduced [53].

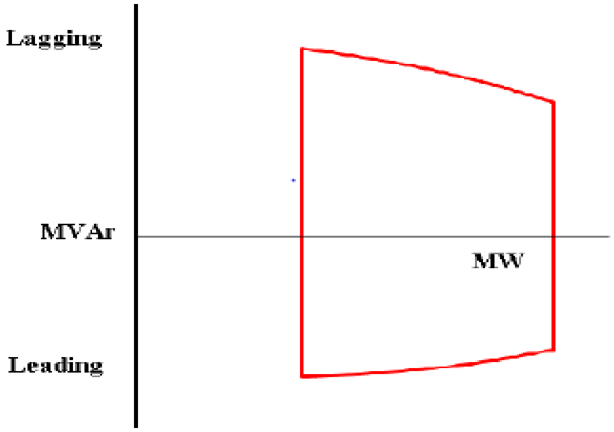


Fig. 2.9: An illustration of reactive power capability of a synchronous generator, taking into consideration power plant minimum load [53].

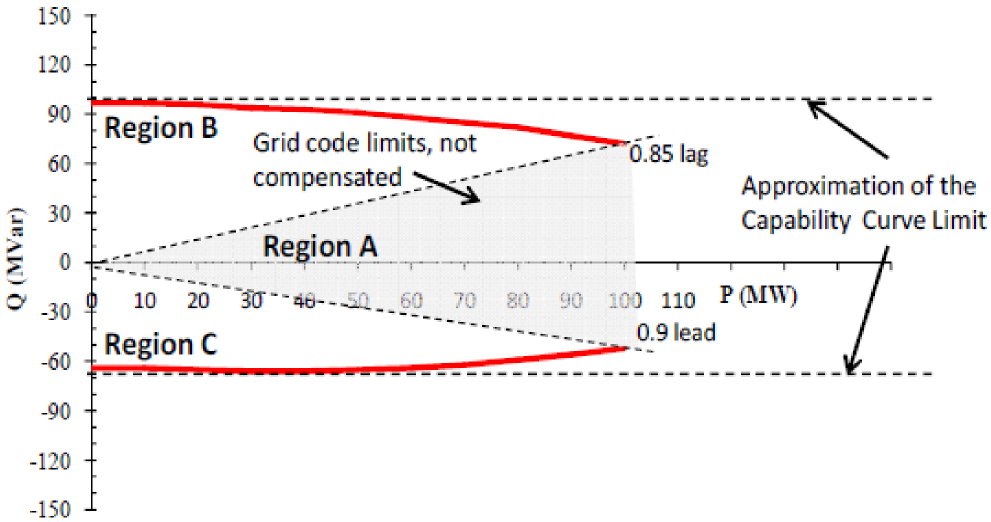


Fig. 2.10: Generator capability curve [52].

Reactive power reserve is filtered into potential reactive power output and dynamic reactive power output. Potential reactive power reserve is the difference between the maximum reactive power output and current output in a certain power system operation mode. Putting into consideration software and hardware restrictions of generator unit. It represents generator's ability to increase reactive power output under current output conditions. Dynamic reactive power reserve refers to the difference between actual maximum reactive power output by electricity generation and the steady-state reactive power output before failure occurs in a certain power system operation mode. It represents the activated and released part of the potential reactive power reserve when a generator is involved in specific transient process. Only dynamic reactive power reserve can be utilized to improve the dynamic characteristics of an electricity grid architecture. Non-activated reactive power reserve is potential reactive power reserve minus dynamic reactive power reserve [54]. Figure 2.11 represents an illustration of reactive power reserve.

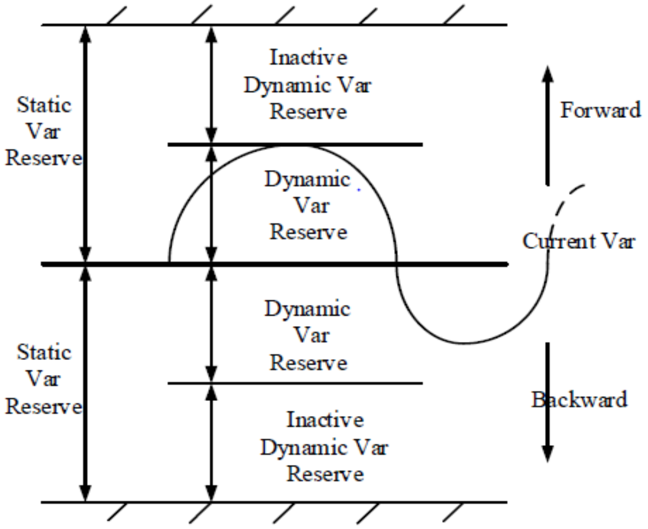


Fig. 2.11: An illustration of reactive power reserve [54].

To achieve optimal voltage control as regards to minimum cost and increased reliability of electricity supply to consumers at transmission network buses. It is necessary to deploy full available generator reactive capability. While maintaining reactive reserve as high as possible. In addition to generators supplying active power in mega-watt (MW) to satisfy load requirements in an electricity grid architecture. Generators equally deliver reactive power to support voltages across electricity grids. Conventional generators are the main source of reactive power in power systems. Research have shown that voltage instability often occurs after key generators reach their reactive capability limit. Proper reactive power support from generators is crucial for maintaining voltage stability of electricity grid architectures. Reactive power from this compensator is required to provide voltage support, meet the reactive component of load and losses, and enable transmission of active power across an electricity grid architecture. Reactive power capability, that is ability of a compensator to generate reactive power, is a built-in function of the generator. The rated power factor of generators is usually 0.85 or 0.90. A lower power factor generator has a higher reactive capability at rated MW output. Reactive power support ability nonetheless, does not come free of charge. Normally, a standard 0.90 power factor generator costs approximately 6% less than a 0.85 power factor generator [55] – [56].

Independent System Operator (ISO) is ultimately responsible for proper allocation of reactive power sources as well for maintaining enough system reactive power reserve. To facilitate these actions, generator owners always must be fully aware of available generators reactive power (Q) capability. Generator capability diagram, that is D-diagram or generator performance chart, provided by a manufacturer at the time of commissioning of a generator unit, determines the boundaries for delivering reactive power at given real (active) power output. These boundaries, when reached, may sometimes results in violation of various constraints imposed by other system equipment's and processes within the plant. Although the generator itself might be able to operate entirely in a safe condition. An auxiliary equipment voltage limits, stator or transformer winding voltage limits, over and under excitation limits and the accelerated ageing of generator and step-up transformer parts, are some of the typical constraint violations that might occur when a generator is strictly following original D diagram provided by a manufacturer [56].

Power plant operators performs real and reactive power allocation among the generators in a power plant. But despite this, it is hard to achieve optimal power distribution among generators owing to different D-diagrams of individual generators and additional technical limitations that can reduce the operating range of power generators. Hence sometimes power system operators drive the generator operating point outside the D-diagram owing to lack of information about all relevant limitations imposed by power generators and equipment's. Power plant operators cannot always adequately estimate the distance between the actual operating point of generators and the actual D–diagram boundaries owing to inability to update D-diagram in real time according to changes in generator terminal voltage. Nevertheless, fixed manufacturer D-diagrams does not provide an insight into all operational and physical limitations of power generators. Particularly terminal voltage limits, auxiliary services voltage limits and coordination with excitation limiters and protection. These limits are not fixed and depends on system operating conditions. Power plants and system operators will benefit from an on-line capability curve that would include, in real time, all operational and physical limitations on generators and information about the actual available reactive power range of generators in an electricity grid architecture [56].

2.2.3 Distributed Generators

Distributed Generation (DG) is an electric power source connected directly to the distribution network or on the customer site of electricity meter [57]. It refers to small generating sources or units using real and reactive power to uplift voltage profile established near local loads and load centers. Distributed generation systems are located at or near point of electricity product utilization. This moderates the necessity of electricity grid architecture expansion. DGs can be expounded in several ways, it ranges from a few KW to 50 MW. It can be described as a generating plant serving consumer onsite or yielding aid to an electrical system linked to an electricity grid architecture at various voltage levels. DGs are of different types ranging from conventional fossil fuel-based combustion to renewable energy base, including micro turbines, wind, photovoltaic, Combined Heat and Power (CHP) systems also known as cogeneration, small hydro turbines or hybrid renewable schemes. Distributed Generation is impressionistic and varies with locality [57] – [58].

The changing regulatory and economic scenarios in the electrical industry; the need for more flexible electrical systems; technological advances; rising global fuel prices; and renewed interest in environmental issues are playing a key role in the development of distributed generation schemes. As part of a long-established practice, ancillary services are supplied by large conventional generators. But, with the huge penetration of DGs as a result of the growing interest in satisfying energy requirements and considering the benefits it brings along to the electrical system and the environment. Ancillary services in electricity grid architectures could equally be provided by DGs in an economical and efficient way. Researches have considered DGs as potential providers of ancillary services. Many of these researches involve the use of DGs as providers of reactive power support. DGs are already being used to provide reactive power for grid stability in compliance with grid codes in many countries. Reactive power can be provided by DGs such as Photovoltaic (PV) plants, wind turbine plants and CHP plants. Generally, the power generated by DGs based on renewable resources such as wind and solar radiation varies considerably over time. A high degree of variability reduces the available capability of these DGs. Since their power output is uncertain. To determine the true available capability of DGs based on renewable resources for ancillary services. Uncertainty must be reduced, so that DGs based on renewable resources can be regarded as a reliable alternative. Particularly in the provision of sensitive services such as ancillary services [59] – [60].

Variable electricity generating plants used to be considered as very small relative to conventional power generating units. Characteristically, it is either induction generator wind plants or line-commutated inverters PV plants that have no inherent voltage regulation capability. Bulk power system voltage regulation was provided almost exclusively by synchronous generators. But, the growing level of penetration of renewable power generation, especially from wind and solar power. Led to the need for renewable generation to contribute more significantly to power system voltage and reactive power regulation. Variable electricity generation resources such as wind and solar PV are often located in remote locations, with weak transmission line connections. Therefore, it is not uncommon for wind and solar PV parks to have short circuit ratios of 5 or less, that is the ratios of three-phase short circuit Mega Volt-Amperes (MVA) divided by nominal MVA rating of a power plant. Ancillary service for voltage support in power systems is very vital, as it prevents voltage instability and ensures good power transfer [53].

2.2.3.1 Reactive Power Control with PV Inverter and Wind Generator

Voltage regulation is an important issue in low and medium voltage electricity distribution systems. It is the responsibility of electricity distribution system operators to keep distribution grid voltage within acceptable range. Solar PV renewable energy systems have negative impacts on voltage profiles of electricity grid architecture. PVs usually consists of PV array, which is interfaced to electricity distribution systems through an inverter. With high penetration of PV renewable energy systems in electricity distribution circuits, real power injected to distribution grid schemes tend to cause local voltage profile to increase. This voltage rise can be large enough to cause adverse voltage fluctuations to electricity consumers loads connected to the distribution grid. Figure 2.12 shows the power generation profile of PV and the spare capacity of its inverter. The capability of PV inverter is shown in Fig. 2.13. Where $P_{PV,}$ Q_{PV}, and PF_{PV}, are the output power of PV system, reactive power of PV system injected through an inverter, and power factor of PV system respectively. At night there is no power generation from PV system, so PV inverter supplies the maximum value of reactive power which is equal to its rating. Even so, PV inverter can inject enough reactive power to increase the output voltage within the voltage boundary. During day time PV array supplies active power onto electricity grid architecture. However, during this time output voltage is larger than upper limit voltage boundary. Hence, PV inverter absorbs reactive power from electricity grid, in order to reduce voltage profile below upper limit voltage boundary. But note that absorbed value of reactive power is according to the rating of PV inverter. The spare capacity of PV inverter is almost zero during maximum PV power generation. Therefore, PV inverter cannot help in solving voltage rise issues at this instant, especially with high PV penetration [61].

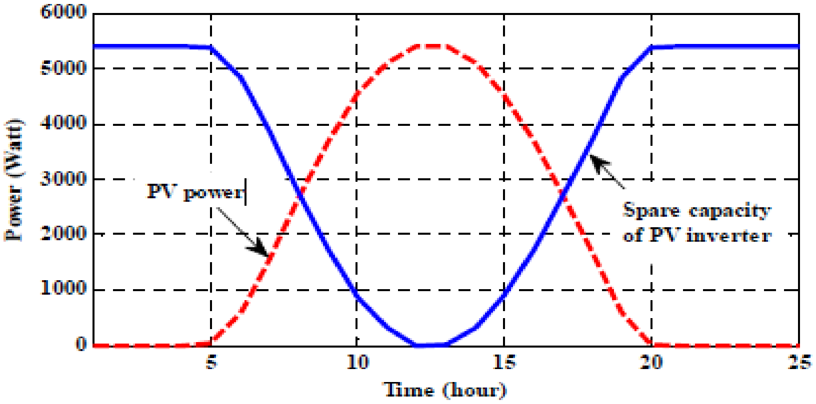


Fig. 2.12: Power generation profile of PV and spare capacity of its inverter [61].

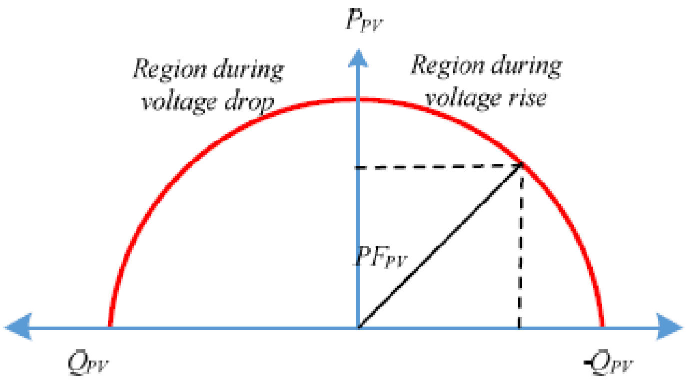


Fig. 2.13: Capability curve of PV inverter [61].

Wind power generators with converter interface are often designed for operation from 90% to 110% of rated terminal voltage. Lagging capability of wind turbines may diminish as terminal voltage increases, owing to internal voltage constraints. It can equally diminish as terminal voltage decreases, owing to converter current constraints. Leading capability of wind energy generators normally increases with increasing terminal voltage. Doubly fed and full converter wind power generators are often sold with “triangular,” “rectangular,” or “D shape” reactive capability characteristic as shown in Fig. 2.14. This represents the reactive power capability of individual wind generators or PV inverters. Machines with rectangular or D-shaped reactive capability characteristic can be employed to provide voltage regulation service, when such machines are not producing active power by operating in a STATCOM mode during voltage reduction. Take for instance, a low-wind-speed condition for a wind energy resource or at night for solar PV energy resource. Although, this capability might not be available or enabled by default. Unlike doubly fed or full-converter wind turbine generators, induction-based wind generators without converters are unable to control reactive power. Under steady-state conditions, they absorb reactive power just like any other induction machine. Usually, mechanically switched capacitors are applied at wind generator terminals in order to correct power factor to unity. Several capacitor stages are used to maintain power factor near unity over several ranges of output of PV inverters, having similar technological design to full converter wind generators. These are increasingly being sold with similar reactive power capability. Historically, PV inverters are designed for deployment in electricity distribution system. where applicable interconnection standards (IEEE 1547) do not currently allow for voltage regulation. Inverters for such grid applications are designed to operate at unity power factor. They are sold with kilowatt (kW) rating, as opposed to kilovolt-ampere (kVA) rating. At low DC voltages, that is Maximum Power Point (MPP) voltage. Many PV inverters cannot provide full reactive power support, as they are in overexcited mode. With the increased use of PV inverters on electricity transmission grid, the electricity industry is moving towards the ability to provide reactive power capability. Certain PV inverters have the capability to absorb or inject reactive power. Provided that current and terminal voltage ratings are not exceeded. The cost of an inverter is related to the current rating of power plant. The provision of reactive power at full output means that inverter rating needs to be larger than plant MW rating. This comes at a higher cost compared to existing industry practice. Fundamentally, inverters can provide reactive power support at zero power, like STATCOM compensator. But this functionality is not standard in the electricity industry. PV inverters are normally disconnected from the electricity grid at night, in which case inverter-based reactive power capability is not available. This practice can be modified, if site conditions dictate the use of reactive capability during periods when generation is normally offline [53].

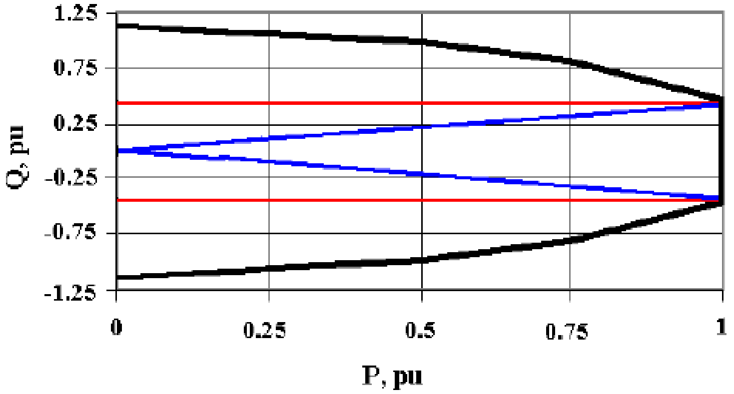


Fig. 2.14: Individual wind generators/PV inverters triangle, rectangular, and D-Shape capability curve for 0.9 power factor at rated output/nominal voltage [53].

Wind farms uses asynchronous induction machines to convert wind energy to electricity. Thus, in order to synchronize with the grid, wind farm generators use power converters such as AC-DC-AC converters. AC-DC-AC power conversion provides independent control of reactive power. Reactive power is not dependent on real power for dynamic power system conditions. But, in order to maintain a continuous power factor and independent control of reactive power, it is required to oversize the converter by 10% of generator's rating. Solar panels use Maximum Power Point Tracking (MPPT) and inverters to convert solar energy into electricity. These inverters can equally provide reactive power control. For dynamic situation, reactive power is dependent on real power. Oversizing inverters by 10% of generator's capacity, make available 46% reactive power at 100% real power or 110% reactive power at zero real power [4], [62].

Reactive power capability considering power plant interconnection, are specified at the Point of Interconnection (POI). In between the POI and generator terminals is a series of collection feeders designed to collect output power of individual generator. When given the spatial dispersion of generators for a given electricity grid architecture. There is added impedance which impacts reactive power delivered at the point of interconnection relative to generators reactive power contribution. This is a very important consideration for wind and solar power plants. This implying that several technical options can be considered in designing the plant to meet interconnection requirements. Technically speaking, a plant with inverter-based wind or solar generators can rely on the inverters to provide part or all the necessary reactive power range at the point of interconnection. Although, using external static and dynamic devices such as Static Synchronous Compensator (STATCOM), Static VAR Compensator (SVC), or Mechanically Switched Capacitors (MSCs) might be more economical. The additional amount of reactive support required depends on the reactive capability of individual wind generator or PV inverters and how the generator is utilized. Occasionally, external dynamic reactive power support is required to assist electricity grids voltage ride-through compliance. During times of low availability of wind or solar resource, some generators in a power plant may be disconnected from the grid. Also, the DC voltage for solar PV inverters may limit the reactive power capability of inverters. These issues should be taken into consideration when specifying reactive power capability for variable electricity generation plants. Below a certain output level, the specification should show a reduced power factor range, or a permissive MVAr range. The interconnection requirements such as shown in Fig. 2.15 are often applied to transmission-connected wind power plants. In the case of PV transmission-connected plants, a requirement to maintain reactive power range at full output represents a change with respect to historical electricity industry practice. Cost impact can be substantial, if PV plants relies on PV inverters to provide a portion or all the required plant-level reactive power capability. In order to achieve a power factor range of 0.95 lead or lag at the point of interconnection at rated plant output using only inverters. Overall total inverter rating would have to be increased by as much as 10%. Taking into consideration reactive power losses. PV plants and inverter-based wind plants are technically capable of providing reactive capability at full kVA output. Here, the difference between PV plants and inverter-based wind plants is that such a requirement is new to the solar renewable electricity industry, as compared to the wind renewable power industry. In order to keep pace with the needs of the electricity industry, inverter manufactures have de-rated their inverters and presently make available both kW and kVA ratings in the market [53].

Wind farm converters have limitations of terminal voltage. While inverters have limitations of terminal voltage, real power produced by PV panels, and current rating to produce reactive power. Equally, inverters produce reactive power at zero or very low wind and solar energy generation capacity. Its implementation requires keeping grid-connected power plants even at no wind and sun availability. Figure 2.15 shows the capability of such plant producing reactive power at zero real power. P and Q are the real power and reactive power respectively in per-unit (pu) at the point of interconnection with 0.95 power factor, at rated output with different combinations. This reactive power provision is not enough as compared to the imbalance. Therefore, this cannot fully replace conventional synchronous generators reactive power production. In usual practice, when reactive capability of variable generation resources is specified for transmission line interconnections, it is done at the point of interconnection. The point at which power is delivered to the transmission line [4], [53].

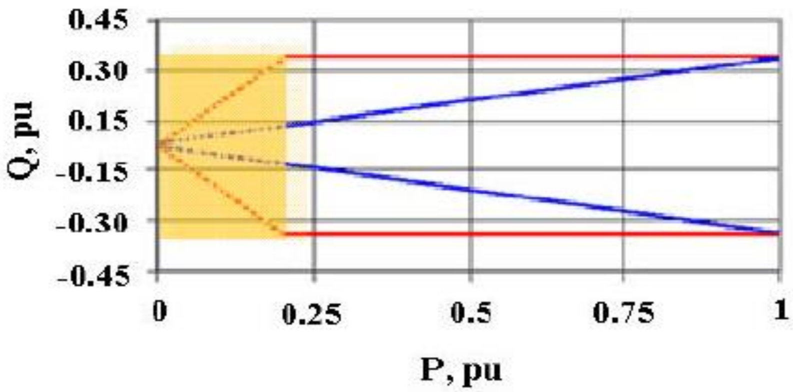


Fig. 2.15: Reactive power capability specifications at the point of interconnection for 0.95 power factor at rated output, reduced capability or permissive range is below 0.2 pu. At low output levels, as indicated by the shaded area, a permissive reactive range may be considered. implying several possible reactive power capability specifications for variable generation, applicable at the point of interconnection [53].

Distributed generators can absorb or inject reactive power for voltage regulation and operation optimization of an electricity grid architecture. The capability curve defines the distributed generators permissible operating region for a given terminal Voltage (V). This region is generally bounded by equipment limitations expressed by maximum voltage or current limits. Therefore, companies that supplies distributed generators should provide information regarding DGs capability at different operating conditions. Many control schemes assume fixed DG power limits. Reactive power limits vary depending on actual generator active power (P) and terminal voltage (V). Figure 2.16 represents a typical reactive power capacity of a DG as a function of active power production and terminal voltage. Here, the reactive power capacity increases as active power reduces. If a distributed generators reactive capacity is fixed at Q_{lim}, the generator capacity will be underused for low active power values. Hence, updated reactive power limits can be utilized to take full advantage of distributed generators capabilities. The use of fixed limits unnecessarily restricts DGs participation in voltage control and electricity grid architecture optimization. Hence, the limits can be obtained from generic capability curves as approximations of actual curves. Therefore, approximations can be utilized for efficient estimation of distributed generators reactive capabilities in on-line applications [5], [63] – [64].

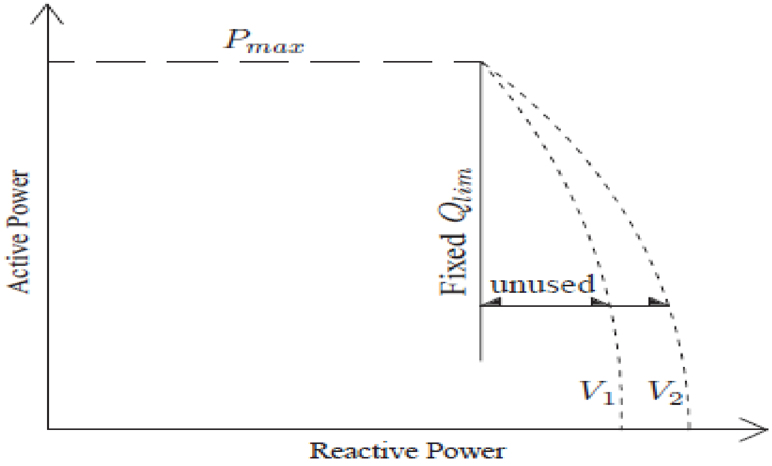


Fig. 2.16: Fixed and actual reactive power limits [64].

2.2.3.2 Generator Utilization in Renewable Energy Technology for Distributed Generation Systems

There are basically two types of generators that can be used to convert mechanical energy to electrical energy. These are synchronous and asynchronous generators. Both generators have considerable advantages and disadvantages. But owing to cost associated with the size and complexity in designing generators. Asynchronous or induction generators are preferred to synchronous generators, considering its rotor design. This is because a generator must match the amount of rotational energy produced from kinetic energy. Hence, the choice of using an induction generator introduces reactive power loss. An induction generator is a source of active power but a sink of reactive power. A considerable amount of reactive power is drawn to magnetize its iron core even when active power output is zero. Just as increasing torque is applied to generate active power, extra reactive power is absorbed due to the reactive power consumed by the series reactance. If a distributed generator is connected to the grid, then absorption of reactive power will have an adverse effect on the electricity grid architecture. But without enough reactive power, voltage sags down and it is impossible to push the power required by the loads of electricity product consumers through power lines [35].

Reactive power is needed to setup the rotating magnetic field in an induction generator, this can be imported from the electricity grid. With the electricity grid/power lines issues, it is more economical to generate reactive power locally. This can be achieved using Power Factor Correction (PFC) principle, such as bank of capacitors. PFC capacitors could be installed at the base of power systems to generate required reactive power. Bringing the overall power factor of an electricity grid architecture close to unity. Banks of capacitor are usually divided into sections to give room for independent switching. Hence, the reactive power generated in a grid network can be adjusted to match with that consumed by the induction generator as operating conditions of power system changes. This solution is greatly valued by power system operators, since it reduces losses on electricity transmission lines. Reactive power control can be implemented using different techniques of power factor control principles. [35], [65]. Figure 2.17 shows an induction generator with power factor correction mechanism.

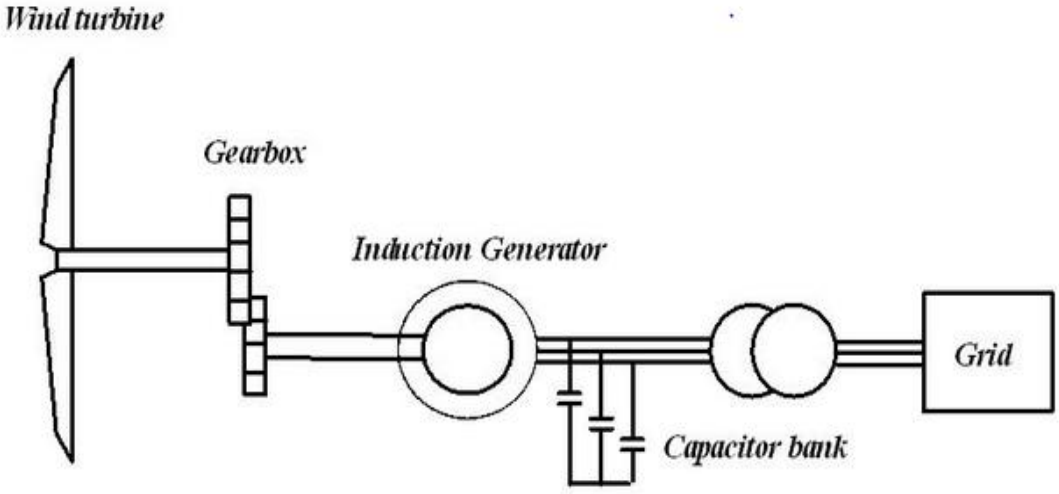


Fig. 2.17: Induction Generator with Power Factor Correction [65].

2.2.3.3 Demerits of Renewable Energy Technology in Distributed Generation Systems

The fastest growing renewable energy technologies are solar photovoltaics and wind energy. But, one characteristic they share is their variability and relative unpredictability. This presents a challenge in integrating these renewable resources in electricity distribution networks that have been designed to operate with conventional power generators whose availability appears certain. This characteristic, however, can be stabilized with the use of power electronic converters in the distribution system. This will allow onward dispatch of electricity product to the grid. Another major drawback is the absorption of reactive power in generators utilized in converting mechanical energy to electrical energy [35]. These issues must be properly taken of, for reliable, efficient and sustainable electricity product from distributed generation schemes.

2.2.4 Static Var Compensators (SVC)

A Static Var Compensator (SVC) is a thyristor-controlled generator of reactive power, either lagging or leading, or both. Since it is thyristor controlled, it is therefore called static. This implying that, this equipment is a static reactive compensator. An SVC is a high voltage device that regulates effectively electricity network voltage at its coupling end. Its major function is to keep grid voltage constantly at a set reference point. Other control characteristics of SVC are: voltage control, reactive power control, damping of power oscillations, and unbalance control. The design and configuration of SVC device is all the time modified to project specifications. An SVC is one of the regulators founded on power electronics and other static devices known as Flexible Alternating Current Transmission Systems (FACTS) regulator, which is used to improve the ability and the flexibility of electricity transmission grid [66] – [69]. Static Var Compensator is a shunt-linked static VAR producer or assimilator whose output is regulated to exchange capacitive or inductive current to keep in good condition or regulate specific parameters of an electricity grid architecture, in most cases bus voltage. SVC is founded on thyristors without gate turn-off ability. The operating concept and features of thyristors achieved variable reactive power impedance SVC includes two main parts and their fusion: these are Thyristor-Controlled Reactor (TCR) and Thyristor-Switched Reactor (TSR); and Thyristor Switched Capacitor (TSC). The objectives of SVC designs are reactive power and load imbalance compensation. Utilizing traditional quantities in SVCs regulator, make it suitable in collaborative compensation methods in smart electricity grids [69] – [71]. Static VAR systems are applied to rapidly control the voltage at a weak point in an electricity grid architecture. SVCs are installed at the low-voltage side of transformer to compensate for unbalanced load and to reduce apparent power losses in power systems [72]. SVCs structure include Thyristor Switch Capacitor-Thyristor Controlled Reactor (TSC-TCR) configuration, as shown in Fig. 2.18.

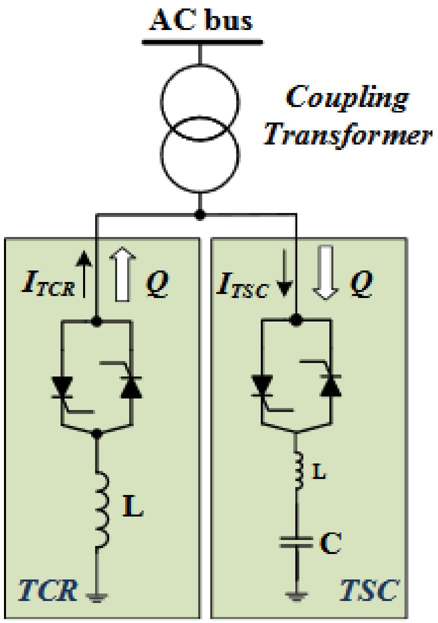


Fig. 2.18: Configuration of SVC [72].

An SVC is a shunt-connected VAR generator or absorber whose output is regularly adjusted to exchange capacitive or inductive current to control specified parameter of an electrical power system. It is made from thyristors without gate turn-off capability. The operating principle and characteristics of thyristors makes SVC an automated impedance matching device, designed to bring an electricity power system closer to unity power factor. A typical one-line diagram of an SVC comprises of: Thyristor-Controlled and Thyristor-Switched Reactor (TCR and TSR); Thyristor-Switched Capacitor; Harmonic Filters; and Mechanically switched capacitors or reactor - usually switched by a circuit breaker [35]. The switching of this device takes place in sub-cycle timeframe, like in less than 1/60 of a second. Thus, providing continuous range of control. The range can be designed to span from absorbing to generating reactive power. Consequently, the controls can be designed to provide very fast and effective reactive power support and voltage control. Since SVCs uses capacitors, they suffer from the same degradation in reactive capability as voltage drops. They equally do not have short-term overload capability of synchronous condensers. SVC applications usually require harmonic filters to reduce the quantity of harmonics injected into an electricity grid architecture. Synchronous Voltage Condensers (SVCs) is another technique, employing switched capacitors as a part of its system. Consequently, it still has the issue of non-linear voltage dependency [4], [35]. Figure 2.19 shows a Static VAR Compensator consisting of a Thyristor controlled Reactor (TCR). It is an inductance in series with a bidirectional thyristor switch. The reactor is in parallel with a corrective capacitor to adjust for leading or lagging power factor. The main function of an SVC is to absorb or supply reactive power based on the changing VAR requirement of consumer load. Therefore, an SVC allows for the application of power factor correction to maintain unity power factor for variable consumer load [73].

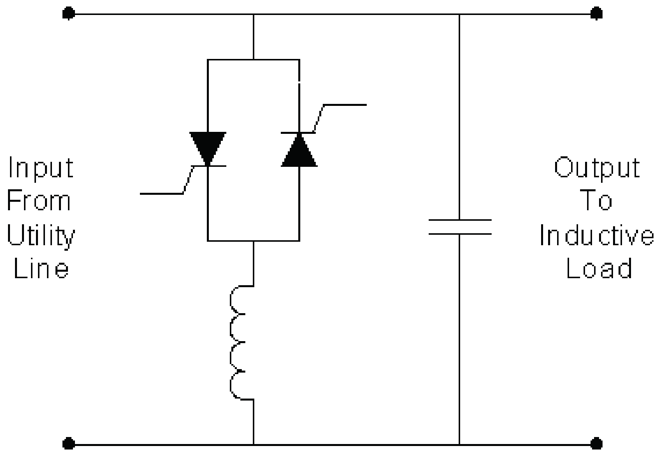


Fig. 2.19: SVC circuit [73].

Voltage stability is defined as the capability of an electricity grid architecture to retain an acceptable potential difference between its buses. The primary requirement to avoid voltage instability is that an electricity grid should be capable of moving reactive power from source to end users throughout steady operating situation. Hence, SVC is one of the main equipment of outmost importance to electricity utility authorities. SVC is a first-generation FACTS device and it is a reactive power compensator. SVC controls reactive power for bus voltage regulation. SVC continuously compensates reactive power in an electricity grid architecture, to increase power factor and power quality. It is a shunt FACTS device and it can function as both inductive and capacitive reactive power compensation. SVC is unable to exchange active power in an electricity grid architecture. A couple of thyristors which are attached in a back to back arrangement is used to control the current through an SVC [58].

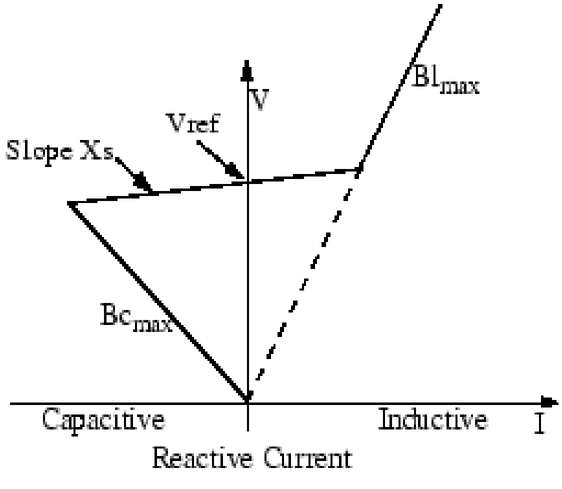


Fig. 2.20: Static Var Compensator V-I characteristic [74].

SVCs can be operated in two different modes: Voltage regulated mode - that is voltage is regulated within limits and VAR control mode – that is the SVC susceptance is kept constant. When an SVC is operated in voltage regulated mode, it implements the following Voltage-Current (V-I) characteristic. From Fig. 2.20. if the SVC susceptance B stays within maximum and minimum susceptance values imposed by total reactive power of capacitor banks (Bc_{max}) and reactor banks

(Bl_{max}), voltage is regulated at the reference voltage V_{ref}. However, voltage drops usually between 1% and 4% at maximum reactive power output is normally used. The V-I characteristic has the slope indicated in Fig. 2.20 [74]. In active control range, current/susceptance and reactive power is varied to regulate voltage according to slope characteristic. The slope value depends on the desired sharing of reactive power production between various sources, and other needs of an electricity grid architecture. The slope is typically 1-5 percent. At the capacitive limit, the SVC becomes a shunt capacitor. At the inductive limit, the SVC becomes a shunt reactor where the current or reactive power might equally be limited [75]. A classical SVC system design is shown in Fig. 2.21.

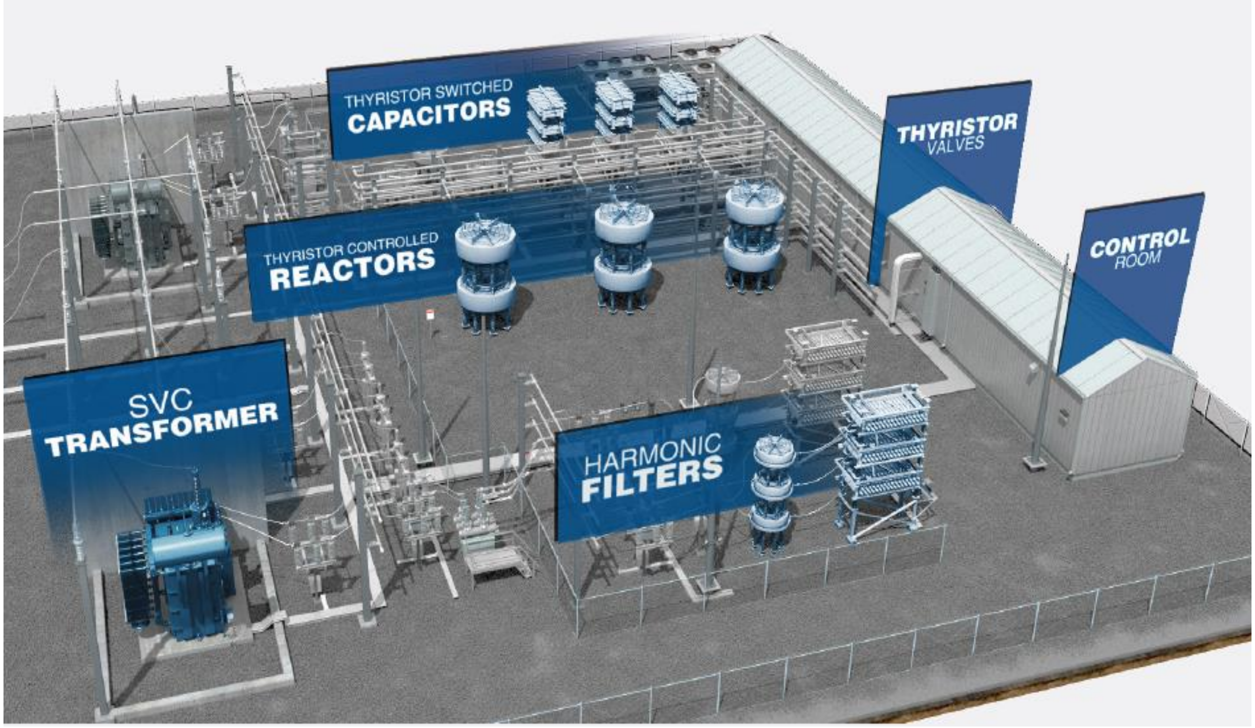


Fig. 2.21: Typical SVC system and main components [76].

2.2.4.1 Types of Static Var Compensators (SVCs)

Thyristor-Controlled Reactor (TCR): TCR is defined as a shunt-linked thyristor-controlled inductor whose effective reactance is regulated in a continuous manner by partial conduction regulation of the thyristor valve. It is a thyristor regulated inductor whose effective reactance differs in a steady way by partial conduction regulation of thyristor valve. A thyristor-controlled reactor is one of the traditional SVC used in the field of power quality enhancement. With the TCR type of SVC put together with fixed capacitors, when operating a system with small reactive power. Almost 100% reactive power is produced at the reactor unit and the general system reactive power is decreased. It can draw-up sustain reactive power at the primary frequency of an electricity grid architecture. But it delivers appreciable odd harmonics which could cause many unpleasant consequences, such as; over currents, extra power losses, and noises to telecommunication systems [68], [77] – [78]. The one-line diagram to compensate reactive power and voltage flicker enhancement in power system comprising Electric Arc Furnace (EAF) with a thyristor regulated reactor compensation, with fixed capacitor (TCR/FC) is shown in Fig. 2.22 [79]. TCR is also illustrated in Fig. 2.23 and 2.24 [70].

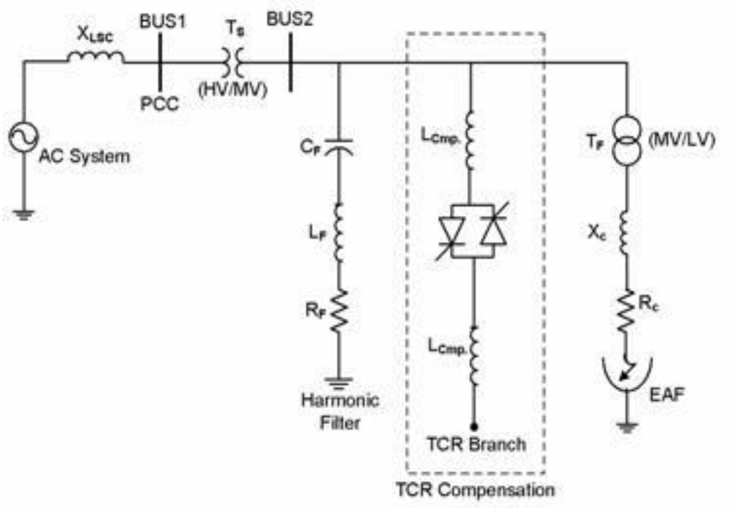


Fig. 2.22: Configuration of a TCR/FC connected to an EAF [79].

Thyristor-Switched Reactor (TSR): This is defined as a shunt-linked, thyristor-switched inductor whose effective reactance is differed in a stepwise appearance by full-conduction or zero-conduction management of thyristor valve. Thyristor switched reactors are shunt compensators that can draw-up reactive power. The TSRs has the following qualities: its operating principle is simple, it has a delay of one-half cycles and it does not generate harmonics. The most general design of SVCs is made-up of a fixed shunt capacitor (FC) and a TCR. Filters are conventionally used to draw-up harmonic produced by SVC designs and large industrial loads [80] – [81]. A typical TSR is presented in Fig. 2.23 [70].

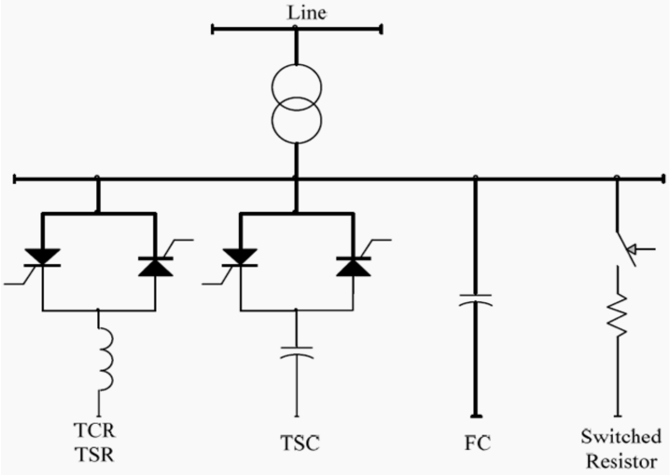


Fig. 2.23: General design of Static VAR Compensators, made-up of TCR/TSR, TSC, FC and Mechanically Switched Resistor [70].

Thyristor-Switched Capacitor (TSC): TSC is defined as a shunt-linked, thyristor-switched capacitor whose effective reactance is differed in a stepwise way by full-conduction or zero-conduction operation of the thyristor valve. It has similar composition and same operational mode as TSR, but the reactor is substituted by a capacitor. The reactance can only be either fully connected or fully disconnected zero due to the features of capacitor. The reactive power of a TSC is modified in steps decided by the number of banks of the capacitor. To avoid in-rush of current which occurs when linking capacitor to power lines. Capacitor is charged approximately to the peak evaluation of the source voltage made during thyristor switch off period. Additionally, thyristor switch is turned on only at the region of the time point where the voltage across both ends of the switch is zero. Therefore, the capacitor applicable time is once per source cycle per phase and maximum 360-degree time delay can be made for regulation [77], [80], [82]. A typical TSC is illustrated in Fig. 2.23 and 2.24.

Thyristor-Controlled Reactor (TCR) and Thyristor-Switched Reactor (TSR) Combined: TCR and TSR are both made-up of shunt-linked reactor regulated by two parallel, reverse-controlled thyristors. TCR is regulated with thorough firing angle input to function in a continuous way. While TSR is regulated without firing angle control which brings about a step change in reactance. TSC has the same make-up and same operational mode as TSR. But the reactor is substituted by a capacitor. The reactance can only be either fully connected or fully disconnected zero owing to the features of capacitor. With non-identical combinations of TCR/TSR, TSC and fixed capacitors, an SVC can meet various requirements to draw-up or produce reactive power from or to an electricity transmission line. The TSR system provides stepped variation of current and TCR provides consistent variation of current. To make-up for the limitations of TSC, variable reactors are linked in parallel so that an electricity grid architecture entire reactive power can be fine-tuned continuously. The combined type has the merits of both TCR and TSC. It is normally suited to a capacitor in a substation for power system transmission lines. Which regulates reactive power for both leading and lagging phases. Usually it is at stand-by when in zero (0) VAR state and modifies reactive power speedily when fault happens on a power line. Appropriate Static Var Compensator technology combinations are normally selected base on several factors such as the responsibility, minimum adjustment width, operating efficiency and economy. The diagram of an SVC combined technology is shown in Fig. 2.23 and 2.24 [70], [77], [82] – [83].

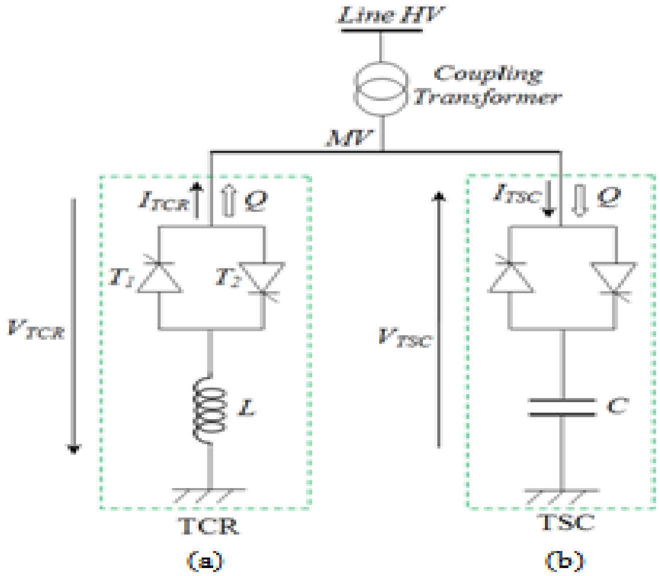


Fig. 2.24: Structure of SVC Device, TCR and TSC Combined, (a)TCR and (b) TSC [84].

2.2.4.2 Merits of Static VAR Compensators

The merits of SVCs are as follows [85]:
It increases power transmission capability of electricity transmission lines.
It improves transient stability of an electricity grid architecture.
It helps to control the steady state and temporary over-voltages in grid networks.
It helps to improve consumer load power factor, and therefore, reduces power line losses and improved power system capability.
Static VAR compensator has no rotating parts. It is employed for surge impedance compensation and reactive power compensation by sectionalizing long electricity transmission lines.

2.2.5 Static Synchronous Compensator (STATCOM)

Static Synchronous Compensators (STATCOMs) are part of FACTS device lineage. Their primary aim is to provide a fast acting, precise, and adjustable quantity of reactive power to an AC electricity grid architecture to which they are linked. STATCOMs accomplish this by modifying the magnitude and polarity (that is the phase) of the reactive constituent of the current flowing in and out of the alternating current side of a grid network. This allows STATCOMs to regulate the quantity and direction of movement of reactive power swapped with alternating current grid networks. They are frequently applied for dynamic power factor correction. Such as dynamic reactive power compensation, in industrial machinery working with large arbitrary peaks of reactive power needed. STATCOMs multiplies power factor of machinery, reduces voltage variations at machinery input. Thereby preventing harm to power plants and minimizes equipment's operating costs. STATCOMs can be used for voltage compensation at the receiver end of alternating current transmission power lines. Hence substituting banks of shunt capacitors. When STATCOM is used for this intention, it provide several benefits over banks of shunt capacitors. These are including of tighter regulation of voltage compensation at the receiver end of alternating current transmission power line and a rise in power line stability during load variations [86] – [87]. A typical STATCOM system nomenclature is shown in Fig. 2.25. LV---low-voltage, LVRT---low-voltage ride through, MSC---mechanically switched capacitor, MSCDN---mechanically switched capacitive damping network, MSR---mechanically switched reactor, PCC---point of common coupling, PLC---power line carrier, POC---point of connection, RI---radio interference, rms---root-mean-square, RTDS---real time digital simulator, SIL---switching impulse level, STATCOM---static synchronous compensator, SVC---static var compensator (thyristor-based), SVS---static var system, SWC---surge withstand capability, TCR---thyristor controlled reactor [88].

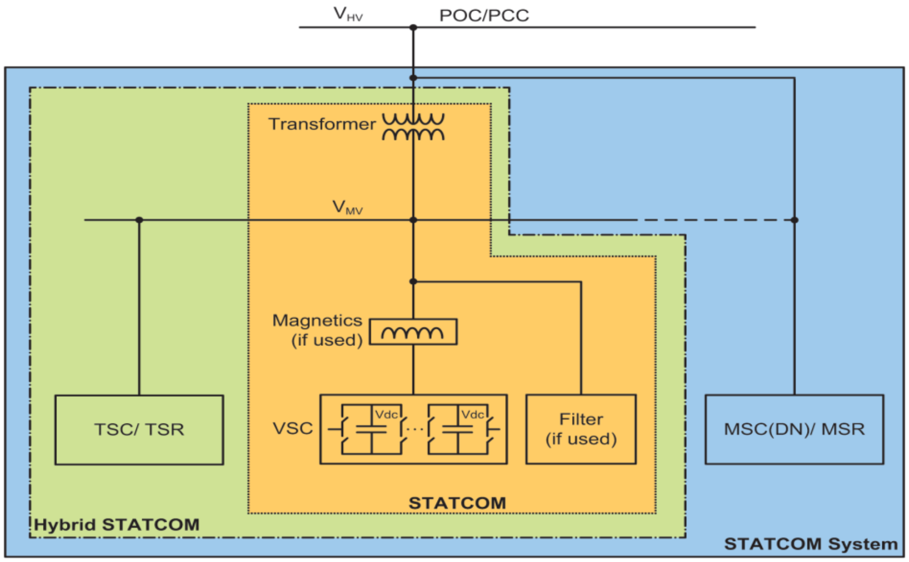


Fig. 2.25: A typical STATCOM system nomenclature [88].

Figure 2.26 shows the equivalent circuit of a STATCOM. The STATCOM functions like a synchronous condenser – the difference being the absence of inertia and its superiority in terms of better dynamics, lower investment cost and lower operating and maintenance costs. A complete system basically consists of a direct current voltage source, self-commutated converters using Gate Commutated Turn-off (GCT) thyristors, and a step-up transformer. The GCT thyristor has an improved gate structure and gate drive circuitry. This dramatically reduces the system operating losses owing to the elimination of snubber circuit. In contrast, the snubber circuit is required in the conventional switching operation of Gate Turn-Off (GTO) thyristor, as well as Insulated-Gate Bipolar Transistor (IGBT) devices. Consequently, fewer components, as well as lower losses, are achieved in the GCT-based converter application. Static Synchronous Compensator is a dynamic technique with power electronics current controlled devices, in place of voltage-controlled capacitors. Thus, the issue of non-linear voltage dependency is eliminated. The cost here is higher than that of switched capacitors, but lower than that of synchronous condensers. There is equally no loss of real power due to reactive power. The reactive capability of power electronic converters differs from those of synchronous machines since they are normally not power-limited, as synchronous machines are. But limited by internal voltage, temperature, and current constraints [4], [35], [53], [89].

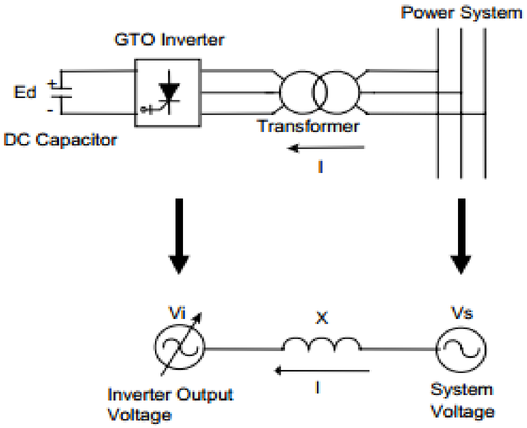


Fig. 2.26: Equivalent circuit of a Gate Turn-Off (GTO) based STATCOM [35].

The output voltage of the Gate Turn-Off converter (Vi) is controlled in phase with the power system voltage (Vs) and the output current (I) varies depending on Vi. If Vi = Vs, then no reactive power is delivered to the power system. Leading or lagging reactive power can only be produced when Vi > Vs and Vi < Vs respectively as presented in Fig. 2.27. The STATCOM smoothly and continuously controls voltage from V_1 to V_2, as shown in Fig. 2.28. However, if the power system voltage exceeds a low-voltage (V_1) or high-voltage limit (V_2). The STATCOM acts as a constant current source by controlling the converter voltage (Vi) appropriately. Thus, when operating at its voltage limits, the amount of reactive power compensation provided by the STATCOM is more than the most-common competing FACTS controller, such as the Static VAR Compensator. This is so since at low voltage limit, the reactive power drops off as the square of the voltage for Static VAR Compensator. But drops off linearly with the STATCOM. This makes the reactive power controllability of the Static Synchronous Compensators superior to that of the Static VAR Compensator, particularly during times when an electricity grid architecture experiences distress [35].

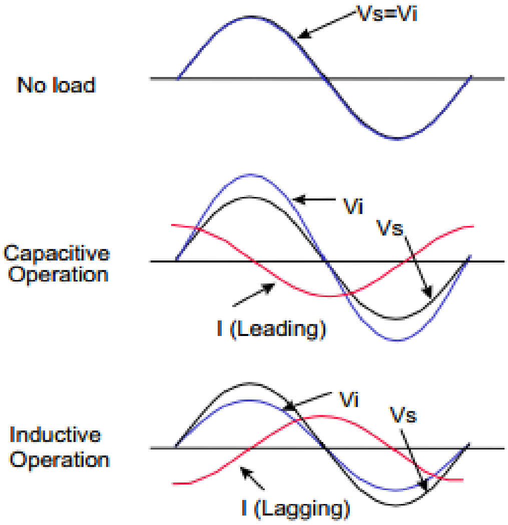


Fig. 2.27: Principle of operation of a STATCOM [89].

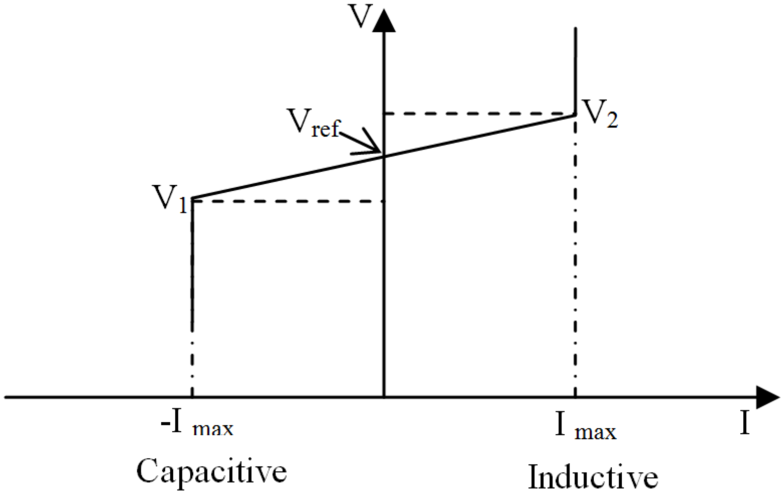


Fig. 2.28: Voltage-Current (V-I) characteristic of a STATCOM [35].

STATCOM is a shunt connected power electronic device which is connected at the mid-point of an electricity transmission line through coupling transformer. The reason for its location is that the maximum variation in voltage is at the middle point of a transmission power line. It has Voltage Source Converter (VSC), a capacitor at the direct current side of converter and controller to generate pulse for inverter. Inverter is the heart of STATCOM. 3-phase Insulated-Gate Bipolar Transistor (IGBT) based self-commutated voltage source converter is used to generate controllable alternating current instantaneous output voltage. This voltage magnitude and phase angle decides the reactive power absorbed or generated by STATCOM. If the voltage of the inverter output is greater than alternating current bus voltage, under this circumstance STATCOM injects reactive power. If the inverter output voltage is less than AC bus voltage, STATCOM absorbs reactive power. If the angle between voltage and current of the inverter is 90 degree, then it only exchanges reactive power. When the angle between inverter output voltage and current is less than 90 degree, it exchanges both active and reactive power [90] – [94]. Several manufacturers see STATCOM undervoltage performance as superior. While SVCs is a master when dealing with over voltage situations [95]. A basic STATCOM configuration with its main components is presented in Fig. 2.29.

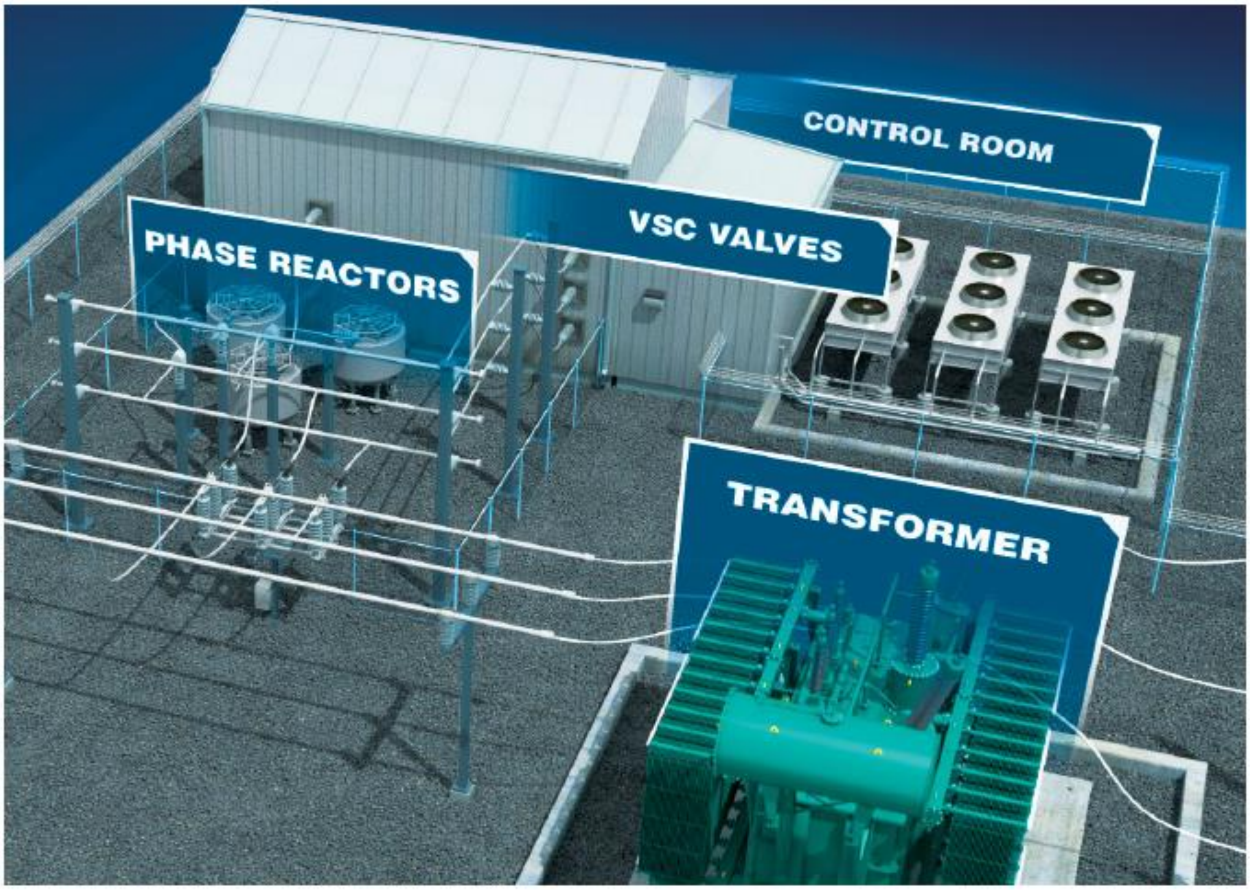


Fig. 2.29: A basic STATCOM configuration with its main components [96].

2.2.5.1 Basic Structure of a STATCOM

The basic structure of STATCOM is presented in Fig. 2.30. Where Vs is the source voltage, V_{dc}-direct current voltage and C-capacitor. The STATCOM is a power electronic based Synchronous Voltage Generator (SVG). From a DC capacitor, it generates a three-phase voltage in synchronism with electricity transmission line voltage. It is connected to a transmission line through a coupling transformer. By controlling STATCOM's output voltage magnitude, reactive power is exchanged between STATCOM and electricity transmission system. Hence, the amount of shunt compensation can be controlled [97] – [98]. STATCOM is based on the principle that it regulates voltage at its terminal by controlling the amount of reactive power injected or absorbed by an electricity grid architecture. When system voltage is low, STATCOM generates reactive power, implying STATCOM capacitive. But when system voltage is high, it absorbs reactive power, implying STATCOM inductive. The variation of reactive power is performed by means of a Voltage-Sourced Converter (VSC) connected on the secondary side of a coupling transformer. From overall cost point of view, voltage-source converters seem to be preferred [99]. The VSC uses forced-commutated power electronic devices, such as Gate Turn-Offs (GTOs), Insulated-Gate Bipolar Transistors (IGBTs) or Integrated Gate-Commutated Thyristor (IGCTs) to synthesize voltage from direct current voltage source. Depending on the power rating of STATCOM, different technologies are used for the power converter. High power STATCOMs with ratings of several hundreds of MVars normally uses GTO-based converters, and square-wave voltage sourced converters (VSC). While lower power STATCOMs with rating up to tens of Mvars uses IGBT-based or IGCT-based Pulse Width Modulation (PWM) voltage sourced converter [97].

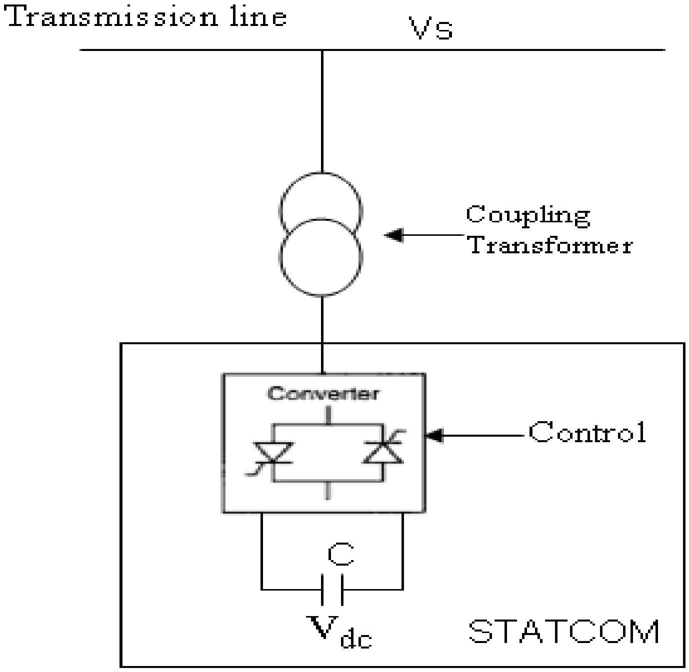


Fig. 2.30: Basic structure of the STATCOM [97].

2.2.5.2 Block Diagram of a STATCOM System

STATCOM produces a three-phase voltage source which has internal reactance, amplitude and phase angle control. When the alternating voltage output of inverter is higher or lower than the bus voltage. The inverter generates leading or lagging current. The difference of the amplitude of the two voltage, decides the magnitude of current. This is used to control reactive power [100] – [101]. The device is mainly comprised of voltage signal condition, current signal condition, controller, impulsator and three-level main circuit. STATCOMs main block diagram is shown in Fig. 2.31. The working process of the STATCOM system is as follows; TV is voltage transformer and TA is current transformer. They are used to measure three-phase voltage and three-phase current signal of the STATCOM system. Voltage signal U_{abc} and current signal I_{abc} passes through the voltage and current conditioning circuits respectively. These signals are then converted to analog signal that Alternating/Direct (A/D) signal converter can accept. These analog signals then pass through a controller after A/D conversion. The controller completes the process of the STATCOM systems. This system has reactive power output and helps to control voltage. That is the STATCOMs output voltage and systems voltage phase difference (δ). The impulsator produces multiplex drive pulse that its phase and pulse width change along with the systems voltage phase difference. These pulses are sent into each power switch, causing the device to produce reactive power needed by an electricity grid architecture [102].

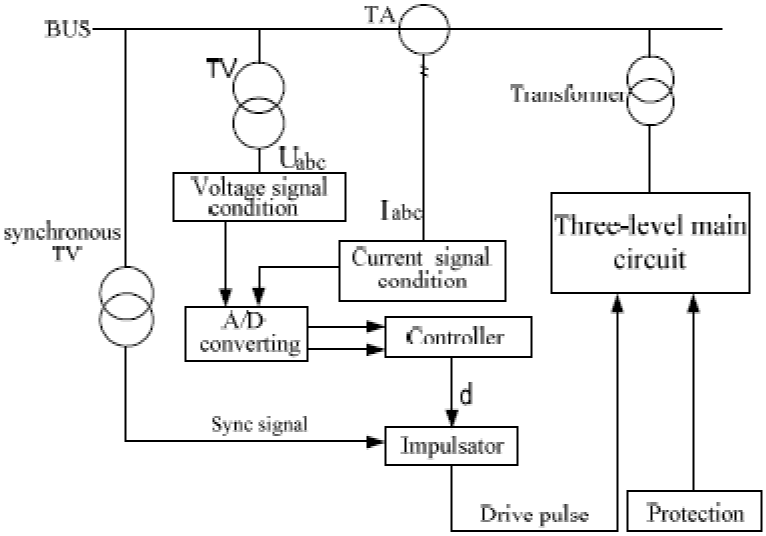


Fig. 2.31: STATCOM system block diagram [101].

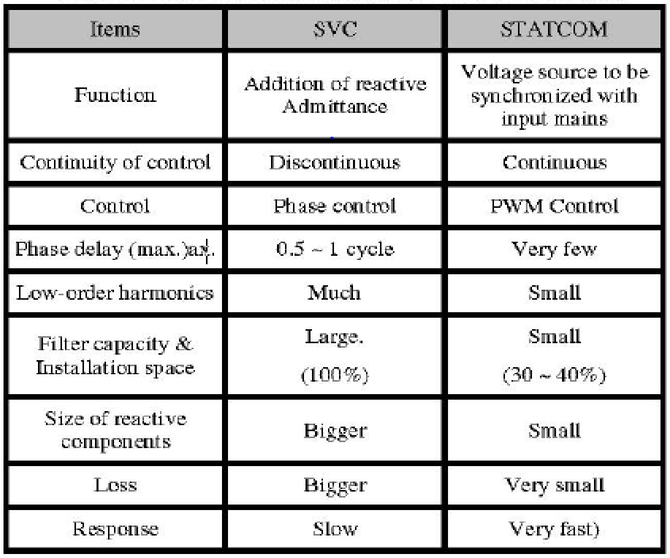
2.2.5.3 Comparison Between SVC and STATCOM

Most critical loads in an industrial low voltage alternating current system have unbalanced and/or nonlinear characteristic. This is so, since it is a single-phase rectifier with a capacitor or thyristor-based three phase rectifier. The unbalanced and nonlinear characteristic of the load has an undesirable effect on the power quality of input utility authorities' mains and adjacent load side. Therefore, reactive power should be generated and compensated properly to improve the power quality of input utility authorities' mains. Typically, the response time and the bandwidth of the closed voltage regulation loop of STATCOM is a shunt-connected synchronous voltage source. These are significantly better than that of SVC which is shunt-connected reactive admittance.

Consequently, STATCOM are more effective than SVC in an industrial low voltage alternating current power system [103].

Unbalanced load or nonlinear loads, such as single-phase lighting load, computer load or inverter to drive induction motor have a bad influence on the power quality of utility authorities' mains. Equally, it is necessary for reactive power to be compensated, since most industrial loads are inductive and makes a lagging displacement of power factor. There are two types of controllable reactive power shunt generators. There is the Static Var Compensator (SVC), whose output is adjusted discontinuously to inject or absorb reactive current. It can be treated as a shunt connected reactive admittance. Typical SVC systems are the Thyristor Controlled Reactor (TCR), Thyristor-Switched Reactor (TSR) and Thyristor-Switched Capacitor (TSC). While the other is the Static Synchronous Compensator (STATCOM), whose output is adjusted continuously to inject or absorb reactive current. It is a shunt connected synchronous voltage source. Table 2.I gives a vivid comparison of an SVC and STATCOM. Generally, STATCOM is more effective and more rapid compensator, when compared to SVC as regards to V-I characteristic, V-Q characteristic, transient stability and response time [103] – [104].

Table 2.1: Comparison Between SVC and STATCOM [103]



Items	SVC	STATCOM
Function	Addition of reactive Admittance	Voltage source to be synchronized with input mains
Continuity of control	Discontinuous	Continuous
Control	Phase control	PWM Control
Phase delay (max.)ax.	0.5 ~ 1 cycle	Very few
Low-order harmonics	Much	Small
Filter capacity & Installation space	Large. (100%)	Small (30 ~ 40%)
Size of reactive components	Bigger	Small
Loss	Bigger	Very small
Response	Slow	Very fast)

Considering the curves which relate voltage magnitude to current (V-I) or reactive power (V-Q). Here, for both SVC and STATCOM, as they are commonly used for voltage support capabilities. A decrement in electricity grid architecture load level results in an increase in voltage magnitude at all grid nodes. SVC and STATCOM holds voltage magnitude by absorbing inductive current. On the other hand, an increase in electricity grid architecture load level produces a decrease in nodal voltage magnitudes. For this condition, both SVC and STATCOM devices maintains grid voltage magnitude by injecting capacitive current. In Fig. 2.32, V-I and V-Q curves for SVC and STATCOM are presented. With reference to Fig. 2.32a, STATCOM's ability to provide current compensation is more extensive than that of SVC's. Even at low voltage levels STATCOM can continue to supply full rated reactive current to an electricity grid architecture. It should be noted that the output current of STATCOM is independent of system voltage. Whereas the compensating current of SVC decreases linearly with system voltage [105].

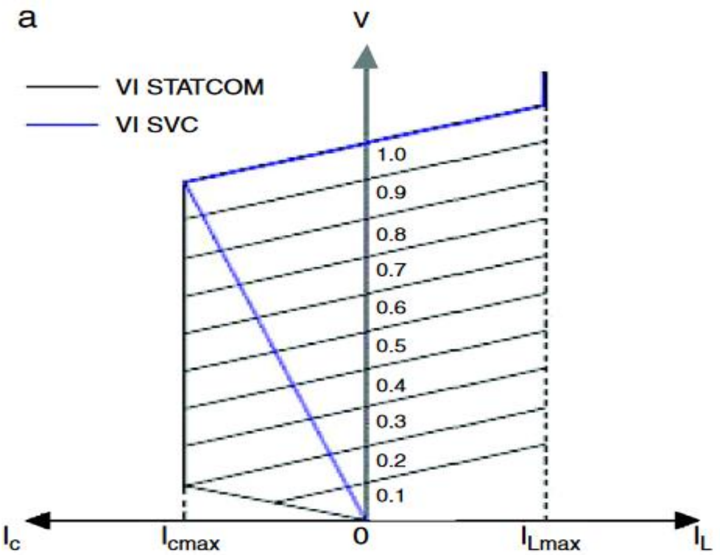


Fig. 2.32a: V-I curves for SVC and STATCOM [105].

A similar approach is taken for reactive power compensation for both SVC and STATCOM. In this case, Fig. 2.32b shows that the maximum VAR generation or absorption of STATCOM changes linearly with system voltage. Additionally, SVC cannot transiently increase the generation of VAR since high capacitive current consumed is determined strictly by the size of capacitor bank and system voltage magnitude. Moreover, in SVC if system voltage is lower than reference voltage, impedance of the reactor is high. Additionally, if the system voltage is increased to exceed the reference voltage, then the mechanism of SVC switches reactors to decrease the impedance of the inductive branch. The impedance of the capacitive branch varies linearly with applied voltage according to the characteristic of capacitor admittance. Note that if SVC has an upper voltage level, it behaves as an inductive element and hence absorbs reactive power. But for a lower voltage level, SVC behaves as a capacitive element, implying that it adds or injects reactive power [105].

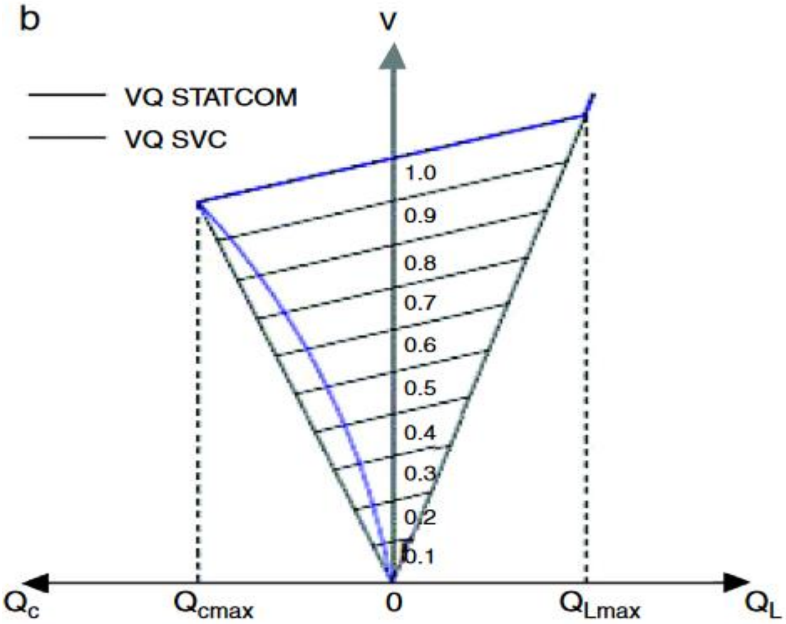


Fig. 2.32b: V-Q curves for SVC and STATCOM [105].

2.2.6 Synchronous Condenser Technology

A synchronous condenser is identical to a synchronous motor. Naturally, a synchronous motor loads a power line with a leading Power Factor (PF). To increase the PF further, the mechanical load is removed, hence, over-exciting its field. This shows that a synchronous condenser is intentionally designed to allow its shaft to spin freely. Consequently, its purpose is not for energy conversion, but solely to adjust conditions on the electricity grid architecture. Its field is controlled by a voltage regulator to either generate or absorb reactive power as needed to adjust grid's voltage, or to improve power factor. The main advantage with this control strategy is that reactive power generated can be continuously adjusted. It equally has the capability of increasing current as voltage decreases to ensure adequate reactive power is generated. However, it increases power loses of an electricity grid architecture. Synchronous condensers are synchronous generators which serve the purpose of compensation of reactive power only, and not real power. It consumes a little portion of real power to provide reactive power capacity. This dynamic reactive power capability technique has high maintenance and conversion costs [4], [34], [106]. The synchronous condenser technology is discussed in detail in chapter three.

2.2.7 Unified Power Flow Controller (UPFC)

Flexible Alternating Current Transmission Systems (FACTS) is a power electronic-based system. They are static equipment that provide control of one or more alternating current transmission system parameters to enhance controllability and increase power transfer capability [107]. FACTS are widely used for reactive power compensation in Extra High Voltage (EHV) or High Voltage (HV) electricity transmission systems. FACTS may be classified into different categories. One classification is according to the connection of FACTS device, either shunt or series FACTS. Static VAR Compensator (SVC) and Static Synchronous Compensator (STATCOM) are examples of FACTS shunt compensation. Thyristor-Switched Series Capacitor (TSSC), Thyristor-Controlled Series Capacitor (TCSC), GTO Thyristor-Controlled Series Capacitor (GCSC), Thyristor-Switched Series Reactor (TSSR), and Thyristor- Controlled Series Reactor (TCSR) are examples of FACTS series compensation [108].

On the other hand, FACTS devices may be classified according to the technology used in the switching devices, this can be classified into two main categories; Current Source Converter (CSC) and Voltage Source Converter (VSC). The former is equally known as Line Commutated Converter (LCC) in which the switching device can only be turned on (not off). There is the turn off state reached naturally by the line voltage commutation action. Thyristor valves are used in LCC technology in SVC applications [109]. On the other hand, in VSCs the switching devices can be turned on and off independent of line voltage. VSCs uses Gate Turn-off Thyristor (GTO) or Insulated-Gate Bipolar Transistor (IGBT) [107].

Unified Power Flow Controller (UPFC), Interline Power Flow Controller (IPFC), and Hybrid Power Flow Controller (HPFC) are recent FACTS devices not earlier than 1991. They consist of shunt and series VSCs [110] – [112]. Development of economic electricity transmission systems with bulk power transfer capability is a very essential demand of residential and industrial electricity consumers. FACTS devices have ability to control and optimize power flow in electricity transmission lines. It equally has the capability to improve power transfer in transmission networks. Among different types of FACTS devices, UPFC is considered as a comprehensive multi-variable FACTS controller owing to its capability to control selectively or simultaneously with multiple power system parameters. In the past, UPFC have been proposed to control power flow, reduce power losses and improve voltage profile. However, the biggest challenge of UPFC implementation is the design of its internal controller. It has 4 different control capabilities and all of them are adjusted properly to avoid any fault or failure of the controller functions [113] – [119]. Despite the advantages of using UPFC within an electricity grid architecture. It has significant challenges on existing protection system reliability, especially for conventional distance relay. As UPFC is used to modify line series impedance, terminal voltage, and line angle. Distance relay reach is affected both in magnitude and phase. Hence, distance relay is subject to either underreaching or overreaching [120] – [123].

2.2.7.1 Principle of Operation and Basic Structure of UPFC

The Unified Power Flow Controller (UPFC) is an associate of the cluster of FACTS equipment's that offers synchronous voltage source for efficient power control of electricity grids. Within the structure of traditional power transmission concepts, UPFC can control simultaneously or selectively the parameters affecting power in an electricity grid architecture [119]. The Unified Power Flow Controller is the most complex and powerful FACTS device. It is a comprehensive compensation device consisting of parallel or shunt static compensator (STATCOM) and series Static Synchronous Series Compensator (SSSC) through DC coupling. It helps in controlling node voltage and regulation of both active and reactive current of a power line. For active power control, the UPFC parallel converter absorbs or emits active power from access point through a parallel transformer. Active power flows through series converter of DC coupling. Thereafter, active power is finally delivered to the power line through a series transformer. UPFC provides active power transmission channel for power lines. Considering reactive power regulation, both UPFC parallel and series converters exchanges reactive power with grid node through a transformer. Owing to the presence of DC capacitor, reactive power exchange does not occur between parallel and series converters. A typical UPFC is composed of two back-to-back voltage source converters. The converters share DC bus, one of them is connected to AC node through a parallel transformer. While the other converter is connected to the AC line through a series transformer. Each converter individually emits or absorbs active and reactive power. The active power can flow bi-directionally between both converters through a DC link [120] – [126].

UPFC includes series and shunt part, and its core equipment is the Voltage Source Converter (VSC). This is connected back-to-back at the DC terminal as shown in Fig. 2.33. A voltage source converter is integrated into the power network by a shunt transformer. This is used to control DC voltage and AC reactive power or voltage, it is like a STATCOM. The other voltage source converter is series connected to power network by a series transformer. It is equivalent to a voltage source with amplitude and phase control linked to a power transmission line. The active and reactive power of a transmission line can be regulated accurately and independently by voltage source converter control. Which is used to regulate the distribution of power flow in an electricity grid architecture. Generally, series voltage source converters can exchange both active and reactive power with power line while carrying out its function. Active power flows bi-directionally between the two voltage source converters. Here, UPFC combines the functions of STATCOM and Static Synchronous Series Compensator (SSSC). The series part is the core of UPFC and can complete many control functions. According to the needs of an electricity grid architecture, UPFC can select one or more of the following combination of features as the control target: Voltage regulator---The injected voltage of series voltage source converter is in-phase or reversed-phase with the voltage at the sending terminal. This is used to regulate voltage amplitude, but not the phase; Series compensator---The injected voltage of series voltage source converter is vertical to phasor current of a power transmission line. Which is equivalent to a capacitance or reactor and can compensate impedance of power transmission lines; Phasor regulator---The injected voltage of series voltage source converter is used to regulate phase voltage, but not the amplitude. This is equivalent to a phase shifter; Composite controller---It integrates the three functions of voltage regulation, series compensation, and phasor regulation. In addition to voltage source converters, it includes serial or parallel transformers, Thyristor Bypass Switch (TBS) and rapid mechanical bypass switch in the UPFC [127].

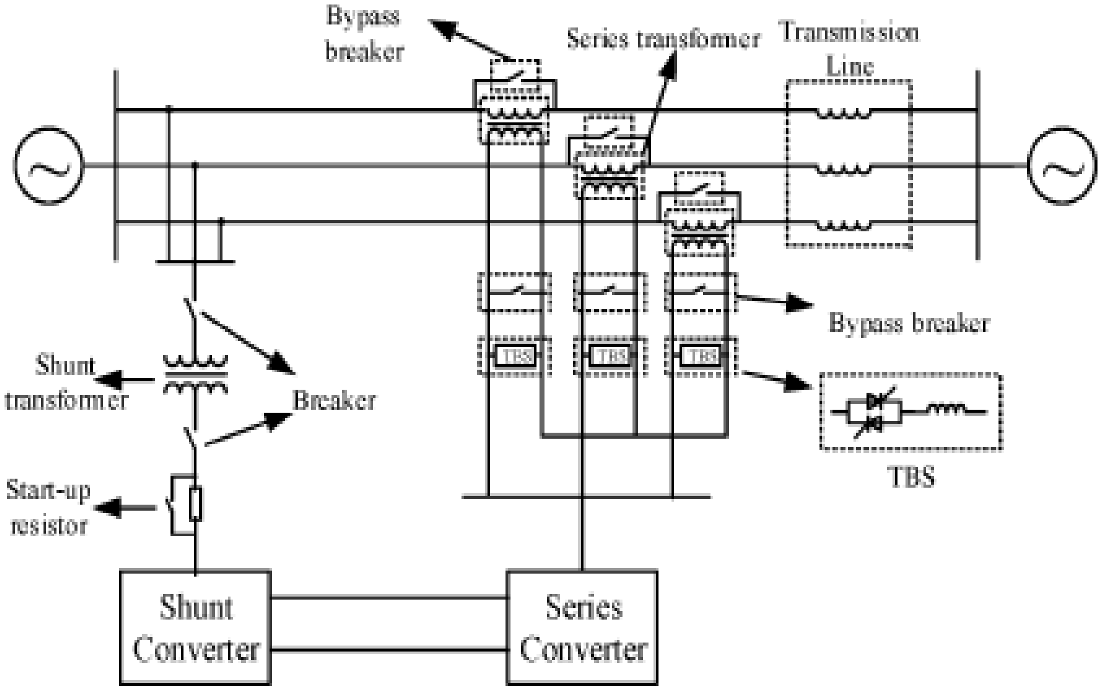


Fig. 2.33: Structure of a typical UPFC [127].

2.2.7.2 Hierarchical Structure of UPFC Control System

The UPFC control system has hierarchical control structure. This consists of system level control, converter level control and valve level control [128]. System level control---The system level control is the highest level of control. It is used to coordinate the control objectives of different voltage source converters. These are including of power coordination control of the double-circuit power transmission lines, power flow control of specific interface and so on. Converter level control---The converter level control consists of various control function of converter, such as start up and out of operation of converter, power flow control of single line, dc-link voltage control, reactive power control of shunt voltage source converter, AC bus voltage control, fault-ride-through control and so on. Valve level control---Valve level control is the lowest level of control and provides trigger signals to the submodules based on the reference voltage or number of submodules which should be put into operation. This is given by the converter level control. Besides, it equally monitors the states of the submodules.

2.2.7.3 Control Mode of Unified Power Flow Controller

The control mode of unified power flow controller is basically made up of shunt and series converter [129].

Shunt converter*:* UPFC has many possible operating modes. Particularly, shunt converter operates in such a way to inject controllable current into power transmission lines. A component of this current balances active power of series converter. The other component is reactive which is set to desired reference level, either inductive or capacitive within the capability of converter. Reactive compensation control modes of the shunt converter are very similar to that of the STATCOM and SVC. The shunt converter can be controlled in two different modes:
(a) VAR Control Mode: In reactive control mode, the reference input is inductive or capacitive VAR. In Var control mode the reference input is Var. This is maintained by the control system regardless of bus voltage variation.
(b) Automatic Voltage Control Mode: In voltage control mode, the shunt converter reactive current is automatically regulated to maintain transmission line voltage at the point of connection to a reference value. For this mode of control, voltage feedback signals are obtained from the sending end bus feeding the shunt transformer.

Series converter: Series inverter controls the magnitude and angle of voltage injected in series with power line. This voltage injection is intended to influence the flow of power on the line. But voltage is dependent on the operating mode selected for UPFC to control power flow. The actual value of injected voltage can be obtained in several ways.
(a) Direct Voltage Injection Mode: The series converter generates a voltage vector with magnitude and phase angle requested by reference input. This operating mode may be advantageous when a separate system optimization control coordinates the operation of UPFC. Also, other FACTS controllers are installed in the transmission system.
(b) Phase Angle Shifter Emulation mode: Here, the reference input is phase displacement between sending and receiving voltage.
(c) Line Impedance Emulation mode: The reference input is an impedance value insert in series with power line impedance. This is done on purpose to control the magnitude of voltage vector, in proportion to the size of power line current. The desired impedance is specified by reference input. Generally, impedance may be complex with resistive and reactive components of either polarity. This operating mode can be selected to match existing series capacitive line compensation in the system.
(d) Automatic Power Flow Control Mode: The magnitude and phase angle of injected voltage vector is controlled to adjust power line current vector. This results in the desired active and reactive power flow in power line. In automatic power flow control mode, series injected voltage is determined automatically and continuously by a vector control system. Ensuring that desired values of active and reactive power is maintained on the transmission line despite system changes. With this operating mode, there is possibilities of power flow scheduling and management. Which is not achievable with conventional power line compensating equipment.
(e) Stand-Alone Shunt and Series Compensation: UPFC circuit has the possibility of operating independently as shunt and series converters. This is achieved by disconnecting the common DC terminals and splitting the capacitor bank. Here, the shunt converter operates as stand-alone STATCOM, and the series converter as a stand-alone SSSC. This feature can be included in UPFC

structure to handle contingencies. In the event of failure of any converter, the UPFC will be very much adaptable to power system changes. This makes the use of either converters for shunt only or series only compensation very innovative. In stand-alone mode, neither converters are capable of absorbing or generating active power. Operation is only possible in reactive power domain. Since injected voltage must be in quadrature with line current, only controlled voltage compensation or reactive impedance emulation is possible for power flow control.

2.2.8 Unified Power Quality Conditioner (UPQC)

There is a more complex network in an electricity grid architecture, in which generating stations are connected with load centers through long transmission and distribution power lines. To improve the performance of electricity distribution network. A new concept came into existence known as custom devices. One of custom power devices is Unified Power Quality Conditioner (UPQC) [130]. Conventional power quality mitigation equipment's uses passive elements. These conventional power quality mitigation devices do not always respond correctly to grids power quality challenges, since conditions of electricity grid architecture continually changes. Active power filters are being exploited in the latest generation of power semiconductor devices. With improvements in power and control circuits, active filters are becoming a more viable alternative to passive filters. The term Active Power Filter (APF) is a widely used terminology in the area of power quality improvement. Unified power quality conditioner is an active power filter family member [130]. UPQC consists of combined shunt and series active power filters for simultaneous compensation of voltage and current. Hence, it helps to improve power quality on both source and load side of an electricity grid architecture [131] – [132]. Unified power quality conditioner has great potential owing to its high controllability [133]. The function of a unified power quality conditioner is to mitigate disturbances that affects the performance of a grids critical load. Normally, UPQC has two inverters that share one DC link capacitor. The two voltage-source series and shunt inverters are connected in three-phase four-wire or three-phase three-wire configuration. The series inverter is connected through transformers between the source and common connection point. While the shunt inverter is connected in parallel with the common connection point through transformers. The series inverter operates as a voltage source and the shunt inverter operates as a current source. UPQC can be used to compensate voltage sag and swell, harmonic current and voltage, power flow and voltage stability. It should be of note that UPQC cannot compensate voltage interruption since it has no energy storage in its DC link [134].

2.2.8.1 Basic Configuration of UPQC

Among reactive power compensation equipment's, UPQC is highlighted due to its unique ability in simultaneous compensation of utility voltage and load current. UPQC in its usual configuration is an integration of Parallel Active Filter (PAF) and Series Active Filter (SAF) with a common DC bus. Usually, PAF compensates for load current and regulates DC bus voltage. While SAF compensates for poor voltage quality of utility side of a grid [135] – [139]. UPQC consists of both shunt and series converters connected through a DC capacitor with each other. Two types of UPQC can be considered; These are left-shunt and right-shunt UPQC. The difference between them is that a shunt converter is connected at the utility or load side of an electricity grid architecture. Figure 2.34 shows the basic configuration of a left-shunt UPQC. In Fig. 2.34, L_1 is the interconnecting inductance and V_s is the inserted voltage of the series inverter. In some cases, the differences in the UPQC configuration affects its operating characteristics and effectiveness [133], [140] – [141].

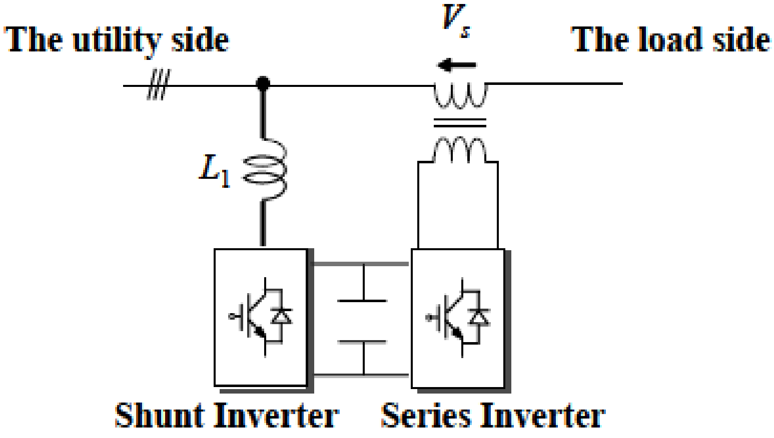


Fig. 2.34: Basic configuration of the left-shunt UPQC [132].

2.2.8.2 Components of a UPQC

The various components used in UPQC is the series inverter, shunt inverter, DC link capacitor, LC filter and injection transformer:

Series inverter: The inverters connected in series to the supply is known as series active filter. This is a voltage source inverter, which helps to eliminate voltage interruption. Implying that series inverter is a voltage-source inverter connected in series with an alternating current power line through a series transformer. It is a voltage source inverter that helps to mitigate voltage distortions. UPQC assists in eliminating supply voltage flickers and imbalances from load terminal voltage. The control of series inverter output is performed using Pulse Width Modulation (PWM). The hysteresis band PWM technique is frequently used for controlling series inverter output, owing to its ease of implementation. Besides fast response, this technique does not need any knowledge of system parameters [130], [142].

Shunt inverter: The inverter connected in shunt to the supply line is known as shunt active filter. It helps to eliminate current related harmonics and equally minimizes reactive current in load circuit. This is a voltage-source inverter connected in shunt with an alternating current power line to cancel current distortions, compensate reactive current of load and improve power factor of system. The shunt inverter equally assists in DC-link voltage regulation. Which results in a significant reduction of direct current capacitor rating. The output current of a shunt converter is adjusted using dynamic hysteresis band method. This is done by controlling the status of the semiconductor switches such that output current follows the reference signal and remains in a predetermined hysteresis band [130], [142].

DC link Capacitor: Capacitor or inductor are usually used as common DC link. The capacitor in UPQC is used as DC link supplying direct current voltage. The shunt and series voltage source inverters are connected back to back with each other through UPQC capacitor. The voltage across the UPQC capacitor provides self-supporting direct current voltage for proper operation of the shunt and series inverters [130], [142].

LC filter: The output of the series active filter of a UPQC produces high switching ripples. The LC filter combining inductors (L) and capacitors (C) helps to minimize ripples in a system. The LC filter acts as low-pass or high-pass filter. The ripples during switching mode are minimized using the high-pass filter. Low-pass filter is used to attenuate high-frequency components of voltages at the output of series converter. These are generated by high-frequency switching of the voltage source inverter. High-pass filter is installed at the output of shunt converter to absorb ripples produced due to current switching [130], [142] – [143].

Injection transformer: Series injection transformer is connected to series convertor. The necessary voltage generated by series inverter to maintain pure sinusoidal load voltage at a desired value, is injected into power line through series transformers [130], [142].

Chapter 3

3.0 Literature Review of Main Parts of Simulation Set-up: Electricity Grid Architecture, Synchronous Condenser (SC), and Wind Plant

The purpose of this chapter is to describe the main components used in the simulation set-up of this thesis. The grid architecture has been explained. While the synchronous condenser technology has been comprehensively presented in Paper Three, Four, Five, Six and Seven, detailed in the contributions section of this thesis. Thereafter, the wind power plants are explained with its various types available now in the market discussed.

3.1 Electricity Grid Architecture

The electricity grid is a network that allows the distribution of electricity from suppliers to consumers. Operationally, conventional electrical grid starts at power generating systems such as power stations that generate three-phase alternating current electricity. Here, three-phase alternating current is passed through an electricity transmission substation that uses transformers to step up voltage from thousands to hundreds of thousands of volts. Increased voltage allows for efficient transmission of electricity over long distances. After being converted to high voltage, three-phase electricity is sent over long-distance transmission lines through three lines, one for each phase. Before electricity can be distributed to end users, it must pass through power substation that steps down voltage with transformers. Thereafter, electricity is then distributed to communities to be used in homes and businesses at the correct voltage [144]. According to system connection, electricity grid architecture can be classified as Radial, Ring main, and Meshed or Inter-connected networks.

3.1.1 Radial Electricity Grid Architecture

Radial electricity grid architecture is the most commonly used system for power distribution grids [145] – [146]. The radial electricity grid architecture topology is tree shape, where close loops does not exist. Since there are no closed loops in radial systems, power can be delivered from one bus to another bus without tracking down the original bus. But there will be a need to find the original bus while turning backwards. Radial electricity grid architecture topology is the simplest and cheapest topology for an electrical grid. But with this topology, if a power line is disconnected for some reason, all the lines downstream will equally be deprived of power [147].

Radial electricity grid architecture has a structure which begins from the root node where generation is connected. Lateral line follows the root node or main node in radial network. This line begins from the main feeder and connecting loads. Sub-lateral line begins from the lateral line. Finally, minor lines begin from sub-lateral line. Distributed power systems with radial electricity grid architectures can be analyzed somewhat as an extension of conventional power grid distribution system. Since it is one of the most commonly used approaches in power distribution systems [147], [148] – [152].

In radial electricity grid architecture, separate feeders radiate from a single substation and feed the distributors at one end only. Figure 3.1 shows a single line diagram of a radial electricity grid architecture for a direct current distribution line. A feeder OC supplies a distributor AB at point A. Visibly, the distributor is fed at one end only, that is point A is this case. Figure 3.2 shows a single line diagram of a radial electricity grid for alternating current distribution. Radial electricity grid architecture is employed only when power is generated at low voltage and substation is located at the center of load [153].

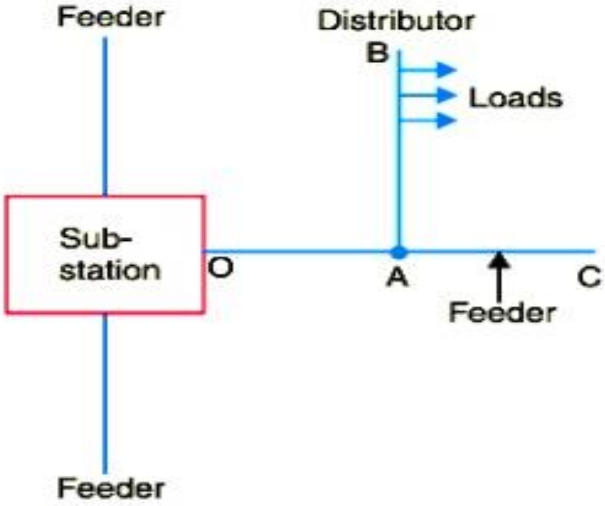


Fig. 3.1: A single line diagram of a radial electricity grid architecture for (DC) distribution [153].

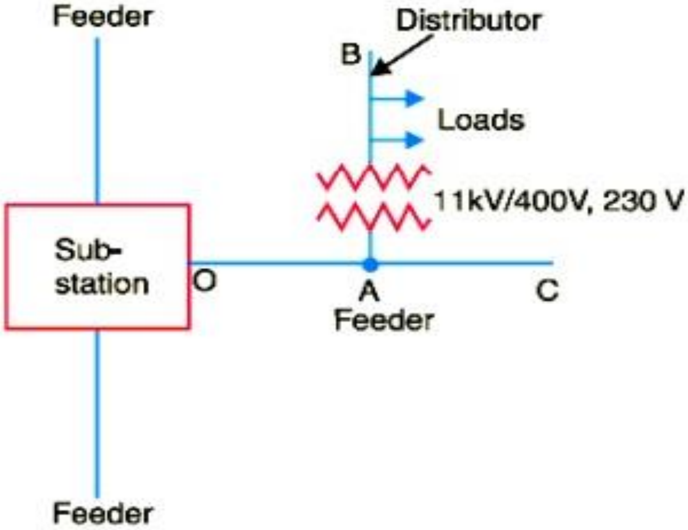


Fig. 3.2: A single line diagram of radial electricity grid architecture for AC distribution [153].

3.1.1.1 Application of Radial Electricity Grid Architecture

The general configuration of a radial electricity grid architecture consists of generators only at the starting point. This is connected through distribution transformer to load center. The nodes are numbered in ascending order. Every adjacent node is connected by branches which are numbered uniquely. Radial electricity grid architecture includes four important parts, these are: master controller, control system, correspondence system, and distribution line. The master controller is the central controller saddled with the activities of systems parameters identification, investigation control and client interfacing. The control system allows multilayer control, it uses an interchange system to communicate data [147], [154]. The radial electricity grid architecture is a remarkably adaptable system which empowers the creation and trial approval of new topologies, fittings, controls, correspondence, and security. Deterministic and stochastic parts can be incorporated together in radial electricity grid architecture. The limited inactivity of distributed network helps to intensify sensitivities to stochastic segments [155]. Distribution lines are used for interconnecting source, loads, and energy space units in radial electricity grid architecture [147].

3.1.1.2 Merits of Radial Electricity Grid Architecture

Radial electricity grid architecture has a relatively simple circuit protection scheme to coordinate and design. With radial grid architecture, it is quite easy to determine grid component rating requirements [156]. In a radial grid, voltage compensation technique such as reactive power compensators can be easily implemented. Although, there might be different voltages at each equipment/load caused by unequal conductor length. Careful selection of conductor size minimizes voltage differences. This eliminates some of the electrical noise that might have been induced on power sensitive equipment caused by heavy equipment on power lines [147]. Radial electricity grid architecture is the simplest power system, since it is only fed at one end. The initial cost of a radial electricity grid architecture is low. A radial network is very useful if generation is at low voltage. Radial power system is preferred when power stations are located at the center of load. This helps in the simplicity to analyze and operate a power system [157].

3.1.1.3 Demerits of Radial Electricity Grid Architecture

Radial electricity grid architecture has very limited growing flexibility as regards to planning. This is so, since load addition or new generation integration would necessitate installation of new cables or other components. With the exception, if the initial installed cables and other components were oversized. This adds on to extra costs [147]. In a radial electricity grid architecture, the end of distributor near to power substation gets heavily loaded. When the load on the distributor changes, electricity product consumers at the distant end of the distributor faces serious voltage fluctuations. Electricity product consumers are dependent on a single feeder and distributor in a radial grid system. Any fault in the power system causes interruption of power supply to all consumers connected to the distributor [158]. Power availability as per each load is lower as compared to other power distribution configuration. Such lower availability of power is not only caused by potential faults at the single point of failure. It can be equally caused by the complex maintenance operation of a grid system [147].

To address power path availability limitations in radial network, an alternative is implemented in radial networks with redundant circuits [159]. This means that at least two circuits are run simultaneously with each other from sources to load. Telecommunication power systems are common illustrations of redundant radial power distribution architecture. Here, two direct current circuits feed each load [147]. A brilliant design and planning of radial distribution system can achieve a fair degree of reliability even without much additional cost. This feeder system is constructed as a network and operates radially. In a Y connected radial system, the neutral conductor is connected through all open switch points, thereby forming a network connecting feeder and substations. This special type of radial distribution grid architecture is called auto-loop or parallel feeder distribution system [157]. An auto-loop or parallel feeder distribution system is differentiated from normal radial distribution system as it has two feeders that ties it to electricity product consumers load. The auto-loop system can automatically sense the loss of one source of voltage. It then quickly and automatically switches the load to the second feeder. This type of radial grid architecture adds reliability benefits by keeping outages to a few seconds or less. But the added cost of having two sets of utility equipment at one location, could be high for each installation [160]. Parallel feeders are common in urban areas or feeders to large single customers. Where load shedding in an emergency is possible. The higher cost of parallel feeders is justified if load is higher, more consumers are being supplied with electricity product, or there are loads such as hospitals which require high levels of reliability [161]. A parallel feeder network is presented in Fig. 3.3.

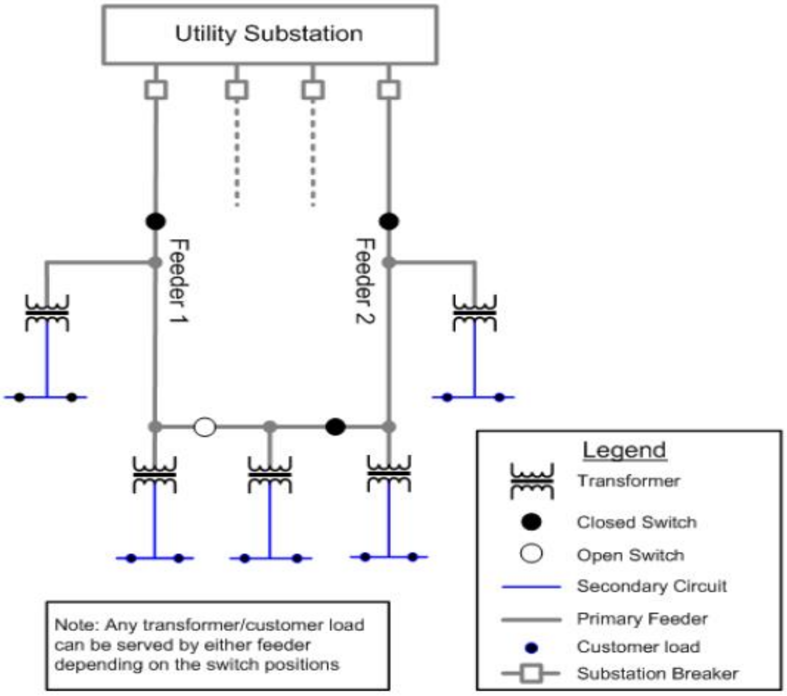


Fig. 3.3: Auto-loop or parallel feeder radial electricity grid architecture [160].

3.1.2 Ring/Loop Electricity Grid Architecture

Ring electricity grid distribution system follows a loop structure that loops the service from a source through a collection of loads and back to the source. All the nodes in ring electricity grid architecture are connected to each other. Making a close loop structure that runs through or around an area serving one or more distribution transformers or load center. It then returns to the same substation [162]. There is a null-point on the loop where no power passes. This layout is basically dynamic radial system with open-point or null-point shifting as loads changes. A loop can meet all power and voltage drop requirements when fed from only one end, not both [157]. In a ring electricity grid architecture, utility authorities provide power in any direction of the ring. Hence, fault can be isolated without disturbing service to many consumer loads on the ring [163]. Ring electricity grid structure is highly attractive for high performance of distributed systems. This is as a result of fault isolation and the flexibility to locate sources with respect to loads. A distribution grid architecture with numerous connecting rings is known as a multi-ring structure. In a multi-ring structure, a wide range of power transfer paths is available. This makes it flexible in the event of needed maintenance or clearing a fault on a section of a power system [147].

Path multiplicity complicates automatic relaying or protection of a multi-ring system. This is so, as it might be difficult to quickly detect and determine the location of a fault and the correct actions to take to minimize interruption of electricity product supply to consumers [164], [165]. The task of isolating faults is better with multi-ring structure as compared to other simpler grid configurations. More than one decision can be implemented to isolate a fault. Thus, an optimal decision varies with operating conditions of a grid architecture [147]. In a loop system, the primaries of distribution transformers form a loop. The loop circuit starts from the substation bus-bars. Making a loop through the area to be served and returns to the substation. Figure 3.4 shows the single line diagram of a ring main system for an alternating current distribution grid. The substation supplies electricity to the closed feeder LMNOPQRS. The distributors are tapped from different points M, O and Q of the feeder through distribution transformers [153].

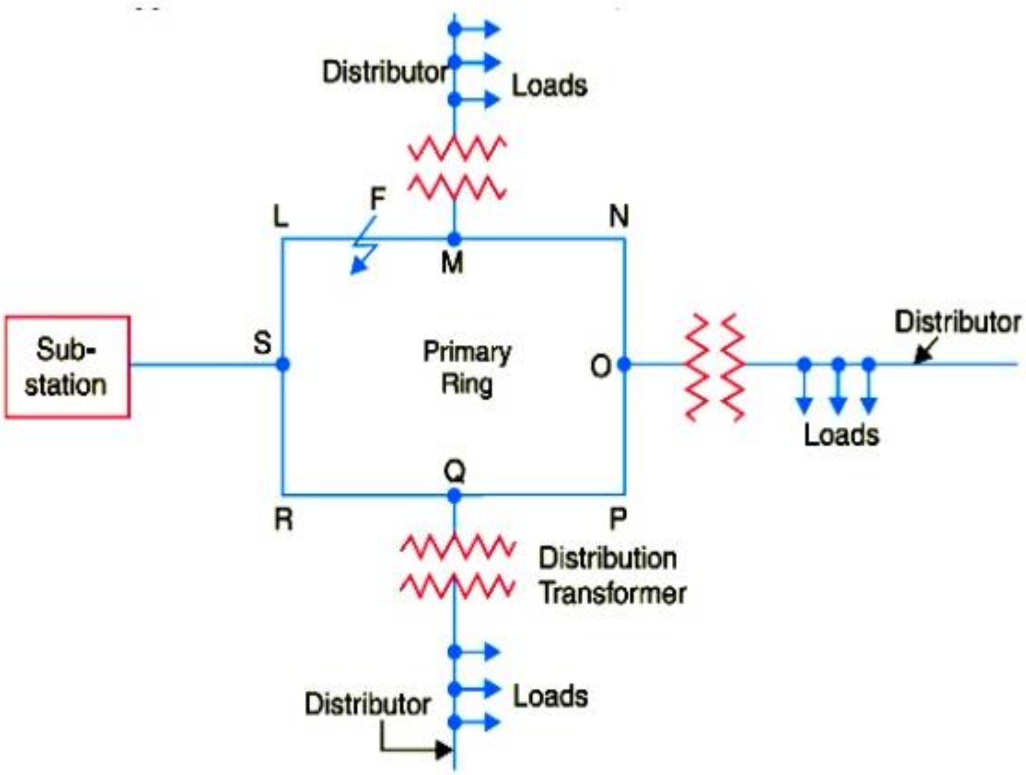


Fig. 3.4: Ring or loop electricity grid Architecture [153].

3.1.2.1 Application of Ring/Loop Electricity Grid Architecture

Ring electricity grid architecture is commonly used in residential areas where electrical current flows in more than one direction. This offers better voltage stability and lower power losses. But it makes protection against faults more difficult. Ring electricity architecture with enhanced fault tolerant capacity can be used with renewable energy and electric vehicle charging stations [166].

3.1.2.2 Advantages of Ring/Loop Electricity Grid Architecture

Ring electricity grid architecture is the most organized grid structure. It forms a closed loop by joining nodes to each other. As a result of this, several zones of protection within the ring system can be implemented. The protections can be implemented on both positive and negative ring bus. The ring electricity grid structure has a better performance rate compared to radial network. Even if the load in ring system increases, it still gives high reliability. The performance is not affected by additional devices added to the electricity network. In case a feeder is under fault or maintenance, the ring distributor is still energized by other feeders connected to it. Despite the fact of savings in cabling/copper as compared to parallel feeders [167]. This implying that power supply to electricity product consumers is not disrupted, even when a feeder is not in operation. Different section in the ring system can equally isolates at different appropriate points. This is to isolate sections of power systems in case of any fault occurrence [147].
A protection scheme for an electricity grid architecture can be achieved using a ring configuration for the mains of a direct current bus. Thereby creating several zones of protection within the ring bus. If a fault is detected in the electricity grid architecture, a controller is used to open the zone breakers. This ensures that all breakers are opened, and the fault zone de-energized. The ring bus splits into zones and each zone is monitored by a segment controller [168].

3.1.2.3 Disadvantages of Ring/Loop Electricity Grid Architecture

A major disadvantage of the ring electricity grid structure is that the system is highly dependent on the cables that connect other components to the network. In terms of complexity, a loop feeder system is only slightly more complicated than a radial system and has a major drawback as it caters for the capacity and cost of the loop scheme [157].

3.1.3 Mesh or Interconnected Electricity Grid Architecture

The electricity grid architecture can equally be organized in mesh or interconnected structure apart from radial and ring structures. Mesh grid structure is normally used with high or medium voltage, while radial grid is used with low level voltage [169]. Hence, mesh electricity distribution grid architecture is used to offset three-phases moment of peak power output. Which is disseminated between three-phases. Allowing a more consistent peak power output. A mesh grid structure follows the radial structure but includes redundant lines in addition to main lines. These are organized as backups for the purpose of re-routing power in the event of failures on the main power line [144]. Mesh electricity grid architecture has the most complicated configuration, when compared to radial systems. Since it includes many alternative connections between nodes. This makes the operation and protection of distributed schemes challenging [170]. Mesh grid is less ideal pertaining to its complexity, as it is the most often used electricity grid architecture rather than ring system configurations. This is so, since mesh distributed systems utilizes existing configuration, instead of installing new network [147]. In a mesh electricity grid architecture, the feeder ring is energized by two or more generating stations or substations. Figure 3.5 shows the single line diagram of a mesh electricity grid architecture. The closed feeder ring ABCD is supplied by two substations S_1 and S_2 at points D and C respectively. Distributors are connected to points O, P, Q and R of the feeder ring through distribution transformers [153].

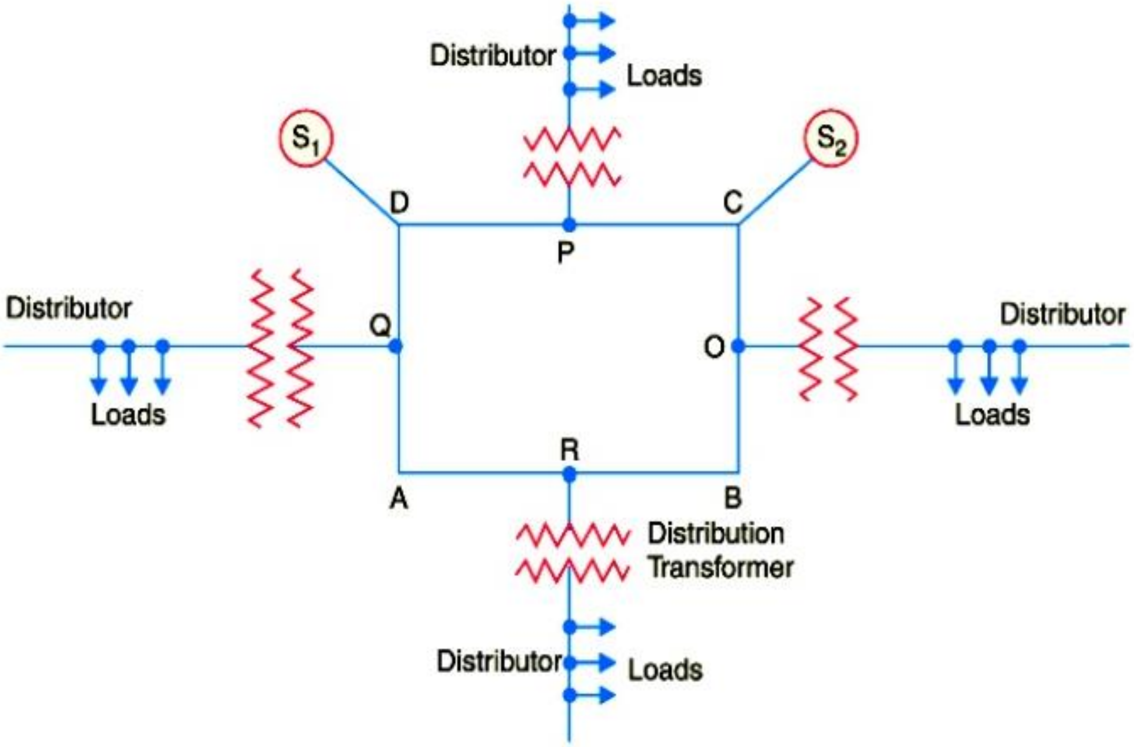


Fig. 3.5: A single line diagram of a mesh electricity grid architecture [153].

3.1.3.1 Application of Mesh Distributed Electricity Grid Architecture

The revolution in the generation, transmission and distribution of electricity is expected to be achieved with smart electricity grid architecture solutions. The smart grid can complement electricity grid penetrated with renewable energy resources, to bring about a cleaner environment. For efficient electricity transmission and avoidance of power losses in an electricity grid architecture. It is essential to have a power structure that is excellent in electricity distribution [147]. Mesh micro-grid structure is efficient for short-distance electricity transmissions. It is very good in incorporating existing power system structure. Implying that it can effectively be upgraded from a radial to a mesh electricity grid structure. Power transmission in mesh grid architecture is carried to an aggregation point. Usually a sub-station that ensures reliability and control of fluctuating generated power [170]. Peak power is generated to various electricity product consumers hopping around power transformers. Hence, enough power is generated and transformed according to the needs of consumers. Mesh grid configurations can be efficiently utilized for distribution characteristics of renewable energy resources. Where interface converters are connected to each other. [171].

3.1.3.2 Advantages of Mesh Electricity Grid Architecture

A droop control system helps to bring stability to the grid. While providing efficient and robust electricity product to consumers. When using traditional droop control method in a distributed electricity grid architecture. Accurate load power sharing accuracy can be obtained, when direct current converter output power is set to be inversely proportional to corresponding droop coefficient. Power sharing error can equally be eliminated if droop coefficient and line impedance satisfy the relationship. Though, this supposition is only suitable for ideal electricity grid architecture. Hence, in a practical power system there is some error. This is the limitation of traditional droop control method in mesh grid configuration for direct current distributed systems [172]. The simplest network structures to protect are radial systems while meshed distribution networks have a higher short circuit power. The advantage of meshed networks is relatively balanced voltage profile and high reliability through redundancy [173].

3.1.3.3 Disadvantages of Mesh Electricity Grid Architecture

Transmission of electricity using Mesh grid architecture utilizes nonlinear methodology. This method suffers from limitation of only focus on lossless distributed networks with purely inductive distribution lines. The results might not be applicable for distributed networks with heterogeneous and mixed R/X ratio lines. Which is common in low voltage distributed electricity grid architecture. Reactive power sharing is often not guaranteed as careful analysis can only be done on droop control [174]. Communication delay in a mesh grid configuration is a very sensitive parameter which can impact largely the stability of the electricity grid architecture [147].

3.1.4 Comparison of the Various Electricity Grid Architecture

Many factors need to be considered when comparing the best suitable system structure between radial, ring and mesh grid architecture. Considering factors are --- location of distributed generations; voltage range; grid structure of transmission target either underground or overhead; climate and environment; principles of operation i.e. directional, over current etc.; types of generators i.e. synchronous, asynchronous, converters; load classification; characterization and load schedules; different failure condition and so on [173], [175]. A radial electricity grid architecture was used for the simulation scheme of this thesis. This grid structure has been chosen due to its simplicity to analyze and operate an electricity grid architecture.

3.2 Synchronous Condenser (SC)

A synchronous condenser is a synchronous device that produces reactive power which leads real power by 90 degrees in phase [176]. It is a piece of equipment like a synchronous motor, whose shaft is not linked to anything but spins freely without constraint. Its objective is not to convert electric power to mechanical power or vice versa, but to regulate situations on the electric power transmission grid. Its field is regulated by a voltage regulator to either give rise to or assimilate reactive power as needed to modify voltage or to enhance power factor in an electricity grid architecture. The synchronous condensers installation and operation are like massive electric motors. Increasing the machines field excitation brings about its provision of reactive power to the electricity grid architecture. Its most important merit is the effortlessness with which the quantity of correction can be modified. The kinetic energy stored in the rotor can help stabilize a power system during short circuits or speedily oscillating loads such as electric arc furnaces. Massive installations of synchronous condensers are occasionally used in connection with HVDC converter stations to provide reactive power to the alternating current grid. Unlike a capacitor bank, the quantity of reactive power from a synchronous condenser can be steadily regulated. Reactive power from a capacitor bank reduces as grid voltage reduces, while a synchronous condenser can build-up reactive current as voltage reduces. Nevertheless, synchronous machines have higher energy losses than static capacitor banks. Most synchronous condensers linked to electrical grids are rated between 20 Mvar and 200 Mvar and a great number of them are hydrogen cooled. There is no eruption threat if the hydrogen concentration is kept in good condition of above 70%, typically above 91% [177]. A typical synchronous condenser system is shown in Fig. 3.6.

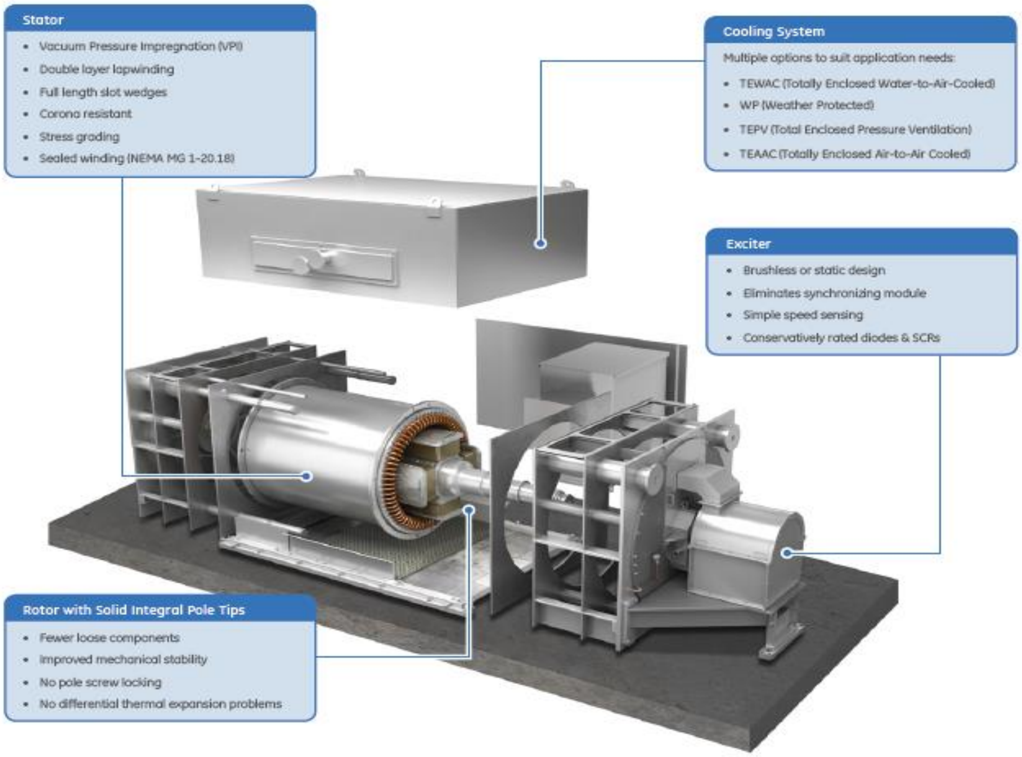


Fig. 3.6: A typical synchronous condenser system [178].

Synchronous condensers were once extensively utilized as a means of supplying reactive power compensation before the introduction of power electronic based devices. Several synchronous condensers were used in electricity grid architectures beginning in the late 1920's to the end of late 1970's. Synchronous condensers have been relevant in the scheme of things in voltage and reactive power control for many years now. Practically, a synchronous condenser is merely a synchronous machine linked to the electricity grid architecture. After the unit is synchronized, the field current is regulated to either generate or draw-up reactive power as needed by alternating

current electricity grid architectures. The device can provide incessant reactive power control when used with the right automatic exciter circuit. Synchronous condensers have been used at both distributions and transmission voltage levels to ameliorate stability and to support voltages within preferred boundaries under varying load states and emergency circumstances [179] – [180].
Although, synchronous condensers are infrequently used today since they need considerable foundations and a significant quantity of starting and protective gadgets. They equally represent a part in short-circuit current. Also, they cannot be adjusted fast enough to balance speedy load changes. Furthermore, their losses are much higher than those related with static compensators, and the cost is much higher when likened with static compensators. Their merit lies in their high temporary over-load ability [179]. Synchronous condensers provide sustenance for network voltage by maintaining efficient and reliable operation of electricity grid architectures through reactive power compensation and extra short circuit power ability [181]. Synchronous condensers are well accepted technology for supplying reactive power and remedying power factor issues in industrial settings. Reliable grid synchronous condensers are precisely designed to meet the requirements of hybrid renewable electricity grid architectures. When compared with diesel generators, they help diesel generators in controlling voltage. In high wind and/or solar times, diesel generators are turned off, and synchronous condenser handles voltage regulation on its own [182]. Synchronous condenser solutions are being initiated worldwide to play a part in the optimal use of energy resources. It offers grid support for now and the future, in order to attain a reliable, secure, efficient, effective and sustainable supply to electricity product consumers [183]. Reactive power capacity is a critical feature of the electrical infrastructure and research underscores its role in avoiding power outages. The reliability of an electricity grid architecture depends not only on electricity generation and distribution equipment reliability. But equally on reactive power capacity, which is required to stabilize local system voltage [184]. An illustration of the capacity of a synchronous condenser is shown in Fig. 3.7.

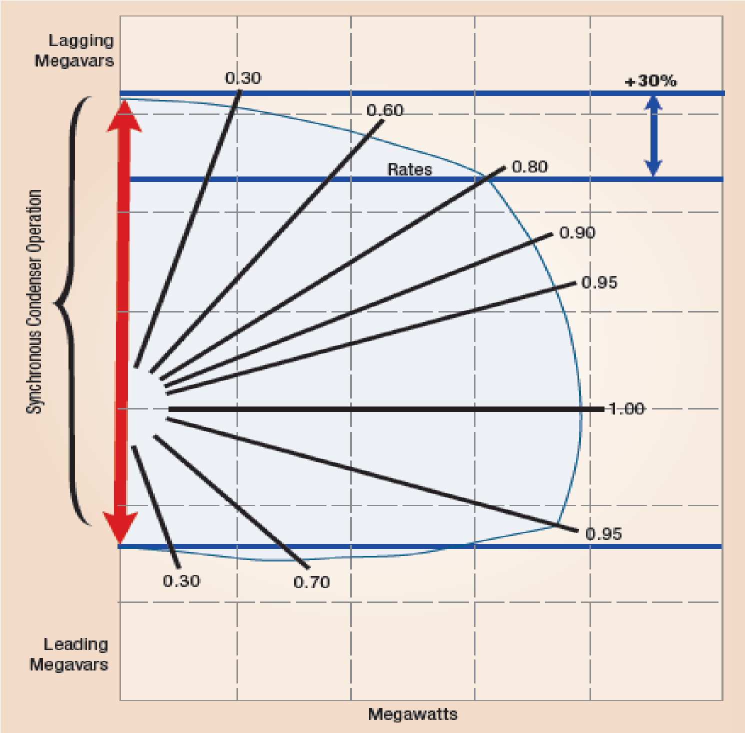


Fig. 3.7: Synchronous condenser reactive power capacity [185].

3.2.1 Types of Synchronous Condensers

Conventional/Traditional Synchronous Condenser: A synchronous condenser is a synchronous motor without any mechanical load. Its field is regulated by a voltage regulator to give rise to or to draw-up reactive power. This is to support electricity grid voltage or to keep a systems power factor at a specified level. Synchronous condensers installation and operation are identical to big electric motors. After the unit is synchronized, the field current is regulated either to give rise to or to draw-up reactive power as needed by AC system. The machine can supply uninterrupted reactive power regulation when used with the appropriate automatic exciter. A rise in the equipment's field excitation brings about the provision of magnetizing power (kVArs) in an electricity grid architecture. Its major merit is the effortlessness in the regulation of the amount of correction [186] – [187]. The basic topology of an adjustable speed synchronous condenser is shown in Fig. 3.8. It is based on a double-fed machine with a conventional three-phase winding in the stator and a three-phase winding in the rotor. The latter is supplied by a three-phase converter connected back-to-back to a second converter, which is connected to an electricity grid architecture. This configuration allows the generation of a rotating magnetic flux in the rotor, which depends on the rotor converter frequency. When the machine is rotating at synchronous speed, the rotor converter operates at zero frequency and the magnetic flux in the rotor is stationary with respect to the rotor itself. In this case, the compensator operates as a conventional synchronous condenser [188].

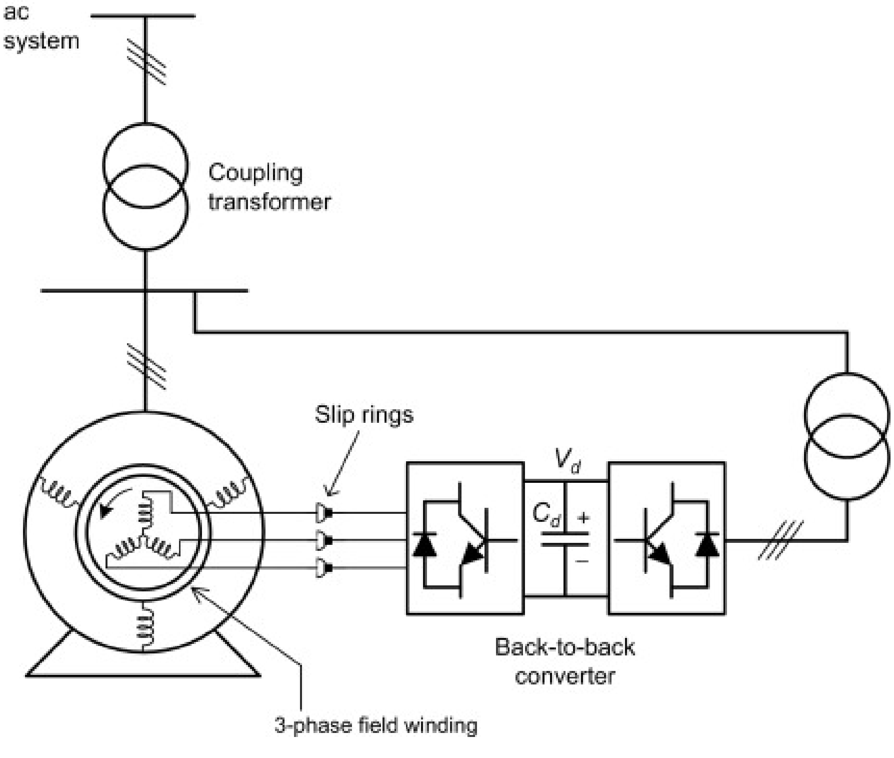


Fig. 3.8: An adjustable speed synchronous condenser (ASSC) [189].

Superconducting Synchronous Condenser (SuperVAR): Only the field windings of this synchronous condenser make use of high-temperature superconductor winding, which is made-cold with a cryocooler subsystem to about 35–40 K. The cryocooler module is laid in a stationary frame and helium gas is used to cool the rotor of the equipment. The stator winding is normal copper winding. However, the winding is not placed in normal iron core teeth, since the iron core saturates owing to high magnetic field, typically 1.5–2.0 T, built in by the field winding. Exclusively, the stator yoke (that is the back iron) uses magnetic iron to supply magnetic shielding and to convey flux between adjacent poles. The omission of iron in many of the magnetic circuits in this machine brings about a very low synchronous reactance (typically 0.3–0.5 p.u). It is asserted that this synchronous condenser machines are more durable than conventional/traditional machines in the course of transient system faults. Whereas transient and sub-transient reactance’s are much the same to those of traditional machines. The lower synchronous reactance of this machine permits the operation of these machines at lower load angles than traditional machines [189] – [190].

SuperVAR synchronous condensers act as reactive power shock-absorbers of an electricity grid architecture. Effectively producing or drawing-up reactive power (VARs), based on the voltage level of a transmission system. SuperVAR machines also react immediately to secure grids and electricity consumer loads in case of voltage sags and surges. This is recognized in the power industry as voltage transients, which can be given rise to by lightning storms, short circuits brought about by tree branches fleetingly touching lines, animals touching transmission elements, and other sources. SuperVAR machines and Dynamic-VAR (D-VAR) systems immediately stabilizes voltage and supply utilities new, economical techniques to actively improve the reliability and maximize the power of transmission grids [190]. A ± 8 MVAR high temperature superconducting dynamic synchronous condenser machine with key components is shown in Fig. 3.9 [192].

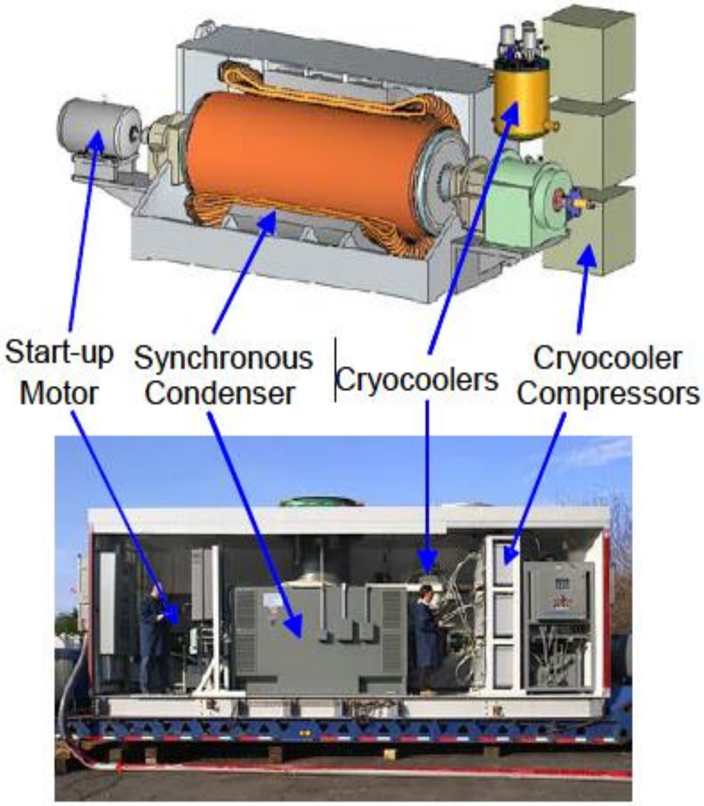


Fig. 3.9: A ± 8 MVAR high temperature superconducting dynamic synchronous condenser machine [192].

3.2.2 Benefits of Using SCs in Modern Electricity Grid Architecture

The main utilizers of synchronous condensers are electricity utility companies and heavy industries that operate transmission, distribution or industrial electricity grids. Reasons for the rebirth of the synchronous condenser comprises the large-scale integration of wind and solar energy resources as well as the introduction of smart grid technologies in electricity grid architectures. Electricity utility companies are currently rediscovering the benefits of conventional synchronous condenser technology and are finding new ways to make use of them in their electricity networks. The synchronous condenser technology can be utilized in power system networks for ---Network frequency stabilization supported by its spinning inertia reserve; ---Contribution to power system short-circuit capacity, making the network more robust against faults; ---Providing voltage support during prolonged voltage sags and interruptions through good fault ride-through capability; ---Reactive power support not affected by network voltage; and ---High over load capability for sustained periods [69], [193] – [199]. Therefore, the reasons for selecting the synchronous condenser technology in reactive power installations remarkably differs from case to case. The main benefits of the synchronous condenser technologies in modern electricity grid architectures are including of:

Power generators can be converted or retrofitted into SCs: Is it possible to convert unused and retired large generators into synchronous condensers, converted generators are now operating as synchronous condensers in today's electricity grid architectures. But compared with new dedicated and optimized synchronous condensers they have some demerits. They are usually old with outdated technologies, aging components and require lots of auxiliaries to run. Their starting is problematic. Lots of strenuous maintenance is needed. They are usually installed in a less favorable location, maybe at remote locations compared with new modern synchronous condenser units which are smaller, simpler and can be installed in any required place. This results in reduced performance and effectiveness [193] – [198].

It can be supplied in various capacity range: Large synchronous generators, motors or condensers can be supplied in powers ranging from 1 to 80 MVA at 3–15 kV system voltage. The voltage chosen depends on the optimization. Since the electricity grid voltage is much higher, so a step-up transformer is needed. Higher outputs can be achieved by utilizing a few units in a standardized module concept. This arrangement gives better redundancy and availability in contrast to one large unit [193].

It helps to strengthen electricity grid with additional short-circuit power in present changing mix of power generation sources: The intermittent and highly variable nature of wind and solar energy resources introduces stresses on electricity networks and dynamic reactive power compensation is needed to make sure that there is secure operation. Renewable energy resources are remotely located and feed power into a single radial line. Synchronous condensers can be installed close to renewable resource connection point to strengthen electricity grid with additional short-circuit power. This improves both the fault ride-through ability and provides additional voltage stability of the grid system installation itself [69], [193] – [200].

SCs can be designed without the constraints of startup considerations: Synchronous machines can be started by a frequency converter, direct online or in the most ideal way by utilizing a pony motor. This afford the synchronous condenser to be designed without the limitations of startup considerations. Small pony motor of between 200–300 kW can be coupled to synchronous condenser and supplied by a frequency converter which is set up for a few minutes start up ramp which brings the speed of the synchronous condenser into synchronous operation, usually at 1500 rpm. The excitation system is there after started and at the right time the main breaker switches the machine online [193].

It helps to maintain short-circuit capacity of electricity grid after the removal of high inertia rotating generators: Electricity utility authorities are phasing out conventional power plants. But in most situation, they are not being replaced. As the synchronous generators at these locations have been supplying the power grid with significant amounts of short-circuit power. Simply removing them would put the stability of the adjacent power network at risk. Hence, synchronous condensers are needed to maintain the short-circuit capacity of power grid after the removal of high inertia rotating generators [69], [193] – [199].

SCs relatively small size allows its installation close to the required point in electricity grid network where they are needed: In many electricity grid architectures, the physical distance between power generating plants and major consumer load centers can be substantial. Typically, reactive power should be produced locally to minimize the losses associated with long distance electric power transmission and to ensure optimal utilization of electricity transmission lines. Synchronous condensers can effectively complement fast-operating static VAr-compensating devices at remote locations where voltage collapse must be avoided at any cost. The relatively small size of synchronous condensers allows installation close to locations in the electricity grid architecture where they are needed to maximize their benefits [193] – [195], [199].

It helps with additional short-circuit capacity and voltage stability in areas with significant seasonal variations in electricity demand: Seasonal changes in heavy industries electricity demand can introduce electrical load fluctuations which brings about significant voltage sags in a local electricity grid architecture. The synchronous condenser technology can be used to strengthen the short-circuit capacity of such electricity grid system to boost voltage and reactive power supply. Electricity consumers with significant seasonal variations in electricity demand and intermittent industrial processes can equally benefit from additional short-circuit capacity and voltage stability margins brought about with the help of synchronous condensers [69], [193] – [199].

New SCs are modern machines with new machine technology: Machines of old had a very slow speed of response, analog control systems and rheostats were not able to provide adequate response to dynamic events. However, present day machines come with latest digital controls and relays and utilizes digital field exciter as found in many modern combined cycle facilities. The speed and precision of modern exciters makes new synchronous condensers to rival SVC in terms of performance. With a rotating exciter built onto the shaft, the synchronous condenser technology can be built as brushless machines. Whereby a small digital exciter excites the rotating exciter, thereby eliminating maintenance elements. Before now synchronous condensers were made with 10 to 12 poles for a slower speed. Its bearings and precise shaft balancing needed to produce a two-pole or four-pole machine are considered special and very expensive. But today a two-pole synchronous generator is considered standard. Modern insulation systems and manufacturing methods allow new synchronous condensers to exhibit a high degree of reliability and availability [200].

SC technology has Fast Project Cycle Time: Synchronous condenser systems only requires integration to electric power delivery components. Thereby resulting in accelerated project cycle times. The design, manufacture, installation and commissioning of a synchronous condenser system can be completed within 16 months. Hence, synchronous condenser systems have on-time project completion and on-budget execution [178].

3.2.3 Cost Implication of Using SC in Modern Electricity Grid Architecture

It can be seen in Table 3.1. that costs favors capacitors/reactors. Generators have exceptionally high capital costs since they are designed to provide real power, instead of reactive power. The incremental cost of reactive power provision from generators is high. However, it is hard to unambiguously split-up reactive power costs from real power costs. Operating costs for generators are high as well, since generators can be associated with real-power losses. Also, since generators have different uses, they undergo opportunity costs when called on at the same time to supply high levels of reactive and real power. Synchronous condensers have the same features as generators. But they are built exclusively to supply reactive support. Synchronous condensers capital costs are not as high as generators and they experience no opportunity cost. SVCs and STATCOMs are high cost equipment’s too. Although their operating costs are lower than those for synchronous condensers and generators. Power system operators can obtain reactive power sources either using mandates/authorization or purchases/acquisition. It might be feasible to establish competitive markets for securing these services. This is based on the condition that reactive power provisions are not geographically confined. It is a widespread opinion that the position constraints on reactive power resources are adequately challenging that competitive markets cannot be established for this service. Some power system operators pay generators their embedded costs for reactive power resources. Notwithstanding, deciding the embedded costs of generators to supply reactive power sustenance leads to uncertainty. This is so since; the same equipment is utilized to supply both real and reactive power. Queries such as what percentages, for instance, of the exciter, generator stator, generator rotor, turbine assembly, and step-up transformer should be allocated to each operation is difficult to answer. In the same vein, there is further uncertainty in deciding the embedded costs of synchronous condensers [201] – [203].

Synchronous machines are costly to procure in the first instance, and the equipment has internal losses, which present a continual operating cost. Normally, the mean cost for a synchronous condenser is between \$10 to \$40 per kVAR. While the maintenance cost ranges from about \$0.4 to \$0.8/kVAR per year. The SuperVAR is a High Temperature Superconductor (HTS) Dynamic Synchronous Condenser equipment, that is meant to operate continually. This equipment cost between \$1 million and \$1.2 million. A SuperVAR is rated at 10 MVA, however its first model was 8 MVA [204] – [208]. Reactive power generating equipment’s/sources vary in their capital and operating costs, as presented in Table 3.1 [209] – [211].

Table 3.1: Cost comparison of reactive power generating equipment's and sources.

Reactive Power Generating Equipment's and Sources	**Investment Cost**		
	Capital Cost (per kVAR)	***Operating Cost***	***Opportunity Cost***
Capacitors/Reactors	$10-30	Very Low	No
Synchronous Generators	Difficult to separate	High	Yes
STATCOM	$50-100	Moderate	No
Static VAR compensators	$40-100	Moderate	No
Synchronous condensers	$10-40	High	No
Distributed Energy Resources (DER) - Inverter	$40-90	High	Yes
Distributed Energy Resources (DER) – Synchronous Generator	$25-40	High	Yes

The cost benefit comparison between capacitor banks and a small generator retrofitted to synchronous condenser, with both rated 5.0 MVAR is tabulated in Table 3.2. it shows that the synchronous condenser come first on precise economic terms as against capacitor banks. Moreover, there are additional advantages from using synchronous condenser equipment's that are difficult to quantify. Capacitors are situated all through utility's service territory. Consequently, maintenance is extra costly as when compared to a single synchronous generator sited at a substation. Power system operators cannot be certain that its capacitors are functioning. Since they are too widely scattered for the monitoring of their status. Unpredicted occurrences, for instance lightning could stop capacitor timers from operating, without the knowledge of utility operators. The unpredictability on the status of the capacitors could be avoided by putting in place more costly control systems for capacitors. Alternatively having one synchronous condenser that can easily be reached or assessed in order to control reactive power flow/movement. Besides, synchronous condenser equipment's can dynamically make available reactive power. It regulates its output depending on the condition of an electricity grid architecture [69], [189], [209] – [216].

Synchronous condensers may deliver extra indirect advantages such as: reduced losses, saved line capacity, and increased transfer capability; as compared to capacitor banks. This is as a result of the fact that injected reactive power from a synchronous condenser equipment is practically constant when voltage is low. But substantially low, that is by voltage squared, for capacitor banks. This meaning that capacitors are least worthwhile when most needed in an electricity grid architecture. Over time, it has been seen that the more shunt capacitors are connected to an electricity grid. The more the possibilities for voltage collapse as the output of shunt capacitors decreases as the square of the measured voltage. Most capacitors that are installed by power system operators in order to keep away from power factor penalties normally in summer seasons are not actually required for the remaining period of the year. At present, utility authorities normally turn off half of its fixed capacitor banks throughout the duration of winter season. This is done to keep away from leading power factor costs. Synchronous condenser devices could assist utility authorities place a limit on installing capacitors that function only just for one third period of the year [209] – [211], [216].

Table 3.2: Cost benefit comparison between capacitors and synchronous condensers.

Costs and Benefits ($/year)	**Capacitor Banks (5.0 MVAR)**	**Small Generator Retrofitted to Synchronous Condenser (5.0 MVAR)**
Capital Cost	$22,000	$50,000
Technology Life Time	10 years	20 years
Preventive Maintenance Cost	$6,000	$3,500
Cost of Voltage Regulator Maintenance	$6,600	$3,300
Annual Cost in Present Value	$14,800	$9,300
Saving from Avoided Power Factor Penalties	$29,200	$29,200
Annual Benefit in Present Value	$29,200	$29,200
Net Annual Saving in Present Value	$14,400	$19,900
Net Annual Saving in Present Value ($/MVAR)	$2,880	$3,980

3.2.4 Practical Implementation of SC Technology in Modern Electricity Grid Architectures

This section aims to establish the practical applications of the synchronous condensers in modern electricity grid architectures. Here, five projects utilizing the synchronous condenser technology is analyzed. These include: the next-generation synchronous condenser installation at the VELCO granite substation; innovative reuse of the Ensted deactivated power plant; conversion of two retired units at Huntington Beach station to synchronous condensers; turnkey delivery of synchronous condenser solutions for the Bjæverskov, Fraugde and Herslev substations; and the Georgia Black Sea HVDC station.

3.2.4.1 Granite Substation

Vermont Electric Power Company, USA commissioned a Synchronous Condenser based reactive power device in the Granite substation as part of its Northwest Vermont Reliability Project. The reactive power device consisted of four +25/-12.5 MVAr synchronous condensers and four 25MVAr shunt capacitor banks. This synchronous condenser based reactive power device was chosen over SVC and STATCOM owing to its merits over these devices. As for the Granite Substation, the synchronous condenser afforded the smallest base nameplate rating and still met the overload and low voltage requirements. Though maintenance is required, it is considered by VELCO to be on par with static device alternatives. The synchronous condenser technology was best suited to handle the local harmonic concerns and appears advantageous from a long-term life of product support standpoint. A picture of the condenser hall at Granite Substation is shown in Fig. 3.10. The units were commissioned in November of 2008 [180].

Fig. 3.10: Granite substation condenser hall [180].

3.2.4.2 Ensted power plant

Converting power plants to synchronous condensers has enabled the innovative reuse of the Ensted deactivated power plant. This has ensured electricity grid stability in Denmark. The plant which was commissioned in 1979, is a former steam power plant located at the head of Aabenraa Fjord in the south of Denmark. Its Unit 3, formerly fired by coal and oil, had been Denmark's largest combined heat and power unit. Ensted was equipped with a total electrical capacity of 626 MW and a heat capacity of 76 MJ/s. The operator had mothballed the power production by 1 January 2013 due to expected lower electricity consumption and a rising share of energy production from renewable energy sources, mainly wind power plants. The Ensted power plant now contributes to the stability of the national Danish electricity grid when required. The rebuilding of the Ensted plant was associated with low investments and low risks: Components from the original manufacturer, the reuse of equipment and the smooth integration of the solution were conducted with minimal effort. The project was completed within the very narrow, challenging time frame of five months [217]. It started operation in 2012, with generator rating of: 1500 MVA, 27 kV, 1500 rpm, and reactive power ability of between: -450 … +850 MVAr [185]. The outcome of this project is the innovative reuse of a deactivated power plant; improved grid stability due to the generation of reactive power and short circuit power through conversion of the generator into synchronous condenser; As well as Low investment and operational costs [217].

3.2.4.3 Huntington Beach station

The units three and four steam turbine generators at the Huntington Beach Generating Station, in California, USA, has been converted to synchronous condensers [218]. Faced with a critical shortfall in voltage support after the loss of the San Onofre nuclear plant. The California Independent System Operator converted two retired units at its Huntington Beach station to synchronous condensers. The experience offers lessons for other electricity utility authorities looking forward to dealing with impending plant retirements and changing grids. Two retired generators at the Huntington Beach plant were converted to synchronous condensers to provide voltage support to the Southern California grid after the unexpected retirement of the San Onofre Nuclear Generating Station. The conversion from generators to synchronous condensers has the plant not only stabilizing the grid and keeping the lights on in times of high demand, but equally keeping the air just a little bit cleaner in the process [219].

The four natural gas fired steam units that make up the Huntington Beach Generating Station are in Huntington Beach, California and owned by AES Southland Holdings, LLC. Units three and four had been retired since 1995. The operating units are of great regional significance as they generate enough power to light nearly a half-million Californian homes and businesses. The power supply of 400,000 homes in Southern California was challenged by the decommissioning of the San Onofre nuclear power plant in Southern California. To maintain grid reliability, it was decided that bringing unit three and four of Huntington Beach out of retirement to serve as synchronous condensers would be a good option. To do so, however, the application needed not only to comply with California's strict environmental regulations, but also meet a short time schedule [218], [220]. The effect of this work is improved grid reliability due to the conversion of the two generators to synchronous condensers. No emissions thanks to synchronous condensers which use no fuel. Hence, further innovative use of shut down units [220].

3.2.4.4 Bjæverskov, Fraugde and Herslev substations

The Danish transmission system operator placed three orders for turnkey delivery of synchronous condenser solutions for the Bjæverskov, Fraugde and Herslev substations. At the end of February 2015, the synchronous condenser solutions of Fraugde and Herslev were handed over to the client's full satisfaction. In May 2015 Bjæverskov substation had been successfully completed and was passed over to the Danish Transmission System Operator. The solutions help stabilize the transmission system. The scope of delivery for the synchronous condenser solutions included a synchronous generator with brushless excitation, a generator step-up transformer and the electrical auxiliary systems, such as control and safety systems, voltage regulators and startup systems. They feature high efficiency, low noise emissions and low installation and commissioning costs [221].

Each synchronous condenser solution can deliver more than 900 MVA of short-circuit power and

+215/-150 MVAr of reactive power. The startup time is designed so that the generators can reach up to 3,000 rpm within 10 minutes and be synchronized with the transmission grid. Since the synchronous condensers are designed for continuous operation and provision of short-circuit currents when voltage dips occur in the grid. Hence, they have a minimum availability of 98 percent. These are important projects for the transmission system operator in Denmark for stabilizing the transmission network, Denmark is one of the few countries to include a large share of wind energy in its energy mix, which is why the country need synchronous condenser solutions to help stabilize her electricity transmission system and to support higher wind power generation in the country [221].

Bjæverskov substation 250 MVAr synchronous condenser solution started operation in 2013, providing the transmission system with a short-circuit power of more than 800 MVA in addition to reactive power control. The installation of this stand-alone synchronous condenser solution enabled the transmission system operator in Denmark to operate the transmission network without the need for a large thermal power plant. This makes the installation an economically and environmentally advantageous investment enabling the infeed of large amounts of renewable energy into the transmission network. Fraugde and Herslev substations synchronous condenser solution can deliver more than 900 MVA of short-circuit power and +150/-75 MVAr of reactive power [222].

3.2.4.5 Georgia Black Sea HVDC Station

The Black Sea Transmission Network Project was started in 2009, to create an asynchronous interconnection between the 500 kV network of Georgia and the 400 kV network of Turkey [222]. Three 60 MVAr synchronous condensers were installed at the Georgia Black Sea HVDC station in June 2012. This synchronous condenser solution supports the transmission network between Georgia and Turkey with the required short-circuit power in order to operate the newly installed HVDC back-to-back station [223]. The Project was successfully completed in 2013. It provides 700MW capacity interconnection between the Georgian and Turkish electricity grids. Through the rehabilitation/construction of 500kV Gardabani-Akhaltsikhe-Zestaponi overhead line and construction of 400kV interconnection line from Akhaltsikhe to Turkish border. As well as the construction of a new 500/400/220kV substation with HVDC back to back plant in Akhaltsikhe. Through this transmission infrastructure Georgia having abundance of renewable power sources, such as hydro and wind can export or wheel eco-friendly electricity to the emerging, demanding markets of Turkey. As well as other countries in eastern or central Europe and Asia [222], [224], [225].

3.2.5 Illustrative Example of Reactive Power Producing Ability of SC Technology

To evaluate the effectiveness of the synchronous condenser reactive power producing ability in an electricity grid architecture. The schematic diagram in Fig. 3.11 is modeled using MATLAB/Simulink software program. This is detailed in Paper Three, Four, Five and Six presented in the contribution section of this thesis. Parameters of the electricity grid architecture are given in Table 3.3. The system has an Active Power (P) of 30 MW, a Capacitive Reactive Power

(Q_C) equal to 0.5 MVAR, and varying Inductive Reactive Power (Q_L) of 4, 7 and 10 MVAR, a load of 33 kV 50 Hz is connected to the grid structure. To test the validity of the power system, both measured and calculated power factor ($\cos\varphi$) values of the electricity grid architecture were obtained. To evaluate the effect of the synchronous condenser on the power system, two possible scenarios of the proposed network were analyzed; Firstly, with the synchronous condenser installed at the terminal end of the power system (Position One, as seen in Fig. 3.12). And secondly, with the synchronous condenser installed at the beginning of the terminal of the electricity grid architecture (Position Two, as seen in Fig. 3.13). Three sets of data were analyzed for each study; data 1, 2, and 3, as tabulated in Table 3.3. The synchronous condenser allows for the input of reactive power on the electricity grid architecture. This helps in the voltage stability and power flow control of the system. Voltage stability and power flow control is very significant most especially for sensitive loads in electricity grids.

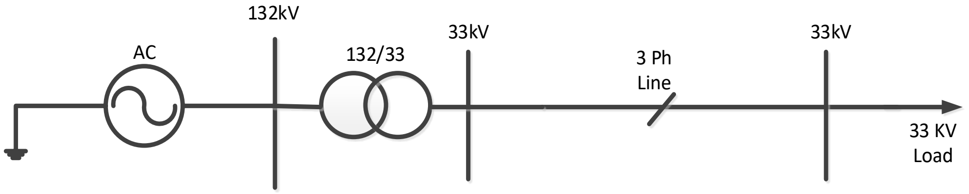


Fig. 3.11: Schematic diagram of the proposed 33 kV MV electricity grid architecture without the installation of the synchronous condenser equipment.

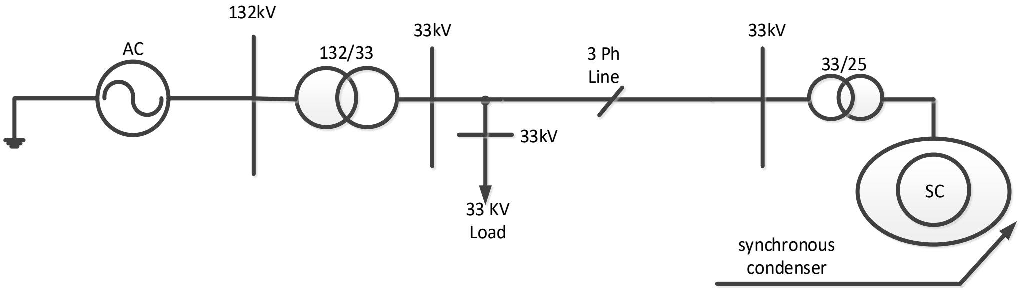


Fig. 3.12: Schematic diagram of the synchronous condenser equipment installed at the terminal end of the 33 kV MV electricity grid architecture (Position One).

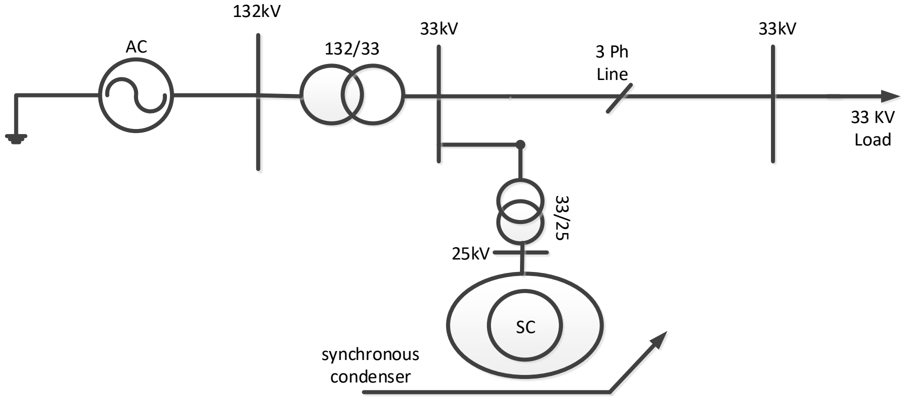


Fig. 3.13: Schematic diagram of the synchronous condenser equipment placed at the beginning of the 33 kV MV electricity grid architecture (Position Two).

Table 3.3: Values of power factor of load ($\cos\varphi$) for the 33 kV 50 Hz loads.

33 kV 50 Hz load				$\cos\varphi$	
Set of Data's	***Active Power P (MW)***	***Inductive Reactive Power Q_L (MVAR)***	***Capacitive Reactive Power Q_C (MVAR)***	***Measured Value***	***Calculated Value***
1	30	4	0.5	0.99	0.99
2	30	7	0.5	0.97	0.97
3	30	10	0.5	0.95	0.95

Calculated Power Factor of Load ($\cos\varphi$) Values: Both measured and calculated $\cos\varphi$ values are tabulated in table 3.3. The power factor of load calculation for data 1, 2, and 3, is done as follows;

Data 1;

$$cos\,\varphi = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}} = \frac{30}{\sqrt{30^2 + 3.5^2}} = 0.99$$

Data 2;

$$cos\,\varphi = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}} = \frac{30}{\sqrt{30^2 + 6.5^2}} = 0.97$$

Data 3;

$$cos\,\varphi = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}} = \frac{30}{\sqrt{30^2 + 9.5^2}} = 0.95$$

Voltage Values and Directions of Power Flow with SC Placed at the End of the 33 kV MV Electricity Grid Architecture (Position One): When the synchronous condenser is installed at the end of the three-phase 33 kV MV electricity grid architecture linked to a 132/33 kV HV/MV transformer source. The observed voltage values at the sending and receiving end of the system is measured for the three set of data's, 1, 2 and 3. The voltage values and directions of power flow are shown in Table 3.4 and 3.5 respectively. Table 3.4 shows the results of the voltage values and power flow direction obtained without the synchronous condenser connected to the end terminal of the electricity grid architecture. There is generally large voltage difference (U_s-U_r) in the network and the direction of power flow is positive (+). This insinuating that voltage flows from the voltage sending (U_S) terminal to the voltage receiving (U_r) terminal of the electricity grid architecture. While Table 3.5 presents the voltage values and power flow direction with the synchronous condenser connected to the end terminal of the 33 kV MV electricity grid. In this case, small voltage differences were observed on the system and the direction of voltage flow is negative (-). This insinuating that power flows from the voltage receiving (U_r) end of the grid terminal to the voltage sending (U_S) terminal end of the 33 kV MV electricity grid architecture.

Table 3.4: Voltage values obtained, and power flow directions observed without (W/O) the synchronous condenser connected to the end terminal of the 33 kV MV electricity grid architecture.

Set of Data's	Sending Voltage (U_s)	Receiving Voltage (U_r)	Voltage Difference (U_s-U_r)	Power Flow Direction
1	32.95	32.39	0.56	+
2	32.00	31.70	0.30	+
3	31.70	31.30	0.40	+

Table 3.5: Voltage values obtained, and power flow directions observed with the synchronous condenser connected to the end terminal of the 33 kV MV electricity grid architecture.

Set of Data's	Sending Voltage (U_s)	Receiving Voltage (U_r)	Voltage Difference (U_s-U_r)	Power Flow Direction
1	32.70	33.10	- 0.40	-
2	32.65	32,95	- 0.30	-
3	32.20	32.40	- 0.20	-

Voltage Values and Directions of Power Flow with SC Placed at the Beginning of the 33 kV MV Electricity Grid Architecture (Position Two): Table 3.6 and 3.7 present the voltage values obtained when the synchronous condenser is installed at the beginning of the three-phase 33 kV MV electricity grid architecture. The voltage at the sending and receiving end of the system is measured for the three set of data's, 1, 2 and 3 as done earlier for position One. The directions of power flow are shown in Table 3.6 and 3.7 respectively. Table 3.6 present the results of voltage values and power flow direction obtained without the synchronous condenser connected to the beginning terminal of the electricity grid architecture. Large voltage difference (U_s-U_r) is observed on the system and the direction of power flow is positive (+). Implying that power flows from the voltage sending (U_s) terminal to the voltage receiving (U_r) terminal of the grid configuration. Table 3.7 clearly show the voltage values obtained and the power flow directions observed when the synchronous condenser is connected at the beginning of the electricity grid architecture. Here, larger voltage differences (U_s-U_r) is observed, as compared to the situation, when the synchronous condenser was not installed at the beginning terminal of the grid. The direction of power flow is equally positive (+), meaning that power flows from the voltage sending terminal (U_s) to the voltage receiving (U_r) terminal of the grid. This suggesting that installing the synchronous condenser at the beginning of the network terminal has no significant positive influence on the voltage profile of the whole electricity grid architecture. Furthermore, it is observed that the direction of power flow remains the same, meaning that there was no change in the direction of power flow on the 33 kV MV electricity grid architecture as seen in Table 3.6 and 3.7 respectively.

Table 3.6: Voltage values obtained and power flow directions without the synchronous condenser connected to the beginning terminal of the three-phase 33 kV MV electricity grid architecture.

Set of Data's	**Sending Voltage (U_s)**	**Receiving Voltage (U_r)**	**Voltage Difference (U_s-U_r)**	**Power Flow Directions**
1	32.90	32.35	0.55	+
2	32.74	31.70	1.04	+
3	32.45	30.98	1.47	+

Table 3.7: Voltage values obtained and power flow directions with the synchronous condenser installed at the beginning terminal of the three-phase 33 kV MV electricity grid architecture.

Set of Data's	Sending Voltage (U_s)	Receiving Voltage (U_r)	Voltage Difference (U_s-U_r)	Power Flow Direction
1	32.70	31.90	0.80	+
2	32.10	31.25	0.85	+
3	31.40	29.60	1.80	+

Simulation Results and Discussion: MATLAB/Simulink is used for the simulation of the system model. The model consists of a 132 kV High Voltage (HV) alternating current power supply source. Connecting a three-phase 33 kV Medium Voltage (MV) electricity grid architecture with the aid of a 132/33 kV HV/MV transformer. The 33 kV MV electricity grid architecture is connected to the MV side of the 132/33 kV HV/MV transformer. A 33 kV 50 Hz load is attached to the three-phase medium voltage power line. Two scenarios were studied; Scenario One, when the synchronous condenser is located at the end terminal of the 33 kV MV electricity grid architecture. Scenario Two, when the location of the synchronous condenser is changed and installed at the beginning of the 33 kV MV electric-power Line,

Simulation Results and Analysis with SC Placed at the End Terminal of the 33 kV MV Electricity Grid Architecture (Position One): Firstly, the power factor ($\cos\varphi$) values for data 1, 2, and 3 were measured and thereafter calculated, this is done to test the validity of the electricity grid architecture. It was observed that the measured and calculated values of the power factors obtained were the same for the three sets of data observed. This is presented in Table 3.3, simulation results for the voltage values obtained at the beginning terminal of the 33 kV medium voltage (MV) power system without and with the synchronous condenser connected at the end terminal of the network is tabulated in Table 3.4 and 3.5 respectively. A graphical illustration with a three-dimensional (3D) diagram is shown in Fig. 3.14. Large voltage difference (U_s-U_r) is observed on the 33 kV medium voltage (MV) grid line. The direction of power flow is from the voltage sending (U_s) terminal to the voltage receiving (U_r) terminal of the power line for data's 1, 2, and 3 observed. At the beginning terminal of the line, the scheme uses up reactive power when the synchronous condenser is not connected to the end terminal of the electricity grid architecture. Here, reactive power is injected onto the 33 kV medium voltage (MV) grid, when the synchronous condenser is installed at the end terminal of the grid.

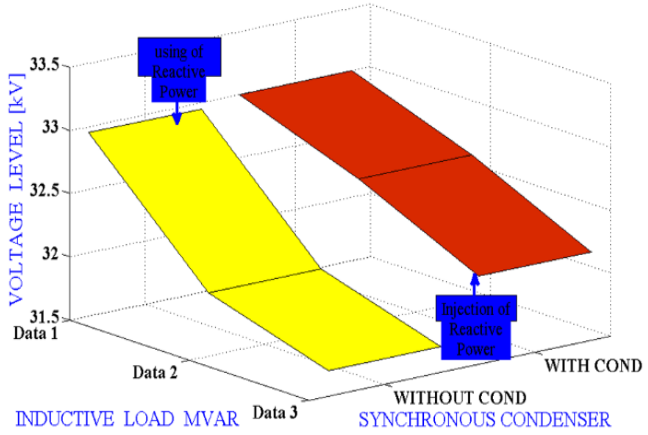


Fig. 3.14: Voltage values at the beginning terminal of the 33 kV MV electricity grid architecture, without and with the synchronous condenser connected at the end terminal of the grid.

Figure 3.15 illustrates the voltage values obtained at the terminal end of the 33 kV medium voltage (MV) electricity grid architecture. Without and with the Synchronous Condenser Installed at the end terminal of the grid. Results shows that when the synchronous condenser is not installed onto the end terminal of the grid, the grid network uses up reactive power. But reactive power is injected into the 33 kV MV network, when the synchronous condenser is installed onto the terminal end of the electricity grid architecture. Here, the results depict a small voltage difference on the power line and the observed power flow direction movement is from the receiving voltage (U_r) terminal end of the proposed scheme to the sending voltage (U_s) terminal end of the electricity grid architecture, this is tabulated in Table 3.5.

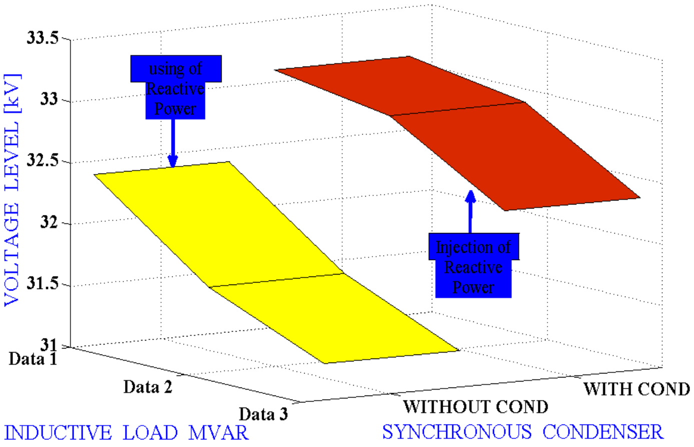


Fig. 3.15: Voltage values at the terminal end of the 33 kV MV electricity grid architecture, without and with the synchronous condenser installed at the end terminal of the network.

Furthermore, Fig. 3.16. vividly show the graphical illustration of the differences in voltage (U_s–U_r) values obtained at the beginning and end terminals of the 33 kV MV power-line. Without and with the synchronous condenser connected at the terminal end of the 33 kV MV electricity grid architecture. Considering the observed directions of power flow for data 1, 2, and 3 shown. Large voltage differences (U_s-U_r) is observed and the direction of power flow is from the sending voltage (U_s) terminal ends to the receiving voltage (U_r) terminal ends of the electricity grid architecture. Implying positive (+) directions of power flow for the situation without the synchronous condenser connected at the terminal end of the electricity grid architecture. The obtained voltage difference (U_s–U_r) for the observed data's 1, 2 and 3, when the synchronous condenser is connected at the terminal end of the power system is small and the directions of power flow is from the receiving voltage (U_r) terminal end to the sending voltage (U_s) terminal end of the grid. Meaning that the observed power flow direction is negative (-). This suggests that the situation with the synchronous condenser connected at the end terminal of the 33 kV MV electricity grid architecture gave favorable results. This is as regards to enhanced voltage stability and power flow control. As compared to the situation without the synchronous condenser installed onto the electricity grid architecture.

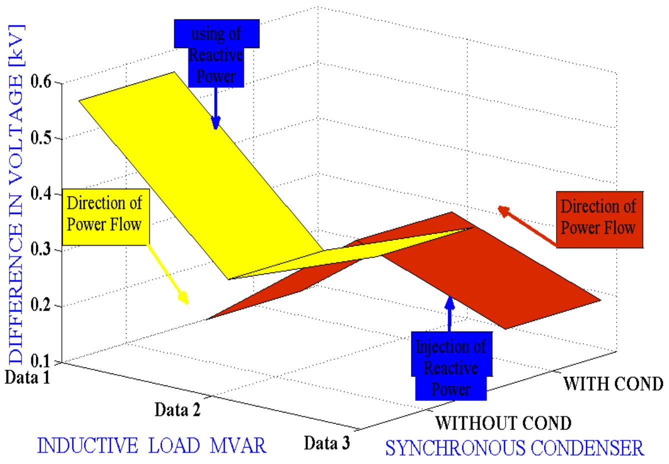


Fig. 3.16: The observed directions of power flow and obtained voltage difference (U_s-U_r) values at the beginning and end terminals of the 33 kV MV electricity grid architecture, without and with the synchronous condenser connected at the terminal end of the grid.

Simulation Results and Analysis with SC Placed at the Beginning of the 33 kV MV Electricity Grid Architecture (Position Two): Simulation results for the voltage values obtained at the beginning terminal of the 33 kV MV electricity grid architecture. Without and with the Synchronous Condenser Connected at the beginning of the grid is tabulated in Table 3.6 and graphically illustrated with a three-dimensional (3D) diagram in Fig. 3.17. Large voltage difference is observed on the 33 kV MV grid. The direction of power flow is from the voltage sending (U_s) terminal of the network to the voltage receiving (U_r) terminal for the three set of data observed. The difference between sending and receiving voltages (U_s-U_r) becomes larger as values of inductive reactive power (Q_L) increases. More so, it is observed that reactive power is being used without the synchronous condenser connected to the beginning terminal of the grid. Whereas reactive power is injected onto the grid as the synchronous condenser is connected to the beginning terminal of the electricity grid architecture. The direction of power flow without and with the synchronous condenser device connected onto the beginning terminal of the network is from the voltage sending (U_s) terminal to the voltage receiving (U_r) terminal of the power system. Implying that power flow direction is positive (+) as can be seen in Fig. 3.17. and Table 3.6.

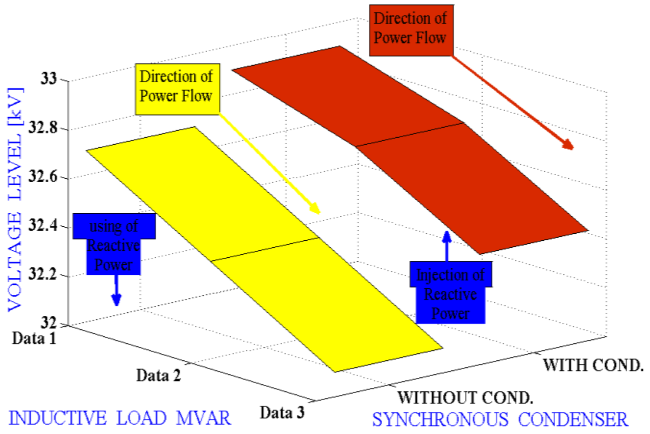


Fig. 3.17: Voltage values at the beginning terminal of the 33 kV MV electricity grid architecture, without and with the synchronous condenser connected at the beginning of the grid terminal.

The results obtained at the terminal end of the 33 kV MV power system without and with the synchronous condenser installed at the beginning of the grid is shown in Table 3.7. This is graphically illustrated in Fig. 3.18 with a 3D diagram. From Fig. 3.18, it is seen that the values of the voltage difference (U_s-U_r) between the sending voltage (U_s) and receiving voltage (U_r) becomes even larger. This is as a result of the installation of the synchronous condenser at the beginning of the 33 kV MV electricity grid architecture. Indicating that there is a gradual increase in the voltage difference (U_s-U_r) on the grid, as values of inductive reactive power (Q_L) increases. The values of the voltage difference (U_s-U_r) obtained is significantly larger when the synchronous condenser is connected at the beginning terminal of the grid. Even when compared to the voltage difference values obtained without the synchronous condenser installed at the beginning terminal of the network. Figure 3.18, and Table 3.7 further shows that the direction of power flow without and with the synchronous condenser device connected to the grid, specifically at the beginning of the power line, is from the voltage sending (U_s) terminal to the voltage receiving (U_r) terminal. Implying a positive (+) direction of power flow. It can as well be seen in Fig. 3.18, that without the synchronous condenser installed at the beginning of the electricity grid architecture. The grid structure utilizes reactive power. But with the synchronous condenser installed at the beginning of the grid terminal. There is injection of reactive power to the electricity grid architecture.

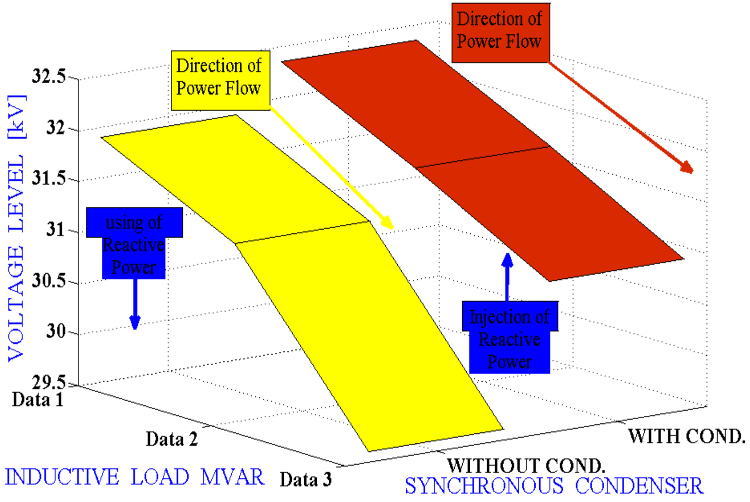


Fig. 3.18: Voltage values at the terminal end of the 33 kV MV electricity grid architecture, without and with the synchronous condenser installed at the beginning of the grid terminal.

Graphical illustration of the comparison of the voltage differences (U_s-U_r) between the sending voltage (U_s) and receiving voltage (U_r), at the beginning and end terminals of the 33 kV MV electricity grid architecture is shown in Fig. 3.19. This is without and with the synchronous condenser connected to the beginning of the electricity grid architecture. This is equally tabulated in Table 3.6 and 3.7. Also, looking at the observed directions of power flow for data 1, 2, and 3 as illustrated in Fig. 3.19. Large voltage differences (U_s-U_r) is observed and the direction of power flow is from sending voltage (U_s) terminal ends to the receiving voltage (U_r) terminal ends of the grid. Indicating positive (+) direction of power flow for the situation without the synchronous condenser installed at the beginning terminal of the grid. The obtained voltage difference (U_s-U_r) for observed data's 1, 2, and 3. When the synchronous condenser is installed at the beginning of the grid is much larger. But the directions of power flow are still from the sending voltage (U_s) terminal ends to the receiving voltage (U_r) terminal ends of the grid. This indicating that the observed power flow direction is positive (+) for both situations. Without and with the synchronous condenser installed at the beginning of the electricity grid architecture. This implying that installing the synchronous condenser at the beginning of the terminal of the 33 kV MV grid system. Negatively affects voltage stability and power flow control of the electricity grid architecture.

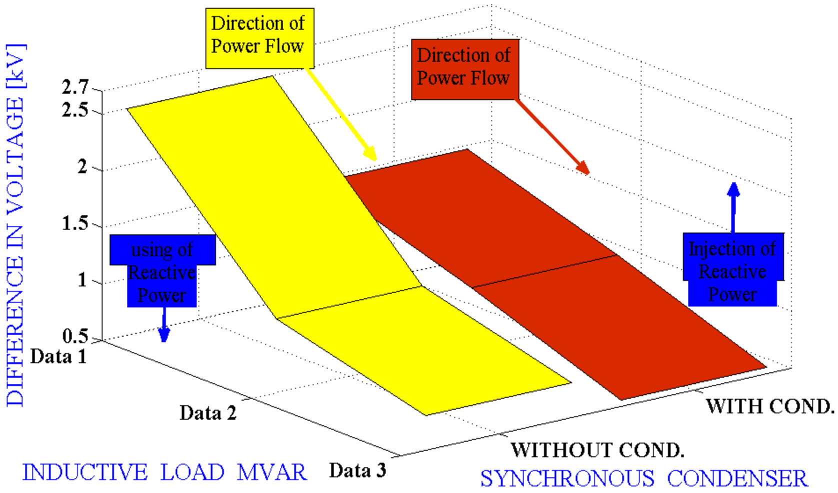


Fig. 3.19: The observed directions of power flow and obtained voltage difference (U_s-U_r) values, at the beginning and end terminals of the 33 kV MV electricity grid architecture, without and with the synchronous condenser installed at the beginning terminal of the grid.

3.3 Wind Plant

Wind power is the kinetic energy of wind, harnessed and redirected to perform a task mechanically or to generate electricity. It is the capturing and converting of the energy from moving air into electricity [226] – [227]. A wind plant is a wind energy installation that converts the kinetic energy of wind into electrical energy [228]. The energy from the wind has been harnessed by mankind for millennia to carry ships across oceans and later to pump water and grind grain. The conversion of wind kinetic energy to electrical energy started in 1887, with an automated wind turbine equipped with a 12 kW direct current generator. To generate electricity from wind turbines more efficiently, reliably, and to compete against fossil fuel-based power plants. Many improvements have been made in the design of wind turbine mechanical and electrical components. Wind turbine technology reached maturity level by 1980s leading to the commissioning of the first 50 kW utility-scale wind turbines [229] – [231].

Among all renewable energy sources, wind energy is increasingly becoming accepted and competitive with conventional sources of energy. The cumulative installed wind power capacity increased exponentially from 6100 megawatt (MW) in 1996 to 282.6 GW by 2012. It is anticipated that, following the current trend, the cumulative wind capacity would reach 760 GW by 2020. Cumulative wind capacity is expected to further increase as many countries are embracing wind energy technology in their electricity generation mix. In 2012, approximately 45 GWs of new wind power was added which represents investments of about Euros 56 billion. The wind energy industry is equally providing many direct or indirect job opportunities, leading to significant stimulus in economic development. The wind power industry demonstrated an excellent growth rate of more than 19% and represents 1.9% of the world's net electricity production. Currently many countries are using wind energy on a commercial basis to generate electricity. Cost

reduction, government incentive programs, and technological advancements are some of the main reasons behind this impressive growth rate [231] – [233].
According to aerodynamic properties, the power output of a wind turbine is proportional to the square of a rotor diameter and a cubic of wind speed [232] – [233]. Large turbines can capture higher wind power with lower installation and maintenance costs. As compared to a group of small turbines. Owing to this fact, the size of commercial wind turbines has exponentially increased over the years as demonstrated in Fig. 3.20. Turbine size has increased from 50 kW in 1980 to 7.5 MW in 2010 [234] - [235]. Wind turbine rotor diameter has equally increased from 15 m in 1980 to 126 m in 2010. The largest wind turbine reported by 2014 is 8MW with a diameter of 164 m. Wind turbines manufacturing companies has ambitious plans to develop 15MW and larger sizes of turbines. This is to further enhance turbine capability. Offshore technology is another important driving force behind this amazing growth size in wind turbines. The rotor diameter and power ratings of offshore wind turbines are higher as compared to onshore wind turbines. In 2013, the average size of onshore and offshore wind turbine is reported as 1.926 and 3.613 MW respectively. It is hoped that 10–20 MW turbines will be operational in near future with rotor diameters exceeding 150 m. This is approximately twice the length of a Boeing 747 airplane [231], [236].

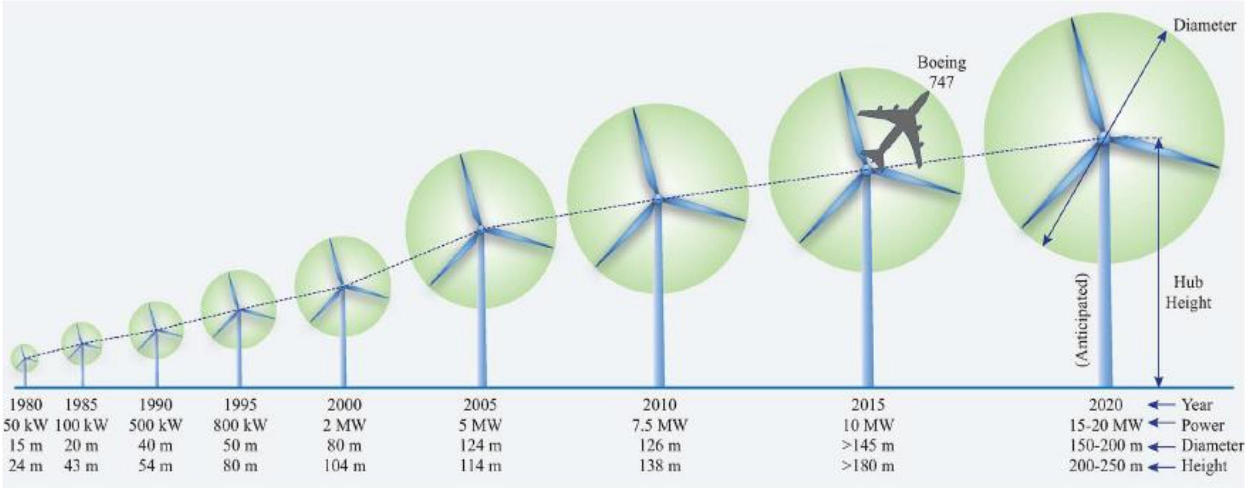


Fig. 3.20: Evolution in the size of commercial wind turbines [231].

The basic configuration of grid-connected MW Wind Energy Conversion System (WECS) is depicted in Fig. 3.21. The WECS is composed of several components that convert wind kinetic energy into electric energy in a controlled, reliable and efficient manner. The major components of a WECS can be broadly classified as mechanical, electrical and control systems. The mechanical components include tower, nacelle, rotor blades, rotor hub, gearbox, pitch drives, yaw drives, wind speed sensors, drive-train, and mechanical brakes [237]. The electrical components include electric generator, possible power electronic converter along with generator and grid-side harmonic filters, step-up transformer and three-phase grid or collection-point [238]. The control related components are used with both the mechanical and electrical energy conversion systems [233], [239]. The most visible parts in large wind turbines are tower, nacelle and rotor blades, and the rest of the components are housed inside the wind turbine [231].

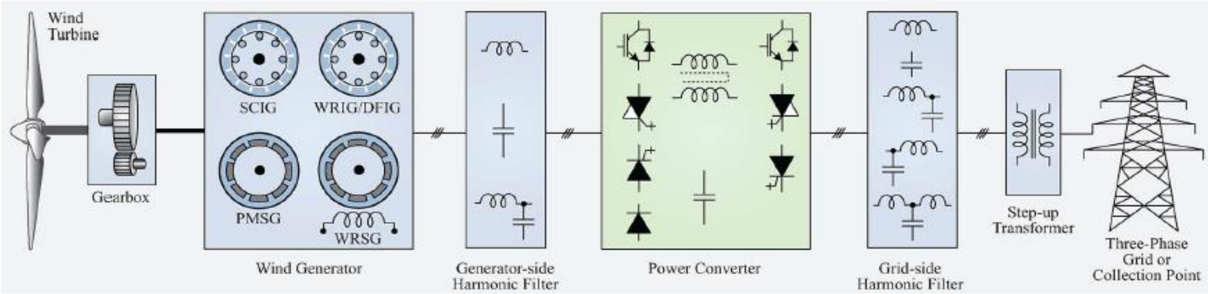


Fig. 3.21: Basic configuration of a grid-connected megawatt wind turbine [231].

3.3.1 Types of Wind Energy Conversion System Base on Configuration

The major electrical components in WECS are the generator and power electronic converter. Using different designs and combinations with these two components, a wide variety of WECS configurations can be achieved. The type 1, 2, 3, 4, and 5 WECS are the main five configurations that have been analyzed, documented and commercialized extensively for now.

3.3.1.1 Type 1 WECS Configuration

A fixed-speed Squirrel Cage Induction Generator (SCIG) based WECS without power converter interface, also called Type 1 turbine is illustrated in Fig. 3.22. where the generator is connected to the grid through a soft starter and step-up transformer [240] - [242]. This is the oldest and very first technology developed for the wind turbines. In high-power WECS, the SCIG contains 4 or 6 poles for 50 or 60 Hz operation. The generator speed varies within 1% around the corresponding synchronous speed at different wind speeds. Thus, this configuration is called fixed-speed WECS. A gearbox is normally required to match the speed difference between the turbine and generator. After the start-up procedure, the soft-starter is by-passed by a switch, and the system essentially works without any power converter. The SCIG draws reactive power from the grid. To compensate for this, three-phase capacitor banks are usually employed [179], [238]. This configuration features simplicity, low initial costs, and reliable operation. The major drawbacks include: lower wind energy conversion efficiency; changes in the wind speed are reflected to the grid; and the grid faults cause severe stress on the mechanical components of wind turbine [243]. The fixed-speed wind turbines are equipped with additional hardware, such as STATCOM, to comply with grid codes [244], [245]. Despite its drawbacks, this configuration has been accepted by the wind industry and commercial solutions are available in MW range such as: 1.65 and 2.3 MW. Fixed speed turbines technology used to be popular, before it slowly became seldom due to its inherent disadvantages. These turbines which have been installed already are still in operation to generate electricity [231].

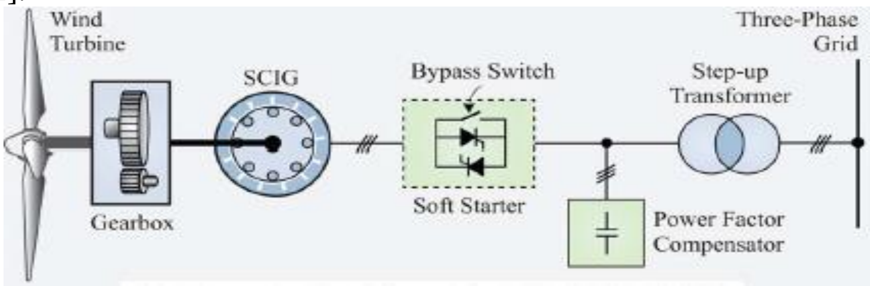


Fig. 3.22: Type 1: Fixed-speed (+/-1%) SCIG WECS [231].

3.3.1.2 Type 2 WECS Configuration

The variable-speed operation of wind turbine increases energy conversion efficiency, and reduces mechanical stress caused by wind gusts, reduces wear and tear of gearbox and bearings, reduces maintenance requirements, and thus increases wind turbines life cycle. A semi variable-speed WECS using Wound Rotor Induction Generator (WRIG) and partial rated (10%) power converter is shown in Fig. 3.23. This is equally known as Type 2 WECS configuration. The change in the rotor resistance affects the torque/speed characteristic of the generator. Thereby enabling variable speed operation of turbine. This configuration is often called Optislip control [246]. The rotor resistance is normally made adjustable by a power converter composed of a diode-rectifier and chopper [238]. The speed adjustment range is typically limited to about +/-10% of its rated speed. With variable-speed operation, the system can capture more power from the wind. But it experiences energy losses in the rotor resistance. This configuration equally requires a gearbox, soft starter, and reactive power compensation. The WRIG with variable rotor resistance has been in use since the mid 1990's with a power rating up to a couple of megawatts. A few commercial solutions range from 2.0-2.1 MW. This configuration is also becoming less important among wind turbine manufacturers due to limited speed range and low energy conversion efficiency [231].

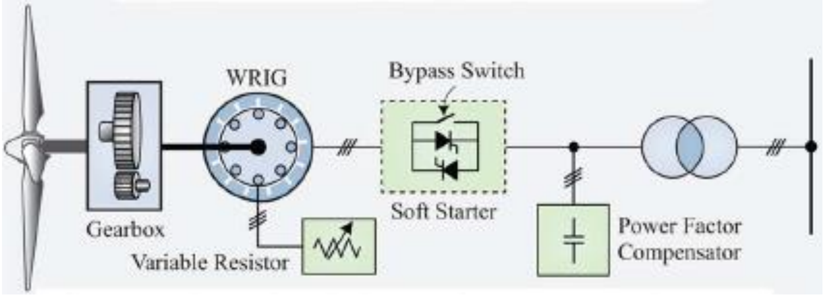


Fig. 3.23: Type 2: Semi-variable speed (+/-10%) WRIG WECS [231].

3.3.1.3 Type 3 WECS Configuration

Another semi variable-speed WECS using Doubly-Fed Induction Generator (DFIG) is shown in Fig. 3.24. This is equally known as the Type 3 WECS configuration [247] – [248]. As the name implies, the power from the generator is fed to the grid through both stator and rotor windings. A partial rated (30%) power converter is employed in the rotor circuit to process the slip power. This is approximately 30% of the rated generator power. Like Type 1 and 2 wind energy conversion configurations, this configuration also uses gearbox. But there is no need for soft starter and reactive power compensation [249].

The use of the power converters allows bidirectional power flow in the rotor circuit and increases the speed range of generator. This system features improved overall power conversion efficiency by performing maximum power point tracking (MPPT) [250], [251], extended speed range (+/-30%), enhanced dynamic performance and robustness against power system disturbances, as compared to Type 1 and 2 turbines [252] – [253]. These features made the DFIG WECS one of the dominating technologies in today's wind industry with a market share of approximately 50% [254], [255].

The Fault Ride-Through (FRT) capability of Type 3 turbines is limited due to the use of partial scale power converter in its configuration. The gearbox increases overall turbine cost, weight and it requires regular maintenance. Moreover, the power converter is connected to the rotor windings through slip rings and brushes. The average life time of brushes is 6–12 months only, and thus regular maintenance is essential in the Type 3 turbines. These major drawbacks impede the Type 3 turbine being applied in offshore wind farms where maintenance cost is quite expensive. A few high power DFIG turbine range from 6 MW, 5 MW and 3 MW [231].

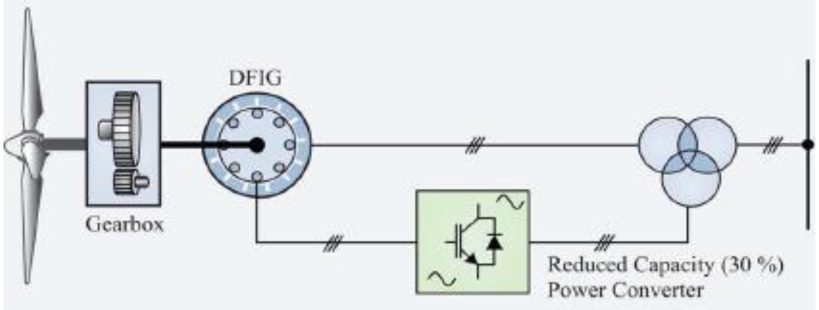


Fig. 3.24: Type 3 semi-variable speed (+/-30%) DFIG WECS [231].

3.3.1.4 Type 4 WECS Configuration

The performance of WECS can be greatly enhanced with the use of full-scale (100%) power converters as shown in Fig. 3.25. This is equally called Type 4 wind energy conversion system configuration. Permanent Magnet Synchronous Generator (PMSG), Wound Rotor Synchronous Generator (WRSG), and Squirrel Cage Induction Generator (SCIG) have all found applications in this type of configuration with a power rating of up to several megawatts. Since power converters must be rated same as generator capacity, the size, cost and complexity of the overall system of this configuration increases. Furthermore, losses in power converter are higher leading to lower efficiency. But with full-scale power converter, the generator is fully decoupled or disengaged from the electricity grid architecture. Hence, it can operate at full speed range from 0 to 100% [231], [256] – [260].

Power converters equally enable the system to perform reactive power compensation and smooth grid connection. The wind energy conversion efficiency is highest in these turbines compared to other types of turbines [261] – [263]. The best FRT compliance can equally be achieved without any external hardware. Although the cost of power converter is high, it is just a small fraction approximately 7%–12% of total wind turbine cost [264]. The need for gearbox can be eliminated by using a high-pole number PMSG/WRSG. This configuration is more robust when dealing with power system faults as compared to Type 1, 2, and 3 wind turbine configurations [265]. Typical commercial Type 4 wind turbines range from 7.5 MW, 5 MW, and 3 MW [231].

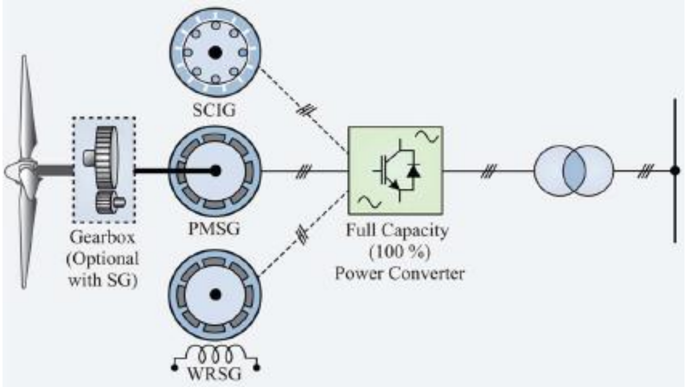


Fig. 3.25: Type 4 Full-variable speed (0–100%) SCIG, PMSG or WRSG WECS [231].

The distributed drive-train concept is used in recent megawatt Type 4 wind turbines. Although SCIG and WRSG can be used in this concept. The PMSG is most suitable since it eliminates the need for slip rings/brushes, thereby making the design simple [266]. The gearbox drives multiple generators at higher speeds. Owing to the presence of distributed drive-train and multiple generators, a higher power density can be achieved [267]. One available commercial application is the Clipper Liberty. It uses a quantum drivetrain, 4 generators and 4 converters as shown in Fig. 3.26 [268].

Higher torque is distributed among the four drive trains. The power rating of the converters is one-fourth of the system rating. This configuration equally offers effective fault tolerant operation. On the instance that one converter fails, the other three converters can still deliver power to the grid [238]. To minimize circulating currents, multi-winding transformer is used on the grid-side. The main disadvantage with this configuration is complicated drive-train [231].

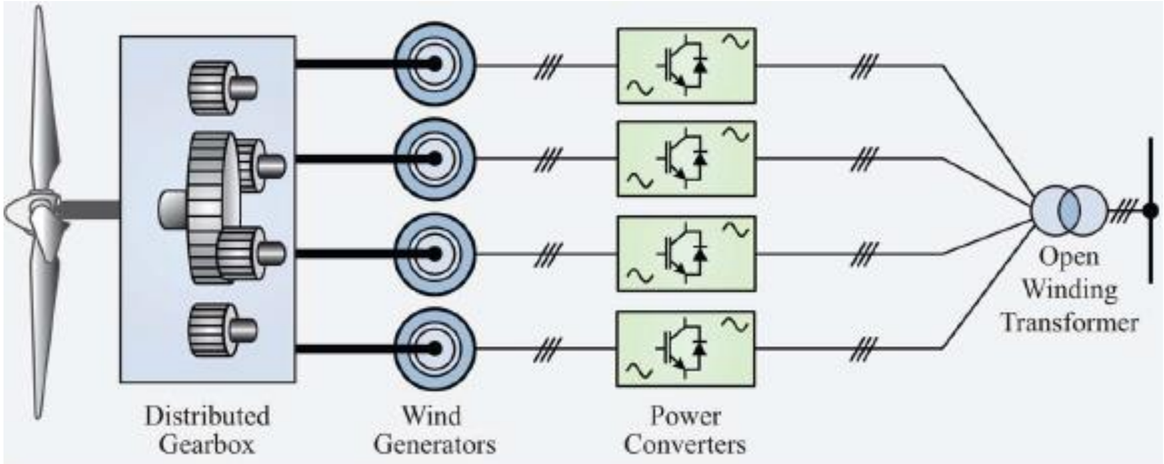


Fig. 3.26: Type 4 WECS with distributed drive-train and quantum generators [231].

3.3.1.5 Type 5 WECS Configuration

The Type 5 wind turbine with direct grid-connected WRSG and speed/torque converter is shown in Fig. 3.27. This is rather an old concept for wind turbines. Variable speed operation is achieved by mechanical converter rather than utilizing electrical converter [268] – [269]. The torque/speed converter, equally called Variable Ratio Transmission (VRT) converts variable speed of wind turbine to constant speed. The generator operates at a fixed-speed and it is directly connected to the grid through a synchronizing circuit breaker. The overall system cost and space is lower than Type 4 turbine as no power electronic converter is needed. The generator is directly connected to MV collection point without any step-up transformer. Since there is no restriction imposed by the power electronic converter unlike in Type 4 wind turbine. Despite the advantages of this configuration, it is rarely used in the wind energy industry. This is due to limited knowledge about this technology, and issues related to the mechanical converter. Commercial solutions are available in range of 2.2 MW and 2.0 MW [231].

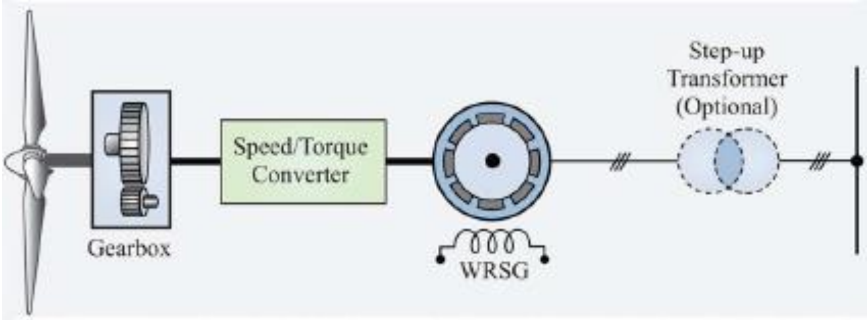


Fig. 3.27: Type 5 Full-variable speed (0–100%) WRSG WECS [231].

3.3.2 Induction Generator for Wind Energy Conversion Systems

An induction generator is an asynchronous electrical machine that can function as a motor or as a generator. In the case of an asynchronous motor, the rotor spins less than the synchronous speed of the field. But as a generator, it spins faster than the synchronous speed. An induction generator is a type of asynchronous generator, meaning the waveform that is generated is not synchronized to the rotational speed. Induction generators are widely used in wind turbines and some smaller hydro-electric installations owing to their simplicity [270]. For a medium-size three-phase induction generator wind turbine. The stator coils are the armature coils on an induction generator. While the ends of these coils are connected to terminals that are accessible in a terminal box. In a true induction machine, the rotor creates the magnetic field only through induction as it turns past the stationary coils, so no slip rings or brushes are required. This is a great advantage in cases where minimum maintenance is important. Another advantage of induction generator is safety. If the electricity grid goes down, the generator loses its field and stops so that it cannot send power to the electricity grid architecture. The drawback of induction generators is that they are less efficient than synchronous generators [270].

Induction generators are one of the major generating facilities utilized in the wind power industry. The two most common wind power generating concepts employing induction machines are the fixed speed concept using conventional fixed-frequency induction machines. There is also the variable speed generating concept using doubly-fed induction machines. Although there are differences between the two induction machines. The fixed-speed induction machine is treated as a special case of a doubly-fed induction machine by assuming the rotor circuit of the DFIG is shorted. For this reason, a DFIG model can be used as a general model for WECS study for both wind power generating concepts [271] – [272].

An induction generator is not a self-excited machine. Hence, in order to develop the rotating magnetic field, it requires magnetizing current and reactive power. The induction generator obtains its magnetizing current and reactive power from various sources like supply mains or another synchronous generator. An induction generator cannot work in isolation since it continuously requires reactive power from supply system. But there is a self-excited or isolated induction generation, when using a capacitor bank for reactive power supply instead of alternating current supply system. There are two types of induction generators. These are externally excited and self-excited induction generators; Externally excited generators are widely used for regenerative breaking of hoists driven by three-phase induction motors. While self-excited generators are used in wind mills. Thus, self-excited generator helps in converting unconventional sources of energy into electrical energy. Some disadvantages of induction generators are as follows: The efficiency of the externally excited generator is not so good; Externally excited generator cannot be used for lagging power factor, this is a major demerit of this type of generator; The amount of reactive power required to run an externally excited generator is quite large; It cannot generate reactive voltamperes. It requires reactive voltamperes from supply line to furnish its excitation. The induction generator equally has advantages, these includes: It has robust construction requiring less maintenance; It is relatively cheaper; It has mall size per kW output power, that is high energy density; It runs in parallel without hunting; and No synchronization to the supply line is required as in the case of synchronous generator [272].

3.3.2.1 Singly Fed Induction Generator

Instead of taking mechanical power from the rotor of an induction generator. The rotor can be driven by a prime mover such as wind. It can be driven to move faster than the synchronous speed and starts producing electrical power instead of consuming it. In this case, the basic induction motor becomes an induction generator. Electrical power is now taken from the stator, which now becomes the armature. Owing to its dual nature, an induction machine is sometimes referred to as a motor/generator. In the case of induction generator, after passing synchronous speed, the magnetic field is induced into the rotor from alternating current that is applied to the stator. A prime mover such as the wind turns the rotor faster than the synchronous speed, and power is generated. The prime mover equally returns power to the grid from the stator windings. The simplest induction generators are referred to as Singly Fed Induction Generators (SFIGs). It uses a squirrel cage. Since squirrel-cage induction machines look inductive, power factor correction capacitors are added to generators. Additionally, a soft-starter unit is usually used to reduce inrush current during start-up [270]. The basic structure of a Singly Fed Induction Generator (SFIG) used in a wind turbine is shown in Fig. 3.28.

The main parts of a SFIG wind turbine system are the stator, which houses the armature windings; the squirrel-cage rotor, which provides the rotating field; and the end plates, which houses the bearings that support the ends of the rotor shaft. The electrical terminals of the generator are in the terminal box of the generator, so that connections can be made easily. For a four-pole generator with a 50 Hz output, the synchronous speed is 1,500 rpm. While for a 60 Hz output, it is above 1,800 rpm. But if the number of poles doubles, the synchronous speeds are halved. Converting a slow-moving wind turbine to a higher speed generally requires adding a gearbox to the system or adding many poles to the generator. To produce power, the wind speeds need to be above the transition speed. Otherwise the motor/generator acts as a motor. Induction generators are used in larger wind turbine designs as three-phase alternating current machines. The alternating current voltage is typically increased to 12,470 V or more and connected to the electricity grid architecture [270].

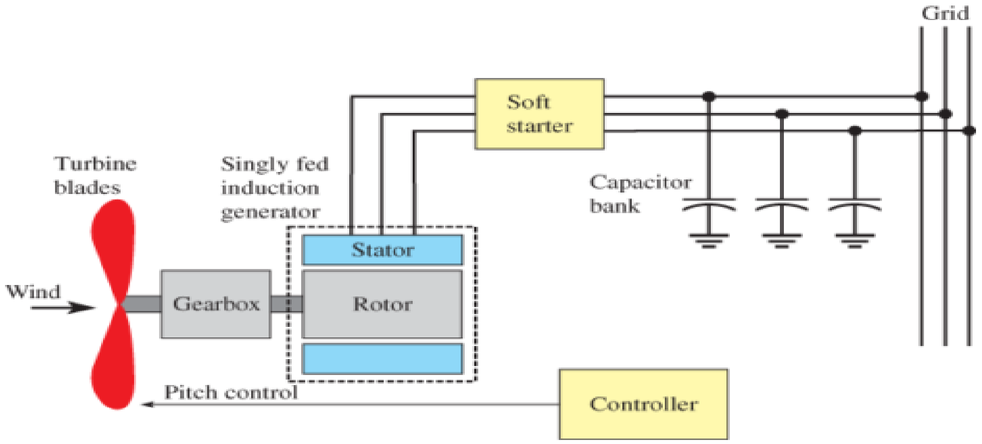


Fig. 3. 28: A block diagram showing the basic structure of a singly fed induction generator used in a wind turbine [270].

3.3.2.2 Doubly Fed or Double-Excited Induction Generator

Just as in the case of singly fed machines, doubly fed machines can operate either as a motor or a generator. As a motor, this machine is useful for driving variable-speed devices such as certain tools or pumps. The doubly fed induction generator (DFIG) is particularly useful for wind turbines. It is used in many larger wind turbines. A doubly fed induction generator has a wound rotor that is connected to a different source of alternating current than the stator. It has a three-phase wound rotor connected through brushes and slip rings to a secondary alternating current source that can be controlled for frequency, phase, and voltage. If the secondary field is 0, DFIG acts like an asynchronous generator. Here, the output frequency depends strictly on the rotor's rotational speed and the number of poles. But if the rotor has a secondary frequency included. The rotational speed of the magnetic field is a combination of the rotor speed and the alternating current fed to the rotor [270]. DFIG appears in several applications in different fields, such as; railway, marine, aeronautics, wind energy and so on. This is mainly as a result of the degrees of freedom it offers, owing to the accessibility of its rotor. Thus, there is the possibility of powering it with a converter on both stator and rotor side [274].

Magnetic field's rotational speed can either be increased or decreased by changing the phasing of alternating current to rotor. When the magnetic field owing to rotor's applied alternating current rotates in the same direction as the movement of the rotor. Then the frequency induced in the stator is high. In reverse, if it rotates in the opposite direction as the movement of the rotor. It then implies that the frequency induced in the stator is low. This means that the magnetic field's net rotational speed can be tightly controlled to generate exact match to the stator's frequency. Hence, this is afterwards synchronized to utility frequency despite variations in rotor speed. This is a merit to wind turbines, since the rotor can be varied to follow changing winds speed without affecting the output frequency of the electricity grid architecture [270]. In wind energy conversion systems, a fascinating solution in using DFIG is to connect the stator directly to the electricity grid architecture. While its rotor is fed through an interface composed of two static converters, Multilevel Inverter (MLI) three-phase reversible. A converter is in AC/DC mode, while the other converter is in DC/AC mode. Implying a back to back mode [274].

The secondary frequency is provided directly to the rotor through slip rings and brushes. This is without the losses experienced when the rotor receives its voltage by induction. The controller determines the optimum characteristics of the alternating current of rotor. It equally controls the blade pitch, which determines the speed of the rotor and optimizes power for the given conditions. The stator is connected directly to the electricity authority’s utility line. Here, the frequency is either 50 Hz or 60 Hz, depending on the value used in a locality. The doubly fed induction generator can maintain an exact match of the grid frequency, in order to return electricity to the electricity grid architecture [270]. DFIG’s structure is like that of the wound induction motor. Its stator and rotor are both installed with three-phase symmetric winding. The stator winding is connected to the electricity grid through a transformer. It is excited by symmetric three-phase power with fixed frequency [275]. Its rotor winding is excited by symmetric three-phase power with variable frequency. The frequency can be regulated by back-to-back Pulse Width Modulation (PWM) converter, rotor side converter and the grid side converter. They are controlled by Digital Signal Processor (DSP) controller [276]. A block diagram of the basic structure of a typical DFIG system is shown in Fig. 3.29.

DFIG is more complicated than a singly fed generator and thus costs more. But it has higher overall efficiency than a SFIG and can harvest energy at various wind speeds. It is equally very useful when the amount of energy surpasses intermittent machine rating. Since other generators are usually taken offline or operated with reduced load, when they are exposed to conditions that exceed their design rating. A DFIG generator accepts extra input energy. The generator speed increases for a short period of time and then continues to produce grid frequency. This continuous operation improves the overall efficiency of a DFIG generator. One very important control factor that is responsible for the widely usage of DFIG in wind turbines and microhydraulic systems, is attributed to the ac-dc-ac converter used to control the frequency of the voltage fed to the rotor. The slip rings and brushes in this system carries only current for the field. Although power is produced via the rotor. This is only about 20% of the total. Since rotor current is small as compared to total system current. The brushes can be made smaller. Thus, lesser wear is experienced [270]. If the doubly fed induction generator is used with a wind turbine, it produces power with a constant utility frequency rating of 6 mph to 50 mph in wind speeds. This allows wind turbines to accept gusting winds. It equally allows the blades to harvest extra energy at very high wind speeds. This improves the efficiency of wind turbines. For very large wind turbines of say 2 MW or larger. Individual wind turbine blade adjustments and nacelle directional yaw adjustments is incorporated onto the control system to harvest maximum amount of wind available. The doubly fed induction generator is used in micro hydrogeneration and other renewable energy systems where generator speed might be varied [270]. DFIG wind turbines allows prime mover to operate in a wider speed range. This helps to simplify the adjustment device and reduce mechanical stress during changing motor speed. Besides, DFIG system’s frequency converter occupies only part of the rated capacity. Thereby reducing the size of the frequency conversion device and cost [276]. Variable speed wind turbines with doubly fed induction generator (DFIG) are becoming the most common type of wind turbine. This is due to the low power converter rating of this wind turbine. Another reason is its ability to supply power at constant voltage and frequency, while the rotor speed is varied [277] – [279].

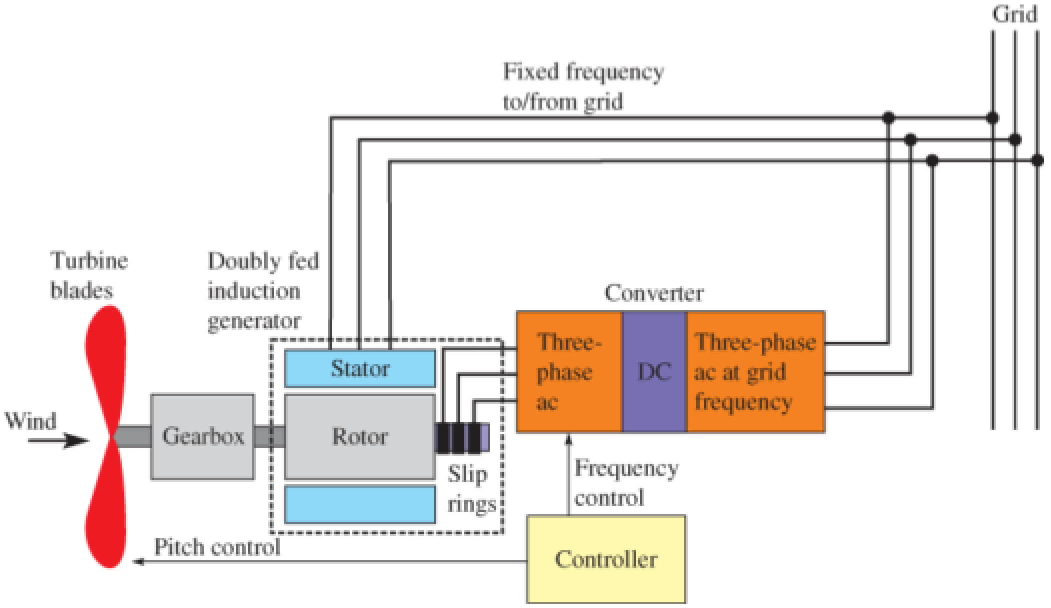


Fig. 3.29: A block diagram of a typical Doubly Fed Induction Generator [270].

3.3.2.2.1 Benefits of Doubly Fed Induction Generator for WECS

Benefits can be derived from DFIG due to its low power converter rating. It equally can supply power at constant voltage and frequency while the rotor speed varies. For a variable speed wind turbine with doubly fed induction generator, the load torque can be controlled directly at the generator side. This assists in varying the speed of the turbine rotor within certain limits. In a variable speed wind turbine, the rotor speed can be adjusted in proportion to wind speed in low to moderate wind speeds to maintain optimal tip speed ratio. At this tip speed ratio, the aerodynamic efficiency (Cp) is at maximum value. Implying that energy conversion is maximized. Generally, variable speed wind turbines have two different control goals, depending on wind speed. The control goal in low to moderate wind speeds, is to maintain a constant optimum tip speed ratio for maximum aerodynamic efficiency. While the control goal in high wind speeds is to maintain rated output power [279].

Doubly fed induction generator wind turbine installation is increasing globally. This can be attributed to its low installation cost, low power rating of converter, and its active and reactive power controllability [280]. DFIG wind turbine faces two inevitable problems, like fault ride through (FRT) capability and output power fluctuation [281]. Since DFIG wind turbine is very vulnerable to grid faults, it might not be able to ride through. These faults can result in a large voltage dip at the connection point of DFIG. Subsequently, the stator and rotor of the machine is damaged owing to voltage dip causing overcurrent in the stator and rotor windings [248]. A doubly fed induction generator must be disconnected from the electricity grid architecture, for it to be protected from grid faults. As a result, electricity grid stability is adversely affected. But due to high penetration of grid-connected wind power sources, FRT capability is required for DFIG wind turbines to mitigate system instability. DFIG wind turbine equally suffers from output power fluctuation problem during normal grid operation. This negatively influences power quality, stability, and electricity grid architectures frequency and voltage [282] – [283].

3.3.2.3 Variable-Speed Induction Generator

An option for handling various range of wind speeds in a generator configuration is Variable-Speed Induction Generator (VSIG). It uses many poles and requires no gearbox. VSIG is associated with losses and maintenance issues. Mechanical loading in the drive train is reduced since the generator is completely decoupled from the electricity grid architecture. VSIG configuration uses electrical or permanent magnet excitation and allows the generator to optimize power at an uncontrolled frequency. A full-scale frequency converter performs reactive power compensation and conversion to grid quality alternating current. VSIG wind turbine systems can take advantage of input in wind speeds ranging from a few mph during start-up to over 40 mph. A variable-speed induction generator uses a full-scale electronic frequency converter to match grid frequency. The drawback of this configuration is the high cost implication of the power electronics converter and large multipole generator. Figure 3.30 shows a block diagram of a Variable-Speed Induction Generator [270]. Although the variable speed configuration is a better solution for renewable energy electricity generation systems. It does present issues like how the operation at variable speed of the electrical generator can be adapted to feed electrical loads operating at fixed frequency. This can be solved with the use of an AC-DC-AC power converter, whose basic topology consists of two back-to-back power inverters connected by a direct current bus [284].

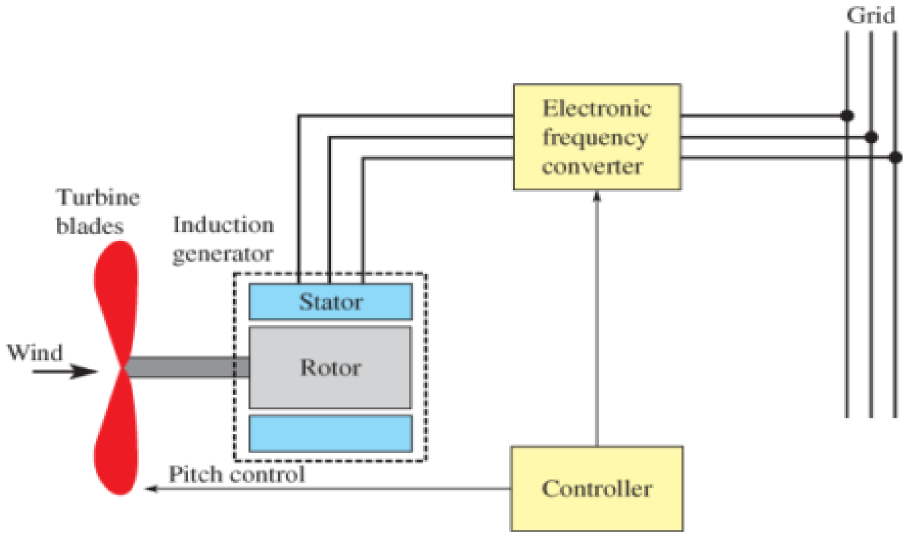


Fig. 3.30: A block diagram of a typical variable-speed induction generator [270].

3.3.3 Comparison of WECS Configurations

The Type 3 wind turbines hold the highest market share in the wind energy industry. This technology with different models is used by most wind turbine manufacturers around the globe. The Type 4 wind turbines follows the Type 3 wind turbine in terms of global market shares. Type 4 turbines offers direct drive solutions. This implies that the best-selling wind turbines in today's market uses Type 3 and 4 technologies. It is expected that the Type 4 wind turbine technology would take over the wind energy market in the coming years. They are compared using generator; capacity of power converter; speed-range achievable; requirement for soft-starter, gearbox and external reactive power compensation; maximum power point tracking (MPPT) ability;

aerodynamic power control, compliance with fault ride-through requirement; technology status; and market penetration. Overall, the Type 3 and 4 wind turbines are most favorable for MW-level applications [231]. In this thesis, the Type 3 wind turbine configuration has been used for this simulation framework. But with the reactive power decoupled. This is to enable production and injection of only active power from Type 3 wind plants.

Chapter 4

4.0 Simulation Framework

The purpose of this chapter is to briefly describe the developed MATLAB/Simulink simulation framework, detailed in Paper One, Two and Three as presented in the contributions section of this thesis. This chapter is organized as follows. Section 4.1 summarizes the modelling of the Point of Reference Data and its Elements. Next, in Section 4.2 The Point of Reference Lines, Transformer, Load and Three-phase Lines Parameters is presented. Then Section 4.3 provide detail modelling of the Synchronous Condenser (SC), and Section 4.4 shortly introduces the modelling of the Type-3 wind machine. The methodology is summarized in Section 4.5. Finally, the algorithm is presented in Section 4.6.

4.1 Modelling of the Point of Reference Electricity Grid Architecture Data and Elements

In this thesis, a 50 Hz, 33 kV grid and 50 MVA substation base on a standard utility Medium Voltage (MV) electricity grid architecture as shown in Fig. 4.1, is presented as the benchmark Case for this thesis. There are two load points each totaling 11.18 MVA each. The MV distribution grid architecture has two 33 kV power lines L1 and L2 of lengths 30 km and 40 km respectively connected to it. The lines are interconnected, tieing different parts of the 11kV consumer network to facilitate power exchange among the loads. The installed capacity at the consumer end transformer substation is 25 MVA. Note that all transmission lines are modelled using pi-model.

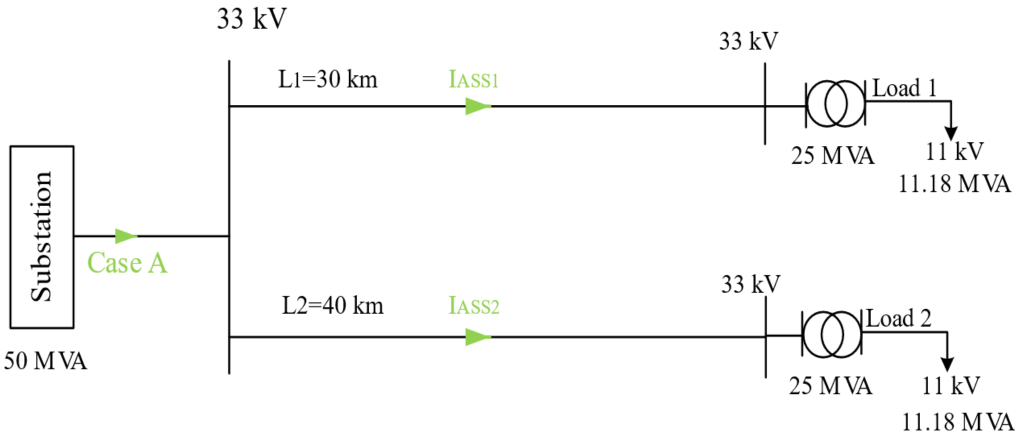


Fig. 4.1: Schematic diagram of the point of reference electricity grid architecture.

4.2 The Point of Reference Lines, Transformer, Load and Three-phase Lines Parameters

The specifications of the power lines are outlined in detail in Table 4.1. Its rated Positive resistances r_1(Ω/km), Zero-sequence resistances r_0(Ω/km), Positive inductances l_1(mH/km), zero-sequence inductances l_0(mH/km), Positive capacitances c_1(nF/km), zero-sequence capacitances c_0(nF/km), and Frequency *f*n(Hz) are same for both lines. But the lines Length (km), Phase resistance R_1(Ω), Phase Inductive reactance X_1(Ω), and Phase susceptance B(μS) differs as presented.

Table 4.1: Parameters of the MV standard electrical power lines.

Line number	1	2
Positive resistances r_1(Ω/km)	0.0922	0.0922
Zero-sequence resistances r_0(Ω/km)	0.312	0.312
Positive inductances l_1(mH/km)	0.61	0.61
zero-sequence inductances l_0(mH/km)	2.83	2.83
Positive capacitances c_1(nF/km)	11.33	11.33
zero-sequence capacitances c_0(nF/km)	5.01	5.01
Frequency f_n(Hz)	50	50
Length (km)	30	40
Phase resistance R_1(Ω)	2.766	3.688
Phase Inductive reactance X_1(Ω)	5.749	7.665
Phase susceptance B(μS)	53.39	71.19

Individual MV power lines supply a 33 kV/11 kV transformer, with a rating of 25 MVA. The specification of this transformer is shown in Table 4.2. It is seen that the Frequency f_n(Hz), Nominal Power S_n(MVA), Magnetization resistance R_m (MΩ), and Magnetization inductance L_m(H) are same for both transformers. While the connection type, V_{rms}(kV), R(Ω), and L(H) is D11, 33, and 0.15682 respectively. 0.005808 is for the high voltage winding. While Yg is 11, 0.016639. 0.00061625 is for the low voltage winding.

Table 4.2: Parameters of the three-phase 33/11 kV transformers.

Transformer 1,2	Higher voltage winding	Lower voltage winding
Connection type	D11	Yg
V_{rms}(kV)	33	11
R (Ω)	0.15682	0.016639
L (H)	0.005808	0.00061625
Frequency f_n (Hz)	50	
Nominal Power S_n (MVA)	25	
Magnetization resistance R_m (MΩ)	0.06534	
Magnetization inductance L_m (H)	207.98	

The 25 MVA transformer at the consumer end busbar supply consumer load level of 11kV. The recorded values of consumer load are tabulated in Table 4.3. The Frequency f_n(Hz), and consumer's voltage (kV) is same for both loads. But Active Power P_L(MW), Reactive Power Q_L(MVAr), Apparent Power S_L(MVA), and P.F $\cos(\varphi_L)$ differs for both electrical loads. The benchmark three-phase line specifications of the standard electricity grid architecture supplying the 25 MVA transformer loads is shown in Table 4.4. It is inclusive of the sending and receiving active power (P), sending and receiving reactive power (Q), sending and receiving voltage (U), and power losses (ΔP). Table 4.4 shows that only the sending voltage (U_s) value is same for both lines. But other specifications differ for both lines.

Table 4.3: Measured values of the load.

Active Power P_L (MW)	10
Reactive Power Q_L (MVAr)	5
Apparent Power S_L (MVA)	11.18
P.F $\cos(\varphi_L)$	0.894
Frequency f_n (Hz)	50
consumer's voltage (kV)	11

Table 4.4: Measured parameters of the benchmark commercial three-phase lines.

Line	P_s (MW)	P_r (MW)	Q_s (MVAr)	Q_r (MVAr)	U_s (kV)	U_r (kV)	ΔP (MW)
1	8.818	8.547	5.088	4.632	32.582	30.946	0.271
2	8.615	8.265	5.064	4.479	32.582	30.432	0.35

4.3 Modelling of the Synchronous Condenser

A 3.125 MVA synchronous condenser has been used in this thesis. It is a round-rotor type machine, modelled in detail with its excitation systems. It is a modified version of the built-in model by MATLAB/Simulink [285]. The setting allows feeding the entire electricity grid architecture with adequate reactive power needs. This type of control strategy focuses on reactive power injection to the local bus or substation. But it depends on the position or point of connection of the synchronous condenser. The synchronous condenser is investigated for reactive power production, when aiding Type 3 wind farm during dynamic situations.

4.4 Modelling of the Type-3 Wind Plant

A wind farm rated 9 MW based on Type-3 wind machine, with a power factor rating of 0.9 is utilized for this thesis. The DFIG model used is a modified version of the built-in model by MATLAB/Simulink [285], it consists of a wound rotor induction generator and an AC/DC/AC/IGBT-based Pulse-Width Modulation (PWM) converter. PWM converters make available a compact solution for converting current into digital pulse width modulated signal. A reference voltage is made available on the PWM output. The doubly fed induction generator is equally equipped with a pitch control system. This is built based on Doubly Fed Induction Generator using back-to-back PWM converters. The generator stator is directly linked to the electricity grid architecture. Whereas the rotor is joined to the electricity grid through an AC/DC/AC converter and slip rings. The converter consists of firstly; the Rotor-Side Converter (RSC) and secondly the Grid-Side Converter (GSC). A capacitor coupling the two converters acts as a DC voltage source, that is the DC bus. Active power is generated by way of a pre-defined power-speed characteristic. The DFIG model is deemed suitable for dynamic stability studies. In a DFIG active power is produced and injected into the electricity grid architecture by utilizing its AC/DC/AC converter system. Contains dq-current regulators, here ‘d’ stands for the d-axis and ‘q’ for the q-axis. Methodically, by controlling the DFIG equations and steering the machines characteristic relations between flux, voltage, current and so on. Active power related equations are gotten. It is of note to know here that reactive power is decoupled. Enabling production and injection of active power only from the wind farm. The DFIG model utilized for this thesis employs a typical vector control scheme. Where active power is controlled by regulating rotor q-axis current and pitch angle. All power regulators use proportional–integral (PI) controllers [247], [249], [286] – [292].

4.5 Methodology

Here two electricity grid architecture modes were studied (Mode One and Two). In each situation, the synchronous condenser and the wind farm positions were interchanged on the electricity grid architecture.

4.5.1 Electricity Grid Architecture - Mode One

For Mode One, five Cases were designed Case A, B, C, D and E, with the point of installation of the SC and wind farm altered in each situation. Case A is the reference case. Case B is the situation when the wind farm is joined to the electricity grid architectures main substation. Case C is the situation with the wind farm connected to the electricity grid close to consumers load. Case D is the situation when the SC is installed at the main substation bus. Case E is the condition with the SC joined to the grid at the consumer load busbar. Schematic diagram of the simulation model and methodology of the reference point situation (Case A), Case B, Case C, Case D and Case E is shown in Fig. 4.2. The parameters of the Benchmark Case are applied in the methodology. Four steps were monitored as shown in Table 4.5. In the table, P is the active power in megawatt, Q is the reactive power in megaVAR, while S is the apparent power in MVA.

Table 4.5: Calculated values of reactive, active and apparent power for various steps of loads.

Steps	Active power P_1 (MW)	Rate increase % P_1	Reactive power Q_1 (MVar)	Rate increase % Q_1	Apparent power S_1 MVA	Rate increase % S_1
1	10	0%	5	0%	11.18	0%
2	12	20%	6	20%	13.416	20%
3	14	40%	7	40%	15.652	40%
4	16	60%	8	60%	17.889	60%

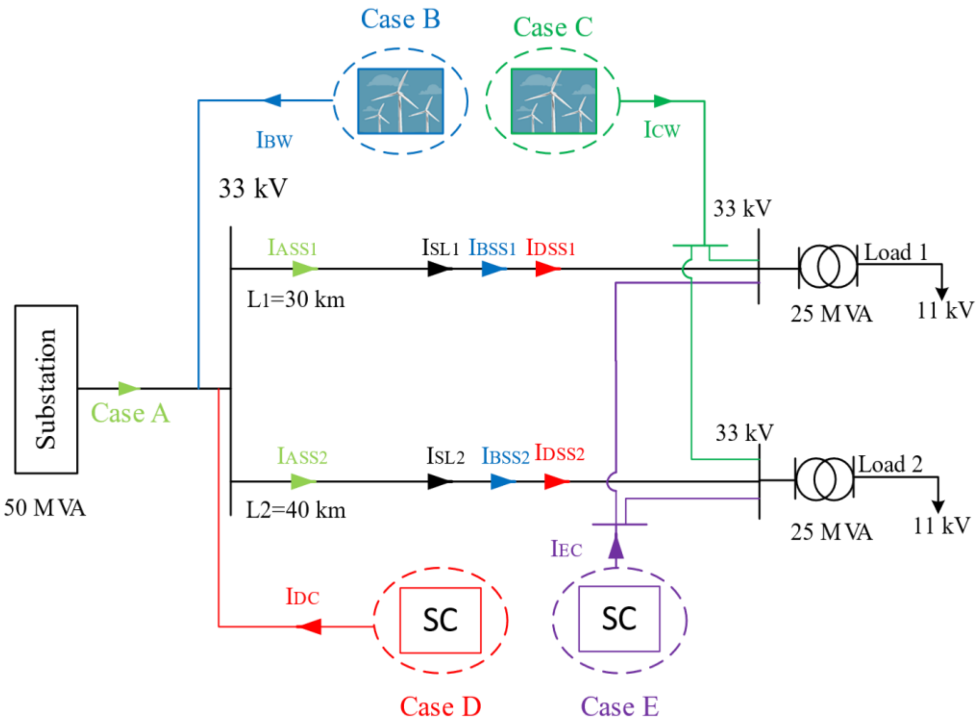


Fig. 4.2: The proposed electricity grid architecture with installed synchronous condenser and wind plants for Case A, B, C, D, and E considering mode one.

4.5.2 Electricity Grid Architecture - Mode Two

For Mode Two, there are three cases. The benchmark case, which is Case A. Case B, when the wind farm is placed at the grid main substation and SC is placed at the consumers load ends. Case C when the SC is placed at the main substation and the wind farm is placed at the consumer load ends. This scheme is vividly shown in Fig. 4.3. The parameters of the benchmark case are put to practical use just like in grid Mode One. Four steps were equally monitored for grid Mode Two. The first step is the benchmark case value parameter of loads. While steps 2 - 4 are increased in various percentage levels of active, reactive and apparent power as presented in Table 4.6 and Table 4.7 for load 1 and 2 respectively. The active power, reactive power and apparent power values are measured and obtained as shown in Table 4.6, for load 1. The measured parameter values for load 2 is presented in Table 4.7.

Table 4.6: Calculated values of reactive, active and apparent power for various steps for load 1.

Steps	Active power P_1 (MW)	Rate increase % P_1	Reactive power Q_1 (MVar)	Rate increase % Q_1	Apparent power S_1 MVA	Rate increase % S_1
1	10	0 %	4	0%	10.77	0%
2	12	20%	5	25%	13	20.71%
3	14	40%	6	50%	15.232	41.43%
4	16	60%	7	75%	17.464	62.15%

Table 4.7: Calculated values of reactive, active and apparent power for various steps for load 2.

Steps	Active power P_1 (MW)	Rate increase % P_1	Reactive power Q_1 (MVar)	Rate increase % Q_1	Apparent power S_1 MVA	Rate increase % S_1
1	12	0%	6	0%	13.416	0%
2	14	16.67%	7	16.67%	15.652	16.67%
3	16	33.33%	8	33.33%	17.889	33.33%
4	18	50%	9	50%	20.125	50%

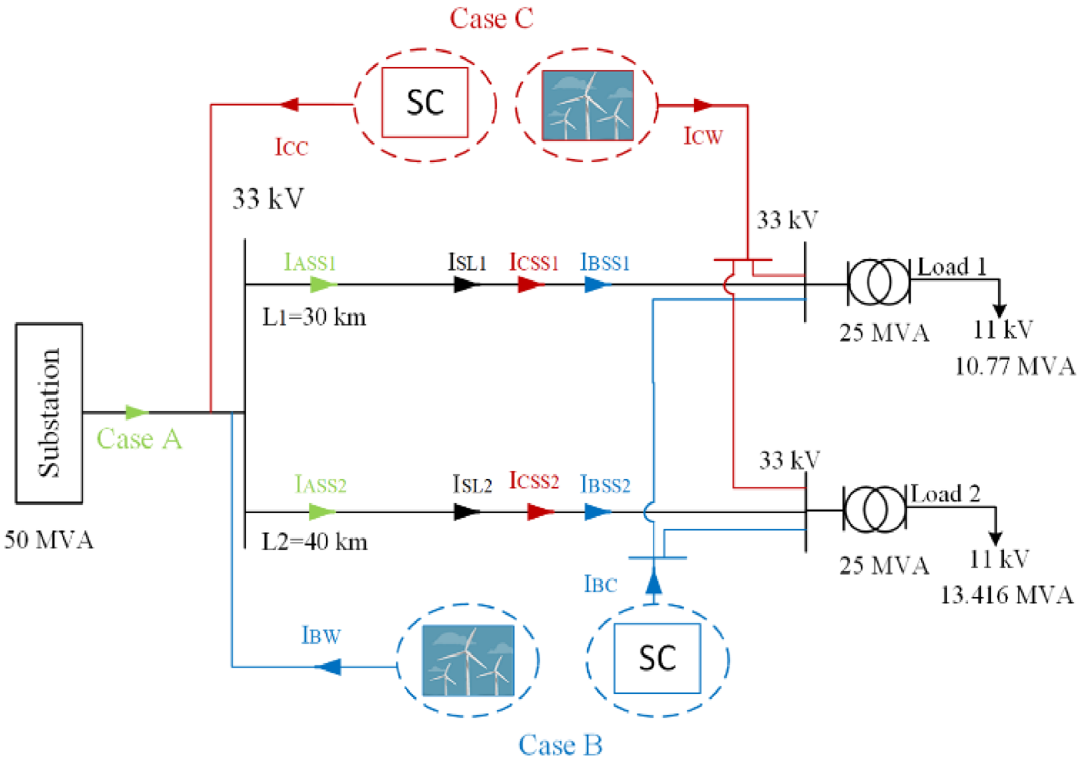


Fig. 4.3: Scheme of the proposed wind plant integrated electricity grid architecture for Case A, B, and C considering grid mode two.

4.6 Algorithm for the Proposed Radial Electricity Grid Architecture (Mode One and Two)

This algorithm is to choose suitable active and reactive power source type for the radial distribution electricity grid architecture. It is done according to loads for grid Mode One and Two respectively. For the algorithm the following has been considered.

1. Each load has active power, reactive power and power factor.
2. Generally, assuming there are two sources. The first source produces active power. While the second source produces reactive power. Hence, this can be expressed as follows:

$$S_{PQ} = P + Q \tag{4.1}$$

3. Now, considering loads 1……. n:

$$S_1 = P_1 + Q_1 \tag{4.2}$$

$$S_2 = P_2 + Q_2 \tag{4.3}$$

$$S_n = P_n + Q_n \tag{4.4}$$

4. Then the power sources are utilized for the distribution electricity grid architecture in all available cases for the two-mode operation:

   Mode One: Active and reactive power separately sourced.

   Mode Two: Active and reactive power combinedly sourced.

5. Afterwards, power losses, voltage drop, sending power factor and receiving power factor are calculated. i.e. $\Delta P, \Delta V, U_s\ deviation, U_r deviation,$ $\cos\varphi_s$ and $\cos\varphi_r$
6. According to these parameters. Suitable mode and position are chosen for the distribution electricity grid architecture.

The control algorithm developed for the electricity grid architecture, considering grid mode one and two is vividly shown in Fig. 4.4. It starts with the measurements of the various parameters. This ends with choosing the best position and capacity for the electricity grid architecture mode one and two respectively.

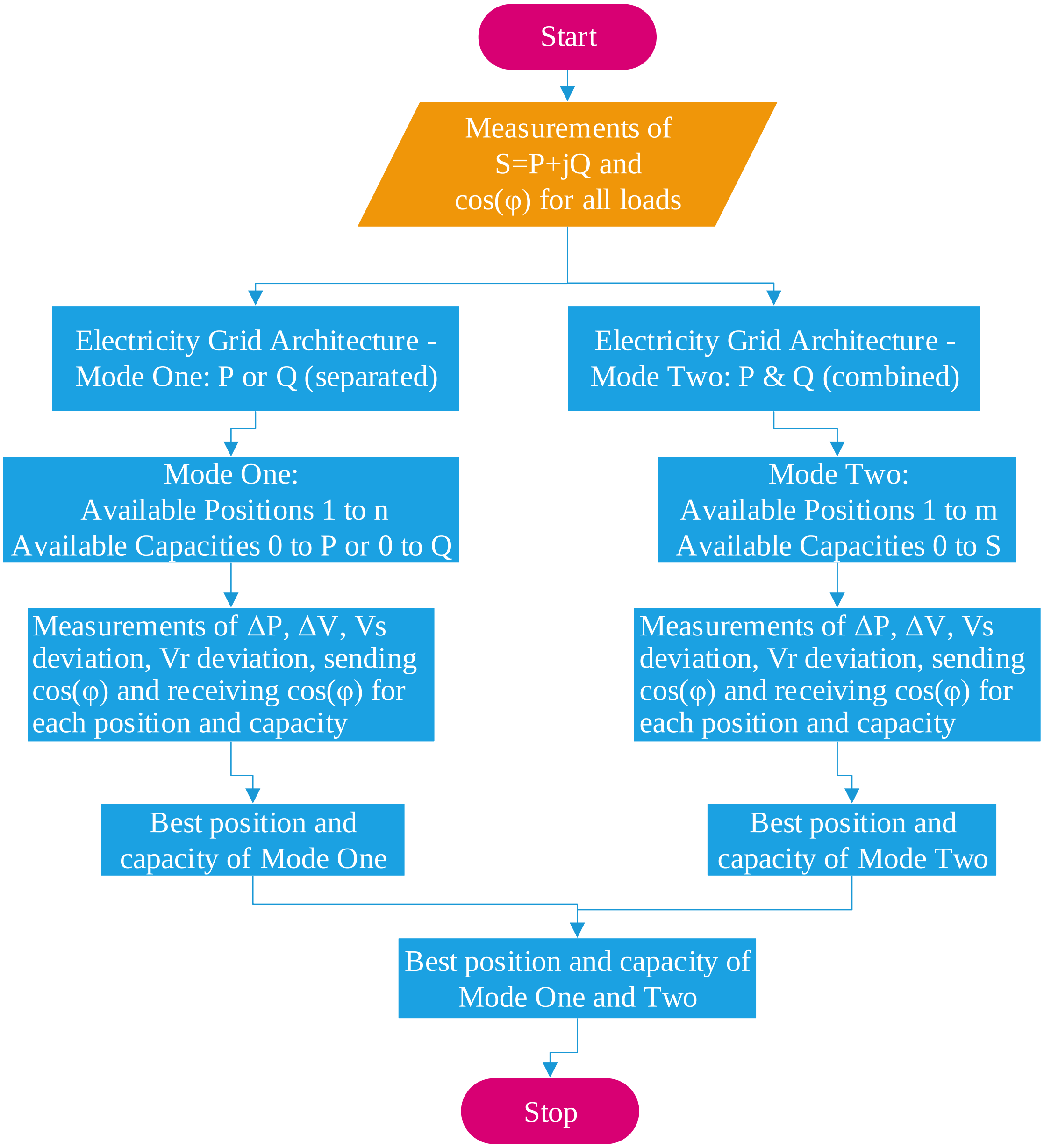


Fig. 4.4: The control algorithm developed for the electricity grid architectures, considering grid mode one and two respectively.

Chapter 5

5.0 Simulation of Electricity Grid Architecture – Mode One: Description, Analysis, Results and Discussion

This chapter summarizes the main contributions within grids Mode One simulation framework, detailed in Paper One. This chapter is organized as follows. Section 5.1 vividly describe the mathematical model of the electricity grid architecture presented in Mode One. Next, in Section 5.2 Mode One electricity grid architecture description, analysis, results and discussion is detailed.

5.1 Mathematical Model for Mode One Electricity Grid Architecture

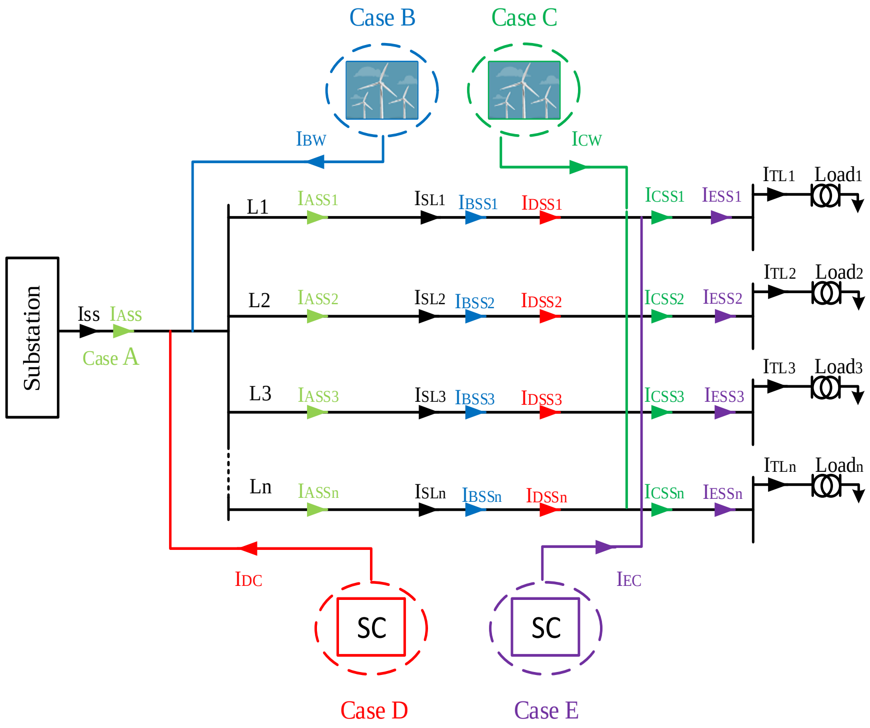


Fig. 5.1: Schematic diagram of simulation model, with its vector components and methodology of the point of reference Case (Case A), Case B, Case C, Case D and Case E for Mode One electricity grid architecture.

Taking into consideration the medium voltage substation network (S. S$_1$) and its vector elements:

$$S_{SS} = \sum_{i=1}^{n} S_{SLi} \quad (5.1)$$

$$I_{SS} = \sum_{i=1}^{n} I_{SLi} \quad (5.2)$$

In this respect:

S_{SS} is the apparent power of the substation system.

I_{SS} is the total line current of the substation system.

I_{SLi} is the line current supplied to the nth number of power lines from the substation.

S_{SLi} is the apparent power supplied to the nth number of power lines from the substation.

$i = 1,2,3, \dots\dots, n$. i.e. nth number of Lines

Hence, for nth lines that supply nth loads at the end of line from the medium voltage (MV) substation. The set of transformer and load is equal to total load. Thus, the total apparent power of each nth number of set is S_{TLi} , in this situation:

i=1,2,3,……,n. i.e. number of Loads. Then, Line number = each load number.

In Fig. 5.1:

$$P_{SLi} = \Delta P_{LLi} + P_{LTi} \quad (5.3)$$

In this condition:

P_{SLi} is the active power supplied to nth number of lines.

ΔP_{LLi} is the active power losses of nth number of lines.

P_{LTi} is the active power of nth number of lines.

From equation (5.3):

$$\Delta P_{LLi} = P_{SLi} - P_{LTi} \quad (5.4)$$

The power losses on the line is given by:

$$\Delta P = 3{I_L}^2 \cdot R_{1L} \tag{5.5}$$

The difference in voltage (that is voltage drop) for each phase is given by:

$$\Delta V = I_L \cdot Z_L \tag{5.6}$$

Considering only Case, A, and from equation (5.5), and Fig. 5.1:

$$\Delta P_{LLi} = 3(I^2{}_{SLi} \cdot R_{1LLi}) \tag{5.7}$$

Therefore, power losses for nth number of lines for Case A will be:

$$\Delta P_{ALLi} = 3(I^2{}_{ASSi} \cdot R_{1LLi}) \tag{5.8}$$

Where:

$$I_{SLi} = I_{ASSi} \tag{5.9}$$

I_{ASSi} is the line current for nth number of power lines and it is equal to I_{SLi} for Case A.

ΔP_{ALLi} is the power losses of nth number of lines for Case A.

Accordingly, the total losses of S. S_1 for Case A will be:

$$\Delta P_{AT} = \sum_{i=1}^{n} \Delta P_{ALLi} \tag{5.10}$$

In like manner, from equations (5.6), and (5.9), and Fig. 5.1:

$$\Delta V_{ALLi} = I_{ASSn} \cdot Z_{LLi} \tag{5.11}$$

Where:

ΔV_{ALLi} is the voltage drop in nth number of lines of Case A.

Z_{LLi} is the longitudinal impedance of nth number of lines.

Taking into consideration Case B:

The wind farm is connected to the bus bar which supply all transmission lines as shown in Fig. 5.1, applying Kirchhoff's current law:

$$I_{BSS} = I_{SS} + I_{BW} \tag{5.12}$$

Where:

I_{BW} : wind farm line current

I_{BSS} : total substation line current of Case B.

From equation (5.12) and the vector directions of the wind farm and synchronous condenser parameters in Fig. 5.1:

$$I_{BSSi} = I_{Sli} + I_{BWi} \tag{5.13}$$

In this instance:

I_{BWi} is a constituent of the wind farm line current going through nth number of lines.

I_{BSSi} is the new line current supplied to nth number of power lines of Case B.

From equation (5.5), (5.12) and (5.13), the power losses for nth number of lines of Case B is written as:

$$\Delta P_{BLLi} = 3({I^2}_{BSSi} \cdot R_{1LLi}) \tag{5.14}$$

$$\Delta P_{BLLi} = 3 \cdot R_{1LLi}({I^2}_{SLi} + {I^2}_{BWi} + 2. I_{Sli}. I_{BWi}) \tag{5.15}$$

In this condition:

ΔP_{BLLi} is the power losses for nth number of lines of Case B.

Consequently, the total losses of S. S$_1$ for Case B will be:

$$\Delta P_{BT} = \sum_{i=1}^{n} \Delta P_{BLLi} \tag{5.16}$$

Likewise, from equations (5.6), (5.12), and (5.13), and Fig. 5.1:

$$\Delta V_{BLLi} = I_{BSSi} \cdot Z_{LLi} \tag{5.17}$$

$$\Delta V_{BLLi} = (I_{SLi} + I_{BWi}) \cdot Z_{LLi} \tag{5.18}$$

Where:

ΔV_{BLLi} is the voltage drop of nth number of lines for Case B.

Now, taking into consideration Case C:

The wind farm is joined to the end of all transmission lines as shown in Fig. 5.1, applying Kirchhoff's current law:

$$I_{CSS} = I_{SS} - I_{CW} \tag{5.19}$$

In this respect:

I_{CW} : wind farm line current

I_{CSS} : total substation line current for Case C.

From equation (5.19) and the vector directions of the wind farm and synchronous condenser parameters in Fig. 5.1:

$$I_{CSSi} = I_{Sli} - I_{CWi} \tag{5.20}$$

Where:

I_{CWi} is a constituent of the wind farm line current going through nth number of lines.

I_{CSSi} is the new line current supplied to nth number of power lines for Case C.

From equation (5.5), (5.19) and (5.20), the power losses for nth number of lines for Case C is written as:

$$\Delta P_{CLLi} = 3({I^2}_{CSSi} \cdot R_{1LLi}) \tag{5.21}$$

$$\Delta P_{CLLi} = 3 \cdot R_{1LLi}({I^2}_{SLi} + {I^2}_{CWi} - 2.I_{Sli}.I_{CWi}) \tag{5.22}$$

Where:

ΔP_{CLLi} is the power losses for nth number of lines of Case C.

On this account, the total losses of S. S$_1$ for Case C will be:

$$\Delta P_{CT} = \sum_{i=1}^{n} \Delta P_{CLLi} \tag{5.23}$$

Correspondingly, from equations (5.6), (5.19), and (5.20), and Fig. 5.1:

$$\Delta V_{CLLi} = I_{CSSi} \cdot Z_{LLi} \tag{5.24}$$

$$\Delta V_{CLLi} = (I_{SLi} - I_{CWi}) \cdot Z_{LLi} \tag{5.25}$$

Where:

ΔV_{CLLi} is the voltage drop of nth number of lines for Case C.

Equally, considering Case D:

The synchronous condenser is joined to the bus bar which supply all transmission lines as shown in Fig. 5.1, applying Kirchhoff's current law:

$$I_{DSS} = I_{SS} + I_{DC} \tag{5.26}$$

In this condition:

I_{DC} : synchronous condenser line current

I_{DSS} : total substation line current for Case D.

From equation (5.26) and the vector directions of the wind farm and synchronous condenser parameters in Fig. 5.1:

$$I_{DSSi} = I_{Sli} + I_{DCi} \tag{5.27}$$

In this respect:

I_{DCi} is a constituent of the synchronous condenser line current going through nth number of lines.

I_{DSSi} is the new line current supplied to nth number of power lines for Case D.

From equation (5.5), (5.26) and (5.27), the power losses for nth number of lines for Case D is written as:

$$\Delta P_{DLLi} = 3(I^2{}_{DSSi} \cdot R_{1LLi}) \tag{5.28}$$

$$\Delta P_{DLLi} = 3 \cdot R_{1LLi}(I^2{}_{SLi} + I^2{}_{DCi} + 2.I_{Sli}.I_{DCi}) \tag{5.29}$$

In this condition:

ΔP_{DLLi} is the power losses for nth number of lines for Case D.

As a result, the total losses of S. S_1 for Case D will be:

$$\mathit{\Delta}P_{DT} = \sum_{i=1}^{n} \mathit{\Delta}P_{DLLi} \tag{5.30}$$

In the same way, from equations (5.6), (5.26), and (5.27), and Fig. 5.1:

$$\mathit{\Delta}V_{DLLi} = I_{DSSi} \cdot Z_{LLi} \tag{5.31}$$

$$\mathit{\Delta}V_{DLLi} = (I_{SLi} + I_{DCi}) \cdot Z_{LLi} \tag{5.32}$$

Where:

$\mathit{\Delta}V_{DLLi}$ is the voltage drop of n^{th} number of lines for Case D.

Furthermore, considering Case E:

The synchronous condenser is linked to the end of all transmission lines as shown in Fig. 5.1, applying Kirchhoff's current law, just as in other Cases:

$$I_{ESS} = I_{SS} - I_{EC} \tag{5.33}$$

In which:

I_{EC} : synchronous condenser line current

I_{ESS} : total substation line current for Case E.

From equation (5.33) and the vector directions of the wind farm and synchronous condenser parameters in Fig. 5.1:

$$I_{ESSi} = I_{Sli} - I_{ECi} \tag{5.34}$$

Where:

I_{ECi} is a constituent of the of synchronous condenser line current going through n^{th} number of lines.

I_{ESSi} is the new line current supplied to n^{th} number of power lines for Case E.

From equation (5.5), (5.33) and (5.34), the power losses for n^{th} number of lines for Case E is written as:

$$\mathit{\Delta}P_{ELLi} = 3({I^2}_{ESSi} \cdot R_{1LLi}) \tag{5.35}$$

$$\mathit{\Delta}P_{ELLi} = 3 \cdot R_{1LLi}({I^2}_{SLi} + {I^2}_{ECi} - 2.I_{Sli}.I_{ECi}) \tag{5.36}$$

In this situation:

$\varDelta P_{ELLi}$ is power losses for nth number of lines for Case E.

Accordingly, the total losses of S. S$_1$ for Case E will be:

$$\varDelta P_{ET} = \sum_{i=1}^{n} \varDelta P_{ELLi} \tag{5.37}$$

Equivalently, from equations (5.6), (5.33), and (5.34), and Fig. 5.1:

$$\varDelta V_{ELLi} = I_{ESSi} \cdot Z_{LLi} \tag{5.38}$$

$$\varDelta V_{ELLi} = (I_{SLi} - I_{ECi}) \cdot Z_{LLi} \tag{5.39}$$

Where:

$\varDelta V_{CLLi}$ is the voltage drop of nth number of lines for Case E.

5.2 Description, Analysis, Results and Discussion for Mode One Electricity Grid Architecture

Fig. 4.2 in chapter 4, represents the proposed scheme with installed synchronous condenser and wind farm. This part of the thesis confirms the effectiveness of the synchronous condenser with Type-3 DFIG-based wind machine installed in the electricity grid architecture. Here, two performance criteria are used. First is the synchronous condenser capability to produce reactive power, and second is the wind farm active power generation ability. Furthermore, the wind farm and the synchronous condenser are then connected to the electricity grid architecture by changing their positions. The Type-3 DFIG wind machines are operated in active power regulation mode such that its reactive power regulation mode is decoupled. The results with the synchronous condenser installed and the Type-3 wind machine farms connected to the grid are compared with that of Case A.

The parameters of the point of reference Case are put to practical use by utilizing the methodology proposed in chapter four. Four steps monitored values were obtained. The first step is the point of reference case value parameter of loads. While steps 2 - 4 are increased in 20% for each step levels of active, reactive and apparent power as presented in Table 4.5 in chapter 4, for load 1 and 2 respectively. Note that the observed measured values for both lines are the same, since the loads connected to both lines are equally the same. The active power, reactive power and apparent power values are measured and obtained as shown in Table 4.5, for load 1 and 2 respectively.

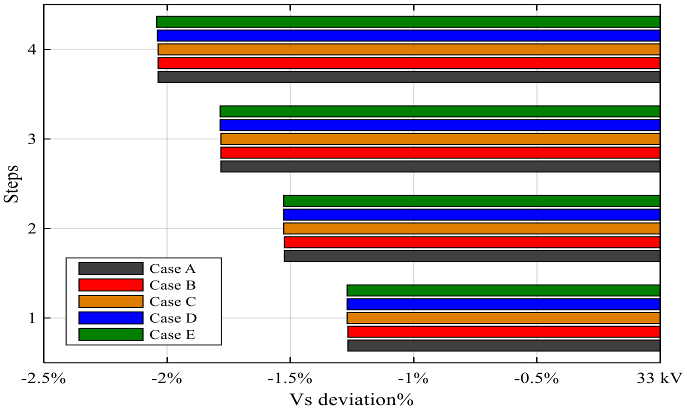


Fig. 5.2: Percentage of sending voltage deviation from nominal voltage of 33 kV for different steps of Case A, B, C, D and E for Mode One electricity grid architecture.

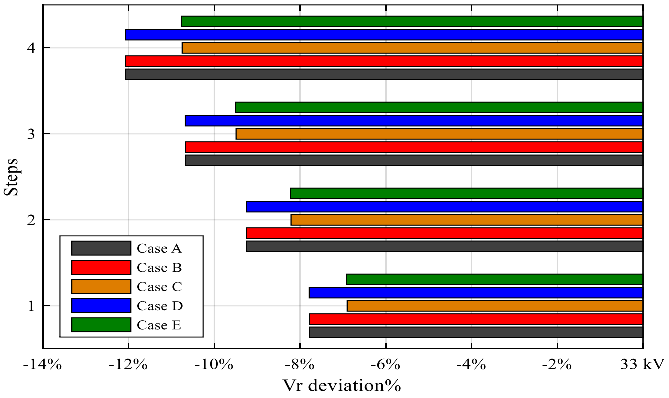


Fig. 5.3: Percentage of receiving voltage deviation from nominal voltage of 33 kV for different steps of Case A, B, C, D and E for Mode One electricity grid architecture.

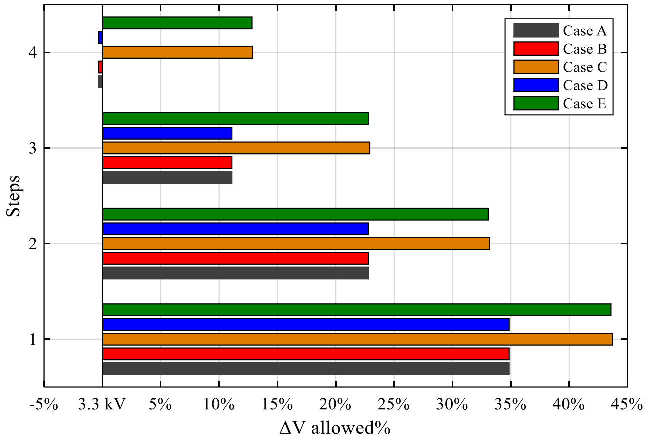


Fig. 5.4: Percentage of allowed additional voltage drop for different steps of Case A, B, C, D and E for Mode One electricity grid architecture.

Fig. 5.2 shows that the sending voltage deviation from the nominal voltage of 33 kV has the same value for all cases. it should be noted that the sending voltage deviation increases moving from step 1 through 4. It can be inferred that the position of the wind farm or synchronous condenser does not have any effect on the sending voltage deviation. The percentage of receiving voltage deviation from nominal voltage of 33 kV for different steps of Case A, B, C, D and E is plotted in Fig. 5.3. The result shows that receiving voltage deviation decreases with about 1% for Case C and E. Results for Case B and D is the same. Implying that when the wind farm or synchronous condenser is connected to the end of the 33 kV transmission lines, voltage deviation is reduced. The point of reference Case (Case A) result is equally the same with Case B and D.

Furthermore, the percentage of allowed additional voltage drop for different steps of Case A, B, C, D and E is graphically presented in Fig. 5.4. It shows that the allowed additional voltage drop increases between 8 - 10 % for Case C and E. But the observed results for Case B and D is the same. Therefore, itt can be deduced from the foregoing that position or placement of the wind farm or synchronous condenser is very important especially for high values of loads, such as in step 4 were the observed voltage drop is seen to be higher than 3.3 kV for Case B and D. Here, the standard Case (Case A) result is equally the same with Case B and D. It implies that as more loads are added to transmission lines, the more current flows. Current provision is limited to a given capacity owing to limitations of the ability of electricity grid architectures to produce charge imbalances. Consequently, the more the voltage drop. Note that current is the movement of charges. Whenever electrical load is connected to any power line. It draws more current than before and when current increases then voltage decreases. When load is applied to an electricity grid architecture, it means that current begins to flow. If there is any resistance in the lines connected to it, the resulting change in voltage will be in the dictate of reducing the voltage applied to the load.

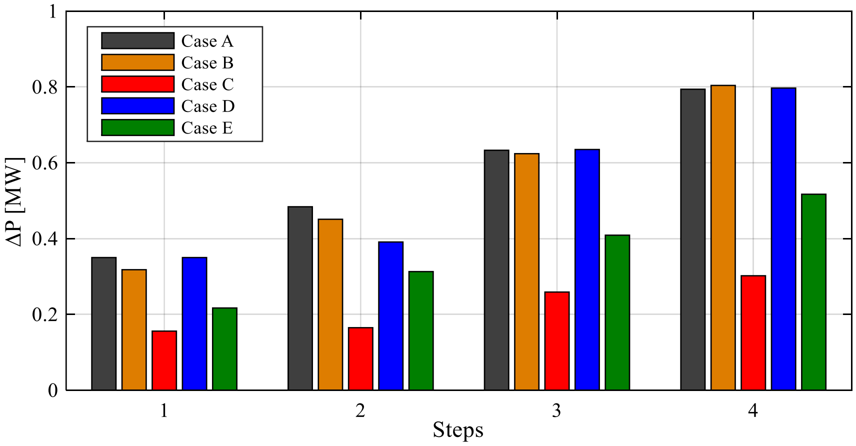


Fig. 5.5: Power losses for different steps of Case A, B, C, D and E for Mode One electricity grid architecture.

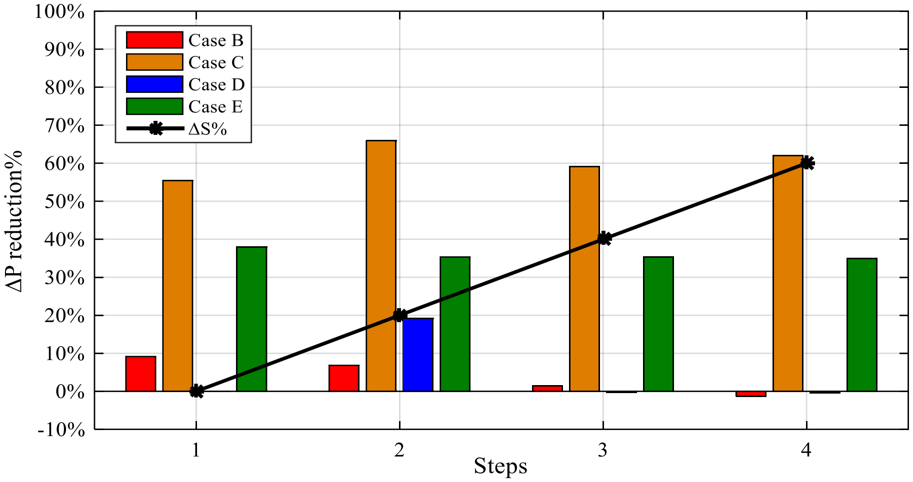


Fig. 5.6: Percentage of power losses reduction for different steps of Case B, C, D and E compared with Case A for Mode One electricity grid architecture.

Under the analysis of power losses for different steps of Case A, B, C, D, and E. Power losses reduces slightly or did not change or increased slightly as regards to Case B and D. The point of reference Case result is the same with the observed results for Case B and D. But considering Case C and E power losses is significantly reduced especially in Case C. Hence, it can be inferred that when the wind farm or synchronous condenser is joined to the beginning of the electricity grid architecture, power losses reduced slightly. But when the wind farm or synchronous condenser were installed to the end of the transmission lines, power losses is drastically reduced. Note that the effect of the wind farm is much higher due to its nominal power, which is 9 MVA. The nominal power of the synchronous condenser is 3.125 MVA, which is lower than that of the wind farm. The results for the power losses are presented in Fig.5.5.

Figure 5.6 shows that investigating the percentage of power losses reduction for Case B and D, just as is the case for power losses in Fig. 5.5. Percentage power losses in Case B and D decreased slightly or did not change or increased slightly as compared with Case A. But for Case C and E the percentage power losses decrease significantly as compared to Case A. Figure 5.6, vividly shows that the percentage of power losses reduction in Case C is about 60% and that of Case E is about 35%. It can therefore be said that the position of the wind farm and synchronous condenser played a vital role in reducing power losses and nominal power.

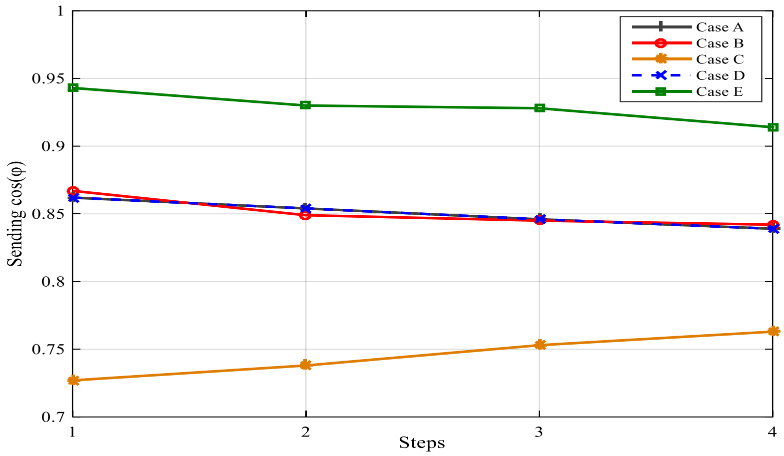


Fig. 5.7: Sending power factor for different steps of Case A, B, C, D and E for Mode One electricity grid architecture.

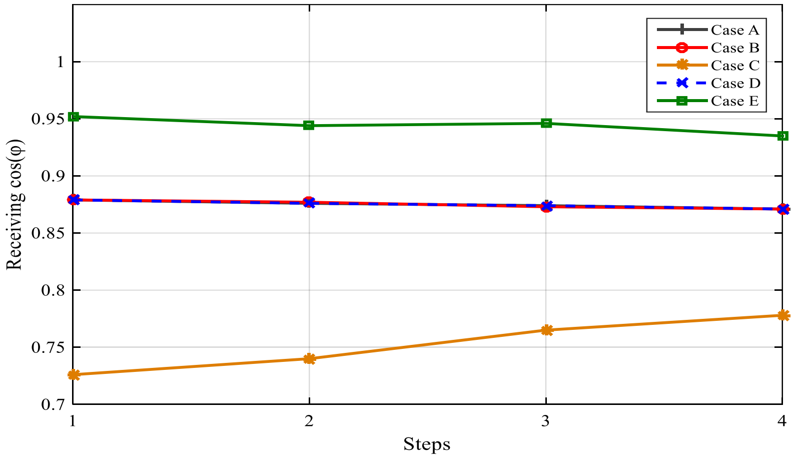


Fig. 5.8: Receiving power factor for different steps of Case A, B, C, D and E for Mode One electricity grid architecture.

Fig. 5.7 reports the sending power factor values recorded for all the Cases observed. There were no remarkable changes seen in Case B and D. This equally applies to the benchmark Case (Case A). The observed sending power factor for Case C decreases in value from about 0.85 to 0.75, while that for Case E increases to about 0.95. Figure 5.8 is a graphical presentation of the receiving power factor values for all the Cases observed. The results gotten are like the results obtained for the sending power factor analysis. The observed steady power factor for Case A, B and D is owing to the wind farm and synchronous condenser being installed to the 50 MVA main substation busbar. Hence, the changes in the power flow though the transmission lines are very small. But considering Case C, the sending power factor decreases owing to the wind farm being connected to the end of the transmission line busbars. Therefore, the active power which flows through the transmission lines becomes smaller, thereby leading to a decrease in the power factor values. Also, taking into consideration Case E, the sending power factor results obtain is seen to increase owing to the synchronous condenser being installed at the end of the 33 kV transmission lines busbar connected to the two step-down transformers. For this reason, the reactive power which flows through the transmission lines reduces. This brings about an increase in the value of power factor of the electricity grid architecture.

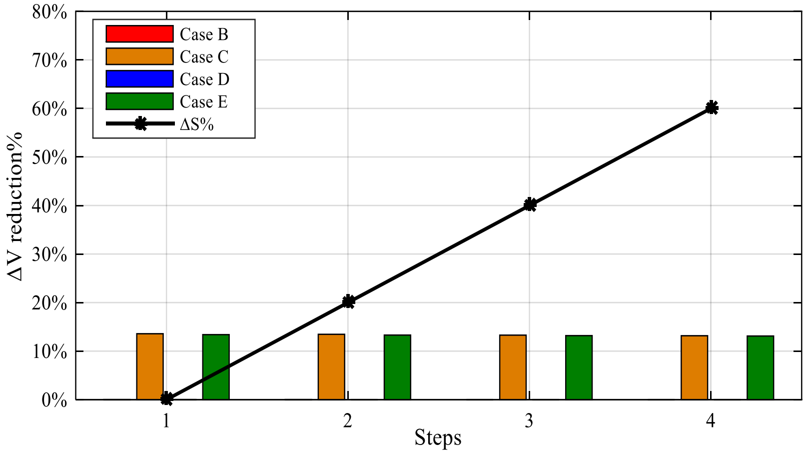


Fig. 5.9: Percentage of voltage drop reduction for different steps of Case B, C, D and E compared with Case A for Mode One electricity grid architecture.

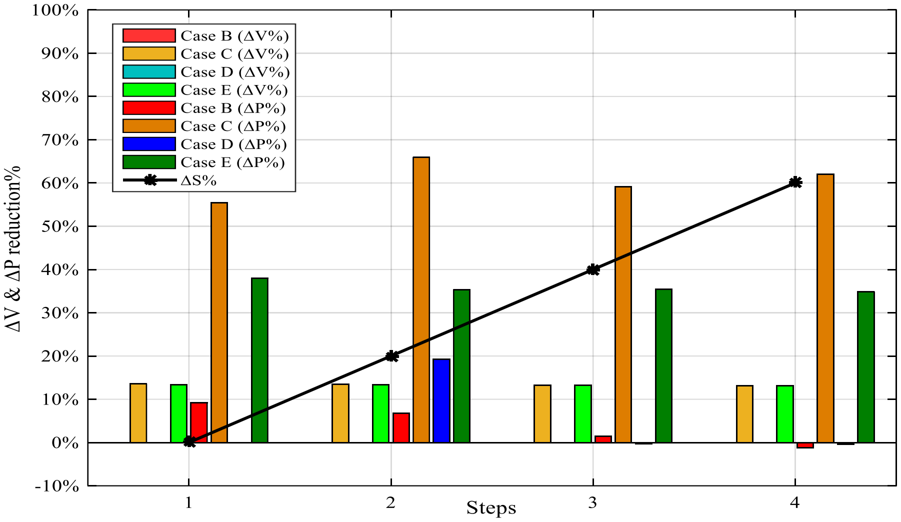


Fig. 5.10: Percentage of voltage drop and power losses reduction for different steps of Case B, C, D and E compared with Case A for Mode One electricity grid architecture.

The percentage of voltage drop reduction for different steps of all the cases is presented in Fig. 5.9. Observed findings shows that voltage drop decreases only in Case C and E, with a decrease in voltage drop of 12%. This insinuating that the voltage drop could only be reduced when the wind farm or synchronous condenser is coupled to the end of the 33 kV electricity grid architecture close to the consumer substation. Note here that the percentage of voltage drop reduction is the same for all the steps observed. Figure 5.10 displays the percentage of voltage drop and power losses reduction for the different cases observed. The reduction in the parameters monitored is exceptional only for Case C and E. Voltage drop decreases with about 12% for these two cases. The power losses equally decrease with 60% for Case C and 35% for Case E. This is due to the reasons earlier mentioned.

Chapter 6

6.0 Simulation of Electricity Grid Architecture – Mode Two: Description, Analysis, Results and Discussion

This chapter provides a summary of the main contributions of Mode Two electricity grid architecture. This is detailed in Paper Two and Three presented in the contributions section of this thesis. The chapter is organized as follows. Section 6.1 briefly talk about the mathematical modelling. It refers to chapter 5 for a detailed mathematical modelling, as the scheme for Mode One electricity grid architecture was equally modeled just as the scheme for Mode Two electricity grid architecture. Section 6.2 provides a vivid illustration of Mode Two electricity grid architecture as shown in Fig. 4.3 of chapter 4.

6.1 Mathematical Model for Mode Two Electricity Grid Architecture

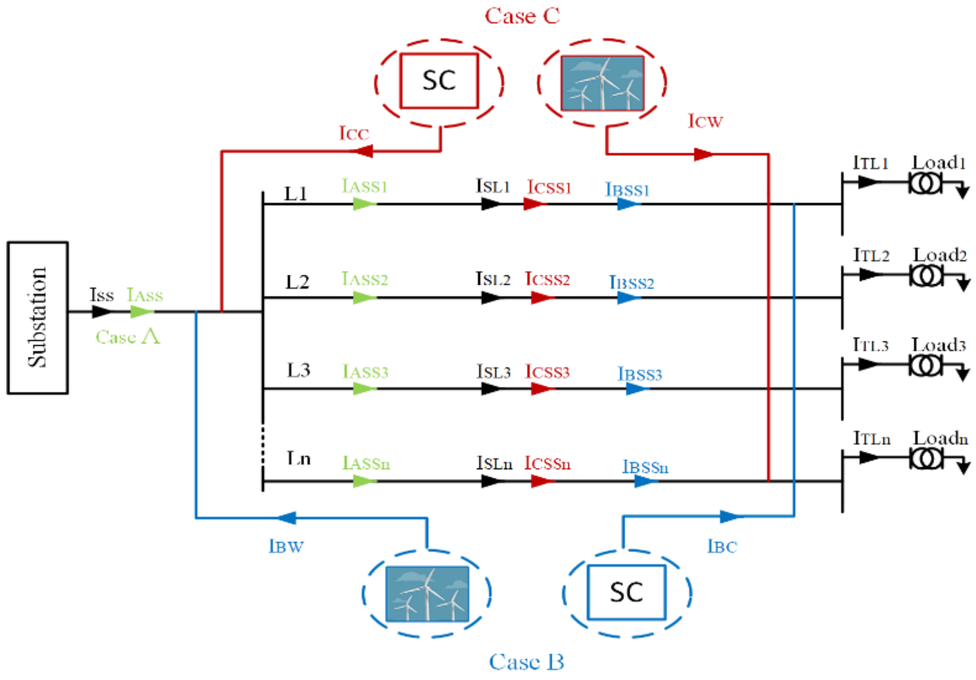


Fig. 6.1: Diagram of the simulation model and methodology scheme of benchmark Case (Case A), Case B and Case C for Mode Two electricity grid architecture.

The synchronous condenser is modelled in detail with its excitation systems. All transmission lines of the proposed electricity grid architecture are modelled using pi-model. The grid architecture for Mode Two was mathematically modeled just as in the electricity grid architecture for Mode One, as presented in section 5.1 of Chapter 5.

6.2 Description, Analysis, Results and Discussion for Mode Two Electricity Grid Architecture

In this section, load 1 simulation is executed at several active power levels of 0%, 20%, 40%, and 60%. While the reactive power levels are executed in 0%, 25%, 50%, and 75% respectively, as depicted in Table 4.6. The apparent power levels are 0%, 20.71%, 41.43%, and 62.15% for load 2 as tabulated in table 4.7. With active, reactive and apparent power, levels of 0%, 16.67%, 33.33%, and 50%, implying that the same level of increment was used for the various steps. The percentage of sending voltage deviation from the nominal voltage of 33 kV for different steps in Case A, B and C is presented in Fig. 6.2. It shows that the differences between Case A, B and C is very small and unremarkable. It also portrays that the load increase in each step, brought about an increase in the sending voltage deviation from the nominal voltage value of 33 kV. Equally, Fig. 6.3 renders that the deviation of receiving voltage in Case B and C is lower than that of Case A. This is owing to the power injected onto the grid at the end of the 33 kV MV electricity grid architecture. It is noticed that the deviations in Case B and C are very close.

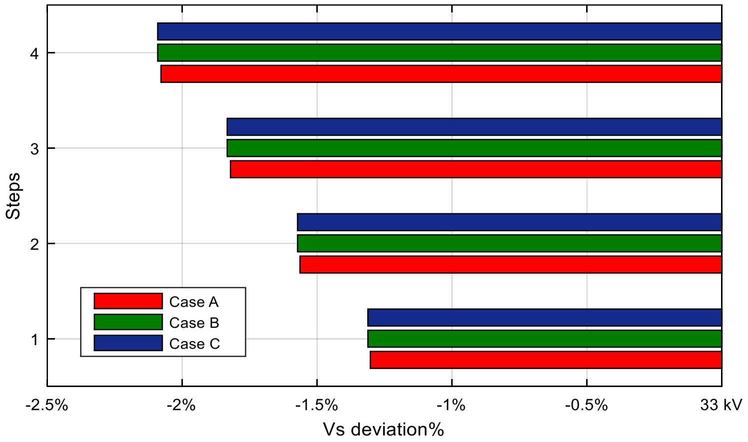


Fig. 6.2: Percentage of sending voltage deviation from the nominal voltage of 33 kV for different steps of Case A, B and C for Mode Two electricity grid architecture.

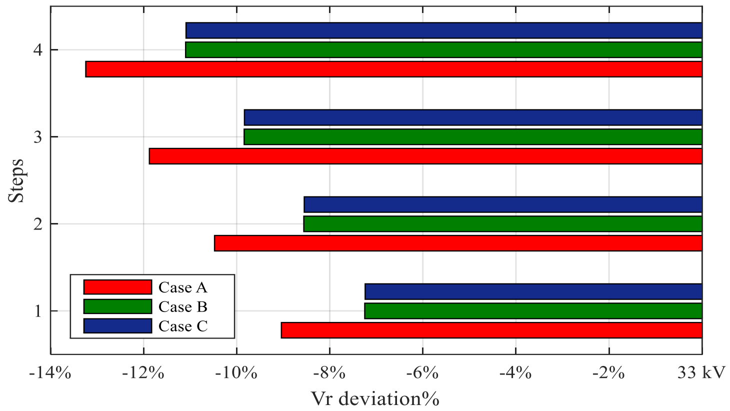


Fig. 6.3: Percentage of receiving voltage deviation from the nominal voltage of 33 kV for different steps of Case A, B and C for Mode Two electricity grid architecture.

The performance of the wind plant and synchronous condenser as regards to the percentage of allowed additional voltage drop for different steps in Case B and C, as well as for Case A is plotted in Fig. 6.4. It shows that the percentage of allowed additional voltage drops of the lines before the voltage drop exceeds 3.3 kV. This is 10% of the nominal voltage. Here, the maximum allowed voltage drop is 3.3kV. While the safety margin of Case B and C is higher than that of Case A. But the achievable voltage drops in steps 3 and 4 did not exceed 3.3 kV, going by 1% for step 3 and 12 % for step 4. Fig. 6.5 pictures the power losses for the different steps in Case A, B and C. In this analysis, power losses for Case B and C is lower than that of Case A. In addition, power losses in Case B is less than that of Case C. This implying that using wind power plants to inject active power at the start point of the grid, and the synchronous condenser to produce reactive power at the consumer end of the 33 MV electricity grid architecture is more effective compared to the results obtained by the reverse positioning.

From Fig 6.6 it is observed that the percentage of power losses reduction for different steps in Case B and C compared with Case A decreases for all Cases and steps. But the reduction in Case B is observed to be higher. It is vividly seen that the reduction in all steps was generally the same in each Case. The apparent power is the percentage increase in load, as the load increases the results becomes more favorable.

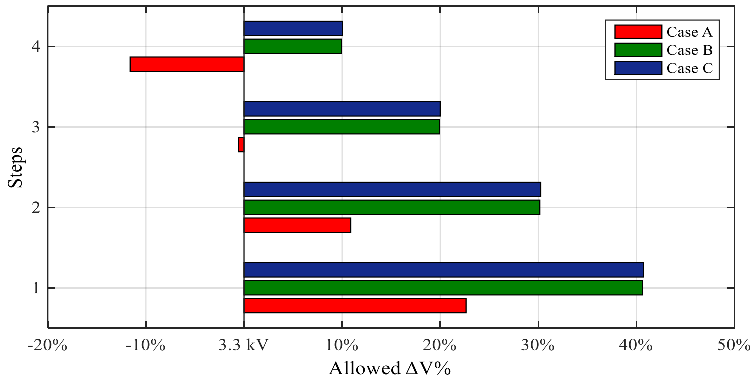


Fig. 6.4: Percentage of allowed additional voltage drop for different steps of Case A, B and C for Mode Two electricity grid architecture.

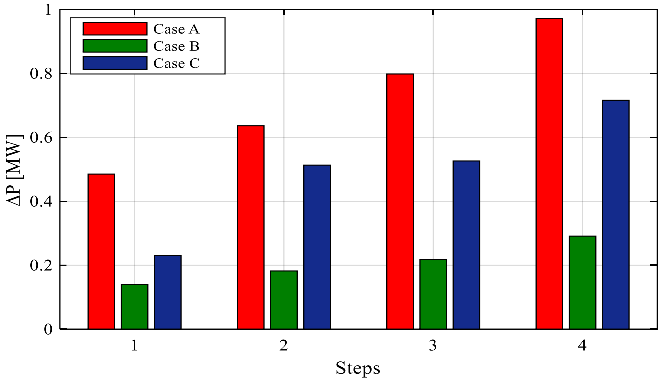


Fig. 6.5: Power losses for different steps of Case A, B and C for Mode Two electricity grid architecture.

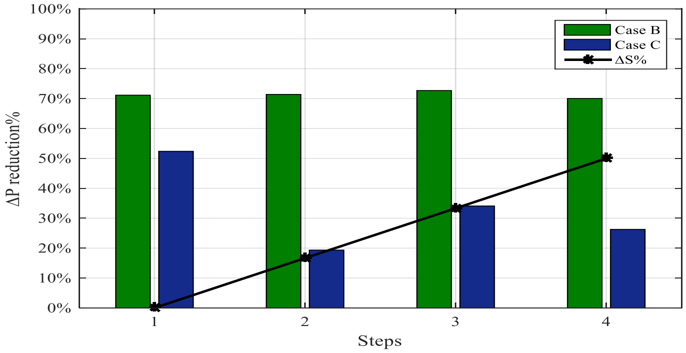


Fig. 6.6: Percentage of power losses reduction for different steps of Case B and C compared with Case A for Mode Two electricity grid architecture.

The sending power factor for different steps of Case A, B and C is plotted in Fig. 6.7. In this analysis, the sending power factor for Case B and C is higher than that of Case A. It ranges between 0.97 and 0.93, whereas the result for Case A is between 0.86 and 0.83. Note that the sending power factor for Case C is higher than that of Case B. The receiving power factor for different steps of Case A, B and C is shown in Fig. 6.8. This result is like that gotten in Fig. 6.7, where the power factor for Case B and C is higher than that of Case A. The power factor values recorded for Case B and C range between 0.99 and 0.95, whereas the values observed for Case A is between 0.88 and 0.87. It can be seen in Fig. 6.8, that the sending power factor as regards to Case C is higher than that of Case B.

In the proposed electricity grid architecture, active power and a little amount of reactive power is needed. But with low power factor the reactive power is higher than usually needed. low power factor in the circumstance of Case A imply that reactive power is higher than active power. Hence, low power factor means dealing with high amount of reactive power. Therefore, low power factor drawback is the drawback of excessive reactive power. Hence, with low power factor the amount of apparent power in the grid is increased. Although the power in kW is still the same. This associates some significant losses both on the lines and on the consumer side as is the situation for

Case A. But the reverse is the situation for Case B and C were the losses on both the lines and the consumer side of the scheme is minimized due to the installation of the wind plant for active power regulation and synchronous condenser for reactive power generation. Furthermore, the voltage drop of the proposed MV grid distributors increases as the power factor values decreases. In order to keep up with the voltage at the receiving end. The Type-3 wind plants for active power control only and synchronous condensers for reactive power control only must be installed onto the proposed scheme. The 33kV line voltage is maintained owing to the observed power factor standing for both Case B and C.

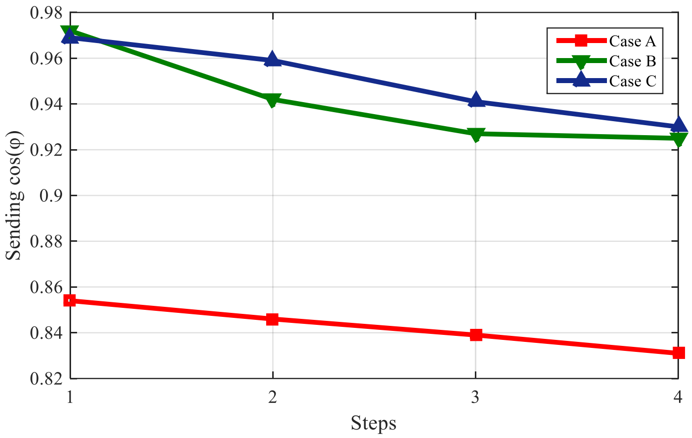


Fig. 6.7: Sending power factor for different steps of Case A, B and C for Mode Two electricity grid architecture.

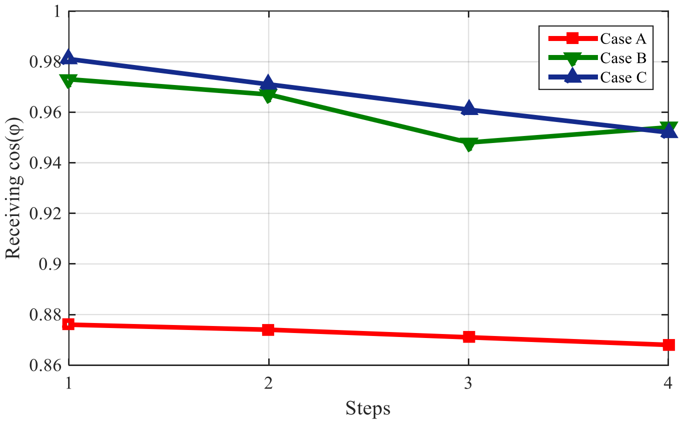


Fig. 6.8: Receiving power factor for different steps of Case A, B and C for Mode Two electricity grid architecture.

In Fig. 6.9, the percentage of voltage drop reduction for different steps of Case B and C compared with Case A is presented. It can be vividly seen that voltage drop is reduced in Case B and C as compared with Case A. The performance of the various Case situations as regards voltage drop is the same for all steps. Additionally, the percentage of reduction of voltage drop is approximately the same for all steps (that is 20%), but with corresponding small decrease when moving from step 1- 4. On the contrary for Case A, the percentage of voltage drop steadily increases when moving from step 1 – 4. A Voltage drop performance analysis is required to ensure that the end of the power lines has enough power to drive the final load. The issue of voltage drop only gets worse as more loads are connected onto the power lines. As the length of power lines increases or as the current increases, so does the voltage drop. Note that leaving some margin for future loads ensures that electricity consumers gets reliable electricity product from the electricity grid architecture. The resulting measured and modelled percentage of voltage drop and power losses reduction for different steps in Case B and C compared with Case A is graphically illustrated in Fig. 6.10. It shows the general comparison of Case B and C with Case A. Here, it is observed that the methodologies used in Case B and C are better than that used in Case A. Results for Case B and C showed the same performance of voltage drop, which is about 20%. But regarding to power losses on the proposed electricity grid architecture, Case B fared better in terms of performance than Case C. The power losses reduction for Case B is about 70%, but it is 50% for Case C. Overall, the performance of Case B is seen to be the best-Case situation observed.

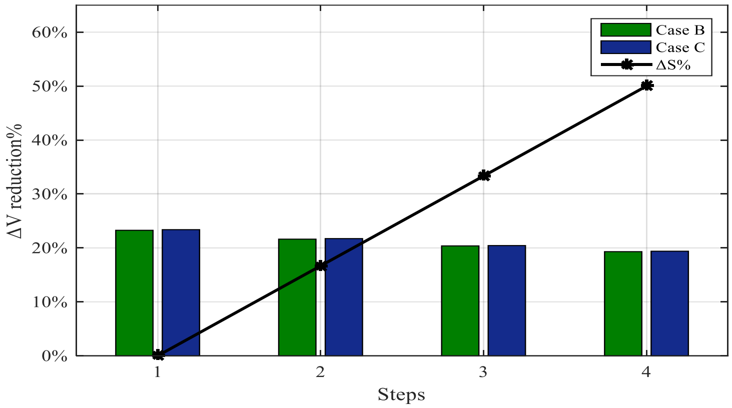


Fig. 6.9: Percentage of voltage drop reduction for different steps of Case B and C compared with Case A for Mode Two electricity grid architecture.

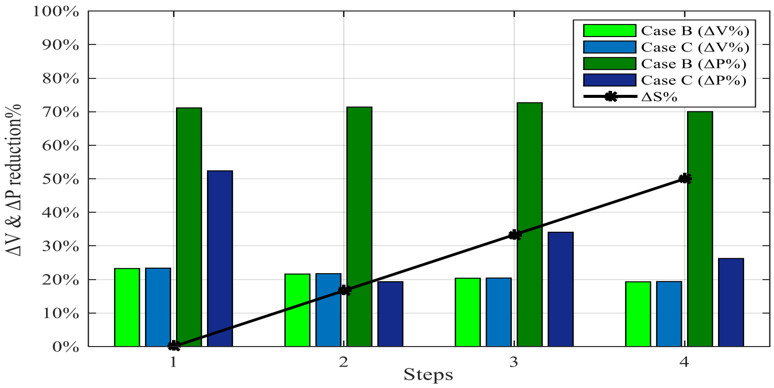


Fig. 6.10: Percentage of voltage drop and power losses reduction for different steps of Case B and C compared with Case A for Mode Two electricity grid architecture.

Chapter 7

7.0 Concluding Remarks and Future Research

This chapter summarizes the work presented in this thesis and provide conclusions on the research. Subsequently, suggestions for future work are provided. Paper One, Two, Three, Four, Five, Six and Seven have shown the capabilities offered by the synchronous condenser technology. Purposely developed simulation model was given substance to in a 33kV electricity grid architecture modes (Mode One and Mode Two) involving active power control by wind power plants and reactive power control using the synchronous condenser technology. This was achieved by effective positioning of both the wind plants and synchronous condenser. In this model, the Type-3 renewable wind power plant has been used to generate active power. While the synchronous condenser was used to produce reactive power. By choosing different points on the proposed electricity grid architecture to separately and combinedly connect the wind renewable source and the synchronous condenser. The grid is kept stable and power losses are equally reduced, even when the loads are increased. Implying that the proposed electricity grid architecture can absorb more loads. Hence, it can be posited that the Type-3 wind plant and the synchronous condenser scheme is effective and economical. It is worth mentioning that the proposed technique used in this thesis can be applied to different loads deployment in any electricity grid architecture. This will help to establish stability in preserving acceptable security performances of electricity grids.

This thesis has shown that wind power plants and the synchronous condenser can play a great role in reducing power losses and voltage drop in modern electricity grid architectures. This work opens a variety of opportunities to utilize new or retrofitted synchronous condenser for further advanced research in future work. Since it has established an effective application of the synchronous condenser technology for the deployment of reactive power and the wind power plant for the deployment of active power in modern electricity grid architecture. Thereby generating useful data for managers, engineers and researchers in the electricity industry. This research data can be used to improve modern electricity grid architectures growth plans and formulate new electricity development strategies and action plans. This data is important for electricity managers to develop management strategies and development plans, which allow electricity resources to be utilized more effectively in a sustainable manner. Equally this data will help to improve power system security by providing adequate active and reactive power for stability of the electricity grid architecture and minimization of power system losses. Therefore, this work is likely to bring significant technical and financial benefits to power system operators.

Although the synchronous condenser technology has been in use for a long time now. It remains an interesting topic for future work. This thesis focus was on dynamic case study on a radial electricity grid architecture related to active power, reactive power, power losses and voltage control. Hence, further studies should be encouraged considering fault situation and more complex electricity grid architectures.

Chapter 8

8.0 Literature

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8.2 Authors Publications

8.2.1 Publications in the Framework of the Thesis

8.2.1.1 Publications in Impact Factor (IF) Journals (Indexed in WoS and Scopus)

1. F. O. Igbinovia, G. Fandi, J. Kubica, Z. Muller, F. Janicek and J. Tlusty, “Utilizing the synchronous condenser for robust functioning of wind farm implanted electric grid,” Journal of Electrical Engineering, 2019, vol. 70, no. 2, pp. 152 – 158. IF: 0.636, ISSN: 1339-309X. Contribution by authors: 16.7%, 16.7%, 16.7%, 16.7%, 16.7%, 16.7%.

2. F. O. Igbinovia, G. Fandi, I. Ahmad, Z. Muller and J. Tlusty, “Modeling and Simulation of the Anticipated Effects of the Synchronous Condenser on an Electric-Power Network with Participating Wind Plants,” Sustainability, MDPI Open Access Journal, 2018, vol. 10, no. 12, 4834. IF: 2.592, ISSN: 2071-1050. Contribution by authors: 20%, 20%, 20%, 20%, 20%.

8.2.1.2 Publications in Reviewed Journals (Not Indexed in WoS and Scopus)

1. F. O. Igbinovia, G. Fandi, Z. Muller, and J. Tlusty, “Progressive Usage of the Synchronous Machine in Electrical Power Systems,” Indian Journal of Engineering, 2018, vol. 15, pp. 117 – 126. ISSN 2319-7757; EISSN 2319-7765. Contribution by authors 25%, 25%, 25%, 25%.

8.2.1.3 Publications in Conference Proceedings (Indexed in WoS and Scopus)

1. F. O. Igbinovia, G. Fandi, Z. Müller, and J. Tlusty, “Reputation of the Synchronous Condenser Technology in Modern Power Grid,” International Conference on Power System Technology (POWERCON), 6th – 8th November 2018, Guangzhou, China, pp. 2108 – 2115. Publisher: IEEE 2018. Contribution by authors: 25%, 25%, 25%, 25%.

2. F. O. Igbinovia, G. Fandi, Z. Müller, J. Švec, and J. Tlusty, “Cost Implication and Reactive Power Generating Potential of the Synchronous Condenser,” 2nd International Conference on Intelligent Green Building and Smart Grid (IGBSG), 27th – 29th June 2016, Prague, Czech Republic, pp. 212 – 217. Publisher: IEEE 2016. Contribution by authors 20%, 20%, 20%, 20%, 20%.

3. F. O. Igbinovia, G. Fandi, Z. Müller, J. Švec, and J. Tlustý, “Optimal Location of the Synchronous Condenser in Electric-Power System Networks,” 17th International

Scientific Conference on Electric Power Engineering (EPE), 16th – 18th May 2016, Prague, Czech Republic, pp. 85 – 90. Publisher: IEEE 2016. Contribution by authors: 20%, 20%, 20%, 20%, 20%.

4. F. O. Igbinovia, G. Fandi, J. Švec, Z. Müller, and J. Tlusty, “Comparative Review of Reactive Power Compensation Technologies,” 16th International Scientific Conference on Electric Power Engineering (EPE), 20th – 22nd May 2015, Kouty nad Desnou, Czech Republic, pp. 2 – 7. ISBN: 978-1-4673-6788-2. Publisher: IEEE 2015. Contribution by authors: 20%, 20%, 20%, 20%, 20%.

8.2.1.4 Publications in Conference Proceedings (Not Indexed in WoS and Scopus)

1. P. M. Dusane, M. Dang, F. O. Igbinovia, and G. Fandi, “Analysis of the Synchronous Machine in its Operational Modes: Motor, Generator and Compensator,” 19th International Student Conference on Electrical Engineering. (CD-ROM) 14th May 2015, Prague, Czech Republic. [Online] Available from: radio.feld.cvut.cz ISBN 978-80-01-05728-5. Contribution by authors: 25%, 25%, 25%, 25%.

2. A. S. Sengar, R. Chhajer, G. Fandi, and F. O. Igbinovia, “Comparison of the Operational Theory and Features of SVC and STATCOM,” 19th International Student Conference on Electrical Engineering. (CD-ROM) 14th May 2015, Prague, Czech Republic. [Online] Available from: radio.feld.cvut.cz ISBN 978-80-01-05728-5. Contribution by authors: 25%, 25%, 25%, 25%.

8.2.2 Other Publications

8.2.2.1 Publications in Impact Factor Journals (Indexed in WoS and Scopus)

1. G. Fandi, V. Krepl, I. Ahmad, F. O. Igbinovia, T. Ivanova, S. Fandie, Z. Muller and J. Tlusty, “Design of an Emergency Energy System for a City Assisted by Renewable Energy, Case Study: Latakia, Syria,” Energies, MDPI Open Access Journal, 2018, vol. 11, no. 11, 3138. IF: 2.707. ISSN 1996-1073. Contribution by authors: 12.5%, 12.5%, 12.5%, 12.5%, 12.5%, 12.5%, 12.5%, 12.5%.

2. G. Fandi, I. Ahmad, F. O. Igbinovia, Z. Muller, J. Tlusty and V. Krepl, “Voltage Regulation and Power Loss Minimization in Radial Distribution Systems via Reactive Power Injection and Distributed Generation Unit Placement,” Energies, MDPI Open Access Journal, 2018, vol. 11, no. 6, 1399. IF: 2.707. ISSN 1996-1073. Contribution by authors: 16.7%, 16.7%, 16.7%, 16.7%, 16.7%, 16.7%.

3. G. Fandi, F. O. Igbinovia, J. Tlustý, and R. Mahmoud, “Voltage Regulation and Power Losses Reduction in a Wind Farm Integrated MV Distribution Network,” Journal of

Electrical Engineering, 2018, vol. 69, no. 1, pp. 85 – 92. IF: 0.636, ISSN 1339-309X. Contribution by authors: 25%, 25%, 25%, 25%.

8.2.2.2 Publications in Reviewed Journals (Indexed in Scopus)

1. F. O. Igbinovia, G. Fandi, R. Mahmoud, and J. Tlustý, "A Review of Electric Vehicles Emissions and Its Smart Charging Techniques Influence on Power Distribution Grid," Journal of Engineering Science and Technology Review (JESTR) 2016, vol. 9 no. 3, pp. 80 – 85. ISSN: 1791-2377. Contribution by authors: 25%, 25%, 25%, 25%.

8.2.2.3 Publications in Reviewed Journals (Not Indexed in WoS and Scopus)

1. G. Fandi, F. O. Igbinovia, and I. Ahmad, "Reactive power producing capability of wind turbine systems with IGBT power electronics converters," Indian Journal of Engineering, 2018, vol. 15, pp. 198–208. ISSN 2319-7757; EISSN 2319-7765. Contribution by authors: 33.4%, 33.4%, 33.4%.

2. F. O. Igbinovia, "An Overview of Renewable Energy Potentials in Nigeria: Prospects, Challenges and the Way Forward," Energetika Journal. Prague, Czech Republic. November 2014, pp. 570–579. Index 46 507, ISSN 0375-8842. Contribution by author: 100%.

8.2.2.4 Publications in Conference Proceedings (Indexed in WoS and Scopus)

1. F. O. Igbinovia, G. Fandi, Z. Müller, J. Švec, and J. Tlusty, "Effect of Improved Electricity Product Development on the Business Performance of a Public Electricity Transmission Company," IEEE PES Power Africa Conference, 27th – 30th June 2017, Accra, Ghana, pp. 46 – 51. Publisher: IEEE 2017. Contribution by authors: 20%, 20%, 20%, 20%, 20%.

2. G. Fandi, F. O. Igbinovia, I. Ahmad, J. Svec, and Z. Muller, "Modeling and Simulation of a Gearless Variable Speed Wind Turbine System with PMSG," IEEE PES Power Africa Conference, 27th – 30th June 2017, Accra, Ghana, pp. 59 – 64. Publisher: IEEE 2017. Contribution by authors: 20%, 20%, 20%, 20%, 20%.

3. G. Fandi, F. O. Igbinovia, J. Švec, Z. Müller, and J. Tlustý, "Advantageous Positioning of Wind Turbine Generating System in MV Distribution Network," 17th International Scientific Conference on Electric Power Engineering (EPE), 16th – 18th May 2016, Prague, Czech Republic, pp. 124 – 129. Publisher: IEEE 2016. Contribution by authors: 20%, 20%, 20%, 20%, 20%.

4. G. Fandi, F. O. Igbinovia, Z. Müller, J. Švec, and J. Tlusty, "Using Renewable Wind Energy Resource to Supply Reactive Power in Medium Voltage Distribution Network," 16th International Scientific Conference on Electric Power Engineering (EPE), 20th – 22nd

May 2015, Kouty nad Desnou, Czech Republic, pp. 169 – 173. Publisher: IEEE 2015. Contribution by authors: 20%, 20%, 20%, 20%, 20%.

8.2.2.5 Publications in Conference Proceedings (Not Indexed in WoS and Scopus)

1. F. O. Igbinovia, "Strategies for Adequate, Reliable and Sustainable Energy in Africa," African Engineering Conference on Energy, Nigerian Society of Engineers (NSE) Annual General Meeting, and UNESCO African Engineering Week, Uyo, Nigeria, 21st–25th November 2016. Contribution by author: 100%.

2. F. O. Igbinovia, and J. Tlusty "Electrical Energy in Africa: The Status of Interconnections," World Engineering Conference on Sustainable Infrastructure (WECSI), 2nd – 7th November 2014, Abuja, Nigeria. [Online] Available from: www.wfeo.org Contribution by authors: 50%, 50%.

3. F. O. Igbinovia, "A Review of Electrical Energy Systems in Nigeria: Proposal to Increase Consumption," 18th International Student Conference on Electrical Engineering. (CD-ROM) 15th May 2014, Prague, Czech Republic. [Online] Available from: radio.feld.cvut.cz ISBN 978-80-01-05499-4. Contribution by author: 100%.

Contributions

Paper One

Utilizing the Synchronous Condenser for Robust Functioning of Wind Farm Implanted Electric Grid

Igbinovia Famous Oghomwen, Fandi Ghaeth, Kubica Juraj, Muller Zdenek,
Janicek Frantisek, and Tlusty Josef

Contributor	Statement of Contribution
Igbinovia Famous Oghomwen (Candidate)	Simulation and modelling (16.7%); Result interpretation and discussion (16.7%); Paper writing and review (16.7%).
Fandi Ghaeth	Simulation and modelling (16.7%); Result interpretation and discussion (16.7%); Paper writing and review (16.7%).
Kubica Juraj	Simulation and modelling (16.7%); Result interpretation and discussion (16.7%); Paper writing and review (16.7%).
Muller Zdenek	Simulation and modelling (16.7%); Result interpretation and discussion (16.7%); Paper writing and review (16.7%).
Janicek Frantisek	Simulation and modelling (16.7%); Result interpretation and discussion (16.7%); Paper writing and review (16.7%).
Tlusty Josef	Simulation and modelling (16.7%); Result interpretation and discussion (16.7%); Paper writing and review (16.7%).

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Abstract: Present-day electricity grids are equipped with sophisticated devices that allow to meet various grid code requirements. These include reactive and active power controls to ensure robust functioning of the grid. Robust operation of the electricity grid entails favourable voltage and frequency profile adjustments that can be achieved through reactive and active power controls. This study presents the synchronous condenser capability of providing voltage regulation and reactive power output, and the active power possibility path of a Type-3 wind machine for dynamic state conditions and voltage stability issues. Simulations carried out in the MATLAB/Simulink environment prove the efficiency of the proposed methodology.

Keywords: active power, reactive power, synchronous condenser, wind farm, voltage stability, power losses

1. Introduction

It is observed that the high impedance of a weak grid bond places a limit on the output power of a wind farm functioning at unity power factor. This shortcoming can be taken care of by adequately providing reactive power support to the grid. Even though it is feasible for wind power machines to generate the needed reactive power, this technique can markedly increase the volt-ampere (VA) rating need and consequently the cost of wind power machines and control inverters. Power system engineers in the electric-power industry have repeatedly had reactive power compensation as a concern owing to its influence on the active power transfer and on sustaining voltage levels at distinct buses and on the network security. It is noticeable that more than 90% of regional blackouts in some countries have been brought about by voltage collapse of the transmission network because of inadequate local sources of reactive power, predominantly dynamic or fast acting sources of reactive power provision like that supplied by generators, and flexible alternating current transmission system (FACTS) devices [1,2]. The issue of voltage collapse can be successfully resolved by the synchronous condenser (SC) supplying adequate reactive power to the grid [3-7]. It may be surprizing to mention the synchronous condenser as a new technology as it has been in use for many years. The synchronous condenser is a long-established, pre-deregulation era technology that serves as a source of reactive power compensation. Synchronous condensers can provide inertia, short-circuit power contribution, short-term overload capability, and reactive power compensation to the electricity transmission network. To provide the required functionality, new synchronous condensers can be installed in existing transmission substations or, on the other hand, retired generators can be retrofitted to synchronous condensers [8].

Apart from reactive power compensation in electricity grids, the active power is equally an issue in modern electric power grids. Power production from renewable supplies is increasing rapidly as compared with traditional fuels. Wind is the fastest growing renewable energy source [9]. As electric power production mix advances to a higher spread of wind farms, there are points on the electricity grid where stability becomes a problem. Hence, the need arises for active and reactive power regulation using wind machines for the former and the synchronous condenser technology [10]. The Type-3 Wind machines are more efficient in extracting power than other types of wind power machines [11]. The coefficients of performance of Type-3 wind machines can be between 0.4 and 0.5 [12,13]. Hence, the doubly fed asynchronous/induction generator (DFAG/DFIG), thus a Type-3 wind machine technology, has been recommended for wind farm electricity generation.

The active power priority mode for Type-3 wind power machines is recommended in this work. This is to allow wind farms to produce adequate active power during normal operating conditions. In this work, the Type-3 wind machine is set in the active power mode, while the reactive power path of the wind machine is decoupled. The DFAG/DFIG-based wind machines are extensively used in existing wind farms [14], where each DFAG/DFIG unit is linked to the collector network directly through its stator, while its rotor is connected to the grid through a back-to-back converter scheme. The converter scheme permits independent control of the active power delivery to the electricity grid via the Type-3 DFAG/DFIG-based wind farm and the reactive power exchange with the synchronous condenser. The rotor-side converter (RSC) of the wind machine often controls the stator power flow based on a smaller percentage of power injected into the rotor circuit of the suggested scheme. For this reason, the back-to-back converter is in most cases rated between 30 and 40% of the wind machine rated power. The reduced size of the Type-3 machine converter implies a lower cost of both the converter and its filter. Additionally, it minimizes converter losses as compared with the full rated converter wind energy technology.

Owing to the utilization of the synchronous condenser in electricity networks, additional inertia and short-circuit current could be made available, which could in turn enhance the functioning of the wind farm implanted grid. However, the synchronous condenser and wind machines are adopted for reactive and active power regulation. An obvious question that arises and needs to be answered by this research is the point or position, where the synchronous condenser and wind farm should be deployed. This query still has not been answered in existing research works. Therefore, this research work develops a methodology to evaluate the required position or point to locate the synchronous condenser and the wind farm on the electricity grid. To examine the effectiveness of the proposed methodology, it is applied to a medium voltage (MV) power grid with proliferated wind production. The reactive and active power control strategies and encountered issues are discussed including the methodology, measurements and simulation results from study cases. The results of this research will help in advising electricity utility providers to make better use of new synchronous condensers and retired retrofitted generators to provide the required functionality for the electricity grid, which will finally prepare the way for further integration of wind power machines and other renewables in present-time power systems.

The rest of this research paper is organized as follows: In the second section, the standard power system and its elements are modelled. In the third section, the methodology for this research is presented. In the fourth section, analysis of results obtained with installed synchronous condenser and wind power plants is presented. The last part of this paper brings the conclusion.

2. Modelling of the Standard Power System and its Elements

In this research work, a 50 Hz, 33 kV grid and 50 MVA substation base on a standard utility medium voltage (MV) transmission power system is presented as a standard or reference case as shown in Fig. 1.

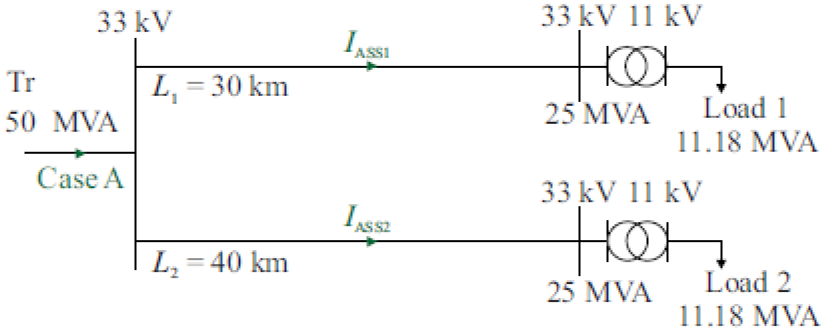

Fig. 1 Schematic diagram of the standard network.

There are two load points, each totalling 11.18 MVA. The MV distribution system has two 33 kV power lines L1 and L2 of lengths 30 km and 40 km connected to it. The lines interconnect different parts of the 11 kV consumer network to facilitate power exchange between the loads. The installed capacity at the consumer end transformer substation is 25 MVA. Note that all transmission lines are modelled using pi-model.

Specifications of the power lines are given in Table 1. The rated positive resistances r_1 (Ω/km), zero-sequence resistances r_0 (Ω/km), positive inductances l_1 (mH/km), zero-sequence inductances l_0 (mH/km), positive capacitances c_1 (nF/km), zero-sequence capacitances c_0 (nF/km), and frequency f_n (Hz) are the same for the two lines. The lines lengths (km), phase resistances R_1 (Ω), phase inductive reactances X_1 (Ω), and phase susceptances B (μS) differ as presented.

Table 1 Parameters of the MV electrical power lines

line number		1	2
positive resistances r_1	(Ω/km)	0.0922	0.0922
zero-sequence resistances r_0	(Ω/km)	0.312	0.312
positive inductances l_1	(mH/km)	0.610	0.610
zero-sequence inductances l_0	(mH/km)	2.83	2.83
positive capacitances c_1	(nF/km)	11.3	11.3
zero-sequence capacitances c_0	(nF/km)	5.01	5.01
frequency f_n	(Hz)	50.0	50.0
length	(km)	30.0	40.0
phase resistance R_1	(Ω)	2.77	3.69
phase inductive reactance X_1	(Ω)	5.75	7.67
phase susceptance B	(μS)	53.4	71.2

The MV power lines supply 33 kV/11 kV transformers rated at 25 MVA. As shown in Table 2, the frequency , nominal power, magnetization resistance and magnetization inductance are the same for the two transformers.

Table 2 Parameters of the three-phase 33/11 kV transformers

Transformer 1, 2	Higher voltage winding	Lower voltage winding
connection type	D11	Yg
V (V)	33.0	11.0
R (Ω)	0.157	0.0166
L (H)	0.00581	0.000620
frequency f_n (Hz)	50.0	
nominal power S_n (MVA)	25.0	
magnetization resistance R_m (MΩ)	0.0653	
magnetization inductance L_m (H)	208	

The 25 MVA transformer at the busbar end supplies the consumer load at a level of 11 kV. The recorded values of the load are shown in Table 3. The frequency and the load voltage are same for both loads, but the active power, reactive power, apparent power and the power factor differ for single loads.

Table 3 Measured values of the load

active power P_L (MW)	10.0
reactive power Q_L (MVAr)	5.00
apparent power S_L (MVA)	11.2
cos φ	0.894
frequency f_n (Hz)	50.0
consumer voltage (kV)	11.0

Measurements of the source and load powers and voltages (thus of power losses and voltage drops) for the two lines were taken in the reference case, this is shown in Table 4. Subscripts ‘s’ and ‘r’ denote the sending and receiving ends of the lines, respectively.

Table 4 Measured parameters of the benchmark commercial three-phase lines

Line	P_s (MW)	P_r (MW)	Q_s (MVAr)	Q_r (MVAr)	U_s (kV)	U_r (kV)	ΔP (MW)
1	8.82	8.55	5.09	4.63	32.6	31.0	0.271
2	8.62	8.27	5.06	4.48	32.6	30.4	0.350

3. Methodology

A 3.125 MVA synchronous condenser has been used in this research work. It is a round-rotor type machine, modelled in detail with its excitation systems. It is a modified version of the built-in model by MATLAB/Simulink. The setting allows feeding the entire power system with adequate reactive power needs. This type of control strategy focuses on reactive power injection to the local bus or substation, depending on the position or point of connection. The synchronous condenser is investigated for reactive power production aiding the wind farm during dynamic situations.

A wind farm rated 9 MW based on Type-3 wind machine with a power factor rating of 0.9. The DFIG model used in this study is a modified version of the built-in model by MATLAB/Simulink [15]. It consists of a wound rotor induction generator and an AC/DC/AC/IGBT-based pulse-width modulation (PWM) converter. PWM converters provide a compact solution for converting current into a digital pulse width modulated signal, a reference voltage is made available on the PWM output. It is also equipped with a pitch control system and it is based on a doubly fed induction generator using back-to-back PWM converters. The generator stator is directly linked to the electric-power grid, whereas the rotor is joined to the electricity grid through an AC/DC/AC converter and slip rings. The converter consists of the rotor-side converter (RSC), and of the grid-side converter (GSC). A capacitor coupling the two converters acts as a DC voltage source (DC bus). Active power is generated by pre-defined power-speed characteristic. The DFIG model is deemed suitable for dynamic stability studies. In a DFIG the active power can be produced and injected into the electric-power grid by utilizing its AC/DC/AC converter system which contains dq-current regulators (‘d’ stands for the d-axis and ‘q’ for the q-axis). Methodically, by influencing or controlling the DFIG equations and steering the machine characteristic relations between flux, voltage, current and so on, one gets active power related equations (note here that the reactive power is decoupled), enabling production and injection of active power only from the wind farm. The DFIG model utilized for this study employs a typical vector control scheme, where the active power is controlled by regulating the rotor q-axis current and the pitch angle. All power regulators use proportional-integral (PI) controllers [16-22].

4. Analysis with Installed Synchronous Condenser and Wind Plants

We have designed a MATLAB/Simulink model with different positioning of the synchronous condenser and the wind farm. Five cases have been considered A, B, C, D and E, with the positions of the synchronous condenser and wind power plants altered in each case. Case A is the standard or reference case as detailed in section 2. Case B is a wind farm rated 9 MW connected to the grid at the busbar of the 50 MVA main substation. Case C is the situation, when the wind farm rated 9 MW is connected to the grid at the busbar close to the consumer loads of the network through two step-down transformers. The consumer load bus system is connected to the larger electricity grid and the main substation through a bus tie. The larger medium voltage grid is modelled as an equivalent source with a 33 kV three-phase voltage source in series with an RL-impedance with a short-circuit capacity of 50 MVA. In case D there is a 3.125 MVA synchronous condenser installed at the 50 MVA main substation bus. Case E is a 3.125 MVA synchronous condenser connected to the electricity grid at the consumer load busbar through two step-down transformers each rated 25 MVA. The synchronous condenser is modelled in detail with its excitation systems. All transmission lines of the proposed scheme are modelled using pi-model. Details on modelling the system were published in [10,23].

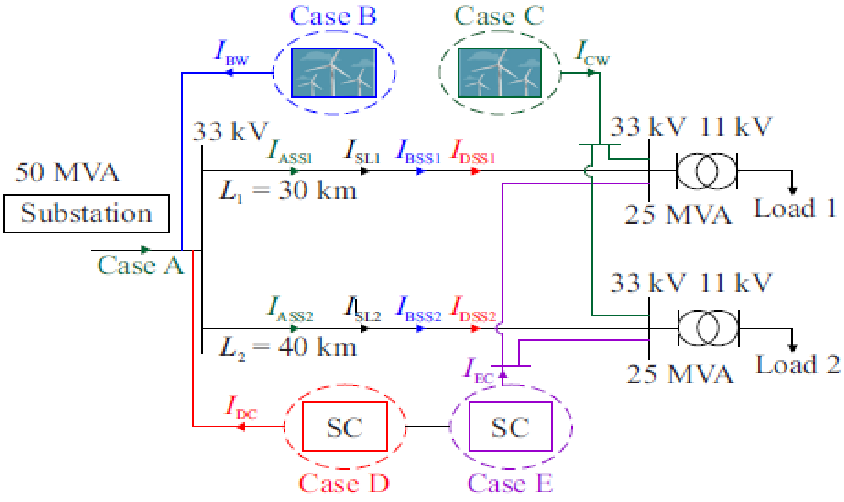

Fig. 2 The proposed scheme with installed synchronous condenser and wind plants.

Figure 2 shows the scheme with installed synchronous condensers and wind farms. Two performance criteria are used: first the synchronous condenser capability to produce reactive power, and second the wind farm active power generation ability. Furthermore, both the wind farms and the synchronous condensers are connected to the grid by changing their positions. The Type-3 DFIG wind machines are operated in an active power regulation mode such that its reactive power regulation mode is decoupled. The results with the synchronous condenser installed and the Type-3 wind machine farms connected to the grid are compared with that of case A.

Four monitored steps values were obtained. The first step is the standard or reference case value of loads, while steps 2 to 4 are increased by 20% in each step.

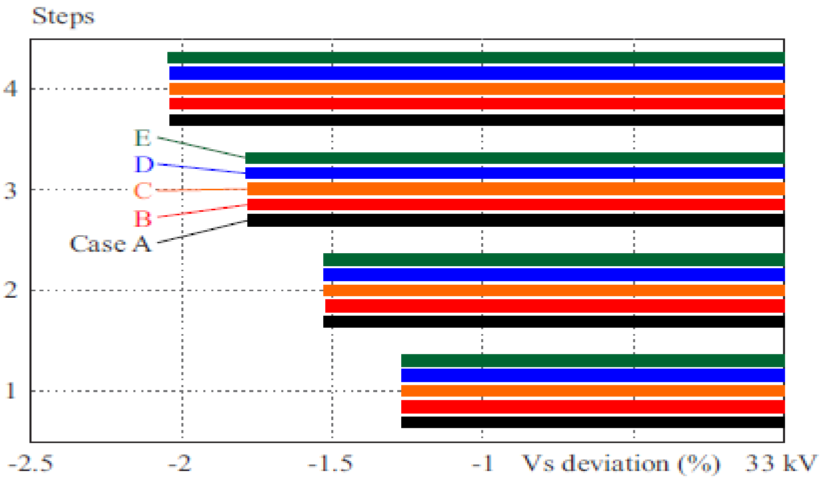

Fig. 3 Percentage of source voltage deviation from the nominal voltage of 33 kV for different steps of cases A, B, C, D and E.

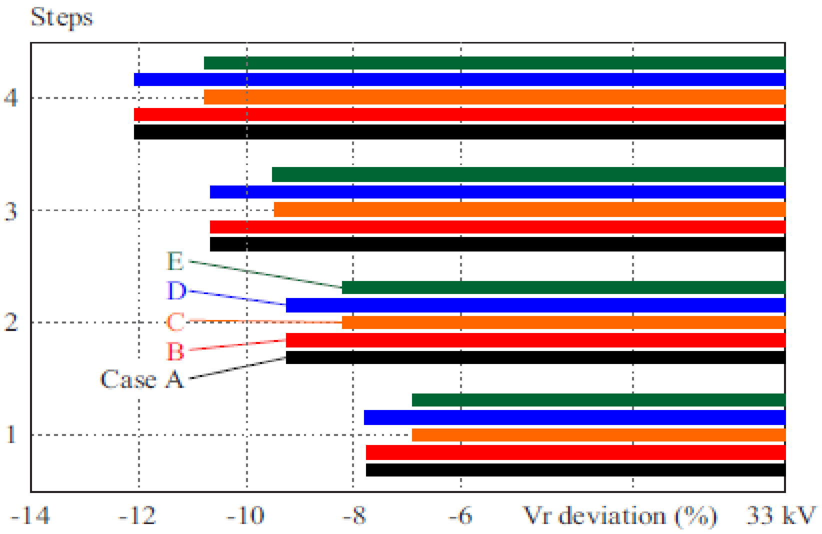

Fig. 4 Percentage of load voltage deviation from the nominal voltage of 33 kV for different steps of cases A, B, C, D and E.

Figure 2 shows that the source voltage deviation from the nominal voltage of 33 kV has the same value for all cases. It should be noted that the source voltage deviation increases as we move from step 1 to 4. Positions of the wind farm or synchronous condenser do not have any effect on the source voltage deviation. The percentage of the load voltage deviation from the nominal voltage of 33 kV for different steps of case A, B, C, D and E is plotted in Fig. 3. The load voltage deviation decreased by a few percent in cases C and E. Results for cases B and D are the same. The result for reference case A is also the same with cases B and D.

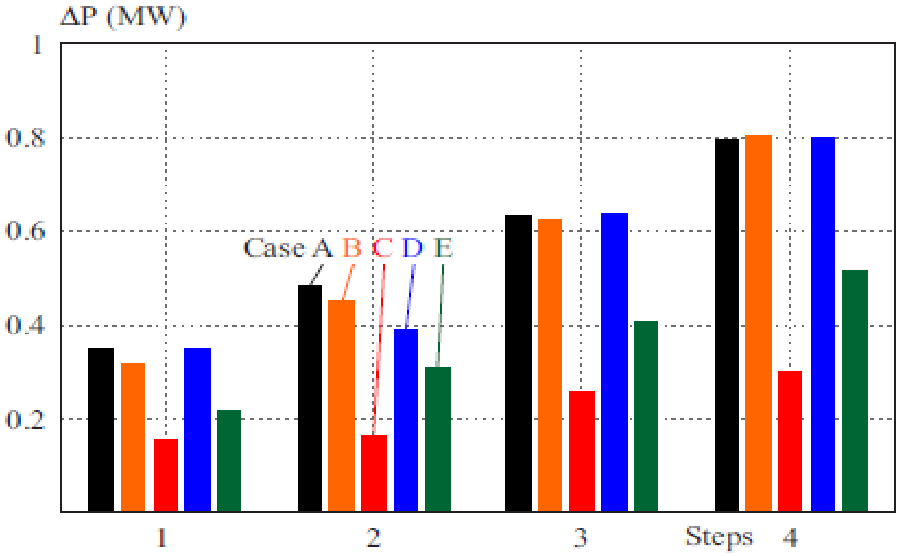

Fig. 5 Power losses for different steps of cases A, B, C, D and E.

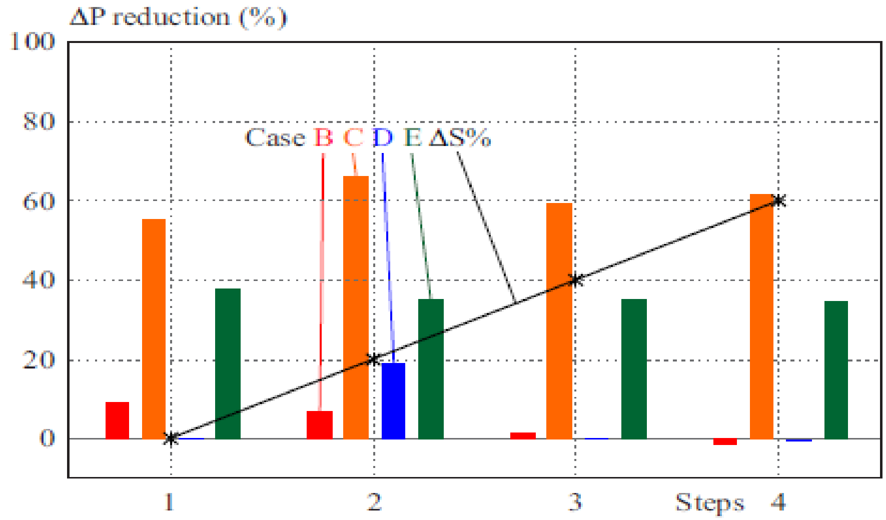

Fig. 6 Percentage of power losses reduction for different steps of cases B, C, D and E compared with case A.

When the wind farm or synchronous condenser is joined to the beginning of the transmission lines, the power losses reduce slightly, but when the wind farm or synchronous condenser were installed to the end of the transmission lines, power losses are reduced markedly. Note that the effect of the wind farm is much stronger due to its nominal power9 MVA. The nominal power of the synchronous condenser is 3.125 MVA. The results for the power losses are presented in Fig. 5.

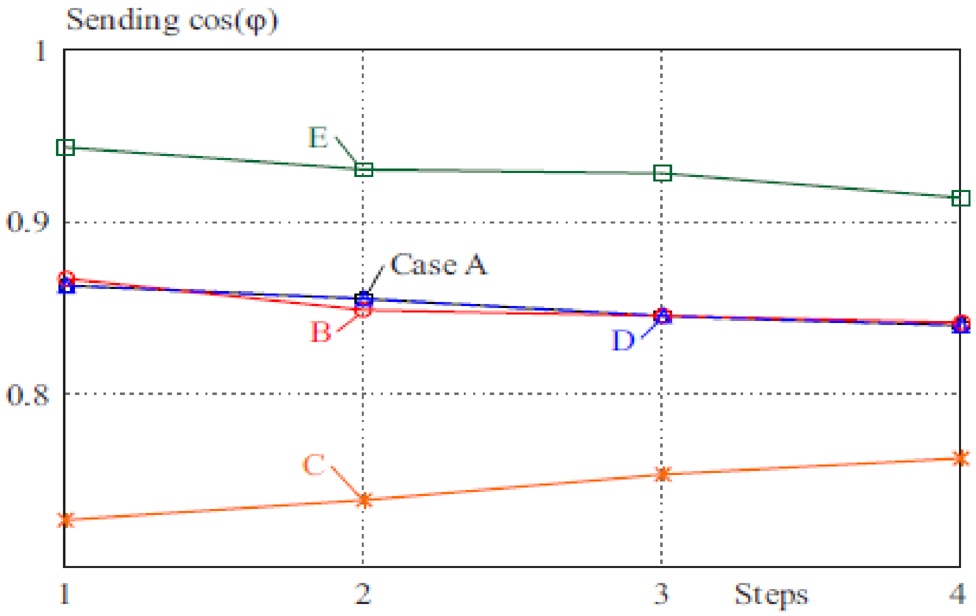

Fig. 7 Sending power factor for different steps of Cases A, B, C, D and E.

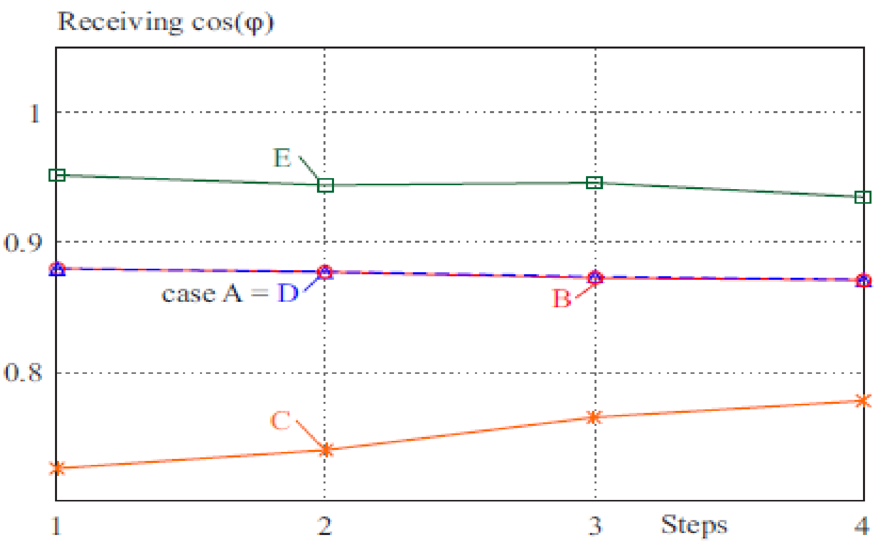

Fig. 8 Receiving power factor for different steps of Cases A, B, C, D and E.

Figure 8 reports the source power factor values recorded for cases A to E. No remarkable changes were seen in cases B and D, this also applies to the reference case A. The observed source power factor for case C decreases from about 0.85 to 0.75, while that for case E increases to about 0.95. Figure 9 is a graphical presentation of the load end power factor values. The power factors for cases A, B and D are steady because of the wind farm and synchronous condenser installed to the 50 MVA main substation busbar. Hence, the changes in the power flow though the transmission lines are very small. When considering case C, the source power factor decreases owing to the wind farm connected to the end of the transmission line busbars, therefore the active power flowing through the transmission lines becomes smaller, thereby leading to a decrease in the power factor values. Also, taking into consideration case E, the source power factor results is seen to increase owing to the synchronous condenser installed at the end of the 33 kV transmission lines busbar connected to the two step-down transformers. For this reason, the reactive power flowing through the transmission lines becomes lower, bringing about an increase in the value of the power factor.

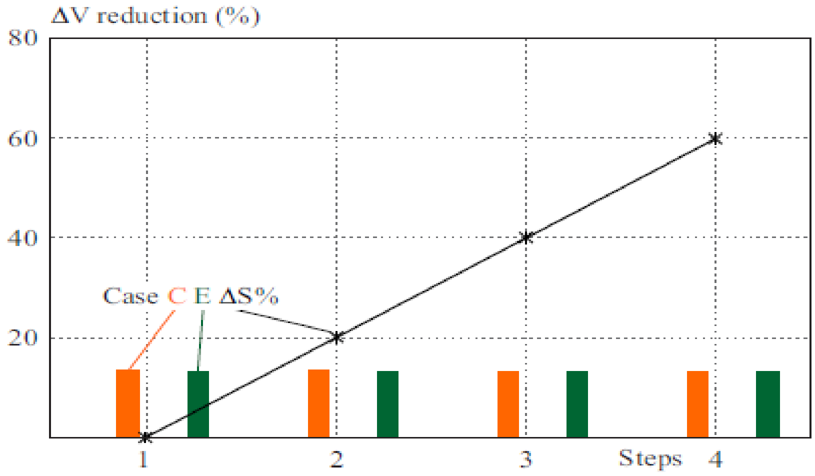

Fig. 9 Percentage of voltage drop reduction for different steps of cases B, C, D and E compared with case A.

The percentage of voltage drop reduction for different steps of all the cases is depicted in Fig. 9. The voltage drop decreases only in cases C and E (the decrease in voltage drop is 12%). This suggests that the voltage drop could only be reduced, when the wind farm or synchronous condenser is coupled to the end of the 33 kV transmission lines close to the consumer substation. Note here that the percentage of voltage drop reduction is the same for all the steps observed.

5 Conclusions

A purposely developed simulation model based on the proposed methodology was applied to a variety of cases involving active power control by wind power plants and reactive power control using the synchronous condenser, and effective positioning of both the wind plants and the synchronous condensers. The authors have shown that wind power plants and the synchronous condenser can play a great role in reducing the power losses and voltage drop in modern power systems. Additionally, the effect of position and power capacity, when wind plants or synchronous condensers are joined to the end of transmission lines, brought about a higher reduction in power losses in the proposed scheme because the power flow through the transmission lines is reduced or lowered. It was also observed that when the power capacity is high, power losses are drastically reduced. The presented work opens a variety of opportunities to utilize new or retrofitted synchronous condensers for a further advanced research in future work. Although being an old technology, the synchronous condenser remains an interesting topic for future work. Moreover, the synchronous condenser can be used for studies related to reactive power, power losses and voltage control.

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Paper Two

Modeling and Simulation of the Anticipated Effects of the Synchronous Condenser on an Electric-Power Network with Participating Wind Plants

Famous O. Igbinovia, Ghaeth Fandi, Ibrahim Ahmad, Zdenek Muller, and Josef Tlusty

Contributor	Statement of Contribution
Famous O. Igbinovia (Candidate)	Simulation and modelling (20%); Result interpretation and discussion (20%); Paper writing and review (20%).
Ghaeth Fandi	Simulation and modelling (20%); Result interpretation and discussion (20%); Paper writing and review (20%).
Ibrahim Ahmad	Simulation and modelling (20%); Result interpretation and discussion (20%); Paper writing and review (20%).
Zdenek Muller	Simulation and modelling (20%); Result interpretation and discussion (20%); Paper writing and review (20%).
Josef Tlusty	Simulation and modelling (20%); Result interpretation and discussion (20%); Paper writing and review (20%).

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Abstract: Installing the Synchronous Condenser (SC) onto the electricity grid can assist in the area of reactive power needs, short-circuit strength and consequently system inertia, and guarantees better dynamic voltage recovery. This paper summarizes the practical potential of the synchronous condenser coordinated in an electric-power network with participating wind plants to supply reactive power compensation and injection of active power at their Point of Common Coupling; it provides a systematic assessment method for simulating and analyzing the anticipated effects of the synchronous condenser on a power network with participating wind plants. A 33KV power line has been used as a case study. The results indicate that the effect of the synchronous condenser solution adopted model in MATLAB/Simulink environment provides reactive power, enhances voltage stability and minimizes power losses, while the wind power plants provides active power support with given practical grid rules.

Keywords: Active power; Reactive power; Reactive power compensation; Synchronous condensers; Wind plants; Electric-power network

1. Introduction

For most electricity utility companies making sure of grid reliability, efficiency and security is a major task. As electric-power grid develops and electrical load profiles change, pressure is being put onto the electricity transmission and distribution grids, thereby making the need for voltage reinforcement and electric-power grid management much more demanding. Universally, electric-power utility authorities are facing many new electricity grid challenges and circumstances including: changes in electric-power production mix, decreases in traditional power production, increases in renewable power production and distributed generation, changes in environmental and regulatory policies, the retirement of traditional thermal producing stations. These challenges have an operational effect on electric-power infrastructure, particularly bringing about a general inadequacy in: reactive power compensation, voltage stability, power system inertia, and low short circuit strength. As compared with traditional power sources, wind renewable power has a reputation of strong randomness, intermittency and volatility, it has in common the intermittent feature of renewable power sources which are controlled by environmental elements such as instantaneous changes of weather which eventually give rise to voltage and frequency instability. Application related instances prove that connecting wind power plants to existing electricity grid have an adverse effect on the security and stable operation of the now present modern electrical power system [1-5]. High impedance of a fragile or weak electricity grid connection limits the output power of a wind plant operating at unity power factor. This limitation can be reduced by adequately providing high reactive power compensation with the help of the synchronous condenser technology. Although it is feasible for the Type-4 wind power plants to produce the requisite reactive power compensation. This technique can appreciably increase the active power rating need and hence reduce the cost of wind power plant and control inverters, since only the Type-3 wind power plants are involved in this instance [6].

Synchronous condensers (SCs) were once generally put to practical use as a means of supplying reactive power compensation to power grid before the introduction of power electronic devices. Benefits of the synchronous condenser technology solution include being a long standing, well known and understood technology. It is a very resilient solution, can have high overload capacity, and can provide excellent reactive power support for the grid under low voltage situations. Synchronous condensers are origin of short circuit availability which can be a significant benefit in weak electric-power grids and they are not sources of harmonics. Drawbacks of the Synchronous condenser can include a higher level of losses, slower response time as compared to power electronic devices and mechanical wear [7-12]. Synchronous condensers have been utilized conventionally in the electric- power industry to support weak electricity grids with poor voltage regulation. Static power electronics equipment such as static VAR compensators (SVCs) and static synchronous compensators (STATCOMs) are now frequently utilized for reactive power production. These static power electronics devices give the benefit of faster responses [13-15]. Under certain electric-power grid fault circumstances, SCs provide higher reactive power compensation, and, more significantly, the kinetic energy stored in the rotor makes available inertial assistance to the electricity grid during faults condition [16-19]. The inertia support ability of SCs becomes more significant as the electric-power grid connection needs, such as low-voltage ride-through for distributed generation networks, become stricter and SCs are needed to supply additional services of supporting electric-power grid stability [20-21]. With the continuous growth of the scale of wind power plants inclusion in electrical networks, the interconnection of wind renewable plants with electricity grids has brought remarkable drawbacks for electric-power system dispatching. Apart from the operating situation, wind plants are susceptible to many other factors such as component faults, weather problems, and power system disturbance, etc., bringing growingly conspicuous threat on power system stability [22-32]. Therefore, active and reactive power assessment methodologies and mechanisms have become a top priority among stake holders in the electric-power industry.

This research work develops a methodology to generate active power by utilizing the Type-3 wind plant and reactive power by using the synchronous condenser, particularly on a 33KV power network. To scrutinize the successfulness of the suggested methodology, it is applied to an interconnected power system with proliferated wind renewable electricity production. As net result this paper will help to put in place strict guidelines for electricity network operators to make a better use of the synchronous condensers for reactive power generation and the Type-3 wind plant for active power generation, which will at long last pave the way for further integration of wind power plants onto the electricity grid.

The remaining part of this article is organized in the following manner. In Section 2, the vulnerability of the modern grid as a result of high penetration of wind power plants is discussed. In Section 3, the benchmark case setup of the research is given. This consists of the benchmark line parameters, the benchmark transformer parameters, the benchmark load and three-phase lines parameters. And implementation of the benchmark case using MATLAB/Simulink software. Section 4 explains the methodology used in this study and explores data from the simulation setup. Section 5 presents the mathematical model of the system. Section 6 illustrates a vivid case study. While Section 7, provides results and discussions considered in the study case. Conclusions are presented in Section 8.

2. Vulnerability of the Modern Grid as a Result of High Penetration of Wind Power Plants

Increasing grid voltage instability, reactive power control, short circuit strength, power system inertia, frequency control and more with each of them independently, and in some cases in combination, affects the ability of the modern grid to effectively make use of high renewable energy penetration systems such as wind power plants. These also affect the demand for electricity and ability to access, produce, and distribute it. An evaluation of these impacts, both positive and negative is needful to inform forward-looking endeavor to increase power system security. These effects occur and affect all modern electricity grid and the vulnerabilities faced by various stakeholders in the power industry may vary remarkably depending on their degree of specific exposure to wind renewable power penetration. In general, large-scale wind farms, consisting of many wind power plants, often cover large areas. When wind plants run at nearly full power, the voltage drop of line becomes significant [33].

With the increasing share of wind renewable power plants in present day electric-power production mix, traditional fossil fuel-based synchronous generators continue to be substituted from the electric-power production fleet. High availability of wind power may equally be accountable for the planned retirement of thermal power plants. Nowadays, wind power plants are mostly based on Type-3 and Type-4 machine plants. These variable speed wind plants are decoupled from the corresponding electricity grid by power electronic converters. Different from synchronous generators, some types of wind plants are not able to play a part in frequency control activities such as inertia and governor response after a disturbance [34-38]. Although several control methodologies have been developed to allow the Type-3 and Type-4 wind plants to be used for frequency regulation [39-40], such solutions are still not mandatory and normally not operating for the Type-3 wind plant. Thus, owing to increased wind production, sustaining enough frequency response is becoming of vital concern for network operators. Aside from frequency response, short-circuit operation is one more vital issue in power system security owing to higher wind renewable penetration on the grid [41]. Short-circuit operation is determined by making use of an indicator called Short-Circuit Ratio (SCR). Short-circuit ratio at the electric-power grid connection point or Point of Common Coupling (PCC) of a wind power plant is defined as the ratio between the short-circuit level at its PCC and the rated efficiency of the wind power plant [42]. A minimal value of SCR at the PCC of a wind power plant is necessary for protection equipment to distinguish between a development of a fault or not. Owing to the limitation of power electronics efficiency, the Type-3 and Type-4 wind power plants commonly generate less fault current compared with traditional synchronous generators of equivalent rating [43]. Consequently, the possibility of obtaining undesirable SCR at the PCC of modern grid with wind plants very much increases for high penetration of wind machines [44]. The insertion of a large numbers of wind renewable power plants has changed the robustness of alternating current (AC) grid and made the electric-power grid ineffectual, which is marked by low short circuit ratio (SCR) or low inertia [45]. SCR is closely associated with voltage stability, so the lower-level the SCR of wind power plants at the PCC, the quicker to respond to voltage fluctuation will be. This will give rise to instability and occasion wind plants to trip leading to breakdown of grid stability [46], mostly in situations where a large concentration of wind power plants is joined to a relatively weak electric-power grid [47-49].

It is obvious from the foregoing that in most situations, frequency response and short-circuit functioning are scrutinized as separate issues. Traditionally, they are individually enhanced when necessary. Regardless of how, both are related to modern grid security as a result of high wind plants penetration and should be simultaneously considered. Owing to the accumulative entrance of wind power plants on today’s modern grid, most thermal power plants may be subjected to planned retirement [50]. These traditional power generators perhaps would be taken out, which will result in misuse of assets and leads to economic concern. Thus, a second use of these traditional plants could be anticipated in order to get some monetary return. For this reason, there is the need for retrofitting reasonable portion of these synchronous generators into synchronous condensers. As a result of the utilization of new SCs or synchronous generators being retrofitted to SCs and joined to existing electricity substations to provide the required functionality of reactive power compensation, additional inertia and short-circuit current are made available to the grid, which in turn improves the security performances of the grid in case of high wind plant generation [44].

3. Benchmark Case Setup

The benchmark Case setup utilized in this work consists of a commercial medium voltage (MV) distribution network with a substation transformer rating of 50 MVA and voltage level of 33 kV. The MV distribution system has two power lines L1 and L2 of lengths 30 km and 40 km respectively connected to it. Fig. 1 gives an overview of the benchmark system. A more detailed description of the elements of the system is provided hereafter.

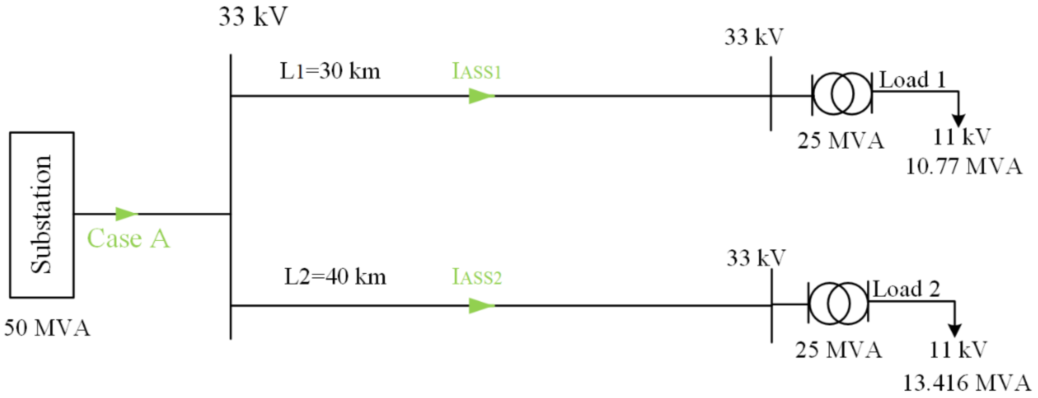

Figure 1. The Benchmark System.

3.1. Benchmark Line Parameters

The parameters of the power lines are described in detail in Table 1. Here, it suffices to illustrate the lines main characteristics. Its rated positive resistances r_1(Ω/km), zero-sequence resistances r_0 (Ω/km), positive inductances l_1 (mH/km), zero-sequence inductances l_0(mH/km), positive capacitances c_1 (nF/km), zero-sequence capacitances c_0 (nF/km), and frequency f_n (Hz) are the same for both lines. But the lines Length (km), phase resistance R_1 (Ω), phase Inductive reactance X_1 (Ω), and phase susceptance B (µS) vary as presented.

Table 1. Parameters of the MV commercial electrical power lines

Line number	1	2
Positive resistances r_1(Ω/km)	0.0922	0.0922
Zero-sequence resistances r_0 (Ω/km)	0.312	0.312
Positive inductances l_1 (mH/km)	0.61	0.61
zero-sequence inductances l_0(mH/km)	2.83	2.83

Positive capacitances c_1 (nF/km)	11.33	11.33
zero-sequence capacitances c_0 (nF/km)	5.01	5.01
Frequency f_n (Hz)	50	50
Length (km)	30	40
Phase resistance R_1 (Ω)	2.766	3.688
Phase Inductive reactance X_1 (Ω)	5.749	7.665
Phase susceptance B (μS)	53.39	71.19

3.2. Benchmark Transformer Parameters

Each of the power line supply a 33kv/11kv transformer, with a rating of 25 MVA, the parameters of this transformer detailed in Table 2, show that the frequency f_n (Hz), Nominal Power S_n (MVA), Magnetization resistance R_m (MΩ), and Magnetization inductance L_m (H) are the same for both transformers while the connection type, V_{rms}(kV), R (Ω), and L (H) is D11, 33, 0.15682, 0.005808 for the high voltage winding and Yg, 11, 0.016639, and 0.00061625 for the low voltage winding.

Table 2. Parameters of the three-phase 33/11 kV transformers

TRANSFORMER 1,2	High voltage winding	Low voltage winding
Connection type	D11	Yg
V_{rms}(kV)	33	11
R (Ω)	0.15682	0.016639
L (H)	0.005808	0.00061625
Frequency f_n (Hz)	50	
Nominal Power S_n (MVA)	25	
Magnetization resistance R_m (MΩ)	0.06534	
Magnetization inductance L_m (H)	207.98	

3.3. Benchmark Load and Three-phase Lines Parameters

Each of the 25 MVA transformers supply consumer load level of 11kV, the measured values of consumer load are tabulated in Table 3, the Frequency f_n (Hz), and consumer's voltage (kV) is the same for both loads. But Active Power P_L (MW), Reactive Power Q_L (MVAr), Apparent Power S_L (MVA), and P.F $\cos(\varphi_L)$ vary for both electrical loads. The benchmark three-phase line parameters of the standard power lines that supply the 25 MVA transformer loads is presented in Table 4. It includes the sending and receiving active power (P), sending and receiving reactive power (Q), sending and receiving voltage (U), and power losses (ΔP). Table 4 shows that only the sending voltage (U_s) value is the same for both lines, but other parameters differ.

Table 3. Measured values of Consumer load 1, and 2

parameters Load 1,2		
Active Power P_L (MW)	10	12
Reactive Power Q_L (MVAr)	4	6
Apparent Power S_L (MVA)	10.77	13.416
P.F $\cos(\varphi_L)$	0.928	0.894
Frequency f_n (Hz)	50	50
consumer's voltage (kV)	11	11

Table 4. Measured parameters of the benchmark commercial three-phase lines

Line	P_s (MW)	P_r (MW)	Q_s (MVAr)	Q_r (MVAr)	U_s (kV)	U_r (kV)	ΔP (MW)
1	8.929	8.673	4.237	3.814	32.570	31.077	0.256
2	10.061	9.576	6.131	5.261	32.570	30.017	0.485

3.4. Implementation of Benchmark Case in MATLAB/Simulink

Just as presented by Fig.1, and then described in Sections 3.1–3.3, only the benchmark parameters were added onto the benchmark simulation scheme specifically for this research work and implemented with a MATLAB/Simulink software. This benchmark system, which is a standard normal power system network is referred to as Case A.

4. Method

In the suggested approach, the system is modelled by MATLAB/Simulink simulation software. There are three case studies: first is the Benchmark Case, here after referred to as Case A, next is the second Case, which is the Case when the wind power plant, which is modeled as Type-3 wind machines is installed at the main substation of the system for producing active power only and the synchronous condenser is placed at the consumer transformer load ends for reactive power generation, this is referred to as Case B. Finally case C refers to the situation where the synchronous condenser is placed at the substation for producing reactive power only and the Type-3 wind power plants is placed at the consumer transformer load ends for producing active power only. These arrangements are tested on a 33KV power network. This methodology is adopted to achieve stability and reduce power losses in the system. This is vividly illustrated in Fig. 2, and Fig. 3 respectively.

Authors are going to discuss the results and how they can be interpreted in perspective of previous studies and of the working hypotheses. The findings and their implications will be discussed in the broadest context possible. Future research directions may also be highlighted.

5. Mathematical Model of the System

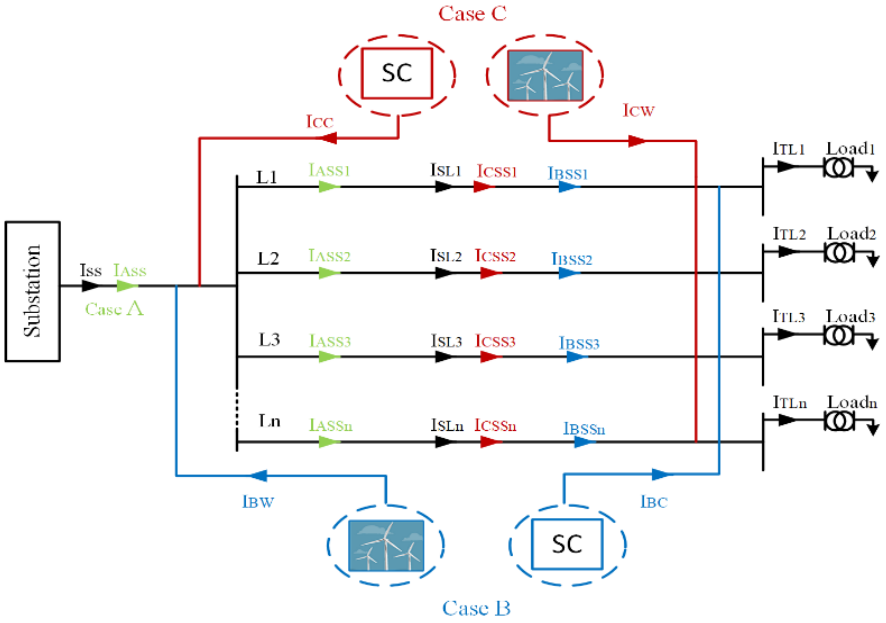

Figure 2. Diagram of the simulation model and methodology scheme of Benchmark Case (Case A), Case B and Case C.

Considering the MV substation system (S. S_1) and its vector components:

$$S_{SS} = \sum_{i=1}^{n} S_{SLi} \tag{1}$$

$$I_{SS} = \sum_{i=1}^{n} I_{SLi} \tag{2}$$

Where:

S_{SS} is the apparent power of the substation system.

I_{SS} is the total line current of the substation system.

I_{SLi} is the line current supplied to n number of power lines from the substation network.

S_{SLi} is the apparent power supplied to n number of power lines from the substation network.

$i = 1,2,3, \ldots \ldots, n.$ i.e. nth number of Lines

Hence, for n number of lines that supply n number of loads on the end of line from the MV substation, the set of transformer and load is equal to the total number of loads. Thus, the total apparent power of each n number of set is S_{TLi} ,where:

i=1,2,3,……,n. i.e. number of Loads. Therefore, Line number = each load number.

Hence, in Fig. 2:

$$P_{SLi} = \Delta P_{LLi} + P_{LTi} \qquad (3)$$

Where:

P_{SLi} is the active power supplied to n number of lines.

ΔP_{LLi} is the active power losses of n number of lines.

P_{LTi} is the active power of n number of lines.

From equation (3):

$$\Delta P_{LLi} = P_{SLi} - P_{LTi} \qquad (4)$$

The power losses on the line is given by:

$$\Delta P = 3{I_L}^2 \cdot R_{1L} \qquad (5)$$

And the difference in voltage (voltage drop) of each phase is given by:

$$\Delta V = I_L \cdot Z_L \qquad (6)$$

Considering case A only, and from equation (5) and Fig.2:

$$\Delta P_{LLi} = 3(I^2{}_{SLi} \cdot R_{1LLi}) \qquad (7)$$

Consequently, power losses for n number of lines for Case A will be:

$$\Delta P_{ALLi} = 3(I^2{}_{ASSi} \cdot R_{1LLi}) \qquad (8)$$

Where:

$$I_{SLi} = I_{ASSi} \qquad (9)$$

I_{ASSi} is the line current for n number of power lines and it is equal to I_{SLi} for Case A.

ΔP_{ALLi} is power losses of n number of lines for Case A.

Therefore, the total losses of S. S_1 for Case A will be:

$$\Delta P_{AT} = \sum_{i=1}^{n} \Delta P_{ALLi} \qquad (10)$$

Similarly, from equations (6), and (9), and Fig. 2:

$$\Delta V_{ALLi} = I_{ASSn} \cdot Z_{LLi} \qquad (11)$$

Where:

ΔV_{ALLi} is the voltage drop on n number of lines of Case A.

Z_{LLi} is the longitudinal impedance of n number of lines.

Also, considering Case B, the wind power plants are connected to the bus bar which supply all transmission lines and the synchronous condenser is installed at the end of the MV transmission lines as shown in Fig. 2, applying Kirchhoff's current law:

$$I_{BSS} = I_{SS} + I_{BW} - I_{BC} \qquad (12)$$

Where:

I_{BW} : wind plant line current

I_{BC} : synchronous condenser line current

I_{BSS} : total substation line current of Case B.

From equation (12) and the vector directions of the wind power plants and synchronous condenser parameters in Fig. 2:

$$I_{BSSi} = I_{Sli} + I_{BWi} - I_{BCi} \tag{13}$$

Where:

I_{BWi} is a constituent of the wind power plant line current going through n number of lines.

I_{BCi} is a constituent of the synchronous condenser line current going through n number of lines.

I_{BSSi} is the new line current supplied to n number of power lines of Case B.

From equation (5), (12) and (13), the power losses for n number of lines of Case B is written as:

$$\varDelta P_{BLLi} = 3({I^2}_{BSSi} \cdot R_{1LLi}) \tag{14}$$

$$\varDelta P_{BLLi} = 3 \cdot R_{1LLi}({I^2}_{SLi} + {I^2}_{BWi} + {I^2}_{BCi} + 2.I_{Sli}.I_{BWi} - 2.I_{Sli}.I_{BCi} - 2.I_{BCi}.I_{BWi}) \tag{15}$$

Where:

$\varDelta P_{BLLi}$ is the power losses for n number of lines of Case B.

Therefore, the total losses of S. S_1 for Case B will be:

$$\varDelta P_{BT} = \sum_{i=1}^{n} \varDelta P_{BLLi} \tag{16}$$

Similarly, from equations (6), (12), and (13), and Fig. 2:

$$\varDelta V_{BLLi} = I_{BSSi} \cdot Z_{LLi} \tag{17}$$

$$\varDelta V_{BLLi} = (I_{SLi} + I_{BWi} - I_{BCi}) \cdot Z_{LLi} \tag{18}$$

Where:

$\varDelta V_{BLLi}$ is the voltage drop of n number of lines of Case B.

In the same vein, considering Case C:

The synchronous condenser is installed into the bus bar which supplies power to all sections of the MV transmission lines and the wind machine is connected to the end of the transmission lines as shown in Fig. 2, Applying Kirchhoff’s current law:

$$I_{CSS} = I_{SS} - I_{CW} + I_{CC} \tag{19}$$

Where:

I_{CW} : wind plant line current

I_{CC} : synchronous condenser line current

I_{CSS} : total substation line current of Case C.

From equation (19) and the vector directions of the wind power plants and synchronous condenser parameters in Fig. 2:

$$I_{CSSi} = I_{Sli} - I_{CWi} + I_{CCi} \tag{20}$$

Where:

I_{CWi} is a constituent of the wind plants line current going through n number of lines.

I_{CCi} is a constituent of the of synchronous condenser line current going through n number of lines.

I_{CSSi} is the new line current supplied to n number of power lines of Case C.

From equation (5), (19) and (20), the power losses for n number of lines of Case C is written as:

$$\mathit{\Delta} P_{CLLi} = 3(I^2{}_{CSSi} \cdot R_{1LLi}) \tag{21}$$

$$\mathit{\Delta} P_{CLLi} = 3 \cdot R_{1LLi}(I^2{}_{SLi} + I^2{}_{CWi} + I^2{}_{CCi} - 2.I_{Sli}.I_{CWi} + 2.I_{Sli}.I_{CCi} - 2.I_{CCi}.I_{CWi}) \tag{22}$$

Where:

$\mathit{\Delta} P_{CLLi}$ is the power losses for n number of lines of Case C.

Therefore, the total losses of S. S$_1$ for Case C will be:

$$\mathit{\Delta} P_{CT} = \sum_{i=1}^{n} \mathit{\Delta} P_{CLLi} \tag{23}$$

Similarly, from equations (6), (19), and (20), and Fig. 2:

$$\mathit{\Delta} V_{CLLi} = I_{CSSi} \cdot Z_{LLi} \tag{24}$$

$$\Delta V_{CLLi} = (I_{SLi} - I_{CWi} + I_{CCi}) \cdot Z_{LLi} \quad (25)$$

Where:

ΔV_{CLLi} is the voltage drop of n number of lines of Case C.

6. Case Study

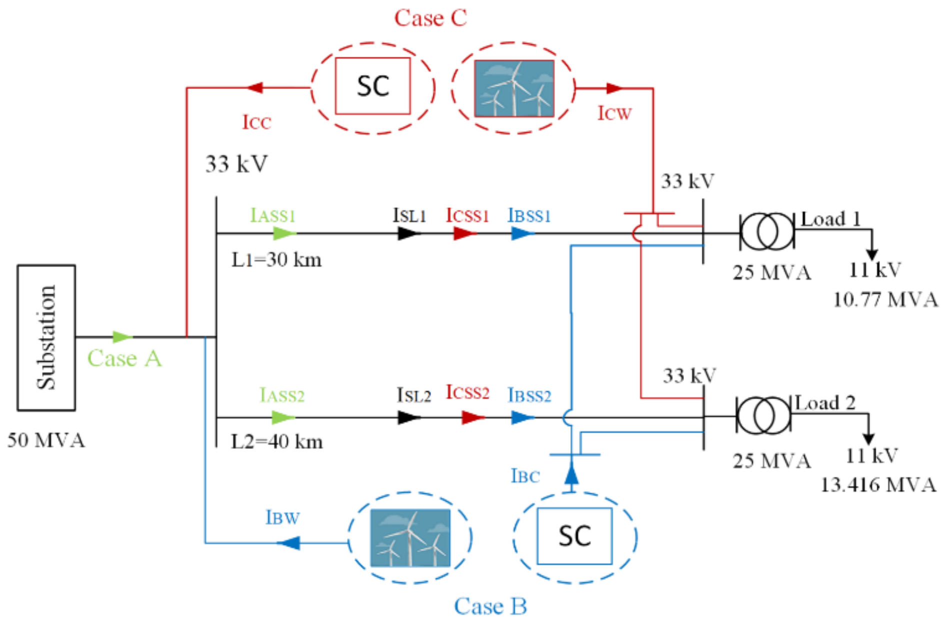

Figure 3. Scheme of the proposed wind plant integrated power system.

This section examines the efficacy of the wind power plant and the synchronous condenser. Two operative criteria were utilized: the first is the wind farm ability to generate active power and the second is the capability of the synchronous condenser to produce reactive power. The parameters of the wind plant are of the capacity P=9MW and the power factor = 0.9. And that of the synchronous condenser is S= 3.125 MVA. Fig. 3 represents the scheme of the proposed wind plant integrated system. The parameters of the Benchmark Case are applied in the methodology. Values were measured during four steps of load application, the first step is the benchmark case parameter of loads values, while steps 2 - 4 are increased in various percentage values of active, reactive and apparent power as presented in Table 5 and Table 6 for load 1 and 2 respectively. The active power, reactive power and apparent power values are measured and obtained as shown in Table 5, for load 1. The measured parameter values for load 2 are presented in Table 6.

Table 5. Calculated values of reactive, active and apparent power for various steps for load 1 as stated before in the text

Steps	Active power P_1 (MW)	Rate increase % P_1	Reactive power Q_1 (MVar)	Rate increase % Q_1	Apparent power S_1 MVA	Rate increase % S_1
1	10	0 %	4	0%	10.77	0%
2	12	20%	5	25%	13	20.71%
3	14	40%	6	50%	15.232	41.43%
4	16	60%	7	75%	17.464	62.15%

Table 6. Calculated values of reactive, active and apparent power for various steps for load 2 as stated before in the text.

Steps	Active power P_1 (MW)	Rate increase % P_1	Reactive power Q_1 (MVar)	Rate increase % Q_1	Apparent power S_1 MVA	Rate increase % S_1
1	12	0%	6	0%	13.416	0%
2	14	16.67%	7	16.67%	15.652	16.67%
3	16	33.33%	8	33.33%	17.889	33.33%
4	18	50%	9	50%	20.125	50%

7. Results and Discussion

In this section, load 1 simulations are executed at several active power levels of 0%, 20%, 40%, and 60%, while the reactive power levels are 0%, 25%, 50%, and 75% respectively, as depicted in Table 5. The apparent power levels are 0%, 20.71%, 41.43%, and 62.15% For load 2, active, reactive and apparent power, levels are of 0%, 16.67%, 33.33%, and 50%, implying that the same level of increment was used for the various steps. The percentage of sending voltage deviation from the nominal voltage of 33 kV for different steps in Case A, B and C is presented in Fig. 4. It shows that the differences between Case A, B and C are very small and unremarkable. It also depicts that the load increase in each step brought about an increase in the sending voltage deviation from the nominal voltage value of 33 kV. Equally, Fig. 5 shows that the deviation of receiving voltage in Case B and C is lower than that of Case A owing to the power injected onto the grid at the end of the 33 kV MV transmission lines. It can be noticed that deviations in Case B and C are very close to each other.

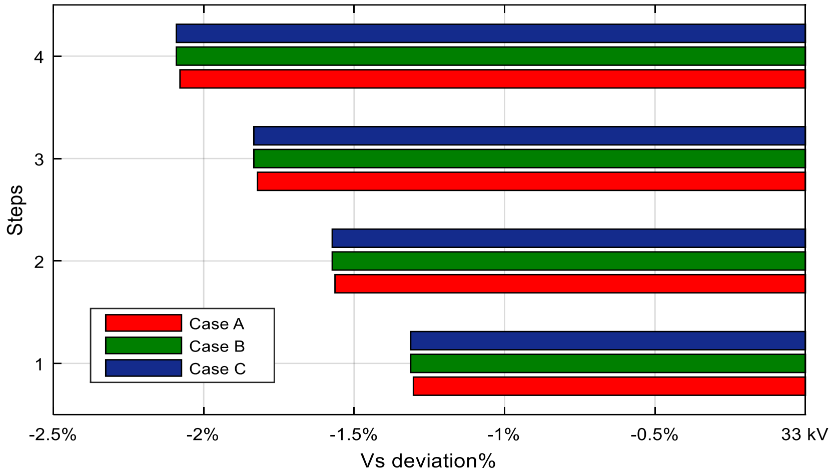

Figure 4. Percentage of sending voltage deviation from the nominal voltage of 33 kV for different steps of Case A, B and C.

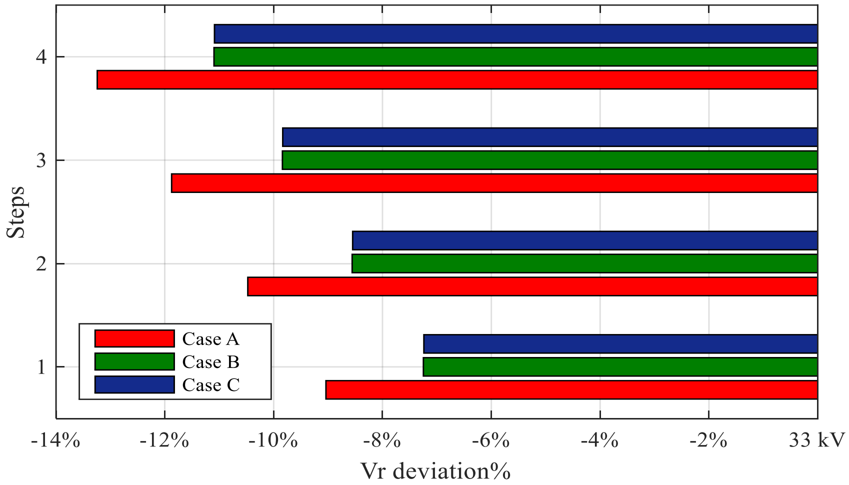

Figure 5. Percentage of receiving voltage deviation from the nominal voltage of 33 kV for different steps in Case A, B and C.

The performance of the wind plant and the synchronous condenser as regards to the percentage of allowed additional voltage drop for different steps in Case B and C, as well as for Case A is plotted in Fig. 6; it shows that the percentage of allowed additional voltage drops of the lines before the voltage drop exceeds 3.3 kV, which is 10% of the nominal voltage. Here, the maximum allowed voltage drop is 3.3kV and visibly the safety margin of Case B and C is higher than that of Case A. Meanwhile, the achievable voltage drops in steps 3 and 4 did not exceed 3.3 KV, going by 1% for step 3 and 12 % for step 4. Fig. 7 shows the power losses for the different steps in Case A, B and C. In this analysis, the power losses for Case B and C is lower than that of Case A. In addition, power losses in Case B is less than in case C, which means that using the wind power plants to inject active power at the start point of the 33 MV transmission line and the synchronous condenser to produce reactive power at the consumer end of the power line, is more effective than what is obtained by the reverse positioning.

From Fig 8, it is observed that the percentage of power losses reduction for different steps in Case B and C compared with Case A decreases for all Cases and steps, but reduction in Case B is higher. It is observable that the reduction in all steps was generally the same in each Case. The apparent power is the percentage increase in load, as the load increases the results becomes more favorable.

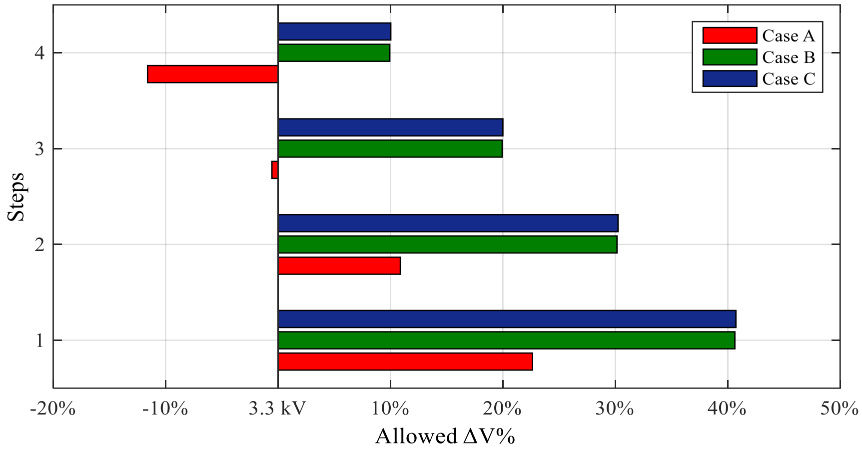

Figure 6. Percentage of allowed additional voltage drop for different steps of Case A, B and C.

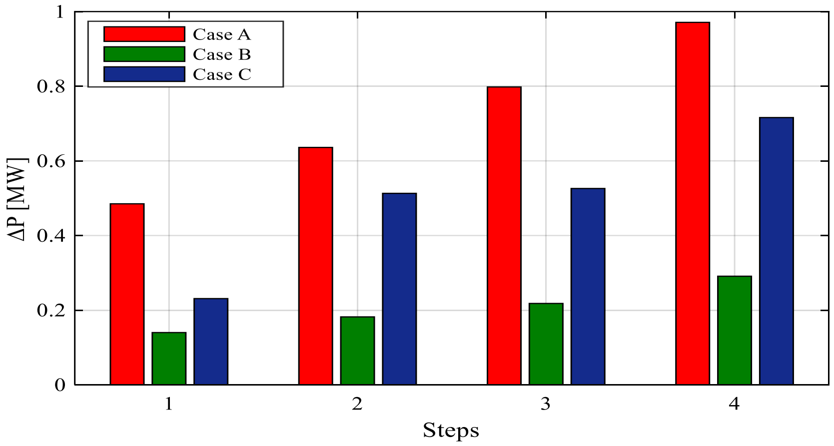

Figure 7. Power losses for different steps in Case A, B and C.

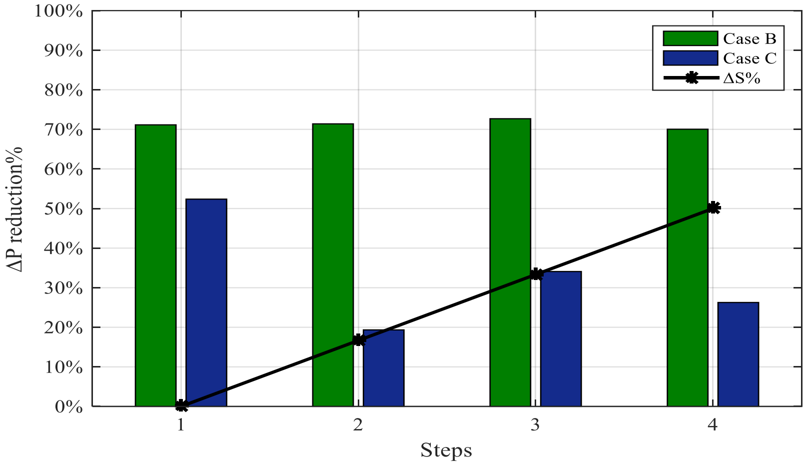

Figure 8. Percentage of power losses reduction for different steps of Case B and C compared with Case A.

The sending power factor for different steps of Case A, B and C is plotted in Fig. 9. In this analysis, the sending power factor for Case B and C is higher than that of Case A, ranging between 0.97 and 0.93 whereas the result for Case A is between 0.86 and 0.83. Note that the sending power factor for Case C is higher than that of Case B. The receiving power factor for different steps of Case A, B and C is shown in Fig. 10. The result here is like that gotten in Fig. 9, were the power factor for Case B and C is higher than that of Case A, the power factor values recorded for Case B and C range between 0.99 and 0.95, whereas the values observed for Case A are between 0.88 and 0.87. It can be seen in Fig. 10, that the sending power factor as regards to Case C is higher than that of Case B.

In power systems such as the proposed scheme, active power and a little amount of reactive power is needed. But with low power factor the reactive power is higher than usually needed. low power factor in the circumstance of Case A imply that reactive power is higher than active power. Hence, low power factor means dealing with high amount of reactive power. Therefore, low power factor drawback is the drawback of excessive reactive power. Hence, with low power factor the amount of apparent power in the network is increased, although the power [KW] is still the same. This associates some significant losses both on the transmission line and on the consumer side as is the situation for Case A, but the reverse is the situation for Case B and C were the losses on both the transmission line and the consumer side of the scheme are minimized due to the installation of the wind plant for active power regulation and synchronous condenser for reactive power generation. In addition, the voltage drop of the proposed MV transmission lines and distributors increases as power factor values decreases. In order to keep up with the voltage at the receiving end, Type-3 wind plants for active power control only and synchronous condensers for reactive power control only must be installed into the proposed scheme. The 33kV transmission line voltage is also maintained owing to the observed power factor standing for both Case B and C.

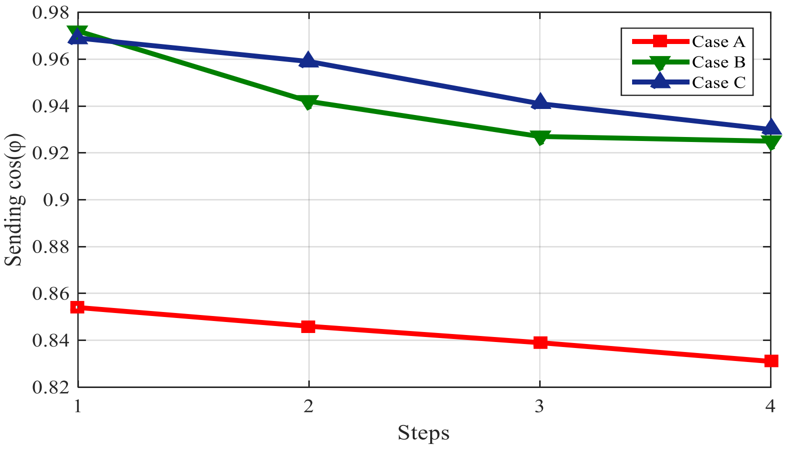

Figure 9. Sending power factor for different steps of Case A, B and C.

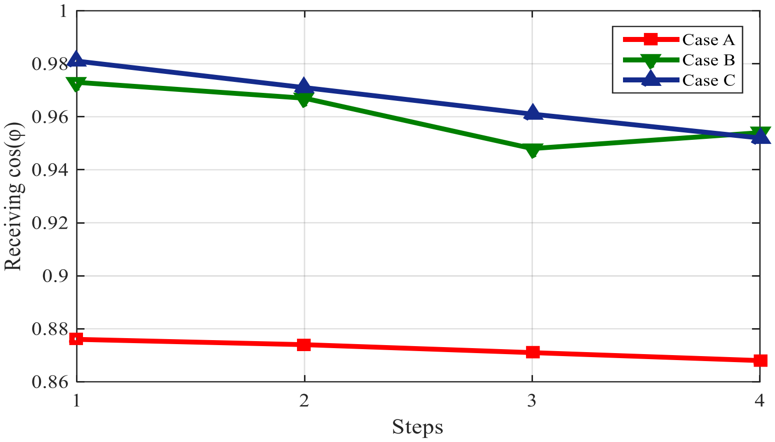

Figure 10. Receiving power factor for different steps of Case A, B and C.

In Fig. 11, the percentage of voltage drop reduction for different steps of Case B and C compared with Case A is presented. It is vividly clear that the voltage drop is reduced in Case B and C as compared with Case A and the performance of the various Case situations is the same for all steps. Additionally, it could be noticed that the percentage of reduction of voltage drop is approximately the same for all steps (that is 20%) but with corresponding small decrease as we move from step 1- 4. On the contrary for Case A, the percentage of voltage drop steadily increases as we move from step 1 – 4. A Voltage drop performance analysis is required to ensure that the end of the power lines has enough power to drive the final load. The issue of voltage drop only gets worse as more loads are connected onto the power lines. As the length of power lines increases or as the current increases, so does the voltage drop. Note that leaving some margin for future loads will ensure that electricity consumers gets reliable power system as expected. The resulting measured and modelled percentage of voltage drop and power losses reduction for different steps in Case B and C compared with Case A is graphically illustrated in Fig. 12, it shows the general comparison of Case B and C with Case A, where it is observed that the methodologies used in Case B and C are better than that used in Case A. Results for Case B and C showed the same performance of voltage drop, which is about 20%. But as regards to the power losses on the proposed scheme, Case B showed better performance than Case C. The losses reduction for Case B is about 70%, but it is 50% for Case C. Overall, the performance of Case B is seen to be the best-Case situation observed.

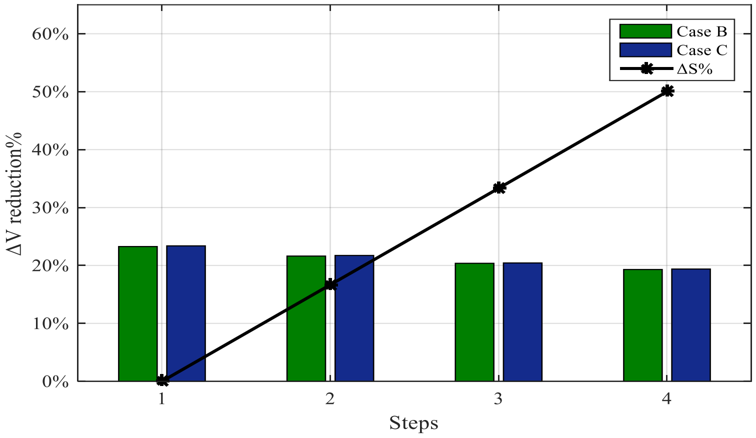

Figure 11. Percentage of voltage drop reduction for different steps of Case B and C compared with Case A.

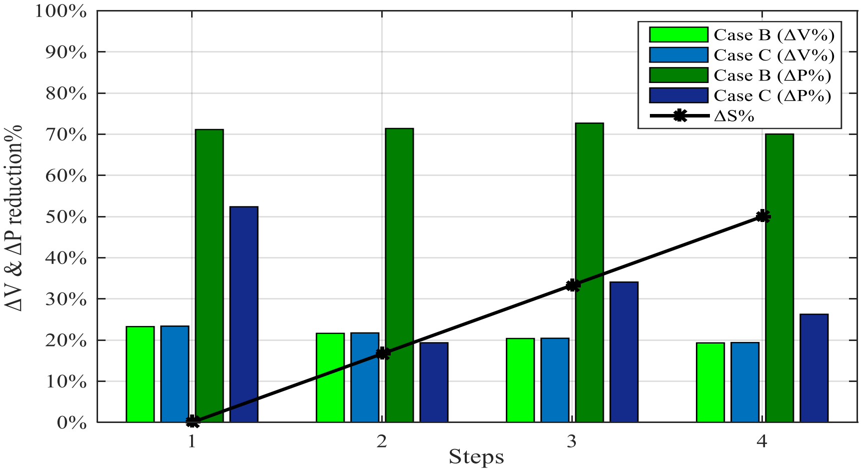

Figure 12. Percentage of voltage drop and power losses reduction for different steps in Case B and C compared with Case A.

8. Conclusions

From the analysis of a normal power system, it is observed that when additional generation sources of active and reactive power are spread along the network, the proposed scheme attained stability. Conclusively, in traditional power system, like that of Case A in the design model, the limitation of increasing load, creates issues for the regulation of voltage level and this brings about increase in the voltage drop of the MV power line, sometimes more than the allowed ratio of 10% from nominal voltage value and this increases the power losses too. All these issues cause instability, power losses and are harmful to loads. In this model, the Type-3 renewable wind power plant has been used to generate active power and the synchronous condenser to produce reactive power, by choosing different points on the proposed scheme to separately connect both the wind renewable source and the synchronous condenser. The network is kept stable and power losses are equally reduced, even when the loads are increased implying that the proposed scheme can absorb more load. Hence, it can be posited that the Type-3 wind plant and the synchronous condenser scheme is economical. It is worth mentioning that the proposed technique of this paper can be applied to different loads deployment in any power systems in order to establish stability to preserve acceptable security performances of electricity grids. This research paper establishes an effective application of the synchronous condenser technology for the deployment of reactive power and the wind power plant for the deployment of active power in a modern electricity scheme. This methodology could effectively simulate the effect of anticipated synchronous condenser on a power grid with participating wind plants, thereby generating useful information for managers, engineers and researchers in the electricity industry. This information can improve modern electricity growth plans and can be used to formulate new electricity development strategies and action plans. It is important for electricity managers to develop management strategies and development plans, which allow electricity resources to be utilized more effectively in a sustainable manner. It aids to improve power system security by providing adequate active and reactive power for stability of the electricity grid and minimization of power system losses. Therefore, the proposed methodology is likely to bring significant technical and financial benefits to power system operators.

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Paper Three

Reputation of the Synchronous Condenser Technology in Modern Power Grid

Famous O. Igbinovia, Ghaeth Fandi, Zdenek Müller, Josef Tlusty

Contributor	Statement of Contribution
Famous O. Igbinovia (Candidate)	Simulation and modelling (25%); Result interpretation and discussion (25%); Paper writing and review (25%).
Ghaeth Fandi	Simulation and modelling (25%); Result interpretation and discussion (25%); Paper writing and review (25%).
Zdenek Müller	Simulation and modelling (25%); Result interpretation and discussion (25%); Paper writing and review (25%).
Josef Tlusty	Simulation and modelling (25%); Result interpretation and discussion (25%); Paper writing and review (25%).

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Abstract: The synchronous condenser nowadays contributes an essential share of resources for generating reactive power to ensure voltage stability in modern power systems. Such resource has to be taken care of by owners of electricity infrastructures. In any case, real projects, experiments and simulation results have shown need to use the synchronous condenser for enhancing power quality of the grid. Hence, traditional generators are being retrofitted to synchronous condensers in order for them to serve a better purpose of voltage stabilization after they are retired and new synchronous condensers are installed by electricity utility managers to serve same purpose too. This paper presents the synchronous condenser technology. It discusses the experience and lessons learnt from the use of the synchronous condenser in real projects. It also provides an outlook on the development of the use of the technology in modern power grid using two simulation study scenarios. These developments include Scenario One: utilizing only the synchronous condenser for voltage regulation on a power grid. And Scenario Two: Installing the synchronous condensers with Type-3 wind farm for voltage support on an electricity network, such contextualization is towards voltage stability in modern power grids.

Index Terms: Electricity network, modern power grid, renewable energy resource, synchronous condenser, wind power

1. Introduction

Many electricity utility authorities now face the issue of rising electricity prices, growing demand for electricity, compliance with international greenhouse gas commitments and lack of grid resilience, reliability, and availability. A possible solution could be the synchronous condenser (SC) technology, a rebirth technology that is becoming very significant again as one of the most effective means to maintain grid quality, fault ride-through and fault support, which is essential to maintain electricity supply. Synchronous condensers help to increase the transmission capacity of individual transmission lines, intersystem or interstate long-distance transmission lines. They are responsible for correction of electrical power flow along circuits with different voltage values in multi-contour electrical grids to obtain positive technical or commercial effects [1] – [5]. Synchronous condensers can provide strong dynamic reactive power demand for electricity transmission systems, and its operation characteristics are related to excitation parameters. The force excitation voltage ratio and low excitation voltage ratio of the synchronous condenser can affect dynamic reactive response and power grid voltage. The dynamic characteristic of reactive power is mainly related to the parameters of synchronous condensers. [6] – [8].

The voltage supporting ability of large capacity synchronous condenser has been payed more attention to by electrical engineers. The accuracy and the precision of the synchronous condenser electrical parameter is directly related to the stability of power system and the estimate of the synchronous condenser's dynamic voltage supporting ability [9] - [11]. Power systems which transmits large active power does not provide reactive power for Alternating Current (AC) electricity systems, so the dynamic reactive reserve and the voltage stability decline significantly as the power system feeds back to the AC system [7], [12], [13], [14]. The inherent reactive power output characteristic of the synchronous condenser coincides with the dynamic reactive power demand of the power grid during fault situation. When the system has serious voltage drop in fault situation, the synchronous condenser will enter the strong excitation state, providing considerable supply of reactive power to the system in a short time, thereby improving the system voltage, helping to quickly restore the power and system voltage, and on the long run preventing voltage collapse [7], [15].

Electricity utility authorities around the world are considering the utilization of synchronous condensers as part of their overall power transmission solution. More interesting reason is its practical applications in power networks with high penetrations of renewable power sources. Such electricity systems magnify the benefits provided by the synchronous condenser. The increasing penetration of renewable power sources such as solar and wind power generators in today’s energy mix is unfortunately reducing the resilience and stability of electricity networks. This is owing to the fact that these renewable energy resources are inherently intermittent and variable. Moreover, they lack the ability to support or tolerate the faults that do happen on electricity networks. SCs can play a significant role in compensating these shortcomings and soon, it is expected that they will help to alleviate many power systems challenges and enhance the reliability of electric-power systems. The synchronous condenser has also been utilized in this present time by electrically placing it near HVDC installations in order to increase power network short circuit MVA, the technology has been used to support and provide auxiliary services to the electricity grid for almost as long as power systems have been in existence [1], [15] – [16]. New challenges of the modern power grids can be solved by new built synchronous condensers or conversion of existing/retired power plants to synchronous condenser units, this new business model in the electricity industry ensures profitable growth by generation of reactive power [17]. Fig. 1. shows a synchronous generator working as a synchronous condenser, it can be of the range value between 5 - 1.500 MVAr (+/-).

The rest of the paper is organized as follows: in Section II, the synchronous condenser technology is presented. Section III, gave practical usage of the synchronous condenser technology in modern grid. In Section IV, two simulation scenarios were presented. The first scenario has a power system with only the synchronous condenser employed for reactive power production, While the second scenario has a synchronous condenser installed network with implanted wind farm, these models helps in improving the power system voltage stability. Finally, Section V concludes the paper.

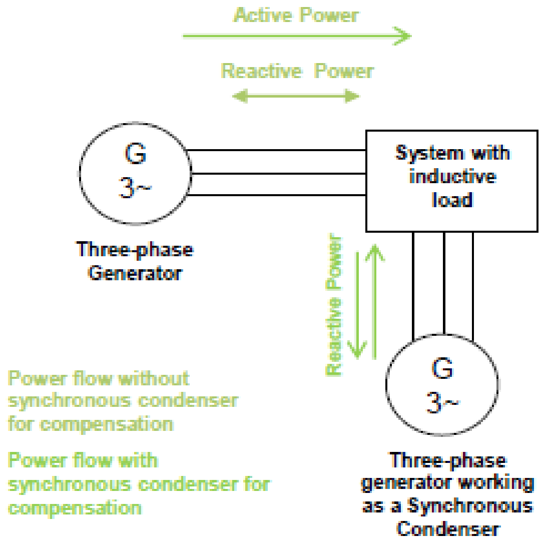

Fig. 1. Synchronous generator working as synchronous condenser 5….1.500 MVAr (+/-) [17].

2. The Synchronous Condenser Technology

Synchronous condensers were used at the dawn of electricity grids as the primary plant to regulate voltage, and hundreds of them were built and installed on the electricity network. Thereafter, new power electronics technology emerged such that Static VAr Compensators (SVCs) and STATCOMs, with their lower costs, replaced synchronous condensers in electricity networks. Despite that, today synchronous condensers offer more significant benefits to the electricity grid. Hence their more recent renaissance [18] - [19]. Synchronous condensers were once widely applied as a means of providing reactive power compensation in power grid prior to the introduction of power electronic-based devices. The application of synchronous condensers on the power system is well understood, it is fundamentally a rotating VAR generator. A synchronous motor or generator can be applied as a synchronous condenser where the field voltage is regulated in order to generate or absorb reactive power. Advantages of using the synchronous condenser include being a long standing, well known and understood technology. It is a very robust solution, it can have a high overload capability, and can provide good reactive power support under low voltage conditions. Synchronous condensers are a source of short circuit availability which can be a major advantage in weak power systems and they are not sources of harmonics. Disadvantages of the synchronous condenser technology can include higher level of losses, mechanical wear, and a slower response time than with power electronic technologies [20] - [22].

Many transmission entities around the world are considering the use of new synchronous condensers or power plants retrofitted as synchronous condensers to be part of their overall transmission solution. Synchronous condensers can provide many benefits to a power system. They have useful characteristics with regard to voltage support, especially when considering use of their short-term overload capability. They can provide rotating inertia to a power system and can also increase system short circuit strength. These traits can be helpful as systems adapt to higher penetrations of renewable power sources, such as wind or solar. Power system challenges and the effectiveness of synchronous condenser solution can be more pronounced in smaller grids such as island power systems. Synchronous condensers can not only help with system inertia and short circuit strength, but also support the use of existing and even possible future DC links. Although they have existed for many years and were once considered obsolete, the value and usefulness of the synchronous condenser is again resurfacing [15].

Conventional synchronous condensers are often overlooked as solutions for voltage regulation and stability problems primarily since such units have high operating losses and large maintenance requirements. An alternative to the conventional synchronous condenser is the High Temperature Superconductor Dynamic Synchronous Condenser (HTS DSC) which is a synchronous condenser featuring as a rotor wound with HTS wire; allowing the device to overcome these deficiencies of conventional SCs. The HTS DSC machine also is capable of running with a very high field current (up to 2.0 p.u.) for a period of time on the order of tens of seconds. This allows the machine to deliver up to 3.0 times rated output during a transient low voltage event. One possible solution to wind farm integration challenges (such as: Ability of the wind farm to regulate voltage with a defined amount of leading and lagging reactive capability; Ability of the individual turbines within the wind farm to survive, or ride through, transient low voltage events such as system faults; Ensuring that the installation of the wind farm does not result in a reduction in system stability or post-fault voltage performance such that utility performance standards are compromised; And ensuring that the installation of the wind farm does not result in a violation of utility flicker standards) is the HTS Dynamic Synchronous Condenser. The SuperVAR machine concept shown in Fig. 2, is a dynamic synchronous condenser (DSC) with rotor windings comprised of high temperature superconductor wire. Like a conventional synchronous condenser, the HTS DSC machine adds system inertia and is a reactive power support device that injects or absorbs reactive power in order to hold voltages stable at the point where the device is connected to the power system. However, unlike a conventional synchronous condenser, the HTS DSC machine has very low real power losses and requires very little maintenance [23]. While conventional synchronous condensers have been widely used in the power grid, their relatively low efficiency has limited their potential applications, and their useful lifetime has been limited by field winding insulation degradation caused by field current heating during cyclic operation [24]. The field current of a conventional machine must be increased by three times between no-load and full-load and this causes significant field winding heating leading to premature failure [23].

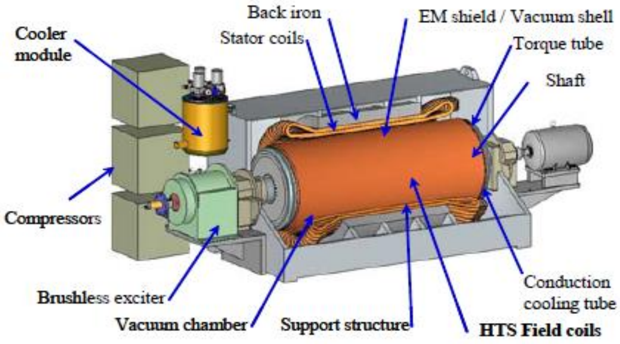

Fig. 2. The HTS Dynamic Synchronous Condenser Concept [24].

3. Practical Usage of the Synchronous Condenser Technology in Modern Power Grid

This section aims to establish the practical applications of the synchronous condensers in modern power grids. Here, five projects utilizing the synchronous condenser technology is analyzed. These include: the next-generation synchronous condenser installation at the VELCO granite substation; innovative reuse of the Ensted deactivated power plant; conversion of two retired units at Huntington Beach station to synchronous condensers; turnkey delivery of synchronous condenser solutions for the Bjæverskov, Fraugde and Herslev substations; and the Georgia Black Sea HVDC station.

A. *Granite Substation*

Vermont Electric Power Company, USA commissioned a Synchronous Condenser based reactive power device in the Granite substation as part of its Northwest Vermont Reliability Project. The reactive power device consisted of four +25/-12.5 MVAr synchronous condensers and four 25MVAr shunt capacitor banks. This synchronous condenser based reactive power device was chosen over Static Var Compensators and STATCOM owing to its merits over these devices. As for the Granite Substation, the synchronous condenser afforded the smallest base nameplate rating and still met the overload and low voltage requirements. Though maintenance is required, it is considered by VELCO to be on par with static device alternatives. The synchronous condenser technology was best suited to handle the local harmonic concerns and appears advantageous from a long-term life of product support standpoint. A picture of the condenser hall at Granite Substation is shown in Fig. 3. The units were commissioned in November of 2008 [20].

Fig. 3. Granite Substation Condenser Hall [20].

B. *Ensted power plant*

Converting power plants to synchronous condensers has enabled the innovative reuse of the Ensted deactivated power plant in order to ensure electricity grid stability in Denmark. The plant which was commissioned in 1979, is a former steam power plant located at the head of Aabenraa Fjord in the south of Denmark. Its Unit 3, formerly fired by coal and oil, had been Denmark's largest combined heat and power unit. Ensted was equipped with a total electrical capacity of 626 MW and a heat capacity of 76 MJ/s. The operator had mothballed the power production by 1 January 2013 due to expected lower electricity consumption and a rising share of energy production from renewable energy sources, mainly wind power plants. The Ensted power plant now contributes to the stability of the national Danish electricity grid when required. The rebuilding of the Ensted plant was associated with low investments and low risks: Components from the original manufacturer, the reuse of equipment and the smooth integration of the solution were conducted with minimal effort. The project was completed within the very narrow, challenging time frame of five months [25]. It started operation in 2012, with Generator rating of: 1500 MVA, 27 kV, 1500 rpm, and Reactive Power ability of between: -450 … +850 MVAr [17]. The outcome of this project is the innovative reuse of a deactivated power plant; improved grid stability due to the generation of reactive power and short circuit power through conversion of the generator into a synchronous condenser; As well as Low investment and operational costs [25].

C. *Huntington Beach station*

The units 3 and 4 steam turbine generators at the Huntington Beach Generating Station, in California, USA, has been converted to synchronous condensers [26]. Faced with a critical shortfall in voltage support after the loss of the San Onofre nuclear plant, the California Independent System Operator converted two retired units at its Huntington Beach station to synchronous condensers. The experience offers lessons for other electricity utility authorities looking to deal with impending plant retirements and changing grids. Two retired generators at the Huntington Beach plant were converted to synchronous condensers to provide voltage support to the Southern California grid after the unexpected retirement of the San Onofre Nuclear Generating Station. The conversion from generators to synchronous condensers has the plant not only stabilizing the grid and keeping the lights on in times of high demand, but also keeping the air just a little bit cleaner in the process [27].

The four natural gas fired steam units that make up the Huntington Beach Generating Station are located in Huntington Beach, California and owned by AES Southland Holdings, LLC. Units 3 and 4 had been retired since 1995. The operating units are of great regional significance as they generate enough power to light nearly a half-million Californian homes and businesses. The power supply of 400,000 homes in Southern California was challenged by the decommissioning of the San Onofre nuclear power plant in Southern California. To maintain grid reliability, it was decided that bringing unit 3 and 4 of Huntington Beach out of retirement to serve as synchronous condensers would be a good option. To do so, however, the application needed not only to comply with California’s strict environmental regulations, but also meet a short time schedule [26], [28]. The effect of this work is improved grid reliability due to the conversion of the two generators to synchronous condensers. No emissions thanks to synchronous condensers which use no fuel. Hence, further innovative use of shut down units [28].

D. *Bjæverskov, Fraugde and Herslev substations*

The Danish transmission system operator placed three orders for turnkey delivery of synchronous condenser solutions for the Bjæverskov, Fraugde and Herslev substations. At the end of February 2015, the synchronous condenser solutions of Fraugde and Herslev were handed over to the client’s full satisfaction. In May 2015 Bjæverskov substation had been successfully completed and was passed over to the Danish Transmission System Operator. The solutions help stabilize the transmission system. The scope of delivery for the synchronous condenser solutions included a synchronous generator with brushless excitation, a generator step-up transformer and the electrical auxiliary systems, such as control and safety systems, voltage regulators and startup systems. They feature high efficiency, low noise emissions and low installation and commissioning costs [29].

Each synchronous condenser solution can deliver more than 900 MVA of short-circuit power and +215/-150 MVAr of reactive power. The startup time is designed so that the generators can reach up to 3,000 rpm within 10 minutes and be synchronized with the transmission grid. Since the synchronous condensers are designed for continuous operation and the provision of short-circuit currents when voltage dips occur in the grid, they have a minimum availability of 98 percent. These are important projects for the transmission system operator in Denmark for stabilizing the transmission network, Denmark is one of the few countries to include a large share of wind energy in its energy mix, which is why the country need synchronous condenser solutions to help stabilize her electricity transmission system and to support higher wind power generation in the country

[29].

Bjæverskov substation 250 MVAr synchronous condenser solution started operation in 2013, providing the transmission system with a short-circuit power of more than 800 MVA in addition to reactive power control. The installation of this stand-alone synchronous condenser solution enabled the transmission system operator in Denmark to operate the transmission network without the need for a large thermal power plant. This makes the installation an economically and environmentally advantageous investment enabling the infeed of large amounts of renewable energy into the transmission network. Fraugde and Herslev substations synchronous condenser solution is capable of delivering more than 900 MVA of short-circuit power and +150/-75 MVAr of reactive power. The projects are running in trial operation as of August 2014 [30].

E. Georgia Black Sea HVDC station

The Black Sea Transmission Network Project (BSTN) was started in 2009, to create an asynchronous interconnection between the 500 kV network of Georgia and the 400 kV network of Turkey [30]. Three 60 MVAr synchronous condensers were installed at the Georgia Black Sea HVDC station in June 2012. This synchronous condenser solution supports the transmission network between Georgia and Turkey with the required short-circuit power in order to operate the newly installed HVDC back-to-back station [31]. The Project was successfully completed in 2013, providing 700MW capacity interconnection between the Georgian and Turkish electricity grids through rehabilitation/construction of 500kV Gardabani-Akhaltsikhe-Zestaponi overhead line and construction of 400kV interconnection line from Akhaltsikhe to Turkish border, as well as the construction of a new 500/400/220kV substation with HVDC back to back plant in Akhaltsikhe. Through this transmission infrastructure Georgia having abundance of renewable power sources, such as hydro and wind is able to export or wheel eco-friendly electricity to the emerging, demanding markets of Turkey as well as of other countries of eastern or central Europe and Asia [30], [32], [33].

4. Simulation Studies

Two simulation studies were conducted. First simulation study is a synchronous condenser installed on a 33kV power line connected to a 132KVA substation as shown in Fig 5. And the second simulation study is a power network installed with synchronous condenser and embedded with wind farm on a 33kV line, connected to a 50KVA substation as presented in Fig. 7. MATLAB/Simulink software package is used to accomplish both simulation task. both methodologies is to achieve voltage stability in the networks.

A. First Simulation Study: 33kV Medium Voltage Model with Synchronous Condenser Connected

For this simulation study, a three phase 33 kV power line was used for the simulation study. And a 33 kV 50 Hz load is joined to the three-phase 33 kV electricity power line, a synchronous condenser is placed at the terminating end of the three-phase power system. The performance of the complete system was monitored in real time with the implementation in MATLAB/Simulink software. The dynamic response of the synchronous condenser on the system shows that the voltage drop before installing the synchronous condenser on the network is positive (the value is between 0.3 kV and 0.56 kV), whereas the voltage drop after installation of the synchronous condenser on the network is negative, which imply that power flow is in the opposite direction.

Fig. 4, Shows the schematic diagram of the proposed 33 kV MV electric-power system network without the installation of the synchronous condenser equipment. Fig. 5, depicts the synchronous condenser equipment installed at the terminal end of the 33 kV MV power system network. While Fig. 6, represents the graphical illustration of the voltage difference between the sending voltage (U_s) and the receiving voltage (U_r), that is (U_s-U_r) on the 33kV electric-power system network without and with the synchronous condenser connected at the terminal end of the network under study. The voltage at the sending and receiving ends of the network is measured in three steps increment of the inductive load (4, 7 AND 10 MVars, for step 1, 2 and 3. The reactive power and active power ratings are constant, having values of 0.5MVar and 30 MVA respectively. Results obtained shows that the synchronous condenser can supply reactive power for stabilizing voltage on the grid line.

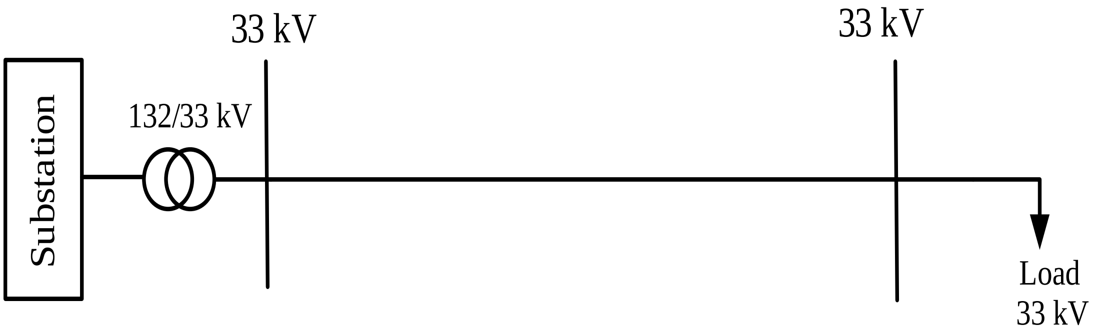

Fig. 4. Schematic diagram of the proposed 33 kV MV electric-power system network without installation of the synchronous condenser equipment.

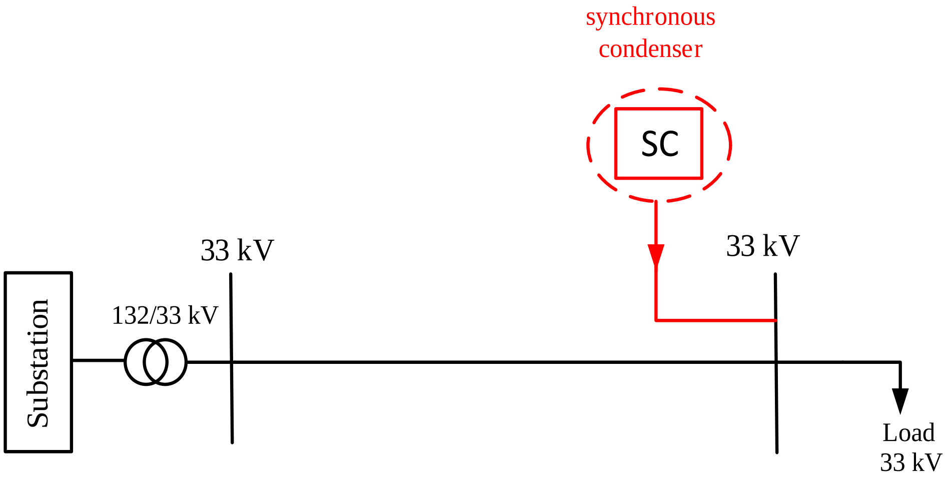

Fig. 5. Schematic diagram of the synchronous condenser equipment installed at the terminal end of the 33 kV MV power system network.

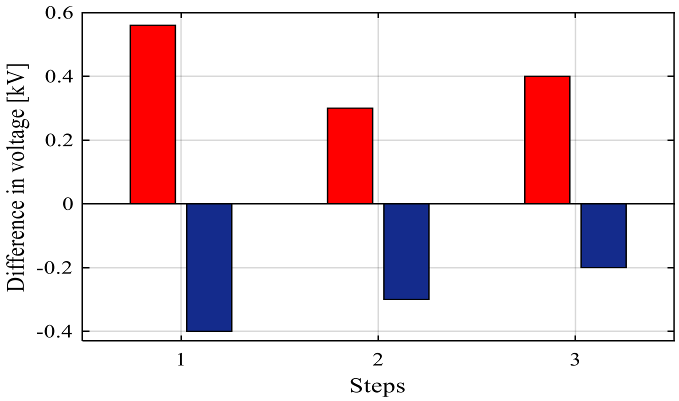

Fig. 6. voltage difference (Us-Ur) values of the 33kV electric-power system network without and with the synchronous condenser connected at the terminal end of the network.

B. Second Simulation Study: 33kV Medium Voltage Model with Synchronous Condenser and Wind Farm Connected

For the other simulation study, a 33kV power line is connected to a 50 MVA substation. For this scenario three cases were examined. That is Case A, B, and C, with the location of the SC and wind farm altered in each Case. Case A; This is the point of reference case. Case B; is a wind farm connected to the power network at the busbar of the main substation and the synchronous condenser is installed at the consumer load ends of the network. the wind farm is modelled as a Type-3 wind generator for producing active power only and the synchronous condenser is modelled for reactive power generation, Case C; this is the state when the wind farm is joined to the power network at the busbar close to the consumer loads and the synchronous condenser is placed at the main substation bus, the synchronous condenser is placed at the substation for producing reactive power only and the Type-3 wind generator is placed at the consumer transformer load ends for producing active power only. Four steps values were monitored. The first step is the point of reference case value parameter of loads, while steps 2 - 4 are increased in 20% for each step levels of active, reactive and apparent power, for load 1 and 2 respectively. The schematic diagram of the second simulation model with its point of reference (Case A), Case B, and Case C is presented in Fig. 7.

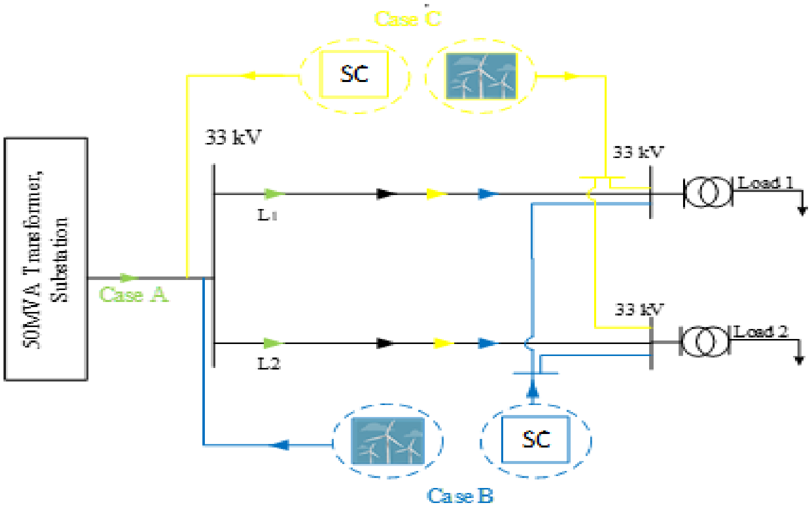

Fig. 7. Schematic diagram of the simulation model with the synchronous condenser and wind farm connected, showing its point of reference (Case A), Case B, and Case C.

The behavior of the second simulation study monitored in real time with the help of MATLAB/Simulink software shown in Fig. 8, reveals that the differences between Case A, B and C is not that remarkable. That is the load increase in each step brought about an increase in the sending voltage deviation from the nominal voltage value of 33 kV. While, Fig. 9, shows that the deviation in receiving voltage in Case B and C is lower than that of Case A as a result of the power injected onto the grid at the end of the transmission lines. It can be seen that deviation in Case B and C are very close.

Fig. 10, is a graphical representation of the percentage of voltage drop reduction for different steps of Case B and C compared with Case A. It is clear that the voltage drop is reduced in Case B and C as compared with Case A and the performance of the various Case situations is the same for all steps. Furthermore, the percentage of reduction of voltage drop is approximately the same for all steps (that is 20%) but with corresponding small decrease as it is monitored from step 1- 4. But considering Case A, the percentage of voltage drop steadily increases as it is observed from step 1 – 4. Table 1, 2, and 3 tabulates the measured voltage values for Case A, B and C respectively. Hence, the results imply that the synchronous condenser have been used to supply reactive power to stabilize the network voltage.

Table 1. Measured values of voltage for Case A

Step	Line	U_s (kV)	U_r (kV)	ΔV (kV)
1	1	32.57	31.077	1.493
	2	32.57	30.017	2.553
2	1	32.484	30.679	1.805
	2	32.484	29.543	2.941
3	1	32.399	30.287	2.112
	2	32.399	29.081	3.318
4	1	32.314	29.903	2.411
	2	32.314	28.63	3.683

Table 2. Measured values of voltage for Case B

Step	Line	U_s (kV)	U_r (kV)	ΔV (kV)
1	1	32.567	30.608	1.959
	2	32.567	30.608	1.959
2	1	32.481	30.176	2.305
	2	32.481	30.176	2.305
3	1	32.395	29.753	2.642
	2	32.395	29.753	2.642
4	1	32.31	29.338	2.972
	2	32.31	29.338	2.972

Table 3. Measured values of voltage for Case C

Step	Line	U_s (kV)	U_r (kV)	ΔV (kV)
1	1	32.567	30.611	1.956
	2	32.567	30.611	1.956
2	1	32.481	30.179	2.302
	2	32.481	30.179	2.302
3	1	32.395	29.755	2.64
	2	32.395	29.755	2.64
4	1	32.31	29.341	2.969
	2	32.31	29.341	2.969

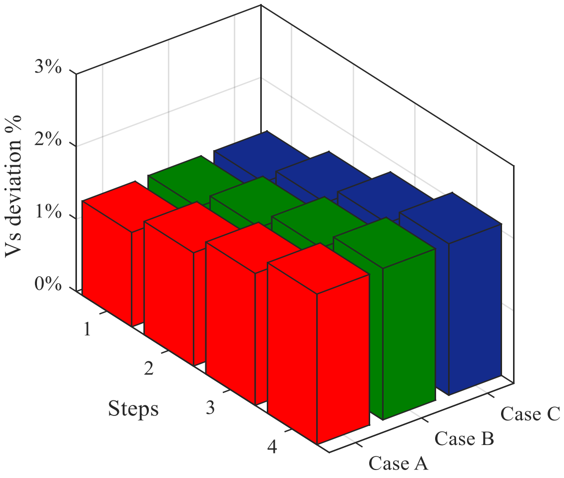

Fig. 8. Percentage of sending voltage deviation from nominal voltage 33 kV for different steps in Case A, B and C.

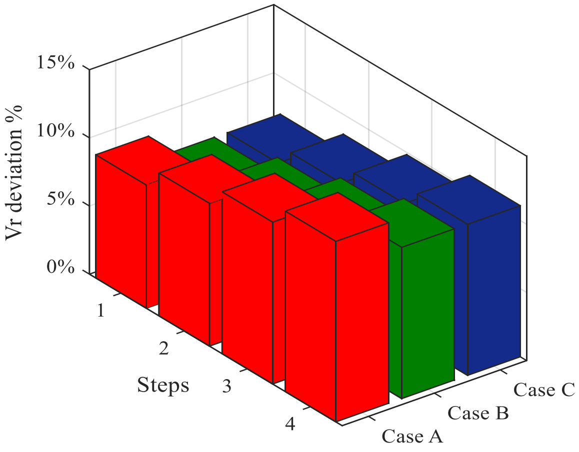

Fig. 9. Percentage of receiving voltage deviation from nominal voltage 33 kV for different steps in Case A, B and C.

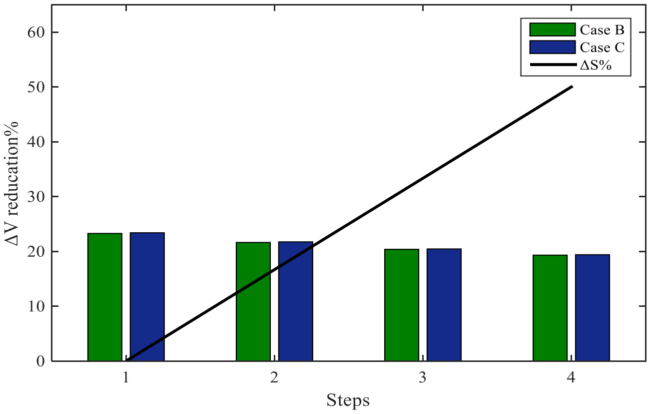

Fig. 10. Percentage of voltage drop reduction for different steps in Case B and C compared with Case A.

5. Conclusion

The synchronous condenser technology has proven to be a solid and efficient way to provide reactive power. The technology has successfully demonstrated its potential in addressing a variety of issues facing the modern grid. It allowed the retrofitting of old synchronous generators to synchronous condensers and it is one of the enabling technologies used in modern power projects. This study has been carried out based on the synchronous condenser technology application for wind energy systems. The performance of the synchronous condenser technology with the proposed systems is demonstrated for voltage stability by connecting actual loads to the system without and with the SC. And thereafter with a wind farm. The two simulation scenarios studied emphasis the fact that the synchronous condenser is able to supply reactive power for stabilizing voltage in modern electricity grid network. Further research will be to calculate power losses on the proposed electricity networks.

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Paper Four

Progressive Usage of the Synchronous Machine in Electrical Power Systems

Famous O. Igbinovia, Ghaeth Fandi, Zdenek Muller, Josef Tlusty

Contributor	Statement of Contribution
Famous O. Igbinovia (Candidate)	Simulation and modelling (25%); Result interpretation and discussion (25%); Paper writing and review (25%).
Ghaeth Fandi	Simulation and modelling (25%); Result interpretation and discussion (25%); Paper writing and review (25%).
Zdenek Muller	Simulation and modelling (25%); Result interpretation and discussion (25%); Paper writing and review (25%).
Josef Tlusty	Simulation and modelling (25%); Result interpretation and discussion (25%); Paper writing and review (25%).

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Abstract: In traditional electric-power systems, synchronous generator based center electric-power plants have been the main origin of dynamic reactive power sustenance, but owing to the steady growth in the number of renewable power generating plants across the globe and the concurrent dismantling of these rotating synchronous machines principally driven by the demand to decrease carbon emission and reliance on fossil fuels, the need for grid-stabilizing systems is increasing. Also, traditional electric-power generating units are approaching the end of their useful operational life and utility authorities are faced with a difficult resolution of retiring electric-power plants. One way of resolving these issues is the refurbishment of these machines, that is the electric-power plants to synchronous condensers. This paper presents a brief assessment of the synchronous machine and the motivation for this research work. It discusses the importance of the synchronous machine in electrical power systems, and the progressive trend in the use of the synchronous machine in electric-power networks. It stresses the need for the use of the synchronous machine for reactive power compensation purposes, with a vivid description given with MATLAB/Simulink simulation model. When the synchronous condenser is connected to the power system model at the terminating end of the network and switched ON, the medium voltage (MV) electrical power network simulation model effectively allows the control of reactive power, which improves voltage stability and power flow control of the proposed network.

Keywords: synchronous machine; refurbished synchronous machine; synchronous motor; synchronous generator; synchronous condenser; reactive power compensator; electrical power systems.

1. Introduction

A machine is a device using mechanical power and having various parts, each with a well-defined purpose and jointly performing a specific task. In usual term, it is a semi or fully automated piece of equipment that magnifies human physical and/or mental ability in carrying-out one or more task. And, from systems frame of reference, it is a purposefully efficient set of components whose interconnections and inner mechanism are clearly understood. The behavior of a correctly functioning machine is absolutely predictable: its current state controls its next state, and the same inputs every time produces the same outputs. [1], [2], [3], [4], [5], [6], [7], and [8]. Synchronous means happening at the same time; contemporaneous; coinciding in time; simultaneous, happening, existing, or arising at exactly the same time, recurring or operating at exactly the same periods, requiring or designating synchronism, having the same period; also, having the same period and phase [9] and [10].

Synchronous machines are rotating electrical machines with Direct Current (DC) field winding on the rotor, and Alternating Current (AC) armature winding on the stator; it works as a generator when it changes mechanical energy to electrical energy. Also, it can function as motor when it changes electrical energy to mechanical energy [11] and [12]. It supplies vital part of the energy in an electrical power system, and usually comprises of a few kVA to a few hundred MVA, the largest are normally rated 1500 MVA. This machine plays significant part in electric power systems, in that they impose the frequency of sinusoidal voltages and currents, they supply energy buffer, through the kinetic energy deposited in their rotating masses. And they can supply or absorb reactive power, which is needed to control voltage in electrical networks [13]. A synchronous machine is an AC rotating machine whose speed under steady state situation is proportional to the frequency of the current in its armature. The magnetic field generated by the armature currents rotates at the same speed as that generated by the field current on the rotor, which is rotating at synchronous speed, and a steady torque result is produced. Synchronous machines are often utilized as generators mainly for sizeable power systems, such as turbine and hydroelectric generators in electrical grid power supply. Because the rotor speed is proportional to the frequency of excitation, synchronous motors can be utilized in circumstances where constant speed drive is essential. Since the reactive power produced by a synchronous machine can be modified by controlling or regulating the magnitude of the rotor field current, unloaded synchronous machines are as well frequently inserted in power systems exclusively for power factor rectification or for regulation of reactive kVA flow. Such machines, known as synchronous condensers, can be made cheaper with the production of bigger dimensions of the device [14], [15], and [16].

This research paper emphasizes the need for the refurbishment of the synchronous machine to synchronous condenser for reactive power control purposes, a clear illustration is established with the MATLAB/Simulink simulation of a 33 kV MV electrical power network supply. Simulation results obtained with the Synchronous condenser installed onto the network, shows that, the synchronous condenser when switched ON effectively allows the regulation of reactive power which improves voltage stability and power flow control of the proposed electrical network model.

2. Motivation for this Research Work

Nowadays, renewable energy generating plants are being added promptly to power system networks worldwide, this is principally motivated by the need to minimize carbon emission and over-reliance on fossil fuels. Many countries have set goal to realize its electricity generation from renewable power sources. This has led to the continual displacement of traditional electric-power plants by renewable power generating plants as hitherto being accomplished in some countries, center Conventional Power Plants (CPPs) are even then being taken out of the electric-power grid network with the desired result of least or non CPPs attached to the grid in the near future [17], [18], [19], [20], and [21].

Traditional electric-power plants are being replaced by renewable power generating plants, nevertheless as an alternative to dismantling these traditional power plants, the refurbishment of these machines to synchronous condenser by de-clutching their turbine shaft from the rotor shaft can be one of the practical solution to the much-needed problem of dynamic reactive power provision in large-scale renewable power integrated electric-power systems. Also, every power plant will one day get to the end of their useful operational life and utility authorities are confronted with a difficult resolution of retiring the plants, the option is still to refurbish these existing electric-power plants to synchronous condensers. Refurbishment of conventional power plants in existence or operation at this current time to synchronous condensers can be one of the straightforward method to realize a cost-effective approach to tackle dynamic voltage control issues in electric-power systems. This methodology can reduce or even keep away utility authorities from installing new infrastructure that or else would be required to continue dependable and steady functioning of large-scale renewable integrated electric-power systems. Nonetheless, in addition to the dynamic reactive power provision gotten from the equipment, refurbished Synchronous Condensers (SCs) can as well provide more services such as short term overloading, inertia etc. It is of benefit to know that the operating and maintenance cost estimate of synchronous condensers is on the high side as compared to its Flexible Alternating Current Transmission Systems (FACTS) technology counterparts [20], and [21].

3. Importance of the Synchronous Machine in Electrical Power Systems

The synchronous machine is a significant electro-mechanical energy converter. Synchronous generators normally function together or in parallel, to form a big power system providing electrical energy to consumers. For these applications, synchronous machines are built in big units, their rating spanning tens to hundreds of megawatts. For high-speed machines, the prime movers are normally steam turbines utilizing fossil or nuclear energy resources. Low-speed machines are frequently driven by hydro-turbines that use water power for generation. Smaller synchronous machines are occasionally employed for private generation and as standby units, with diesel engines or gas turbines as prime movers. In a big generator, the rotor is magnetized by a coil wrapped around it. Figure 1, shows a two-pole rotor, it will be of note that salient-pole rotors usually have more than two poles. When intended for use as a generator, big salient-pole machines are driven by water turbines. Figure 2, displays the three-phase voltage gotten at the terminating ends of the generator and the equation given portrays the speed of the machine, its number of poles, and the frequency of the voltage outcome.

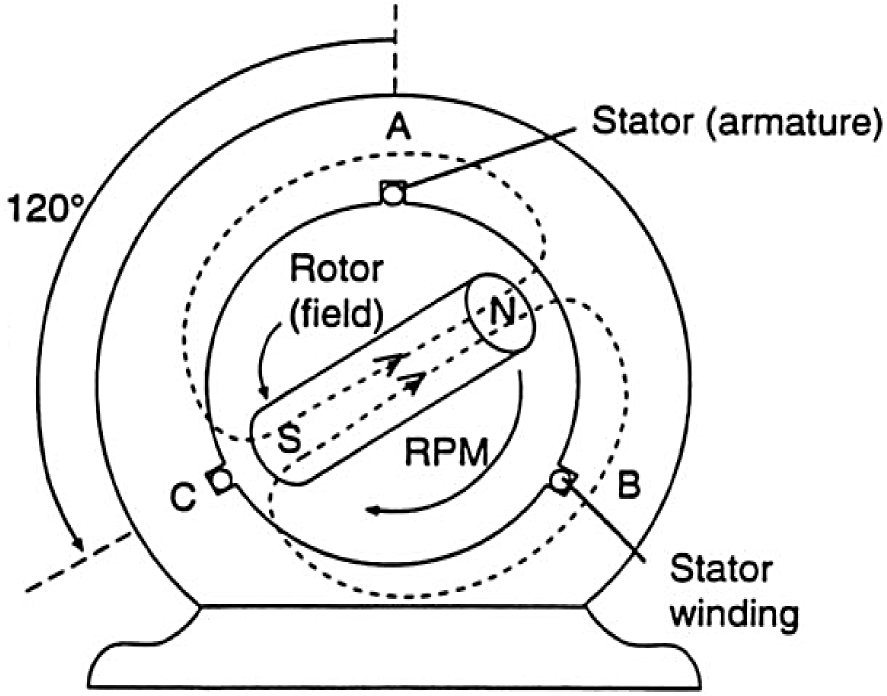

Figure 1. Schematic cross section of a salient-pole synchronous machine [22].

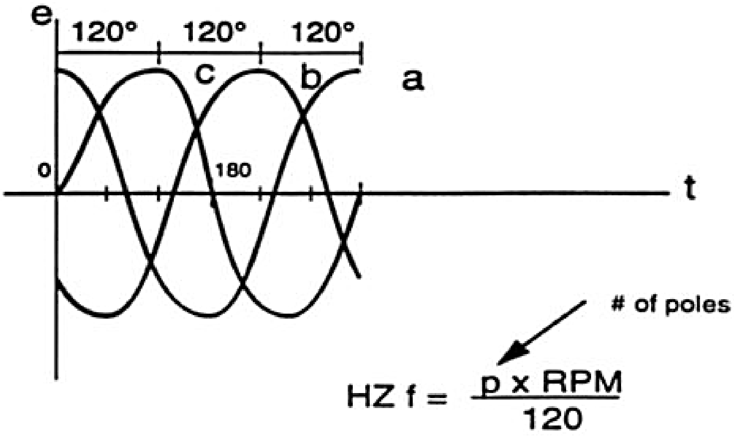

Figure 2. A three-phase voltage waveform gotten at the terminating ends of a salient-pole synchronous machine used as a generator [22].

Where in figure 2; f = electrical frequency in Hz, p = number of poles of the machine and RPM = speed of the revolving field in revolutions per minute (rpm).

Synchronous machines can also be utilized as motors, but they are normally built in very big dimensions. The synchronous motor functions at an exact synchronous speed, and consequently is a constant-speed motor; it has variable power factor attributes, and thus fits for power factor correction applications. A synchronous motor functioning without mechanical load is called a compensator or synchronous condenser. It acts correctly as a variable capacitor when the field is over-excited, and as a variable inductor when the field is under-excited. It is frequently utilized in critical locations in electrical power system network for reactive power control [23].

4. Progressive Trend in the Use of the Synchronous Machine in Transmission and Distribution Networks

Electrical power utility authorities always make sure that grid reliability, efficiency, and security is their main concern. But as grid network progresses and load profiles undergo changes, transmission and distribution networks are also being overstretched, which then make the need for voltage support and grid management much more demanding. Universally, electric power utilities are facing numerous new grid challenges and conditions, these includes: Transformations in generation mix; Reduction in conventional or traditional generation; A rise in renewable and distributed generation; Environmental and regulatory policy alterations, and driving the retirement of traditional generating stations. These problems have operational effect on electrical infrastructure, particularly producing an overall deficiency in: Reactive compensation support; Voltage support; System inertia; and Low short circuit strength. This has raised renewed interest and necessity for synchronous condensers in fragile grid applications, most especially in support of renewable generation and High Voltage Direct Current (HVDC) Systems. The synchronous condenser provides electricity utility authorities an easy and dependable solution to address reactive power compensation and voltage support requirements. It supply’s power system operators with proven robust and reliable solution, which can deliver both steady state and dynamic support to electric power systems efficiently. Synchronous condensers have been utilized conventionally in electric power applications to sustain electrical networks that has insufficient power factor and to regulate or control voltage in a network. The function of the synchronous condenser has been relatively fulfilled by static devices such as static VAR compensators (SVCs) and static synchronous compensators (STATCOMs). These static devices have the benefit of quicker responses. In some grid fault conditions, the synchronous condenser supply higher reactive power, and, more significantly, the kinetic energy accumulated in the rotor gives inertial support to the power grid during fault situations. The inertial support ability and fast response time become more significant as the grid-connection prerequisites, such as low voltage ride-through become more inflexible. Synchronous condenser devices are capable of providing real power during fault conditions in electrical grid networks, the real power is supplied by the rotating mass inertial response [15], [24], [25], [26], [27], [28], [29], [30], [31], [32], [33], [34], [35] and [36].

As renewable energy sources are being added rapidly to power systems globally, traditional power plants are therefore being displaced by renewable power generation. Gas and steam power production plants are in the same vein being retired and some advancing towards the end of their functional life, power plant owners faces a difficult resolution between refurbishing and dismantling/retiring their plants. Dismantling/retiring a power production unit can decrease a plant's reactive power ability, perhaps resulting in shortfalls that directly have an effect on the local system's reliability. If a unit is dismantled/retired, the challenge will be to keep in good condition grid voltage at or near the plant interconnection point, in order to make sure that there is grid reliability. Nevertheless, there is possibly a more economical and beneficial solution: which is converting existing synchronous generators into synchronous condensers. A recent refurbishment from generator to synchronous condenser has the plant not only stabilizing the grid and keeping the lights on in situations of high demand, but as well keeping the air cleaner in the process. [37], [38], [39], and [40].

Synchronous machines that are designed solely to provide reactive power sustenance are called synchronous condensers. Synchronous condensers have all of the response speed and controllability benefits of generators without the requirement to construct the rest part of the power plant, such as fuel handling equipment and boilers. Because they are rotating machines with moving parts and auxiliary structures, they may need notably more maintenance than static substitutes. They also consume or use-up real power, equivalent to about 3% of the machine's reactive power grading. The synchronous condenser supports voltage regulation, by drawing-up leading current when line voltage sags, which increases generator excitation thereby restoring the electrical power line voltage, this is illustrated in Figure 3, showing the curves with and without (w/o) the synchronous condenser connected to an electrical power line. The ability of a synchronous condenser can be improved by substituting the copper wound iron field rotor with an ironless rotor of high temperature superconducting wire, which have to be cooled to liquid nitrogen boiling point of 77oK (-196oC). Synchronous machines, be it motor or generator with controllable field has reactive power abilities. Active power is the energy made available to run a motor, heat an apartment, or light-up an electric bulb, reactive power provides the main purpose of regulating voltage. If voltage on the system is not adequate, active power cannot be supplied in an electrical grid network. Reactive power is utilized to supply the voltage levels essential for active power to do beneficial tasks. Reactive power is necessary to move active power all through transmission and distribution networks to the electricity consumer. Reactive power (VAR) is a prerequisite to keep in good condition the voltage to convey active power (watts) through electrical transmission lines. Motor loads and other loads need reactive power to convert or change the flow of electrons into beneficial work. When there is not enough reactive power, the voltage sags down and it is not feasible to push the power required by loads through electrical power lines [13], [14], [15], [23], [41] and [42].

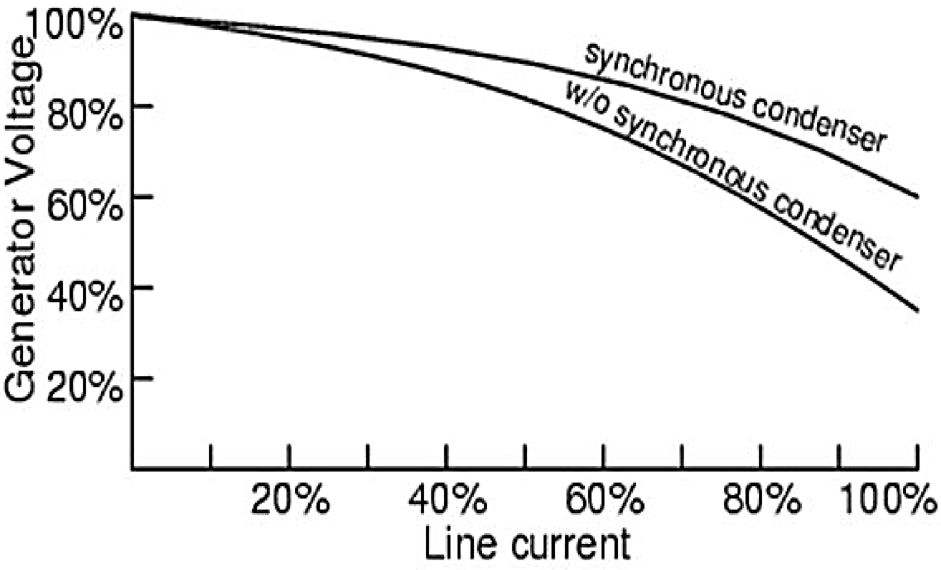

Figure 3. Illustration of the curves obtained with and without (w/o) the synchronous condenser connected to an electrical power line [41].

5. Methodology

5.1. Description of Method

The research model under study consists of a 132 kV high voltage (HV) alternating current (AC) power supply system source linking a three phase 33 kV medium voltage (MV) power line network with the aid of a 132/33 kV HV/MV transformer. The 33 kV MV power line network is then linked to the MV side of the 132/33 kV HV/MV transformer. Thereafter, a 33 kV 50 Hz load is joined to the three phase 33 kV MV electric-power system, with a synchronous condenser placed at the terminating end of the three-phase power line network via a 33/25 kV MV transformer. The schematic diagram of the proposed model without and with the synchronous condenser installed on the proposed power system network are presented in Figure 4 and Figure 5 respectively.

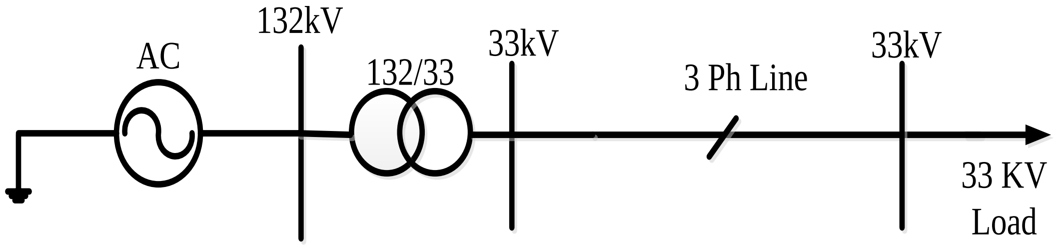

Figure 4. Schematic diagram of the proposed 33 kV MV power system network without the synchronous condenser installed on the network.

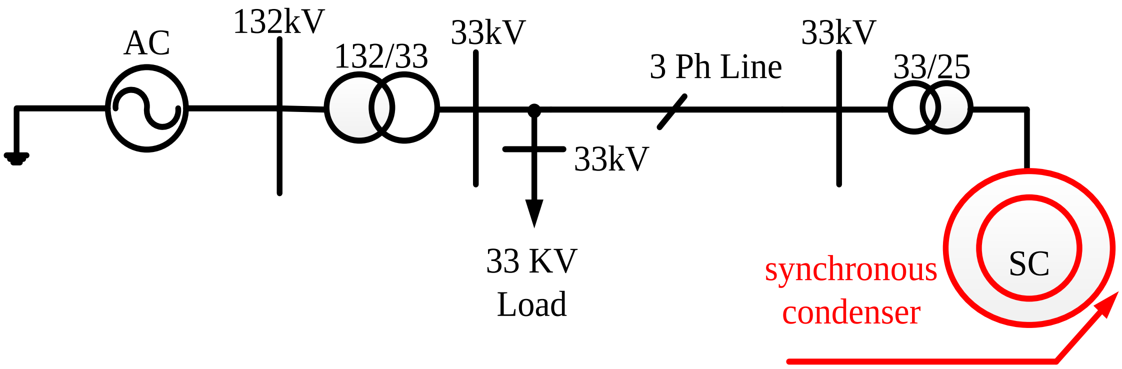

Figure 5. Schematic diagram of the proposed 33 kV MV power system network with the synchronous condenser placed at the extreme end of the network.

To validate the model, three sets of datas have been analyzed, data 1, 2, and 3. With different values of inductive loads of 4, 7 and 10 MVARs, an active power of 30 MW and a capacitive load of 0.5 MVAR joined to the electric-power system network. The results of both measured and calculated values of the power factor (Cos φ) gotten from the network is 0.99, 0.97 and 0.95 for Data 1, 2, and 3 respectively. The power factor of the network is measured and caculated in order to test the validity of the proposed electric-power system network.

5.2. Voltage measurement and direction of power flow

The voltage values measured at the sending and receiving ends of the 33 kV MV electric-power system network for the three sets of data's 1, 2 and 3, with their direction of power flow is obtained. The results of the voltage values obtained and power flow direction observed when the synchronous condenser is switched OFF on the proposed network shows that for data 1 Sending Voltage (U_s) is 32.95, while Receiving Voltage (U_r) is 32.39, therefore Voltage Difference for data 1= 0.56 Volts ; In the same vein for data 2 - Sending Voltage (U_s) is 32.00, while Receiving Voltage (U_r) is 31.70, hence Voltage Difference for data 2 = 0.30 Volts; Also, considering data 3 - Sending Voltage (U_s) is 31.70, while Receiving Voltage (U_r) is 31.30, hence Voltage Difference for data 3 = 0.40 Volts. It can be seen that large voltage differences were gotten from the electric-power system and the direction of power flow observed is positive (+), which means that power flowed from the voltage sending (U_s) end to the voltage receiving (U_r) end of the power line. While the voltage values documented and the power flow directions monitored with the synchronous condenser switched ON for data 1 is Sending Voltage (U_s) is 32.70, and Receiving Voltage (U_r) is 33.10, therefore Voltage Difference for data 1= - 0.40 Volts ; for data 2 - Sending Voltage (U_s) is 32.65, while Receiving Voltage (U_r) is 32,95, hence Voltage Difference for data 2 = - 0.30 Volts; Equally, for data 3 - Sending Voltage (U_s) is 32.20, while Receiving Voltage (U_r) is 32.40, and Voltage Difference for data 3 = - 0.20 Volts, but unlike the previous situation when the synchronous condenser is switched OFF, in this case with the synchronous condenser switched ON, small voltage differences were gotten from the network and the direction of power flow monitored is negative (-), this means that power flows from the receiving (U_r) end to the sending (U_s) end of the proposed 33 kV MV electric-power system network.

6. Simulation Results and Discussion

6.1. Simulation

MATLAB/Simulink software program has been utilized for the simulation of the proposed electric-power system network, two scenarios were considered, first is the Case when the synchronous condenser is switched OFF on the 33 kV MV electric-power system network, which resulted in large voltage differences on the power line. The second scenario is the Case with the synchronous condenser switched ON as regards to the 33 kV MV electric-power line, which gave rise to a small voltage difference on the proposed electric-power system network.

6.2. Results and Analysis

To start with, power factor for data 1, 2, and 3 were measured and thereafter calculated, this has been done as formerly expressed to test the authenticity or validity of the proposed electric-power system under consideration. It was noticed that the measured and calculated values of the power factor gotten were the same for the three sets of data monitored. Simulation model results for the voltage values gotten at the beginning end of the 33 kV medium voltage (MV) electric-power system network with the Synchronous Condenser switched OFF and ON is recorded and a clear and vivid explicit details is presented with a 3D diagram in Figure 6, large voltage differences were noticed on the 33 kV medium voltage (MV) network as compared to the readings recorded at the terminating end of the power line and the direction of power flow is from the voltage sending (U_S) end of the network to the voltage receiving (U_r) end of the power line for data's 1, 2, and 3 monitored. At the beginning end of the electric-power line, results show that the scheme uses up reactive power, when the synchronous condenser is switched OFF. And reactive power is injected into the 33 kV medium voltage (MV) electric-power system network, when the synchronous condenser is switched ON as regards to the proposed network. Also, it is seen that the voltage profile is better when the synchronous condenser is switched ON.

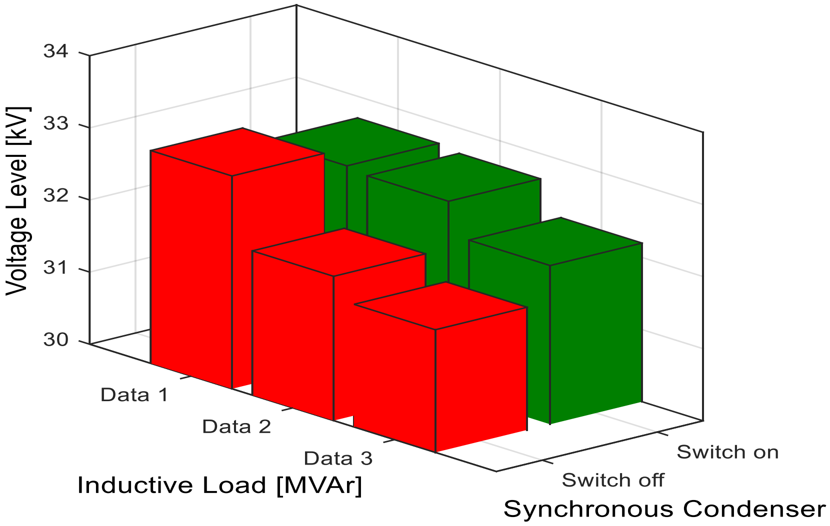

Figure 6, Voltage values at the beginning end of the 33 kV MV electric-power system network when the Synchronous Condenser is swithced OFF and ON.

The Synchronous Condenser is equally switched OFF and ON at the terminating end of the line as seen in Figure 7. Results gotten shows that when the synchronous condenser is switched OFF, the electric-power line uses up reactive power. But reactive power is injected onto the 33 kV medium voltage (MV) power line network, when the synchronous condenser is switched ON. Here, the results depict a small voltage difference on the power line as compared to larger values recorded at the starting point of the proposed electric-power system network and the observed power flow direction movement is from the receiving voltage (U_r) end of the proposed electric-power model to the sending voltage (U_s) end of the network. It is also observed that the system experiences drop in voltage values during the whole time when the synchronous condenser was switched OFF, but a better voltage profile is observed when the synchronous condenser is switched ON. This has been illustrated in Figure 7.

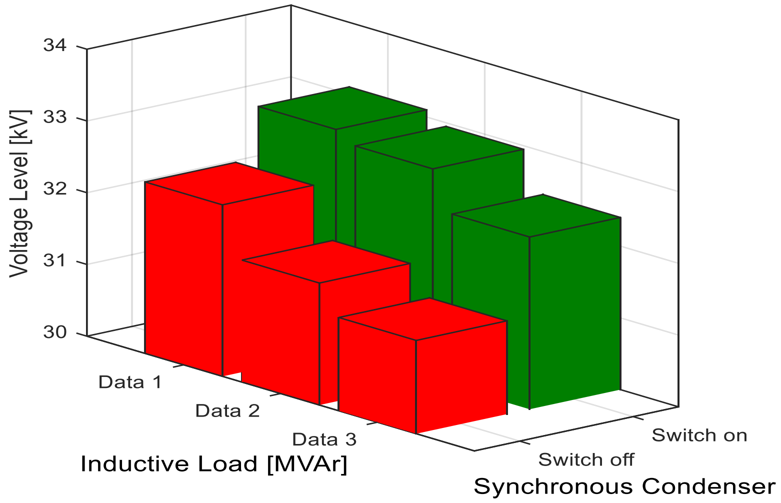

Figure 7, Voltage values at the terminating end of the 33 kV MV electric-power system network with the synchronous condenser swithed OFF and ON.

The graphical illustration of the differences in voltage values gotten at the beginning and terminating end of the 33 kV MV electric-power line with the synchronous condenser switched OFF and ON is shown in Figure 8, the noticed directions of power flow for data 1, 2, and 3 is also displayed. Large voltage difference values are noticed and the direction of power flow is from sending voltage (U_s) end to the receiving voltage (U_r) end of the electric-power line, which imply positive (+) direction of power flow for the scenario when the synchronous condenser is switched OFF. Also, the obtained voltage difference values for the observed data's 1, 2 and 3, when the synchronous condenser is switched ON as regards to the electric-power system network is small and the directions of power flow is from the receiving voltage (U_r) terminating ends to the sending voltage (U_s) ends of the proposed network under study, which means that the monitored power flow direction is negative (-). This imply that the case with the synchronous condenser switched ON as regards to the 33 kV medium voltage (MV) electric-power system network gave more favorable result for enhanced voltage stability and power flow control as compared with the scenario when the synchronous condenser is switched OFF. Also, the monitored voltage difference reduces as we observe data 1 through 3 for both switched OFF and ON situations.

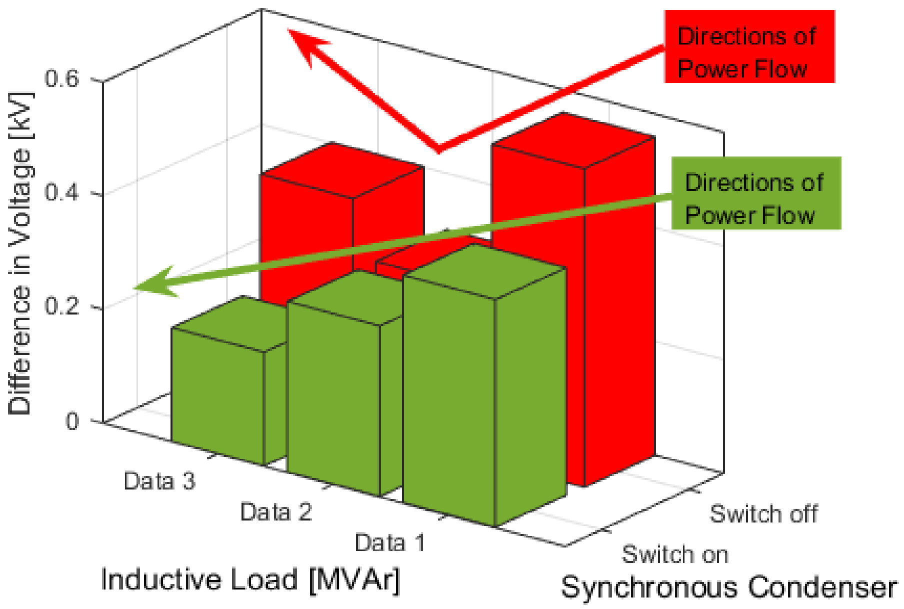

Figure 8, The observed directions of power flow, and the obtained difference in voltage values at the beginning and end terminals of the 33 kV MV power line when the synchronous condenser is swithced OFF and ON.

7. Conclusion

Globally, renewable power generating plants are being added continuously to the electricity grid network and many power plants are also getting to the end of their useful operational life time. Thus, electric-power plant utility authorities and other stakeholders in the industry are faced with the difficult decision between dismantling or retiring these plants. The authors of this paper suggest that these rotating synchronous machines should be refurbished to synchronous condensers exclusively for reactive power compensation on the electric-power grid network. The reactive power of a synchronous condenser can be effortlessly regulated by means of its excitation and when placed across electric-power system line, ideally at the receiving terminating end, makes it a good strategy for achieving voltage stability and power flow control in power lines; Synchronous condensers make available active compensation in electric-power lines: the reactive power absorbed or supplied utilizing these devices are by itself with little or no direct human control so as to maintain voltage of the bus bar to which it is connected in an electrical grid network.

This research have been able to establish the fact that the synchronous condenser technology allows the regulation or control of reactive power which improves voltage stability and power flow control of electrical power networks. And the authors therefore posit that instead of dismantling and/or retiring power plants, same should be refurbished to synchronous condensers and utilized specifically for reactive power control and probably other applications in electrical power systems; Future research will be; How to sustain stable voltage and ascertain the direction of power flow in a consederably extensive electric-power system network with many branches and also to develop an appropriate control scheme for optimal reactive power compensation in ensuring voltage stability and power flow control in electrical power lines by utilizing the synchronous condenser technology.

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Paper Five

Cost Implication and Reactive Power Generating Potential of the Synchronous Condenser

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Contributor	Statement of Contribution
Famous O. Igbinovia (Candidate)	Simulation and modelling (20%); Result interpretation and discussion (20%); Paper writing and review (20%).
Ghaeth Fandi	Simulation and modelling (20%); Result interpretation and discussion (20%); Paper writing and review (20%).
Zdenek Müller	Simulation and modelling (20%); Result interpretation and discussion (20%); Paper writing and review (20%).
Jan Švec	Simulation and modelling (20%); Result interpretation and discussion (20%); Paper writing and review (20%).
Josef Tlusty	Simulation and modelling (20%); Result interpretation and discussion (20%); Paper writing and review (20%).

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The layout has been revised.

Abstract: The objective of this study is to examine the cost implication and reactive power generating potential of the synchronous condenser. Universally, increase in electricity demand constitutes new issues for power generation, transmission and distribution. Synchronous condenser solutions are being initiated globally to be instrumental in the best usage of power resources and offer grid systems support for todays and future sustainable, stable and reliable electrical grid network. This research x-rays the cost implication of the synchronous condenser in today's challenging environment. A vivid description of the reactive power generating potential of the synchronous condenser is shown with MATLAB/Simulink environment simulation of a medium voltage (MV) power system network. It is observed that the synchronous condenser is cost-effective as compared to other reactive power generating equipment's and sources. Furthermore, MATLAB/Simulink simulation results of the MV electric-power network shows an effective scheme for reactive power generation.

Keywords: reactive power; reactive power generation; power flow control; synchronous condenser; cost implication

1. Introduction

All around the globe, utility authorities are facing many grid issues and market environment undergo changes including: Adjustments in generation mix; Reduction in conventional generation; Rise in renewable and distributed generation; Environmental and regulatory policy amendment; And managing the retirement of conventional coal power generating stations. These issues have operational consequences on electrical infrastructure, particularly in bringing about a substantial shortage in: Reactive power sustenance; Voltage support/ fortification; System inertia; And Low short circuit ratios on electrical power network. Synchronous Condenser devices are invented and designed to proffer a highly dependable and cost-effective solution to tackle reactive power generation and voltage support conditions, furnishing power system operators an optimized way out for cost, performance and operational resilience. Synchronous Condensers are traditionally designed to furnish power system operators with a proven, robust and reliable solution for reactive power generation. Reactive power Q and real power P are linked by the relation below, where S is the apparent power [1], [2], [3], [4], [5], [6] and [7].

$$S^2 = P^2 + Q^2 \qquad (1)$$

Equipment's which accumulates energy by means of a magnetic field created by the movement of current are said to consume reactive power; and equipment's which accumulates energy by means of electric fields are said to generate reactive power. The movement of Reactive Power on an electrical network will influence Voltage levels. Dissimilar to system frequency, which is steady across a network, voltages encountered at points across an electric-power system network produce a 'voltage profile', which is distinctly connected to the existing real and reactive power provision and need. Hence, the exigency to control voltage levels on a local level to satisfy the diverse requirements of power system networks. Without suitable infusion of reactive power at proper positions, the voltage profile of a power system grid network will go beyond statutory planning and operational boundary lines. This brings about the necessity to make use of reactive power generating devices in order to control voltage levels [6]. Reactive power (VARs) is essential to support voltage level in electric-power grid network in order to supply active power (watts) through electric-power systems. Motor loads and other loads need reactive power to change the movement of electrons into beneficial work. When there is shortage of reactive power, the voltage drops down and it is not feasible to send the power required by loads through electric-power systems. Reactive power does not supply beneficial work, it is vitally important for AC electrical power system networks, motors, and numerous kind of consumer loads. For motor loads, adequate VAR levels are required to escape voltage drops that impede the change and movement of watts to meet up with load requirements. Consequently, actual or practical electric-power system networks need both real and reactive power to work correctly [2], [8], [9], [10], [11], and [12].

The electrical power-system designer and operator utilizes variety of devices and sources obtainable for generating reactive power, these include; capacitor banks; Reactors; Conventional generators; Inductors; Synchronous condensers; power electronics control devices such as Static VAR Compensators (SVCs), Flexible AC Transmission Systems (FACTS), and Static Synchronous Compensators (STATCOMs); Unified Power Flow controller (UPFC); switching converter inside Distributed Energy Resources (DER); Synchronous generators; and FACTS controllers. DER are proficient in supplying reactive power counting on their grid-coupling converter. Internal Combustion Engines (ICEs) with synchronous generators can generate reactive power side by side with real power. Batteries, Fuel Cells (FCs), and renewable energy resources like photovoltaic (PV) normally give rise to Direct Current (DC), and make use of inverters in order to link Alternating Current (AC) power system grids, while micro-grids (MCs) utilize DC internally. All these devices are occasionally proficient in supplying reactive power based on the abilities of their power electronics and do offer dynamic voltage regulation [2], [7], [9], [10], [13], [14] and [15]. The aim of this research is to investigate the cost implication of using the synchronous condenser, and the reactive power generation ability of the device by installing the equipment on a three-phase 33 kV MV electric-power distribution network.

2. Methodology

This research paper is made up of two sections:

Section 1: This section deals with the analysis of the cost implication of using synchronous condensers: The authors used research materials mainly from secondary sources in order to investigate the cost implication of using the device. Scholarly research publications were consulted to have a rich and well-structured paper, these data's were further edited as tabulated in Table I. and II.

Section 2: This section has to do with the simulation and analysis of the synchronous condensers reactive power generation potential in electrical power grid networks; The research model consists of a 132 kV high voltage (HV) alternating current (AC) power supply source connecting a three-phase 33 kV medium voltage (MV) electric-power system network with the aid of a 132/33 kV HV/MV transformer. The 33 kV MV power system network is connected to the MV side of the 132/33 kV HV/MV transformer. A 33 kV 50 Hz load is attached to the three-phase 33 kV MV power system. Thereafter, a synchronous condenser is installed at the beginning of the network terminal of the three-phase electric-power system network via a 33/25 kV MV transformer, the scheme is modeled using Matlab/Simulink environment.

A. Cost Implication of the Synchronous Condenser in Today's Challenging Environment

It can be seen in Table I. that costs favors capacitors/reactors. Generators have exceptionally high capital costs since they are designed to provide real power, instead of reactive power. To a greater extent the incremental cost of reactive power provision from generators is high. However, it is hard to unambiguously split-up reactive power costs from real power costs. Operating costs for generators are high as well since generators can be associated with real-power losses. Also, since generators have different uses, they undergo opportunity costs when called on at the same time to supply high levels of reactive and real power. Synchronous condensers have the same features as generators; however, since they are built exclusively to supply reactive support, synchronous condensers capital costs are not as high as generators and they experience no opportunity cost. SVCs and STATCOMs are high cost equipment's too, in spite of the fact that their operating costs are lower than those for synchronous condensers and generators. Power system operators can obtain reactive power sources either using mandates/authorization or purchases/acquisition. It might be feasible to establish competitive markets for securing these services, on condition that the reactive power provisions are not geographically confined. It is a widespread opinion that the position constraints on reactive power resources are adequately challenging that competitive markets cannot be established for this service. Some power system operators pay generators their embedded costs for reactive power resources. Notwithstanding, deciding the embedded costs of generator to supply reactive power sustenance leads to uncertainty. This is so since; the same equipment is utilized to supply both real and reactive power. Queries such as what percentages, for instance, of the exciter, generator stator, generator rotor, turbine assembly, and step-up transformer should be allocated to each operation is difficult to answer. In the same vein, there is further uncertainty in deciding the embedded costs of synchronous condensers [16], [17], and [18].

Synchronous machines are costly to procure in the first instance, and the equipment has internal losses, which present a continual operating cost. Normally, the mean cost for a synchronous condenser is between $10 to $40 per kVAR and the maintenance cost ranges from about $0.4 to $0.8/kVAR per year. The SuperVAR is a High Temperature Superconductor (HTS) Dynamic Synchronous Condenser equipment, that is meant to operate continually, this equipment cost between $1 million and $1.2 million. A SuperVAR is rated at 10 MVA, however its first model shown at the Tennessee Valley Authority (TVA) in Gallatin, TN was 8 MVA [19], [20], [21], [22] and [23]. Reactive power generating equipment's/sources vary in their capital and operating costs, as presented in Table I [7], [15] and [24].

Table 1. Cost Comparison of Reactive Power Generating Equipments and Sources

Reactive Power Generating Equipment's and Sources	**Investment Cost**		
	Capital Cost (per kVAR)	***Operating Cost***	***Opportunity Cost***
Capacitors/Reactors	$10-30	Very Low	No
Synchronous Generators	Difficult to separate	High	Yes
STATCOM	$50-100	Moderate	No
Static VAR compensators	$40-100	Moderate	No
Synchronous condensers	$10-40	High	No

Distributed Energy Resources (DER) - Inverter	$40-90	High	Yes
Distributed Energy Resources (DER) – Synchronous Generator	$25-40	High	Yes

The cost benefit comparison between capacitor banks and a Small Generator Retrofitted to Synchronous Condenser, with both rated 5.0 MVAR is tabulated in Table 2. it shows that the files separate until after the text has been formatted and styled. synchronous condenser come first on precise economic terms as against capacitor banks. Moreover, there are additional advantages from using synchronous condenser equipment's that are difficult to quantify. Capacitors are situated all through utility's service territory and consequently maintenance is extra costly as when compared to a single synchronous generator sited at a substation. The power system operator cannot be certain that its capacitors are functioning, as they are too widely scattered for the monitoring of their status. Unpredicted occurrences, for instance lightning could stop capacitor timers from operating, without the knowledge of utility operator. The unpredictability on the status of the capacitors could be avoided by putting in place more costly control systems for the capacitors or alternatively having one synchronous condenser that can easily be reached or assessed in order to control reactive power flow/movement. Besides, synchronous condenser equipment's can dynamically make available reactive power and regulate its output depending on power system circumstances [2], [7], [8], [9], [10], [11], [12], [15], [24] and [25].

Synchronous condensers may deliver extra indirect advantages such as: reduced losses, saved line capacity, and increased transfer capability; as compared to capacitor banks. This is as a result of the fact that injected reactive power from a synchronous condenser equipment is practically constant when voltage is low. But substantially low, that is by voltage squared, for capacitor banks. This meaning that capacitors are least worthwhile when most required. Over time, it has been seen that the more shunt capacitors are connected to an electrical power system, the more the possibilities for voltage collapse as the output of shunt capacitors decreases as the square of the measured voltage. Most capacitors that are installed by power system operators in order to keep away from power factor penalties normally in summer seasons are not actually required for the remaining period of the year. At present, utility authorities normally turns off half of its fixed capacitor banks throughout the duration of winter season, this is done to keep away from leading Power Factor costs.

Synchronous condenser devices could assist utility authority's place a limit on installing capacitors that function only just for one third period of the year [7], [15], [24] and [25].

Table II COST BENEFIT COMPARISON BETWEEN CAPACITORS AND SYNCHRONOUS CONDENSERS

Costs and Benefits ($/year)	**Capacitor Banks (5.0 MVAR)**	**Small Generator Retrofitted to Synchronous Condenser (5.0 MVAR)**
Capital Cost	$22,000	$50,000
Technology Life Time	10 years	20 years
Preventive Maintenance Cost	$6,000	$3,500
Cost of Voltage Regulator Maintenance	$6,600	$3,300
Annual Cost in Present Value	$14,800	$9,300
Saving from Avoided Power Factor Penalties	$29,200	$29,200
Annual Benefit in Present Value	$29,200	$29,200
Net Annual Saving in Present Value	$14,400	$19,900
Net Annual Saving in Present Value ($/MVAR)	$2,880	$3,980

B. Validity Test Results, Voltage Measurements and Directions of Power Flow of the Three-phase 33 kV MV Electric-power System Network,

The parameters for the proposed grid network has an Active Power *(P)* of 30 MW and a Capacitive Reactive Power (Q_C) of 0.5 MVAR. Three sets of data's were analyzed, data 1, 2, and 3. With varying values of Inductive Reactive Power (Q_L) loads of 4, 7 and 10 MVARs. Measured and calculated values of power factors of load for the three data's were obtained to test the validity of the system. Results for the validity test are shown in Table III. The schematic diagram for the proposed network, when the synchronous condenser is installed at the beginning of the network terminal is illustrated in Fig. 1.

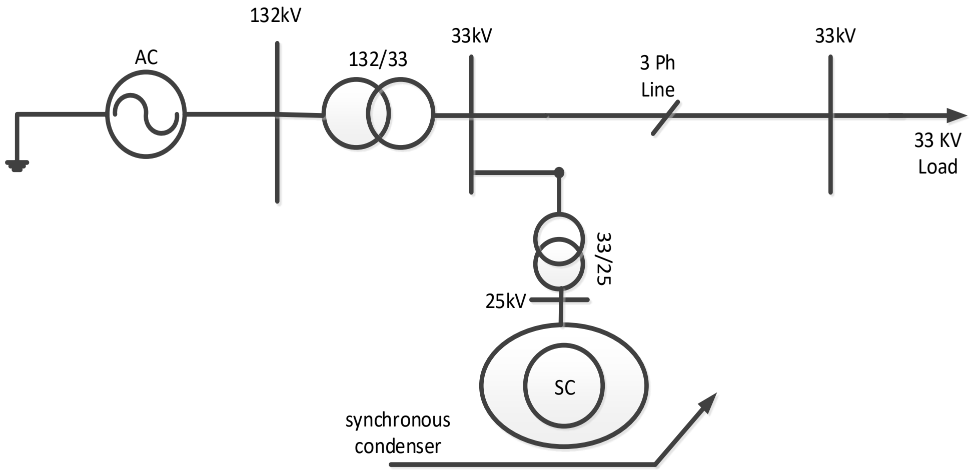

Fig. 1. Schematic diagram of the synchronous condenser placed at the beginning terminal of the 33 kV MV power system network.

Table III VALUES OF POWER FACTOR ($\cos\varphi$) FOR THE 33 kV 50 Hz LOADS

33 kV 50 Hz load				$\cos\varphi$	
Set of Data's	***Active Power P (MW)***	***Inductive Reactive Power QL (MVAR)***	***Capacitive Reactive Power QC (MVAR)***	***Measured Value***	***Calculated Value***
1	30	4	0.5	0.99	0.99
2	30	7	0.5	0.97	0.97
3	30	10	0.5	0.95	0.95

Data 1;

$$cos\,\varphi = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}} = \frac{30}{\sqrt{30^2 + 3.5^2}} = 0.99$$

Data 2;

$$cos\,\varphi = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}} = \frac{30}{\sqrt{30^2 + 6.5^2}} = 0.97$$

Data 3;

$$cos\,\varphi = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}} = \frac{30}{\sqrt{30^2 + 9.5^2}} = 0.95$$

Table IV. and V. shows the voltage values obtained without and with the synchronous condenser installed at the terminal of the beginning of the three-phase 33 kV MV electric-power system network. The voltage at the sending and receiving ends of the network is measured for the three set of data's, 1, 2 and 3, with directions of their power flow also determined. Table IV. illustrate the results of voltage values and power flow directions obtained without the synchronous condenser connected to the network, it can be seen that large voltage differences were experienced by the network and the direction of power flow is positive (+), which means that power flows from the voltage sending (U_s) terminal to the voltage receiving (U_r) terminal of the network. Table 5. clearly show the voltage values and power flow directions observed when the synchronous condenser is installed at the beginning terminal of the proposed grid network, larger voltage differences were experienced by the 33 kV MV network and the directions of power flow is still positive (+), this also imply that power flows from the voltage sending terminal (U_s) end of the proposed power grid system to the voltage receiving (U_r) terminal of the network. Implying that installation of the synchronous condenser at the beginning of the network terminal has significantly increased the reactive power generated by the power system grid network.

TABLE IV. VOLTAGE VALUES OBTAINED AND POWER FLOW DIRECTIONS WITHOUT THE SYNCHRONOUS CONDENSER CONNECTED TO THE THREE-PHASE 33 kV MV ELECTRIC-POWER SYSTEM NETWORK

Set of Data's	**Sending Voltage (U_s)**	**Receiving Voltage (U_r)**	**Voltage Difference (U_s-U_r)**	**Power Flow Directions**
1	32.90	32.35	0.55	+
2	32.74	31.70	1.04	+
3	32.45	30.98	1.47	+

TABLE V. VOLTAGE VALUES OBTAINED AND POWER FLOW DIRECTIONS WITH THE SYNCHRONOUS CONDENSER INSTALLED AT THE BEGINNING TERMINAL OF THE THREE-PHASE 33 kV MV ELECTRIC-POWER SYSTEM NETWORK

Set of Data's	**Sending Voltage (U_s)**	**Receiving Voltage (U_r)**	**Voltage Difference (U_s-U_r)**	**Power Flow Direction**
1	32.70	31.90	0.80	+
2	32.10	31.25	0.85	+
3	31.40	29.60	1.80	+

3. SIMULATION RESULTS AND DISCUSSION

MATLAB/Simulink environment is used for the simulation of the proposed system network as shown in Fig. 2. two scenarios were studied, first is the situation without the synchronous condenser connected to the 33 kV MV power system network, which resulted in large voltage differences on the network. The second situation is the scenario with the synchronous condenser installed at the beginning terminal of the 33 kV MV electric-power system network, which resulted in larger voltage differences on the proposed power system network. Implying that the synchronous condenser, has the potentials to produce or generate reactive power.

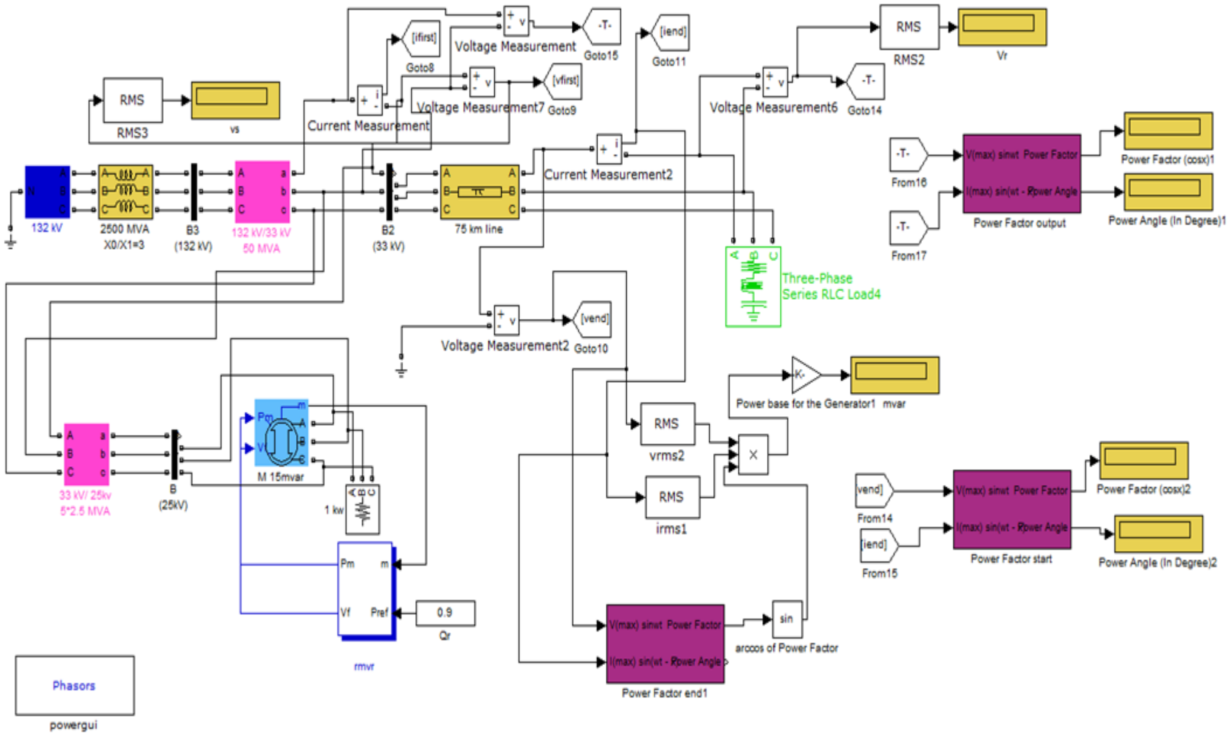

Fig. 2. MATLAB/Simulink simulation model of the proposed 33 kV MV electric-power system network, with the synchronous condenser installed at the beginning terminal of the network.

Simulation results for the voltage values obtained at the beginning terminal of the 33 kV medium voltage (MV) electric-power system network without and with the synchronous condenser installed at the beginning terminal of the network is graphically illustrated with a three-dimensional diagram in Fig. 3., there were large voltage differences experienced by the 33 kV medium voltage (MV) network and the direction of power flow is from the voltage sending (U_s) terminal of the network to the voltage receiving (U_r) terminal of the electric-power system for the three set of data's observed. The differences between sending and receiving voltage (U_s-U_r) values becomes more as the values of inductive reactive power *(Q_L)* loads (measured in MVAR) increases. Furthermore, it is observed that reactive power is being used without the synchronous condenser connected to the network. And reactive power is being injected onto the electric-power system grid as the synchronous condenser is connected to the network. Thus, insinuating that the synchronous condenser has the potential to generate reactive power onto an electric-power system network. The direction of power flow without and with the synchronous condenser device connected onto the network is from voltage sending (U_s) terminal to voltage receiving (U_r) terminal of the network, this is to say that power flow is in the positive (+) direction, as illustrated in Fig. 3.

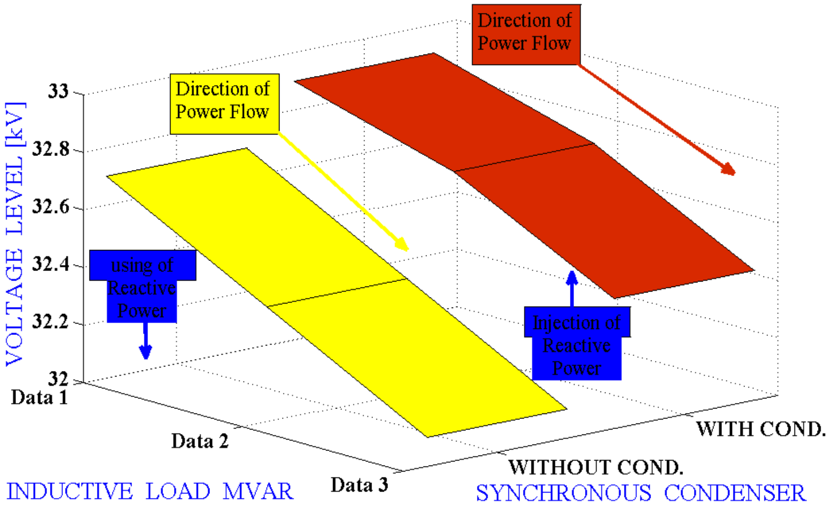

Fig. 3. Voltage values and power flow directions at the beginning terminal of the 33 kV MV electric-power system network without and with the synchronous condenser Installed.

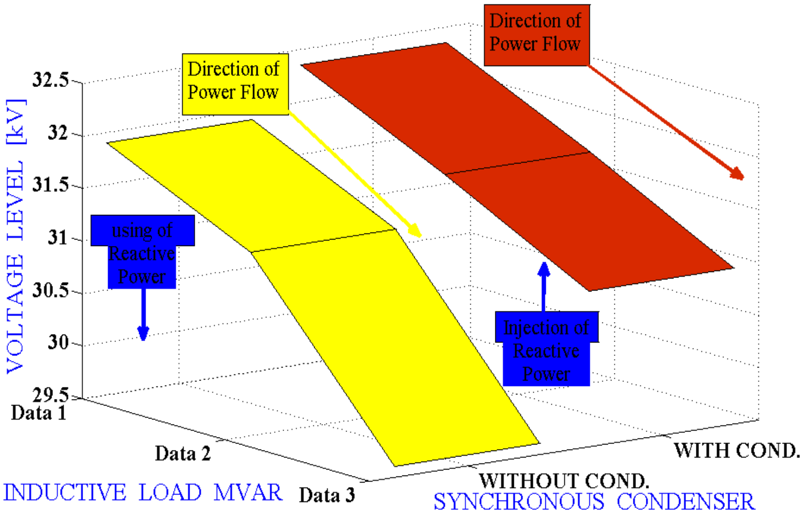

Fig. 4. Voltage values and power flow directions at the terminal end of the 33 kV MV power system network without and with the synchronous condenser installed.

The results obtained at the terminal end of the 33 kV medium voltage (MV) power system network without and with the Synchronous Condenser installed is graphically illustrated in Fig. 4., with a three-dimensional diagram. Fig. 4., shows the values of the voltage differences (U_s-U_r) between the sending voltage (U_s) and receiving voltage (U_r), which becomes even larger as the synchronous condenser is installed at the beginning of the 33 kV medium voltage (MV) power system network. Here, the result vividly depicts a gradual increase in the voltage difference on the power system network as values of inductive reactive power (Q_L) loads increases. Hence, it implies that the values of the voltage differences obtained are significantly larger when the synchronous condenser is installed onto the electric-power grid as compared to voltage difference values obtained without the synchronous condenser installed on the network. Fig. 4., also present the directions of power flow of the network, the power flow direction is from the voltage sending (U_s) terminal to the voltage receiving (U_r) terminal, this is to say that power flow direction is positive (+). It can also be seen in Fig. 4., that without the synchronous condenser installed on the network, the electric-power network is using reactive power. But with the synchronous condenser installed, there is injection of reactive power onto the power system network, which imply that the synchronous condenser do have the potential to generate or supply reactive power to an electric-power system network.

Graphical illustration of the comparison of the voltage differences (Us-Ur) between the sending voltage (Us) and receiving voltage (Ur) at the beginning and end terminals of the 33 kV MV power system network without and with the synchronous condenser connected is shown in Fig. 5. The observed directions of power flow for data 1, 2, and 3 is also illustrated. Large voltage differences is observed and the direction of power flow is from the sending voltage (Us) terminal to the receiving voltage (Ur) terminal ends of the power system network, which imply a positive (+) direction of power flow for the scenario without the synchronous condenser installed on the electric-power system network. The obtained voltage differences for the observed data's 1, 2 and 3, when the synchronous condenser is installed at the beginning of the power system network is much more larger, as compared to the scenario without the installation of the synchronous condenser equipment and the directions of power flow is same for both scenarios, this is to say that power flow is still from the sending voltage (Us) terminal to the receiving voltage (Ur) terminal of the network, implying that the observed power flow directions are positive (+) in both situation, without and with the synchronous condenser. It can be seen in Fig. 5., that reactive power is being used for the scenario without the synchronous condenser installed to the network. And reactive power is being injected onto the electric-power system as the synchronous condenser is installed onto the network. All the results so far obtained further goes on to buttress the point that synchronous condenser devices has the potential to generate or produce reactive power on an electric-power grid network.

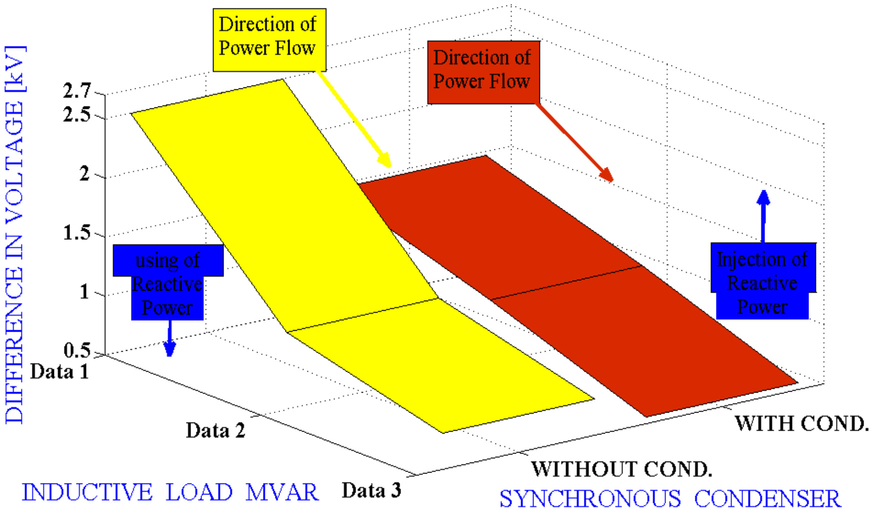

Fig. 5. Differences in voltage values and the observed directions of power flow at the beginning and end terminals of the 33 kV MV electric-power system network without and with the synchronous condenser installed at the beginning terminal of the network.

4. Conclusion

This research paper has shown that the synchronous condenser triumph on precise economic points as compared to other reactive power generating equipment's and sources. Results of MATLAB/Simulink modeling of medium voltage power system components, that is transmission line, distribution line and loads of the proposed 33 kV MV electric-power system network, with synchronous condenser installed at the beginning of the network shows that the synchronous condenser device is able to generate or produce reactive power onto an electric-power grid network. Several concerns need to be met in the future, in order for the synchronous condenser to become widely integrated as a reactive power generating/producing equipment, these includes; The overall costs of retrofitting synchronous condenser devices for generating or producing reactive power need to be reduced; Also, a suitable position for installing the Synchronous condenser equipment on an electric-power system networks need to be investigated for its optimal use.

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Paper Six

Optimal Location of the Synchronous Condenser in Electric-Power System Networks

Famous O. Igbinovia, Ghaeth Fandi, Zdeněk Müller, Jan Švec, Josef Tlustý

Contributor	Statement of Contribution
Famous O. Igbinovia (Candidate)	Simulation and modelling (20%); Result interpretation and discussion (20%); Paper writing and review (20%).
Ghaeth Fandi	Simulation and modelling (20%); Result interpretation and discussion (20%); Paper writing and review (20%).
Zdeněk Müller	Simulation and modelling (20%); Result interpretation and discussion (20%); Paper writing and review (20%).
Jan Švec	Simulation and modelling (20%); Result interpretation and discussion (20%); Paper writing and review (20%).
Josef Tlustý	Simulation and modelling (20%); Result interpretation and discussion (20%); Paper writing and review (20%)

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Abstract: In this paper, authors focus on the use of the synchronous condenser device for voltage stability and power flow control on a three-phase 33 kV Medium Voltage (MV) electric-power system network. Matlab/Simulink is used for the simulation of the proposed system model. To test the validity of the system, measured and calculated power factor values were obtained. Two scenarios were studied; Firstly, is the scenario with the synchronous condenser located at the terminal end of the 33 kV MV network (position 1). And secondly, is the scenario with the synchronous condenser placed at the beginning of the 33 kV MV power Line (position 2). Simulation results obtained from the study are compared in order to determine the most appropriate location for situating the synchronous condenser device. It is observed that the locations of the synchronous condenser equipment have different impacts on the electric-power system network. However, the proposed study of the simulation model base on the location of the synchronous condenser at the terminal end of the 33 kV MV electric-power system network (position 1) demonstrate a more effective and suitable scheme of the electric-power network concerning issues of voltage stability and power flow control.

Keywords: reactive power; reactive power compensation; synchronous condenser; voltage stability; Power flow control; electric-power system networks

1. Introduction

Nowadays, voltage stability and instability has come to be an important area of study in the operation and control of electric-power systems following several voltage instability occurrence in many parts of the world, non-success in discovering voltage instability or taking perfect control of the situation may result in wide-ranging electric-power system failure. Consequently, to sustain the reliability of an electric-power system, it is very important that voltage stability is correctly and promptly sustained at all time. Voltage instability is accountable for several system break-down and power-cuts, and is now given appreciable care in many electric-power system networks. Thus, making voltage stability a critical topic as regards to electric-power system security [1], [2], [3], [4], [5], [6], [7] and [8]. Electric-power systems are used under growing increased over-stretched circumstances than they normally had previously. There are several elements accountable for this, these include: continuous increase in interconnections; utilization of recently developed technologies; large volume of transmitted electric-power over- stretching power-lines; environmental stress on power-lines; growth in electric-power utilization in bulky load localities, that is areas where it is not practicable or cheap to situate additional generating plants; novel system loading methods owing to the windows of opportunities in the electricity market, that is electricity trade deregulation; increasing utilization of induction machines; and huge penetration of wind generators and localized clumsy regulations or control in electric-power systems. In these over-stretched circumstances electric-power systems can display different kind of unsteady actions, specifically, voltage instability. If generators are located near loads, its excitation can be utilized to retain the stable voltage situation. But over lengthy connections the voltage variations are difficult to manage and needs reactive power compensation, this is a means to strengthen the voltage stability of power-lines [9], [10], and [11].

Moreover, attraction in the practicability to regulate power flows (that is active power flow) in electric-power systems has grown. This is as a result of several rationality, arising both from the utilization aspect such as power system operation and from the technological aspect such as emergence of present-day system constituents like semiconductor structured equipment's and synchronous condenser devices. In several nations of the world, the operations of electric-power systems have been modified as a result of increasing usage of power-system network and profitable operations of the electric-power trade. In profit oriented situations electric-power transmitted volume is considered as a product, for making use of power lines, payments have to be made, and electric-power network managers rely on these profitable payments. Accompanied by the profitable reliance on the electric network comes the need to be capable of regulating the electric-power system as much as conceivable. The new constituents that are becoming practicable are to a great extent as a result of advances in the conceptual structure of power electronics devices and associated technologies such as the synchronous condenser device. The principal rationale why power flow is significant in the present-day scheme of things are inclusive of; overload reduction, contractual needs, loss alleviation and autonomous electric-power projects [12], [13], [14], [15], [16], and [17].

This study brings out some interesting features about the synchronous condenser performance and their impact when used in an electric-power system network; it focuses on the optimization of reactive power using synchronous condenser device for voltage stability and power flow control in an electric-power system. And thereafter presented and discussed the results of the comparison obtained when the synchronous condenser is placed at the terminal end and beginning of the proposed 33kV medium voltage (MV) electric-power system network. Matlab/Simulink is used for the simulation of the system model.

2. Methodology

To evaluate the effectiveness of the synchronous condenser for voltage stability and control of power flow in an electric-power system network, the schematic diagram is modeled using Matlab/Simulink software program. Parameters of the system are given in Table 1. The system has an Active Power (P) of 30 MW, a Capacitive Reactive Power (Q_C) equal to 0.5 MVAR, and varying Inductive Reactive Power (Q_L) of 4, 7 and 10 MVAR, a load of 33 kV 50 Hz is connected to the network. To test the validity of the power system, both measured and calculated power factor ($\cos\varphi$) values of the system were obtained. And to evaluate the effect of the synchronous condenser on the network, two possible scenarios of the proposed network were analyzed; Firstly, with the synchronous condenser installed at the terminal end of the system network (position 1, as seen in Fig. 2.). And secondly, with the synchronous condenser installed at the beginning of the terminal of the network (position 2, as seen in Fig. 3.). Three sets of data's were analyzed for each study; data 1, 2, and 3, as tabulated in Table 1. The synchronous condenser allow for the input of reactive power on the electric-power network, which help in the voltage stability and power flow control of the system. Voltage stability and power flow control is very significant most especially for sensitive loads in electric-power systems. The schematic diagram of the electric-power system network without the synchronous condenser installed is shown in Fig. 1.

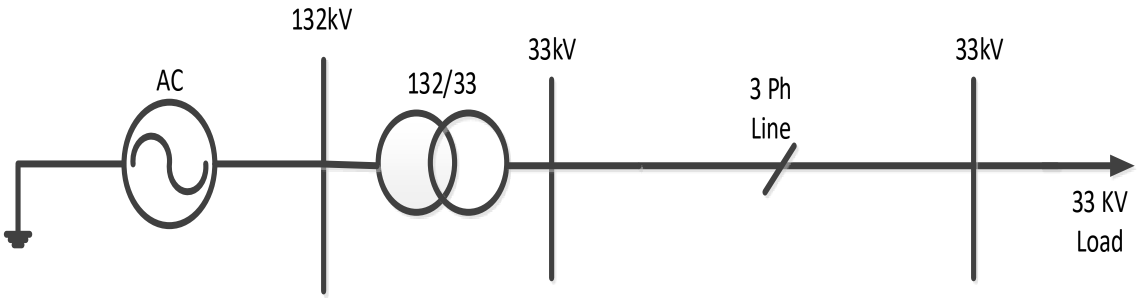

Fig. 1. Schematic diagram of the proposed 33 kV MV electric-power system network without the installation of the synchronous condenser equipment.

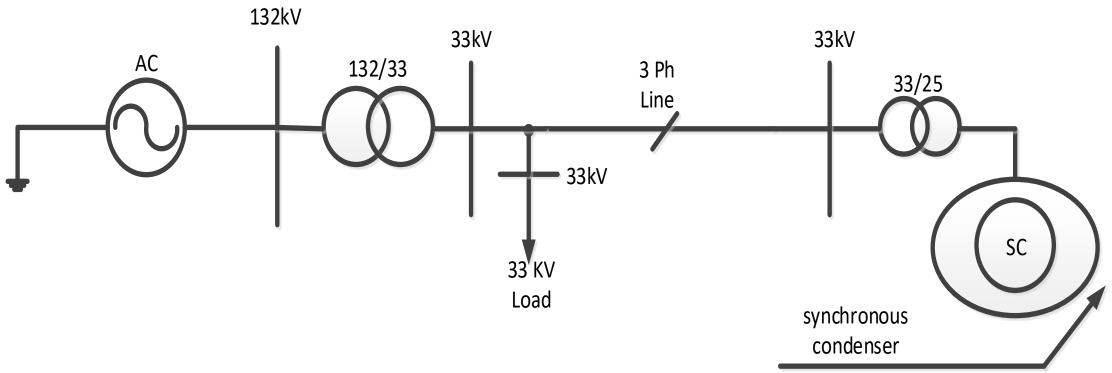

Fig. 2. Schematic diagram of the synchronous condenser equipment installed at the terminal end of the 33 kV MV power system network (Position 1).

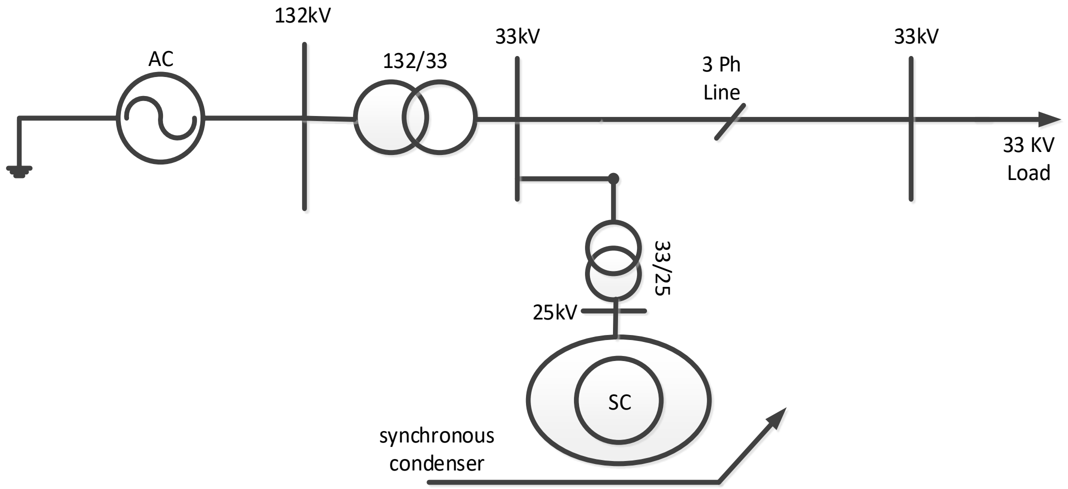

Fig. 3. Schematic diagram of the synchronous condenser equipment placed at the beginning of the 33 kV MV power system network (Position 2).

TABLE 1. VALUES OF POWER FACTOR OF LOAD ($\cos\varphi$) FOR THE 33 kV 50 Hz LOADS

33 kV 50 Hz load				$\cos\varphi$	
Set of Data's	***Active Power P (MW)***	***Inductive Reactive Power Q_L (MVAR)***	***Capacitive Reactive Power Q_C (MVAR)***	***Measured Value***	***Calculated Value***
1	30	4	0.5	0.99	0.99
2	30	7	0.5	0.97	0.97
3	30	10	0.5	0.95	0.95

A. *Calculated Power Factor of load ($\cos\varphi$) Values*

Both measured and calculated $\cos\varphi$ values are tabulated in table 1. The power factor of load calculation for data 1, 2, and 3, is done as follows;

Data 1;

$$cos\,\varphi = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}} = \frac{30}{\sqrt{30^2 + 3.5^2}} = 0.99$$

Data 2;

$$cos\,\varphi = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}} = \frac{30}{\sqrt{30^2 + 6.5^2}} = 0.97$$

Data 3;

$$cos\,\varphi = \frac{P}{S} = \frac{P}{\sqrt{P^2 + Q^2}} = \frac{30}{\sqrt{30^2 + 9.5^2}} = 0.95$$

A. *Voltage Values and Directions of Power Flow with the Synchronous Condenser Placed at the End of the 33 kV MV line (Position 1)*

When the synchronous condenser is installed at the end of the three-phase 33 kV MV electric-power system network linked to a 132/33 kV HV/MV transformer source. The observed voltage values at the sending and receiving end of the network is measured for the three set of data's, 1, 2 and 3, the voltage values and directions of power flow are shown in Table 2 and 3,. Table 2., shows the results of the voltage values and power flow direction obtained without the synchronous condenser connected to the end terminal of the network, there was generally large voltage difference (U_s-U_r) in the network and the direction of power flow is positive (+), which insinuate that voltage flows from the voltage sending (U_s) terminal to the voltage receiving (U_r) terminal of the network. While Table 3. depicts the voltage values and power flow direction with the synchronous condenser connected to the end terminal of the 33 kV MV network, in this case, small voltage differences were observed on the network and the direction of voltage flow is negative (-), this insinuating that power flows from the voltage receiving (U_r) end of the network terminal to the voltage sending (U_s) terminal end of the 33 kV MV network.

TABLE 2. VOLTAGE VALUES OBTAINED AND POWER FLOW DIRECTIONS OBSERVED WITHOUT (W/O) THE SYNCHRONOUS CONDENSER CONNECTED TO THE END TERMINAL OF THE 33 kV MV POWER SYSTEM NETWORK

Set of Data's	Sending Voltage (U_s)	Receiving Voltage (U_r)	Voltage Difference (U_s-U_r)	Power Flow Direction
1	32.95	32.39	0.56	+
2	32.00	31.70	0.30	+
3	31.70	31.30	0.40	+

TABLE 3. VOLTAGE VALUES OBTAINED AND POWER FLOW DIRECTIONS OBSERVED WITH THE SYNCHRONOUS CONDENSER CONNECTED TO THE END TERMINAL OF THE 33 kV MV POWER SYSTEM NETWORK

Set of Data's	Sending Voltage (U_s)	Receiving Voltage (U_r)	Voltage Difference (U_s-U_r)	Power Flow Direction
1	32.70	33.10	- 0.40	-
2	32.65	32,95	- 0.30	-
3	32.20	32.40	- 0.20	-

B. Voltage Values and Directions of Power Flow with the Synchronous Condenser Placed at the Beginning of the 33 kV MV line (Position 2)

Table 4 and 5 show the voltage values obtained when the synchronous condenser is installed at the beginning of the three-phase 33 kV MV electric-power system network. The voltage at the sending and receiving end of the network is measured for the three set of data's, 1, 2 and 3 as done earlier in the previous scenario. The directions of power flow are shown in Table 4 and 5. Table 4, illustrate the results of voltage values and power flow direction obtained without the synchronous condenser connected to the beginning terminal of the network, large voltage difference (U_s-U_r) is observed on the network and the direction of power flow is positive (+), which imply that power flows from the voltage sending (U_s) terminal to the voltage receiving (U_r) terminal of the network. Table 5., clearly show the voltage values obtained and the power flow directions observed when the synchronous condenser is connected at the beginning of the power line, larger voltage differences (U_s-U_r) is observed, as compared to the situation, when the synchronous condenser was not installed at the beginning terminal of the network and the direction of power flow is also positive (+), meaning that power flows from the voltage sending terminal (U_s) to the voltage receiving (U_r) terminal of the network. Suggesting that installing the synchronous condenser at the beginning of the network terminal has no significant positive influence on the voltage profile of the whole network. Furthermore, it is observed that the direction of power flow remains the same, meaning that there was no change in the direction of power flow on the 33 kV MV power line as seen in Table 4 and 5.

TABLE 4. VOLTAGE VALUES OBTAINED AND POWER FLOW DIRECTIONS WITHOUT THE SYNCHRONOUS CONDENSER CONNECTED TO THE BEGINNING TERMINAL OF THE THREE-PHASE 33 kV MV ELECTRIC-POWER SYSTEM NETWORK

Set of Data's	**Sending Voltage (U_s)**	**Receiving Voltage (U_r)**	**Voltage Difference (U_s-U_r)**	**Power Flow Directions**
1	32.90	32.35	0.55	+
2	32.74	31.70	1.04	+
3	32.45	30.98	1.47	+

TABLE 5. VOLTAGE VALUES OBTAINED AND POWER FLOW DIRECTIONS WITH THE SYNCHRONOUS CONDENSER INSTALLED AT THE BEGINNING TERMINAL OF THE THREE-PHASE 33 kV MV ELECTRIC-POWER SYSTEM NETWORK

Set of Data's	**Sending Voltage (U_s)**	**Receiving Voltage (U_r)**	**Voltage Difference (U_s-U_r)**	**Power Flow Direction**
1	32.70	31.90	0.80	+
2	32.10	31.25	0.85	+
3	31.40	29.60	1.80	+

3. Simulation Results and Discussion

MATLAB/Simulink is used for the simulation of the system model, The model consist of a 132 kV high voltage (HV) alternating current (AC) power supply source connecting a three-phase 33 kV medium voltage (MV) electric-power system network with the aid of a 132/33 kV HV/MV transformer. The 33 kV MV power system network is connected to the MV side of the 132/33 kV HV/MV transformer. A 33 kV 50 Hz load is attached to the three-phase medium voltage line. Two scenarios were studied; Scenario 1, when the synchronous condenser is located at the end terminal of the 33 kV MV power-system network. Scenario 2, when the location of the synchronous condenser is changed and installed at the beginning of the 33 kV MV electric-power Line. The proposed system MATLAB/Simulink simulation model is shown in Fig. 4.

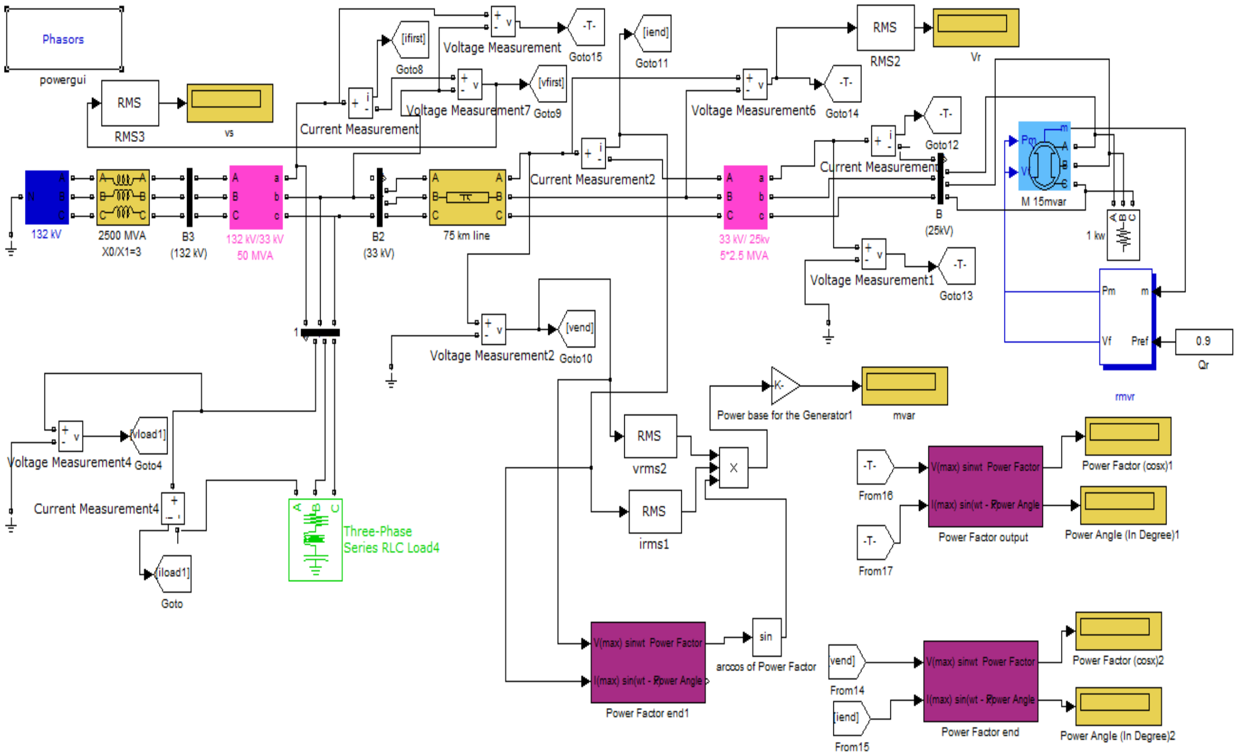

Fig. 4. MATLAB/Simulink simulation of the 33 kV MV power system network.

A.Simulation Results and Analysis with the Synchronous Condenser Placed at the End Terminal of the 33 kV MV line (Position 1)

Firstly, the power factor ($\cos\varphi$) values for data 1, 2, and 3 were measured and thereafter calculated, this is done as earlier stated to test the validity of the proposed power system. It was observed that the measured and calculated values of the power factors obtained were the same for the three sets of data's observed; this is presented in Table 1, simulation results for the voltage values obtained at the beginning terminal of the 33 kV medium voltage (MV) power system without and with the Synchronous Condenser Connected at the end terminal of the network is tabulated in table 2 and 3. And graphically illustrated with a three-dimensional (3D) diagram in Fig. 5., large voltage difference (U_s-U_r) is observed on the 33 kV medium voltage (MV) network and the direction of power flow is from the voltage sending (U_s) terminal to the voltage receiving (U_r) terminal of the power line for data's 1, 2, and 3 observed. At the beginning terminal of the line, the scheme uses up reactive power when the synchronous condenser is not connected to the end terminal of the network. And reactive power is injected onto the 33 kV medium voltage (MV) network when the synchronous condenser is installed at the end terminal of the network.

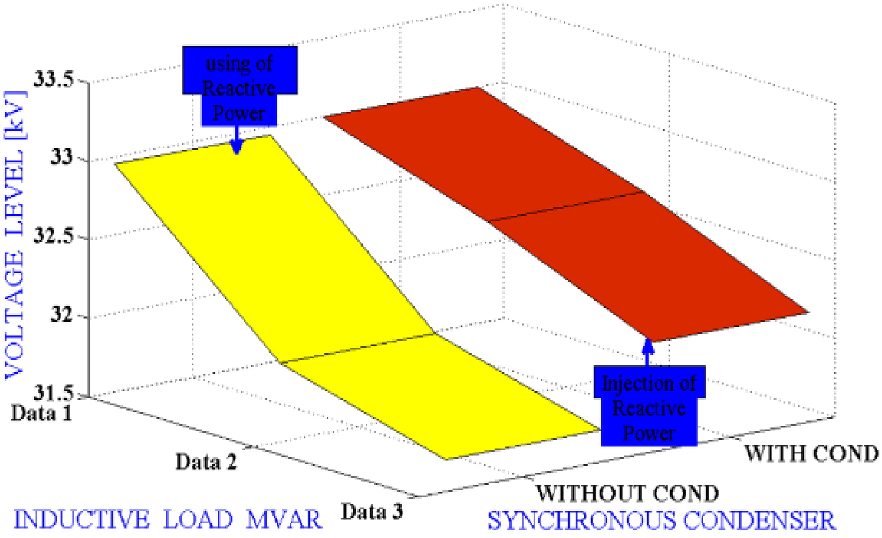

Fig. 5. Voltage values at the beginning terminal of the 33 kV MV power system network without and with the Synchronous Condenser connected at the end terminal of the network.

Fig. 6. illustrates the voltage values obtained at the terminal end of the 33 kV medium voltage (MV) power system network without and with the Synchronous Condenser Installed at the end terminal of the network. Results shows that when the synchronous condenser is not installed onto the end terminal of the electrical network, the power line uses up reactive power. But reactive power is injected into the 33 kV MV network, when the synchronous condenser is installed onto the terminal end of the network. Here, the results depict a small voltage difference on the power line and the observed power flow direction movement is from the receiving voltage (U_r) terminal end of the proposed scheme to the sending voltage (U_s) terminal end of the power system network, this is tabulated in table 3.

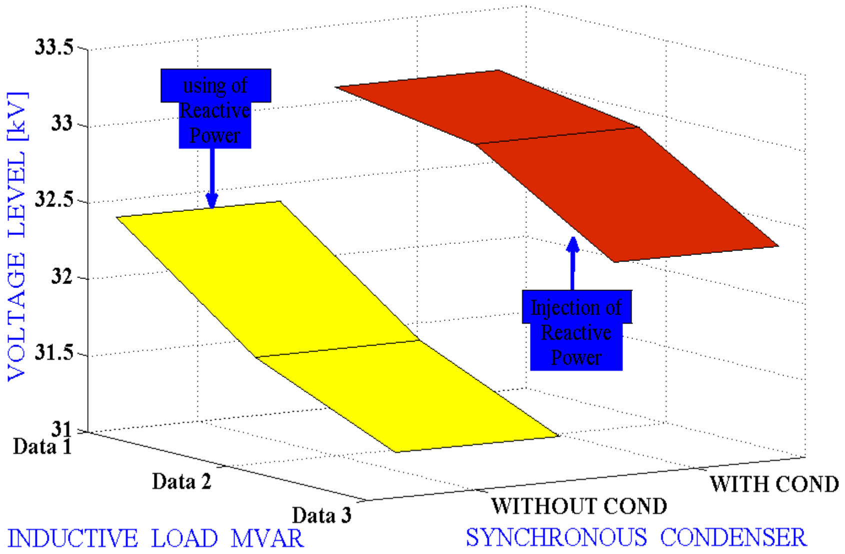

Fig. 6. Voltage values at the terminal end of the 33 kV MV power system network without and with the synchronous condenser installed at the end terminal of the network.

Furthermore, Fig. 7. vividly show the graphical illustration of the differences in voltage (U_s–U_r) values obtained at the beginning and end terminals of the 33 kV MV power-line without and with the synchronous condenser connected at the end terminal of the 33 kV MV power system network, and the observed directions of power flow for data 1, 2, and 3 is shown. Large voltage differences (U_s-U_r) is observed and the direction of power flow is from the sending voltage (U_s) terminal ends to the receiving voltage (U_r) terminal ends of the power line, which imply positive (+) directions of power flow for the situation without the synchronous condenser connected at the terminal end of the electric-power system network. The obtained voltage difference (U_s–U_r) for the observed data's 1, 2 and 3, when the synchronous condenser is connected at the terminal end of the power system network is small and the directions of power flow is from the receiving voltage (U_r) terminal end to the sending voltage (U_s) terminal end of the network under study, which means that the observed power flow direction is negative (-). This suggest that the situation with the synchronous condenser connected at the end terminal of the 33 kV MV electric-power system network gave a favourable result for enhanced voltage stability and power flow control compared with the situation without the synchronous condenser installed onto the network.

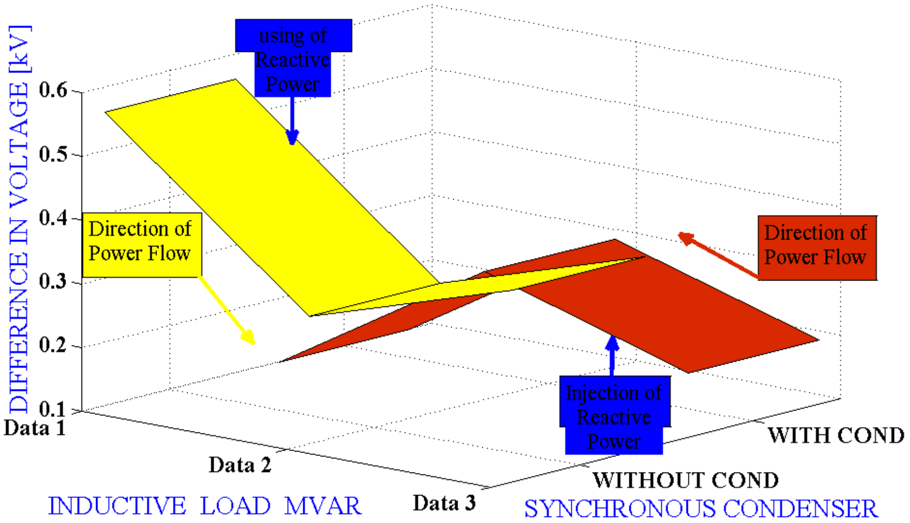

Fig. 7. The observed directions of power flow, and the obtained voltage difference (U_s-U_r) values at the beginning and end terminals of the 33 kV MV electric-power system network without and with the synchronous condenser connected at the terminal end of the network.

C. Simulation Results and Analysis with the Synchronous Condenser Placed at the Beginning of the 33 kV MV Power-line (Position 2)

Simulation results for the voltage values obtained at the beginning terminal of the 33 kV MV power system network without and with the Synchronous Condenser Connected at the beginning of the network is tabulated in Table 4 and graphically illustrated with a three-dimensional (3D) diagram in Fig. 8., there were large voltage difference observed on the 33 kV MV network and the direction of power flow is from the voltage sending (U_s) terminal of the network to the voltage receiving (U_r) terminal of the power line for the three set of data's observed. The difference between sending and receiving voltages (U_s-U_r) becomes larger as values of inductive reactive power (Q_L) increases. Moreso, it is observed that reactive power is being used without the synchronous condenser connected to the beginning terminal of the network. And reactive power is being injected onto the network as the synchronous condenser is connected to the beginning terminal of the network. The direction of power flow without and with the synchronous condenser device connected onto the beginning terminal of the network is from the voltage sending (U_s) terminal to the voltage receiving (U_r) terminal of the network, that is positive (+) direction, as can be seen in Fig. 8. and Table 4.

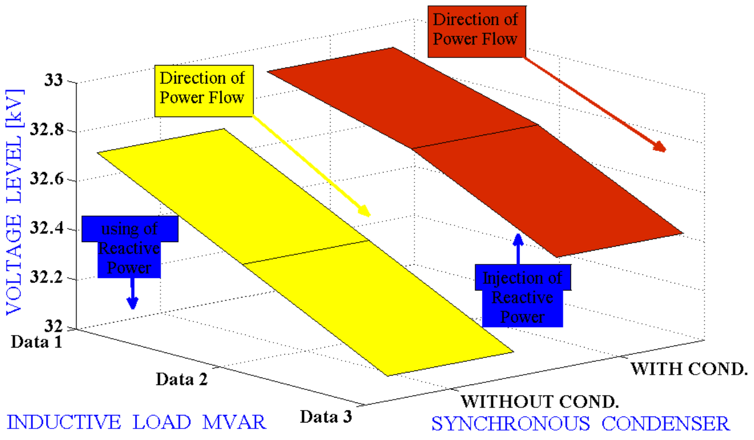

Fig. 8. Voltage values at the beginning terminal of the 33 kV MV power system network without and with the Synchronous Condenser Connected at the beginning of the network terminal.

The results obtained at the terminal end of the 33 kV MV electric-power system network without and with the Synchronous Condenser Installed at the beginning of the network is shown in Table 5 and graphically illustrated in Fig. 9., with a 3D diagram. From Fig. 9., it is seen that the values of the voltage difference (U_s-U_r) between the sending voltage (U_s) and receiving voltage (U_r) becomes even larger as the synchronous condenser is installed at the beginning of the 33 kV MV electric-power system network. Indicating that the result vividly shows a gradual increase in the voltage difference (U_s-U_r) on the power system network as values of inductive reactive power (Q_L) increases. Hence, implying that the values of the voltage difference (U_s-U_r) obtained is significantly larger when the synchronous condenser is connected at the beginning terminal of the electric-power system network as compared to the voltage difference values obtained without the synchronous condenser installed at the beginning terminal of the network. Fig. 9., and Table 5, further shows that the direction of power flow without and with the synchronous condenser device connected onto the network at the beginning of the line is from the voltage sending (U_s) terminal to the voltage receiving (U_r) terminal, that is positive (+) direction. It can as well be seen in Fig. 9., that without the synchronous condenser connected at the beginning of the system network, the power system is using reactive power. But with the synchronous condenser connected at the beginning of the network terminal, there is injection of reactive power onto the power system network.

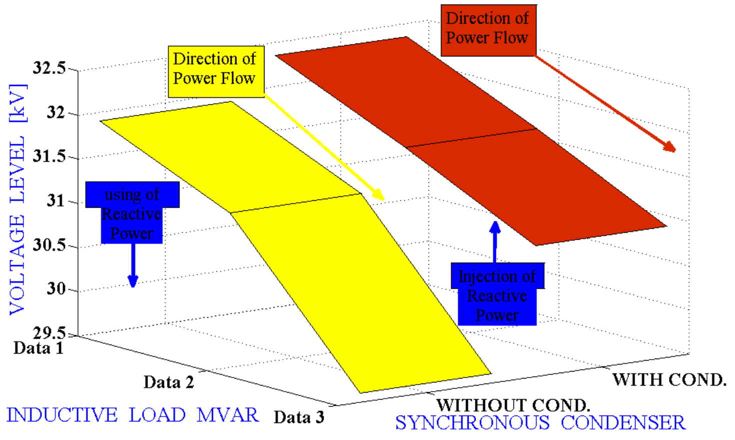

Fig. 9., Voltage values at the terminal end of the 33 kV MV power system network without and with the synchronous condenser installed at the beginning of the network terminal.

Graphical illustration of the comparison of the voltage differences (U_s-U_r) between the sending voltage (U_s) and receiving voltage (U_r) at the beginning and end terminals of the 33 kV MV electric-power system network without and with the synchronous condenser connected to the beginning of the network is shown in Fig. 10., and tabulated in table 4 and 5. Also, the observed directions of power flow for data 1, 2, and 3 is illustrated. Large voltage differences (U_s-U_r) is observed and the direction of power flow is from sending voltage (U_s) terminal ends to the receiving voltage (U_r) terminal ends of the electric-power system network, which indicate positive (+) directions of power flow for the situation without the synchronous condenser connected to the beginning terminal of the electric-power system network. The obtained voltage difference (U_s-U_r) for the observed data's 1, 2 and 3, when the synchronous condenser is connected at the beginning of the power system network is much larger and the directions of power flow is still from the sending voltage (U_s) terminal ends to the receiving voltage (U_r) terminal ends of the proposed network, indicating that the observed power flow direction is positive (+) for both situations, without and with the synchronous condenser installed at the beginning of the network. This implying that with the synchronous condenser connected at the beginning of the terminal of the 33 kV MV electric-power system network, a negative impact is observed on the voltage stability and power flow control of the proposed electric-power system.

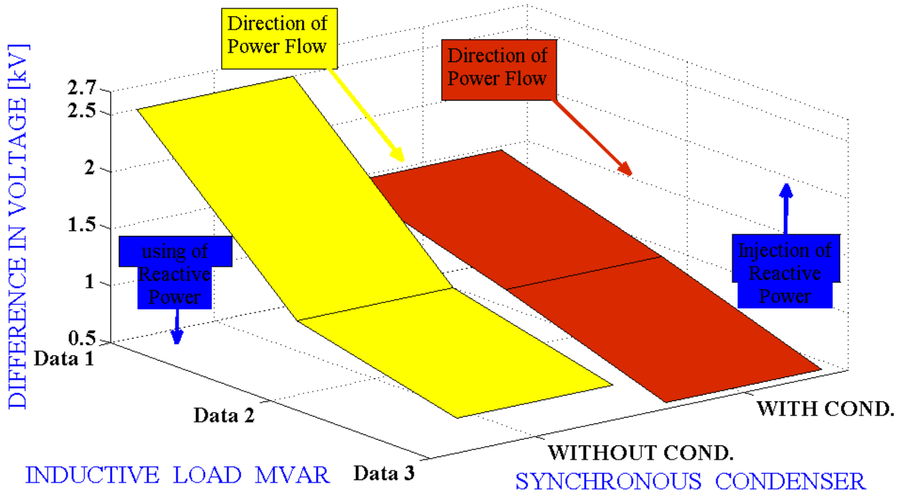

Fig. 10. The observed directions of power flow, and the obtained voltage difference (U_s-U_r) values at the beginning and end terminals of the 33 kV MV power line without and with the synchronous condenser connected to the beginning terminal of the network.

4. Conclusion

This research paper made a comparative analysis of the synchronous condenser on different positions in an electrical grid for voltage stability and power flow control. First, the synchronous condenser is placed at the end of the 33 kV MV electric-power line (Position 1) and thereafter, the synchronous condenser is placed at the beginning of the 33 kV MV electric-power line (Position 2). Results shows that the Synchronous condenser has a positive impact on the voltage stability and power flow control of the power system network when placed at position 1, compared to its location at position 2. The proposed analysis shows the efficiency of the synchronous condenser in voltage stability and power flow control. However, to obtain optimal behaviour of the electric-power system network, the synchronous condenser has to be placed at the end of a power network to avoid large values of voltage difference (U_s-U_r) between sending voltage (U_s) and receiving voltage (U_r). Moreover, a change in the direction of flow of power is observed, when the synchronous condenser is located at the end of the electrical power system, that is to say that power flows from the receiving voltage (U_r) terminals to the sending voltage (U_s) terminals. In conclusion, locating the synchronous condenser at the terminal end of an electric-power system network seems to be a good solution to voltage stability and power flow control in power lines. Additional analysis should be made to optimize reactive power compensation in a much larger electric-power system network with many nodes using the proposed analysis. However, the proposed method allows selecting a good location for placing the synchronous condenser for better system performance.

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Paper Seven

Comparative Review of Reactive Power Compensation Technologies

Famous. O. Igbinovia, Ghaeth Fandi, Jan Švec, Zdenek Müller, Josef Tlusty

Contributor	Statement of Contribution
Famous. O. Igbinovia (Candidate)	Paper writing and review (20%); Discussion (20%).
Ghaeth Fandi	Paper writing and review (20%); Discussion (20%).
Jan Švec	Paper writing and review (20%); Discussion (20%).
Zdenek Müller	Paper writing and review (20%); Discussion (20%).
Josef Tlusty	Paper writing and review (20%); Discussion (20%).

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Abstract: The quality of electrical power in a network is a major concern which has to be examined with caution in order to achieve a reliable electrical power system network. Reactive power compensation is a means for realising the goal of a qualitative and reliable electrical power system. This paper made a comparative review of reactive power compensation technologies; the devices reviewed include Synchronous Condenser, Static Var Compensator (SVC) and Static Synchronous Compensator (STATCOM). These technologies were defined, critically examined and compared, the most promising technology is recommended for the realisation of an effective, efficient, sustainable, qualitative and reliable electrical power network.

Keywords: Reactive power compensation; synchronous condenser; static Var compensator; static synchronous compensator; reactive power compensation technology

1. Introduction

There is a heightening concern in power efficiency and energy savings among policy makers, economics and academics from the aspect of technology, economic, policy and human behavior point of view. Thus, the needs to further promote and explore energy efficient, reliable and sustainable technology such as synchronous condenser for reactive power compensation in electrical power systems [1].

Reactive power (Q) is an expression used for the un-real power from inductive loads like motor or capacitive loads, which normally is not so much common. It is widely calculated in units of VARs, that is volt-amps reactive. In order to maintain the most advantageous circumstances for a power system from engineering and economical point of view, it is very important to always apply the most advantageous reactive power compensation technology in an electrical power system [2], [3]. Reactive power compensation is defined as the administration of reactive power to ameliorate the production of Alternating Current (AC) in an electrical network. The idea of reactive power compensation encompasses an extensive and divergent field of both system and consumers problems, mostly connected with power quality matters, since most power quality issues can be resolved with appropriate control of reactive power [4].

The basic function of any electric power system is to convey electricity reliably and at a well synchronized frequency and voltage. Reliable and efficient Power Systems has accomplished these goals through technological advancement. Reactive power compensation is an effective technique to enhance the electric power network, there is need for regulated reactive power compensation which can be done either with synchronous condensers, Static Var Compensators (SVCs) or Static Synchronous Compensators (STATCOM) [1], [4], [5].

There are different technologies for reactive power compensation, these includes; Capacitor Bank, Series Compensator, Shunt Reactor, Static Var Compensator (SVC), Static Synchronous Compensator (STATCOM), and Synchronous Condenser. But for the purpose of this paper, three different reactive power technologies are reviewed as possible sources for reactive power compensation. The technologies investigated includes; Synchronous Condenser, Static Var

Compensator (SVC) and Static Synchronous Compensator (STATCOM). The most promising technology is recommended for reactive power compensation in electrical power networks.

2. Synchronous Condensers

A. Definition and Overview

A synchronous condenser is a synchronous device that produces reactive power which leads real power by 90 degrees in phase [6]. It is a piece of equipment similar to a synchronous motor, whose shaft is not linked to anything but spins freely without constraint. Its objective is not to convert electric power to mechanical power or vice versa, but to regulate situations on the electric power transmission grid. Its field is regulated by a voltage regulator to either give rise to or assimilate reactive power as needed to modify the grids voltage, or to enhance power factor. The quantity of reactive power from a synchronous condenser can be steadily regulated. Reactive power from a synchronous condenser can build-up reactive current as voltage reduces. Nevertheless, synchronous machines have higher energy losses. Most synchronous condensers linked to electrical grids are rated between 20 Mvar and 200 Mvar and a great number of them are hydrogen cooled. There is no eruption threat as long as the hydrogen concentration is kept in good condition of above 70%, typically above 91% [7].

Synchronous condensers were once extensively utilized as a means of supplying reactive power compensation before the introduction of power electronic based devices. A number of synchronous condensers were used in electrical power systems beginning in the late 1920’s to the end of late 1970’s. Synchronous condensers have been relevant in the scheme of things in voltage and reactive power control for more than 50 years. Practically, a synchronous condenser is merely a synchronous machine linked to the power system. After the unit is synchronized, the field current is regulated to either generate or draw-up reactive power as needed by AC power systems. The device can provide incessant reactive power control when used with the right automatic exciter circuit. Synchronous condensers have been used at both distributions and transmission voltage levels to ameliorate stability and to support voltages within preferred boundaries under varying load states and emergency circumstances [4], [8].

However, synchronous condensers are infrequently used today because they need considerable foundations and a significant quantity of starting and protective gadgets. They also represent a part in short-circuit current, and they cannot be adjusted fast enough to balance speedy load changes. Furthermore, their losses are much higher than those related with static compensators, and the cost is much higher when likened with static compensators. Their merit lies in their high temporary over-load ability [4]. Synchronous condensers provide sustenance for network voltage by maintaining efficient and reliable operation of electrical power grids through reactive power compensation and extra short circuit power ability [9]. Synchronous condensers are well accepted technology for supplying reactive power and remedying power factor issues in industrial settings. Reliable Power Systems Synchronous Condensers are precisely designed to meet the requirements of hybrid renewable power systems. When compared with diesel generators, they help the diesels in controlling voltage. In high wind and/or solar times, the diesel generators are turned off, and the Synchronous Condenser handles voltage regulation on its own [10]. Synchronous condenser solutions are being initiated worldwide to play a part in the optimal use of energy resources and offer grid support for now and the future, in order to attain a reliable, secure, efficient, effective and sustainable electrical power supply [11]. The capacity of a synchronous condenser operation is depicted in figure 1.

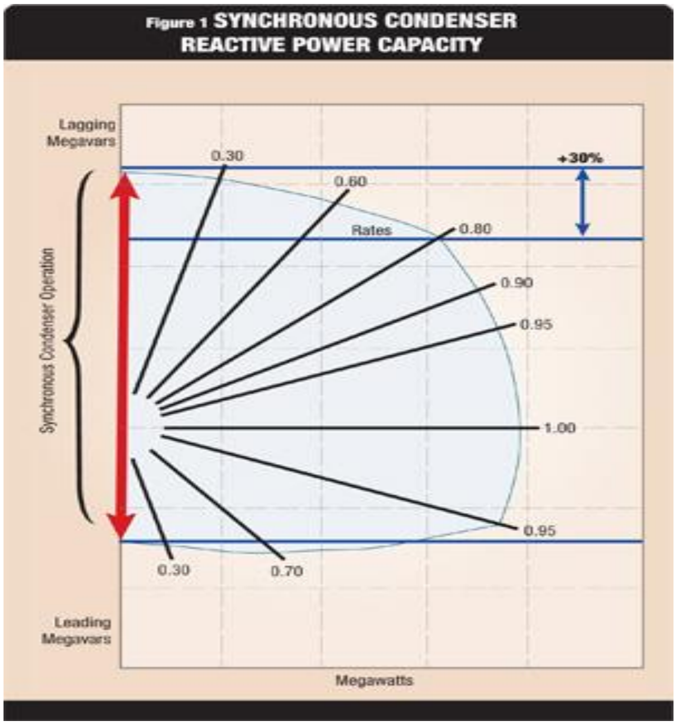

Fig 1 *Synchronous Condenser Reactive Power Capacity [12]*.

B. Types of Synchronous Condensers

Conventional/Traditional Synchronous Condenser: This is a synchronous motor without any mechanical load. Its field is regulated by a voltage regulator to give rise to or to draw-up reactive power to support an electrical power system voltage or to keep *a* systems power factor at a specified level. Synchronous condensers installation and operation are identical to big electric motors. After the unit is synchronized, the field current is regulated either to give rise to or to draw-up reactive power as needed by AC system. The machine can supply uninterrupted reactive power regulation when used with the appropriate automatic exciter. A rise in the equipments field excitation brings about the provision of magnetizing power (kVArs) to an electrical power system. Its major merit is the effortlessness in the regulation of the amount of correction. [5], [13]. A single-phase scheme with a synchronous condenser is shown in figure 2.

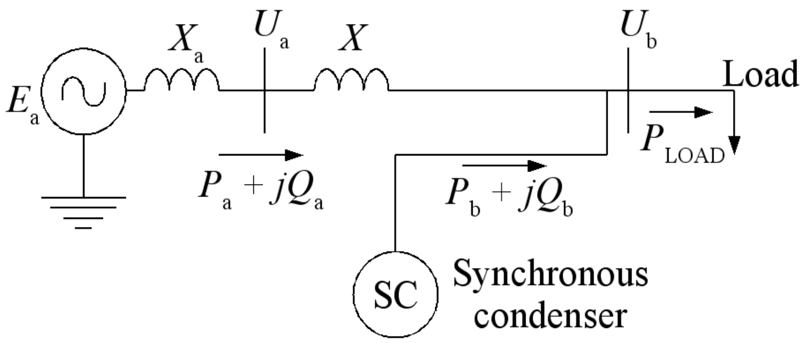

Fig 2 *Single phase diagram with a synchronous condenser connected to grid [13].*

Superconducting Synchronous Condenser (SuperVAR):

Only the field windings of the superVAR make use of high-temperature superconductor winding, which is made-cold with a cryocooler subsystem to about 35–40 K. The cryocooler module is laid in a stationary frame and helium gas is used to cool the rotor of the equipment. The stator winding is normal copper winding. Nevertheless, the winding is not placed in normal iron core teeth, since the iron core saturates owing to the high magnetic field, typically 1.5–2.0 T, built in by the field winding. Exclusively, the stator yoke (that is the back iron) uses magnetic iron to supply magnetic shielding and to convey flux between adjacent poles. The omission of iron in many of the magnetic circuits in this machine brings about a very low synchronous reactance (typically 0.3–0.5 p.u.). It is asserted that this Synchronous Condenser machines are more durable than conventional/traditional machines in the course of transient system faults, whereas, transient and sub-transient reactances are much the same to those of traditional machines. The lower synchronous reactance of the superVAR permits the operation of these machines at lower load angles than traditional machines [3], [14], [15].

SuperVAR synchronous condensers act as reactive power shock-absorbers of an electrical power system grid, effectively producing or drawing-up reactive power (VARs), and base on the voltage level of a transmission system. SuperVAR machines also react immediately to secure grids and electricity consumers in case of voltage sags and surges, which is recognized in the power industry as voltage transients, which can be given rise to by lightning storms, short circuits brought about by tree branches fleetingly touching lines, animals making contact with transmission elements, and other sources. SuperVAR machines and Dynamic-VAR (D-VAR) systems immediately stabilizes voltage and supply utilities with economical techniques to actively improve the reliability and maximize the power of transmission grids [14]. The conceptual diagram of a Dynamic Synchronous Condenser (DSC) can be seen in figure 3. (a) and (b).

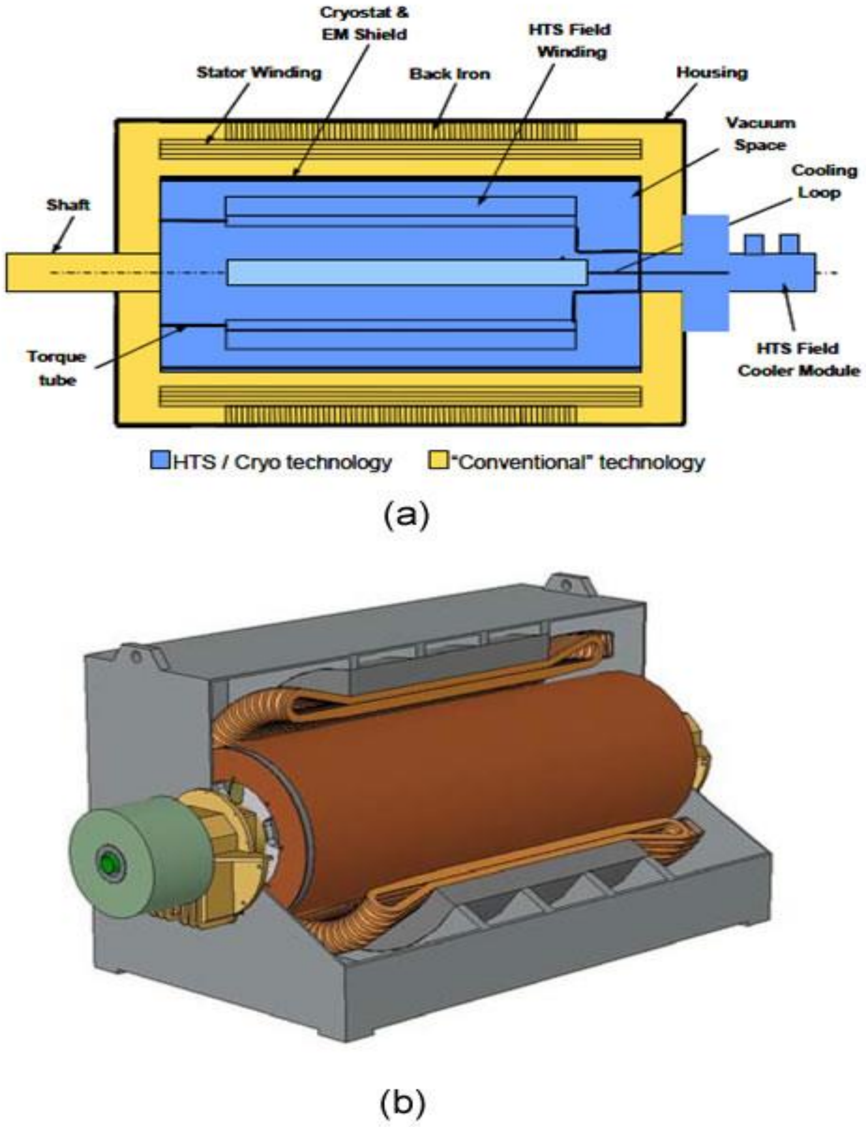

Fig 3. Conceptual diagram of a DSC [15]. (a) Superconducting field winding in cryocooler, (b) DSC model picture.

3. Static VAR Compensator (SVC)

A. Definition and overview

A Static Var Compensator (SVC) is a thyristor-controlled (since it is thyristor controlled, thus it is called static) generator of reactive power, either lagging or leading, or both. This piece of equipment is also called a static reactive compensator. An SVC is a high voltage device that regulates effectively the network voltage at its coupling end. Its major function is to keep the network voltage constantly at a set reference point. Some other control characteristics of SVC are: voltage control, reactive power control, damping of power oscillations, and unbalance control. The design and configuration of an SVC device is all the time modified to the particular project specifications. An SVC is one of the regulators founded on Power Electronics and other static devices known as Flexible Alternating Current Transmission Systems (FACTS) regulator, which is used to improve the ability and the flexibility of a transmission network. [16], [17], [18].

Static Var Compensator is a shunt-linked static VAR producer or assimilator whose output is regulated to exchange capacitive or inductive current so as to keep in good condition or regulate specific parameters of an electrical power system, typically bus voltage. SVC is founded on thyristors without gate turn-off ability. The operating concept and features of thyristors achieved variable reactive impedance SVC includes two main parts and their fusion: Thyristor-controlled Reactor (TCR) and Thyristor-switched Reactor (TSR); and Thyristor-switched capacitor. The objectives of SVC design are reactive and load imbalance compensation, and with the use of traditional quantities in its regulator, it may be utilized in collaborative compensation methods for smart grids [19], [20].

B.Types of Static Var Compensator (SVC)

Thyristor-controlled Reactor (TCR): TCR is defined as a shunt-linked thyristor-controlled inductor whose effective reactance is regulated in a continuous manner by partial conduction regulation of the thyristor valve. A thyristor-controlled reactor (TCR) is one of the traditional SVC used in the field of power quality enhancement. With the TCR type of SVC put together with fixed capacitors, when operating the system with a small reactive power, almost 100% reactive power is produced at the reactor unit and the general system reactive power is decreased. It can draw-up sustained reactive power at the primary frequency of the power system network, but it delivers appreciable odd harmonics which could cause many unpleasant consequences, such as; over currents, extra losses, and noises to telecommunication systems [18], [21], [22]. One-line diagram to compensate reactive power and voltage flicker enhancement in power system comprising Electric Arc Furnace (EAF) with a thyristor regulated reactor compensation, and fixed capacitor (TCR/FC) is shown in figure 4. [23]. TCR is also illustrated in figure 5 and 6. [19].

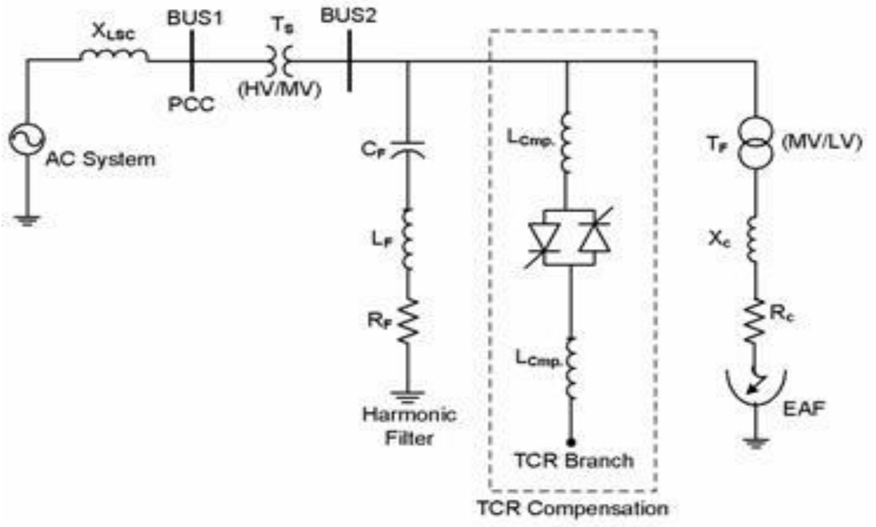

Fig 4 *Configuration of a TCR/FC connected to an EAF [23]*.

Thyristor-Switched Reactor (TSR): This is defined as a shunt-linked, thyristor-switched inductor whose effective reactance is differed in a stepwise appearance by full-conduction or zero-conduction management of the thyristor valve. Thyristor Switched Reactors are shunt compensators that can draw-up reactive power. The TSRs operating principle is simple; it has a delay of one half cycles and does not generate harmonics. The most general design of an SVC is made-up of a fixed shunt capacitor (FC) and a TCR. Filters are conventionally used to draw-up harmonic produced by SVC design and large industrial loads [24], [25]. A typical TSR can be seen in figure 5. [19].

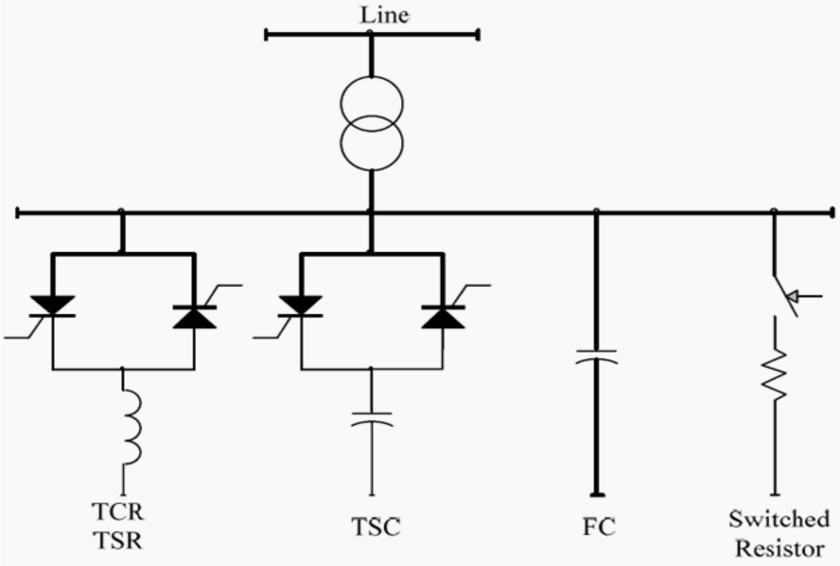

Fig 5. *Static VAR Compensators (SVC): TCR/TSR, TSC, FC and Mechanically Switched Resistor [19]*.

Thyristor-Switched Capacitor (TSC): TSC is defined as a shunt-linked, thyristor-switched capacitor whose effective reactance is differed in a stepwise way by full-conduction or zero-conduction operation of the thyristor valve. It has similar composition and same operational mode as TSR, but the reactor is substituted by a capacitor. The reactance can only be either fully connected or fully disconnected zero due to the features of capacitor [24], [26]. The reactive power of a TSC is modified in steps decided by the number of banks of the capacitor. [21]. A typical TSC is illustrated in figure 5 and 6.

Thyristor-Controlled Reactor and Thyristor-Switched Reactor (TCR/TSR) Combined: TCR and TSR are both made-up of a shunt-linked reactor regulated by two parallel, reverse-controlled thyristors. TCR is regulated with thorough firing angle input to function in a continuous way, while TSR is regulated without firing angle control which brings about a step change in reactance. TSC has the same make-up and same operational mode as TSR, but the reactor is substituted by a capacitor. The reactance can only be either fully connected or fully disconnected zero due to the features of capacitor. With non-identical combinations of TCR/TSR, TSC and fixed capacitors, an

SVC can meet various requirements to draw-up or produce reactive power from or to the transmission line, The TSR system provides stepped variation of current and TCR provides consistent variation of current [19], [21], [26], [27].

To make-up for the limitations of the TSC, variable reactors are linked in parallel so that the general network reactive power can be fine-tuned continuously. The combined type has the merits of both the TCR and TSC, it is normally suited to a capacitor in a substation for power system transmission lines, which must regulate reactive power for both the leading and lagging phases, usually it is standing by at zero (0) VAR state, and must modify reactive power speedily when a fault happens on the line. Appropriate Static Var Compensator (SVC) technology combinations are normally selected base on several factors such as the responsibility, minimum adjustment width, operating efficiency and economy. The diagram of an SVC combined technology is shown in figure 5 and 6. [19], [21].

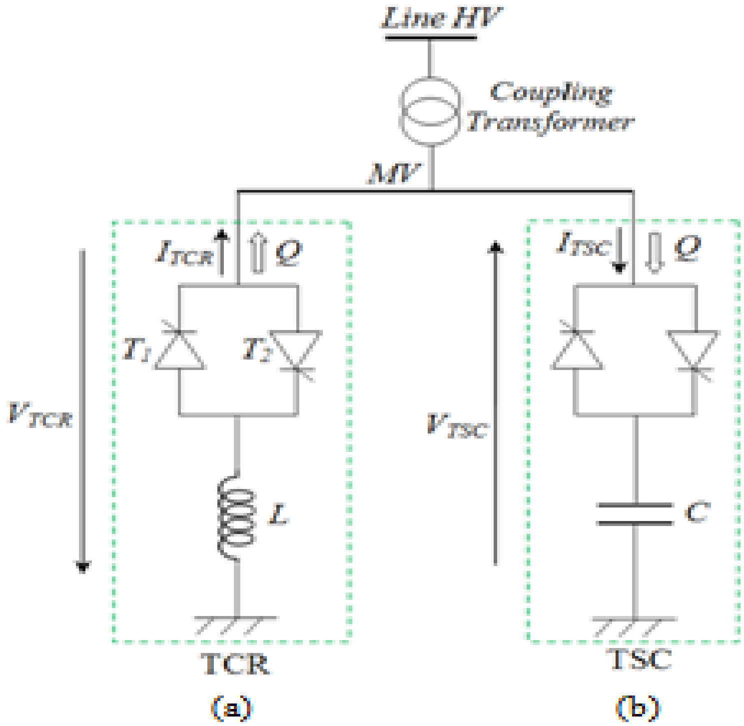

Fig. 6. *Structure of SVC Device, TCR and TSC Combined, (a)TCR and (b) TSC [28]*.

4.Static Synchronous Compensator (STATCOM)

Static synchronous compensators (STATCOMs) are part of FACTS device lineage. Their primary aim is to provide a fast acting, precise, and adjustable quantity of reactive power to an AC power system network to which they are linked. STATCOMs accomplish this by modifying the magnitude and polarity (phase) of the reactive constituent of the current flowing into and out-of their AC side. This allows STATCOMs to regulate the quantity and direction of movement of the reactive power swapped with the AC power systems. They are frequently applied for dynamic power factor correction, such as dynamic reactive power compensation, in industrial machinery working with large arbitrary peaks of reactive power needed. STATCOMs multiply the power factor of machinery, reduces voltage variations at machinery input, which prevents harm to the plant, and minimizes equipments operating costs [29].

STATCOMs can be used for voltage compensation at the receiver end of AC transmission system lines [29]. Figure 7 shows a Single Machine Infinite Bus (SMIB) system, with STATCOM connected at the middle of the transmission line [30].

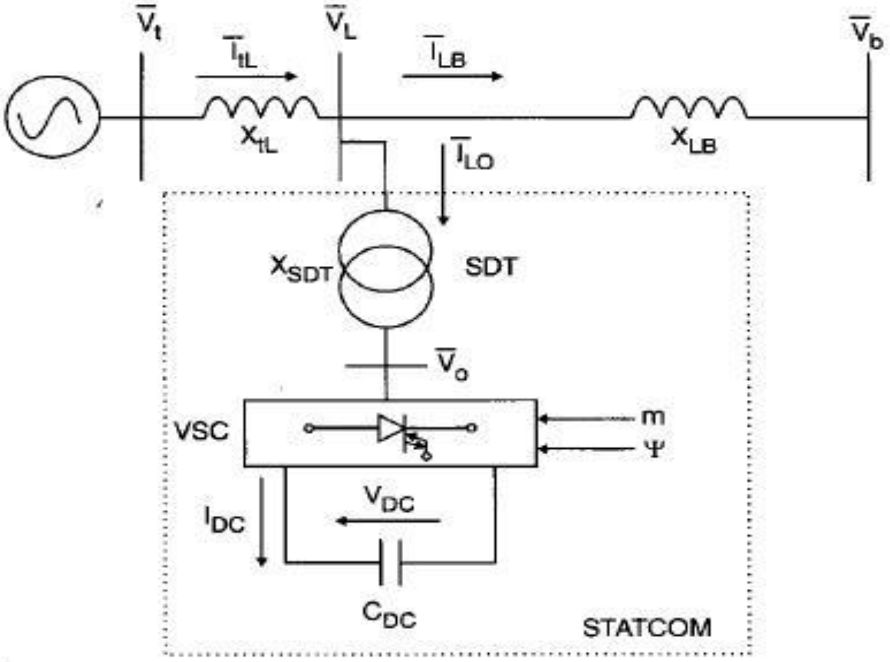

Fig. 7. *STATCOM installed in a Single Machine Infinite Bus (SMIB) system.[30].*

5. Technology Comparison and Selection

Here, three technologies have been examined, selection of the preferred technology will be made base on the following yardsticks; Control Coordination, Harmonics, Low-Voltage Ride-Through, Maintainability, Availability of Spare-parts, and Overload Duty-Cycle [5], [8], [31], [32].

Control Coordination: Examining the three technologies, both SVC and STATCOM applications stands for a notable risk of control coordination, making control coordination a challenge in SVC and STATCOM devices. And a plus for synchronous condensers compared to the other two technologies.

Harmonics: Both SVC and STATCOM technologies have the potential to produce harmonics, while the synchronous condenser does not. In addition to not producing harmonics, a synchronous condenser can act as a sink for harmonics in a network were harmonics do occur. This attribute benefits the synchronous condenser.

Low-Voltage Ride-Through: Looking at low-voltage ride-through, the SVC performance is less appealing than synchronous condenser or STATCOM. Synchronous condensers are a long-standing answer as reactive power sources that can and do ride-through low-voltage situations.

Maintainability: One of the demerits normally connected with synchronous condensers is maintainability due to friction and wear. Static devices do require maintenance of auxiliary cooling systems, valve replacements, and control system upgrades. They also need special training of maintenance personnel who may not be used to working on such devices. Assessing the three technologies, the anticipated maintenance and up-keep costs for synchronous condenser technologies, and that of static technologies are even. In some situation, synchronous condenser maintenance may be simpler than that of an SVC and a STATCOM. Thus, there is no defined advantage in maintenance as regard the technologies reviewed.

Availability of Spare-Parts: One of the difficulties connected with maintaining older equipment has to do with capability to obtain needed spare parts. Advancements in technology are normally regarded as positive in terms of cost, performance or both. On the other hand, old technology is occasionally regarded as obsolete or ineffective, when in fact it may not be. Considering availability of spare-parts; particularly beyond twenty to thirty year window, there is greater certainty of parts and support for synchronous condenser-based reactive power device.

Overload Duty-Cycle: The synchronous condenser is well suited to manage overload duty. Depending on the design of the machine, and ceiling of the excitation system, the occasional overload rating of a synchronous condenser can be twice nameplate or more, for several seconds. This type of duty-cycle favours the synchronous condenser over SVC and STATCOM technologies.

6. Conclusion

All three technologies are capable of supporting power system networks. Using the criteria’s listed above, this review suggest that the synchronous condenser technology is the most adequate and the best solution for reactive power correction in power system network. It is the most effective device to improve power systems performance; it helps to increase reliability and the quality of power delivery in a network. Synchronous condensers will be used on a much wider scale in the future as grid performance and reliability becomes an issue of more importance to policy makers, economics and academics, since having better grid controllability will allow utilities to reduce investment, most especially on a long-term basis. Further research should be on comparing experimental and simulation results for the three reactive power compensation technologies on a grid setup and the authors are planning to do further studies in this area of concern.

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