CZECH TECHNICAL UNIVERSITY IN PRAGUE
Faculty of Electrical Engineering
Department of Electrical Power Engineering

A Stand-Alone Power Generation and Smart Distribution systems

Doctoral thesis

Author: Mr. Urbanus F. Melkior

Supervisor: Prof. Ing. Josef Tlustý CSc.
Supervisor specialist: Doc. Ing. Zdeněk Müller Ph.D.

Study program: Electrical Engineering and Information Technology (P2612)
Branch of study: Electric Power Engineering (3907V001)

May 2023, Prague

ACKNOWLEDGEMENT

I would like first to give my heartfelt to God the almighty Father for his glorious guidance. Also I would like to thank everyone who contributed in one way or another to complete this work and complete my studies. I sincerely thank my family, particularly my wife, children and parents for their great support throughout the study. My Special thanks go to my supervisor Prof. Ing. Josef Tlustý, CSc. for valuable advice, countless ideas and excellent access to work management. My gratitude thanks also be extended to my supervisor specialist and Head of the Department of Electrical Power Engineering, Faculty of Electrical Engineering, Czech Technical University in Prague Doc. Ing. Zdeněk Müller, PhD. for valuable advice, ideas and very valuable consultations. My sincere thanks also go to Dr. Andrew Kassembe for the support and encouragement during my study. My thanks also go to Dr. Erick V. Mgaya from the Arusha Technical College for his kind assistance during my study. Special thanks also go to Asst. Prof. Ghaeth Fandi for his assistance.

DECLARATION

I hereby declare I have written this doctoral thesis independently and quoted all the sources of information used in accordance with methodological instructions on ethical principles for writing an academic thesis. Moreover, I state that this thesis has neither been submitted nor accepted for any other degree.

Prague, 26th May 2023

…………………………………

Urbanus F. Melkior

ABSTRAKT

Samostatné energetické systémy jsou stále více preferovanými možnostmi ve vzdálených a ostrovních lokalitách, kde není technicky možné se připojit k síti. Využití zdrojů větrné a vodní energie pro výrobu energie v oblasti s bohatými zdroji může být nástrojem při podpoře ekologické a čisté výroby energie pro izolované komunity. Nicméně, protože větrná energie podléhá přerušované dodávce, výroba elektřiny nemusí vždy odpovídat poptávce. Pro zajištění konzistentního napájení je nutné skladování energie.

Hybridní napájecí systémy nabízejí četné výhody, jako je zvýšená účinnost, spolehlivost a bezpečnost při minimalizaci provozních nákladů. Hlavní překážkou, s níž se potýkají aplikace hybridních energetických systémů, je však splnění požadavků na zatížení v rámci specifikovaných omezení. To vyžaduje účinnou kontrolu a koordinaci každé jednotky na výrobu energie. Zajištění odolnosti systému řízení energie je navíc zásadní, aby se zabránilo výpadkům systému v případech, kdy napájení z energetických zdrojů nestačí k podpoře všech zátěží.

Studie podrobně popsala způsob provozu a řízení hybridního energetického systému navrženého pro samostatný provoz. Systém podle této studie se skládá z větrné turbíny, palivového článku, elektrolyzéru, akumulátoru a skupiny zátěží. Navržená strategie řízení má dvouúrovňovou strukturu, přičemž první úrovní je systém energetického managementu a regulace výkonu. Jeho primárním cílem je zajistit, aby byl systém dobře koordinovaný a řízený.

Tento systém také zvládá plánování zátěže v reakci na výkyvy větru, a to i v případech, kdy akumulace energie nestačí k zabránění selhání systému. Vytváří dynamické referenční pracovní body pro jednotlivé dílčí systémy na základě převládajících větrných a zátěžových podmínek. Místní regulátory pro větrné turbíny, palivové články, elektrolyzéry a akumulátorové jednotky pak regulují jejich provoz v souladu s těmito referenčními body.

Rychlost rotoru větrné turbíny je regulována místním ovladačem pro extrakci referenčního výkonu z kolísavého větru. Vodíkový regulátor a boost konvertor řídí palivový článek, zatímco buck-konvertor řídí elektrolyzér. Pro řízení nabíjení a vybíjení bateriového úložného systému se používá obousměrný DC-DC měnič. Řídicí systém je navržen pomocí softwaru MATLAB Simpower a vyhodnocen za různých podmínek větru a zatížení. Získané výsledky jsou prezentovány a analyzovány.

KLÍČOVÁ SLOVA

Samostatné energetické systémy, obnovitelné zdroje, větrná elektrárny, palivové články, vodní elektrárny, skladování energie, řízení energetického systému, stabilita energetického systému, distribuční soustava

ABSTRACT

Stand-alone power systems are increasingly as preferred options in remote and island locations where it is not feasible technically to connect to the grid. Tapping of wind and hydro power resources for energy generation in the area with plentiful sources of can be an instrumental in promoting eco-friendly and clean energy production for isolated communities. Nonetheless, because wind energy is subject to intermittent supply, electricity generation may not always align with demand. To ensure consistent power supply, energy storage is necessary.

Hybrid power systems offer numerous advantages such as enhanced efficiency, reliability, and security while minimizing operational costs. However, the major obstacle faced by hybrid power system applications is meeting the load demand within specified constraints. This necessitates the need for effective control and coordination of each energy generation unit. Additionally, ensuring the resilience of the energy management system is crucial to avoid system blackouts during instances where power from energy sources is insufficient to support all loads.

The study detailed the operation and control approach for a hybrid power system designed for stand-alone operation. The system under this study comprises of a wind turbine, a fuel cell, an electrolyzer, a battery storage unit, and a group of loads. The proposed control strategy has a two-level structure, with the first level being the energy management and power regulation system. Its primary aim is to ensure that the system is well-coordinated and controlled.

This system also manages load scheduling in response to wind fluctuations, even in cases where energy storage is insufficient to prevent system failures. It creates dynamic reference operating points for individual sub-systems based on the prevailing wind and load conditions. Local controllers for wind turbines, fuel cells, electrolyzers, and battery storage units then regulate their operations in accordance with these reference points.

The rotor speed of a wind turbine is regulated by the local controller to extract the reference power from the fluctuating wind. The hydrogen regulator and boost converter control the fuel cell, while the buck-converter controls the electrolyzer. To manage the charging and discharging of the battery storage system, a bi-directional DC-DC converter is utilized. The control system is designed with MATLAB Simpower software and evaluated under diverse wind and load conditions. The obtained results are presented and analyzed.

KEYWORDS

Stand-alone Power Systems, Renewable Surces, Wind Generation, Fuel Cell, Hydro Power, Energy Storage, Power System Control, Power System Stability, Distribution system

CONTENTS

LIST OF ABBREVIATIONS

AFC	Alkaline Fuel Cell
ANFIS	Adaptive Neuro-Fuzzy Inference System
DFIG	Doubly-fed Induction Generator
DMFC	Direct Methanol Fuel Cell
EIA	Energy Information Administration
EMPRS	Energy Management and Power Regulation System
EV	Electric Vehicle
FSC	Full Scale Power Converter
HFAC	High Frequency Ac- coupled
IG	Cage Induction
IPM	IPM Interior Permanent Magnet
IPMSG	Interior Permanent Magnet Synchronous Generator
KOH	Potassium Hydroxide
MAS	Multi-Agent System
MCFC	Molten Carbonate Fuel Cell
MMF	Magneto-motive force
NiCad	Nickel/ Cadmium
NiMH	Nickel/ Metal Hydride Pcomp Compressor Power
PEM	Proton Exchange Membrane
PEMFC	Proton Exchange Membrane Fuel Cell
PFAC	Power Frequency Ac-coupled
PHEV	Plug-in Hybrid Electric Vehicle
PID	Proportional, integral and derivative
PMG	Permanent- Magnet Generator
PMSG	Permanent- magnet Synchronous Generator
PWM	Pulse-width Modulation
SCIG	Squirrel- Cage Ibduction Generator
SG	Synchronous Generator
SMES	Super- Conducting Magnetic Energy Storage
SPM	Surface Permanent Magnet
SOC	State of Charge
SOFC	Solid Oxide Fuel Cell

SOH	State of Health
VRLA	Valve-Regulated Lead -Acid
WECS	Wind Energy Conversion System

LIST OF FIGURES

1 INTRODUCTION

1.1 Thesis organization

This dissertation is divided into six chapters, including the introduction and conclusion. The introductory chapter "**standalone power generation**" is focused on approaching the issue of power generation in terms of legislation, defining the parameters of power generation, power distribution systems, and power storage. The sources of power generation highlighted in this dissertation are wind and hydropower.

The chapter "**wind energy**" discussed in detail the technology which focuses on the electrical part wind turbine and generators. The chapter also highlighted on various technology of generators suitable for wind energy conversion systems.

Further to that, the dissertation has chapter hydropower system. This contains various technology used in hydropower systems including various types of turbines and various generator used with hydropower system. Furthermore, the modelling of the system was also presented.

Also, the dissertation contains the chapter of energy resources optimization using Homer computer software. The resources optimized are wind energy, hydropower, and energy storage.

1.2 State of art

Standalone power generation can provide several benefits, including increased energy independence, reduced dependence on fossil fuels, and lower electricity costs. However, it also requires significant upfront costs for installation and maintenance of the equipment. Nevertheless, as technology continues to advance and costs continue to decrease, standalone power generation is likely to become more widely adopted in the coming years.

Increased energy independence: By generating their own electricity, users can become less reliant on centralized power grids and their associated infrastructure. This is especially useful in remote areas where grid power may not be available or reliable. It also provides a sense of control over energy usage and costs.

Reduced dependence on fossil fuels: Many standalone power generation technologies rely on renewable energy sources such as solar, wind, and hydro power. This reduces reliance on finite fossil fuels, which are a finite resource and also have significant environmental impacts when extracted, transported and burned.

Lower electricity costs: Once the initial installation costs are paid off, standalone power generation can provide electricity at a lower cost than grid power. This is especially true for solar and wind power, which have no fuel costs.

Environmental benefits: Renewable energy sources used in standalone power generation produce fewer greenhouse gas emissions and pollutants than traditional power generation sources such as coal, natural gas or diesel. This means that standalone power generation can help reduce local air and water pollution, and mitigate climate change impacts.

Despite these benefits, standalone power generation also comes with some challenges. The upfront costs of installation can be significant, especially for large-scale projects, and the maintenance requirements must also be considered. Additionally, standalone power generation may not be suitable for all areas or situations, such as where there is limited sunlight or wind, or where a high demand for energy cannot be met by the available technology.

However, as technology continues to improve and costs decrease, standalone power generation is likely to become more widely adopted, and this could bring significant benefits to individuals, businesses, and communities around the world

A smart distribution system, also known as a smart grid, is an advanced electrical power system that incorporates innovative technologies and communication systems to improve the efficiency, reliability, and safety of energy distribution.

Smart distribution systems are designed to meet the growing demand for electricity while minimizing environmental impact, reducing costs, and improving the quality of service for consumers.

Some of the key components of a smart distribution system include:

Advanced Metering Infrastructure (AMI): This is a network of smart meters that collect data on energy consumption and communicate with the utility company to provide real-time information on usage, billing, and outage management.

Distribution Automation: This technology enables utilities to remotely monitor and control the distribution network, including the ability to reroute power around faults, and quickly restore power in the event of an outage.

Renewable Energy Integration: Smart distribution systems can integrate renewable energy sources such as solar, wind, and hydro power into the grid, allowing for more efficient and sustainable energy generation.

Energy Storage: Energy storage systems such as batteries can be used to store excess energy generated by renewable sources during low demand periods and release it during peak demand periods, improving overall grid stability and reducing costs.

Demand Response: Smart distribution systems can enable utilities to incentivize customers to reduce their energy consumption during periods of high demand, which can help avoid the need for expensive upgrades to the grid.

Cybersecurity: With the increased use of digital technologies and communication systems, smart distribution systems must also incorporate robust cybersecurity measures to ensure the security and privacy of data and prevent cyber-attacks.

Overall, a smart distribution system represents a significant improvement over traditional grid infrastructure, providing greater flexibility, efficiency, and resilience in the face of changing energy demands and environmental challenges.

1.3 Defining objectives

Following the previous subchapter, the following objectives are set:

1. To ensure individual power plants operate at their optimal level.
2. To ensure proper management of state of charge (SOC), for a longer life of battery storage system.
3. To ensure efficient operation of the fuel cell.
4. To ensure continuous operation of the system

2 HYBRID POWER SYSTEM

2.1 Introduction

A stand-alone power system is a self-sufficient electricity generation system that operates independently and is not connected to the main grid. These systems are commonly used in isolated areas, such as islands or remote parts of a country where a grid connection is not economically feasible. The power for these systems can be generated from renewable energy sources such as wind, hydro, or solar, as well as from diesel generators.

Diesel generators are a popular choice for remote area power systems due to their reliability, low installation costs, ease of starting, and compact power density [1], [2]. In stand-alone power system applications, the size of the diesel engines is determined by the peak system load requirements. However, diesel generators have certain disadvantages, including the fact that they are becoming more expensive to operate due to the rising cost of diesel fuel [3]. Additionally, they require a high level of maintenance costs [4], [5]. Diesel generators are also most efficient when operating at their rated power output [5], and consume more fuel when operating under loaded constant speed. As a result, the manufacturers recommend that diesel generators be operated at least 30% of their load capacity to achieve optimal performance [6]. Figure 1.1 illustrates the operation of a 50 kVA diesel generator, which operates at a high efficiency of approximately 33% when running at its rated load. However, when loaded up to 30% of its rated capacity, its efficiency is reduced to 20%.

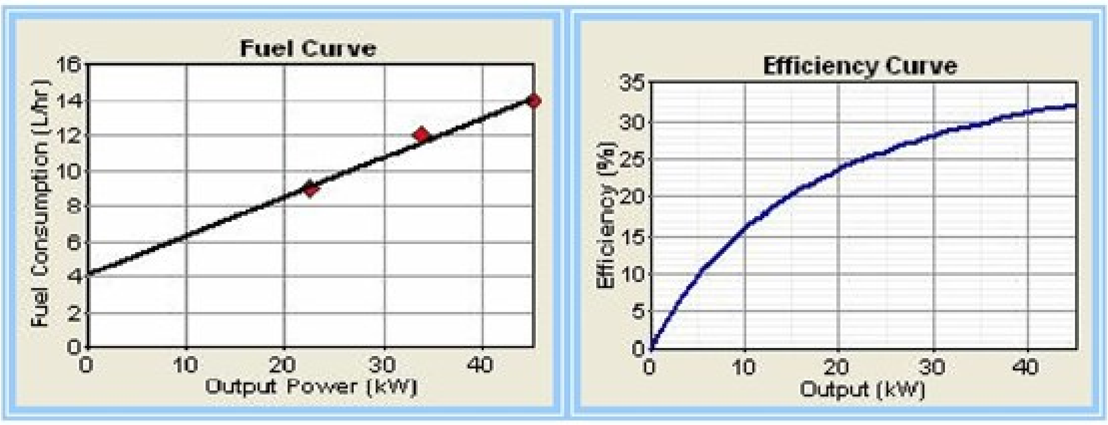


Figure 2.1 Typical fuel consumption and fuel efficiency curve of a diesel generator

Continuous fuel supply is crucial for Diesel generators to function, but their use results in greenhouse gas emissions that pollute the environment [6], [7]. To provide clean energy for islanded communities, renewable energy sources can be used as alternative power sources for stand-alone grid applications. Most remote areas have immense potential for utilizing renewable energy sources to offer a clean and eco-friendly power supply to the community. However, the availability of power from renewable energy sources can vary daily and seasonally, which may not always match the load requirements of the system. To address this issue, a standby generator or energy storage device can be installed with renewable energy generation systems to make them more reliable. Such a power generation system, which combines renewable energy sources with backup generation or energy storage, is referred to as a "hybrid power system." The main aim of these systems is to generate as much energy as possible from renewable sources while maintaining acceptable power quality and reliability. Nonetheless, using renewable energy in stand-alone power supply systems presents a number of technical challenges due to the intermittent nature of renewable power, variable loads, and low inertial of such systems [8]. The technical challenges associated with using renewable energy in stand-alone power supply systems are listed below:

a) The variability and intermittency of renewable energy sources, such as wind and solar, present a significant challenge for their effective use [8]-[15]. Hybrid power generation systems that incorporate these sources typically require substantial backup generation or energy storage capacity to mitigate their fluctuating and intermittent nature [8]-[15]. Moreover, electricity consumption is not constant and exhibits temporal fluctuations, including moment-to-moment changes and hourly, daily, weekly, and seasonal patterns [16]-[18]. Consequently, renewable energy-based hybrid power systems must be able to adapt to these load changes.
b) Power quality refers to the characteristics and properties of electricity, including its voltage and frequency. In an ideal scenario, power quality would be perfect, with a continuous, sinusoidal voltage having a constant amplitude and frequency [19]-[22]. To ensure adequate power quality, national and international standards specify the quality of voltage that must be maintained. Voltage disturbances, including voltage variation, flicker, transients, and harmonic distortion, can affect the voltage quality. These disturbances may arise due to factors such as the intermittent nature of renewable energy sources and load fluctuations. In addition, the presence of non-linear loads and power electronic converters in the system can cause voltage flicker and harmonics [23], [24]. Transients may also occur due to the dynamic characteristics of the renewable energy sources and loads.
c) One of the key challenges in developing a control strategy for hybrid power systems is ensuring the transient stability of their integrated components, which operate as a single unit. Standalone power systems often face disturbances such as load fluctuations, which require

fast-response energy storage facilities to maintain transient stability [25, 26]. However, various energy storage facilities in a hybrid system may respond differently to different power system disturbances [25]-[28]. To ensure better transient stability of standalone power systems, coordinated control systems must be implemented.

d) In hybrid stand-alone power systems, energy storage is critical for ensuring both short-term transient stability and long-term load leveling and peak shaving of appliances [25]. Proper management of energy storage is essential to provide a continuous, reliable, and high-quality power supply. Additionally, back-up power generation is often employed in stand-alone power systems to supplement power demand, especially during peak load conditions when the power generated from renewable energy sources and the energy reserves in the storage system are insufficient to meet the demand.

e) The term "security of supply" refers to the capacity of a power system to withstand unexpected disruptions [32], [33]. This requires having enough generation resources to meet predicted demand, as well as having additional reserves in case of unforeseen events [32], [33]. Moreover, security of supply entails that the power system remains functional, even in the event of power outages or equipment malfunctions. Therefore, it is crucial to implement effective system planning and operation strategies.

f) Demand-side management (DSM) has traditionally been used to lower peak electricity demands [34], [35]. In stand-alone power systems, DSM can be particularly beneficial for reducing the frequency of electrical system emergencies and minimizing the number of blackouts, which ultimately improves the system's reliability [34], [35]. Additionally, DSM helps to decrease dependence on costly non-renewable fuels, resulting in lower energy expenses and fewer harmful emissions. Lastly, DSM is a key strategy in postponing high-cost investments in generation, transmission, and distribution networks for long-term asset planning. Overall, DSM applications in electricity systems can provide substantial economic, reliability, and environmental advantages.

g) In stand-alone power supply systems, load demand may gradually increase due to population growth and sustained economic development of the surrounding community [36, 37, 38]. Thus, it's crucial that the system's structure and control strategy be adaptable enough to enable a boost in generation capacity in response to rising load demand.

Meeting the technical and financial challenges associated with renewable energy- based hybrid power systems requires research in several areas. These are identified and categorized as follows:

a) In order to achieve the maximum power output from renewable energy sources, it is crucial to implement adequate controls that enable each energy generation source to operate at its optimal level. Hence, it is imperative to install proper controls for renewable energy sources
b) To attain the highest power output from renewable energy sources, it is essential to establish effective controls that facilitate optimal operation of each energy generation source. Therefore, the installation of appropriate controls for renewable energy sources is imperative.
c) The appropriate selection of energy storage devices is crucial for a hybrid power system, as they play a vital role in its operation. Energy storage can be categorized as either short-term or long-term storage. Short-term energy storage devices can rapidly release or absorb significant amounts of energy, enhancing the system's transient stability in the event of sudden fluctuations in energy resource or load conditions [25], [26]. Long-term energy storage is utilized for load leveling or peak-shaving functions [27]-[30]. To ensure reliable, cost-effective, and stable standalone power generation in remote and isolated areas, the proper selection of energy storage is essential.
d) Regulating the output voltage and frequency is a critical obstacle in a hybrid power system. Voltage harmonics and distortions can occur due to non-linear, unbalanced load conditions. Additionally, the system frequency can be influenced by sudden load changes and the intermittent nature of renewable energy sources due to low inertia. Consequently, power quality concerns must be tackled to ensure a stable power supply with regulated voltage and frequency.
e) Determining the ideal location of renewable energy sources and storage systems is crucial. The geographic location significantly impacts the power output from renewable energy sources, and a better location can enhance their utilization [46], [47]. Additionally, in stand-alone power systems, distribution losses can result in a voltage profile at the distribution level that falls below operating standards. Energy storage devices installed in critical areas can improve the system's voltage profile.
f) Determining the optimal size of renewable energy sources and storage systems is essential to ensure the reliable and cost-effective power generation of a hybrid power facility [42]. Considering the practical challenges associated with hybrid stand-alone power supply applications, the following are the main objectives of this thesis:

2.2 Composition of Hybrid Stand-Alone Power System

When considering various renewable energy sources for a project, wind and hydro power are considered due to their availability in the area, and in this case, a hybrid power system based on wind energy and hydro power is being considered as the primary source of power supply for the island [47].

There are different types of energy storage systems available for use in power systems, including pumped hydro, compressed air, flywheel, thermal, hydrogen, batteries, superconducting magnetic, and super-capacitors, each serving various applications and purposes. Fuel cells and electrolyzes, which have higher power density with slower time responses, are more suited for long-term load leveling applications and producing oxygen gas for hospitals [27-31].

In the context of energy storage system for a wind turbine-based hybrid power system, a combination of fuel cells and electrolyzes could be a suitable option. This approach would allow excess power from wind and water to be used to generate hydrogen using an electrolyzer.

2.3 Energy Management and Power Regulation System

To ensure optimal energy utilization and coordination of local controllers for each energy generation source, a supervisory controller for energy management and power regulation is installed. The system generates reference dynamic operating points for the local controls of individual subsystems and controls load scheduling operations during unfavorable wind conditions with insufficient energy storage to prevent system blackouts.

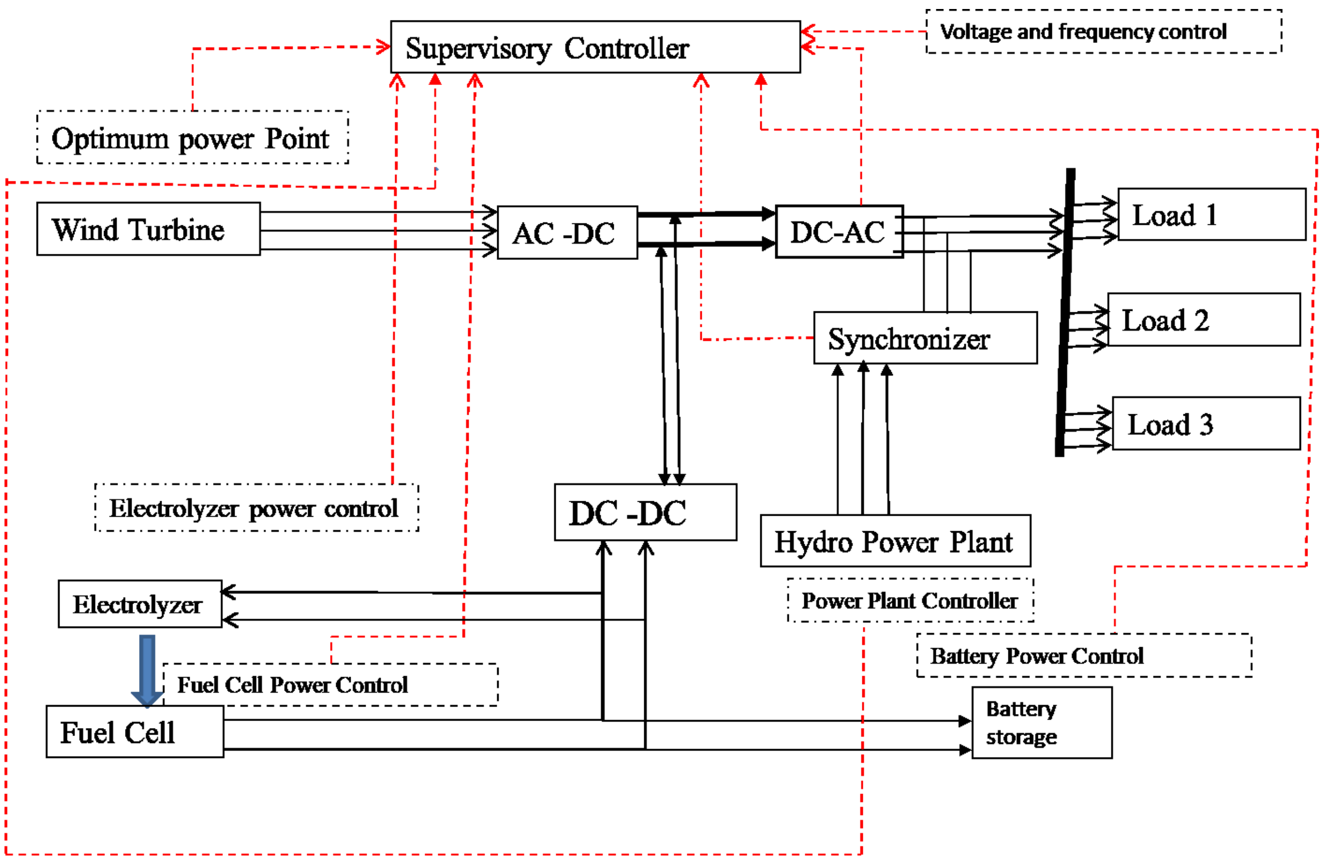


Figure 2.2 Block diagram of proposed hybrid power system.

2.4 Overview of Hybrid Power System

Renewable energy technologies are becoming increasingly important in meeting the challenges of power generation, distribution, and usage, particularly due to growing concerns about environmental pollution. For remote and isolated communities, stand-alone power systems fueled by renewable energy sources offer a cost-effective solution, as extending the grid is often not feasible due to technical and economic constraints.

Diesel generators have traditionally been the go-to choice for stand-alone power supply in remote areas due to their reliability, ease of installation, and portability. However, the rising cost of fuel and the negative impact on the environment make them less practical. Renewable energy sources, such as wind and solar or wind and hydro, are a viable alternative for providing clean and cost-effective power. Hybrid combinations of renewable energy sources and energy storage can improve reliability and ensure a continuous and cost-effective power supply.

To achieve higher energy efficiency and improve system performance, renewable energy sources must be operated in tandem. For example, wind and hydro power can complement each other on a daily basis. In renewable energy-based hybrid power system applications, energy storage is an important component for improving system stability and reliability. However, selecting the right technology, operation and control strategies, system structure, and generation unit sizing are also vital for constructing a reliable and robust renewable energy-based hybrid power supply system.

2.5 Structure of Hybrid System

Integrating multiple energy sources with different operating characteristics is crucial in designing an effective hybrid system. An ideal hybrid system incorporates various renewable energy sources, energy storage facilities, and loads to function as a self-sufficient unit [68]. Such a system should possess a "plug-and-play" capability and be able to integrate different devices without requiring system reprogramming [68], [69]. To ensure reliability and robustness, a hybrid system must be designed with different integration methods, including dc-coupled, ac-coupled, and hybrid-coupled approaches. This can be achieved by leveraging the benefits of the different methods and integrating various energy sources and storage to form a robust hybrid power system [70]-[74]

2.5.1 DC-Coupled Systems

The dc-coupled system involves the direct or converter-based connection of all renewable energy sources to a dc bus. This system can then be linked to dc loads via an appropriate dc-dc converter, ac loads through a dc-ac converter, or the utility grid using a bi-directional dc-ac converter. Additionally, the system offers flexibility as it can be linked to 50Hz ac loads. Unlike other coupling schemes, the dc-coupling approach is not required to be synchronous with the ac system, making it relatively simple. However, it does suffer from a few shortcomings. For instance, if the converter that connects the utility grid to the bus fails, the entire system is incapable of providing ac power. This can be addressed by connecting multiple inverters in parallel and ensuring proper synchronization of output ac voltage and power sharing to achieve the desired load distribution [75].

2.5.2 AC-Coupled Systems

The AC-coupled system can be classified into two types: power frequency (PFAC) and high frequency (HFAC) systems. These systems involve combining multiple energy sources through their own power electronic interfacing circuits to a power frequency ac bus. To ensure proper installation of such systems, coupling inductors are required to interface with the ac bus and achieve the desired power flow management.

2.5.3 Hybrid-Coupled Systems

The hybrid-coupled system involves connecting various distributed generation (DG) sources to the dc or ac buses of the hybrid system. Hybrid systems can utilize different energy sources directly without the need for power electronic interfacing systems, resulting in energy cost savings. However, the control and management of the energy system is more complex compared to dc-coupled or ac-coupled systems. Different coupling schemes have their own appropriate applications, with a dc-coupling system suitable for systems that generate dc power connected to substantial dc loads, and an ac-coupling system suitable for AC power systems with substantial AC loads. For power generation systems that combine both ac and dc power, the hybrid-coupled system is the best option.

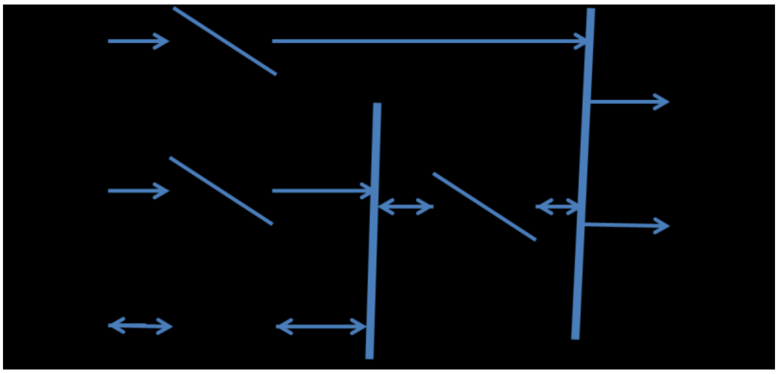


Figure 2.3 Schematic diagram hybrid-coupled hybrid energy system

2.6 Wind Energy Conversion System

As a renewable energy source, wind power generation systems have been increasingly adopted as an environmentally-friendly and cost-effective alternative to traditional conversion energy sources. A typical wind energy conversion system (WECS) utilized in large utility, micro-grid (weak grid), or stand-alone systems consists of a wind turbine, generator, and control systems. The generator used in WECSs can be a doubly-fed induction generator (DFIG), cage induction generator (IG), or synchronous generator (SG).

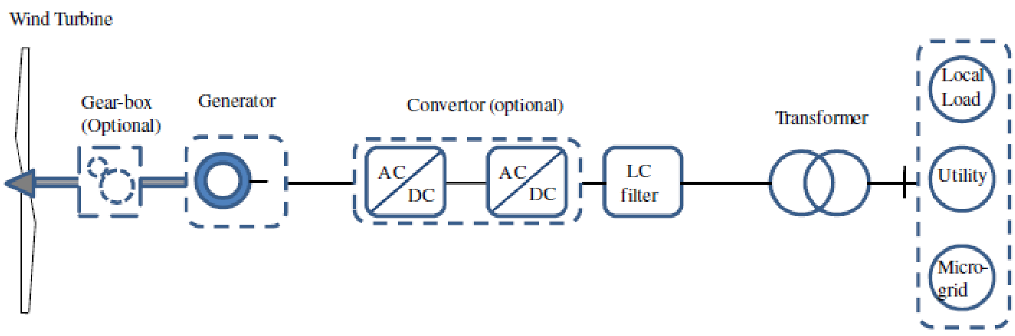


Figure 2.4 Wind energy conversion systems

2.6.1 Doubly-Fed Induction Generator DFIG- based WECS

Generators that can operate at variable speeds are commonly used in wind-energy applications [76-81], with the DFIG-based wind turbine currently occupying 50% of the wind energy market. The system employs a back-to-back power converter that is connected in the rotor to control the speed difference during operation, which is necessary due to variations in wind energy resources. The system uses slip rings to interconnect the machine-side converter [78-79], and the rotor-side converter is used to regulate the speed for the desired electrical torque, optimizing power extraction from the wind. The active and reactive power of the system can be controlled, giving it capacity on the grid [82-84].

However, the direct connection between the stator and grid may limit the capacity of the generator during a fault period, as it can contribute to short-circuit power that may produce relatively high currents in the machine stator windings. To improve fault handling capacity, a crowbar option is used to limit the currents and voltages to a safe level in the rotor circuit where the back-to-back power converter is used. The DFIG is transferred to a standard IG by short-circuiting the three-phase rotor winding via the closed crowbar switch. During the switching operation, the high currents produced may cause sudden torque loads on the drive train. While most major wind turbine producers manufacture WECSs based on DFIGs, difficulties in complying with grid fault ride-through requirements may limit its use in the future [85-86].

2.6.2 SCIG-based WECS

The mechanical simplicity and robust construction of the squirrel-cage induction generator (SCIG) make it a popular choice for wind energy conversion systems (WECS). Minimal maintenance is required apart from bearing lubrication, and the SCIG can be used in both fixed-speed and variable-speed WECS. The system has a complete grid connection capacity as it is designed with a frequency converter that is completely decoupled from the grid.

However, the SCIG has some limitations as power converters are necessary for operating the system. The direct-drive operation using multi-poles is technically infeasible as the result, SCIGs are not suitable for variable-speed operation.

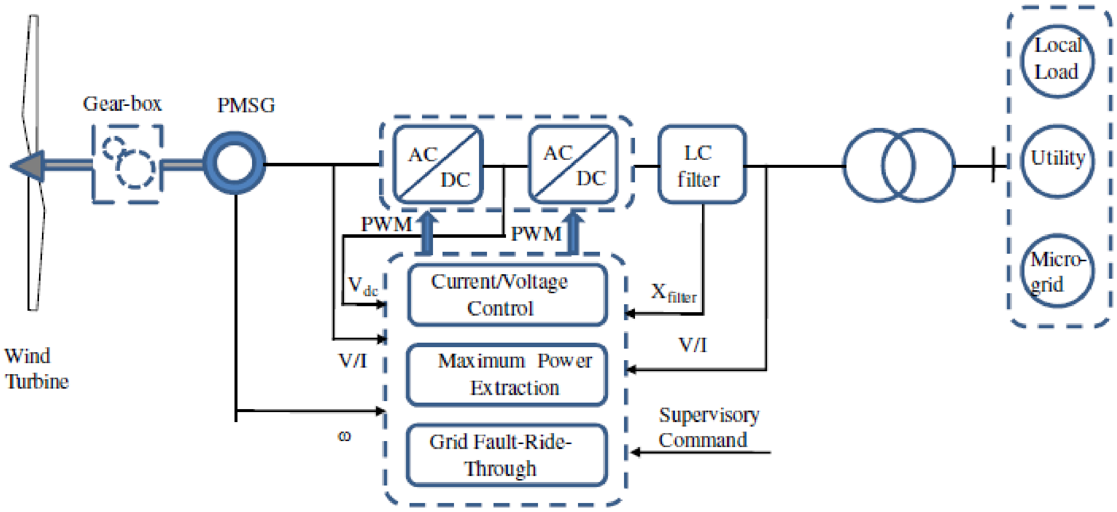


Figure 2.5 Multibrid concept.

2.6.3 SG-based WECS

In wind energy conversion systems (WECS) using synchronous generators (SG), the rotor windings require full-scale power converters (FSCs) for excitation, which can be costly. To reduce costs, a smaller scale converter can be used to control excitation in synchronous machines. Compared to doubly-fed induction generators (DFIG), SG-based wind turbines are more expensive, heavier, and larger in size. However, the direct drive SG is a reliable option due to the absence of a gearbox, slipping rings, and brushes. This makes it suitable for challenging logistical environments where robustness is essential, such as offshore wind parks. Additionally, they have better ride-through capability.

2.6.4 PMSG-based WECS

Among the various technologies for higher wind energy systems, the permanent-magnet synchronous generator (PMSG) is considered as one of the most reliable options because it requires full-scale power converters (FSCs) for operation. In particular, the direct-drive PMSG has high efficiency, with power losses limited to just 65% of those in typical doubly-fed induction generator (DFIG)-based WECS [88]. However, PMSG-based wind turbines are more expensive, heavier, and larger in size compared to DFIG.

The direct-drive PMSG has a high level of reliability due to the absence of a gearbox, slipping rings, and brushes, making it more suitable for challenging environments where robustness is critical, such as offshore wind parks. In fact, the system with full-power back-to-back converters is expected to become the preferred configuration for most large wind-turbine manufacturers in the future, replacing the DFIG as the main generator in the wind-energy market. In addition to its reliability, the direct-drive generator also offers noise reduction by eliminating the gearbox from the WECS [89]. This makes it well-suited for offshore applications where oil spillage from the gearbox is a concern.

2.6.5 Multibrid Concept (PMSG with Single Gearbox)

When a machine's power rating increases in a direct-drive operation system using this type of generator, it may require electrical machines that are significantly larger, heavier, and more expensive. To address this issue, the Multibrid system has been developed for a wind energy conversion system (WECS) that uses a medium-speed permanent magnet synchronous generator (PMSG) and a single-stage gearbox with a gear ratio of 6-10, resulting in a reduced system weight and the size generator. This gearbox technology is less heavy, more reliable, and cheaper than the standard three-stage gearbox with a typical ratio of 80%-100%.

One of the most popular types of WECS is the doubly-fed induction generator (DFIG) based system, which uses standard components to offer a light and low-cost solution. However, due to high losses in the gearbox, this system has a low energy yield. Major improvements in performance or cost reduction cannot be expected as it mainly consists of copper and iron standard components.

On the other hand, the direct-drive PMSG generator appears to be a more feasible option since it reduces the active material weight of the generator by almost half for the same air-gap diameter and offers a several percent higher energy yield. Despite being more expensive than generator systems with a gearbox, it has the highest energy yield. Moreover, further improvements are expected as the cost of permanent magnets and power electronics continues to decrease.

2.7 Energy Storage System

In a hybrid renewable stand-alone power system, energy storage systems play a crucial role in ensuring power quality, reliability, and security. An ideal energy storage system would offer fast access to power, high capacity power and energy, a long lifespan, and competitive pricing. Unfortunately, the perfect storage system does not exist in the project area, and selecting the appropriate technology is essential for renewable energy-based hybrid power systems.

There are various applications for energy storage systems in stand-alone hybrid renewable energy power systems. For instance, energy storage facilities can help with renewable matching and power smoothing, load leveling, and power quality. Renewable energy sources are intermittent, and energy storage facilities can assist in matching power generation with the load profile or demand cycle. In addition, energy storage systems can store bulk energy produced during peak wind conditions and discharge it during low or no wind conditions to ensure continuous system operation. Furthermore, properly installed energy storage systems can provide reliable, high-quality power to sensitive loads.

Energy storage facilities are classified as long-term and short-term based on the application of the system. Capacity-oriented energy storage technologies such as pumped hydroelectric systems, compressed air energy storage, and hydrogen storage are suitable for long-term energy storage because they do not have a fast response time. On the other hand, storage devices with a fast response time, such as batteries, flywheels, super-capacitors, and super-conducting magnetic energy storage (SMES), are applicable in short-term response situations, such as fast load transients and power quality-related issues.

Energy storage can be electrochemical, mechanical, electromagnetic, thermal, or hydrogen-based. Electrochemical energy storage includes lead-acid, lithium-ion, flow, and sodium-sulfur batteries. Mechanical energy storage includes pumped hydroelectric, compressed air energy, and flywheels. Electromagnetic storage systems such as superconducting magnetic energy storage (SMES) and thermal energy storage can include solar thermal and thermal storage for heating, ventilation, and air conditioning. Finally, hydrogen storage includes electrolyzers and fuel cells.

2.7.1 Electrochemical Energy Storage

For renewable energy-based power systems, it is essential to use dependable, long-lasting, and secure batteries for storing and supplying energy. There are several battery technologies available that show potential for use in standalone or grid-connected renewable energy systems. These include lead-acid, lithium-ion, flow, and sodium-sulfur batteries.

a) Lead-acid batteries have proven to be a reliable and established technology in several applications, such as frequency regulation, bulk energy storage for variable renewable energy integration, and distributed energy storage systems. These batteries are an attractive option due to their relatively low cost, ease of manufacturing, rapid electrochemical reaction kinetics, and good life cycle under controlled conditions [92]. Typically, conventional lead-acid batteries have a power density of 4 kW/kg and achieve 20-30 Wh/kg [92]. In various applications such as automotive, marine, telecommunications, and uninterruptible power supply systems, maintenance-free valve-regulated lead-acid (VRLA) batteries, also known as sealed lead-acid batteries, have mostly replaced conventional high maintenance flooded cell batteries. However, flooded lead-acid technology is still considered as the best alternative for large storage system applications for grid support [93]. The lifetime of lead-acid batteries varies significantly depending on the discharge rate, the number of deep discharge cycles, and the application. In renewable energy-based power systems, traditional lead-acid batteries may have a short life cycle and require significant maintenance due to uncontrollable charging and discharging operating cycles.

b) Nickel-based batteries come in two forms, Nickel/Cadmium (NiCad) and Nickel Metal Hydride (NiMH) systems. NiCad batteries are commonly used in portable electronics, while NiMH batteries are a viable alternative due to their superior performance and environmental advantages. Unlike lead-acid and NiCad batteries, NiMH does not contain toxic substances such as cadmium or lead. In addition, NiCad batteries have a longer life, higher energy density, and lower maintenance than lead-acid batteries. However, the energy density of NiCad cells is only 25-30% higher than that of NiMH cells, which is still lower than rechargeable Li-ion batteries [94].

c) Lithium-ion batteries are an attractive option for battery technology due to their high reduction potential and lightweight nature [93]. These rechargeable batteries are commonly found in consumer electronic products and comprise the majority of the global production volume of 10 to 12 Giga-watt hours per year [93]. Li-ion batteries are widely used in plug-in hybrid electric vehicles (PHEV) and electric vehicles (EV). While Li-ion technology is relatively new compared to the long history of lead-acid batteries, it is expected that advancements in Li-ion battery technology will substantially benefit the EV and energy storage market. The high energy density and relatively low weight make them a viable choice for electric vehicles and other applications where space and weight are important. Due to their long cycle life and compactness, with higher round trip energy of 85-90% [95], Li-ion battery manufacturers may be used for various utility grid-support applications, including distributed energy storage systems at the community scale, commercial end-user energy management, home backup energy management systems, frequency regulation in wind and photovoltaic power smoothing applications.

d) A flow battery is a type of rechargeable battery in which an electrolyte containing one or more dissolved electro-active species flows through an electrochemical cell that converts chemical energy to electricity [93]. Vanadium redox battery technology is one of the most developed flow battery systems, with an expected life of about 15 years [93]. However, the large volume of electrolyte required for utility-scale projects results in a physically large battery. Flow batteries are an attractive energy storage option for the grid due to their ability to store a large amount of energy with a potentially longer life cycle.

e) The sodium-sulfur battery is characterized by its high energy and power density, as well as its high electrical efficiency, making it an excellent choice for electric power system applications [93]. The positive electrode in this type of battery uses sulfur as the active material, while the negative electrode uses sodium. The electrodes are separated by a solid electrolyte made of a sodium-ion-conductive ceramic material. To maintain the active materials in a liquid state, the battery operates at a high temperature

f) Super-capacitors are devices that store electrical energy as charge separation in porous electrodes. The electrodes themselves remain solid, resulting in efficient performance over the lifetime of the discharge [93]. Ultra-capacitors, in particular, have several advantages, including the highest capacitance density of any capacitor technology, low cost per farad, reliability, long life, high cycle-life, maintenance-free operation, environmental safety, a wide range of operating temperatures, high power density, and good energy density [92]. These features, especially the greater power and energy densities, bridge the gap between standard batteries and traditional capacitors for high-power, short-duration energy storage. As a result, they are widely used in utility applications for transmission line stability, spinning reserve, frequency control, voltage regulation, power quality, and uninterruptible power supply applications [74].

2.7.2 Mechanical Energy Storage

Pumped hydro, compressed air energy storage and flywheels can be classified as mechanical energy storage.

a) Pumped hydroelectric storage is a commercially available energy storage technology that has been in use for over a century. The process involves two large reservoirs located at different elevations and a supply of water. During off-peak hours, water is pumped from the lower reservoir to the upper reservoir using excess electricity. When needed, the water is released to the lower reservoir and drives turbines, generating electricity. The technology provides reliable power on short notice, typically within one minute, with an efficiency range of 70-85% [95]. Although pumped hydro is one of the most mature technologies, further improvements are unlikely. It is currently the dominant form of energy storage globally, with around 90GW of pumped storage in operation, accounting for 3% of global generation capacity [96]. However, the high capital costs of construction remain a limiting factor, which depends on the local topography and other factors.

b) Flywheels are a type of mechanical energy storage that store energy in the form of kinetic energy of a spinning rotor. Recent advancements in flywheel technology have led to improved efficiency [93]. A modern flywheel energy storage system consists of a large, spinning cylinder supported by magnetically levitated bearings to reduce friction and extend the lifespan of the system. The flywheel operates in a low-pressure environment to further increase efficiency. When electricity is drawn from a primary source, it spins the high-density cylinder at speeds greater than 20,000 rpm. In the event of a power outage, the motor acts as a generator, providing power to the grid as the flywheel continues to rotate. Flywheels have a high energy density of 50-100 Wh/kg and an efficiency of around 90% depending on the speed range of the flywheel [96]. Since flywheels do not require chemical management or disposal, they offer certain environmental advantages over battery systems.

c) Compressed air energy storage (CAES) is a system that stores energy by compressing air into underground mines or caverns using off-peak electricity. This process enhances the efficiency of gas turbines [93]. The compressed air can then be used in combination with a gas turbine to generate electricity, which reduces gas consumption by up to 60% compared to generating the same amount of electricity directly from gas [93]. Additionally, CAES can be paired with a wind farm to store excess power during high wind conditions. The energy efficiency of CAES is approximately 80%. However, the availability of large underground storage spaces could have potential environmental impacts, and the lack of suitable locations for underground air storage presents a constraint on this technology.

2.7.3 Electro-magnetic storage

Superconducting magnetic energy storage (SMES) is a technology that enables the storage of electrical energy in a magnetic field within a superconducting coil that has been cooled to a temperature below its superconducting temperature (-269^{o}C). This cooling process significantly reduces the electrical resistance of the coil, enabling high efficiency of up to 97% in energy storage and retrieval.

SMES technology is particularly useful in applications where customers require a high-quality power output and immediate energy release. One major safety concern with SMES is the need of extremely low temperatures, which could pose a hazard if not properly managed. Additionally, larger scale SMES systems may require significant protection to address issues related to magnetic radiation in the immediate vicinity.

2.7.4 Hydrogen Energy Storage

Hydrogen-based energy storage systems are currently receiving considerable attention due to the long period over which hydrogen can be stored, and owing to the potential hydrogen holds for replacing petroleum products as the energy carrier for the transport sector. When coupled with a renewable energy source or low carbon energy technology, hydrogen energy storage has the potential to reduce greenhouse gas emissions.

The essential elements of a hydrogen storage system consist of an electrolyzer unit, to convert electrical input to hydrogen during off-peak periods, the storage component and an energy conversion component to convert the stored chemical energy into electrical energy when demand is high or for use in transportation systems.

Hydrogen is attracting considerable option for energy storage potential due to its long-term capabilities and its potential to replace petroleum-based products in the transport sector [93]. When combined with renewable energy sources, hydrogen energy storage has the potential to reduce significantly greenhouse gas emissions.

A typical hydrogen storage system consists of three main components such as electrolyzer unit that converts electrical input to hydrogen during off-peak periods, a storage component to store the produced hydrogen, and an energy conversion component that converts the stored chemical energy into electrical energy when demand is high or for use in power generation systems [95].

The electrolyzer and fuel cell components can produce hydrogen through an electrochemical process or convert hydrogen back to electricity in fuel cell mode [96]. Proton Exchange Membrane (PEM) fuel cell technology has been extensively used for reversible electrolyzer operation, also solid oxide fuel cell (SOFC) and alkaline fuel cell (AFC) technologies can be applied reversibly.

However, one of the main concerns with hydrogen systems is the overall cycle efficiency, as energy is lost during the process of converting electricity to hydrogen, storing, transporting, and then re-converting it to electricity in a fuel cell with estimated energy loss range of 60% to 75% [97].

To address this issue, more advanced fuel cell technologies are being developed, such as Direct Methanol Fuel Cells (DMFC), Molten Carbonate Fuel Cells (MCFC), and Solid Oxide Fuel Cells (SOFC). MCFCs and SOFCs operate at extremely high temperatures of around 620°C and 1,000°C, respectively. MCFCs are approaching 60% efficiency for the conversion of fuel to electricity, and it is expected that SOFCs will achieve similar efficiency levels. When the waste heat is captured and used, the efficiencies of both MCFCs and SOFCs can reach up to 85% [93].

2.8 Control Strategy and Energy Management

To achieve continuous, reliable, and cost-efficient operation in stand-alone hybrid power systems with multiple renewable energy sources and energy storage, proper control and energy management strategy are crucial. The overall control and energy management system of such a system is responsible for managing energy storage effectively, enabling the hybrid system to supply the required power to the connected load with the desired quality at all times.

In a typical stand-alone power system, the control system plays a vital role in determining and allocating the active and reactive output power of each energy source while maintaining the output voltage and frequency at the desired level. Additionally, the control system must ensure the power supply security of the renewable energy-based hybrid power system during adverse conditions such as no wind or solar to prevent system blackouts.

2.9 Control Structure of Hybrid Power System

The control structure of hybrid systems are classified into centralized, distributed, and hybrid control models. In all option each energy source has been assumed to have its own controller which can control the optimal operation of the next unit basing on the current information

a) Centralized control model- In this control model, the measurement signals of all energy units are sent to a centralized controller, as shown in Fig. 1.6. This acts as a supervisor controller which makes decisions. The main objective of this is to optimize energy use among the various energy sources of the system. The control signals are then sent to the corresponding energy sources. The advantage of this control structure is that the multi-objective energy management system can achieve global optimization based on all available information. However, the scheme suffers from a heavy computation burden and is subject to single-point failure.

b) The control and management structures of hybrid systems can be categorized into centralized, distributed, and hybrid models. Each energy source in these models is assumed to have its own controller or management system, which can optimize the operation of the next unit based on current information. In the centralized control or management model, all measurement or activity signals from the energy units are sent to a centralized controller or supervisor, as illustrated in Figure 1.6. This controller is responsible for making decisions to optimize the use of energy sources in the system. The resulting control or management signals are then sent to the corresponding energy sources. The advantage of this structure is that it enables global optimization of the multi-objective energy management system using all available information. However, it requires significant computational resources and is vulnerable to single-point failure.

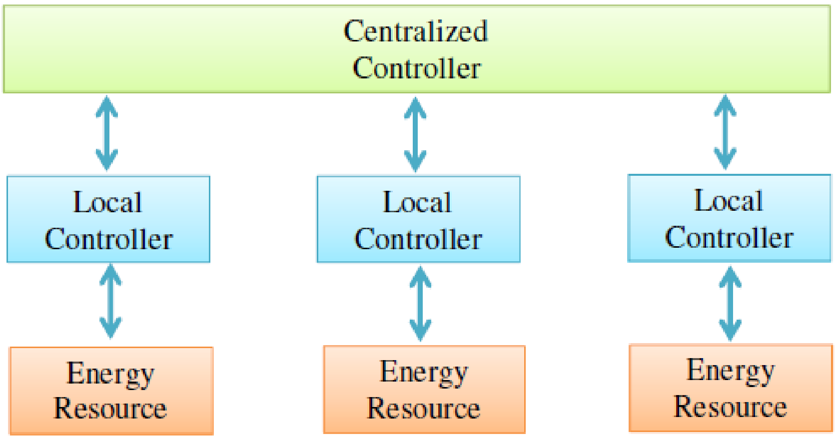


Figure 2.6 Centralized control paradigm.

c) In a fully distributed control paradigm, the measured signals from the energy sources in a hybrid system are transmitted to their respective local controllers, as depicted in Figure 1.7. These controllers collaborate and communicate with each other to make decisions in order to achieve specific objectives. One advantage of this scheme is the ability to have a "plug-and-play operation". With this control structure, the computational burden of each controller is significantly reduced and there are no single-point failure issues. However, a potential drawback is the complexity of the communication system. A promising solution for distributed control problems is the use of a multi-agent system (MAS) [101]. MAS has been employed for power system integration, restoration, reconfiguration, and power management of micro-grids [100]-[104].

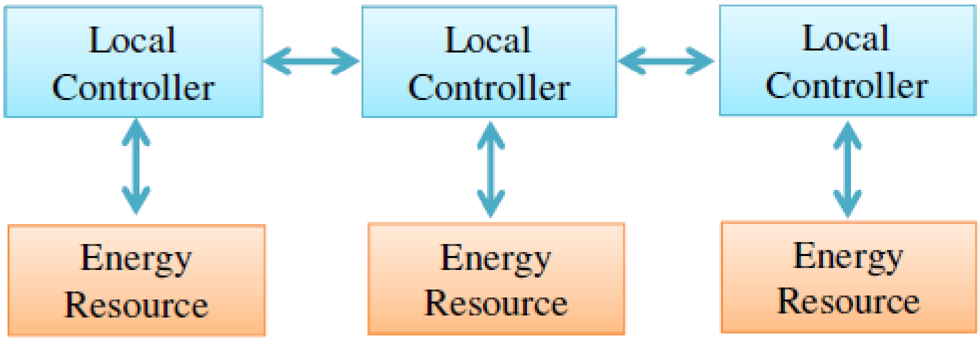


Figure 2.7 Distributed control paradigm.

d) The hybrid control paradigm is a combination of centralized and distributed control schemes, as illustrated in Figure 1.8 [105], [106]. The distributed energy sources are organized into sub-systems, with centralized control used within each group and distributed control applied to a set of groups. This approach reduces the computational burden of each controller and minimizes the risk of single-point failure. Another hybrid control scheme, known as the multilevel control framework, is shown in Figure 1.9. This is similar to the hybrid control scheme mentioned above, but with an additional supervisory (strategic) control level. At the operational level, real-time decisions are made regarding each energy unit's control objectives, and the actual control is performed rapidly, within a millisecond range. The tactical level focuses on making operational decisions for a group of local control units or the entire subsystem, with a relatively longer timeframe, ranging from seconds to minutes. Strategic decisions regarding the overall operation of the system, such as system "startup" or "shutdown," are made at the top level [107]. Two-way communication exists between the different levels to facilitate the execution of decisions.

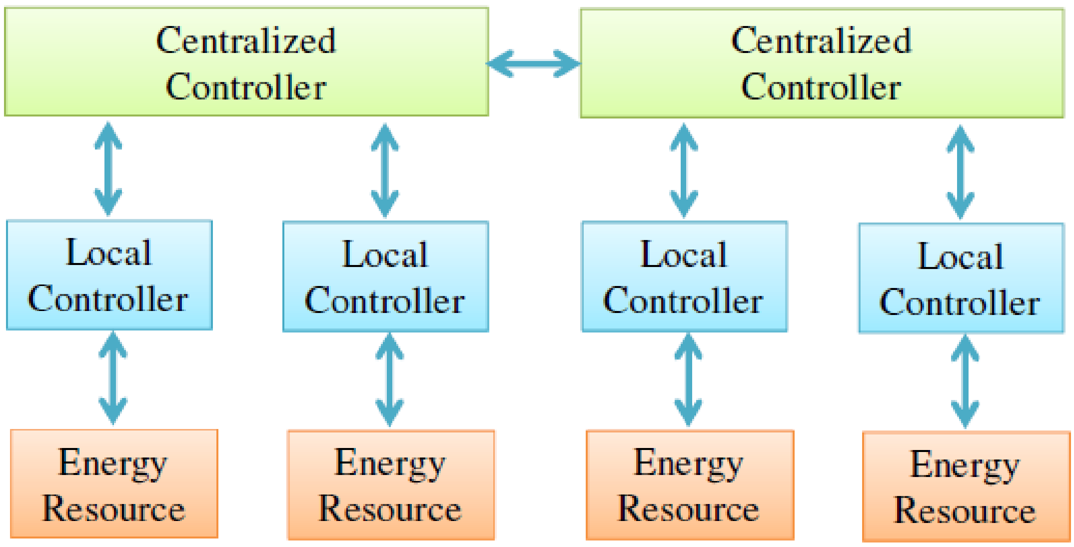


Figure 2.8 Hybrid centralized and distributed control paradigm.

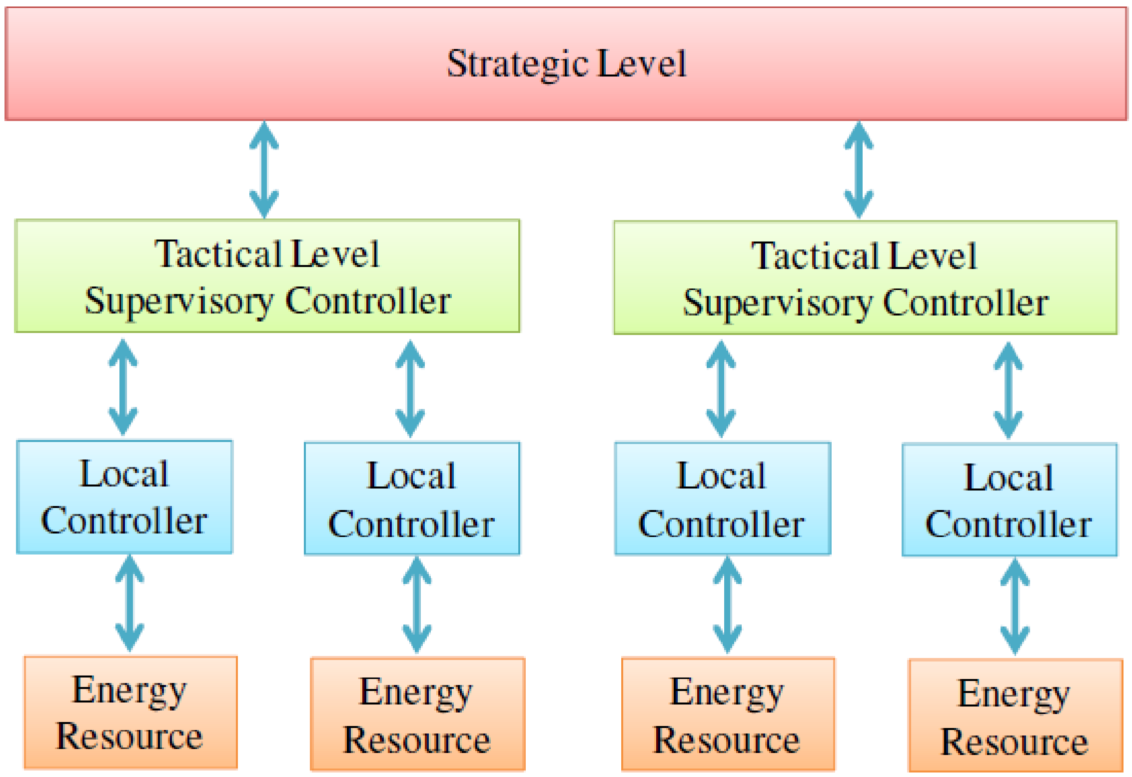


Figure 2.9 Multi-level control paradigm.

e) Over the past decade, renewable energy sources have experienced the most rapid growth in electricity production on a global scale. The Tanzania anticipates that non-hydro renewable power generation will continue to count substantial growth in the near future. Nevertheless, currently, the majority of non-hydro renewable energy technologies are not able to compete with fossil fuel-based generation sources from an economic standpoint. Consequently, government incentives are the catalyst for the installation of renewable energy generation facilities.

2.10 Challenges for the Renewable Energy Hybrid Power System

Despite the significant environmental benefits of renewable energy sources and their potential for sustainable energy development, they are generally more expensive to install than traditional fossil fuel-based power generation technologies [109]. As a result, government incentives from are often required to make hybrid renewable energy systems economically feasible [107].

In order to ensure a continuous and reliable power supply with the desired quality, energy storage is a necessary component of standalone hybrid renewable energy systems. Energy storage is also crucial for accommodating grid-scale renewable generation sources in high-penetration power systems [108]. While pumped hydroelectric storage and underground CAES are competitive in terms of system cost, they are limited geographically and only suitable for large grid-scale applications. Batteries are the most common energy storage technology for distributed hybrid renewable energy systems, but their system cost and durability remain key barriers. Additionally, accurately estimating the state of charge and state of health of batteries is highly challenging [112]. Therefore, new battery technologies require further research and development to improve their durability and performance while lowering their cost.

As the deployment of hybrid renewable energy systems in the form of independent standalone power systems increases, the need for real-time energy management and robust communication between individual energy sources becomes an important task that requires further attention.

2.11 Conclusion

This chapter offers an overview of existing and ongoing research on optimal design methods for hybrid renewable energy systems. Various approaches for configuring, controlling, and managing energy in hybrid systems are outlined, along with a comprehensive examination of wind energy conversion and energy storage systems. The chapter also delves into the technical and financial obstacles faced by standalone renewable energy systems. In the subsequent chapter, the focus will be on the control strategy of the wind turbine, which serves as the primary power source for the proposed hybrid system.

3 WIND ENERGY CONVERSION SYSTEM MODELING AND CONTROL

3.3 Introduction

This chapter will explore the modeling and control of wind energy conversion systems. The examine a system comprising of a variable speed wind turbine, an interior permanent magnet synchronous generator, and a rectifier controlled by pulse width modulation (PWM). The wind turbine with its variable speed capabilities is responsible for capturing aerodynamic power from the wind, while the interior synchronous generator converts the wind energy into usable electrical power. To ensure the generator's rotor speed is optimized for capturing aerodynamic power, the PWM controlled rectifier is employed. Figure 3.1 provides a visual representation of the wind energy conversion system's structure.

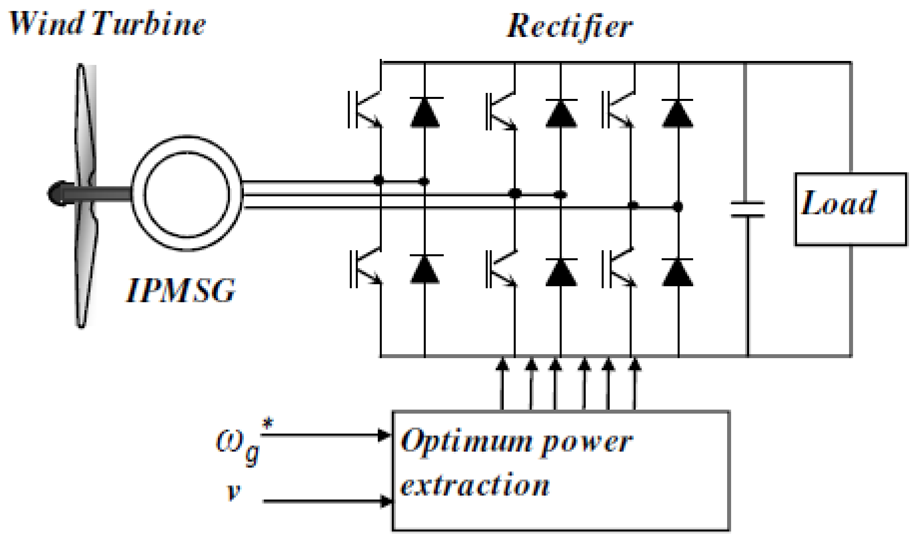


Figure 3.1 Configuration of wind energy conversion system

3.2 Variable Speed Wind Turbine Model

Wind turbines are devices that harness the kinetic energy of the wind and convert it into usable mechanical energy. The blade and generator are two of the most fundamental components of a wind turbine. The blade, typically made of lightweight materials such as fiberglass or carbon fiber, captures the energy of the wind as it flows over the surface of the blade [91]. The shape of the blade is carefully designed to maximize its surface area and create lift, which causes it to rotate [92]. This rotation generates rotational kinetic energy, which is then transferred to the generator through a shaft or gearbox.

The generator is responsible for converting the rotational kinetic energy into electrical energy. In modern wind turbines, the generator is usually a permanent magnet synchronous generator (PMSG), which consists of a rotor with permanent magnets and a stator with copper windings [94]. As the rotor turns, the magnetic field induces a current in the copper windings, which generates electrical power. The electrical power generated by the PMSG is then fed into an inverter, which converts the direct current (DC) output of the generator into alternating current (AC) that can be used to power homes and businesses [96].

Overall, wind turbines are an important source of renewable energy, providing clean and sustainable power to help reduce our reliance on fossil fuels.

$$E = \frac{1}{2}mv^2 \quad 3.1$$

Substituting the particle mass as a product of air density (ρ), wind speed (v), and time (t), that applies a rotor blade of a circular swept area (A) with radius (r), the expression of mass of the air particle can be expressed as [91]-[93]:

$$m = \rho Avt = \rho\pi r^2 vt \quad 3.2$$

Substituting m from (2.2) in (2.1), the expression of the kinetic energy can be as follows [91]-[93]:

$$E = \rho Av^3 t \quad 3.3$$

The available power (P_{wind}) is the time derivative of the energy given below [91]-[96]

$$P_{wind} = \frac{dE}{dt} = \frac{1}{2}\rho Av^3 \quad 3.4$$

The power coefficient (C_p) is defined as the ratio of the aerodynamic rotor power (P) to the power (P_{wind}) available from the wind as given below [91]-[96]:

$$C_p = \frac{P}{P_{wind}} \quad 3.5$$

The aerodynamic rotor power can be expressed as a function of aerodynamic torque (τ_{aero}) and rotor angular speed (ω) as given by [91]-[96]:

$$P = \tau_{aero}\omega \quad 3.6$$

The torque applied to the generator (τ_c) can be given by

$$\tau_c = K\omega^2 \quad 3.7$$

Where K is given by

$$K = \frac{1}{2}\rho AR^3 \frac{C_p}{\lambda}$$

2.8

Assuming that the rotor is rigid, the angular acceleration ω is given by

$$\omega = \frac{1}{J}(\tau_{aero} - \tau_c) \qquad 3.9$$

Where J is the combined rotational inertial of the rotor, gearbox, generator, and shafts. Depending on wind speed, a variable-speed wind turbine has three main regions of operation as shown in Figure. 3.2. In region 1, the wind speed is below the cut in speed (vo) which is not enough to start a turbine. Region 2 is an operational region of wind turbine where the wind speed remains between the cut in speed (vo) and cut out (vi) region. In region 3, the turbine must limit the captured wind power as the wind speed is above the cut out speed (vi), so as to ensure safe electrical and mechanical operating limits.

Figure 3.2 demonstrates the steady-state relationship between extracted aerodynamic power and wind speed. The dotted line represents the power in the unimpeded wind passing through the rotor swept area, while the solid curve represents the power extracted by a typical variable speed wind turbine.

Classic control techniques such as proportional, integral and derivative (PID) control of blade pitch are typically used to limit power and speed on both the low and high-speed shafts for turbines operating in region 3, while generator torque control is usually used in region 2.

For a variable speed wind turbine operating in region 2, the control objective is to ensure maximum energy capture by operating the wind turbine at the peak of the C_p – TSR as shown in Figure 3.3. The power coefficient Cp (λ, β) is a function of the tip speed ratio (TSR) λ and the blade pitch β. The TSR is defined as [91]-[96]:

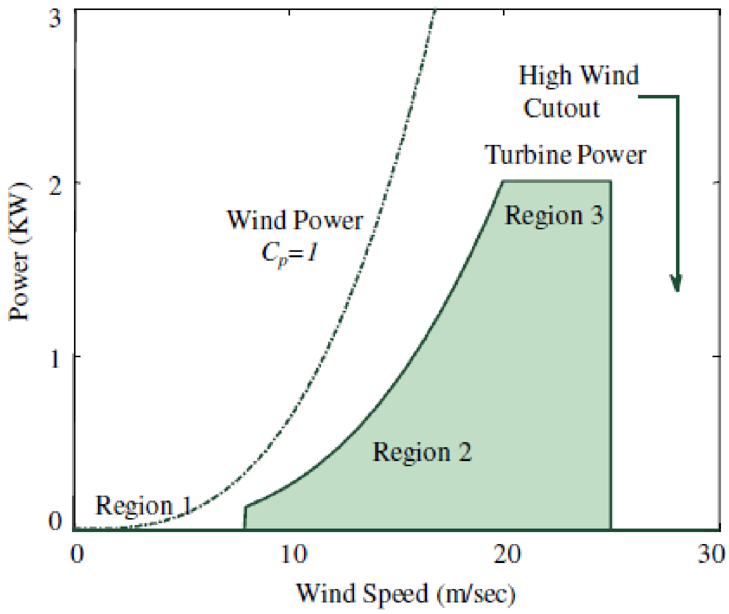


Figure 3.2 Steady-state power curve of wind turbine

$$\lambda = \frac{\omega R}{v} \qquad 3.10$$

From equation 3.5, the rotor aerodynamic power P increases with C_p as a result, the wind turbine should be operated at the maximum power coefficient C_{pmax}. The relationship between TSR λ and blade pitch can be expressed as follows:

$$\lambda = \frac{1}{\frac{1}{\lambda+0.02\beta} - \frac{0.02}{\beta^3+1}} \qquad 3.11$$

To calculate C_P for the given value of λ and β, the following numerical approximation has been used:

$$C_p(\lambda.\beta) = 0.73\left[\frac{15.1}{\lambda} - 0.58\beta - 0.002\beta^2 - 13.2\right] exp^{\frac{18.4}{\lambda}} \qquad 3.12$$

From (2.9), the relationship between Cp and λ for different β is shown in Figure 3.3

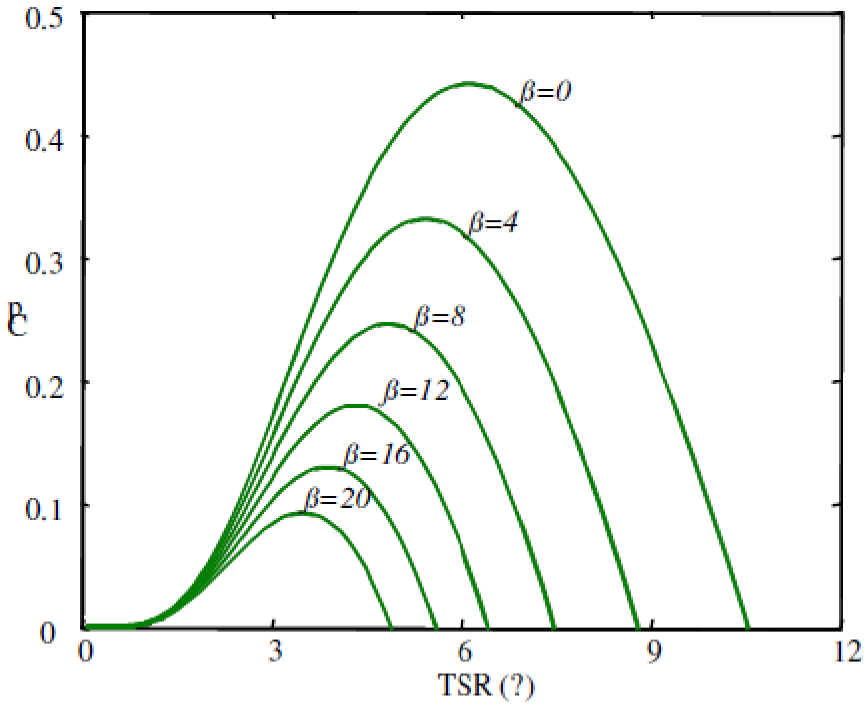


Figure 3.3 Cp – λ curves for different pitch angles (β)

The steady-state power curve of the wind turbine for different wind speeds is given in Fig. 2.4.

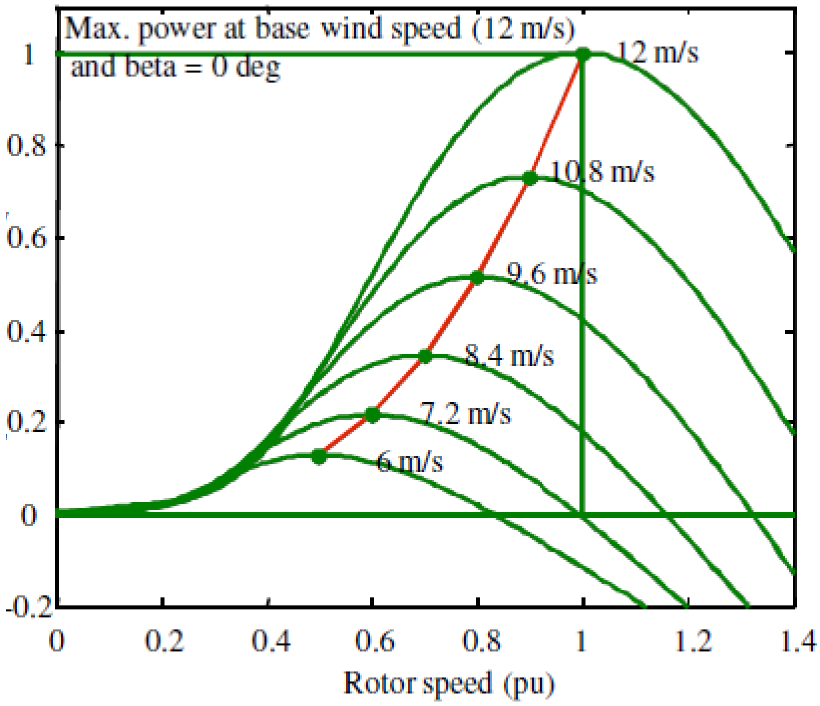


Figure3.4 Steady-state power curve of wind turbine at different wind and rotor speed

3.3 Permanent Magnet Synchronous Generator (PMSG) Model

Synchronous AC machines rotor consist of permanent magnets are known as permanent magnet synchronous generator (PMSG). These machines have a stator winding that is similar to that of a squirrel cage induction generator (SCIG), but instead of a rotor winding, they use permanent magnets. The advantage of this design is that it reduces copper losses, increases power density, reduces rotor inertia, and results in a more robust rotor construction. However, there are also some disadvantages to this design, such as a loss of flexibility in field flux control, possible demagnetization or saturation of magnetic material, and parameter variation over time.

PMSGs can be divided into two categories based on the placement of the permanent magnets on the rotor: surface permanent magnet machines (SPM) and interior permanent magnet machines (IPM). In SPM machines, the permanent magnets are mounted on the rotor surface. The rotor itself has an iron core, which can be either solid or made of punched laminations with skewed poles to minimize cogging torque. This design is relatively simple and easy to build. However, it is typically used for low-speed operations, as the magnets may fly off during high-speed operation.

The permeability of the magnetic material used in SPM machines is similar to that of air, which effectively increases the air gap between the rotor and stator. Additionally, the smooth rotor surface design helps to minimize saliency in the rotor, which contributes to a low armature reaction effect due to low magnetization inductance.

IPM synchronous machines have magnets located within the rotor, making them a salient pole machine due to their uneven distribution of effective air gap. Although difficult to manufacture, the IPM rotor's robust design makes it well-suited for high-speed applications. Additionally, the machine's direct axis inductance is lower than its quadrature axis inductance ($L_d < L_q$).

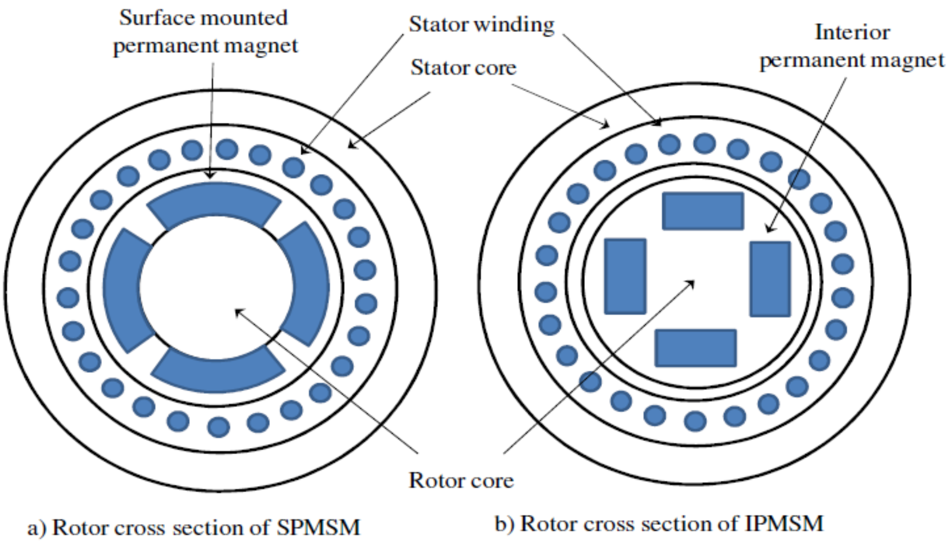


Figure 3.5 Cross sectional view of rotor design of a) SPMSG and b) IPMSG

3.3.1 Operating Principle of PMSG

Permanent magnet synchronous machines utilize a rotor with alternating N and S poles, resulting in the creation of magnetic flux in the air gap. The stator windings, when energized, generate their own magnetic flux. The interaction between the magnetic fields of the rotor and stator produces electromagnetic torque in the rotor.

A simplified cross-sectional view of a 3-phase, 2-pole PMSG with symmetrical stator windings is depicted in Figure 3.6. These windings are displaced from each other at a 120° electrical angle. As the rotor and stator move relative to each other, sinusoidal MMF waves are induced on the magnetic axes of the respective phases. The phase difference between the magnetic flux of the rotor and the magnetic axis of the stator phase-a winding is referred to as the rotor position angle (θr). The rate of change of the rotor position angle can be used to calculate the angular rotor speed (ωr).

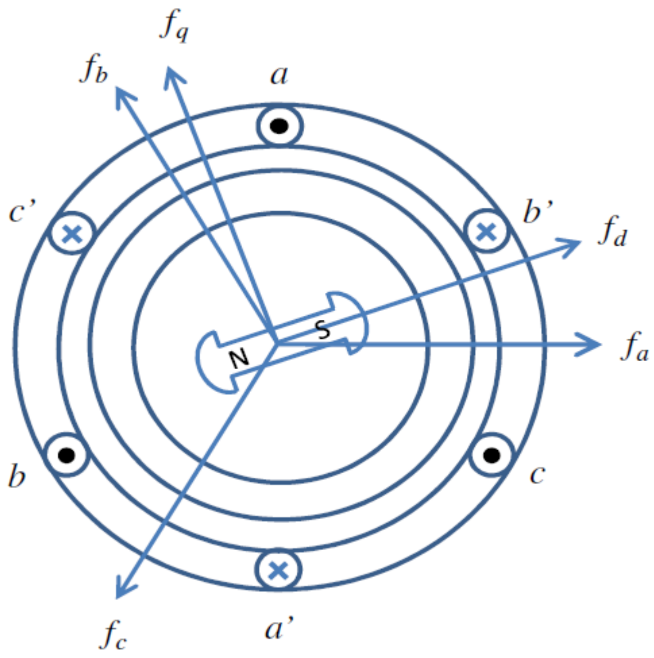


Figure 3.6 Cross-section view of 3-phase, 2-pole PMSG

3.3.1 Generalized Model of PMSG

In a PMSG with a sinusoidal flux distribution, there is no distinction between the back electromotive force (emf) produced by a permanent magnet rotor and a wound rotor. Therefore, the mathematical model for a PMSG is similar to that of a wound rotor synchronous machine. The stator voltage equations for a PMSG, in the abc reference frame, can be expressed in terms of instantaneous currents and stator flux linkages as shown in [97]:

$$V_{abc} = R_{sabc} i_{abc} + p\lambda_{abc} \qquad 3.14$$

Where

$$V_{abc} = [V_a \quad V_b \quad V_c]^T$$

$$i_{abc} = [i_a \quad i_b \quad i_c]^T$$

$$\lambda_{abc} = [\lambda_a \quad \lambda_b \quad \lambda_c]^T$$

$$R_{sabc} = diag[R_s \quad R_s \quad R_s]$$

Rs is the stator resistance and p is the differentiating operator d/dt. For a linear magnetic system, the stator flux linkage can be calculated as follows:

$$\lambda_{abc} = L_{abc} i_{abc} + \lambda_{mabc} \qquad 3.14$$

Where

$$L_{abc} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \quad 3.15$$

and

$$\lambda_{mabc} = \lambda_m \begin{bmatrix} \cos\theta_r \\ \cos\left(\theta_r - \frac{2\pi}{3}\right) \\ \cos\left(\theta_r + \frac{2\pi}{3}\right) \end{bmatrix} \quad 3.16$$

The stator winding inductances in equation (3.15) can be expressed as

$$L_{aa} = L_{is} + L_{0s} + L_{2s}\cos 2\theta_r \quad 3.17$$

$$L_{bb} = L_{is} + L_{0s} + L_{2s}\cos 2\left(\theta_r - \frac{2\pi}{3}\right) \quad 3.18$$

$$L_{cc} = L_{is} + L_{0s} + L_{2s}\cos 2\left(\theta_r + \frac{2\pi}{3}\right) \quad 3.19$$

$$L_{ab} = L_{is} + L_{0s} + L_{2s}\cos 2\left(\theta_r - \frac{\pi}{3}\right) \quad 3.20$$

$$L_{ac} = L_{is} + L_{0s} + L_{2s}\cos 2\left(\theta_r + \frac{\pi}{3}\right) \quad 3.21$$

$$L_{bc} = L_{is} + L_{0s} + L_{2s}\cos 2(\theta_r + \pi) \quad 3.22$$

In the above given equations, L_{aa}, L_{bb}, and L_{cc} are the self inductances of each phase, L_{ab}, L_{ac} and L_{bc} are the mutual inductances and λ_m is the flux linkage established by the rotor magnets. The leakage inductance L_{is} consists of magnetizing inductance components L_{0s} and L_{2s} , which are further dependent on the rotor position. Here, L_{2s} is generally negative and L_{0s} is positive in the case of an interior permanent magnet (IPM) synchronous machine, due to their unique rotor design. Therefore, the quadrature-axis magnetizing inductance L_{mq} is larger than the direct-axis magnetizing inductance $L_{md}$of the interior PM motor, which is the opposite to general salient-pole synchronous machines.

The stator flux linkage in equation (3.14) can be written in extended form as:

$$\begin{bmatrix} \lambda_a \\ \lambda_b \\ \lambda_c \end{bmatrix} = \begin{bmatrix} L_{aa} & L_{ab} & L_{ac} \\ L_{ba} & L_{bb} & L_{bc} \\ L_{ca} & L_{cb} & L_{cc} \end{bmatrix} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \lambda_m \begin{bmatrix} \cos\theta_r \\ \cos\left(\theta_r - \frac{2\pi}{3}\right) \\ \cos\left(\theta_r + \frac{2\pi}{3}\right) \end{bmatrix} \quad 3.23$$

3.3.2 Modeling of PMSG in d-q Reference Frame

To facilitate the electromagnetic analysis of a PMSG, a d-q rotating reference frame is often employed. In this approach, the 3-phase machine is evaluated based on a two-axis theory in which fictitious direct and quadrature axis currents (id, iq) flow through the virtual stator windings. This effectively removes all time-varying inductances from the voltage equations of the synchronous machine that arise from electric circuits in relative motion and with varying magnetic reluctance. This can be expressed mathematically as follows:

$$\begin{bmatrix} \mathrm{f}_d \\ \mathrm{f}_q \\ \mathrm{f}_0 \end{bmatrix} = \left(T_{abc\to dq0}\right) \begin{bmatrix} \mathrm{f}_a \\ \mathrm{f}_b \\ \mathrm{f}_c \end{bmatrix} = \frac{2}{3} \begin{bmatrix} \cos\theta_r & \cos\left(\theta_r - \frac{2\pi}{3}\right) & \cos\left(\theta_r + \frac{2\pi}{3}\right) \\ -\sin\theta_r & -\sin\left(\theta_r - \frac{2\pi}{3}\right) & -\sin\left(\theta_r + \frac{2\pi}{3}\right) \\ \frac{1}{2} & \frac{1}{2} & \frac{1}{2} \end{bmatrix} \begin{bmatrix} \mathrm{f}_a \\ \mathrm{f}_b \\ \mathrm{f}_c \end{bmatrix} \quad 3.24$$

$$\begin{bmatrix} \mathrm{f}_a \\ \mathrm{f}_b \\ \mathrm{f}_c \end{bmatrix} = \left(T_{abc\to dq0}\right)^{-1} \begin{bmatrix} \mathrm{f}_d \\ \mathrm{f}_q \\ \mathrm{f}_0 \end{bmatrix} = \begin{bmatrix} \cos\theta_r & -\sin\theta_r & 1 \\ \cos\left(\theta_r - \frac{2\pi}{3}\right) & -\sin\left(\theta_r - \frac{2\pi}{3}\right) & 1 \\ \cos\left(\theta_r + \frac{2\pi}{3}\right) & -\sin\left(\theta_r + \frac{2\pi}{3}\right) & 1 \end{bmatrix} \begin{bmatrix} \mathrm{f}_d \\ \mathrm{f}_q \\ \mathrm{f}_0 \end{bmatrix} \quad 3.25$$

In Equations (3.24) and (3.25), the variable f can refer to either voltage, current, or flux linkage vector variables. The reference frame can rotate at a constant or varying angular velocity or remain stationary, as in the case of the Clark transformation. In a three-phase balanced system, the transformation matrix in Equation (3.24) can be simplified to:

$$V_{dq0} = R_s i_{dq0} + T_{abc\to dq0}\, p\left[\left(T_{abc\to dq0}\right)^{-1}\right]\lambda_{dq0} + p\lambda_{dq0} \quad 3.26$$

Where

$$V_{dq0} = [V_d \quad V_q \quad V_0]^T$$

3.27

$$i_{dq0} = [i_d \quad i_q \quad i_0]^T \quad 3.28$$

$$\lambda_{dq0} = [\lambda_d \quad \lambda_q \quad \lambda_0]^T$$

3.29

Similarly, the stator flux linkage as calculated in equation 3.14 can be written in rotating reference frame as:

$$\lambda_{dq0} = L_{dq0} i_{dq0} + \lambda_{dqo} \qquad 3.30$$

Where the magnetizing flux linkage lies in the direction of d- axis, and hence can be written in matrix form as below:

$$\lambda_{dq0m} = [\lambda_m \quad 0 \quad 0]^T \qquad 3.31$$

$$\lambda_{dq0} = \begin{bmatrix} L_d & 0 & 0 \\ 0 & L_q & 0 \\ 0 & 0 & L_0 \end{bmatrix} \qquad 3.32$$

$$L_d = L_{is} + L_{md} = L_{is} + \frac{3}{2}(L_{0s} + L_{2s}) \qquad 3.33$$

$$L_q = L_{is} + L_{mq} = L_{is} + \frac{3}{2}(L_{0s} + L_{2s}) \qquad 3.34$$

$$L_0 = L_{is} \qquad 3.35$$

Further, the interrelationship between L_d, L_q and L_{0s}, L_{2s} can be given as:

$$L_{md} = \frac{3}{2}(L_{0s} + L_{2s}) \qquad 3.36$$

$$L_{mq} = \frac{3}{2}(L_{0s} + L_{2s}) \qquad 3.37$$

$$L_{0s} = \frac{2}{3}\left(\frac{L_{md}+L_{mq}}{2}\right) = \frac{1}{3}\left(L_{md} + L_{mq}\right) \qquad 3.38$$

$$L_{2s} = \frac{2}{3}\left(\frac{L_{md}-L_{mq}}{2}\right) = \frac{1}{3}\left(L_{md} - L_{mq}\right) \qquad 3.39$$

Where L_d is termed as direct-axis stator inductance and L_q as the quadrature axis stator inductance.

Similarly we can have

$$p\left[\left(T_{abc\rightarrow dq0}\right)^{-1}\right] = \omega_r \begin{bmatrix} -\sin\theta_r & -\cos\theta_r & 0 \\ -\sin\left(\theta_r - \frac{2\pi}{3}\right) & -\cos\left(\theta_r - \frac{2\pi}{3}\right) & 0 \\ -\sin\left(\theta_r + \frac{2\pi}{3}\right) & \cos\left(\theta_r + \frac{2\pi}{3}\right) & 0 \end{bmatrix} \qquad 3.40$$

Thus the following expression is obtained

$$T_{abc\to dq0}p\left[\left(T_{abc\to dq0}\right)^{-1}\right]=\omega_r\begin{bmatrix}0 & -1 & 0\\ 1 & 0 & 0\\ 0 & 0 & 0\end{bmatrix} \qquad 3.41$$

Put equation 3.27 to 3.41

$$\begin{bmatrix}V_d\\ V_q\\ V_0\end{bmatrix}=\begin{bmatrix}R_s & 0 & 0\\ 0 & R_s & 0\\ 0 & 0 & R_s\end{bmatrix}\begin{bmatrix}i_d\\ i_q\\ i_0\end{bmatrix}+\omega_r\begin{bmatrix}0 & -1 & 0\\ 1 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}\begin{bmatrix}L_d & 0 & 0\\ 0 & L_q & 0\\ 0 & 0 & L_0\end{bmatrix}\begin{bmatrix}i_d\\ i_q\\ i_0\end{bmatrix}+\begin{bmatrix}\lambda_m\\ 0\\ 0\end{bmatrix}+$$
$$p\begin{bmatrix}0 & -1 & 0\\ 1 & 0 & 0\\ 0 & 0 & 0\end{bmatrix}\begin{bmatrix}L_d & 0 & 0\\ 0 & L_q & 0\\ 0 & 0 & L_0\end{bmatrix}\begin{bmatrix}i_d\\ i_q\\ i_0\end{bmatrix} \qquad 3.42$$

Rewriting equation 3.42

$$V_d=R_s i_d+L_d\frac{di_d}{dt}-\omega_r L_q i_q \qquad 3.43$$

$$V_q=R_s i_q+L_q\frac{di_q}{dt}+\omega_r L_q i_q+\omega_r\lambda_m \qquad 3.44$$

In a balanced operation of a PMSG, the zero sequence equation may be disregarded. The d and q axes equivalent diagram of a PMSG depicts the back electromotive force (EMF) of the direct and quadrature axes, denoted by Ed and Eq, respectively can be represented as follows:

$$E_d=-\omega_r\lambda_q=-\omega_r L_q i_q \qquad 3.45$$

$$E_q=\omega_r\lambda_d=\omega_r L_d i_d+\omega_r\lambda_m \qquad 3.46$$

The mechanical power developed inside PMSG can be expressed as:

$$P_m=\frac{3}{2}\left(E_d i_d+E_q i_q\right)=\frac{3}{2}\left(\omega_r\lambda_d i_q-\omega_r\lambda_q i_d\right) \qquad 3.47$$

Similarly, from the above derived equations, the expression for electromagnetic torque in rotating reference frame can be written as:

$$T_e=\frac{P_m}{\omega_m}=\left(\frac{p}{2}\right)\frac{P_m}{\omega_r} \qquad 3.48$$

Where ωm is the mechanical speed and p is the number of poles.

Substituting (3.47) in (3.48), the expression for electromagnetic torque can be rewritten as:

$$T_e = \left(\frac{3}{2}\right)\left(\frac{p}{2}\right)\left(\lambda_d i_q - \lambda_q i_d\right) \quad 3.49$$

Substituting the appropriate values for stator flux linkage from equation 3.30 into equation 3.49, then electromagnetic torque equation is:

$$T_e = \left(\frac{3}{2}\right)\left(\frac{p}{2}\right)\left(\lambda_m i_q - \left(L_d - L_q\right) i_d i_q\right) \quad 3.50$$

When a PMSG is operating in generator mode, the current in the stator winding flows in the opposite direction, indicated by a negative sign. As a result, the copper and core losses in the PMSG in the d and q axes are represented in the equivalent circuit diagram.

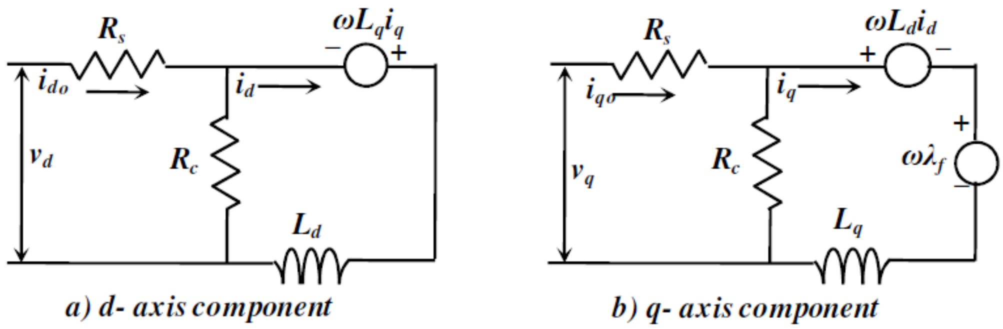


Figure 3.7 d *and* q *axes equivalent circuit diagram of PMSG*

3.3.3 PMSG Controller Modeling

The main goal of PMSG control is to extract optimal power from varying wind while ensuring efficient operation of the PMSG [97].Optimal power extraction refers to the process of extracting the required power from a wind turbine under varying wind conditions [108]. In a variable speed wind turbine, the relationship between rotor speed and the output power for a given wind speed is illustrated in Figure 3.4. A detailed relationship between rotor speed and output power for a given wind speed is provided in the variable speed wind turbine model section. The applied torque or extracted power from the wind can be regulated by controlling the rotor speed, as expressed in equations (3.6) and (3.7). By rearranging equation (3.7), the relationship between applied torque and rotor speed can be defined as follows:

$$\tau_{opt} = K_{opt}\omega^2 \quad 3.51$$

Where K_{opt} is given by

$$K_{opt} = \frac{1}{2}\rho A R^3 \quad 3.52$$

The optimum power can be calculated as

$$P_{opt} = \omega\tau_{opt} = K_{opt}\omega^3 \tag{3.53}$$

From 3.53, the speed of the rotor at optimum power point can be written as follows:

$$\omega = \sqrt[3]{\frac{P_{opt}}{K_{opt}}} \tag{3.54}$$

Equation 3.53 shows that the optimum power can be achieved by controlling the rotor speed, as depicted in Figure 3.8. The graph illustrates the power generated by a turbine as a function of rotor speed for different wind speeds. For instance, consider a specific wind speed (v6); to generate the optimum power (PWopt), the rotor speed should be maintained at either ω1 or ω3. Since ω3 is greater than the base rotor speed, the control system must choose ω1. If the wind speed decreases from v6 to v5, the control system adjusts the rotor speed to ω2 to extract the required power. The primary objective of the PMSG controller is to achieve optimum power extraction from varying wind and ensure efficient PMSG operation. [97]

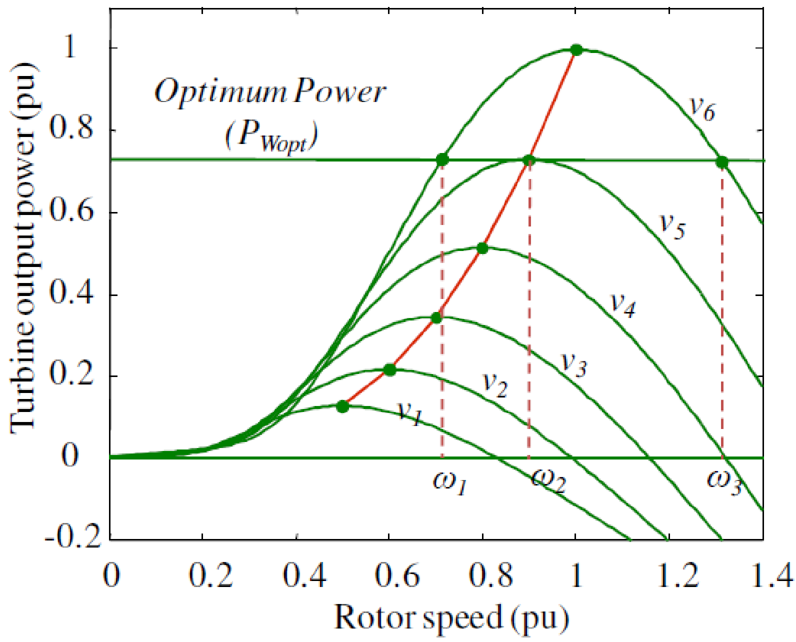


Figure 3.8 Power generation of wind turbine in different rotor and wind speeds

There are different ways to implement optimum power extraction algorithms in wind energy conversion stages. One approach is to use an unregulated two-level rectifier with a boost or a buck-boost converter to regulate the dc-link voltage or rotor speed. However, this arrangement can cause high harmonic distortion, which in turn reduces generator efficiency. To improve these distortions, a regulated two-level rectifier can be used.

The primary objective of the controller in this system is to regulate the d and q axis components of the stator current. The reference value of the optimum d and q axis current determines the operational loss of the IPMSG. The losses of a PMSG can be classified into four components: stator copper loss, core loss, mechanical loss, and stray-load loss. Only the stator copper and core losses depend on the fundamental components of the stator currents. To achieve maximum efficiency of the IPM synchronous generator, it is necessary to minimize copper and core losses. The copper (PCu) and core (PCore) loss for the IPM synchronous generator can be determined using the diagram in Figure 3 and the following equations [127], [103]:

$$P_{cu} = R_s\left(i_d^2 + i_q^2\right) \qquad 3.55$$

$$P_{core} = \frac{\omega^2\left(\left(L_d i_d + \psi_f\right)^2 + \left(L_q i_q\right)^2\right)}{R_c} \qquad 3.56$$

Where R_c is the core losses component

The power output from electrical generator can calculated as

$$P_{out} = P_w - P_{cu} - P_{core} \qquad 3.57$$

$$P_{out} = T_g\omega - R_s\left(i_d^2 + i_q^2\right) - \frac{\omega^2\left(\left(L_d i_d + \psi_f\right)^2 + \left(L_q i_q\right)^2\right)}{R_c} \qquad 3.58$$

Therefore, the optimum value of i_d is obtained from the output power (*Pout*) vs *d* axis stator current (i_d) curve based on equation 3.54-3.58. From Figure 3.9, the optimum value of the *d* axis current component is carefully selected at the point of output power from the machine is maximum.

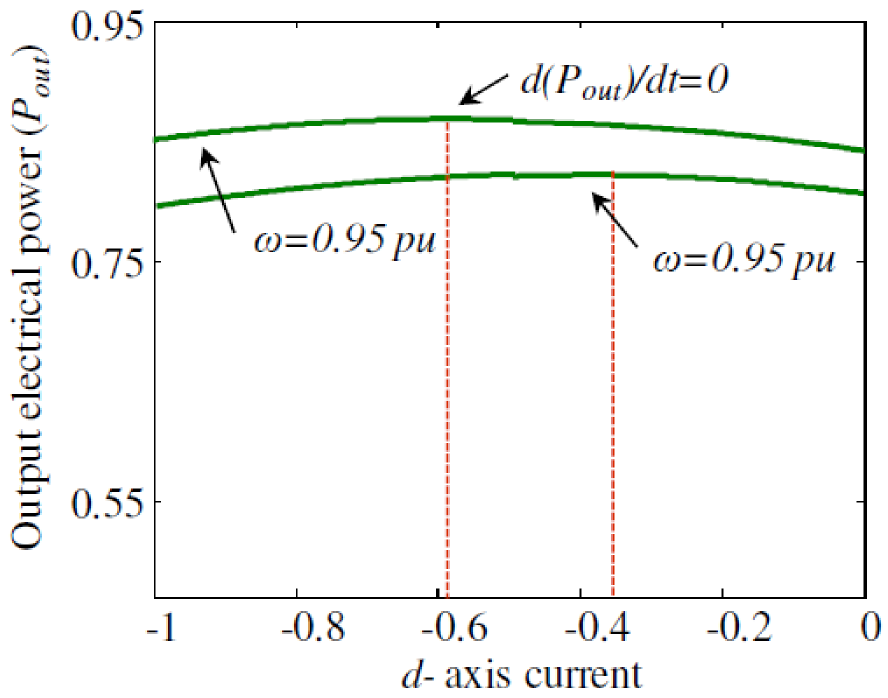


Figure 3.9 the d *axis current vs output electric power*

3.4 Conclusion

This chapter outlines the modeling and control aspects of a wind energy conversion system. The optimum wind power is regulated by controlling the rotor speed. To ensure the efficient operation of IPMSG, the d- and q- axis currents are also controlled.

4 MODELING OF HYDRO POWER

4.1 Introduction

The hydropower system construction varies depending on the specific conditions of the site and the type of hydropower plant to be built. The various types of hydropower plants are run-of-the-river systems, which do not require a large dam and reservoir, pumped storage systems, which allow excess electricity to be stored by pumping water uphill to a higher reservoir during times of low demand, and then releasing the water to generate electricity during times of high demand.

A run-of-river hydropower system is a type of hydroelectric power generation that harnesses the kinetic energy of the flowing water in a river or stream to generate electricity. The systems utilize a channel to divert a portion of the river's natural flow through turbines, which then spin to generate electricity. This diverted water is then returned to the river downstream. The system has minimal impact on the surrounding environment since no large reservoirs, which can significantly alter the river's natural flow.

The water flowing through the powerhouse rotates the hydraulic turbine, which in turn drives the generator rotor to produce electricity. The mechanical power generated by the turbine can be controlled by adjusting the turbine gate opening, which involves adjusting the effective opening of the guide vane for a Francis turbine, or adjusting the effective opening of the nozzles' needle for a Pelton turbine.

In the hydropower industry, "water head" is a technical term that refers to the elevation of water, typically measured in meters or feet, which is used to express pressure. Within this context, the term "head loss" is used to describe the pressure loss resulting from friction within the fluid. To account for the direction of flow, the Darcy-Weisbach equation is used to calculate head loss.

$$H_{loss} = \frac{f_r L \bar{v}|\bar{v}|}{2Dg} = \frac{f_r L \bar{Q}|\bar{Q}|}{2DgA^2} \qquad 4.1$$

The equation 2.1 can be utilized to determine the friction in an open channel by taking into account the length, diameter, and average water flow. The friction factor is unitless and can be adjusted to differentiate between various types of waterways, including open channels and penstocks. Additionally, assuming the hydraulic turbine to be a curved pipe with obstructions, the equation can be employed to calculate the friction loss along the turbine.

4.2 Open channel

The Open Channel is constructed flat terrain using concrete to direct water into the penstock. When modeling the Open Channel, the elasticity of the water inside the channel can be neglected and the Newton's second law can be used in mathematical modeling.

$$F = ma$$

$$a = \frac{dv}{dt}$$

$$F = \Delta pA$$

$$\Delta pA = m\frac{dv}{dt} \qquad 4.2$$

By considering the head loss then the equation 3.1 can be rewritten as

$$m_{c1}\frac{dv_{c1}}{dt} = \rho g\left(H_r - H_{s1} - H_{c\_loss}\right)A_c \qquad 4.3$$

Where as

$$m_{c1} = \rho L_c A_c$$

and

$$v_{c1} = \frac{Q_c}{A_{c1}}$$

Then the dynamic equation for the open channel can be written as

$$\frac{dQ_c}{dt} = \frac{gA_c}{L_{c1}}\left(H_r - H_s - H_{c\_loss}\right) \qquad 4.4$$

4.3 Penstock

A penstock is a closed conduit that directs water from its source towards a hydraulic turbine. The primary driving force for the mechanical power of water in a penstock comes from the potential difference between its inlet and outlet. Thus, a penstock is designed to withstand the internal pressure of water and is typically modeled with considerations for its elasticity. This distinguishes it from other models of water systems, such as those with open volumes. The material used in constructing a penstock may vary and can be reflected in its modeling by a smaller friction factor. Cement and plastic are examples of materials commonly used in penstock construction.

$$\frac{a^2\partial Q}{gA\partial x} + \frac{Q\partial H}{A\partial x} + \frac{\partial H}{\partial t} + \frac{Q}{A}\sin\theta = 0 \qquad 4.5$$

Equation of momentum is also written as

$$g\frac{\partial Q}{\partial x} + \frac{Q\partial H}{A^2\partial x} + \frac{\partial Q}{A\partial t} + g\frac{dH_{loss}}{dt} = 0 \qquad 4.6$$

$$\frac{dH_{p\_out}}{dt} = \frac{gA_p}{L_p}\left(H_{s1} - H_{p\_out} - H_{P\_loss}\right) \qquad 4.7$$

$$\frac{dH_{p\_out}}{dt} = k\left(Q_{p\_in} - Q_{p\_out}\right) \qquad 4.8$$

$$k = \frac{a^2}{gA_pL_p} \qquad 4.9$$

Where subscripts p indicates penstock; s1 indicate upstream tank; out and in indicate inlet flow and outlet flow; t is time.

4.4 Forebay

A forebay is an inlet structure for a water intake system for a hydroelectric power plant. The layout of a forebay depends on the specific design of the intake system and the surrounding topography. The forebay has an inlet structure that is designed to divert water from the main water source to the intake system. This structure may consist of a dam, weir, or other types of control structures. It also has sedimentation basin layout for allowing the settling of sediments and debris present in the water. Furthermore, flow control structures, such as gates or valves, to regulate the flow of water to the intake system. Also forebay include access points and monitoring equipment to allow for inspection and maintenance of the intake system.

$$A_{ss}\frac{dH_s}{dt} = Q_{s-in} - Q_{s\_out} \qquad 4.10$$

4.5 Hydraulic Turbine

The general mechanical power from water P_m

$$P_m = \eta\rho gH_{net}Q_{dis} \qquad 4.11$$

Where η is turbine efficiency

The net head H_{net} is identical to the difference of output water head of penstock, H_{p_out} and the head of downstream surge, head loss within turbine is neglected.

$$H_{net} = H_{p\_out} - H_s \tag{4.12}$$

The model is commonly used for all types of turbines, assuming a constant gate. The effective gate opening, which refers to the area through which water flows (discharged flow)

$$Q_{dis} = k_g OP\sqrt{2gH_{net}} \tag{4.13}$$

Where

$$OP = GA_p$$

G is the percentage opening of the gate, assuming the flow before and after turbine is constant.

$$\Delta G = 1\Delta t \tag{4.14}$$

4.6 Synchronous Generator

Synchronous generator is a reliable way of converting mechanical energy from a hydropower system into electrical energy. Mathematical equation of the synchronous generator is;
q axis

$$T'_{qo}\frac{dE'_q}{dt} = (X_d - X'_d)I_d - E'_q + E_f \tag{4.15}$$

d axis

$$T'_{qo}\frac{dE'_d}{dt} = \left(X'_q - X_q\right)I_q - E'_d \tag{4.16}$$

Where E' Is transient voltage, E_f is the excitation voltage, X is synchronous reactance, X' is the transient reactance, I is the armature current, T'_{do} is d axis open circuit time constant, T'_{qo} is q axis open circuit time constant. The subscript d and q indicate d and q axis respectively
q axis component of terminal voltage

$$U_{td} = E'_d - R_aI_d - X'_qI_q \tag{4.17}$$

q axis component of terminal voltage

$$V_{tq} = E'_q - R_aI_q + X'_dI_d \tag{4.18}$$

Electrical power

$$P_e = E'_dI_d + E'_qI_q + \left(X'_d - X'_q\right)I_dI_q \tag{4.19}$$

Terminal voltage

$$V_t = \sqrt{V_{td}^2 + V_{tq}^2} \qquad 4.20$$

Where R_a is the armature resistance, U_{td} and U_{tq} are terminal voltage on d and q axis

Rotor motion phase angle δ

$$\frac{\mathrm{d}\delta}{\mathrm{dt}} = \omega_o(\omega - 1) \qquad 4.21$$

Angula velocity ω

$$M\frac{d\omega}{dt} = P_{m(pu)} - P_e - Damp\frac{d\delta}{dt} \qquad 4.22$$

Where M is the moment of inertia constant of the machine, Damp is damping coefficient
Considering the voltage from infinite bus v_o, the terminal voltage on d and q axis

$$U_{tq} = V_o \sin\delta + R_e I_d - X_e q \qquad 4.23$$

$$U_{tq} = V_o \cos\delta + R_e I_q - X_e I_d \qquad 4.24$$

Where X_e is the equivalent reactance of transient line

The exciter is simply treated as a second order dynamic model

$$T_E\frac{dE_f}{dt} = k_E(U_r - U_t - U_s) - E_f \qquad 4.25$$

$$T_E\frac{dU_s}{dt} = k_F\frac{dE_f}{dt} - U_s \qquad 4.26$$

Where T_E is exciter time constant; k_E is exciter gain; k_F is stabilized gain; U_r , U_t , U_s are the voltages at reference, stabilizer, and generation terminal respectively. Assuming generated electrical power, P_e , is equal to totally consumed, P_c , and the power demanding, P_d, from costumers for a steady infinite grid.

$$P_e = P_c = P_d \qquad 4.27$$

4.7 Conclusion

This chapter outlines the modeling and control aspects of a Hydroturbine conversion system. The optimum hydro power is regulated by controlling the water flow. To ensure the efficient operation of PMSG, the d- and q- axis currents are also controlled.

5 OPTIMIZATION OF STAND-ALONE POWER GENERATION

5.1 Introduction

Optimizing a wind-hydropower system with a fuel cell layout involves designing and configuring the system to maximize energy production and efficiency while minimizing costs and environmental impact. The availability of water (hydro) and wind energy would allow integration of renewable hybrid systems. However the system will need means of energy storage techniques to overcome the shortage of resource in in dry season (level of water in the river decreases) and off wind hours.

The system's design would utilize HOMER's optimization and sensitivity analysis algorithms to facilitate the assessment of various system configurations [1]. HOMER enables users to put an hourly power consumption profile and match renewable energy generation to meet the required load. It also enables the analysis of micro-grid potential, peak renewables penetration, ratio of renewable sources to total energy, and grid stability, particularly for medium to large scale projects. Additionally, HOMER features a powerful optimization function that aids in determining the cost of different energy project scenarios. This functionality permits cost minimization and scenario optimization based on different factors [1, 2].

To use HOMER, the model inputs should describe the technology options, component costs, and resource availability [2]. HOMER software would utilize these inputs in simulating various system component combinations, generating results that can be viewed as a list of feasible configurations sorted by net present cost. HOMER also presents simulation outcomes in a broad range of tables and graphs, facilitating the comparison of configurations and evaluation based on their economic and technical merits [3, 4].

5.2 Load Profiles Section

The first model system considered in this study in section 1 is shown in Fig. 1, where a PV system and three batteries are connected to the DC terminal and a converter is connected between the AC and DC bus bars. An isolated diesel generator that is not loaded depending on the load profile and the required time that is necessary to come on stream is also shown in the model system. The details of the equipment considered for the model system are given in the HOMER summary input shown in

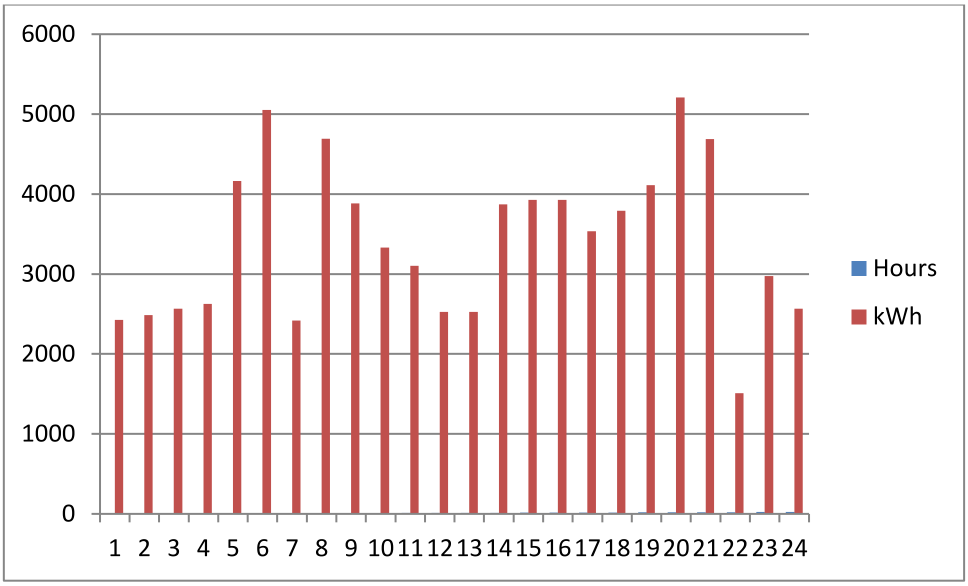


Figure 5.1 Load Profile

As seen from figure 5.1 that the energy demand always vary significantly depending on the time of day and day of the week. Typically, energy demand is highest during the daytime that are 8:00am -11:00 am when people are at work or school and using appliances such as lights, computers, and HVAC systems. Then demand reduces between 12:00 pm and 13:00 pm off working hours (lunch time). Then the demand tends to increase in the late afternoon and early evening when people return home and start cooking dinner or using more electricity for leisure activities.

During the night, energy demand decreases as people turn off lights and go to sleep. Therefore, the lowest demand for energy typically occurs in the early morning hours, usually around 5 or 6 am, before starting to increase again as people start their day.

5.3 Power System Modeling

The model consists of Wind-Hydro renewable energy power system with energy storage through fuel cell as shown Figure 5.2. The system consists of hydro and wind power plant connected AC bus bar. AC and DC busbars are interconnected through inverter charger. Then electrolyzer is connected to DC bus bar

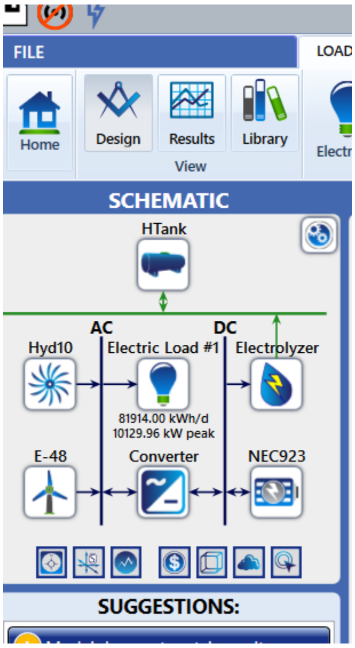


Figure 5.2 Power System Modelling

5.4 Simulation Results and Analyses

The figure 5.3 display simulation results for the two sections examined in this study. Specifically, figure 5.3 to present the results. Figure 5.3 illustrates the possible range of results obtained using the combination of energy sources in the model system. The results are arranged in order of the most energy-efficient system in terms of the net present cost. The optimized result with the lowest net present cost appears in the first array.

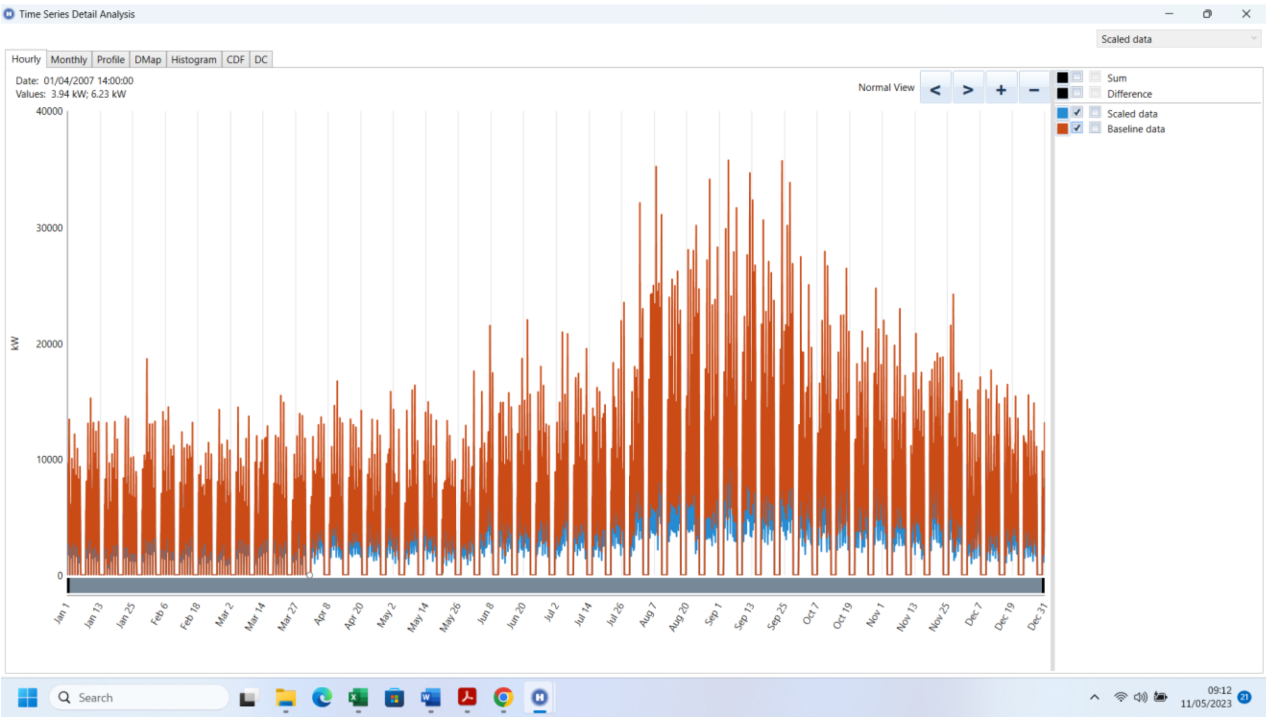


Figure 5.3 Daily Load profile

For the best HOMER configuration with a value of \$0.05/kWh. The costs of constructing and operating a new capacity generation unit are increasing everyday as well as transmission and distribution and land issues for new generation plants. Demand side management (DSM) therefore encompasses load reduction strategies as well as load growth strategies and flexible energy service options. This can be defined as the selection, planning, and implementation of measures intended to have an influence on the demand or customer-side of the electric meter, either caused directly or stimulated indirectly by the utility. DSM programs are peak clipping, valley filling, load shifting, load building, energy conservation and flexible load shape. In designing the system the hydro turbine can generate 4300kW and the wind can generate 800kW. The power from the hydro is constant for almosteight month that is from November to June (the period of rain sesons) and there is sliht change of water level from July to October (the period of dry season).
However, during the rainy season, the river records a water level that is above the amount required. This has been attributed by the increase of amount of rainfall during at theat particular season, which leads to an increase in the amount of water that flows into the river.

The regulation prohibits the construction of water reservoirs in the area where the river is located can be a result of the fact that the river is already being used to supply a state-owned water reservoir. In such cases, the government may have deemed it unnecessary to construct additional reservoirs as it would lead to redundancy and wastage of resources.

input to a control system that manages the power sharing between the hydro power and wind turbine sources. The study also incorporates the use of a storage facility to further optimize power sharing and improve the overall performance of the system.

The main objective of the study is to evaluate the effectiveness of the power sharing between these renewable energy sources and the storage facility. The researchers analyzed the data collected from the hydro power plant, wind turbine, and storage facility to determine the power sharing capabilities of the system.

To achieve this, the study utilized various performance metrics such as energy efficiency, system stability, and power quality to evaluate the system's performance. The researchers also analyzed the impact of different weather conditions on the power sharing capabilities of the system.

The study found that the power sharing between the hydro power, wind turbine, and storage facility sources improved the overall efficiency of the system. The use of the storage facility allowed for better management of power fluctuations and improved the stability of the system. Additionally, the study found that the power sharing capabilities of the system were not significantly affected by varying weather conditions.

Overall, the study provides valuable insights into the performance of power sharing between renewable energy sources and storage facilities. These findings could inform the development and implementation of similar systems in the future, as the world moves towards greater reliance on renewable energy sources to meet its energy needs.

The system has been designed to generate energy, but there are times where the amount of energy produced is not enough to power the load that requires it. In such cases, the system relies on the energy stored in batteries and fuel cells to bridge the energy gap and meet the load's energy requirements.

The system works on the principle of energy storage, where excess energy generated during periods of low energy demand is stored in batteries and fuel cells. When the energy demand increases and exceeds the energy generated by the system, the stored energy in the batteries and fuel cells is released to compensate for the energy shortfall and meet the energy demand of the load.

This method of energy storage and release ensures that the system is always able to meet the energy requirements of the load, regardless of fluctuations in energy demand. The batteries and fuel cells act as a backup energy source, which helps to maintain a stable and reliable energy supply for the load.

Overall, the system's operation is based on the efficient storage and release of energy to ensure that the energy demand of the load is always met, even during periods of low energy generation.

6 ENERGY STORAGE AND INVERTER SYSTEM CONTROL

6.1 Introduction

This chapter outlines the modelling and control strategies of;

a) Energy storage systems, and
b) The load side inverter system of the proposed renewable energy based hybrid stand-alone power system.

The proposed energy storage system consists of both hydrogen and battery storage systems. The hydrogen storage system consists of an electrolyzer, hydrogen tank and fuel cell unit. The control systems of energy storage and inverter systems are implemented in a MATLAB/ Simpower environment and results are presented.

This section presents an overview of the control strategies and models for two components of the hybrid standalone power system:

a) Energy storage systems
b) Load-side inverter system

The energy storage system comprises both battery and hydrogen storage systems. Specifically, the hydrogen storage system comprises an electrolyzer, hydrogen tank, and fuel cell unit. The control mechanisms for the energy storage and inverter systems are realized within a MATLAB/Simpower framework, and the outcomes are reported.

6.2 Overview of Energy Storage System

Effective management of energy storage systems is important in ensuring consistent operation of renewable energy sources such as wind, which are intermittent and volatile. There are various energy storage systems available, such as compressed air, flywheel, pumped hydro, thermal, hydrogen, batteries, superconducting magnetic storage, and super-capacitors, which are used for different applications and purposes. The introductory chapter discusses the advantages and disadvantages of each storage system.

The combination of fuel cell, electrolyzer, and battery is being considered for several reasons;

a) Excess power generated by wind can be either stored in the battery storage system or used to produce hydrogen through the electrolyzer.
b) Batteries respond quickly, ensuring better hybrid system stability during transient periods in case of sudden changes in wind or load.

c) This combination can improve the system's efficiency by power-sharing, enabling the operation of a fuel cell in a high-efficiency region. The following sections will present the control strategy, battery energy, and hydrogen storage system.

6.3 Battery System Modelling and Control

6.3.1 Battery System Modelling

In the proposed project, lead-acid batteries have been chosen for their ability to improve the system during transient stability and to support it with bulk energy. A lead-acid battery is an electrical storage device that uses a reversible chemical reaction to store energy. The charging and discharging equations are shown below [139]-[141]: Discharging mode

$$V_{bat} = E_0 - RI - K\left(\frac{Q}{Q-it}\right)(it - i^*) + Ae^{t} \qquad 6.1$$

Charging mode:

$$V_{bat} = E_0 - Ki - Ki^*\left(\frac{Q}{it-0.1Q}\right) - Kit\left(\frac{Q}{Q-it}\right) + Ae^{t} \qquad 6.2$$

Where

V_{bat} = battery output voltage (V)

E_0 = battery constant voltage (V)

K = polarization constant ($\left(\frac{V}{Ah}\right)$ or polarization resistance (Ω);

Q= battery capacity (Ah);

$1t = \int idt$ is the actual battery charge (Ah);

A = exponential zone time constant inverse $(Ahr)^1$

R = internal resistance (Ω);

i =battery current (A);

i* =filtered current (A).

The state-of-charge (SOC) is defined as the available capacity remaining in the battery, expressed as a percentage of the rated capacity. The SOC is defined as:

$$SOC = 100\left(1 - \frac{\int idt}{Q}\right)\% \qquad 6.3$$

The following assumptions are considered of the model

a) The internal resistance is assumed to be constant during charging and discharging cycles and does not vary with current amplitude.
b) The model's parameters are deduced from the discharge characteristics and assumed to be the same for charging.
c) The battery capacity does not change with the amplitude current.
d) The temperature does not affect the model's behaviour.
e) The battery has no memory effect.

6.3.2 Battery System Control

The interface circuit shown in figure 6.1 is bidirectional DC-DC converter which is widely used for regulating the charging and discharging of battery storage systems. This converter performs as a boost converter during the charging cycle by utilizing Q_2 switch modulation in conjunction with anti-parallel diode D_1. Conversely, during the discharging cycle, the converter operates as a buck converter through modulation of Q_1 switch along with anti-parallel diode D_2, enabling power supply reserve.

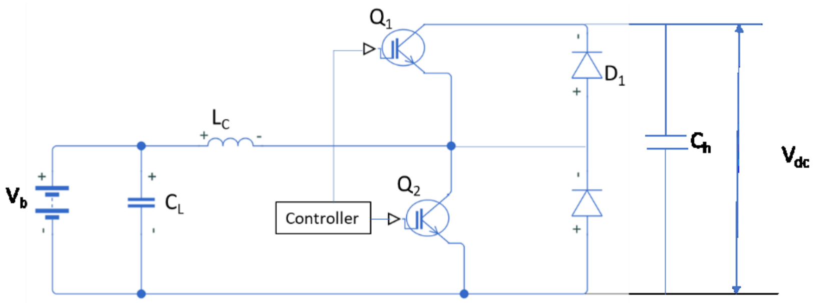


Figure 6.1 Bidirectional dc-dc converte

The bidirectional dc-dc converter should operate as a continuous condition mode for charging and discharging systems applications. The switches Q_1 and Q_2 are switched so as the converter operates in a steady state with four sub-interval time. These are intervals I (t_o to t_1); 2 (t_1 to t_2); 3 (t_2 to t_3); and 4 (t_3 to t_4). During intervals I and 2, the converter works as a boost-converter in battery charging mode, while during interval 3 and interval 4, the converter works as a buck-converter in battery discharging mode. It should be noted that the low voltage battery side is considered as V_B and the high voltage dc-link voltage as V_{dc}.

a) Interval 1(t_o - t_1) at the time of t_0 - t_1 the lower switch Q_2 is ON and upper switch is OFF with diode D_1 and D2 on reversed bias as shown in figure 6.2. During this time, the inductor is charged and the current through the inductor increases. The battery voltage (V_s) and the increased inductor current ($\Delta i_s(+)$) is expressed in following equation:

$$V_B = L_C \frac{di_B}{dt} = L_C \frac{\Delta i_B}{\Delta T} \qquad 3.4$$

$$\Delta i_B(+) = \frac{V_B}{L_C} T_{ON} \qquad 3.5$$

where T_{ON} is the on time of lower switch Q_2.

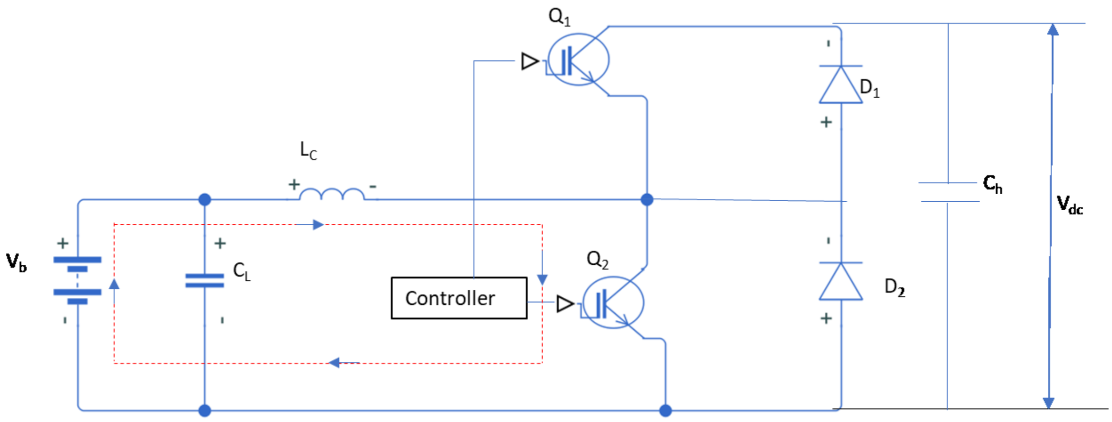


Figure 6.2. Bidirectional dc-dc converte

b) When the time between t_1 - t_2 circuit would switch OFF Q_1 and Q_2. The diode D_1 of the upper switch Q_1 conducts as shown in figure 6.3. In this condition, the inductor current starts decreasing. The decrease of the induction current decreases $\Delta i_B(-)$ during the off state, given by:

$$\Delta i_B(-) = \frac{(V_{dc} - V_B)}{L_C} T_{OFF} = \frac{(V_{dc} - V_B)}{L_C} (T - T_{ON}) \qquad 3.6$$

where T_{OFF} is the OFF time of lower switch Q_2. T is the total time of operation

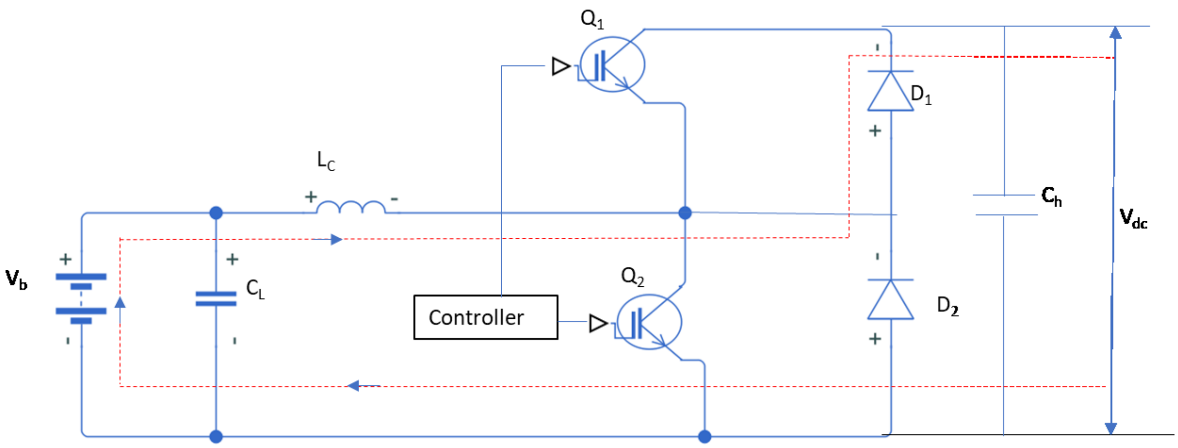


Figure 6.3. Bidirectional dc-dc converter operation (time interval t1-t2).

During steady state operation, $\Delta i_B(+)$ in ON time state and $\Delta i_B(-)$ in OFF time state has Should be equal. Therefore, (6.5) and (6.6) are equated as follows:

$$\Delta i_B(+) = \frac{V_B}{L_C} T_{ON} = \frac{(V_{dc}-V_B)}{L_C}(T - T_{ON}) \qquad 6.7$$

From equation 6.7 the value of battery voltage and DC link voltage expressed as the function of duty cycle as:

$$V_B = DV_{dc} \qquad 6.8$$

Where $D = \frac{T_{ON}}{T}$

Interval 3 (t_2 - t_3)

During the period of t_2 - t_3 the upper switch Q_1 is ON and lower switch Q_2 is OFF with diode D1 and D_2 on the reversed bias, as seen in figure. 6.4. at this interval, the converter is working as a buck converter. The current through the inductor increases and can be expressed as follows:

$$\Delta i_B(+) = \left(\frac{V_{dc}-V_B}{L_C}\right) T_{ON} \qquad 6.9$$

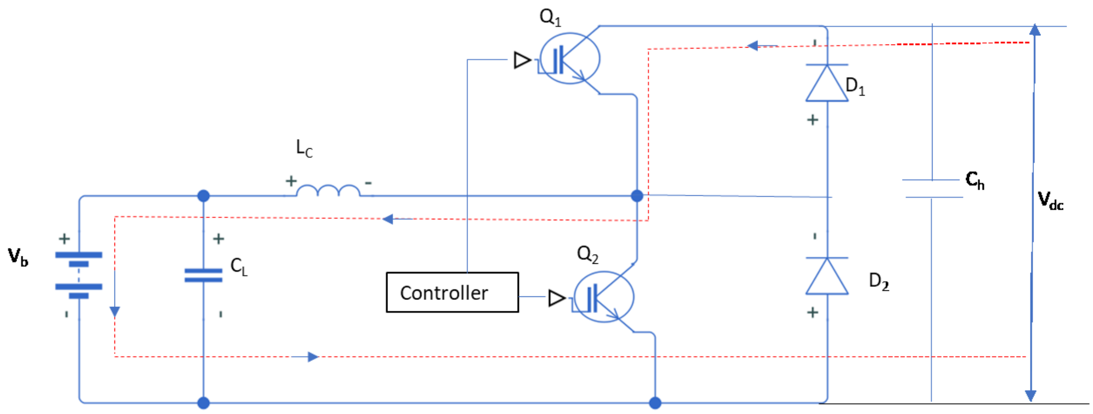


Figure 6.4 Bidirectional dc-dc converter operation (time interval t2-t3)

Time interval 4 (t_3-t_4)

During the time of t_3-t_4 all switches are OFF and the lower diode D_2 conducts as seen in figure 6.5. at this interval the converter is working as buck converter and current through the converter decreases and is expressed as;

$$\Delta i_B(-) = \frac{V_B}{L_C} T_{ON} = \frac{V_B}{L_C}(T - T_{ON}) \qquad 6.10$$

ON time during steady state working period $\Delta i_B(+)$ and OFF time $\Delta i_B(-)$ has to be the same, then both equation should be equated and results to;

$$\left(\frac{V_{dc}-V_B}{L_C}\right) T_{ON} = \frac{V_B}{L_C} T_{ON} = \frac{V_B}{L_C}(T - T_{ON}) \qquad 6.11$$

Also output voltage is expressed as;

$$V_{dc} = \left(\frac{1}{1-D}\right) V_B \qquad 6.12$$

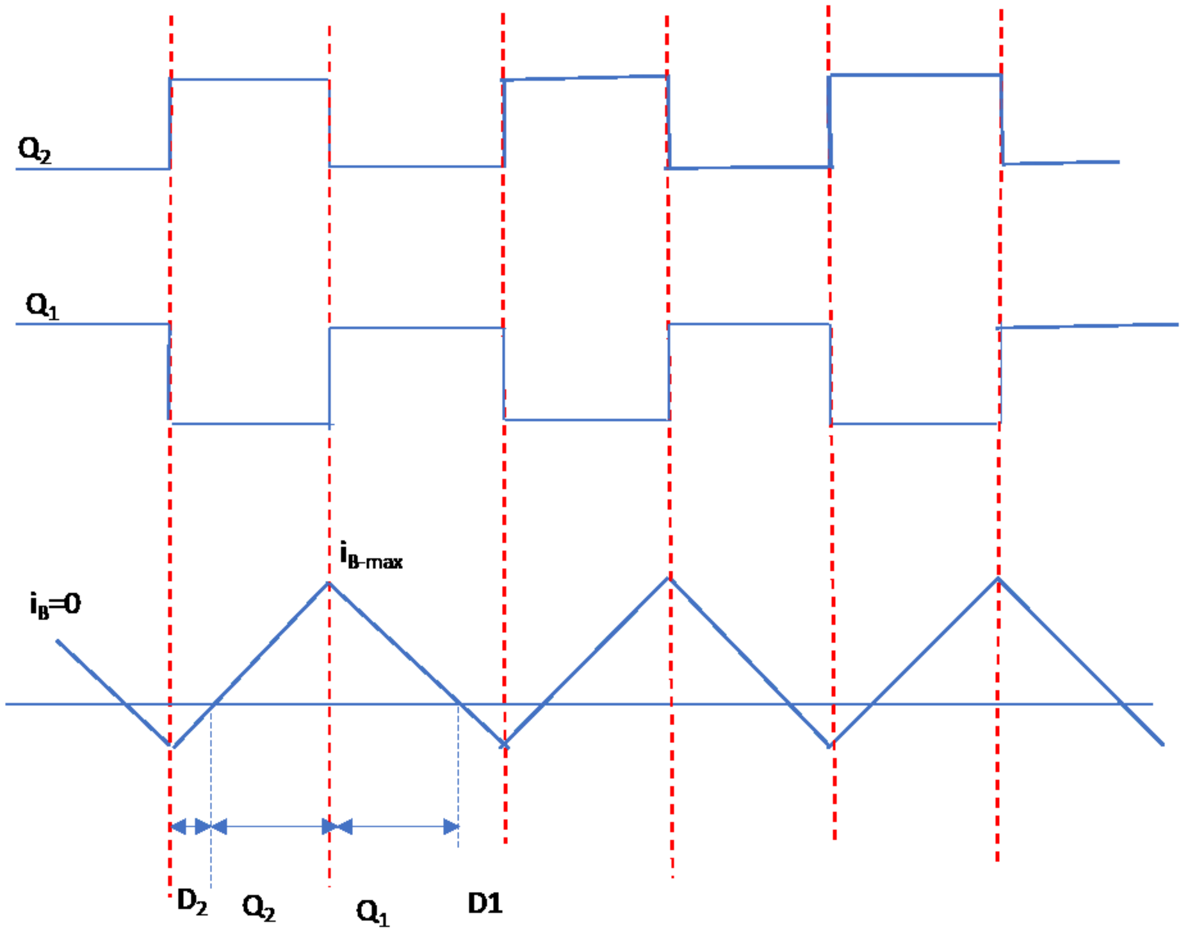


Figure 6.6 Control of the bidirectional dc-dc converter

The inductor value is critical in operation of the bi-directional dc-dc converter while in conduction mode. The conduction mode of operation always depends on input and output values of voltage, current, duty cycle, frequency and inductance value of inductor. The inductance value of the inductor is calculated as:

$$L = \frac{V_B(V_{dc}-V_B)}{I_B f_s V_{dc}} \qquad 6.13$$

Where f_s is the switching frequency.

figure 6.7 shows control circuit of the bi-directional dc-dc converter. This control circuit has voltage and current regulator. The reference current signal is generated basing on the voltage error through comparing battery current. Basing on the error signal, the PI controller generates a suitable pulse-width modulation (PWM) signal for the switch.

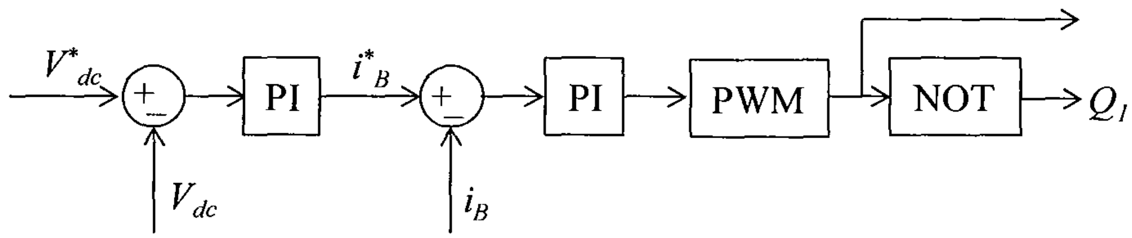


Figure 6.7 Control of the bidirectional dc-dc converter

6.3.3 Simulation of Battery Controller

controller system for the battery performance has been simulated using MATLAB computer software with the overall system configuration shown in figure 6.8. The battery parameters for the system with its controller values are shown in Table 6.1.

Table 6. I. Parameters of battery system and controller

Specification	Data	Unit
Number of batteries in series	5	a/a
Number of batteries in parallel	8	n/a
Rated Voltage	12	Volt (V)
Rated Current	0.5	Amp (A)
Rated Capacity	0.1	amp-hour (Ah)
Inductor	2.7	Mhenry (mH)
Capacitor	64	micro Farad (µF)
Switching frequency	20	k Hz

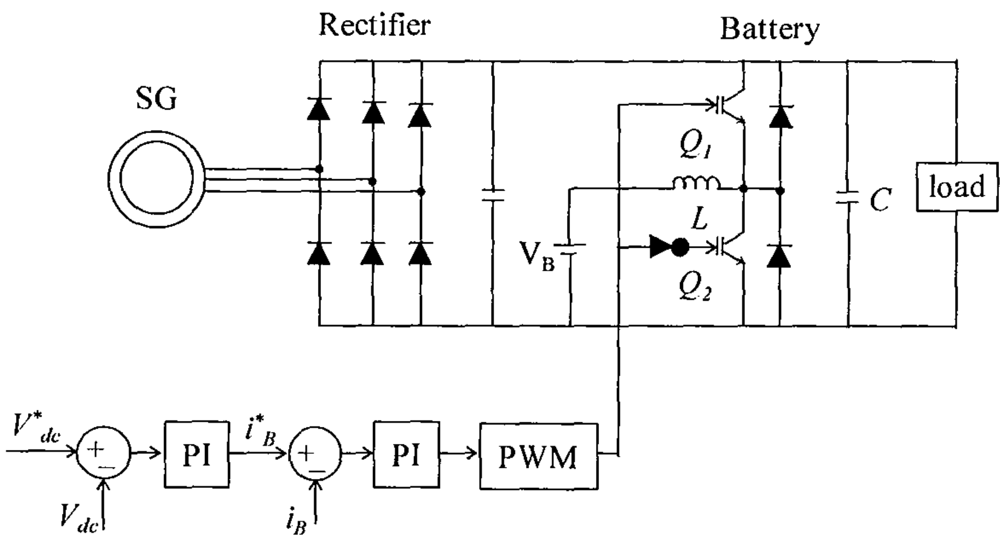


Figure 6.8. A battery storage system with control

In the study, it has been assumed that the synchronous generator would generate a constant power of power 2.7 kW. It has been assumed the generator supplies load variable and the load profile is shown in figure 6.9.

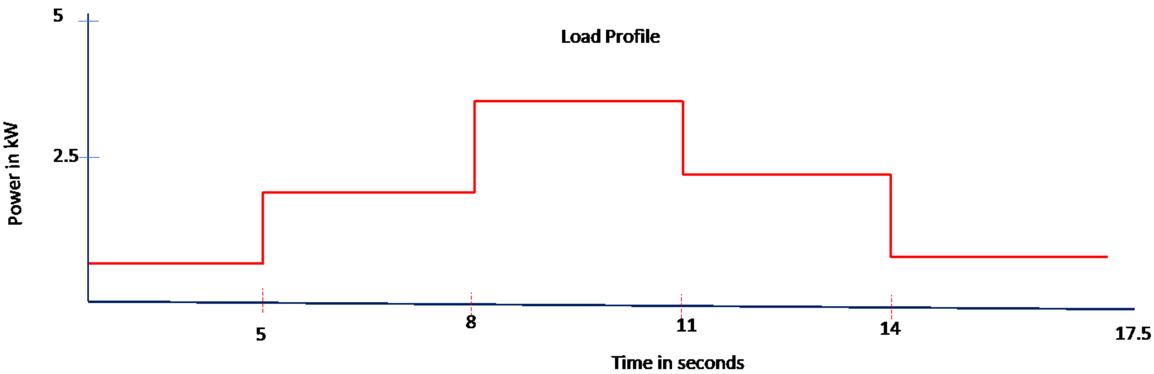


Figure 6.9. Load profile

Figure 6.10 shows the state of batteries that is battery charging and discharging power. From the figure it has been seen that from time of 2.5 to 8 seconds the battery charges, as the load as the requires less than power the synchronous machine's power can provide, then from time of 8 to 11 seconds the battery the battery compensate power difference through discharges to the load by giving 0.8 kW. As from 11 seconds to 14 seconds the load has been reduced the generator capacity and is further reduced therefore, the battery started charging due to load demand is less than the synchronous generator capacity.

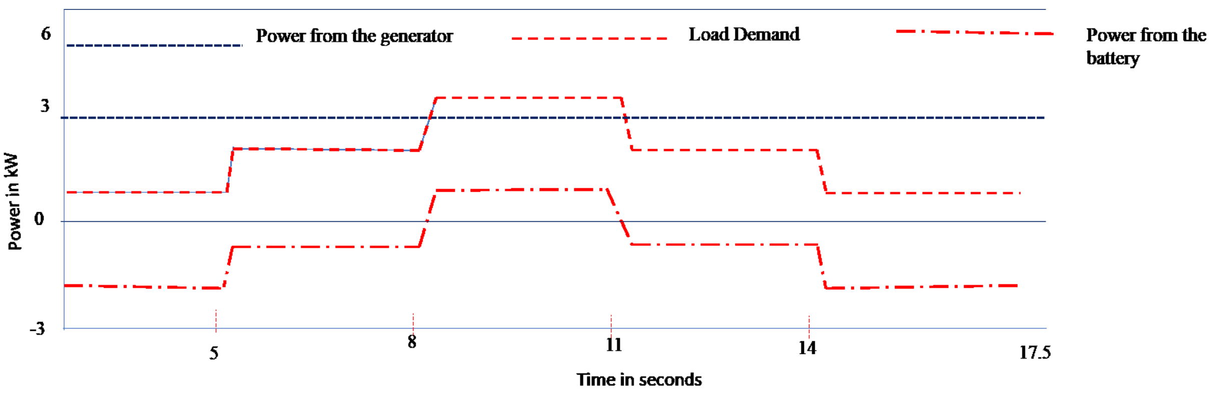


Figure 6. 10 Battery storage system charging and discharging

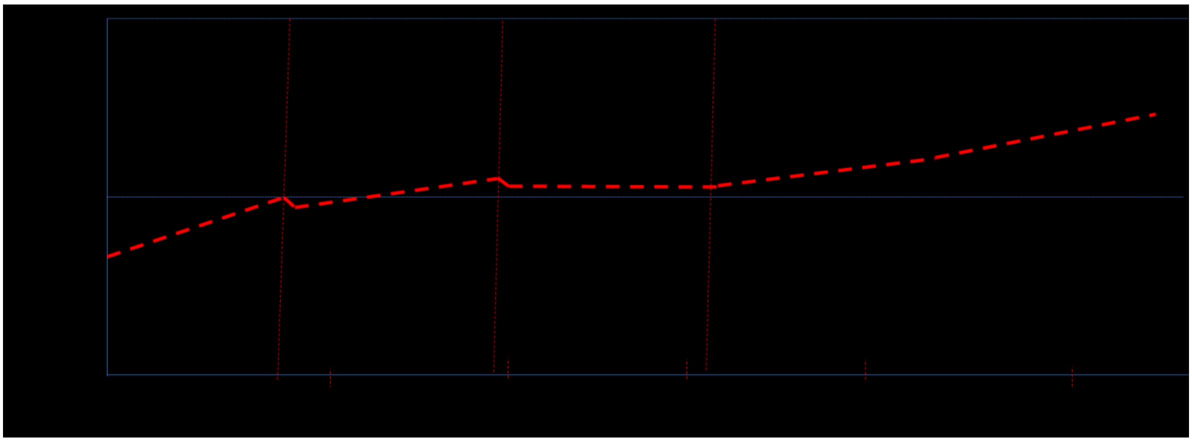


Figure 6.11. Battery voltage.

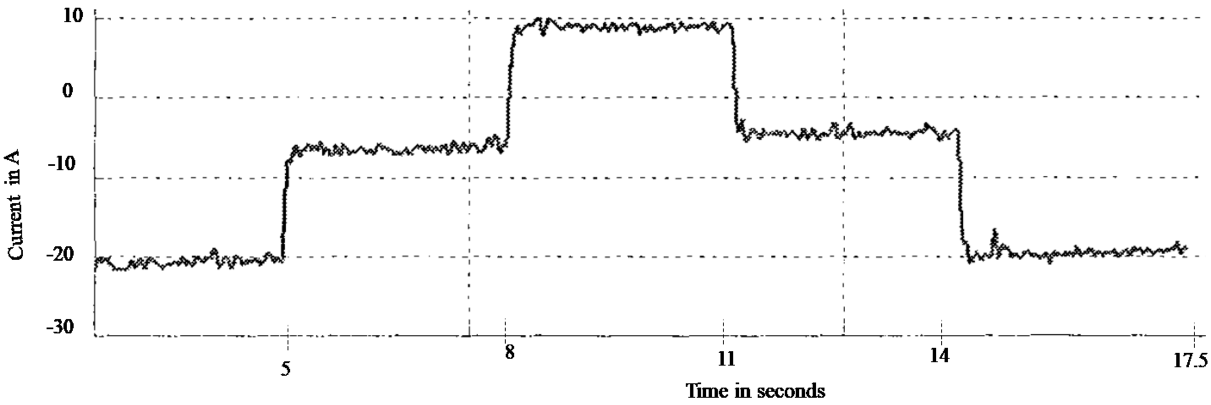


Figure 6.12 Battery current

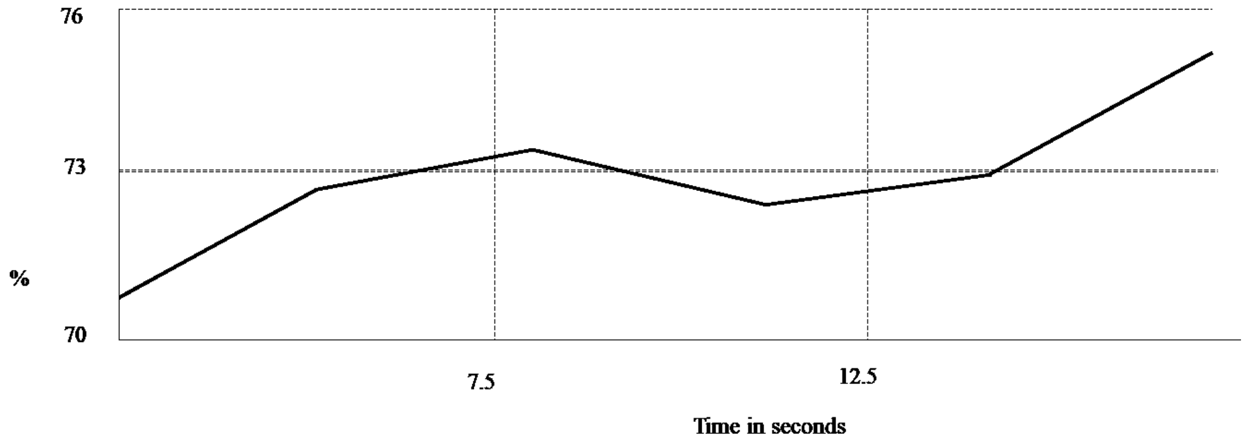


Figure 6.13. SOC of battery storage system

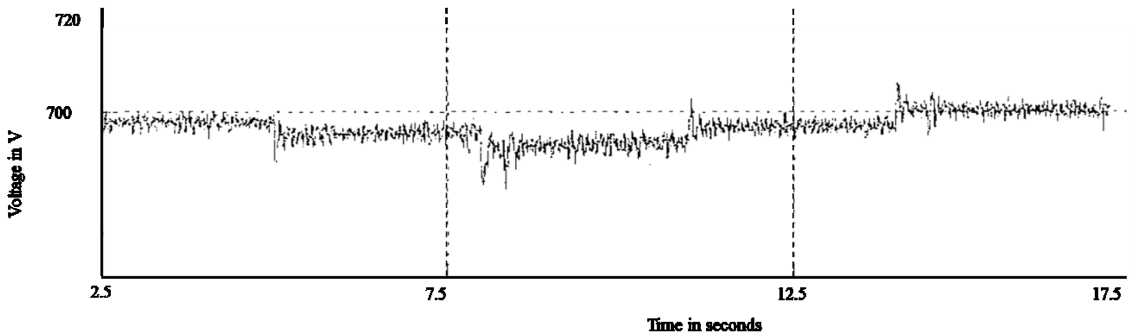


Figure 6.14. dc link voltage

The dc to dc bi-directional converter controller is shown in figures 3.9 to 3.14 for which the balance of power generation from synchronous generator and load demand are matched through energy storage strategies.

6.4 Hydrogen Storage System Modelling and Control

The hydrogen storage system generally consists of the following components; electrolyzer, fuel cell and hydrogen tank as seen in figure 6.15. the figure clearly indicates the electrolyzer and the fuel cell which are connected to dc bus bar through power electronic interface circuits. Furthermore, the fuel cell and electrolyzer are controlled by the system controller, and the hydrogen tank is connected to the electrolyzer and fuel cell. Therefore, the electrolyzer, fuel cell and hydrogen tank are modelled and controlled as follows:

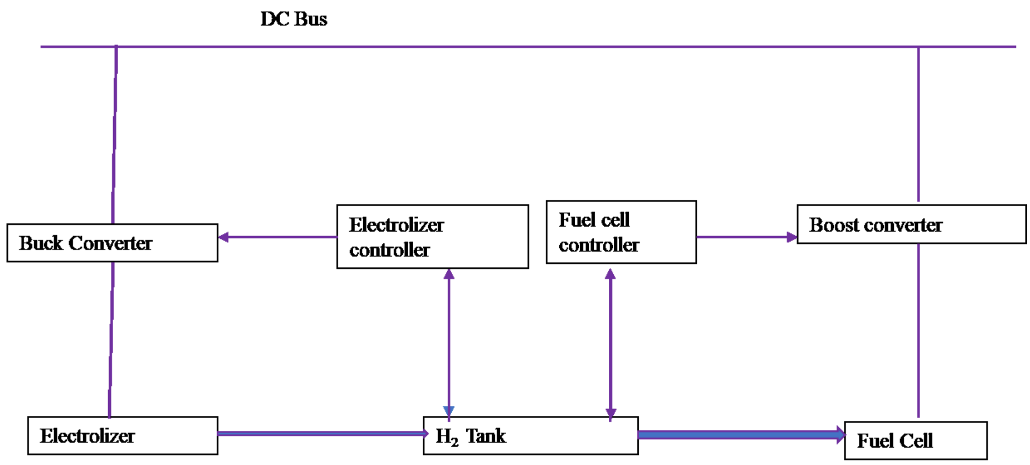


Figure 6. 15 Hydrogen storage system

6.4.1 Fuel Cell Modelling and Control

protons exchange membrane (PEM) fuel cells have shown good results when used as energy storage in distributed generation sources [152]-[161]. The PEMFCs are a good source of energy in power system through providing the reliable supply in steady state conditions. But this would not respond to electric load transients as as fast as possible, due to slow internal electro-chemical and thermodynamic reactions.

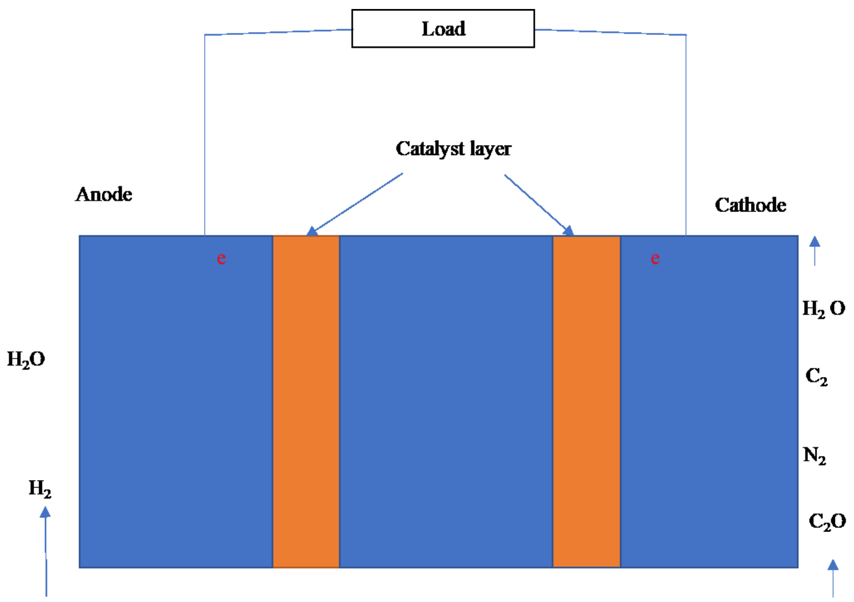


Figure 6.16. PEM fuel cell

The chemical reaction of PEMFC is written as

$$H_2 + \frac{1}{2}O_2 = H_2O \tag{6.14}$$

Where H_2, O_2 and H_2O are hydrogen, oxygen and water in liquid state

$$E_{cell} = E_{o,cell} + \frac{RT}{2F}\ln\left[\frac{PH_2((pO_2))^{0.5}}{(pH_2O)}\right] - E_{d,cell} \tag{6.15}$$

Where

PH_2, pO_2 and pH_2O are the partial pressure of hydrogen, oxygen and water;

$E_{o,cell}$is the reference potential of the cell;

R is the gas constant equal to 8.3143 J/(mol.K), and

F is the Faraday constant equal to 96487 coulombs/mol.

$$PH_2 = \frac{1}{TH_2}\left\{PH_2 + \frac{1}{KH_2}\left(qH_2^{in} - 2K_rI\right)\right\}$$

$$PH_2O = \frac{1}{TH_2O}\left\{PH_2O + \frac{2}{KH_2O}(2K_rI)\right\}$$

$$PO_2 = \frac{1}{TO_2}\left\{PO_2 + \frac{1}{KO_2}\left(qO_2^{in} - 2K_rI\right)\right\}$$

6.16

$K_r$is a constant, which is defined as the relationship between the rate of reactant hydrogen $\left(q_{H_2}^{r}\right)$ and the fuel cell current.

$$q_{H_2}^{r} = \frac{N_{cell}I}{2F} = 2K_rI \tag{6.17}$$

Therefore, reference potential deference is the function of temperature andwould be expressed as:

$$E_{O,Cell} = E_{O,Cell}^{O} - K_E(T - 298) \tag{6.18}$$

where $E_{O,Cell}$ is the standard reference potential at standard state (298°K and 1-atm pressure).

the term $E_{d,Cell}$ would be developed due to the overall effect of the fuel and oxidant delay. The steady-state value of $E_{d,Cell}$ is zero and affects the output voltage during transient. The expression of $E_{d,Cell}$ is as follows:

$$E_{d,Cell} = \lambda_s\left[i(t) - i(t)e^{\left(\frac{-t}{\tau s}\right)}\right]$$

7 VOLTAGE AND FREQUENCY CONTROL IN DISTRIBUTED GENERATION POWER SYSTEM

7.1 Introduction

The electric power industry has traditionally been divided into three sectors: generation, transmission, and distribution. At the generation stage, electricity is produced from primary resources such as fossil fuel, nuclear fuel, renewable energy, or waterfalls [1]. Then, the electric power is injected into the transmission system which is configured as an interconnected network of transmission lines and control devices. Finally, at the distribution stage, the power is taken from the transmission system and delivered to consumers at specific standards of quality and reliability [2].

Most of these energy resources are not evenly distributed all over, hence traditional power generation in most of the locations are dominated by centralized power plants that can be hundreds of kilometers away from the actual users of the primary power source [3]. Therefore, requiring the construction of long transmission lines from generation centers to reach other parts of the location with the scarcity of energy resources (End-user) also can contribute to power losses. Most of the energy resources used for centralizing power generations is from fossil fuel that has disadvantages of contribution to global warming as a result of the greenhouse gas emissions [4]. However, power generation from renewable energy resources is friendly to the environment hence more emphasis has been put on it.

The government in several areas has put in place the incentive to promote the installation of renewable energy to guarantee the power supply and reduce the emission of green gasses. Furthermore, improvement of monitoring and control process technology has facilitated the rapid development of renewable energy [5]. Tanzania has great potential for renewables to meet its energy requirements through exploiting the vast renewable energy resources such as solar, wind, biomass, geothermal mini, and micro-hydro [6]. The interest in increasing renewable energy and energy efficiency initiatives has been driven largely by electricity supply shortages. Furthermore, the changing economics of renewable energy and in particular wind and solar energy and the emergence of new policy concepts such as feed-in tariffs, net metering, auctioning of power supply from Independent Power Producers (IPPs), and clean energy certificates have led to an increase in renewable energy investments [7]. The use of renewable energy has become popular as it is known to provide solutions to improve energy access and security, mitigating greenhouse gas emissions and lessen the region’s carbon footprint, ensure sustainable development and significantly improve socio-economic development. Continuous improvement of electricity generation and distribution will replace the use of wood and fossil fuel as energy source at domestic level increasing production through engaging all members of community in income generating activities.[8]. However, renewables can be deployed in a decentralized manner, which is faster than a centralized power plant system and can provide local employment for deployment and maintenance.

Although the main source of energy in Tanzania is hydropower and gas, interest in solar photovoltaic (PV) and wind energy technologies is growing. The technologies range from small-scale household PV panel arrays to large-scale in the near future. With regards to geothermal, it is estimated that about 4,000 MW of electricity is available along the Rift Valley of Tanzania, Malawi, and Mozambique [8].

7.2 Power Systems in Tanzania

Tanzania has total power installed capacity of 1,357.69 MW comprising of hydro 566.79 MW (42%), natural gas 607 MW (45%), and liquid fuel 171.40 MW (13%)[2]. Further to that, the country imports electricity from Uganda (10 MW), Zambia (5 MW), and Kenya (1MW). Furthermore, Tanzania has 81.9MW isolated stations. The average electricity consumption per capita in Tanzania is 108kWh per year, compared to Sub-Saharan Africa's average consumption of 550kWh per year, and 2,500kWh average world consumption per year [9].

However, the demand for electricity in Tanzania is estimated to be growing at 10–15% per year, with currently only 24% of the total population having access to electricity. In order to meet this demand, the Government is planning to increase Tanzania's generation capacity by more than 500% in the next 10 years, from 1,357.69 MW in 2017 to 10,000MW in 2025[10]. In order to achieve an increase in electricity generation, the emphasis has been put on reforming the Electricity Supply Industry (ESI) involving private capital in the industry (independent power producers) [4].

According to the National Census of 2012, about 70% of Tanzanians reside in rural areas whereas only 16.9% of the rural population is connected to electricity, therefore, the Government plans to increase rural connection levels to 50% by 2025 and at least 75% by 2033[11].

7.3 Power Systems Quality

Power Quality is a broader term and encompasses a set of electrical properties which is responsible for the proper function of the electrical system. In several networks, harmonic distortions, power supply reliability, voltage dips, and electromagnetic compatibility has been noted as the most important issues for the network operators in assuring power quality [12]. However, poor power quality refers to the deviation of the supply (voltage and power) from the ideal or desired conditions. Thus, it (poor power quality) includes voltage sag, voltage swell, frequency variations, transients, harmonics, flicker, an imbalance in the three phases, discontinuity of supply, etc. The possible causes for the poor power quality may be from the load side, from the generating side, or maybe due to unwanted occurrences like faults [13], [14]. Short duration voltage dip (sag) may occur due to faults or starting of large reactive loads demanding large starting currents for energization. Transients may arise due to lightning, faults, or capacitor switching. Under-voltage (or over-voltages) may result due to overloading (or light loading) or improper tap-changer operation. Unplanned and poor distribution of single-phase loads may lead to unbalance while the frequency variations may be due to the connection or disconnection of the loads [15],[16].

Nowadays the most critical power quality issue is the presence of harmonics in the electrical system. The major contributors to the generation of harmonics are the nonlinear loads, which include arc furnaces, arc-welders, discharge lamps, cyclo converters, rectifiers, and other power electronic converter-based equipment. Magnetic cores of transformers, reactors, and rotating machines, when operated under saturated conditions, may also lead to distortion in the supply [17].

7.4 Source of poor Power Quality in the Network

Network operators always receive complaints about power quality problems from the customers (energy consumers) connected to the power system. The most complaint arises when the operation of the customer's devices has been damaged causing techno-economic problems. 70% of the power quality problems are caused by the customer's machinery and equipment while 30% originate from the network [18]. In several studies conducted have earmarked that most of the customer complaints are from; voltage sags (dips) and swells, transient over-voltages, harmonics and grounding related problems [19], [20]. Due to advance in technology, most customers use power electronics appliances at their installations such as televisions (TV), video cassette recorders (VCR), microwave ovens, personal computers (PC), heating-ventilation-air conditioning equipment (HVAC), dishwashers and dryers, photocopiers, printers and lightings [21]. Further to that, the most of the industries used programmable logic controllers (PLC), system automation, data processors, variable speed drives (VSD), soft starters, inverters, and computerized numerical control (CNC) tools [22]. Most of the industries are in a dangerous situation when the long and short duration of power interruptions happened in the system causing unreliability of the power system. Therefore, harmonic transients and surges problems in the power systems are perceived mainly by the commercial organizations and service sectors such as banks, retail, and telecommunication sector [23]. Furthermore, in manufacturing process industries, loss of synchronization of processing equipment, lockups of computers, and switching equipment tripping are the major problems in the installation [24]. The major problem caused by poor power quality issues in service and transport sectors are circuit breaker tripping and loss of data loss while in the industries are the motor-driven system and static converters [25].

Most of the customers have knowledge of power quality-related problems in their installations. However, due to a large amount of power quality problem remedial from the customers' sides, it is difficult for the network operator to maintain high voltage quality at a customer's point of connection [26]. Network operators get inconveniences when harmonics in the network interact with the network components. The operations of power electronic devices produce harmonic currents that lead to additional harmonic power flow and increase the network's total apparent power demand while decreasing the true power factor of the network. The network overloading and extra power losses have been caused by the more harmonic current in the network components [27]. Network overloading and excess power losses normally can cause high thermal stresses and early aging of the network devices. Harmonic currents and high grid impedance have the tendency of increasing voltage distortions in the network and in extreme cases can shift zero-crossing points of the supply voltage waveform [28]. The major components that are highly affected by the power quality problems in the power system networks are; Transformers, cables and power-factor correction (PFC) capacitors [29].

Transformer losses such as core losses, copper losses, and stray-flux losses have been expected to increase when there is harmonic current in the network. Major types of losses found in network transformers are 'no-load losses' and 'load losses'. No load loss is affected by voltage the voltage harmonics however; the increase of this loss with harmonics is small [30]. The losses consist of two components: hysteresis loss (due to non-linearity of the transformers) and eddy current loss (varies in proportion to the square of frequency). The load losses in the transformer vary with the square of load current and increase sharply at high harmonic frequencies. They consist of three components such as copper losses (winding conductors and leads), eddy current (winding conductors, tanks, and structural steelwork), and hysteresis losses. In the presence of harmonic current in the network, eddy current losses have to be taken into consideration []. These losses increase approximately with the square of the frequency. Total eddy current losses are normally about 10% of the losses at full load [31].

7.5 Power System Dynamic Phenomena

Power system stability has been recognized as important since is the source of major blackouts in power systems [32], [33]. Historically, transient instability has been the dominant stability problem on most systems with the focus on industrial attention concerning system stability. Power system stability has various forms of instabilities that cannot be effectively dealt with as a single problem. However, the analysis of stability, including identifying major factors contributing to instability and developing methods of improving stable operation, is greatly facilitated by classifying stability into appropriate categories [34].

7.6 Voltage Stability

Voltage stability is defined as the ability of a power system to operate within the voltage ranges in all power system bus bar after had been exposed to a disturbance for a given initial operating condition [35]. It is, therefore, a characteristic of the power system to remain in a steady state under normal conditions, and to react, restoring the status of the system to acceptable conditions after been subjected to disturbances the voltage should be restored to the value closer to the pre-disturbance situation after a disturbance. When the system voltage is allowed to decrease due to; system design failures, external factors, variations in load, or slow-acting of voltage control devices, will make the system become unstable and enters the stage of voltage instability. The voltage stability depends on the ability to restore equilibrium between the power required by the load and supplied to the load from the power system. This situation may cause instability of progressive fall or rise of voltages of some buses. The result of rising or falling of magnitude of system voltage will lead to voltage instability hence loss of load in a particular area by tripping the protective devices of transmission lines and other power system elements resulting in cascading power outages.

Considering two bus systems shown in figure 7.1

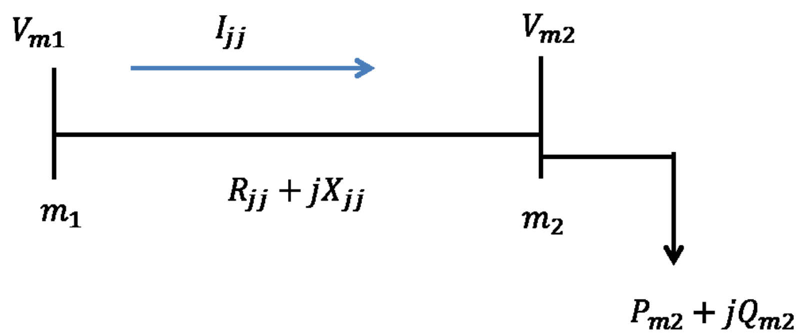


Figure 7.1: Simple two bus system

Where

jj is the branch number

R_{jj} is the resistance of branch jj

X_{jj} is the reactance of the branch jj

V_{m1} is the voltage at node m_1

V_{m2} is the voltage at node m_2

P_{m2} is the total real power fed through node m_2

Q_{m2} is the total reactive power fed through node m_2

$$I = \frac{|V_{m1}|<\delta_{m1} - |V_{m2}|<\delta_{m2}}{R_{jj}+jX_{jj}} \qquad 7.1$$

$$P_{m2} - jQ_{m2} = V_{m2}^{*}I \qquad 7.2$$

Equation 5.1 and 5.2 can be rewritten as follows

$$\frac{|V_{m1}|<\delta_{m1} - |V_{m2}|<\delta_{m2}}{R_{jj}+jX_{jj}} = \frac{P_{m2}-jQ_{m2}}{V_{m2}^{*}<-\delta_{2}} \qquad 7.3$$

Therefore

$$[V_{m1} < \delta_{m1} - V_{m2} < \delta_{m2}]V_{m2} < -\delta_{m2} = [P_{m2} - jQ_{m2}][R_{jj} + jX_{jj}] \qquad 5.4$$

Separating real part and imaginary part of equation 5.4 gives;

$$V_{m1}V_{m2}\cos(\delta_{m1} - \delta_{m2}) = P_{m2}R_{jj} + Q_{m2}X_{jj} + V_{m2}^{2} \qquad 5.5$$

$$V_{m1}V_{m2}\sin(\delta_{m1} - \delta_{m2}) = P_{m2}X_{jj} - Q_{m2}R_{jj} \qquad 5.6$$

Squaring and adding equation 5.5 and 5.6 results to equation 5.7

$$V_{m1}^{2}V_{m2}^{2} = [P_{m2}R_{jj} + Q_{m2}X_{jj} + V_{m2}^{2}]^{2} + [P_{m2}X_{jj} - Q_{m2}R_{jj}]^{2} \qquad 5.7$$

Rearranging equation 5.7 would result to equation 5.8

$$V_{m2}^{4} + [2(P_{m2}R_{jj} + Q_{m2}X_{jj}) - V_{m1}^{2}]V_{m2}^{2} + [(P_{m2}^{2} + Q_{m2}^{2})(R_{jj}^{2} + X_{jj}^{2})] = 0 \qquad 5.8$$

Let

$H = V_{m2}^{2}$

$a = 1$

$b = [2(P_{m2}R_{jj} + Q_{m2}X_{jj}) - V_{m1}^{2}]$

$c = [(P_{m2}^{2} + Q_{m2}^{2})(R_{jj}^{2} + X_{jj}^{2})]$

$$aH^{2} + bH + c = 0 \qquad 5.9$$

The solution of voltage V_{m2}^{2} will be calculated as;

$$V_{m2}^{2} = \frac{-b \pm \sqrt{b^{2}-4ac}}{2a} \qquad 5.10$$

From equation 5.10 when $P_{m2}, Q_{m2}, R_{jj}, X_{jj}$are expressed in per unit, the value of b is always negative that is $2\left(P_{m2}R_{jj} + Q_{m2}X_{jj}\right)$ is smaller than V_{m1}^2 and $4ac$ is negligible when compared to b^2. It has been noted that the system reaches its critical point when the discriminator become zero

$$\left[2\left(P_{m2}R_{jj} + Q_{m2}X_{jj}\right) - V_{m1}^2\right]^2 - 4\left[\left(P_{m2}^2 + Q_{m2}^2\right)\left(R_{jj}^2 + X_{jj}^2\right)\right] = 0 \quad 5.11$$

Voltage stability index (SI) at the node m_2 is shown in equation 5.12

$$SI_{m2} = |V_{m1}|^4 - 4\left[P_{m2}X_{jj} - Q_{m2}R_{jj}\right]^2 - 4\left[P_{m2}R_{jj} - Q_{m2}X_{jj}\right]|V_{m1}|^2 \quad 5.12$$

7.7 Power System Frequency

7.7.1 Frequency stability in electric power systems

Frequency stability is obtained when power generation and the total load of the system balance. The frequency of the system will normally decrease when there is a shortage of generation (power generated is less than power demanded by the load connected to the power system). The decreases of frequency beyond the allowable value will result in successive failure of generator units that may cause total system failure [36]. This situation may call for switching on a standby power plant or load shedding through frequency or voltage relay to prevent the frequency or voltage drop and the system will regain its normal stable condition [37], [38]. The frequency of the system must be kept around the allowable values so as to maintain the quality energy source for the consumers so as to avoid damage to consumer equipment. is the ability of a power system to preserve steady system frequency within specified operational limits after the system is being upset [14]. Hence the system frequency instability will results when the system is incapable to restore the system frequency within the acceptable limit which is caused by a considerable inequity between power supply and load demand [39].

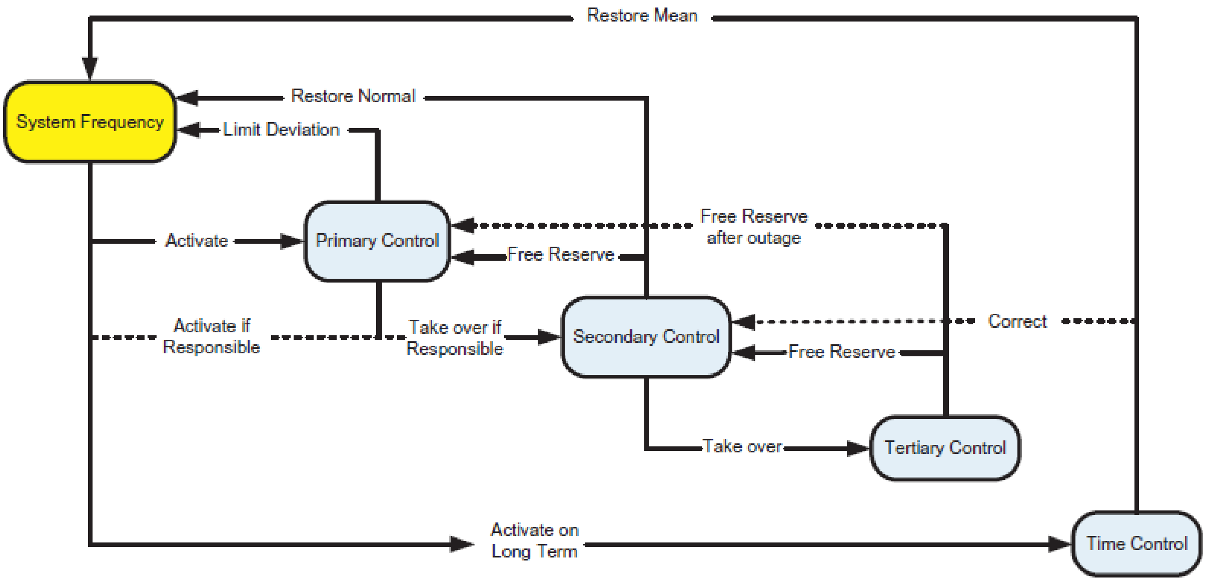


Figure 5.4 shows the various case of power deviation, the primary control will respond to re-establish the equilibrium between power generation and load demand. The set-point is normally 50 Hz for this control action. The primary controllers for all other generators within the power system will respond in few seconds (period from 0 to 10 seconds) [46]. The controller changes the output power for the generating units until the balance between the output power and load demand is achieved.

The secondary control action is usually activated (time period 15 minutes) [40] in order to restore the power and system frequency deviation to their normal value. The secondary reverse must be available to cover any disturbances or outages that may affect production, transmission, and consumption. The secondary control operates for up to several minutes and is therefore timely associated with primary control [41] [42].

In the end, the tertiary control will respond after 15 minutes to restore the remaining power and system frequency deviation to provide adequate secondary control reverse at the right time. A manual or automatic change is required in the working points of generators units or the participating loads. This automatic or manual connected power under control is known as tertiary control reverse. If the system's mean frequency deviates from the nominal frequency value of 50 Hz in the synchronous zone, it can cause a discrepancy between universal time and synchronous time.

$$f = \frac{pn}{60} \qquad 5.13$$

Where

f = System frequency

p = Number of poles for generator and

n = Rotational speed of synchronous machines.

Normally regulation of the generator speed through governor for monitoring and sensing speed variation will maintain the frequency of the power system within the allowable value. However, in standalone electrical power system having one generating unit as load increases, the inertia of the power generator will add up excess energy required. As a result, the generator speed will decrease, and therefore the system frequency decreases.

The role of the governor is to open the turbine gate to increase the turbine speed. The increase in turbine speed will rise the system frequency. The system frequency in this case recovers within acceptable range [42]. For interconnected power systems, the frequency control is employed with a controlling mechanism to recover system frequency during contingencies conditions. Fig. 4 illustrates various control action required to recover system frequency to prevent power system blackout [49].

Furthermore, Eq. (2) informs the relationship between mechanical torque (Tm), electric torque (Te), total inertia moment of the rotor (J), and angular acceleration of the rotor

$$J\frac{d^2\theta_m}{dt^2} = T_a = T_m - T_e$$

There are several steps to be done when the systems frequency drops below the setting value, such as:

a) Increase the total amount of energy supplied to the system by adding a working generating unit.
b) Utilizing the Load Frequency Control or LFC facility that controls the rotation of the generator in accordance with the load fluctuations. When the load increases, LFC will give indication to provide more fuel for the generating unit to generate more energy as needed by the load.
c) When the generating unit is fully operational, it is necessary to reduce load through under frequency load shedding (UFLS) scheme with under frequency relays (UFR) that work under specific circumstances.

7.7.2 Power System Frequency Criteria

The interconnected power systems have to operate in a stable manner [36] and be capable to withstand a wide variety of contingences events [11], in order to avoid cascading faults. The power system frequency has to fulfill tolerance criteria.

7.7.3 Role of Standards

The power system frequency criteria are standardized to ensure satisfactory operation by maintaining system frequency and voltage within acceptable limits [23]. Establishing acceptable frequency deviations operational limits is surprisingly difficult [37]. Deviation system frequency from nominal 50 or 60 Hz can cause equipment malfunction. Malfunction of generation equipment may increase system frequency deviation and lead to cascading malfunctions. This could rapidly lead to total power system collapse, with major financial loss to industry sectors and communities. The role of standards is very important; the system frequency must be managed second by second, far faster than any market mechanism can deliver [38]. The system controller is charged by code with the central management of system frequency to define the standards. These should be set in order to ensure the equipment does not malfunction and will not be damaged.

7.8 The Defense Plan against System Instability

The disturbances of real power balance include unplanned outages for large power plants, which have to be handled by system operators using their own defense plan to protect their own electrical power system [39]. The defense plan describes and reflects the criteria, followed by each electrical power system operator. The operation criteria are created and continuously updated by the researchers to match the extent of electrical power systems and the growth in load demand. Table 3 presents a comparison between two examples of defense plans for European transmission network and Malaysian transmission network, which is approximately close in terms of a system frequency drop. The information in Table3 for European standards is referred from [36] [40] references, while the Malaysian Standards are referred from [41] and [42] references.

7.9 Islanding

Islanding is the situation in which a distribution system becomes electrically isolated from the remainder of the power system, yet continues to be energized by generating stations connected to it [43]. There are two types of islanding in power systems that are intentional and unintentional. In intentional Islanding operation, planning has been made in advance for the generating station to operate without disturbing the load connected to it [44]. The Intentional Islands are practiced by the industries which have surplus energy fuel for electricity generation such as emergency backup power in hospitals, paper mills, sugar mills and independent power producers with their own connected loads [45]. During lightning or thunderstone, these industries can switch to use internally produced electricity hence isolating them from the grid connection. This situation of using internally generated electricity can reduce the risk of disturbances due to lightning strokes and other faults that might affect the production process. However, for voltage and frequency control the DG is choosing as the best option in the islanded grid.

The challenges facing islanding operation are:

a) The safety personnel working in Line can be threatened by secondary sources feeding a system after primary sources have been opened.
b) Difficulty in maintaining within the allowable level of voltage and frequency.
c) Creation of large mechanical torques and currents due to out of phase reclosing of DG hence damaging generators or prime movers.
d) Creation of transients caused by the instantaneous reclosing which mighty damage customer's equipment.

7.10 Islanding Detection

The islanding detection is important in power systems in order to monitor the distributed generators' induced voltage and frequency. The islanding detection can detect the variation of parameters and actuate the correct protective device. There are two islanding detection techniques that are remote islanding detection techniques and Local detection techniques (passive, active, and hybrid techniques)[].

a) Remote islanding detection techniques

Its operation is based on communication between utilities and distributed generators by monitoring the status of all switchgear (circuit breakers and re-closers) that could result in islanding of a distribution system using Supervisory Control and Data Acquisition (SCADA) [46].

b) Power line signaling scheme

Another method for remote control is by using a signal generator that continuously transmits the signal to the distribution feeders using the power line as the signal path that is all DGs are equipped with signal receivers. Therefore, If there is a signal cut off caused by the opening of breakers between the transmission and distribution systems hence island condition is realized [47].

c) Local detection techniques

Techniques for measuring system parameters like voltage and frequency at the generating station are classified as: Passive detection techniques and active detection techniques [48]. In passive methods, the variations of system parameters such as voltage, frequency, harmonic distortion will be measured. The measurements of these parameters are based upon the thresholds set in the system between islanding and grid connection conditions. The setting of threshold value in the system needs special care so as to differentiate islanding from other disturbances in the system [49].

Passive islanding detection techniques use the rate of change of power output during islanding which is expected to be greater compared to that of the DG before is islanded. It has been noted that this method of comparing the power output of DG systems is more effective for distribution systems with DG having an unbalanced load rather than a balanced load [50].

Another method employed by passive islanding techniques is by detecting the variation of frequency during DG islanding.

The rate of change of frequency in the system is given

$$\frac{df}{dt} = \frac{\Delta p}{2HG} f$$

Where

Δp= Power mismatch at the DG side

H = Moment of inertia for DG/system

G = Rated generation capacity of the DG/system

Large systems capacity will have large values of H and G and small systems have small H and G therefore, the setting has been done for the relay to monitors the voltage waveform. The relay will operate if the rate of change of frequency is higher than the set value within a certain duration of time. The setting of the relay has to be chosen in such a way that the relay will operate for island conditions but not for load changes. The rate of frequency variation is a highly reliable way of determining whether there is a large mismatch in power. However; this method fails to operate if DG’s capacity matches with its local loads.

Furthermore, the rate of change of frequency overpower for a small generation system is larger when compared to that of the power system with a larger capacity. The rate of change of frequency overpower uses this concept so as to determine islanding conditions. it has been observed that any variation of power between the DG and local loads will lead to the change of frequency with power demand [51].

Change of impedance in the utility is considerably smaller than the impedance of islanded power system. The impedance of a part of the network shall increase when that part is the isolated grid. [52]. Continuous monitoring of the source impedance shall indicate the status of the system whether is islanded or not.

During islanding, DG has to supply the load which causes voltage unbalances in the system. Therefore, any changes in loading are easily detected by monitoring various parameters in the system such as; voltage magnitude, phase displacement, and frequency change. However, detecting voltage unbalances in the system may not be effective if the changes are small [53]. With the distribution networks comprising of single-phase loads, it is highly possible to detect islanding due to changes in the load balances of DG. Furthermore, even though the variation in DG loading is small, voltage unbalance will occur due to the change in network condition.

The changes in harmonic distortion are used to determine the system islanding. The change in the amount and configuration of load always result in variation of harmonic currents in the network, particularly to the system having inverter based DGs [54]. The islanding in the system will be noticed by monitoring checking any changes in total harmonic distortion (THD) of the terminal voltage at the DG [55].

8 ELECTRICAL POWER DISTRIBUTION

8.1 Introduction

This chapter presents several case studies designed to investigate the application of the proposed hybrid stand-alone power system for a variable wind, load and energy reserve conditions.

8.2 Variables considered for Case Studies

Case studies are performed under actual wind and load data derived from a remote island located in the South Tasmania, with variables listed below:

8.2.1 Wind profile

Figure 8.1 shows the week-long wind speed by indicating that the wind does not follow any trend. From one year data documents, the average wind speed at particular location is 7.87m/sec with a standard deviation is 3.44. The maximum wind speed was 22.83 m/sec.

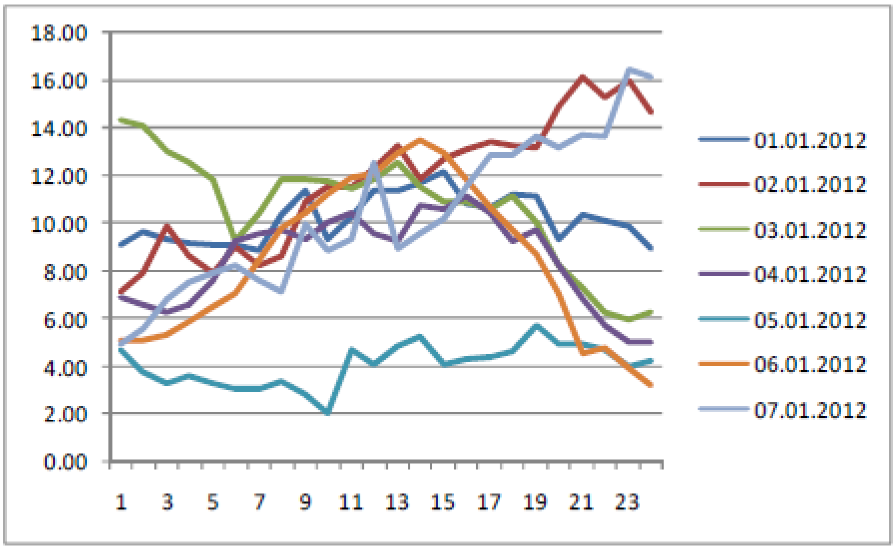


Figure 8.1 Wind profile from

From the data, it has been observed that there are some situations of low or no wind conditions that can occur for long period in several times annually. From figure 8.2 and 8.3 it can be seen that two cases of low wind conditions had occurred for longer period in a day. It is further noted that the low or no wind conditions can also occurs during the peak demand period.

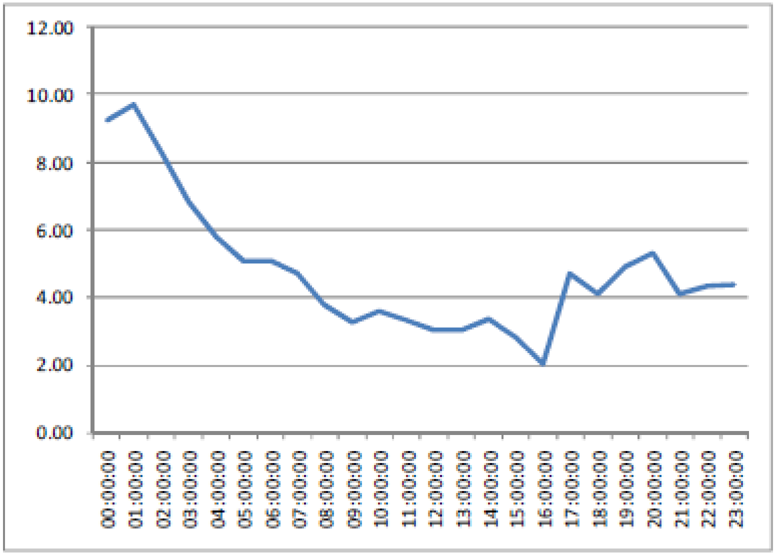


Figure 8.2 Wind profile from 00:00 hour to 24:00 hour

From figure 8.2, it is seen that from 02:00 hours, wind speed declines. At 7:00 hours, a low wind condition occurs when the wind turbine cannot extract any power. However, at 17:00 hours the wind returns, enabling the turbine to extract power.

8.2.2 Load profile

The load has always a unique characteristic, with a peak generally happening in the mornings and evenings and also the load demand has been varying on seasonal basis.

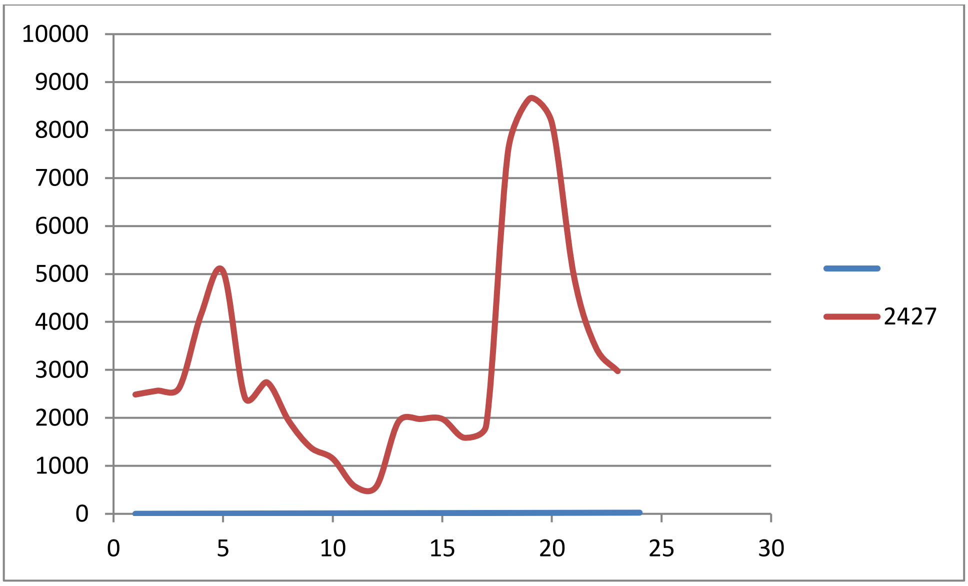


Figure 8.3 Average hourly load demands during dry season.

8.2.3 Low Wind Conditions

For this case study, a wind profile is chosen where a low wind condition occurs during peak demand time. Proposed system performance is evaluated in terms of a) SOC status and b) hydrogen storage status. The wind and load profiles are shown in Figure

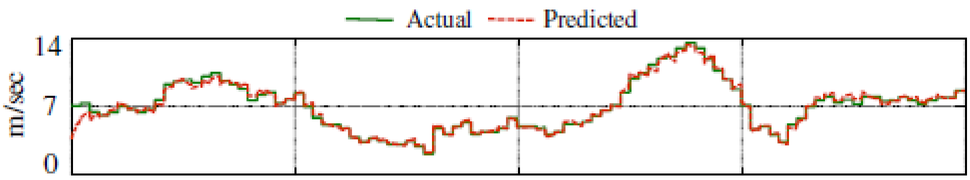


Figure 8.4 wind speed profile

Figure 8.4 Wind and load profiles: a) wind and b) load demand

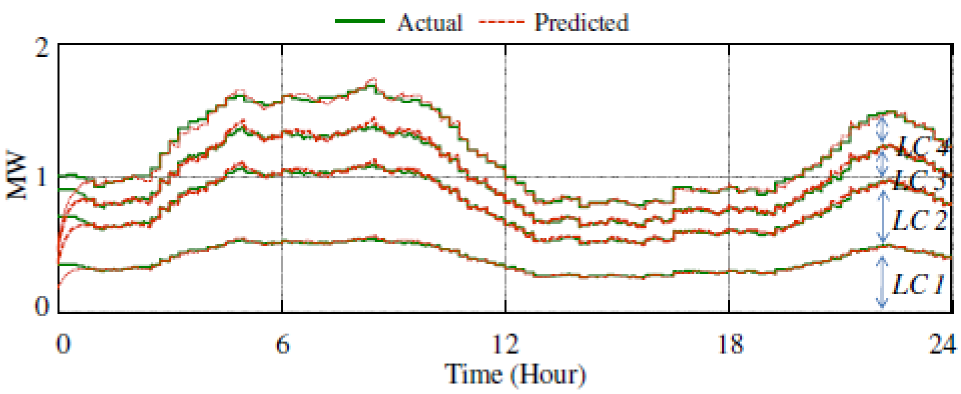
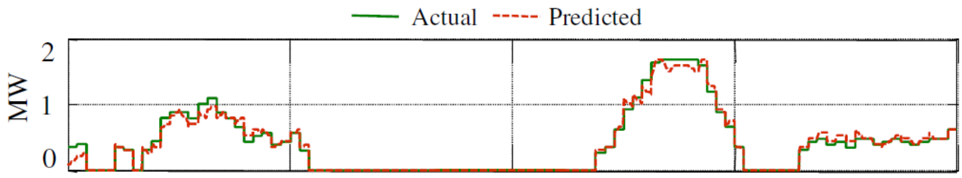


Figure 8.4 b) load profiles load demand

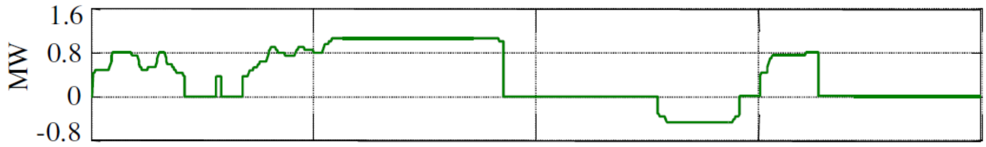
8.2.4 System Performance of Hydrogen and Battery Storage Conditions

The system's performance has been evaluated under of high hydrogen pressure and low battery storage conditions. The study assumed an initial hydrogen pressure of 0.9 pu and a battery storage initial SOC of 77%. Figure 8.5 illustrates the system's response, where Fig. 8.5 (a) displays the wind turbine power output. The power output from the electrolyzer/fuel cell and the hydrogen storage status are depicted in Figs 8.5 (b) and 8.5 (c), respectively. Figs 8.5 (d) and 8.5 (e) show the power output from the battery storage and the SOC status, respectively. As the battery storage SOC is low (77%), it cannot provide any power. and Fig. 8.5(f) shows the connected load.

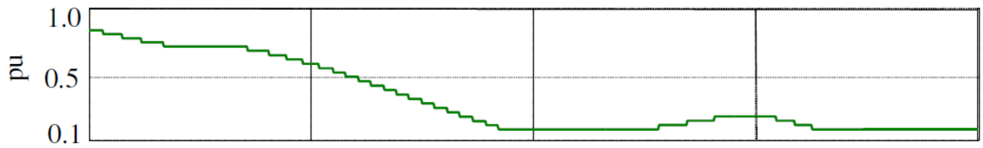
The system depends on the fuel cell and hydropower to compensate for the shortfall in wind power when demand exceeds it. The graph in Figure 8.5(a) clearly indicates that the wind turbine is unable to generate any power from 7:00 to 15:00 due to insufficient wind. Consequently, the hybrid system must activate the diesel generator at 7:00 to fulfill the power requirement. Figures 8.5(b) and 8.5(c) show that the hydrogen storage becomes depleted by 10:54.



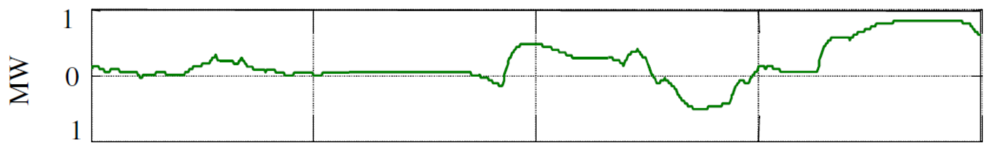
a) Power from the Wind Turbine



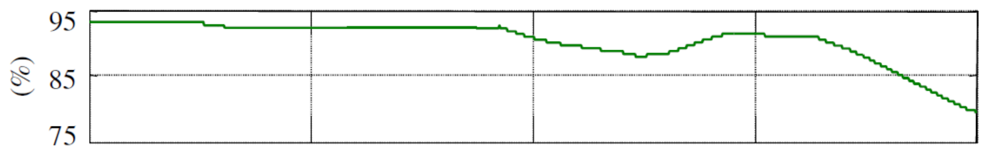
b) Power from Fuel Cell/Electrolyzer



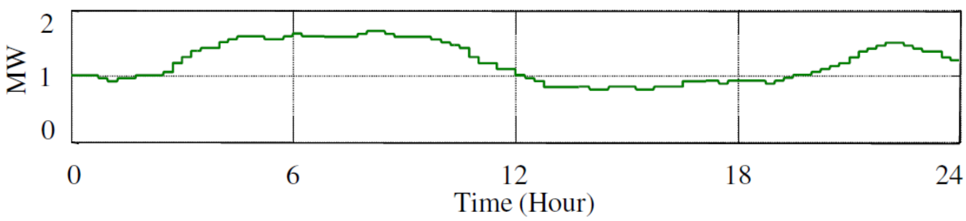
c) Hydrogen storage status



d) Power from the battery



e) Battery State of Charge



f) Connected load

Figure 8.5 Renewable system operation with hydrogen and battery storage

8.3 Conclusion

The chapter shows the effectiveness of under varying wind and load circumstances during the bustling season, while taking into account different battery and hydrogen storage conditions. To guarantee a no-wind scenario transpires during the peak load, the wind profile is selected. Multiple SOC cases for battery and hydrogen storage are examined. The results indicate that the proposed system can fulfill the load requirements when the SOC status of battery and hydrogen storage is high.

In situations where certain conditions are present, the hybrid system must limit the amount of power consumed in order to prevent a system blackout. The case study also highlights an emergency operating condition where the battery storage's state of charge (SOC) is extremely low (below 75%) and the hydrogen storage is low.

Based on recent studies, the implementation of a hybrid power system has proven to be effective in avoiding system blackouts and ensuring emergency loads are supplied. The design of this proposed system is intended to operate even in the worst-case scenario, making it a reliable option for power supply.

It should be noted that power supply cannot be sustained for all customers at all times, but the proposed system ensures that all essential customers will receive the necessary power under any worst-case scenario. This is a significant advantage of the hybrid power system, as it provides a more stable and secure power supply for critical operations and infrastructure.

The hybrid power system combines the benefits of multiple power sources, such as renewable energy sources and traditional power grids, to create a more efficient and reliable system. The use of renewable energy sources, such as solar and wind power, reduces reliance on traditional power grids and decreases the carbon footprint of the system.

Overall, the proposed hybrid power system is a promising solution for ensuring reliable power supply, especially in critical situations. Its ability to provide power to essential customers in worst-case scenarios makes it a valuable investment for infrastructure and industries that require a consistent and dependable power supply.

9 CONCLUSIONS

This thesis proposes a control and overall coordination of a hybrid stand-alone power system. The system comprises of a wind turbine, fuel cell, electrolyzer, battery storage, diesel generator and a set of loads. The overall control strategy of the hybrid system is based on a two-level structure. The top level is the energy management and power regulation system. Depending on wind and load conditions, this system generates reference dynamic operating points to low level individual sub-systems. The energy management and power regulation system also controls the load scheduling operation during unfavorable wind conditions with inadequate energy storage in order to avoid a system black-out. Based on the reference dynamic operating points of the individual subsystems, the local controllers control the wind turbine, fuel cell, electrolyzer storage units.

This thesis proposes a two-level control and coordination strategy for a hybrid stand-alone power system that includes a wind turbine, fuel cell, electrolyzer, battery storage, diesel generator, and a set of loads. The first level is an energy management and power regulation system that generates reference dynamic operating points based on wind and load conditions. These reference points are used to control the individual subsystems at the second level. The energy management and power regulation system also manages the load scheduling operation during unfavorable wind conditions and inadequate energy storage to prevent a system black-out. The local controllers of the wind turbine, fuel cell, and electrolyzer storage units adjust their operations based on the reference dynamic operating points provided by the energy management and power regulation system.

The major achievements of the thesis are summarized as follows:

a) An algorithm for efficient power extraction from variable wind – The proposed algorithm achieves high efficiency of the permanent magnet synchronous generator (PMSG) across a range of wind and rotor speeds by regulating the d- and q-axes current components and controlling the rotor speed of the wind turbine.
b) Hydrogen storage system modelling and control –The hydrogen storage system consists of fuel cell, electrolyzer and hydrogen tank. It is used in the project to support a load leveling application. In this project, power flow of the fuel cell and electrolyzer are regulated by a boost control and buck controller, respectively.
c) Modelling and control of a hydrogen storage system – The hydrogen storage system, comprised of a fuel cell, electrolyzer, and hydrogen tank, is utilized in a load leveling application. A boost control and buck controller are employed to regulate the power flow of the fuel cell and electrolyzer, respectively.

d) Energy management and power regulation system for a multi-source power system – An energy management and power regulation system coordinates the operation of a wind turbine, fuel cell, battery storage system, electrolyzer, diesel generator, and loads. The system generates dynamic reference signals to each controller based on the current wind and load profile and energy storage status, while also controlling load curtailment. The EMPRS is advantageous in preventing system blackouts during low wind conditions or inadequate energy reserves.

10 RECOMMENDATIONS AND SUGGESTIONS FOR FURTHER WORK

In the future, related topics are expected to be introduced in existing systems are:

1. Adding solar panels to existing systems: This can be done by adding more panels to existing installations, or by installing larger systems to generate more electricity. Using new and more efficient solar panels: Advances in solar panel technology are making panels more efficient, which means they can generate more electricity from the same amount of sunlight. Using these new panels can help to expand solar PV without increasing the physical size of the system.
2. Voltage Regulation: Voltage regulation is a method used to maintain a constant voltage level on the distribution system by adjusting transformer taps, installing voltage regulators, or utilizing capacitor banks. This helps to avoid voltage fluctuations and provide a stable voltage level to end-users.
3. Harmonic Filtering: Harmonic filtering involves the installation of filters that eliminate harmonics, which are electrical signals with frequencies that are multiples of the fundamental frequency. Harmonics can cause issues such as overheating, equipment failure, and interference with communication systems. Filters can mitigate these issues and improve power quality.
4. Power Factor Correction: Power factor is a measure of the efficiency of the electrical power system. Power factor correction involves the installation of capacitors that improve the power factor, reducing energy losses and improving the efficiency of electrical equipment.
5. Surge Protection: Surge protection devices protect electrical equipment from voltage spikes that can cause damage or failure. These devices can be installed at the equipment level or at the distribution system level to improve power quality.

11 REFERENCES

1. B. Singh, and J. Solanki, "Load Compensation for Diesel Generator-Based Isolated Generation System Employing DSTATCOM *"IEEE Transaction on Industry Application,* vol. 47, no. 1, pp. 238-244, January/February, 2011.
2. R. J. Best, D. J. Morrow, D. J. McGowan, and P.A. Crossley, "Synchronous Islanded Operation of a Diesel Generator" *IEEE Transaction on Power Systems,* vol. 22, no. 4, pp. 2170-2176, November, 2007.
3. Australian Institute of Petroleum bi-annual report, "Downstream Petroleum 2011" published in 2011. Web address: http://www.aip.com.au/pdf/Downstream Petroleum_ 2011 _ Report.pdf
4. http://www.cumminspower.com/www *II* iterature/techni cal papers/PT-7004-Maintenance-en. pdf
5. C. Y. Nayar, High Renewable Energy Penetration Diesel Generator Systems, http://www.intechopen.com/articles/show/title/high-renewable-energy-penetration-dieselgenerator- systems-.
6. F. Katiraei, and C Abbey, "Diesel Plant Sizing and Performance Analysis of a Remote Wind-Diesel Microgrid" *IEEE Power Engineering Society General Meeting, Tampa, Florida, June 24- 28, 2007,* pp. 1-8.
7. P. Saiyasitpanich, M. Lu, T. C. Keener, F. Liang, and S-J. Khang "The effect of diesel fuel sulfur content on particulate matter emissions for a nonroad diesel generator. *Journal of the Air & Waste Management Association, Volume 55, Issue* 7, *Pages 993-998, Jul 2005.*
8. J. P. Barton and D. G. Infield, "Energy storage and its use with intermittent renewable energy", *IEEE Transactions on Energy Conversion, vol. 19, no. 2, June 2004, pp: 441 - 448.*
9. D. Anderson and M Leach, "Harvesting and redistributing renewable energy: on the role of gas and electricity grids to overcome intermittency through the generation and storage of hydrogen" *Journal on Energy Policy, Vol. 32 pp: 1603-1614, 2004.*
10. P. Moriarty and D. Honnery, "Intermittent renewable energy: The only future source of hydrogen?", *International Journal of Hydrogen Energy Vol 32, pp. 1616-1624, 2007.*
11. M.B. Blarke and H. Lund, "The effectiveness of storage and relocation options in renewable energy systems", *Journal of Renewable Energy, Vol. 33 pp. 1499-1507, 2008.*
12. M. Datta, T. Senjyu, A. Yona, T. Funabashi, and C-H. Kim, "A Coordinated Control Method for Leveling PY Output Power Fluctuations of PY-Diesel Hybrid Systems

Connected to Isolated Power Utility" *IEEE Transaction on Energy Conversion,* vol. 20, no. 1, March, 2009, pp. 153-162.

13. J. Frunt, W. L. Kling, "Mitigation of wind power fluctuations in smart grids", *IEEE PES Innovative Smart Grid Technologies Conference Europe (!SGT Europe), Gothenburg, Germary, October 11- 13,* pp. 1-8.
14. Y. Ozaki, M. Miyatake, D. Iwaki, "Power control of a stand-alone photovoltaic/ wind/ energy storage hybrid generation system with Maximum Power Point Tracker", *International conference on Electrical Machines and Systems (JCEMS), Jncheon, South Korea, October 10- 13, pp 607 -611.*
15. L. Jin, S. Yuan-Zhang, P. Sorensen, L. Guo-Jie, and G. Weng-Zhong, "Method for Assessing Grid Frequency Deviation Due to Wind Power Fluctuation Based on "Time-Frequency Transformation"", *IEEE Transaction on Sustainable Energy,* vol. 3, no. I, pp. 65-73, January, 20 I 2.
16. M. L. Rahman, S. Oka, and Y. Shirai, "Hybrid Power Generation System Using Offshore-Wind Turbine and Tidal Turbine for Power Fluctuation Compensation (HOT-PC)", *IEEE Transaction on Sustainable Energy,* vol. I, no. 2, pp. 92-98, July, 2010.
17. G. Liu, W. Yu and Z. Tu, "Power Management for Alleviation of the Impact on PEM Fuel Cell due to Load Fluctuation", *Sixth International Conference on Intelligent Systems Design and Applications, Jinan, China, 16-18 Oct. 2006, Vol. 1,* pp: I 104- I I IO.
18. H. Asano, and S. Banda, "Load Fluctuation Analysis of Commercial and Residential Customers for Operation Planning of a Hybrid Photovoltaic and Cogeneration System", *IEEE Power Engineering Society General Meeting, Montreal, Quebec, Canada, October 16-20, 2006, pp. 1-6.*
19. E. Muljadi, and H. E. McKenna, "Power Quality Issues in a Hybrid Power System", " *IEEE Transaction on Industry Application,* vol. 38, no. 3, pp. 803-809, May/June, 2002.
20. R. I. Bojoi, L. R. Limongi, D. Roiu, and A. Tenconi, "Enhanced Power Quality Control Strategy for Single-Phase Inverters in Distributed Generation Systems", *IEEE Transaction on power electronics,* vol. 26, no. 3, March, 20 I I, pp. 798-806.
21. C. Han, A. Q. Huang, M. E. Baran, S. Bhattacharya, W. Litzenberger, L. Anderson, A. L. Johnson, and A-A. Edris, "STATCOM Impact Study on the Integration of a Large Wind Farm into a Weak Loop Power System", *IEEE Transaction on energy conversion,* vol. 26, no. I, March 2008, pp. 226- 233.

22. I. Wasiak, M. C. Thoma, C. E.T. Foote, R. Mienski, R. Pawelek, P. Gburczyk, and G. M. Burt, "A Power-Quality Management Algorithm for Low-Voltage Grids With Distributed Resources" *IEEE Transaction on power delivery,* vol. 23, no. 2, April, 2008, pp. I 055-1062,.
23. M. Singh, V. Khadkikar, , A. Chandra, and R. K. Varma, "Grid Interconnection of Renewable Energy Sources at the Distribution Level With Power-Quality Improvement Features", *IEEE Transaction on power delive,y,* vol. 26, no. I, January, 2011, pp. 307- 3 I 5.
24. H. Nian, R. Zeng "Improved control strategy for stand-alone distributed generation system under unbalanced and non-linear loads", *JET Renewable Power Generation,* vol. 5, no. 5, pp 323-331, 2011.
25. N. Gyawali, and Y Ohsawa, "Integrating Fuel Cell/Electrolyzer/ Ultracapacitor System Into a StandAlone Microhydro Plant", *IEEE Transaction on Energy Conversion,* vol. 25, no. 4, December 2010, pp. 1092-1104.
26. C. Wang, and M. H. Nehrir, "Power Management of a Stand-Alone Wind/Photovoltaic/Fuel Cell Energy System", *IEEE Transaction on Energy Conversion,* vol. 23, no. 3, September 2008, pp. 957-967.
27. A. Hajizadeh, M. A. Golkar, and A. Feliachi, "Voltage Control and active Power Management of Hybrid Fuel-Cell/Energy-Storage Power Conversion System Under Unbalanced Voltage Sag Conditions", *IEEE Transaction on Energy Conversion,* vol 25, no. 4, December 2010, pp. 1195- 1208.
28. S. D. G. Jayasinghe, D. M. Vilathgamuwa, and U. K. Madawala, "Direct Integration of Battery Energy Storage Systems in Distributed Power Generation" *IEEE Transaction on Energy Conversion,* vol 26, no. 2, June 2011, pp. 977-685.
29. C. Wang, M. Nehrir, and S. R. Shaw, "Dynamic Models and Model Validation for PEM Fuel Cells Using Electrical Circuits" *IEEE Transaction on Energy Conversion,* vol 20, No. 2, June 2005, pp. 442-451.
30. P. Garcia, L. M. Fernandez, C. A. Garcia, and F. Jurado, "Energy Management System of Fuel-CellBattery Hybrid Tramway" *IEEE Transaction on Industrial Electronics,* vol. 57, no. 12, December 2010,pp.4013-4023.
31. T. Zhou, B. Francois, M. el H. Lebbal, and S. Lecoeuche, "Real-Time Emulation of a HydrogenProduction Process for Assessment of an Active Wind-Energy Conversion

System" *IEEE Transaction on Industrial Electronics,* vol. 56, no. 3, April 2009, pp. 737-746.

32. K. L. Wang and P. Kundur, "Power system security assessment", *IEEE Power and Energy Magazine,* vol. 2 , No. 5, September/ October, 2004, pp. 30 - 39. J. A. Greatbanks, D. H. Popovic, M. Begovic, A. Pregelj, T. C. Green, "On optimization for security and reliability of power systems with distributed generation", *IEEE Power Tech Conference Proceedings,* Bologna, Italy, 23-26 June, 2003.
33. C. W. Gellings, W. M. Smith, "Integrating demand-side management into utility planning", *IEEE proceedings,* vol. 77, No. 6, June 1989, pp. 908-918.
34. G. Strbac, "Demand side management: Benefits and challenges", *Journal on Energy Policy* ,vol. 36, no. I 2, December 2008, pp: 44 I 9--4426.
35. H. L. Wills, H. N. Tram and G. B. Rackliffe "Short-range load forecasting for distribution system planning-an improved method for extrapolating feeder load growth ", *IEEE Transaction on Power Systems,* vol. 7, no. 3, August 1992, pp. 1306-1312.
36. I. Ziari, G. Ledwich, A. Ghosh, and G. Platt, "Integrated Distribution Systems Planning to Improve Reliability Under Load Growth", *IEEE Transaction on Power Delive,y,* vol. 27, no. 2, April 2012, pp. 757-765.
37. Z. A. Yamayee, H. Hakimmashhadi, "A Flexible Generation Planning Approach Recognizing Long Term Load Growth Uncertainty", *IEEE Power Engineering Review,* vol. 4, no. 8, August 1984.
38. A.H. Shahirinia, S. M. M. Tafreshi, A.H. Gastaj, A. R. Moghaddomjoo, "Optimal sizing of hybrid power system using genetic algorithm", *2005 International Conference on Future Power Systems,* Amsterdam, Netherland,vol. 6, Novermber, 2005, pp: 1-6.
39. B. S. Borowy, Z. M. Salameh, "Methodology for optimally sizing the combination of a battery bank and PV array in a wind/PY hybrid system", *IEEE Transaction on Energy Conversion,* vol. 11, no. 2, June, 1996,pp.367-375.
40. W.D. Kellogg, M.H. Nehrir, G. Venkataramanan, and V. Gerez, "Generation Unit Sizing and Cost Analysis for Stand-Alone Wind, Photovoltaic, and Hybrid Wind PV Systems", *IEEE Transaction on Energy Conversion,* pp. 70-75, vol. 13, no. 1, March 1998.
41. A. A. Setiawan, Y. Zhao, and C. V. Nayar, "Design, economic analysis and environmental considerations of mini-grid hybrid power system with reverse osmosis desalination plant for remote areas", *Journal on Renewable Energy,* vol. 34, 2009, Pages 374-383.

42. S. Diaf, M. Belhamel, M. Haddadi, A. Louche, "Technical and economic assessment of hybrid photovoltaic/wind system with battery storage in Corsica island", *Journal on Energy Policy,* vol. 36,2008,pp:743-754.
43. D. B. Das, C. Patvardhan, "Solution of Economic Load Dispatch using real coded Hybrid Stochastic Search", *International Journal of Electrical Power & Energy Systems,* pp 165-170, vol. 2 I, no. 3, March 1999,
44. J. Samaniego, F. Alija, S. Sanz, C. Valmaseda and F. Frechoso, "Economic and technical analysis of a hybrid wind fuel cell energy system", *Journal on Renewable Energy Review,* vol. 33, pp: 839 - 845, 2008.
45. M. El Mnassri, M.; A. S. Leger; "Stand alone photovoltaic solar power generation system: A case study for a remote location in Tunisia" *IEEE Power and Energy Society General Meeting,* Minneapolis, 25-29 July 2010, pages 1-4.
46. P. Hearps, D. McConnell, "Renewable Energy Technology Cost Review", Melbourne Energy Institute, March 2011.
47. B. Singh, and J. Solanki, "Load Compensation for Diesel Generator-Based Isolated Generation System Employing DSTATCOM *"IEEE Transaction on Industry Application,* vol. 47, no. 1, pp. 238-244, January/February, 2011.
48. R. J. Best, D. J. Morrow, D. J. McGowan, and P.A. Crossley, "Synchronous Islanded Operation ofa Diesel Generator" *IEEE Transaction on Power Systems,* vol. 22, no. 4, pp. 2170-2176, November, 2007.
49. A. Roy, S. B. Kedare, and S. Bandyopadhyay, "Optimum sizing of wind-battery systems incorporating resource uncertainty," *Applied Energy,* vol. 87, no. 8, pp. 2712-2727, 2010.
50. C. Wang and M. H. Nehrir, "Load transient mitigation for stand-alone fuel cell power generation systems," *IEEE Transaction Energy Conversion.,* vol. 22, no. 4, pp. 864-872, December 2007.
51. P. Thounthong, S. Rael, and B. Davat, "Analysis of supercapacitor as second source based on fuel cell power generation," *IEEE Transaction Energy Conversion.,* vol. 24, no. 1, pp. 247-255, March 2009.
52. P. K. Goel, B. Singh, S. S. Murthy, and N. Kishore "Isolated Wind-Hydro Hybrid System Using Cage Generators and Battery Storage" *IEEE Transaction on Industrial Electronics,* vol. 58, no. 4, April 2011, pp. 1141-1153.

53. T. Zhou and B. Fram;:ois "Energy Management and Power Control of a Hybrid Active Wind Generator for Distributed Power Generation and Grid Integration" *IEEE Transaction on Industrial Electronics,* vol. 58, no. 1, January 2011, pp. 95-104.
54. N. Gyawali, and Y Ohsawa, "Integrating Fuel Cell/Electrolyzer/ Ultracapacitor System Into a StandAlone Microhydro Plant", *IEEE Transaction on Energy Conversion,* vol. 25, no. 4, pp. 1092-1104, December 2010.
55. C. Wang, and M. H. Nehrir, "Power Management of a Stand-Alone Wind/Photovoltaic/Fuel Cell Energy System", *IEEE Transaction on Energy Conversion,* vol. 23, no. 3, pp. 957-967, September 2008.
56. A. Hajizadeh, M. A. Golkar, and A. Feliachi, "Voltage Control and active Power Management of Hybrid Fuel-Cell/Energy-Storage Power Conversion System Under Unbalanced Voltage Sag
57. *P. Kundur, J. Paserba, V. Ajjarapu, G. Andersson, A. Bose, C. Canizares, N. Hatziargyriou, D. Hill, A. Stankovic, C. Taylor, T. Van Cutsem and V.Vittal, "Optimal Definition and classification of power system stability", IEEE Transactions on Power Systems, 19: 1387-1401, 2004*
58. John F. Kitonga, Pre-Assessment Report of the Tanzanian Energy Sector under the Principles of the International Energy Charter and the Energy Charter Treaty, Brussel
59. Viawan, F. A. and Karlsson, D (2008) Voltage and reactive power control in systems with synchronous Machine based distributed generation, IEEE Transaction on power delivery vol. 23 pp. 1079-1087
60. Mashauri A, A Review on the Renewable Energy Resources for Rural Application in Tanzania, Electrical Engineering Department, Dar es Salaam Institute of Technology, Dar es Salaam,Tanzania 2011
61. Akyoo, A. M, Technology Transfer and Farm-based Renewable Energy Sources: The Potential of BiogasTechnology for Rural Development in Tanzania, Sokoine University of Agriculture Tanzania
62. Prinsloo, C., 2016. Power and Private Sector Participation in Tanzania's Renewable Energy Sector. South African Institute of International Affairs (SAIIA), South Africa.
63. World Bank, (2002). Public and private Electricity provision as barrier to manufacturing competitiveness. Findings African Region Number 221. World Bank, Washington, DC.(Retrieved from world bank web site) http://www.worldbank.org/afr/findings

64. Prinsloo, C., 2016. Power and Private Sector Participation in Tanzania's Renewable Energy Sector. South African Institute of International Affairs (SAIIA), South Africa.
65. Ministry of Energy and Minerals (MEM), (June, 2014). Electricity Supply Industry Reform Strategy and Roadmap, 2014-2025. Available at: https://mem.go.tz/tanzaniaelectricity-supply-industry-reform-strategy-and-roadmap-2014
66. Donna Peng and Rahmatallah Poudineh, 2016. Sustainable electricity pricing for Tanzania, E-40305-TZA-1
67. United Republic of Tanzania, 2018. Tanzania Bureau of statistics, www.tbs.go.tz
68. Keulenaer, H. De. (2003). The hidden cost of poor power quality, Leonardo Energy, European Copper Institute, October 2001. Available: www.leonaro-energy.org
69. M. H. J. Bollen, Understanding Power Quality Problems: Voltage Sags and Interruptions, Piscataway, NJ: IEEE Press, 2002
70. Ahmed M. Azmy, I. Erlich, ―Impact of distributed generation on the stability of electrical power systems, in IEEE Power Engineering Soc. Gen. Meeting, vol.2, pp. 1056-1063 June 2005.
71. L. Helle and S. Munk-Nielsen, ―Comparison of converter efficiency in large variable speed wind turbines, in Proc. IEEE APEC, vol. 1, pp. 628–634, March 2001
72. G. Saccomando and J. Svensson, ―Transient operation of grid-connected voltage source converter under unbalanced voltage conditions,‖ in Proc. IAS, Chicago, IL, vol. 4, pp. 2419–2424, September 2001
73. H. Akagi, Active Harmonic Filters, in Proceedings of the IEEE, vol. 93, no. 12, pp. 2128-2141, December 2005
74. Emanuel, A. E.; McNeil, J. A. (1997). Electric power quality, Annual Rev. Energy Environ, Worcester Polytechnic Institute, Massachusetts, USA. Ref no. 1997.22:263-303
75. McNulty, S.; Primen; & Howe, B. (2002). Power quality problems and renewable energysolutions. Submitted to Massachusetts Renewable Energy Trust, September 2002
76. Melhorn, C.J.; Maitra, A.; Sunderman, W.; Waclawiak, M.; Sundaram, A. (2005). Distribution system power quality assessment phase-II: voltage sag and interruption analysis. Copyright IEEE, paper no. PCIC- 2005-13
77. Caramia, P.; Carpinelli, G.; & Verde, P. (2009). Power quality indices in liberalized markets. A John Wiley & Sons Ltd., ISBN: 978-470-03395-1

78. Bhattacharyya, S.; Cobben, S.; & Kling, W. (2010) Harmonic current pollution in a low voltage network, Presented as a panel list paper in IEEE PES GM 2010 conference, July 2010, Minnesota
79. Milanovic, J.V.; Jenkins, N. (2003). Power quality cost for manufacturing industries. Presented on EDF workshop in Paris, Paris
80. Targosz, R.; Manson, J. (2007). PAN European LPQI power quality survey, Proceedings of 19th International Conference on Electricity Distribution (CIRED 2007), May 2007, Vienna
81. Deokar, S. A. and L. M.Waghmare. Impact of power system harmonics on insulation failure of distribution transformer and its remedial measures. In: 3rd International Conference on Electronics Computer Technology (ICECT). Kanyakumari: IEEE, 2011, pp. 136–140. ISBN 978-1-4244- 8679-1. DOI: 10.1109/ICECTECH.2011.5941817
82. Singh, R. and A. Singh. Aging of distribution transformers due to harmonics. In: 14th International Conference on Harmonics and Quality of Power (ICHQP). Bergamo: IEEE, 2010, pp. 1–8. ISBN 978-1-4244-7246-8. DOI: 10.1109/ICHQP.2010.5625347
83. Hulshorst, W.T.J.; Groeman, J.F. (2002). Energy saving in industrial distribution transformers. KEMA report, reference 40130017-TDC 02-24226A
84. KOLCUNOVA, I., M. PAVLIK and L. LISON. Assessment of Long Thermal Ageing on the Oil-Paper Insulation. Advances in Electrical and Electronic Engineering. 2016, vol. 14, no. 5, pp. 506–511. ISSN 1804-3119. DOI: 10.15598/aeee.v14i5.1836
85. IEEE Standard C57.110. IEEE Recommended Practice for Establishing Liquid-Filled and Dry- Type Power and Distribution Transformer Capability when Supplying Nonsinusoidal Load Currents. New York: IEEE, 2008
86. John F. Kitonga, Pre-Assessment Report of the Tanzanian Energy Sector under the Principles of the International Energy Charter and the Energy Charter Treaty, Brussel 2015
87. Donna Peng & Rahmatallah, Poudineh Sustainable electricity pricing for Tanzania, Oxford Institute for Energy Studies, ISBN 978-1-78467-061-0
88. C. P. Steinmetz, "Power control and stability of electric generating stations," *AIEE Trans.*, vol. XXXIX, Part II, pp. 1215–1287, July 1920.
89. AIEE Subcommittee on Interconnections and Stability Factors, "First report of power system stability," *AIEE Trans.*, pp. 51–80, 1926.
90. P. Kundur, "Power System Stability and Control," New York: *McGraw- Hill*, 1994
91. IEEE TF Report, "Proposed terms and definitions for power system stability," *IEEE Trans. Power Apparatus and Systems,* vol. PAS-101, pp. 1894–1897, July 1982.

92. Dispersed system impacts: Survey and requirements study, final report. Technical Report TR-103337, Electric Power Research Institute, September 1991.
93. E. Mgaya, J. Švec, J. Tlustý and T. Sýkora, "The impact of connecting wind power plant to the distribution network", *Proceedings of The 7th International Conference on Power System Operation and Planning, Cape Town*:6-10, 2007.
[38] Impact of increasing contribution of dispersed generation on the power system. Final Report, CIGRE Study Committee 37 (WG 37-23), CIGRE, Paris, September 1998.
94. N. Jenkins, "Embedded generation – tutorial", *Power Engineering Journal*, pages 145–150, June 1995.
95. IEEE Power Engineering Society Power System Stability Subcommittee, Voltage Stability Assessment: Concepts, Practices and Tools. *Piscataway, NJ*: Aug. 2002.
96. W. F. Tinney, "Compensation Methods for Network Solutions by Optimally Ordered Triangular Factorization", *Proceedings of the PICA Conference*, Boston, MA, May 24-26, 1971, pp. 123-127.
97. S. C. Tripathy, G. D. Prasad, O. P. Malik, and G. S. Hope, "Load Flow Solutions for Ill-Conditioned Power Systems by a Newton-Like Method", *IEEE Transactions on Power Apparatus and Systems*, Vol. PAS-101, No. 10, October 1982, pp. 3648-3657.
98. N. Acharya, P. Mahat, and N. Mithulananthan, "An analytical approach for DG allocation in primary distribution network," International Journal of Electrical Power & Energy Systems, vol. 28, no. 10, pp 669- 678, Dec. 2006
99. IEEE Standard for Interconnecting Distributed Resources into Electric Power Systems, IEEE Standard 1547TM, June 2003
100. R. A. Walling, and N. W. Miller, "Distributed generation islanding implications on power system dynamic performance," IEEE Power Engineering Society Summer Meeting, vol.1, pp. 92-96, 2002
101. M. A. Refern, O. Usta, and G. Fielding, "Protection against loss of utility grid supply for a dispersed storage and generation unit," IEEE Transaction on Power Delivery, vol. 8, no. 3, pp. 948-954, July 1993
102. M. Ropp, K. Aaker, J. Haigh, and N. Sabhah, "Using Power Line Carrier Communications to Prevent Islanding," in Proc. 28th IEEE Photovoltaic Specialist Conference, pp. 1675-1678, 2000

103. S. I. Jang, and K. H. Kim, “An islanding detection method for distributed generations using voltage unbalance and total harmonic distortion of current,” IEEE Tran. Power Delivery, vol. 19, no. 2, pp. 745-752, April 2004

104. S. Jang, and K. Kim, “Development of a logical rule-based islanding detection method for distributed resources,” in Proc. IEEE Power Engineering Society Winter Meeting, vol. 2, pp. 800-806, 2002

105. E. Mgaya, J. Tlustý and Z. Law, “Analysis of Dynamic Behavior of the Distributed Generation Islanding”, In ELEN 2006 Prague, 2006, pg. 1-7, ISBN 80-239-7650-8

106. J. A. P. Lopes, C. L. Moreira, and A. G. Madureira, "Defining control strategies for MicroGrids islanded operation," IEEE Transactions on Power Systems, vol. 21, pp. 916-24, 2006.

107. G. Chatzis, I. Avrimotis-Falireas, L. Roald, F. Abbaspourtorbati, M. Zima and G. Andersson, ”Joint Scheduling of Frequency Control Reserves and Energy Dispatch for Small Islanded Power Systems”, Power System Computation Conference (PSCC), Genoa, Italy, 2016

108. E. Franzen, N. Strauch, and C. Triebel. Switching off the generator: the stable operation of sustainable island grids in the MW range using renewable energy and energy storage, 2015

109. Committee, D Power, I. and Society, E. ‘IEEE Recommended Practice and Requirements for Harmonic Control in Electric Power Systems IEEE Power and Energy Society’, 2014

110. Ogheneovo Johnson, D. (2016) ‘Issues of Power Quality in Electrical Systems’, International Journal of Energy and Power Engineering, 5(4), p. 148. doi: 10.11648/j.ijepe.20160504.12

LIST OF AUTHOR'S PUBLICATIONS

Journal Publications (indexed in Web of Science) related to the dissertation topic

- Melkior, U. F., Ghaeth Fandi, G., Mgaya, E., Muller, Z., Tlusty, J., Stand-alone Solar Photovoltaic Systems for Off-grid Electrification, Renewable Energy Research and Applications, 2024, 5(1), 1-9. ISSN 2717-252X, https://doi.org/10.22044/rera.2023.13015.1218 (WoS code: 001054083400001, Accepted Date 12 May 2023)
- Krepl, V., Fandi, G., Rehabi, M., Ghanem, S., Jrad, F., Muller, Z., Smutka, L., Kyncl, J., Melkior, U. F., Fandie, S., Cabelkova, I., Tlusty, J., Effective Criteria in the Public-private Partnership in Developing Countries to Apply the Sustainable Development Goals: GAN-based Decision Support System for the Renewable Electrical System, Case Study Syria, HELIYON, 2023, D-23-16751R1 (in press)

Conference Publications (indexed in Web of Science) related to the dissertation topic

- Melkior,U.F., Cernan, M., Muller,Z., Tlusty, J., Kasembe, A., the Reliability of the System with Wind Power Generation. In: 2016 17th International Scientific Conference on Electric Power Engineering (EPE 2016). 17th International Scientific Conference on Electric Power Engineering, Praha, 2016-05-16/2016-05-18. New York: IEEE, 2016. International Scientific Conference on Electric Power Engineering. ISBN 978-1-5090-0907-7. DOI 10.1109/EPE.2016.7521833.
- Melkior, U. F., Tlustý, J., Müller, Z. Micro Hydro Power for Off Grid Electrification: A Case Study of Hhaynu River - Mbulu,Tanzania In: 2018 19th International Scientific Conference on Electric Power Engineering (EPE). Brno: Czech Section of the IEEE VUT, 2018. ISSN 2376-5631. ISBN 978-1-5386-4612-0.

Conference Publications (Other Topic)

- Melkior, U. F., Sharing of strength for skill gap bridging, "Conference on TVET Institutions and Industries Collaboration", Proceeding, October, 2012
- Melkior, U.F., Masika, R. J, Senzia, M. A, Mgaya, E. V, Skill gap in Biomedical Equipment Repair and Maintenance in Tanzania, "Improved Health Technology Management for Quality Health Care Delivery", Proceeding, November, 2012

- Melkior, U. F. Mbuya, B., Sademaki, S. L., Effective linkage between academic institutions and employers for promoting employment and entrepreneurship, “Commonwealth Association Polytechnics in Africa ” Proceeding, November, 2013
- Melkior, U.F., Masika, R. J.,Senzia, M.A., and Mgaya, E.V, Skills Gap in Biomedical Equipment repair and maintenance in Tanzania, “Bi-annual Biomedical Engineers and Technicians in East Africa conference” proceeding 2012.
- Melkior, U. F., Dean, D., Developing Novel and Feasible Biotechnology to Screen for and Manage Diabetes, Partnering for Impact in Global and Public Health, 2015

Chapter in the book related to the dissertation topic

- Melkior, U.F., Tlusty, J., Muller, Z., Use of Renewable Energy for Electrification of Rural Community to Stop Migration of Youth from Rural Area to Urban: A Case Study of Tanzania. In: Dependability Engineering. London: IntechOpen Limited, 2018. ISBN 978-1-78923-258-5.

Journal Publications (Reviewed) related to the dissertation topic

- Melkior, U. F.; Müller, Z.; Tlustý, J. Elektroenergetické systémy v jihoafrickém regionu In: Energetika. 2018, 68(4), 248-254. ISSN 0375-8842.