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Guidelines:

1. Introduction
1.1 Background
2. Renewable Energy Sources.
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3. Solar Energy in Saudi Arabia
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The student acknowledges that the master’s thesis is an individual work. The student must produce his thesis without the assistance of others, with the exception of provided consultations. Within the master’s thesis, the author must state the names of consultants and include a list of references.

Date of assignment receipt

Student’s signature

DECLARATION

‘’ I hereby declare that this thesis is the result of my own work and that I have clearly stated all information sources used in the thesis according to Methodological Instructions of Ethical Principle in the Preparation of University Thesis’’.

In Prague, 21.05.2020 Signature ………………..

Abstract

This master thesis deals with large-scale power plants, its applications and control of large-scale power plants using the active and reactive power. The introduction describes the overview of renewable sources and then introduces the renewable sources and energy mix in Saudi Arabia. The work further contains a description of the rules for connecting devices into the distribution grid. Technical flexibility is demonstrated in the case study, which illustrates calculation of the maximal connectable power of PV in the point of common coupling in MV network taking into account the voltage change limit and with/without reactive power regulation.

Keywords

Renewable energy sources, photovoltaic, solar panels, large-scale photovoltaic power plant, maximum power plant tracker, active and reactive power control, DNCalc software, study of connectivity

Abstrakt

Diplomová práce se zabývá výrobnami elektřiny větších výkonů, aplikačním použitím a řízením činného a jalového výkonu. V úvodu je vytvořen přehled obnovitelných zdrojů (OZE) a energetický mix v Saudské Arábii. V práci jsou uvedena pravidla pro připojování zařízení do distribuční soustavy (DS). Technická flexibilita je domonstrována v případové studii, která zachycuje výpočet maximálního připojitelného výkonu fotovoltaické elektrárny (FVE) v místě připojení (PCC) sítě VN, kdy posuzujícím kritériem byla velikost napěťové změny ve stavu bez regulace a s regulací jalového výkonu.

Klíčová slova

Obnovitelné zdroje energie, fotovoltaicka, solární panely, fotovoltaická elektrárna velkého výkonu, řízení činného a jalového výkonu, DNCalc software, studie připojitelnosti

List of Abbreviation

RES:	Renewable Energy Sources
HPP:	Hydropower Plant
PV:	Photovoltaic
CSP:	Concentrated Solar Power
DC:	Direct Current
AC:	Alternating Current
MPPT:	Maximum Power Plant Tracker
LS-PVPP:	Large-Scale Photovoltaic Power Plant
PPC:	Power Plant Controller
PF:	Power Factor

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1 Introduction

Energy is one of the most critical human needs in daily life, and has been for decades, even millennia. When we consider the things, we cannot do without electricity; the necessity of electricity is proven of great significance and becomes even more important as technology advances gradually. [1]

Human life is increasingly dependent on the energy right from running a personal computer to cooking food in this age of modern and materialistic living patterns.

Energy is an integral part of the universe, used as a means of being. Energy is typically derived from natural and non-natural sources and is divided into two main categories, namely: renewable energy, which depends on natural and other non-renewable resources, and which depends on artificial sources but has been created over time and under the influence of a variety of factors. All kinds of this energy need processes, devices, and special techniques to extract it and use it for human benefit.

At the beginning of the twenty-first century, about 80 percent of the world's energy sources were derived from fossil fuels such as coal oil and natural gas. Despite being finite and damaging the atmosphere, fossil fuels have not stopped countries from avoiding using them for energy; in addition, they are still used to supply much of the world's energy source. It is, however, clear that more and more countries around the world are focusing on renewable energies, changing their policies and regulations to mitigate environmental damage. World population is rising as time goes on; thus, the need for energy consumption is growing day by day. Carbon pollution and the greenhouse effect are therefore damaging our environment and affecting both human health and the natural ecosystem. [1]

Renewable Energy Sources (RES), often called green energy sources, is a form of energy that is inexhaustible and does not run out, and its name means that it occurs again until it is near completion. Its source is one of the natural resources, such as wind, water, sun, hot springs, tidal energy, biofuels. In addition, its most significant feature is that it is healthy and environmentally friendly energy, since it does not leave harmful gases; such as carbon dioxide, which does not negatively influence the natural atmosphere because it does not play a role that influences temperature levels. Renewable energy sources are totally at odds with their non-renewable counterparts, such as natural gas and nuclear power, as these counterparts result in global warming and carbon dioxide emission when used.

Figure 1.1: Renewable Energy Sources [2]

2 Renewable Energy Sources

2.1 Renewable Energy Sources compared to Conventional Energy

Unlike fossil fuels that took millions of years to form, one of the benefits of renewable energy is that it is extracted from renewable natural sources like sun, wind, water, and do not cause air emissions or climate change. It also does not cause other human and animal diseases, such as fossil fuel waste or nuclear energy, which causes other diseases such as cancer, and other bottlenecks.

Relative to conventional non-renewable sources and infrastructure, renewable energy technologies and facilities used to store the electricity are much less costly to maintain. When installed, most utilities and services used to harness renewable energy will last for up to 10 years without requiring repairs.

They can be acquired by most countries in the world, and thus do not cause wars and conflicts to possess and control them. Countries guarantee their existence and stability, there is no fear that they will run out and no need to look for future alternatives.

Unlike conventional generation, however, RES generation can be variable and unpredictable. Some renewable energy sources have varying supplies, such as wind and solar. Electricity generators using variable renewable energy sources will only generate electricity when the environment is right (i.e., when the wind blows or the sun shines).

Another major issue with development of renewable energy sources for utility grid operators is reactive power mitigation and voltage stabilization.

Due to inadequate reactive power stores in the power grids, Large blackouts could also be triggered by voltage imbalance. Also, due to the intermittent and unpredictable existence of certain sources of renewable energy, the power grid is likely to become unreliable during grid unforeseen events.

Under transient fault situations, the low inertial wind turbines and the inertia-less photovoltaic systems cannot provide adequate voltage aid to the network without adequate reactive power support structures.

Thus, reactive power control is necessary for regulating system voltage to guarantee an alternating current transmission system operates efficiently and reliably.

2.2 Overview of Renewable Energy Sources

2.2.1 Hydropower

Hydropower plants (HPP) harness the energy to produce electricity from the falling water. The kinetic energy of falling water is transformed into mechanical energy by a turbine. A generator then transforms the turbine's mechanical energy into electric power.

Also known as hydraulic energy, one of the types of energy produced by the movement of water that is continuously falling and is not exhausted. It is considered one of the most significant sources of renewable energy and the history of its use dates back to the first time in the Empire of Rome, where it was used for the operation of flourmills and grain production and then transferred the matter to each from China and the countries of the Far East. In the thirties of the eighteenth century, the use of hydropower reached a peak, as water channels were built for Chavouli's transportation, but in recent times the importance of hydropower expanded to rank first among renewable energy source, as it relies on it to generate a fifth of electricity.

Hydroelectric energy from water energy is considered to be a source of vast amounts of electricity to millions of people in the southern part of Africa’s desert. Energy has great opportunities, but it gives rise to complex challenges that vary depending on the type, location and size of the project.

HPP vary in scale from micro that power just a few homes to massive dams such as the Hoover Dam that provide millions of people with electricity.

Figure 2.1 Hydropower [3]

It also helps good management of water energy projects to improve the management of water resources locally, thus enhancing water security and achieving it effectively, and providing services for irrigation and flood control, which will result in reducing the impacts of climate change and adapt to it.

A traditional hydroelectric project is a three-part system: a power plant where the electricity is created, a dam that can be opened or closed to regulate the flow of water and a reservoir where water is stored. Water passes into an intake behind the dam and pushes in a turbine toward blades, causing them to spin. The turbine to generate electricity powers a generator.

2.2.2 Geothermal Energy

Geothermal energy is a form of renewable energy that has been used throughout history back thousands of years, bathing, cooking food and heating.

Since 1904, an Italian has started to exploit the explosive natural steam in the Larderello field. Since that time, in many countries around the world, such as Japan, Iceland, New Zealand and the United States of America, geothermal energy has become a topic of interest and gain, and it has been used as an alternative source for producing electricity, domestic heating, and others.

In the past, a number of scientists have assumed that the water from the geothermal systems originates from the depths of fiery activities. Recent experiments using the hydrogen and oxygen isotopes have shown that at least 95 percent of this water comes from the atmosphere.

The term geothermal (or geothermal) consists of the Greek terms geo (earth) and thermal (heat), since the heat derived from the Earth's interior is geothermal. Where we can transform this heat into steam or hot water used for heating or producing electricity in buildings. Geothermal energy is a source of renewable energy, since heat is continuously produced in the interior of the Earth.

Figure 2.2: Geothermal Energy [3]

Geothermal energy is produced in the Earth's nucleus, where the slow decomposition of radioactive particles continuously creates hotter temperatures from the sun's surface within Earth, a process that occurs in all rocks.

The vast areas of naturally occurring natural water bodies are called geothermal reservoirs. Most geothermal sources are deep underground, and there is no strong evidence that they are above ground level. Yet often, geothermal energy makes its way to the surface in the form of:

- Volcanoes and volcanic gas nozzles
- Hot springs
- Natural heaters

The most active geothermal energy resources are typically situated along the margins of the major plates where the concentration of earthquakes and volcanoes occurs. As the lava reaches the surface, it elevates groundwater temperatures embedded in porous rocks or flowing water over broken rock surfaces and on cracks. Such are classified as hydrothermal, and they have two common components: heat (thermo) and water (hydro).

The geologists look for geothermal reservoirs using various methods. The most effective way to enter tanks of geothermal energy is to dig a well and test the depth of the Earth's surface.

Some geothermal projects use near-surface temperatures on Earth, while others need miles of drilling within the Ground. The three main geothermal energy uses are:

- Direct use and central heating systems using hot water from springs or tanks near the surface.
- Power plants need exceptionally high water or steam (300- degrees Fahrenheit). In general, geothermal power plants are installed where geothermal reservoirs are situated one to two miles from the surface.
- Geothermal pumps that use earth or water temperatures settled near to the earth's surface to regulate a building's temperature above ground.

2.2.3 Wind Energy

Wind energy is characterized as a type of energy in which the turbines convert the kinetic energy of the wind into mechanical or electrical energy that can be used to produce electricity.

Wind is an indirect source of solar energy resulting from a series of factors including uneven heating of the Earth's atmosphere by sunlight, topographical variations and rotation of earth.

Wind energy is a type of renewable energy that comes from the air that flows over the surface of the earth, and wind turbines harness this kinetic energy and turn it into a usable energy that can provide power for small and medium-sized residential and community projects for homes, farms, schools, or businesses.

Figure 2.3: Wind Energy [3]

Wind energy is one of the world's fastest-growing sources of new electricity generation, and these growth patterns can be related to many benefits, including:

- Green Energy: as wind energy is renewable, that is, it does not contain any emissions or gases.
- Economic growth: In addition to the fact that wind energy is a low-cost commodity, wind energy is a direct-generated source of power that does not need fuel, allowing local communities to retain funds in their economies, build jobs and expand the tax base, which is one of the advantages of any local community economic growth that uses wind energy.

2.2.4 Solar Energy

For billions of years, the sun has generated energy, and is the primary source of all the energy sources and fuels we use today. For thousands of years, people used the sun's rays (solar radiation) to cook and dry meat, fruit, and grains. Over time, people developed technology to collect and turn solar energy into electricity for power.

The Sun is an incredibly strong source of energy, and sunlight is by far the greatest source of energy provided by Earth, but its penetration on the surface of the Earth is very small. This is due in part to the immense radial radiation emitted from the distant Sun. A relatively minor additional loss is due to the atmosphere and clouds on Earth, which consume or disperse as much as 54 per cent of the sunshine incoming. The sunlight entering the ground consists of about 50% visible light, 45% infrared radiation, and smaller quantities of ultraviolet and other electromagnetic radiation sources. [4]

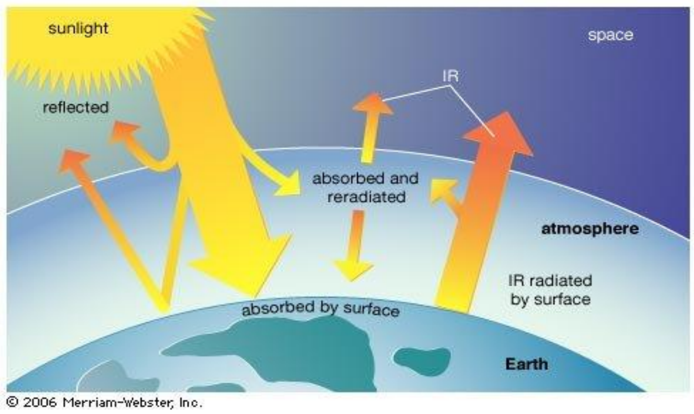

Figure 2.4: Solar Energy [4]

We can harness the energy of the sun in a variety of different ways: [2]

- Photovoltaic (PV) cells that turn sunlight into electricity.

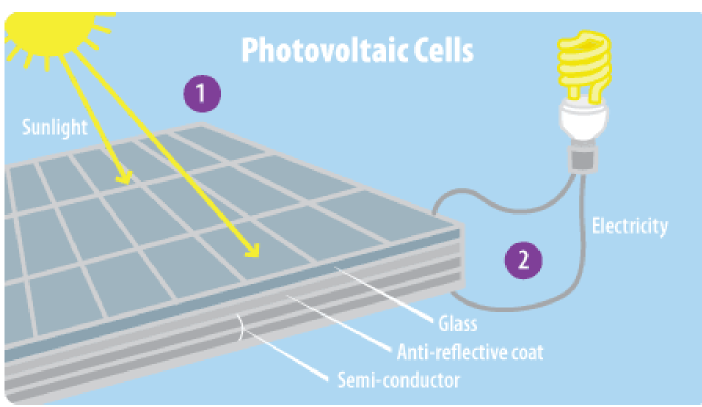

Figure 2.5: PV Cells [2]

- Solar thermal technology, in which sun heat is used to produce hot water or steam.

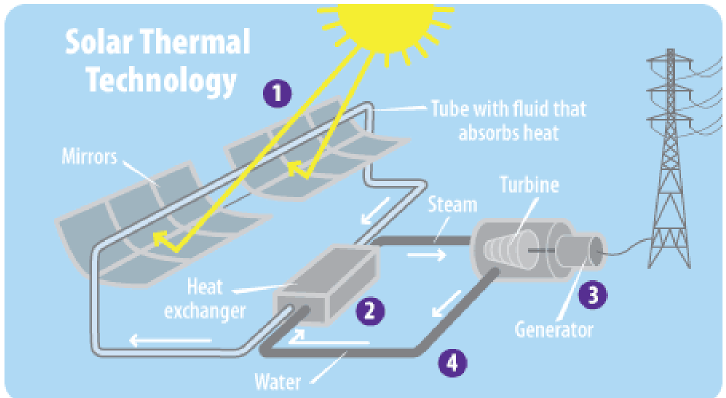

Figure 2.6: Solar Thermal [2]

- Passive solar heating, when sun shine through windows to heat a building's inside.

3 Renewable Energy in Saudi Arabia

Oil supply and demand worries are increasing worldwide. The global demand for oil has been more than world oil supply over the last decade. Saudi Arabia is OPEC's main oil producing country and supplies about 30% of the overall supply of OPEC oil.

Saudi Arabia's domestic consumption currently relies entirely on hydrocarbon fuels, which account for a quarter of its oil and gas production. The government hopes to replace their dependence on it with renewable resources.

In general, the KSA has immense potential for renewable energy, and in particular solar. Despite the availability of significant renewable energy resources, however, electricity generation at the KSA is largely dependent on fossil fuel resources.

Saudi Arabia is planning to supply about 30 percent of its electricity needs from its largest potential energy source, solar power within the next 20 years. It has one of the highest solar radiation rates in the world, and plans to install photovoltaic power of more than 41 gigawatts by 2032.

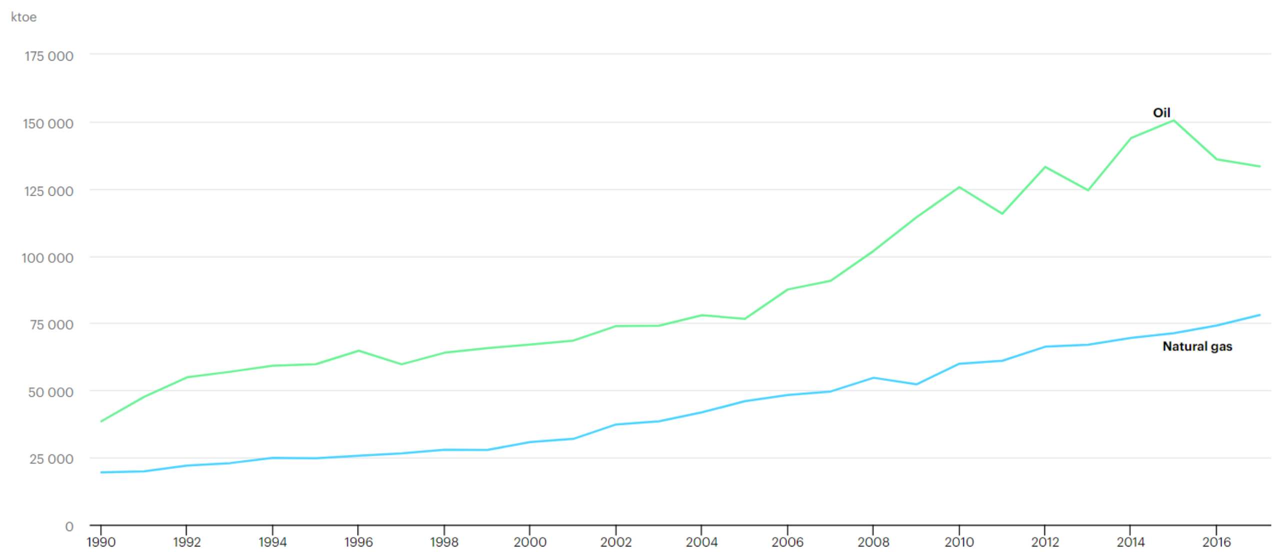

Figure 3.1: Saudi Arabia primary energy supply (Oil & Natural gas) [5]

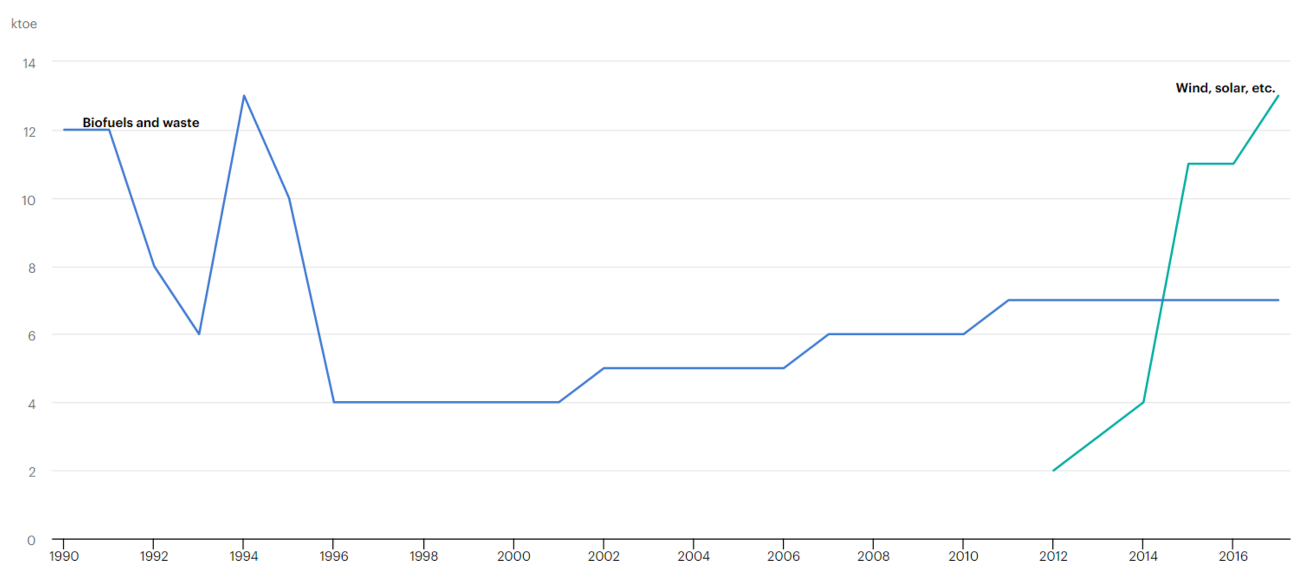

Figure 3.2: Saudi Arabia primary energy supply (Renewables, Biofuels & waste) [5]

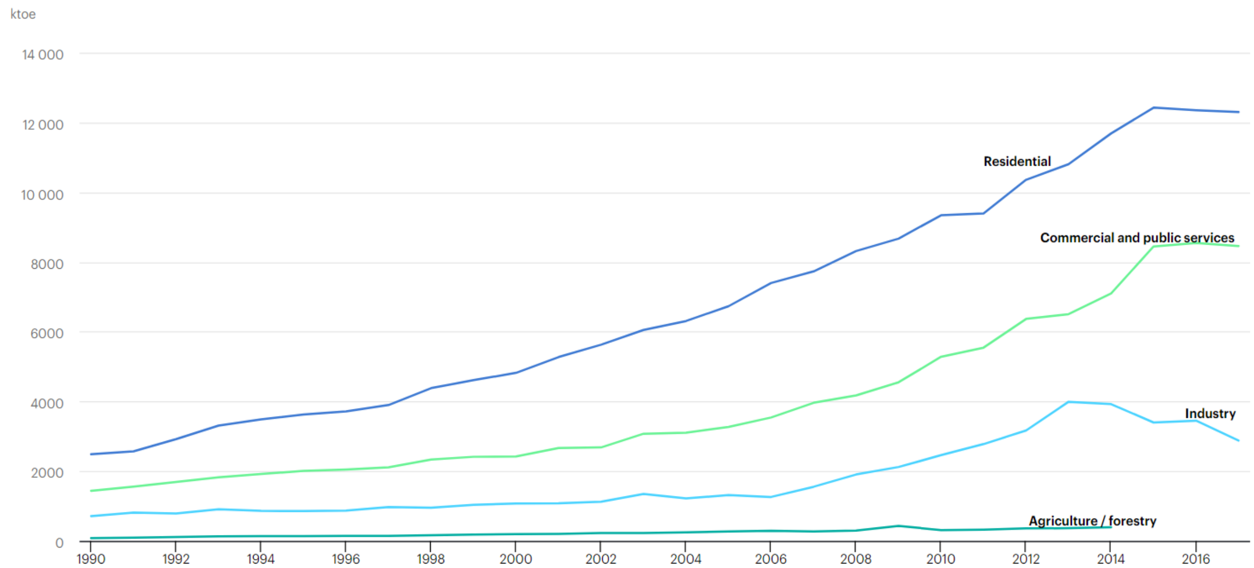

Figure 3.3: Saudi Arabia electricity final consumption by sector [5]

3.1 Solar Energy in Saudi Arabia

The importance of solar energy comes from being a huge energy that can be used anywhere. It is an inexhaustible, free fuel source and is known to be renewable energy, since it can also be used in many areas of agricultural production, water heating and cooling, water desalination and electricity generation.

In the important of preserving, the right of future generations to oil wealth and making the usage of this oil reserves lasts as long as possible and taking in to account the significant increase of electricity consumption in Saudi Arabia and consequently, the costs resulting from the use of fuel for electricity generation are increasing. With importance of greenhouse gas emissions reduction, attention must be paid to developing renewable energy sources in the Kingdom and the most important of them is solar energy.

Saudi Arabia has one of the highest solar radiation in the world, measured at about 2,200 kWh of solar radiation per square metre. In addition to the abundant availability of empty stretches of desert that can accommodate infrastructure for solar power projects, the country is strategically positioned along the Sun Belt. [6].

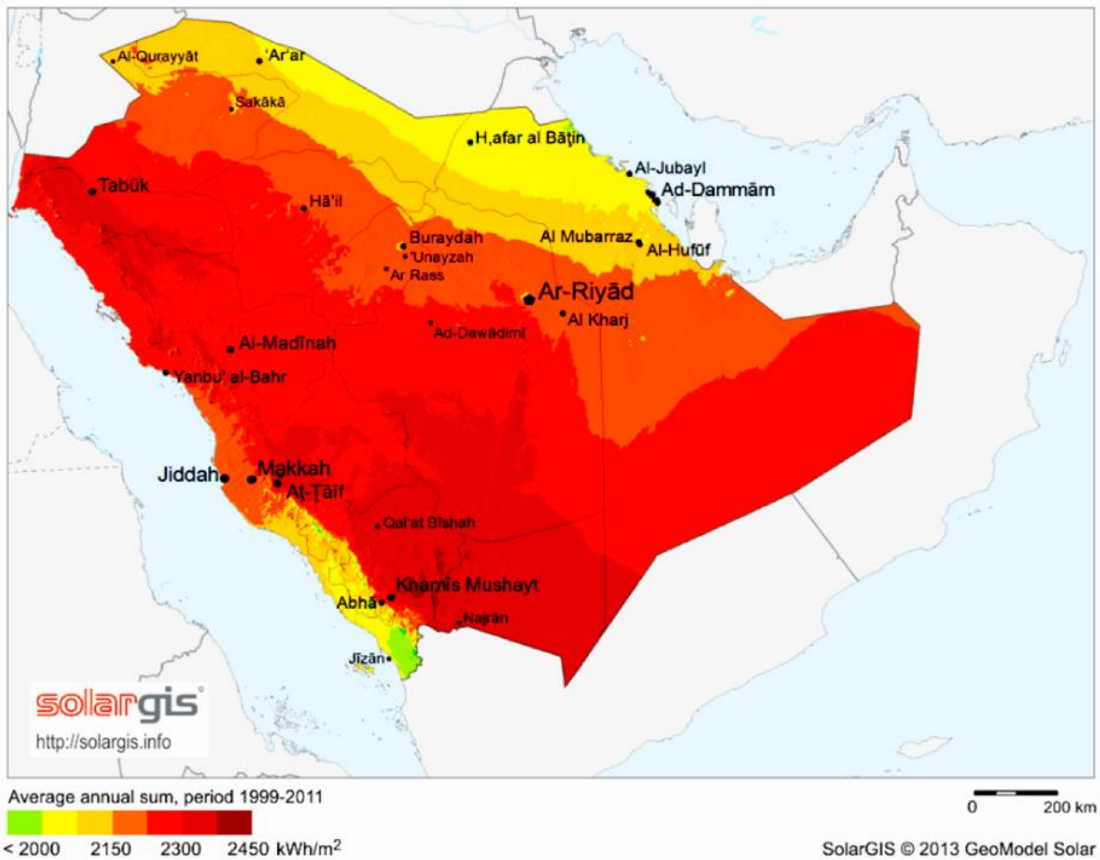

Figure 3.4: Solar irradiation map of Saudi Arabia [7]

The interest in solar energy in the Kingdom of Saudi Arabia has witnessed a continuous increase. This was represented in many governmental initiatives, including the National Water and Electricity Initiative. Using solar energy under the auspices of the King Abdulaziz City for Science and Technology and a project. Solar electric production for King Abdullah University of Science and Technology..

3.1.1 Historical Development of Solar Energy

Saudi Arabia started the solar energy projects in 1960. In 1977, King Abdulaziz City for Science and Technology (KACST) launched research and development on solar energy technology in the Kingdom. Saudi Arabia launched the "solar village" system in 1980, using solar power to provide electricity to three rural villages. In 2010, the King Abdullah University of Science and Technology (KAUST in Thuwal) commissioned the first large-scale photovoltaic rooftop solar system in the Kingdom. This photovoltaic plant has an installation capacity of 2 MW with 9,300 panels which occupies approximately 11,600 m2 of roof space. [7]

Figure 3.5: The 2 MW rooftop solar plant at KAUST [7]

In 2011, a 500 kW solar power plant was launched on Farasan Island, Southwest Saudi Arabia. This solar power plant was the first in Saudi Arabia to save the transition of an average of 28,000 barrels of diesel fuel per year to electricity generation on the island. In 2012, Princess Noura University brought the world's largest solar thermal plant into full operation. The plant uses large flat plate solar collectors of 36,160 m² and produces 25 MW thermal power. [7]

Figure 3.6: Solar power plant on Farasan Island, Southwest Saudi Arabia [7]

Saudi Arabia installed largest solar power plant for a car parking lot. The 10 Megawatts Photovoltaic Carport Project is located at Saudi Aramco's newly constructed offices in Dhahran, at North Park and will cover almost 4,500 parking spaces. [7]

Figure 3.7: The 10 MW Photovoltaic Carport System in Saudi Arabia [7]

3.1.2 Future of Solar Energy

The Saudi government has implemented electricity tariffs and developed energy efficiency steps to reduce the demand for electricity, which will reduce the peak charge of electricity. At midday, the electricity charge curve peaks and is close to the height of the solar irradiance curve.

The goal is to minimize reliance on industrial imports by building significant local factories to serve the economy and to become an exporting nation with the future objective. Due to the local availability of most of the raw materials for the entire value chain, this aim to become self-sufficient in the manufacture of solar components is potentially achievable.

Saudi Arabia will use the Dubai project experience as the framework for its own first hybrid project, which is under construction in the northern industrial town of Waad Al-Shamal and will include Concentrated Solar Power (CSP) 50 megawatts (MW).

3.2 Wind Energy in Saudi Arabia

Saudi Arabia has the ability to generate more than 200GW of onshore wind energy with an average capacity factor of 35.2%, higher than other countries that pave the way for wind energy generation like the US (33.9%), UK (27.8%), Denmark (28.4%) and Germany (19%). Though solar has captured the headlines, wind power is quickly proving to be a cost-competitive option for energizing the kingdom too. [8]

Implementation of shares of renewable energy technologies of total energy production in Saudi Arabia may be the best solution for all fossil fuel issues.

Additionally, there is a shortage of renewable energy (solar and wind) research and studies of these technologies in Saudi Arabia needed to support the introduction of renewable energy and diversify the energy mix

Kingdom areas like Aqaba, Jahid, Taif and Yadamah have high wind speeds and promising capacity factors to turn wind energy projects into a reality. [8]

Area	Mean Wind Speed @100 m (m/s) (MERRA)	Distance to National Grid (km)	Distance to Closest Load Center (km)	Area (km2)	Wind Energy Technical Potential (MW) (*)	Estimated P50 Capacity Factor [%] (**)
Aqaba	7.4	<50	<100	4337	7000	39.0
Yanbu	6.9	<80	<80	3135	7000	32.0
Al Madinah	7.4	<150	<150	13172	30000	32.7
Taif	7.5	70-150	<200	25073	55000	35.3
Jahid	7.9	200	400	25369	55000	39.8
Juaymah	6.7	<50	20-70	4770	11000	31.2
Yadamah	7.7	<200	<200	10560	70000	36.4
TOTAL/ AVERAGE	**7.4**				**>200 GW**	**35.2**

* Assumptions: 1/3 total land usable for wind turbines deployment; 3.45 MW, 126 meters rotor wind turbine used for calculations; Inter-WTG distances 4 X 8 rotor diameters
** 15 % Energy losses (wake effect, electrical, performance, availability, others)

Figure 3.8: Saudi Arabia areas with high wind speed [8]

3.2.1 Future of Wind Energy

Dumat Al-Jandal is an onshore wind farm construction of 400 MW which will become the first utility-scale wind power source in Saudi Arabia.

The wind farm is the second component of the first round of procurement under the NREP, which seeks to reduce carbon emissions. It will allow the achievement of the first phase of NREP's 9.5GW renewable energy target by 2023. This is in line with Saudi Arabia's Vision 2030, which aims to reduce oil dependence on the region.

The Dumat Al Jandal project will be the first wind farm in Saudi Arabia and the largest in the Middle East with an installed capacity of 400 Megawatts (MW). The wind farm will be located 896 km (560 miles) north of Riyadh, in Saudi Arabia's Al Jouf region. [9]

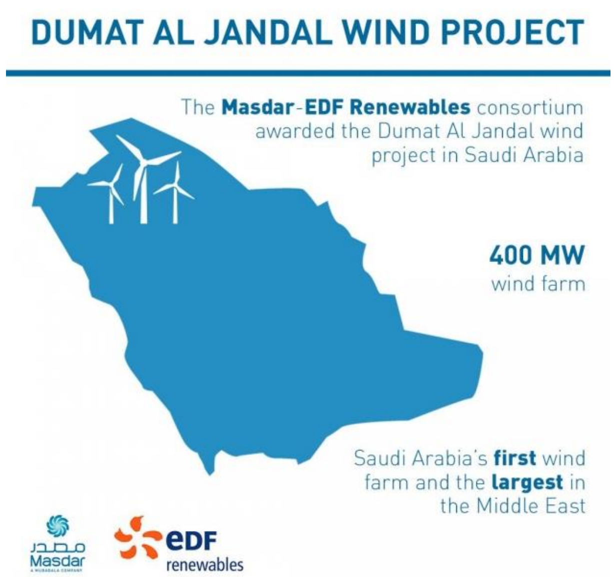

Figure 3.9: Dumat Al-Jandal Wind power plant [9]

3.3 Geothermal Energy

A hallmark of Saudi Arabia 's land is its enriched geological diversity. In Saudi Arabia, the majority of these geothermal resources are concentrated in the western and southwestern parts, in the form of hot springs and surface volcanic eruptions or what is called "Harrats".[10]

The coming thermal waters rise to the surface through a complicated grid of structural components that generally follow the main tectonic components and events that prevail throughout the entire Red Sea region. This allocates a significant number of expected geothermal anomalies and hot springs across the southern parts of the suez gulf of Egypt, the eastern coasts of the countries of the East African Rift and the western and southwestern parts of Saudi Arabia. In Saudi Arabia, however, geothermal energy isn't currently studied.

The region of Jizan lies in the southwestern part of Saudi Arabia between 42.0–43.8 ° E longitudes and 16.5 ° –17.50 ° N latitudes with a region of 40,475 km2. It is part of the Arab shield that is part of the Precambrian crustal plate and is made up of igneous rocks, basalts, diorites, gabbros, and mica-schist. The geology of the Jizan area is divided mainly into two main characteristics: the near-shore deposits, which include several valleys draining towards the sea and the crystalline basement (granite) and metamorphic rocks in the eastern parts of Jizan, which include the amount of hot springs expected. [10]

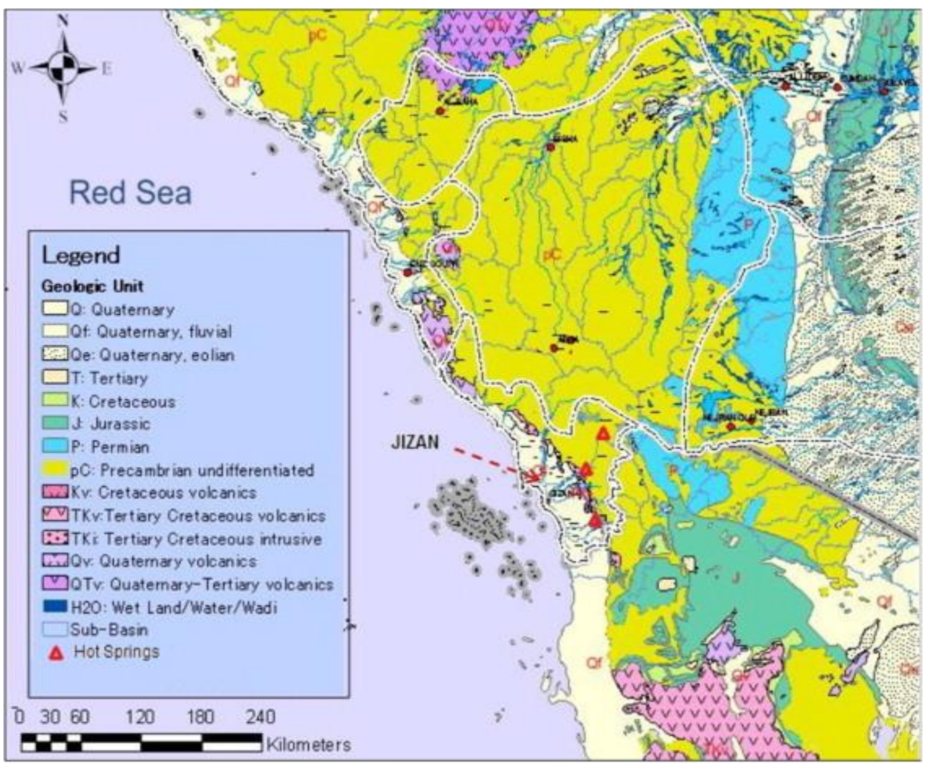

Figure 3.10: *Geologic map of the Jizan area showing the different encountered rock units. [10]*

The Saudi Electric Ministry has developed more advanced technology system for optimization and control that could boost overall plant reliability and deliver operational and maintenance performance over the facility's lifetime.

The current geothermal resources such as hot water springs and harrats are not being used to produce electricity or to heat yet.

4 Legislation, rules and paragraphs about connecting into the distribution grid. [18]

Network disturbances:

Disturbances caused by local generation need to be reduced so the devices of other network users as well as DSO equipment would not be disturbed. Such impacts need to be analyzed based on methods for evaluating disturbances and acceptable limits.

Generation can be connected without need for disturbance evaluation provide that ration between network short circuit power (S_{kV}) and rated power of whole equipment (S_{rA}) is higher than 500.

If equipment is tested by recognized agency, connection assessment can utilize more favorable factor S_{kV}/S_{rG} (<500). Certification, test report, etc. regarding the expected disturbances need to be provide in case of wind generation.

Particular evaluation of connection of one or several generation at one point of connection need to be based on following limits:

Voltage change:

Voltage changes in the operation of the electricity generating plant.Variation in voltage distribution system low voltage by connecting electricity generating plant at the connection point (PCC) must not exceed 3%.

$$\Delta U \leq 3\ \%\ Un$$

Voltage change in the distribution of medium voltage by connecting electricity generating plant at the connection point (PCC) must not exceed 2%.

$$\Delta U \leq 2\ \%\ Un$$

These limits apply only to the case where switching is more frequent as once every 1.5 min.

Flicker:

LONG-TERM FLICKER

For evaluation of one or several generation at point of connection, regarding the voltage variation causing the flicker, limit value needs to be at LV and MV joint point of connection

$$P_{lt} \leq 0.46$$

and for 110 kV joint point of connection

$$P_{lt} \leq 0.37$$

Long-term flicker Plt of single generation can be determine using the flicker factor c as:

$$P_{lt} = c \cdot \frac{S_{nE}}{S_{kV}}$$

where S_{nE} is rated power of equipment (S_{nG} for wind generation). If the value calculated from the above mentioned equation is higher than 0.46, phase angles can be included and following equation can be used:

$$P_{lt} = c \cdot \frac{S_{nE}}{S_{kV}} |\cos(\psi_{kV} + \varphi_i)|$$

If the test report of equipment contains the calculated flicker factor c for network impedance angle ψ thus only c_ψ is determined then this flicker value is used. Then it needs to be taken into account that cos part of equation is not in regarded in such case (or is equal to 1).

Harmonics currents:

Harmonics are generated mostly by equipment that contains inverters or frequency converters. Harmonic currents emit by such equipment has to be specified by manufacturer in e.g. type test report.

Generation in MV network

Allowed overall harmonic currents for single MV point of connection can be calculated by multiplying referential currents ($i_{\nu\, pr}$) given in Table 12 with short circuit power at joint point of connection.

$$I_{v\,pr} = i_{v\,pr} \cdot S_{kV}$$

In case of several equipment connected to the joint point of connection, acceptable each equipment harmonic currents are calculated by multiplying of overall harmonic currents with rate of apparent power of equipment (S_A) and overall connectable/planned power (S_{AV}) at joint point of connection

$$I_{v\,pr} = I_{v\,pr} \cdot \frac{S_A}{S_{AV}} = i_{v\,pr} \cdot S_{kV} \cdot \frac{S_A}{S_{AV}}$$

Substitution of ΣS_{nE} instead S_A can be used for equipment consisting of multiple modules of the same class. Such substitution works for wind generation as well. In case of equipment of various classes this is rough estimation though.

Table 4.1 provides overall acceptable harmonic currents that are related to short-circuit current and which are caused by equipment directly connected to the MV network. In case of harmonic orders divisible by three, the closest order from Table 4.1 is valid unless the current zero sequence of generation is closing to the network.

Table 4.1 – Acceptable reference current of harmonic sources in MV network

Harmonic order μ, ν	**Acceptable reference current of harmonics $i_{\mu,\, \nu pr}$ [A/MVA]**		
	10 kV network	22 kV network	35 kV network
5	0.115	0.058	0.033
7	0.082	0.041	0.023
11	0.052	0.026	0.015
13	0.038	0.019	0.011
17	0.022	0.011	0.006
19	0.016	0.009	0.005
23	0.012	0.006	0.003
25	0.01	0.005	0.003
>25 or even	0.06/ ν	0.03/ ν	0.017/ ν
μ < 40	0.06/ μ	0.03/ μ	0.17/ μ
μ > 40	0.16/ μ	0.09/ μ	0.046/ μ

For sum of harmonic currents generated by both various consumers and generations applies following rules:

- Rectifiers governed by network (6 or 12 pulses)
  For harmonics that are abnormal for the rectifiers (ν < 7) as well as for those that are normal for rectifiers (5th, 7th, 11th, 13th etc.), arithmetic sum can be used

$$I_\nu = \sum_{i=1}^{n} I_{\nu\, i}$$

  For abnormal higher order harmonics (ν > 7), the overall harmonic current of given order is determined as root of sum of power of two of harmonic currents of given order.

$$I_\nu = \sqrt{\sum_{i=1}^{n} I_{\nu\, \mathrm{i}}^2}$$

- Pulse modulated inverters
  For μ order that is not integer on general but for values μ > 11 contains integer values as well, the overall current is equal to the root of sum of order of two for each equipment.

$$I_\mu = \sqrt{\sum_{i=1}^{n} I_{\mu\, \mathrm{i}}^2}$$

If there are any abnormal harmonic currents of order μ < 11 then they are summed arithmetically.

More detailed evaluation is required if acceptable values of harmonic currents (or acceptable inter-harmonic currents) are violated. It must be taken into account that acceptable values of harmonic currents are chosen so they will be valid even for higher frequencies for inductive impedance of network i.e. for mostly overhead network. In networks with high penetration of cables, the network impedance is lower in many cases thus, higher harmonic currents can be acceptable. Presumption is the calculation and evaluation of harmonics voltage at joint point of connection while the real (frequency based) network impedance at given point according to [8] is taken into account. Additionally to all given requirements, voltage shall not violate 0.2 % at frequency between 2 000 Hz and 9 000 Hz.

If there are multiple points of connection, the evaluation of one point of connection has to take into account all other point of connection. MV network state is considered to be acceptable provide that harmonic currents emitted into the network at each and every point of connection not violate following value:

$$I_{\nu\, V\, pr} = i_{\nu\, pr} \cdot S_{kV} \cdot \frac{S_{AV}}{S_s}$$

where:

S_{AV} the sum of injected apparent powers of all equipment at given joint point of connection

S_s is the overall power the network is designed for

If acceptable harmonic currents are violated based on this calculation, the connection is allowed only if more detailed calculation proofs that harmonics voltage levels in network are not violated.

For network voltages different from those provided by Table 12, reference harmonic currents can be calculated from values given in that table (inverse proportion).

More detailed harmonic calculates needs to be done if acceptable values of harmonic currents are violated.

5 Case study - What is the maximum connectable power of PV generation in the point of common coupling (PCC)?

5.1 Large-scale PV power plant

Large-scale PV projects, similar to the rooftop solar, use photovoltaic cells mounted in panels. Although a rooftop network may consist of tens of panels, there may be hundreds of thousands or even millions of panels in a single big project.

Also, it deliver their energy directly to the high-voltage electricity grid and hence share certain resemblances with regulated power stations. Large PV systems also sometimes have their panels rotate throughout the day to track the sun to increase the production of electricity.

Large-scale power plant is considered around 1 to 100 MW. Large-scale power plant components have three functions: converting solar power into electricity, large-scale power point link to grid and to guarantee a consistent performance. The main elements involved are solar panels, PV inverters and transformers.

Figure 5.1: 84 MW Large-Scale Solar Power Generation Plant In Thailand [11]

5.1.1 Structure of large-scale power plant

The standard configuration of the PV-based utility-scale network includes multiple transformers, PV inverters and PV arrays. The relation between these components relies on the topology used by the PV inverter.

Usually, two topologies are often used to link PV modules to the power plant's inner grid: a central and a multi-string inverter. Just one inverter is used in the first configuration to link the PV array to the transformer. Typically, it does have a single level of conversion direct current - alternating current (DC-AC). In the other hand, the multi-string inverter has two conversion phases (DC-DC and DC-AC). Typically, the last topology interlinks a sequence of PV panels with the inner AC grid of the power plant. The central inverter is often the most commonly utilized topology in large-scale power plants. The key benefits of this topology over the other one are favorable cost, reliability, reduced maintenance and lower amount of inverters in the region.

Nevertheless, a multi-string inverter is typically used to improve the regulation of the maximum power point. This may be important when the power plant is placed on uneven terrain.

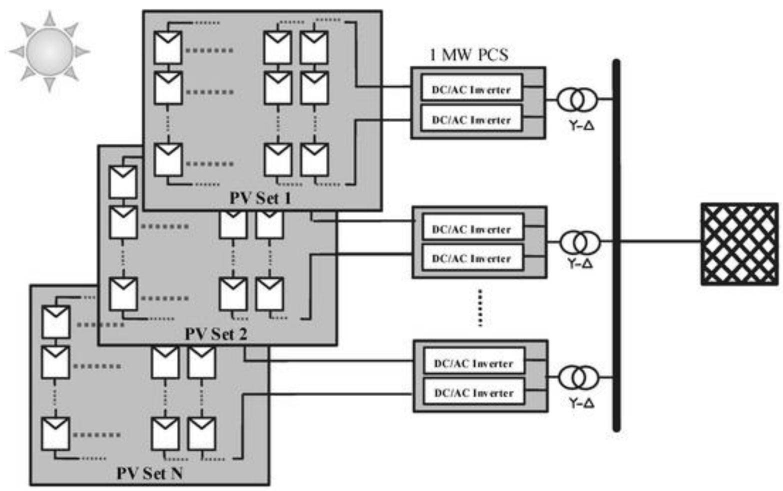

Figure 5.2: A grid-scale PV-based generation network [12]

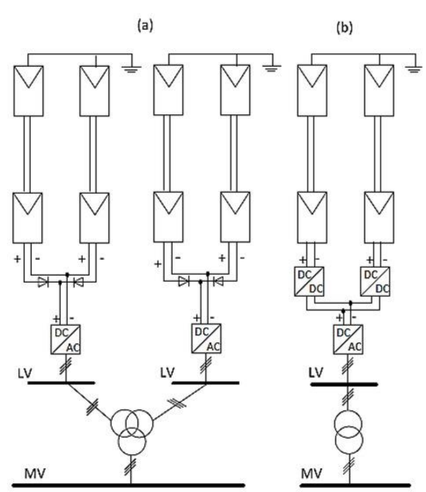

Figure 5.3: a) Central PV inverter b) Multistring PV inverter [12]

5.1.2 Solar Panels

The solar panel is based on the solar cells. Solar cells have the purpose of converting solar energy into electricity. A number of solar cells are connected in sequence, and then embodied to create the PV panel in a special frame.

Various solar cell materials influence the overall performance of the PV panels. Two layers of semi-conductor material usually made of silicon crystals are the most critical components of a PV cell. Alone, crystallized silicon really isn't an effective electricity conductor, however when impurities are purposely added, a method called doping, which is the stage for producing electric current is set.

The lower layer of the PV cell is commonly doped with boron, which combines with the silicon to stimulate a positive charge, whereas the upper layer is doped with phosphorus, which binds with the silicon to stimulate a negative charge. The layer between the related "p-type" and "n-type" semiconductors is known as the P-N junction. Electron motion generates an electrical field on this surface that enables electrons to move from the p-type layer to the n-type layer.

Once the sun light penetrates the cell, the energy of the cell kicks electrons loose in both layers. Owing to the opposite loads of the membranes, the electrons tend to migrate from the n-type layer to the p-type layer. But the electrical field at the P-N junction prevents this from happening.

Nevertheless, the existence of an external circuit creates the required route for electrons in the n-type layer to migrate to the p-type layer. The electrons passing into this circuit, usually thin wires flowing around the top of the n-type layer, provide energy to the cell owner.

Most PV systems are few inches on one side centered on single square cells. On its own, every cell produces so little power so that they are clustered with each other as panels. The panels either are utilized as individual units or are clustered into huge arrays.

There are three major types of solar cells:

- Single-crystal cells are made in long tubes and cut up into thin wafers. Although this method is power-intensive and requires additional resources, it generates the most effective cells capable of turning the most incident sunlight into electricity.
- Polycrystalline cells are composed of liquid silicon poured into ingots and then cut into slices. Though manufacturing costs are lower, cell efficiency is also lower — with highest module efficiency approximately 20 - 30%. Polycrystalline cells comprise almost half of the entire PV market.
- Thin film cells require dumping compounds (amorphous silicon, cadmium-telluride or other) onto metal surfaces in thin film, creating the entire assembly at one step rather than installing single cells. Such strategy leads to decreased efficiencies, which can lead to decreased prices. Thin film cells account for about 10 % of the global PV sector.

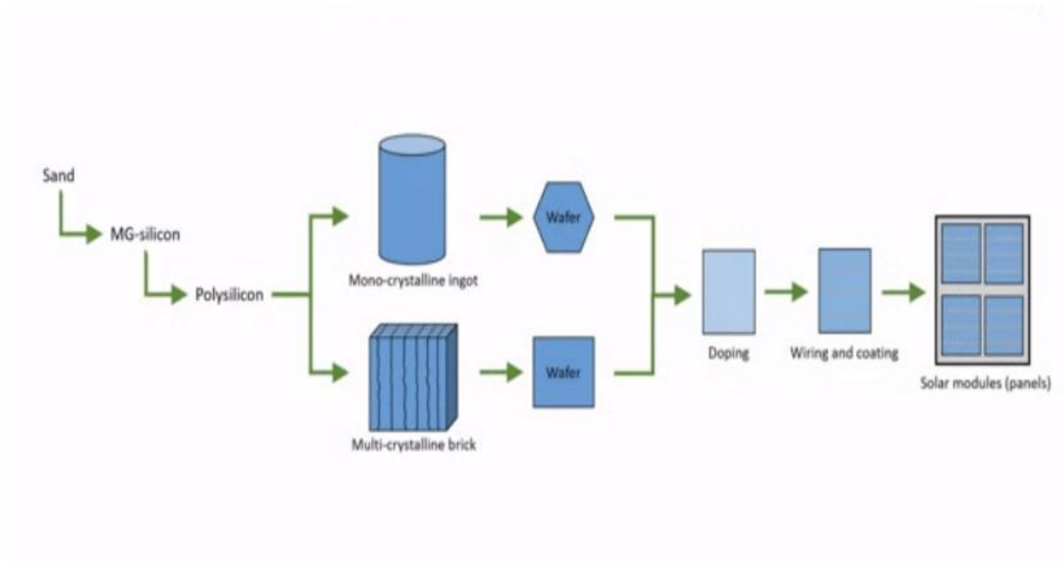

Figure 5.4: Solar panel production [13]

Traditionally, most PV panels have been used for off-grid uses, distant powered houses, mobile phone towers, traffic lights etc. In recent times, though, solar energy has seen a tremendous growth in applications where energy is fed into the power grid. These grid-connected PV technologies currently account a huge portion of the overall solar industry.

5.1.3 Maximum Power Point Tracking (MPPT)

Maximum Power Point Tracker (MPPT) is an electronic DC to DC converter that utilizes the connection between the PV panels and the battery or power grid. Simply defined, they transform the higher voltage DC output from PV panels to the lower voltage required to charge the batteries. In the PV on grid cases, MPPT maximize PV DC output power.

It runs the Photovoltaic (PV) systems in a way that lets the modules to generate most the power they are able to. It is not a mechanical monitoring device that control the modules to have it face more directly to the light. MPPT is a electronic device that adjusts the electrical operating level of the modules such that the modules can provide the highest accessible power. Extra power produced from the modules would be rendered accessible as increased battery.

The solar irradiation impacting the photovoltaic panels has a varying character relying on the latitude, the orientation of the solar field, the season and the hour of the day. In the middle of a day, a shade may be formed on a cell that could be predicted, as in the situation of a building close to the solar field or unpredictable situations as in the case of clouds.

The energy emitted by every photovoltaic cell often relies on its temperature and irradiation. On the basis of such considerations, there is a need to recognize instantly that specific point on the VxI characteristic of the PV generator in which the maximum amount of power is transferred to the grid. [14]

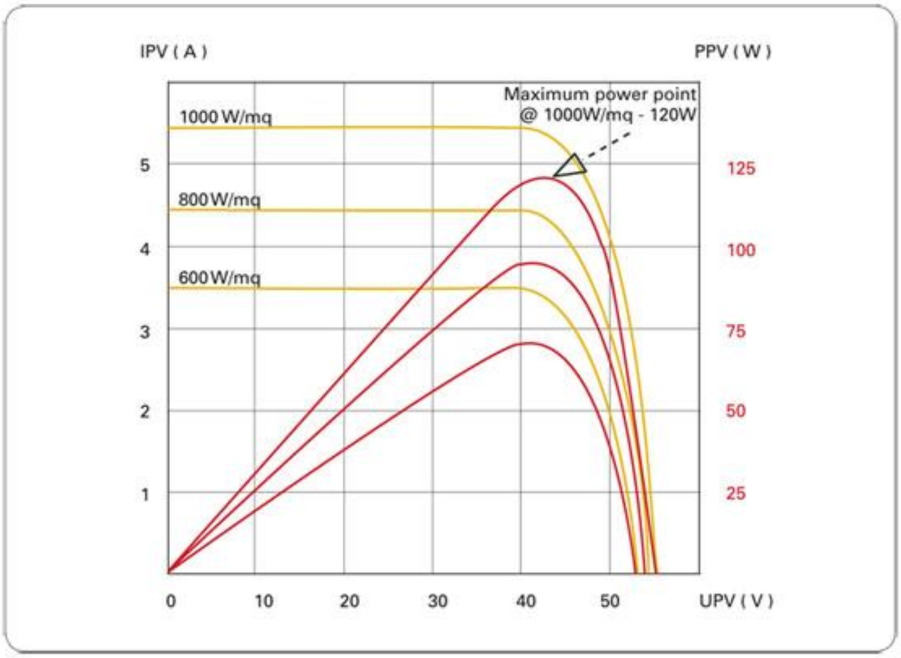

Figure 5.5: Maximum power point tracking [14]

The Maximum Power Point Tracker is needed to collect the full power available from the PV array. Many methodologies can be used to execute the MPPT.

The main ones used for MPPT are the open circuit voltage approach, constant voltage, incremental conductance method, ripple-based method and the perturb and observe technique.

These MPPT methods vary in a number of ways, such as necessary dimensions, effectiveness and cost. The perturb and observe, and incremental conductance method are the most commonly adopted.

Perturb and observe: Perturb and observe method is the most popular for its flexibility, ease of execution and strong results but this process can lead in power output oscillations.

In this method, the controller changes the voltage by a small sum from the array and checks the power if the power decreases, additional modifications in that way are attempted till the power stabilizes. It is known sometime as the hill climbing method, since it relies on the increase of the power curve against the voltage beneath maximum power point and the drop beyond that point.

The key disadvantages of the method are the existence of oscillations across the MPP in steady state operation and the possible divergence from the maximum operating point in the event of quickly shifting temperature and irradiance.

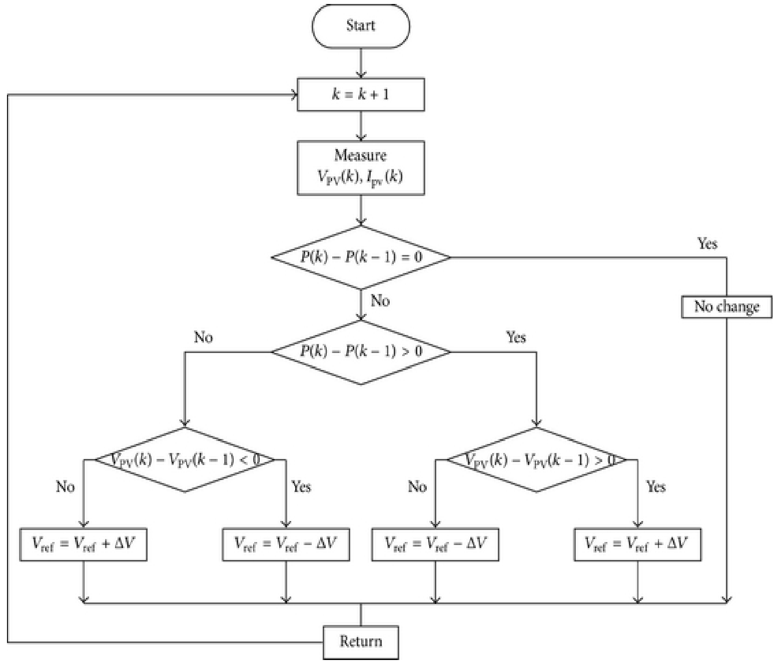

Figure 5.6: Perturb and observe [16]

Incremental conductance: This model was introduced to develop the limits of the P&O algorithm and the advantage of incremental conductance is that it determines the path in which to perturb the operational point of the array to achieve the maximum power point, will decide whether it has finally reached the maximum power point. Therefore, under increasingly evolving circumstances, rapidly increasing and declining irradiance levels can be tracked with better precision than perturb and observe.

This is centred on the assumption that the slope of the PV array is zero relative to the voltage curve of the maximum power point. The maximum power point can be determined using the relationship between dI / dV and – I / V.

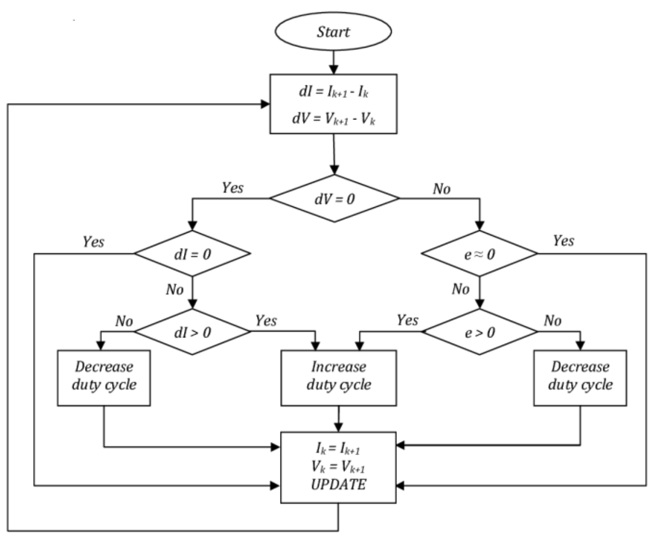

Figure 5.7: Incremental conductance [16]

5.1.4 DC-DC Converter

DC / DC converters are used in applications in which the average output voltage is needed, that might be higher or lower than the input voltage.

The overall efficiency of the PV array relies on the type of DC-DC converter in use and method used to monitor the MPPT, both factors plays a significant part in improving the output of the PV array. The DC-DC converter serves as an intermediary between the load and the PV module for the purpose of converting the maximum energy from the solar PV array to the load or DC-AC converter.

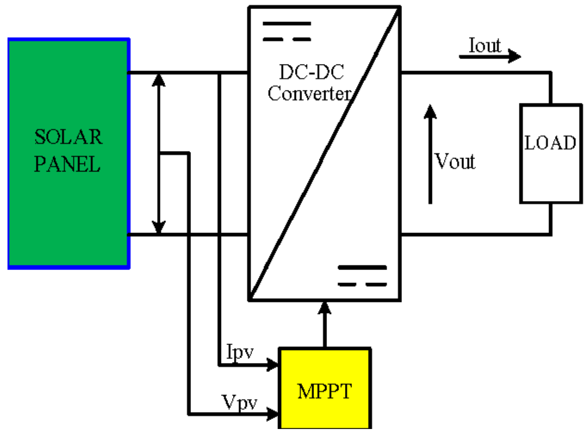

Figure 5.8: DC-DC converter scheme [15]

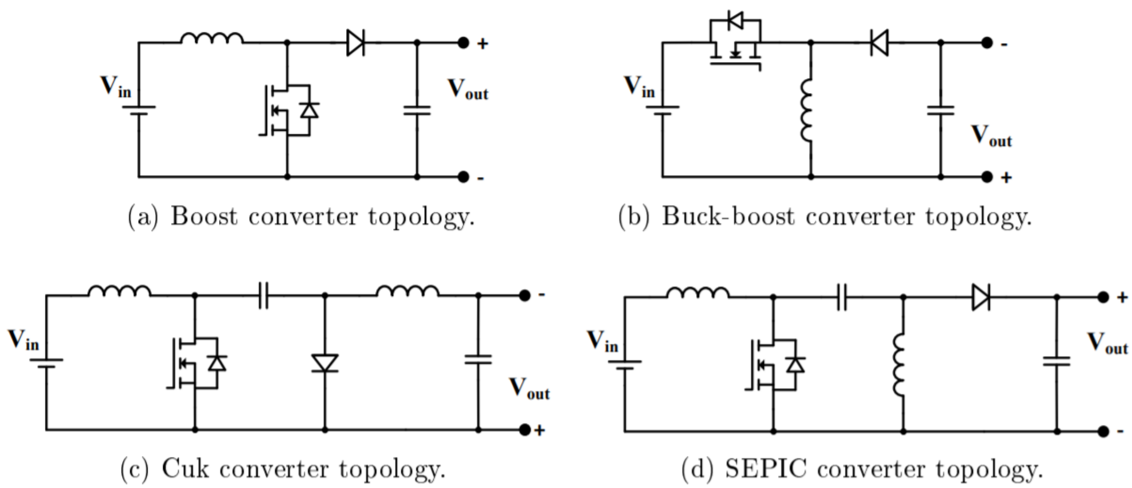

Figure 5.9: DC-DC converters topologies commonly used in PV applications [15]

- **Boost Converter:** Is able to produce output voltage that is greater than its input voltage. The switch of the boost converter is ground-referenced, hence lowering the cost upon its gate driver, as well as the input configuration leads to a continuously input current-an advantage for solar PV applications.
  One disadvantage of this converter opposed to other converter is the voltage conversion ratio, which prevents the converter from offering a decreased voltage output and therefore restricts its flexibility in application. [15]

- **Buck-Boost Converter:** The buck-boost single-switch converter tackles the boost converter restriction by undertaking step-down voltage adjustments, in addition to step-up. Main distinction would be that the input voltage is reversed in polarity with relation to the voltage of the input and the switching device is not ground-referenced, increasing gate driver costs.
  In solar PV applications, the major disadvantage of such a converter would be its intermittent input current-requiring a large decoupling capacitor to ensure optimal current flow from the PV array. [15]

- **Isolated DC-DC Converter:** There are many isolated topologies for DC-DC converters, such as the forward, fly back, push-pull, full bridge isolated, and half bridge isolated. Almost all of these typologies will provide ratios for both step-up and step-down voltage changes.
  The use of an isolation transformer and additional power tools raises these converters' costs and reduces their performance. [15]

- **Cuk Converter:** Is able of both the step-up and the step-down voltage shift ratios, while the output is reversed in polarity with relation to the input just like the buck-boost single-switch converter. The input current is constant, thus mitigating the use of a large decoupling capacitor between the PV array and the input of the Cuk converter compared to the buck boost converter.
  The Cuk converter's other benefit compared to the buck-boost converter is that the switch is ground-referenced, enabling the use of a easy gate driver. This converter has a larger number of components and includes an additional inductor and capacitor. [15]

- **SEPIC converter:** SEPIC converter has several characteristics with the Cuk converter, they have the same number of modules, ground-referenced switch, voltage gain ratio and continuous input current form. A very important technical difference between them is the output voltage polarity, the SEPIC converter has a positive output voltage of magnitude. [15]

5.1.5 DC-AC Converter

Solar PV applications may require converting the power produced from DC to AC, either for export to an AC grid or for self-consumption in off grid applications with AC loads.

The converters should adhere with network connectivity requirements when linking to the transmission network including harmonic distortion, DC injection and anti-islanding.

Inverters used in PV applications must only accept unidirectional power flow, and the kind of chosen inverter is primarily based on the power level of the network, which can be usually categorized into two: [15]

- **Distributed generation:** They are small-scale, decentralized energy networks usually used in house applications as well as small industrial. Many of these photovoltaic systems are installed on the rooftops. In addition, house facilities are small enough that no changes to the utility network will be required.
- **Utility-scale solar farms:** Typically, these systems are not meant to decrease self-consumption. The peak power output of such systems is usually expressed in megawatts, with the world's largest network capable of producing a whopping 1547 MW.

Two features that differentiate the inverter specifications for such implementations are that small-scale systems usually link to low-voltage grids and generally need single-phase output, while large-scale systems traditionally link to the grid at medium or high-voltage and need three-phase outputs.

Large-scale systems will typically use many two level three-phase voltage source converters and transformers, or larger multilevel inverters. [15]

5.1.6 Technical Flexibility in Large scale PV power plant

Flexibility in large-scale power plant can mean the ability to change the power supply or demand of the system as a whole in response to variability.

Flexibility options must be explored and designed in advance in all aspects of the energy network, from power generation to better transmission and distribution networks, storage and more flexible demand in order to handle large-scale variable Renewable Energy generation efficiently.

Today, technical flexibility in renewable sources can be explained in reactive power control. Renewable power source can operate with reactive power control for voltage control, reactive power compensation.

5.1.6.1 Control of Large-scale PV power plant

The key goals of the large-scale photovoltaic power plant (LS-PVPP) control are the control of active and reactive power to regulate voltage and to be part of the primary and secondary frequency modulation.

PV inverters were being used in small PV systems in which there was no requirement confront the ancillary services. Nevertheless, the control of active and reactive power throughout the day seems to have become a concern with the advancement of LS-PVPPs.

Generally, in small PV systems, the advancement in the control of active power was achieved by tracking the maximum power point.

Nevertheless, this method isn't any longer applicable in LS-PVPPs due to their current operating specifications. Another method for active power control is the usage of energy storage, but this creates an rise in cost installations.

Central controller is required as there is several PV generators integrated in a LS-PVPP and local control has to be conducted separately by every PV generator. On Figure 5.10, the control structure is one of the proposed ideas for LS-PVPP. As we can see that the first stage is where there requirements is shared by the transmission system operator. Next, is the power plant control and last stage is the local control of the PV generators. [16]

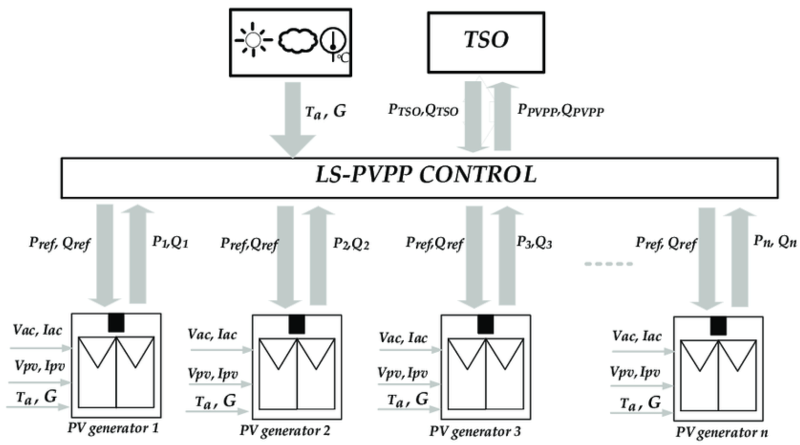

Figure 5.10: LS-PVPP proposed control structure [16]

The LS-PVPP control is concentrated on two major methods and those are to apply grid support actions and to coordinate the control of active and reactive power according to TSO requirements. The total number of active or reactive power measured by the controller is divided by the total number of PV generators in the LS-PVPP and the result is the value over which the PV generators must react. After such relations are evaluated, the PV generator performs its respective control as per the specifications of the grid code and the actions of the internal grid to maintain the ac voltage and the frequency constant. [16]

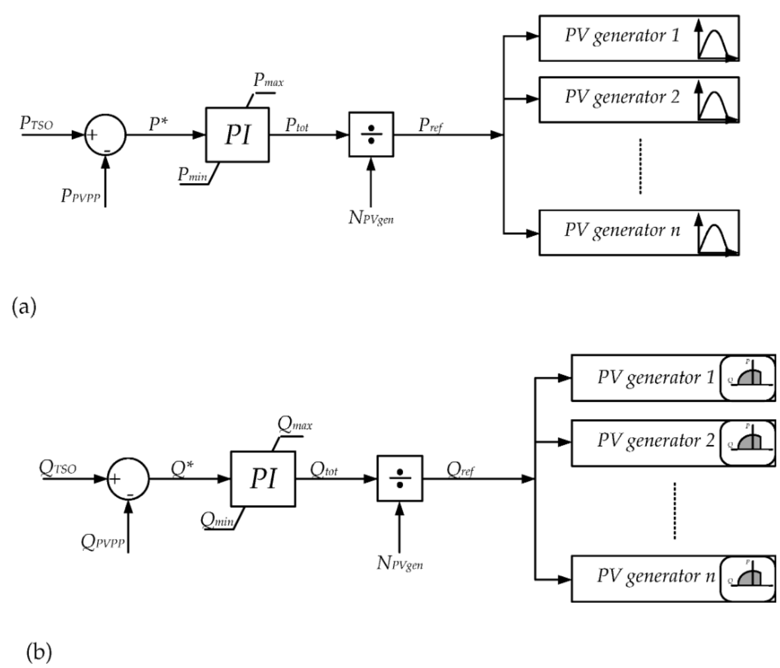

Figure 5.11: a) Active power control and b) Reactive power control [16]

The PV generator has three key methods: MPPT, inverter regulation, and active and reactive power management. The goal of the method MPPT is to look for vmpp at every solar irradiance and temperature as per the characteristics of the P-V curves. The goal of the inverter control method is to connect the PV generator to the internal grid of the PVPP. The goal of the control of active and reactive power is to produce the power needed by the power plant controller (PPC). [16]

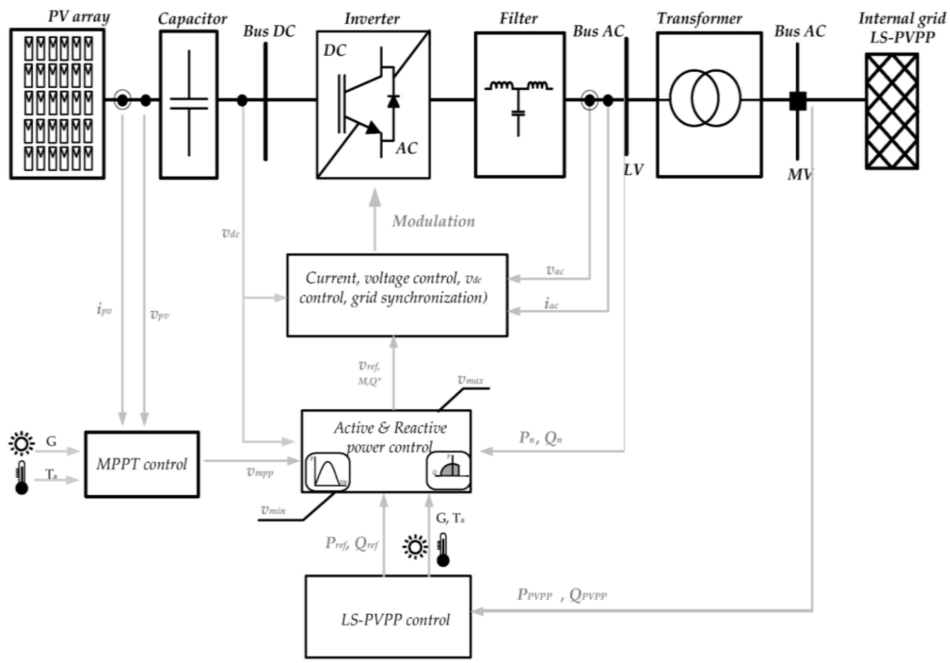

Figure 5.12: General control of a PV generator [16]

Active power control

In order to control active power, two key objectives are achieved and those are power reduction and power reserves, by using the integration of Maximum Power Point Tracker.

Power curtailment, is designed to limit the probable active power which the power plant can produce through the day, depends entirely on the grid requirements., they are also referred to as limiting control. This prerequisite helps to prevent overloading of PVPPs at peak generation times or even when the demand is lower than the available active power generated by the PVPP.

Nevertheless, Ramp rate should be taken into account due to the intermittent nature of the solar source. The goal it is to ease the shift from low to high solar irradiance and conversely otherwise the shift will affect the voltage or frequency.

The power reserve is a decrease in the power output in those few hours of the day. This decrease will vary from 10 to 20 percent of the overall possible output of the PVPP. There are two key methods used to control active power, namely incorporate energy storage and new control strategies of the PV generator. [16]

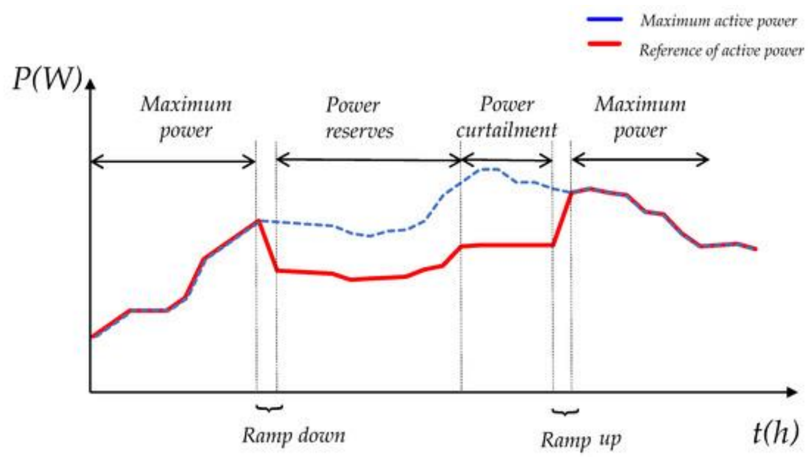

Figure 5.13: Variation of Active power with the new control functions [16]

Reactive power control

Regarding reactive power control, two factors are discussed and those are preference of active over reactive power; and vice versa i.e. preference of reactive over active power. Instant Capacity Curves are taken into account for this types by changing the DC voltage and the modulation index, based on solar irradiance and the temperature that influences the generation of active power.

Grid codes require the LS-PVPP to input or consume reactive power as per a pre-set arrangement between active and reactive power (power factor) or a particular value of reactive power.

China, Germany, South Africa, Romania and Puerto Rico introduced grid codes that asks the LS-PVPP to operate under a particular capability curve. It can be shown from figure 5.14. that Puerto Rico has the highest maximum reactive power requirement (Qmax=±0.623 p.u). Besides Puerto Rico, other countries require a maximum reactive power of around to (Qmax=±0.33 p.u). Generally, STATCOMs or capacitors are inserted at the point of main coupling (PCC) to meet with these grid codes

There are four key parameters that define these curves and those are modulation index, dc voltage, solar irradiance, and atmospheric temperature; [16]

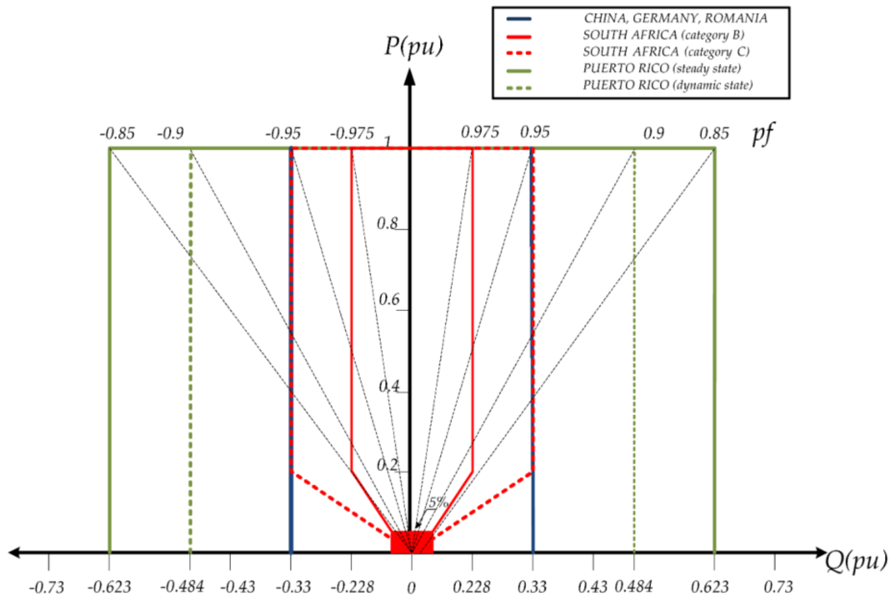

Figure 5.14: Requirements of reactive power [16]

5.2 DNCalc software

5.2.1 DNCalc application

DNCalc application is used for modeling and complex analysis of large, meshed and parallel-operated networks (LV, MV and HV). Main features of the application is covered below:

- Analysis are based on D-A-CH-CZ, EN 50160, EN 60909-0, EN 60909-1, EN 60909-3, IEC 1000-2-2, EN 61000-3-2, EN 61000-3-3, 61000-3-4, EN 61000-4-30, PNE 33 3430 standards and others.
- Tools for evaluation of load and generation connectivity from DS point of view.
- Tools for power quality analyzation.
- Three-phase or four-lines models allow evaluation of each phase.
- Analysis of power grids over map background; from GIS import information to develop and create modeled distribution systems;.
- Supports online calculations and transfer of results to other DSO's systems and applications where they are interconnected.
- Smart Grid analysis.
- Power supply reliability – it is supported by TA CR – switching elements, reconstructions, cable systems, DS status improvements, forest paths, maintenance coordination, SAIDY, SAIFI (MAIFI) reliability indicators, rate of investment return, etc.
- The area of dynamics, which is static and dynamic steadiness.

5.2.2 Methods of calculation in DNCalc software

Newton Raphson power flow is a method for Load Flow calculation in DNCalc software

Power equations for network status

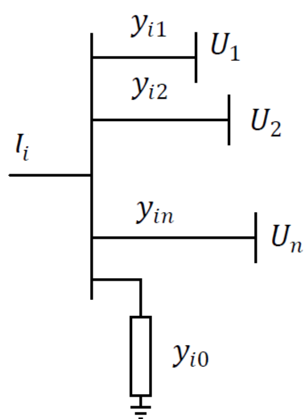

Figure 5.15: Simple node network used for determination of definition relations

If we used the 1st Kirchhoff rule for the network on Figure 1 the equation for node *i* get following form (admittances below use relative values):

$$\hat{I}_i - \hat{y}_{i0}\hat{U}_i - \hat{y}_{i1}(\hat{U}_i - \hat{U}_1) - \hat{y}_{i2}(\hat{U}_i - \hat{U}_2) - \cdots\cdots(\hat{U}_i - \hat{U}_n) = 0,$$

where $\hat{I}_i$ is current injected into the node *i* [A], $\hat{y}_{i0}$ to $\hat{y}_{in}$ are admittances of network branches and $\hat{U}_i$ to $\hat{U}_n$ are node voltages [kV]. By expression of node current *i*,

$$\hat{I}_i = (\hat{y}_{i0}+\hat{y}_{i1} + \hat{y}_{i2} + \cdots\cdots \hat{y}_{in})\hat{U}_1 - \hat{y}_{i1}\hat{U}_1 - \hat{y}_{i2}\hat{U}_2 - \cdots\cdots - \hat{y}_{in}\hat{U}_n$$

More compact form, j≠i

$$\hat{I}_i = \hat{U}_i \sum_{j=0}^{n} \hat{y}_{ij} - \sum_{j=1}^{n} \hat{y}_{ij}\hat{U}_j,$$

Equation (4.) can be expressed as

$$\hat{I}_i = \sum_{j=1}^{n} \hat{Y}_{ij}\hat{U}_{j,}$$

where $\hat{Y}_{ij}$ je is the row of admittance matrix, which provide the relation between system currents and voltages. „*j*“ in above listed equation includes *i*. Elements of admittance matrix are complex numbers with imaginary as well as real part. Complex exponential form of current of $\hat{I}_i$ is as follows

$$\hat{I}_i = \sum_{j=1}^{n} Y_{ij} U_j e^{j(\theta_{ij}+\delta_j)}$$

Where θ_{ij} is an angle of impedance [rad] and δ_j is and angle of voltage in node j [rad]. Equation for active and reactive power can be expressed as follows

$$P_i - jQ_i = \hat{U}_i^* \hat{I}_i$$

where P_i is active power [MW], Q_i is reactive power [MVAr] and $\hat{U}_i^*$ is complex phase-to-phase voltage U [kV] in node. Result of combination aforementioned equations is following expression

$$P_i - jQ_i = U_i e^{-j\delta_i} \sum_{j=1}^{n} Y_{ij} U_j e^{j(\theta_{ij}+\delta_j)},$$

Where δ_i is voltage angle in node *i* [rad]. Using Euler’s formula, which determines the relation between exponential and goniometric functions

$$e^{j\varphi} = cos\varphi + j\ sin\varphi$$

The power can be expressed through goniometric functions. By separating the real and imaginary part:

$$\hat{P}_i = \sum_{j=1}^{n} U_i U_j Y_{ij} \cos(\theta_{ij} - \delta_i + \delta_j)$$

Moreover, for reactive power that is imaginary part of equation

$$\hat{Q}_i = -\sum_{j=1}^{n} U_i U_j Y_{ij} \sin(\theta_{ij} - \delta_i + \delta_j)$$

From above mentioned can clearly be seen that mathematical solution of network status is resulting in system of non-linear equations. One of iteration methods can solve these equations.

Solving the system status using Newton-Raphson method

- Each P,Q node is described through two equation for active and reactive power;
- Each P,U node is described through equation for active power;
- Balancing node (slack) is node described by any equation
- Table below provides the summary

Table 5.1: Node classification

Node type	Defined by	Calculated elements of JFM	Number of equation for node
balancing	U, δ		0
consumption	P, Q	$\frac{\partial P}{\partial U}$ $\frac{\partial P}{\partial \delta}$ $\frac{\partial Q}{\partial U}$ $\frac{\partial Q}{\partial \delta}$	2
regulating	P, U	$\frac{\partial P}{\partial \delta}$	1
compensating	Q, U	$\frac{\partial Q}{\partial \delta}$	1

Program inputs

Calculation utilizes vectors of following parameters:

- **Vector of fixed parameters [Γ]:** Elements of such vector are constant, they represent known system value which contain parameters P_1 to P_n for PQ and PU nodes types and Q_1 to Q_n for PQ nodes type.
- **Vector of status parameters [σ]:** Elements of this vector behave as independent variables. Their values are calculated so the power balance would be achieved. Vector of status parameters includes $\widehat{U}_1$ to $\widehat{U}_n$ of PQ type nodes and δ_1 to δ_n of PQ and PU type nodes. Program uses initially guesstimated values
- **Vector of control quantities [ρ]:** Elements of this vector are constant. These are $\widehat{U}_0$ and δ_0 for reference balancing node of Uδ type (slack) and $\widehat{U}_1$ to $\widehat{U}_0$ of PU type nodes.

Program outputs

Program outputs provide calculated elements of status parameter vector. These represent variables that are searched for by iteration method and that are based on initial estimations. So these are $\boldsymbol{\widehat{U}_1}$ to $\boldsymbol{\widehat{U}_n}$ voltages for PQ type nodes and δ_1 to δ_n in case of PQ and PU type nodes. Therefore, from aforementioned definitions, other characteristic quantities (such as currents, or power flows) can be calculated at each part of the network.

Calculating method is as follows:

Vectors of constant control quantities are created according to the configuration of given system. Initially, voltages and angles ($\boldsymbol{\hat{U}_1}$ to $\boldsymbol{\hat{U}_n}$ voltages for PQ type nodes and δ_1 to δ_n angles for PQ/PU type nodes) are guesstimated based on nominal values at each node. Offset vector – the difference between defined (constant) and calculated values – is determined.

$$\begin{bmatrix} \Delta P_1 \\ \vdots \\ \Delta P_n \\ \vdots \\ \Delta Q_1 \\ \vdots \\ Q_n \end{bmatrix}$$

For n^th^ element of offset vector:

$$\varDelta P_n = P_n - P_n^{(k)}$$

$$\varDelta Q_n = Q_n - Q_n^{(k)},$$

where $\varDelta P_n$ and $\varDelta Q_n$ is offset of active and reactive power respectively for n^{th} node, P_n and Q_n are defined values (constant) of active and reactive power respectively for n^{th} node and $P_n^{(k)}$ a $Q_n^{(k)}$ are values of active and reactive power respectively, calculated in k^{th} iteration. Jacobi's functional matrix is created in next phase:

$$\begin{bmatrix} \Delta P_2^{(k)} \\ \vdots \\ \Delta P_n^{(k)} \\ \Delta Q_2^{(k)} \\ \vdots \\ \Delta Q_n^{(k)} \end{bmatrix} = \begin{bmatrix} \frac{\partial P_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial \delta_n} & \frac{\partial P_2^{(k)}}{\partial U_2} & \cdots & \frac{\partial P_2^{(k)}}{\partial U_n} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial P_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial \delta_n} & \frac{\partial P_n^{(k)}}{\partial U_2} & \cdots & \frac{\partial P_n^{(k)}}{\partial U_n} \\ \frac{\partial Q_2^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial \delta_n} & \frac{\partial Q_2^{(k)}}{\partial U_2} & \cdots & \frac{\partial Q_2^{(k)}}{\partial U_n} \\ \vdots & \ddots & \vdots & \vdots & \ddots & \vdots \\ \frac{\partial Q_n^{(k)}}{\partial \delta_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial \delta_n} & \frac{\partial Q_n^{(k)}}{\partial U_2} & \cdots & \frac{\partial Q_n^{(k)}}{\partial U_n} \end{bmatrix} \begin{bmatrix} \Delta \delta_2^{(k)} \\ \vdots \\ \Delta \delta_n^{(k)} \\ \Delta \left| U_2^{(k)} \right| \\ \vdots \\ \Delta \left| U_n^{(k)} \right| \end{bmatrix}$$

where elements of Jacobi's functional matrix represent partial derivation of all dependent variable based on all independent variables. Upped index (k) represents the sequence number of iteration. The dimension of Jacobi's functional matrix depends on number of node within the system. Jacobi's functional matrix determines the linear relation between the independent variables difference and dependent variables difference (offset). Compact representation:

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix} \begin{bmatrix} \Delta \delta \\ \Delta U \end{bmatrix}$$

Voltages and voltage angles for following iterations are determined within the next phase. This is achieved by inversion of Jacobi's functional matrix, so by calculation of matrix members through differentiation of independent variables

$$\begin{bmatrix} \Delta\delta \\ \Delta U \end{bmatrix} = \begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} \begin{bmatrix} J_1 & J_2 \\ J_3 & J_4 \end{bmatrix}^{-1}$$

Dimension of Jacobi's functional matrix is high since in practice, the calculation is made for networks consisting of high number of nodes. The matrix of independent variables correction is determined from matrix product of Jacobi's functional matrix inversion and offset. These corrections are applied on guesstimated values of independent variables. Thus, the node voltages and angles are improved by every phase. Offset matrix members ΔP and ΔQ are decreasing for each iteration, as independent variables are more accurate. The solution is converging to the result. Calculation is finished after specified number of iteration is made or when specified accuracy of node balance is achieved.

5.3 Study of connectivity

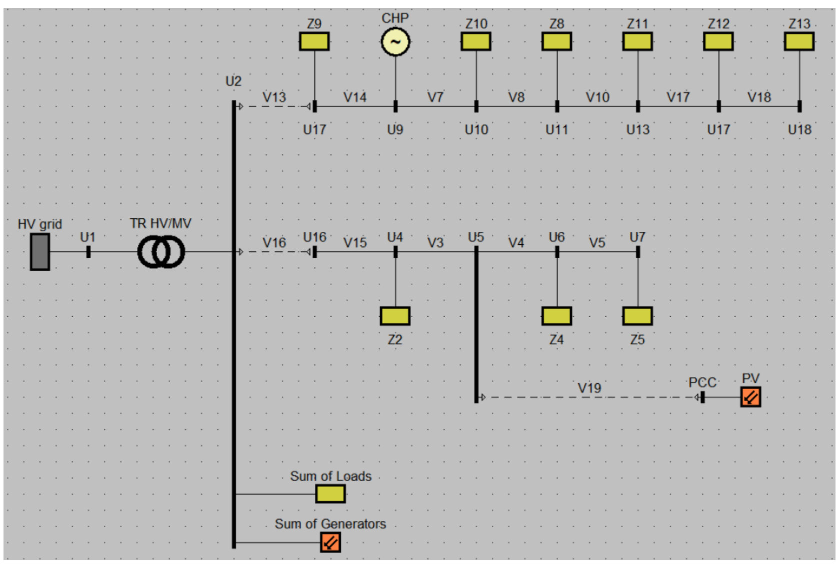

Figure 5.16: Network Topology

The main problems of the grid connected PV systems are the balance and unbalance voltage sags. Their common cause is principally the short circuits and the connection of large load. To maintain a stable connection, many control strategies are developed such as power factor control, active power and reactive power control.

The main goal of this case study is to find maximal connectable power of PV in the PCC in the MV grid, taking into account the limiting parameter for voltage change in the PCC, which is 2%. Calculations are made for two cases:

- When the power factor PF=1
- When the power PF=0,97 i.e. inductive.

The MV network has two feeders that consists of loads and the rest of the feeders are modelled by sum of loads and sum of generation.

Supply node with short circuit power ratio has nominal voltage 110 kV and operated voltage 115kV is modelled as ideal voltage source with serial impedance with real and imaginary part, as we can see that the input parameter for R/X is less than 1 and close to 0. Short circuit power ratio proves to us how strong the power grid is.

Table 5.2: Supply node

Name	Un [kV]	Uop [kV]	Isc [kA]	Ssc [MVA]	R/X	R0/R1
HV grid	110	115	10.4973	2000	0.1	1

HV/MV transformer with tap changer supplies the MV grid. Transformer model is based on ČSN 60909-0.

Table 5.3: Transformer

Name	Un1 [kV]	Un2 [kV]	St [MVA]	Pk [kW]	uk [%]	I0 [%]	P0 [kW]	Primary/ Secondary	Number of taps	Step [%]	In1 [A]	In2 [A]
TR HV/MV	110	23	25	140	11	0.34	27	YN	8	2	131	628

The following tables consists of the input parameter for the overhead line. Overhead lines and cables are modelled by PI section model.

Table 5.4: Overhead line parameters

Name	Type	Cross-section [mm²]	Un [kV]	R [Ω/km]	X [Ω/km]	B [µS/km]	Length [km]	Imax [A]
V10	70/11-1AlFe6	70	22	0.431	0.383	1.431	5	225
V13	240AXEKCY	240	22	0.128	0.198	94	1	506
V14	110/22AlFe6	110	22	0.259	0.368	1.46	2	318
V15	70/11-1AlFe6	70	22	0.431	0.383	1.431	2	225
V16	120AXEKCY	120	22	0.253	0.219	75	0.5	307
V17	50AlFe6	50	22	0.615	0.396	1.407	5	177
V18	35AlFe6	35	22	0.778	0.389	1.339	7	150
V19	120AXEKCY	120	22	0.253	0.219	75	5	307
V3	70/11-1AlFe6	70	22	0.431	0.383	1.431	2	225
V4	70/11-1AlFe6	70	22	0.431	0.383	1.431	2	225
V5	50AlFe6	50	22	0.615	0.396	1.407	1	177
V7	110/22AlFe6	110	22	0.259	0.368	1.46	2	318
V8	70/11-1AlFe6	70	22	0.431	0.383	1.431	5	225

Power grid is assumed as symmetrical i.e. voltages at each phase are the same, load and generation is symmetrical. Loads are connected directly into the nodes along to the power lines and the load profile of each load is described in the below tables. Loads are modelled as constant real and reactive power consumption, voltage dependency is neglected.

Table 5.5: Load

Name	Un [kV]	I [A]	cos φ	P [kW]	Q [kVAr]	S [kVA]
Sum of Loads	22	131.22	0.970	4850	1216.5	5000
Z10	22	10.52	0.998	400	25	400.78
Z11	22	9.16	0.903	315	150	348.89
Z12	22	13.38	0.981	500	100	509.9
Z13	22	6.58	0.997	250	20	250.8
Z2	22	8.08	0.974	300	70	308.06
Z4	22	3.37	0.972	125	30	128.55
Z5	22	14.13	0.928	500	200	538.52
Z8	22	5.35	0.981	200	40	203.96
Z9	22	19.86	0.991	750	100	756.64

Table 5.6: Synchronous machine

Name	Un [kV]	Sn [kVA]	cos φn	Uop [kV]	Poper [kW]	cos φoper
CHP	22	500	1	22	500	1

Table 5.7: Photovoltaic plant

Name	Un [kV]	Sn [kVA]	Pn [kW]	cos φn	Poper [kW]	Qoper [kVAr]	cos φoper
PV	22	22	Target of evaluation	Target of evaluation	Target of evaluation	Target of evaluation	Target of evaluation
Sum of Generators	22	22	3000	3000	1	2000	0

5.3.1 Steady state, without PV

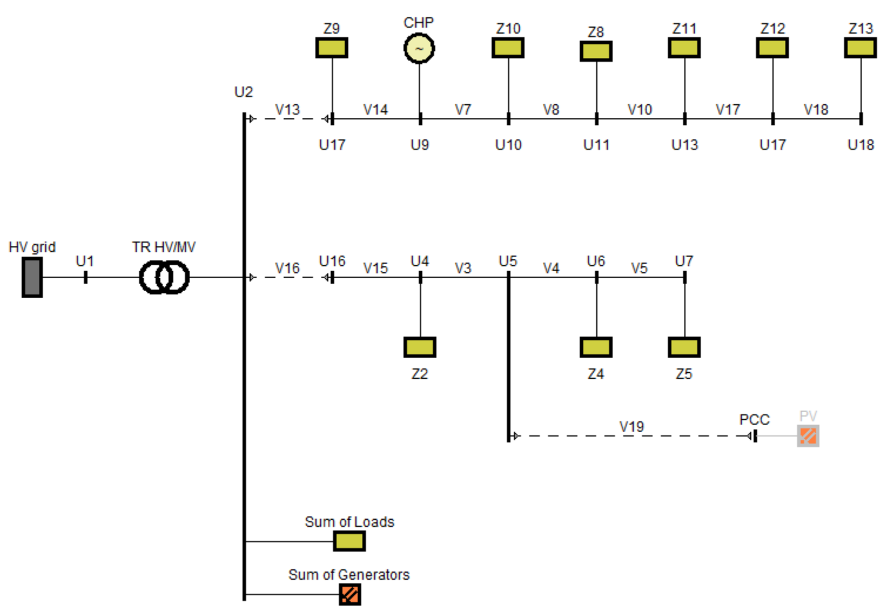

Figure 5.17: Network Topology – Steady state, without PV

In this case, the PV was disconnected, to check the voltage response without PV in the steady state mode. Below tables is the calculated load flow.

LOAD FLOW RESULTS

Table 5.8: Steady state - Conditions at node

	Ua [kV]	αa [deg]	Ub [kV]	αb [deg]	Uc [kV]	αc [deg]	dUna [%]	dUnb [%]	dUnc [%]	Zk [Ω]	α [deg]	Sk [MVA]
U2	22,882	28,43	22,882	-91,57	22,882	148,43	-4,008	-4,008	-4,008	2,494	86,896	194,063
U16	22,876	28,421	22,876	-91,579	22,876	148,421	-3,983	-3,983	-3,983	2,75	82,23	176,022
U1	114,868	29,855	114,868	-90,145	114,868	149,855	-4,426	-4,426	-4,426	6,05	84,289	1999,87
U17	22,867	28,394	22,867	-91,606	22,867	148,394	-3,942	-3,942	-3,942	2,826	81,43	171,289
U9	22,829	28,317	22,829	-91,683	22,829	148,317	-3,77	-3,77	-3,77	4,221	72,281	114,658
U10	22,78	28,199	22,78	-91,801	22,78	148,199	-3,546	-3,546	-3,546	5,671	67,736	85,351
U11	22,632	27,999	22,632	-92,001	22,632	147,999	-2,874	-2,874	-2,874	10,208	55,768	47,412
U13	22,507	27,831	22,507	-92,169	22,507	147,831	-2,303	-2,303	-2,303	14,916	51,245	32,448
U17	22,392	27,7	22,392	-92,3	22,392	147,7	-1,783	-1,783	-1,783	20,79	45,907	23,281
U18	22,327	27,631	22,327	-92,369	22,327	147,631	-1,488	-1,488	-1,488	30,552	39,585	15,842
U4	22,838	28,352	22,838	-91,648	22,838	148,352	-3,808	-3,808	-3,808	4,395	65,625	110,13
U5	22,813	28,303	22,813	-91,697	22,813	148,303	-3,696	-3,696	-3,696	6,206	58,318	77,988
U6	22,782	28,272	22,782	-91,728	22,782	148,272	-3,553	-3,553	-3,553	8,066	54,393	60,005
U7	22,765	28,263	22,765	-91,737	22,765	148,263	-3,476	-3,476	-3,476	9,21	51,598	52,55
PCC	22,818	28,289	22,818	-91,711	22,818	148,289	-3,717	-3,717	-3,717	9,476	53,521	51,079

	Node	Ia [A]	αa [deg]	Ib [A]	αb [deg]	Ic [A]	αc [deg]	P [kW]	Q [kVAr]	S [kVA]
V16	**U2**	23,519	-6,674	23,519	-126,674	23,519	113,326	928,401	82,923	932,097
	U16	23,568	172,127	23,568	52,127	23,568	-67,873	-928,191	-102,371	933,819
HV grid	**U1**	30,519	161,354	30,519	41,354	30,519	-78,646	-5758,29	-1926,76	6072,098
Sum of Loads	**U2**	126,159	-15,639	126,159	-135,639	126,159	104,361	4850	1215,52	4999,999
Sum of Generators	**U2**	50,464	178,43	50,464	58,43	50,464	-61,57	-2000	0	2000
V13	**U2**	50,046	-12,898	50,046	-132,898	50,046	107,102	1944,811	389,605	1983,452
	U17	50,304	165,716	50,304	45,716	50,304	-74,284	-1943,85	-437,295	1992,425
Z9	**U17**	19,104	-9,212	19,104	-129,212	19,104	110,788	750	100,158	756,658
V14	**U17**	31,321	-17,375	31,321	-137,375	31,321	102,625	1193,845	337,137	1240,535
	U9	31,331	162,557	31,331	42,557	31,331	-77,443	-1192,32	-336,495	1238,893
V7	**U9**	43,636	-12,929	43,636	-132,929	43,636	107,071	1692,32	336,495	1725,449
	U10	43,644	167,022	43,644	47,022	43,644	-72,978	-1689,36	-333,808	1722,024
Z10	**U10**	10,158	-5,377	10,158	-125,377	10,158	114,623	400	25	400,78
V8	**U10**	33,602	-15,27	33,602	-135,27	33,602	104,73	1289,36	308,808	1325,825
	U11	33,624	164,574	33,624	44,574	33,624	-75,426	-1282,06	-306,006	1318,069
Z8	**U11**	5,203	-13,306	5,203	-133,306	5,203	106,694	200	39,98	203,957
V10	**U11**	28,425	-15,813	28,425	-135,813	28,425	104,187	1082,056	266,026	1114,278
	U13	28,448	164,004	28,448	44,004	28,448	-75,996	-1076,83	-265,025	1108,962
Z11	**U13**	8,95	-27,628	8,95	-147,628	8,95	92,372	315	149,971	348,879
V17	**U13**	19,764	-10,757	19,764	-130,757	19,764	109,243	761,828	115,054	770,467
	U17	19,778	168,981	19,778	48,981	19,778	-71,019	-758,222	-116,277	767,086
Z12	**U17**	13,147	-13,604	13,147	-133,604	13,147	106,396	500	99,951	509,892
V18	**U17**	6,671	-5,918	6,671	-125,918	6,671	114,082	258,222	16,327	258,738
	U18	6,68	173,046	6,68	53,046	6,68	-66,954	-257,494	-20,649	258,321
Z13	**U18**	6,68	-6,954	6,68	-126,954	6,68	113,046	257,494	20,649	258,321
CHP	**U9**	12,645	178,317	12,645	58,317	12,645	-61,683	-500	0	500
V15	**U16**	23,568	-7,873	23,568	-127,873	23,568	112,127	928,191	102,371	933,819
	U4	23,572	172,036	23,572	52,036	23,572	-67,964	-926,755	-102,589	932,415
Z2	**U4**	7,788	-14,792	7,788	-134,792	7,788	105,208	300	70,057	308,071
V3	**U4**	15,866	-4,619	15,866	-124,619	15,866	115,381	626,755	32,532	627,598
	U5	15,868	175,245	15,868	55,245	15,868	-64,755	-626,103	-33,445	626,996
V4	**U5**	16,868	-21,758	16,868	-141,758	16,868	98,242	626,08	228,627	666,519
	U6	16,881	158,122	16,881	38,122	16,881	-81,878	-625,344	-229,46	666,113
Z4	**U6**	3,258	-15,224	3,258	-135,224	3,258	104,776	125	30	128,549
V5	**U6**	13,651	-23,463	13,651	-143,463	13,651	96,537	500,344	199,461	538,636
	U7	13,657	156,465	13,657	36,465	13,657	-83,535	-500	-199,969	538,505
Z5	**U7**	13,657	-23,535	13,657	-143,535	13,657	96,465	500	199,969	538,505
V19	**U5**	4,94	88,296	4,94	-31,704	4,94	-151,704	0,023	-195,183	195,183
	PCC	0	116,565	0	135	0	75,964	0	0	0
TR HV/MV	**U1**	30,519	-18,646	30,519	-138,646	30,519	101,354	5758,294	1926,764	6072,098
	U2	150,558	161,997	150,558	41,997	150,558	-78,003	-5723,21	-1688,05	5966,965

Table 5.9: Steady state - Conditions in node

In order to have the desired voltage at the secondary of HV/MV transformer which is 22,8 – 23. Tap changer at the HV/MV transformer was used; the TAP was set as 2.

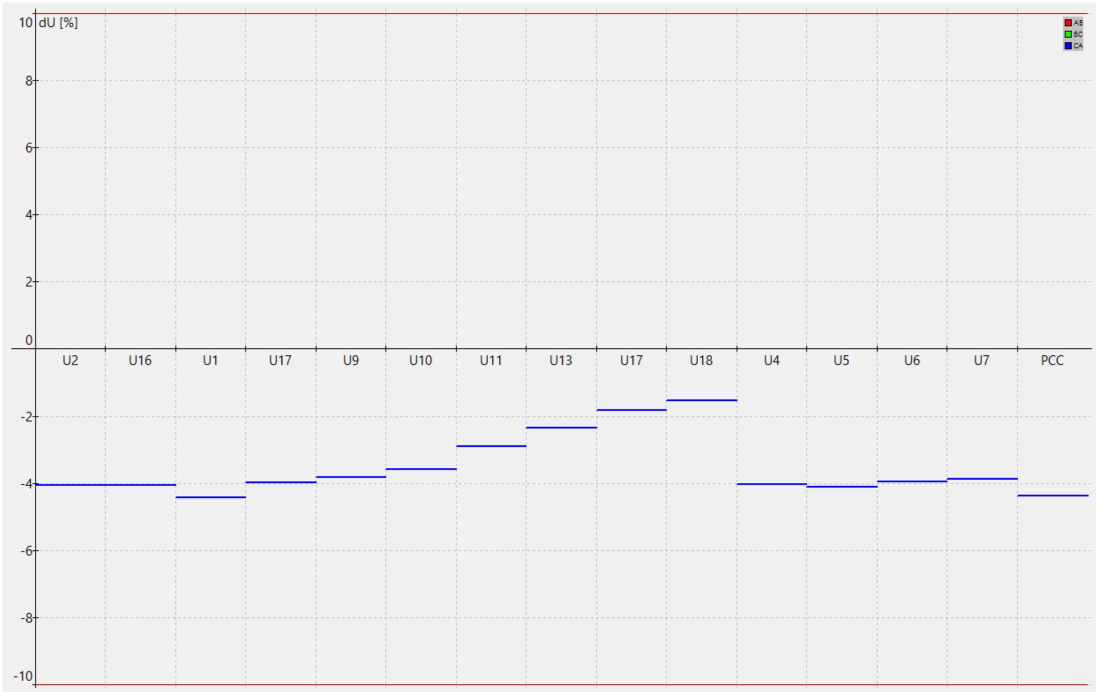

Figure 5.18: Voltage difference along the nodes without PV

5.3.2 Maximal connectable power of PV=3120 kW, power factor = 1 (without Q regulation)

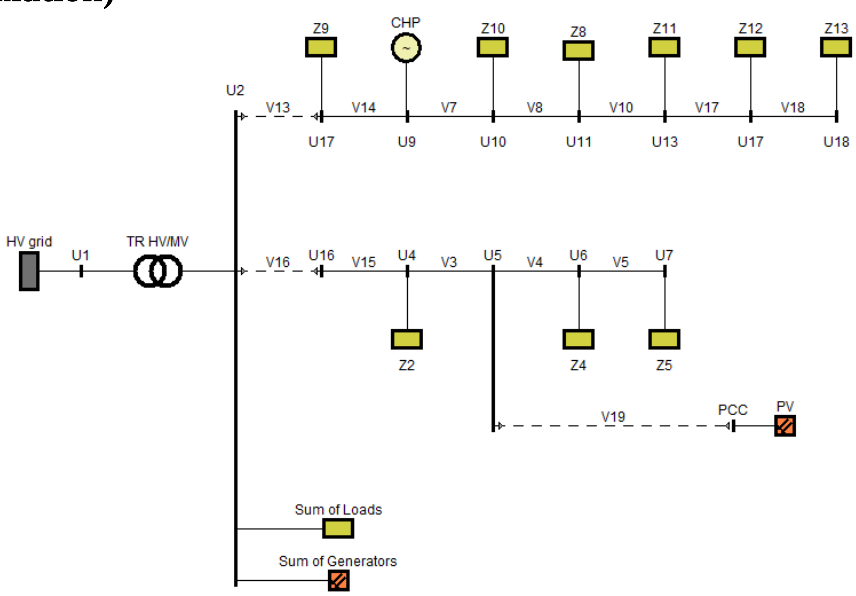

Figure 5.19: Network Topology – without Q regulation

CONNECTIVITY CALCULATION (LIMIT IS 2%)

Table 5.10: Without Q regulation - dU margin

	dUa before[%]	dUa after[%]	Δ dUa	dUb before[%]	dUb after[%]	Δ dUb	dUc before[%]	dUc after[%]	Δ dUc
U2	-4,008	-4,114	0,105	-4,008	-4,114	0,105	-4,008	-4,114	0,105
U16	-3,983	-4,165	0,182	-3,983	-4,165	0,182	-3,983	-4,165	0,182
U1	-4,426	-4,445	0,019	-4,426	-4,445	0,019	-4,426	-4,445	0,019
U17	-3,942	-4,048	0,105	-3,942	-4,048	0,105	-3,942	-4,048	0,105
U9	-3,77	-3,876	0,106	-3,77	-3,876	0,106	-3,77	-3,876	0,106
U10	-3,546	-3,652	0,106	-3,546	-3,652	0,106	-3,546	-3,652	0,106
U11	-2,874	-2,98	0,106	-2,874	-2,98	0,106	-2,874	-2,98	0,106
U13	-2,303	-2,41	0,107	-2,303	-2,41	0,107	-2,303	-2,41	0,107
U17	-1,783	-1,89	0,107	-1,783	-1,89	0,107	-1,783	-1,89	0,107
U18	-1,488	-1,594	0,106	-1,488	-1,594	0,106	-1,488	-1,594	0,106
U4	-3,808	-4,514	0,706	-3,808	-4,514	0,706	-3,808	-4,514	0,706
U5	-3,696	-4,926	1,23	-3,696	-4,926	1,23	-3,696	-4,926	1,23
U6	-3,553	-4,785	1,232	-3,553	-4,785	1,232	-3,553	-4,785	1,232
U7	-3,476	-4,709	1,233	-3,476	-4,709	1,233	-3,476	-4,709	1,233
PCC	-3,717	-5,717	**2**	-3,717	-5,717	**2**	-3,717	-5,717	**2**

In this case, we have connected the PV with installed power 3120 kW with power factor 1 and without Q regulation. We have found that maximal connectable power of PV with no reactive power regulation has voltage change 2% that did not exceed the standard limits (2%). Impact of other power sources was neglected in this calculation.

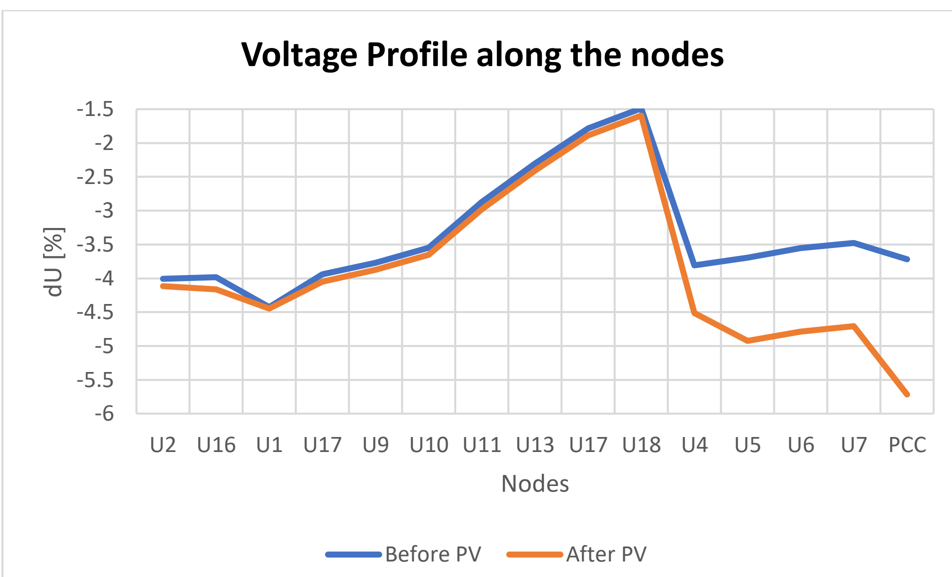

Figure 5.20: Voltage profile along the nodes

LOAD FLOW CALCULATION

Table 5.11: Without Q regulation - Conditions in branches

	Node	Ia [A]	αa [deg]	Ib [A]	αb [deg]	Ic [A]	αc [deg]	P [kW]	Q [kVAr]	S [kVA]
V16	U2	54,329	-177,764	54,329	62,236	54,329	-57,764	-2152,51	110,836	2155,364
	U16	54,356	2,758	54,356	-117,242	54,356	122,758	2153,633	-129,549	2157,526
HV grid	U1	16,304	145,381	16,304	25,381	16,304	-94,619	-2672,1	-1840,18	3244,44
Sum of Loads	U2	126,032	-14,781	126,032	-134,781	126,032	105,219	4850	1215,52	4999,999
Sum of Generators	U2	50,413	179,289	50,413	59,289	50,413	-60,711	-2000	0	2000
V13	U2	50,008	-12,033	50,008	-132,033	50,008	107,967	1945,328	389,485	1983,935
	U17	50,266	166,578	50,266	46,578	50,266	-73,422	-1944,36	-437,277	1992,927
Z9	U17	19,085	-8,354	19,085	-128,354	19,085	111,646	750	100,158	756,658
V14	U17	31,302	-16,51	31,302	-136,51	31,302	103,49	1194,363	337,119	1241,028
	U9	31,312	163,422	31,312	43,422	31,312	-76,578	-1192,84	-336,482	1239,39
V7	U9	43,605	-12,067	43,605	-132,067	43,605	107,933	1692,84	336,482	1725,957
	U10	43,612	167,884	43,612	47,884	43,612	-72,116	-1689,89	-333,805	1722,537
Z10	U10	10,147	-4,519	10,147	-124,519	10,147	115,481	400	25	400,78
V8	U10	33,581	-14,406	33,581	-134,406	33,581	105,594	1289,885	308,805	1326,334
	U11	33,603	165,438	33,603	45,438	33,603	-74,562	-1282,59	-306,019	1318,591
Z8	U11	5,198	-12,447	5,198	-132,447	5,198	107,553	200	39,98	203,957
V10	U11	28,409	-14,949	28,409	-134,949	28,409	105,051	1082,589	266,038	1114,799
	U13	28,432	164,869	28,432	44,869	28,432	-75,131	-1077,37	-265,05	1109,492
Z11	U13	8,94	-26,769	8,94	-146,769	8,94	93,231	315	149,971	348,879
V17	U13	19,758	-9,894	19,758	-129,894	19,758	110,106	762,367	115,079	771,004
	U17	19,771	169,844	19,771	49,844	19,771	-70,156	-758,764	-116,312	767,627
Z12	U17	13,133	-12,745	13,133	-132,745	13,133	107,255	500	99,951	509,892
V18	U17	6,678	-5,058	6,678	-125,058	6,678	114,942	258,764	16,361	259,281
	U18	6,687	173,906	6,687	53,906	6,687	-66,094	-258,034	-20,692	258,863
Z13	U18	6,687	-6,094	6,687	-126,094	6,687	113,906	258,034	20,692	258,863
CHP	U9	12,632	179,175	12,632	59,175	12,632	-60,825	-500	0	500
V15	U16	54,356	-177,242	54,356	62,758	54,356	-57,242	-2153,63	129,549	2157,526
	U4	54,359	2,798	54,359	-117,202	54,359	122,798	2161,274	-124,267	2164,843
Z2	U4	7,736	-13,637	7,736	-133,637	7,736	106,363	300	70,057	308,071
V3	U4	61,817	-179,231	61,817	60,769	61,817	-59,231	-2461,27	54,21	2461,871
	U5	61,818	0,805	61,818	-119,195	61,818	120,805	2471,156	-46,947	2471,602
V4	U5	16,669	-20,339	16,669	-140,339	16,669	99,661	626,055	228,554	666,47
	U6	16,682	159,538	16,682	39,538	16,682	-80,462	-625,336	-229,438	666,098
Z4	U6	3,219	-13,81	3,219	-133,81	3,219	106,19	125	30	128,549
V5	U6	13,49	-22,047	13,49	-142,047	13,49	97,953	500,336	199,438	538,62
	U7	13,497	157,879	13,497	37,879	13,497	-82,121	-500	-199,969	538,505
Z5	U7	13,497	-22,121	13,497	-142,121	13,497	97,879	500	199,969	538,505
V19	U5	77,598	176,361	77,598	56,361	77,598	-63,639	-3097,21	-181,606	3102,531
	PCC	77,451	0,067	77,451	-119,933	77,451	120,067	3120	0	3120
PV	PCC	77,451	-179,933	77,451	60,067	77,451	-59,933	-3120	0	3120
TR HV/MV	U1	16,304	-34,619	16,304	-154,619	16,304	85,381	2672,103	1840,178	3244,44
	U2	79,424	146,295	79,424	26,295	79,424	-93,705	-2642,82	-1715,84	3150,965

Table 5.12: Without Q regulation - Conditions at nodes

	Ua [kV]	αa [deg]	Ub [kV]	αb [deg]	Uc [kV]	αc [deg]	dUna [%]	dUnb [%]	dUnc [%]	Zk [Ω]	α [deg]	Sk [MVA]
U2	22,905	29,289	22,905	-90,711	22,905	149,289	-4,114	-4,114	-4,114	2,494	86,896	194,063
U16	22,916	29,316	22,916	-90,684	22,916	149,316	-4,165	-4,165	-4,165	2,75	82,23	176,022
U1	114,89	29,935	114,89	-90,065	114,89	149,935	-4,445	-4,445	-4,445	6,05	84,289	1999,87
U17	22,891	29,252	22,891	-90,748	22,891	149,252	-4,048	-4,048	-4,048	2,826	81,43	171,289
U9	22,853	29,175	22,853	-90,825	22,853	149,175	-3,876	-3,876	-3,876	4,221	72,281	114,658
U10	22,803	29,057	22,803	-90,943	22,803	149,057	-3,652	-3,652	-3,652	5,671	67,736	85,351
U11	22,656	28,858	22,656	-91,142	22,656	148,858	-2,98	-2,98	-2,98	10,208	55,768	47,412
U13	22,53	28,69	22,53	-91,31	22,53	148,69	-2,41	-2,41	-2,41	14,916	51,245	32,448
U17	22,416	28,559	22,416	-91,441	22,416	148,559	-1,89	-1,89	-1,89	20,79	45,907	23,281
U18	22,351	28,49	22,351	-91,51	22,351	148,49	-1,594	-1,594	-1,594	30,552	39,585	15,842
U4	22,993	29,508	22,993	-90,492	22,993	149,508	-4,514	-4,514	-4,514	4,395	65,625	110,13
U5	23,084	29,716	23,084	-90,284	23,084	149,716	-4,926	-4,926	-4,926	6,206	58,318	77,988
U6	23,053	29,686	23,053	-90,314	23,053	149,686	-4,785	-4,785	-4,785	8,066	54,393	60,005
U7	23,036	29,678	23,036	-90,322	23,036	149,678	-4,709	-4,709	-4,709	9,21	51,598	52,55
PCC	23,258	30,067	23,258	-89,933	23,258	150,067	-5,717	-5,717	-5,717	9,476	53,521	51,079

5.3.3 Maximal connectable power of PV=5580 kW, power factor=0,97 absorption (Q regulation)

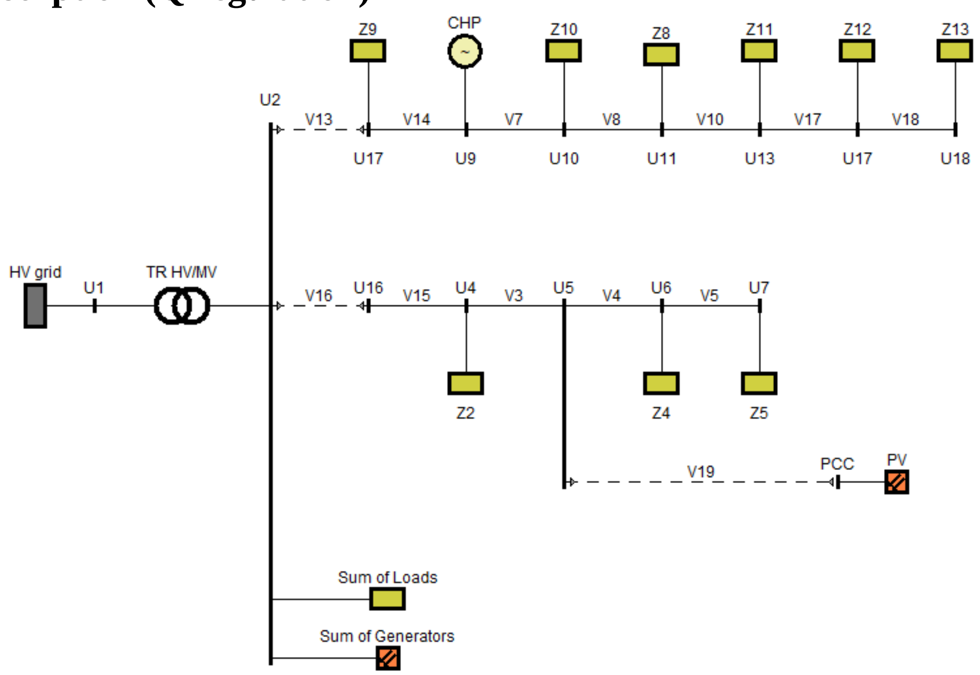

Figure 5.21: Network topology - with Q regulation

In this case, reactive power absorbtion is set. PV absorbes reactive power with PF=0,97. And because It compensate voltage change, the installed power is increased to 5580 kW.

CONNECTIVITY CALCULATION (LIMIT IS 2%)

Table 5.13: With Q regulation - dU margin

	dUa before[%]	dUa after[%]	Δ dUa	dUb before[%]	dUb after[%]	Δ dUb	dUc before[%]	dUc after[%]	Δ dUc
U2	-4,008	-3,409	0,599	-4,008	-3,409	0,599	-4,008	-3,409	0,599
U16	-3,983	-3,487	0,496	-3,983	-3,487	0,496	-3,983	-3,487	0,496
U1	-4,426	-4,384	0,042	-4,426	-4,384	0,042	-4,426	-4,384	0,042
U17	-3,942	-3,343	0,6	-3,942	-3,343	0,6	-3,942	-3,343	0,6
U9	-3,77	-3,17	0,6	-3,77	-3,17	0,6	-3,77	-3,17	0,6
U10	-3,546	-2,945	0,601	-3,546	-2,945	0,601	-3,546	-2,945	0,601
U11	-2,874	-2,27	0,604	-2,874	-2,27	0,604	-2,874	-2,27	0,604
U13	-2,303	-1,697	0,606	-2,303	-1,697	0,606	-2,303	-1,697	0,606
U17	-1,783	-1,176	0,607	-1,783	-1,176	0,607	-1,783	-1,176	0,607
U18	-1,488	-0,882	0,605	-1,488	-0,882	0,605	-1,488	-0,882	0,605
U4	-3,808	-4,016	0,207	-3,808	-4,016	0,207	-3,808	-4,016	0,207
U5	-3,696	-4,616	0,92	-3,696	-4,616	0,92	-3,696	-4,616	0,92
U6	-3,553	-4,474	0,921	-3,553	-4,474	0,921	-3,553	-4,474	0,921
U7	-3,476	-4,398	0,922	-3,476	-4,398	0,922	-3,476	-4,398	0,922
PCC	-3,717	-5,707	**1,99**	-3,717	-5,707	**1,99**	-3,717	-5,707	**1,99**

As we can see that the voltage change is 1,99 % and did not exceed the standard limits (2%). Impact of other power sources was neglected in this calculation.

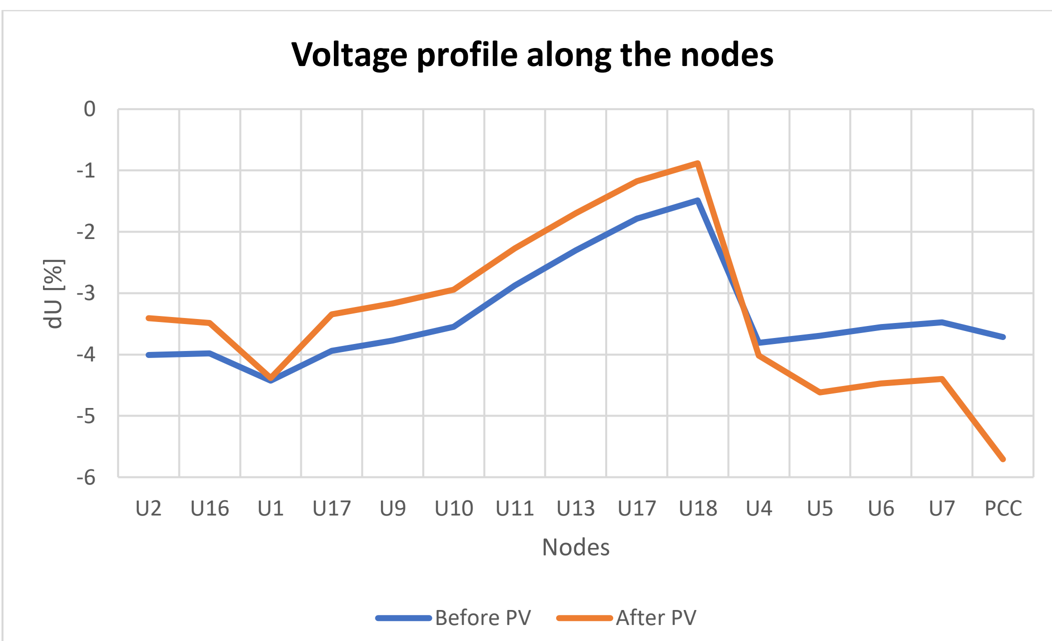

Figure 5.22: Voltage profile along the nodes

Table 5.14: With Q regulation - Conditions in branches

	Node	Ia [A]	αa [deg]	Ib [A]	αb [deg]	Ic [A]	αc [deg]	P [kW]	Q [kVAr]	S [kVA]
V16	U2	121,138	-160,24	121,138	79,76	121,138	-40,24	-4491,21	1616,676	4773,322
	U16	121,305	19,979	121,305	-100,021	121,305	139,979	4496,786	-1631,27	4783,527
HV grid	U1	16,924	95,626	16,924	-24,374	16,924	-144,374	-329,936	-3349,55	3365,76
Sum of Loads	U2	126,89	-14,107	126,89	-134,107	126,89	105,893	4850	1215,52	4999,999
Sum of Generators	U2	50,756	179,963	50,756	59,963	50,756	-60,037	-2000	0	2000
V13	U2	50,267	-11,402	50,267	-131,402	50,267	108,598	1941,886	390,29	1980,719
	U17	50,524	167,226	50,524	47,226	50,524	-72,774	-1940,91	-437,401	1989,586
Z9	U17	19,215	-7,681	19,215	-127,681	19,215	112,319	750	100,158	756,658
V14	U17	31,432	-15,885	31,432	-135,885	31,432	104,115	1190,911	337,243	1237,74
	U9	31,442	164,048	31,442	44,048	31,442	-75,952	-1189,38	-336,568	1236,078
V7	U9	43,817	-11,419	43,817	-131,419	43,817	108,581	1689,375	336,568	1722,575
	U10	43,824	168,532	43,824	48,532	43,824	-71,468	-1686,39	-333,829	1719,115
Z10	U10	10,217	-3,847	10,217	-123,847	10,217	116,153	400	25	400,78
V8	U10	33,725	-13,771	33,725	-133,771	33,725	106,229	1286,391	308,829	1322,942
	U11	33,747	166,075	33,747	46,075	33,747	-73,925	-1279,03	-305,936	1315,113
Z8	U11	5,234	-11,777	5,234	-131,777	5,234	108,223	200	39,98	203,957
V10	U11	28,517	-14,319	28,517	-134,319	28,517	105,681	1079,033	265,956	1111,325
	U13	28,54	165,5	28,54	45,5	28,54	-74,5	-1073,77	-264,882	1105,96
Z11	U13	9,003	-26,101	9,003	-146,101	9,003	93,899	315	149,971	348,879
V17	U13	19,804	-9,254	19,804	-129,254	19,804	110,746	758,771	114,911	767,423
	U17	19,817	170,487	19,817	50,487	19,817	-69,513	-755,151	-116,083	764,021
Z12	U17	13,226	-12,078	13,226	-132,078	13,226	107,922	500	99,951	509,892
V18	U17	6,631	-4,392	6,631	-124,392	6,631	115,608	255,151	16,133	255,66
	U18	6,64	174,572	6,64	54,572	6,64	-65,428	-254,431	-20,403	255,248
Z13	U18	6,64	-5,428	6,64	-125,428	6,64	114,572	254,431	20,403	255,248
CHP	U9	12,718	179,848	12,718	59,848	12,718	-60,152	-500	0	500
V15	U16	121,305	-160,021	121,305	79,979	121,305	-40,021	-4496,79	1631,272	4783,527
	U4	121,318	19,996	121,318	-100,004	121,318	139,996	4534,843	-1598,95	4808,474
Z2	U4	7,773	-12,571	7,773	-132,571	7,773	107,429	300	70,057	308,071
V3	U4	127,937	-161,879	127,937	78,121	127,937	-41,879	-4834,84	1528,887	5070,818
	U5	127,948	18,138	127,948	-101,862	127,948	138,138	4877,174	-1492,78	5100,511
V4	U5	16,719	-18,937	16,719	-138,937	16,719	101,063	626,061	228,572	666,482
	U6	16,732	160,94	16,732	40,94	16,732	-79,06	-625,338	-229,443	666,102
Z4	U6	3,229	-12,406	3,229	-132,406	3,229	107,594	125	29,999	128,549
V5	U6	13,53	-20,644	13,53	-140,644	13,53	99,356	500,338	199,444	538,624
	U7	13,537	159,283	13,537	39,283	13,537	-80,717	-500	-199,969	538,505
Z5	U7	13,537	-20,717	13,537	-140,717	13,537	99,283	500	199,969	538,505
V19	U5	141,646	-165,943	141,646	74,057	141,646	-45,943	-5503,24	1264,206	5646,575
	PCC	142,816	16,019	142,816	-103,981	142,816	136,019	5580	-1398,48	5752,577
PV	PCC	142,816	-163,981	142,816	76,019	142,816	-43,981	-5580	1398,48	5752,577
TR HV/MV	U1	16,924	-84,374	16,924	155,626	16,924	35,626	329,936	3349,55	3365,76
	U2	82,136	95,293	82,136	-24,707	82,136	-144,707	-300,677	-3222,49	3236,483

Table 5.15: With Q regulation – Conditions at nodes

Conditions at nodes												
	Ua [kV]	**αa [deg]**	**Ub [kV]**	**αb [deg]**	**Uc [kV]**	**αc [deg]**	**dUna [%]**	**dUnb [%]**	**dUnc [%]**	**Zk [Ω]**	**α [deg]**	**Sk [MVA]**
U2	22,75	29,963	22,75	-90,037	22,75	149,963	-3,409	-3,409	-3,409	2,494	86,896	194,063
U16	22,767	30,04	22,767	-89,96	22,767	150,04	-3,487	-3,487	-3,487	2,75	82,23	176,022
U1	114,823	30	114,823	-90	114,823	150	-4,384	-4,384	-4,384	6,05	84,289	1999,87
U17	22,735	29,926	22,735	-90,074	22,735	149,926	-3,343	-3,343	-3,343	2,826	81,43	171,289
U9	22,697	29,848	22,697	-90,152	22,697	149,848	-3,17	-3,17	-3,17	4,221	72,281	114,658
U10	22,648	29,729	22,648	-90,271	22,648	149,729	-2,945	-2,945	-2,945	5,671	67,736	85,351
U11	22,499	29,527	22,499	-90,473	22,499	149,527	-2,27	-2,27	-2,27	10,208	55,768	47,412
U13	22,373	29,358	22,373	-90,642	22,373	149,358	-1,697	-1,697	-1,697	14,916	51,245	32,448
U17	22,259	29,226	22,259	-90,774	22,259	149,226	-1,176	-1,176	-1,176	20,79	45,907	23,281
U18	22,194	29,157	22,194	-90,843	22,194	149,157	-0,882	-0,882	-0,882	30,552	39,585	15,842
U4	22,883	30,573	22,883	-89,427	22,883	150,573	-4,016	-4,016	-4,016	4,395	65,625	110,13
U5	23,015	31,12	23,015	-88,88	23,015	151,12	-4,616	-4,616	-4,616	6,206	58,318	77,988
U6	22,984	31,089	22,984	-88,911	22,984	151,089	-4,474	-4,474	-4,474	8,066	54,393	60,005
U7	22,968	31,081	22,968	-88,919	22,968	151,081	-4,398	-4,398	-4,398	9,21	51,598	52,55
PCC	23,255	31,949	23,255	-88,051	23,255	151,949	-5,707	-5,707	-5,707	9,476	53,521	51,079

We can see from the results that we got that the reactive power support depends on PQ diagram (Figure 5.23), short circuit power SK in the PCC, in this case – 51,079 MVA and R/X ratio at the PCC.

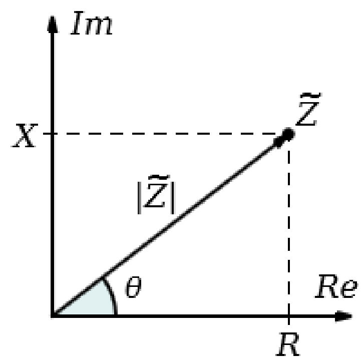

Figure 5.23: R/X Ratio Calculation

$$ImZ = \sin\alpha * \mathrm{Zk} = \sin 53{,}321° * 9{,}476$$

$$ReZ = \cos\alpha * \mathrm{Zk} = \cos 53{,}321° * 9{,}476$$

$$\varphi = \mathrm{arctg}\frac{ImZ}{ReZ} = 0{,}74$$

We found that R/X ratio in PC is 0,74. It was calculated by using the formula above, taking into account the results that we got in PCC in Table 5.15 above

Finally, Evaluation was made according to reference [19], [20], [21], [22].

6 Conclusion

Saudi Arabia is among the top countries that has great opportunities to harness solar energy. Saudi Arabia has plans to increase the production of solar power in order to meet a significant share of the future of the country in energy.

Saudi Arabia is appropriate for PV applications on a large scale with little presence of clouds do not exceed only 20% of the year. Various implementation and research is currently underway with a view to achieving its solar power aim in the near future.

As Saudi Arabia is shifting to more renewable energy, especially PV, challenges arises, mostly balancing the supply and demand, which is important to effectively manage large-scale power plant a number of flexibility sources and methods need to be taken advantage of. That is why the main aim of my case study is involved with PV and according to my case study results; I have concluded that due to flexibility (using the method reactive power control) maximal connectable power can be higher.

Using the DNCalc software, in steady state mode, the load flow calculation we measured the voltage response without the photovoltaic power plants. Then we connected the photovoltaic power plant of installed power 3120 kW with power factor 1, I calculated the voltage response before and after connecting the PVPP in the point of common coupling, (impact of other source was neglected in this case). I was able to verify that the maximal voltage change has not exceeded the limits given by Czech distribution network code (2%), which was exactly 2%.

Then, we added the reactive power absorption PF = 0,97 that increase the connectable power of the PV to 5580 kW. Evaluation of maximal voltage difference caused by PV was done again and the voltage change was 1,99.

Furthermore, we calculated the R/X ratio in point of common coupling and the result was 0,74 lower than 1, which means it is good for reactive power-voltage control. That concluded that the reactive power regulation is effective at the MV voltage level, wher R/X ratio, PQ diagram and Short circuit power ratio are key parameters.

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