Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Electrical Power Engineering

Připojení obnovitelných energetických zdrojů k elektrické síti

Connection of renewable energy sources to the power grid

Bachelor’s Thesis

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BACHELOR'S THESIS ASSIGNMENT

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2. Characterize basic RES type (principles, advantages, disadvantages ...)
3. Rules and standards for connection of RES to distribution network
4. A case study for selected type of RES (photovoltaic) in variants

Bibliography / sources:

[1] Energy outlook 2016
[2] Project More Microgrids, CIGRE 2014
[3] Distribution network code
[4] Application manual eVlivy

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Abstract

This thesis deals with the renewable energy and its main types. The theoretical part is about the general information on renewable energy sources, types of power plants, focusing on photovoltaic power plants. The practical part illustrates the connection of photovoltaic power plant to a medium voltage network (22kV) in Central Bohemia region. The following part is devoted to the rules for connecting dispersed energy sources to the distribution network, voltage profile along the lines before and after connecting the PVPP's into the distribution network.

Keywords

Renewable energy sources, solar power, generation, distributed network, voltage profile, photovoltaic power plant.

Abstrakt

Diplomová práce se zabývá obnovitelnými zdroji energie a druhy, které se nejvíce využívají. Teoretická část je věnována obecným informacím o obnovitelných zdrojích energie, typech elektráren a v další části se zaměřuje na fotovoltaické elektrárny. Praktická část ilustruje připojení fotovoltaické elektrárny do sítě vysokého napětí (22kV) ve Středočeském kraji. Dále jsou v práci uvedena pravidla pro připojení rozptýlených výroben elektřiny z obnovitelných zdrojů energie do distribuční sítě, napěťový profil podél vedení před a po připojení FVE do distribuční sítě.

Klíčová slova

Obnovitelné zdroje energie, soluneční energie, výroba, distribuční síť, profil napětí, fotovoltaická elektrárna

List of Abbreviation

HPP:	Hydropower plant
HAWT:	Horizontal Axis Wind Turbine
VAWT:	Vertical Axis Wind Turbine
GRP:	Glassfiber Reinforced Plastic
DC:	Direct Current
AC:	Alternating Current
PV:	Photovoltaic
CSP:	Concentrating Solar Power
A-Si:	Amorphous Silicon
CdTe:	Cadmium Telluride
CIS/CIGS:	Copper Indium Gallium Selenide
OPC:	Organic Photovoltaic Cells
PVPP:	Photovoltaic Power Plant
MV:	Medium Voltage
LV:	Low Voltage
RES:	Renewable Energy Sources
PQ:	Power Quality

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1 Introduction

1.1 Background

Humans live in an environment of energy. Nature works around us without stopping, giving huge amounts of unlimited energy so that man can use. During most of human history, renewable energy has been the only source of energy used. But during the last few centuries, the interest for those energy dissipated since fossil, oil and lately nuclear energy have been found and used in a non-renewable way. With the appearance of the energy crisis in 1973, this situation had an impact on the use of alternative means of energy generation. Only eight years after the oil embargo, planners and businessmen were urged to think seriously about renewable energy.

Renewable energy is defined as the energy derived from natural, unconventional, inexhaustible sources of energy by modern technology. These include solar, wind, ocean, tidal, geothermal, biomass, biogas and water. Green energy refers to all sources of energy that do not produce waste or gases that increase global warming such as carbon dioxide or harmful gases such as nitrogen oxides. Therefore, they include only a part of renewable energy sources. For example, biogas does not fall under these sources.

The reason for the global interest in alternative sources of energy is mainly due to the growing conviction of economists and politicians that the need for sources different from traditional sources has become clearer than before. In other words, the conviction that new sources of energy are needed has increased not only in terms of depletion but also in the fact that traditional energy sources, at their current levels, are insufficient to meet the needs of humanity over the next 50 to 100 years.

However, although the benefits of renewable alternatives are well known, there are some difficulties in their use. They are not always available on demand and require substantial initial investments.

2 Geothermal energy

Geothermal energy is obtainable naturally from the Earth's internal heat. It has been used throughout history back thousands of years, for bathing, heating and cooking food.

The production of geothermal energy is done by drilling wells into Earth's crust, then the hot water or steam is tapped from underground reservoirs using wells to heat and cool buildings or to generate electricity. A lot of exploring and testing is done before drilling wells by geologists and engineers, to find underground areas that contain this geothermal water. Many power plants still use fossil fuels to boil water for steam. However, geothermal power plants uses steam produced from reservoirs of hot water found below the Earth's surface. [2]

2.1 Types of geothermal power plants

There are three types of geothermal power plants, the type built depends on the temperature and pressure of a reservoir.

- **Dry steam plants:**

  It is the oldest type of geothermal power plants. It uses steam directly from a geothermal reservoir that provides the force to spin the turbine to drive a generator that produces electricity. This system for harnessing the geothermal energy is limited because dry-steam hydrothermal resources are extremely rare.

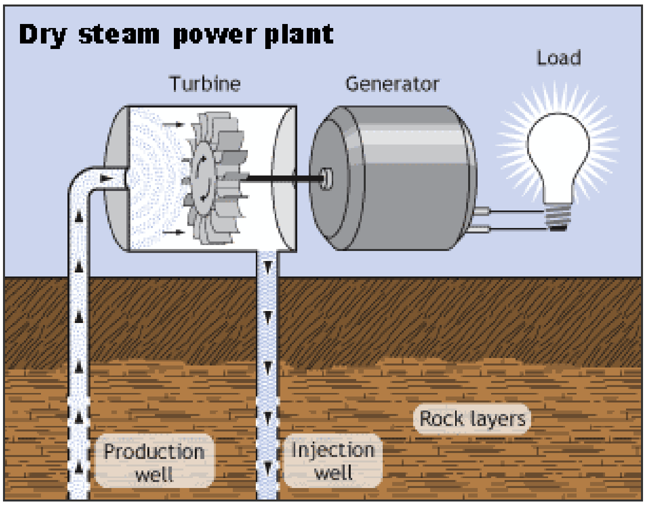

Figure 2.1: Dry steam power plant [4]

- **Flash steam plants**:

  It's the most common type of geothermal technology used nowadays. It takes high-pressure hot water from the underground reservoir, water is available at temperatures above 200 C and convert it to steam, which drives generator turbines to generate electricity. When the steam cools, it condenses to water and is returned to the reservoir to be heated by geothermal rocks again.

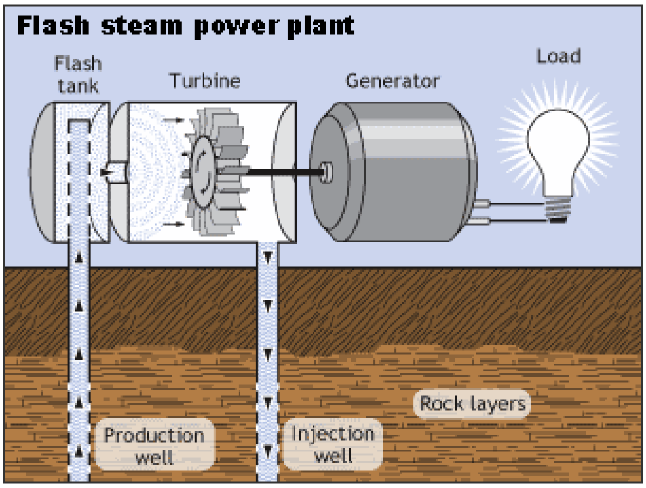

Figure 2.2: Flash steam power plant [4]

- **Binary cycle power plants:**

  If the water temperature is below 200 C, then binary cycle is the most suitable and cost effective for the generation of electricity. It transfers the heat from geothermal hot water to another liquid. The heat causes the second liquid to turn to steam, which is used to drive turbines, producing electricity. The water coming from the underground reservoir through the production wells is never in direct touch with the working fluid. Using a thermal exchanger, the coming water's thermal energy is transferred to the working fluid. The steam then condenses back to its liquid state and is used again.

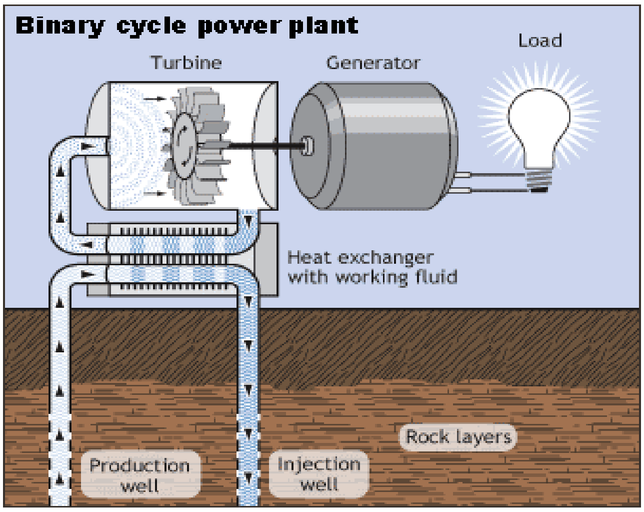

Figure 2.3 Binary cycle power plant [4]

2.2 Geothermal energy for non-electric usage

Geothermal energy usage depends on the temperature of the reservoirs. For no-electricity generation, the temperature of the reservoirs must be below 150 C [1].

2.2.1 Direct geothermal energy

This type of system uses geothermal reservoirs directly, without the need of geothermal power plant. It is one of the oldest type of geothermal technologies. It harnesses the geothermal reservoirs in places that has 20 – 120 C, these places cannot be used to generate electricity by using the flash or binary power plants.

Basically, usually using a well, hot water is taken from the reservoir. Then, it is pumped through a heat exchanger, which transfers the heat from the water to heat homes or buildings. The used fluid is usually reinjected through a disposal system back to the reservoir to be heated by the geothermal rocks again. The tapped heat can be used for different purposes, like bathing, cooking, heating homes and buildings, and fish farming. And also this system can be combined with geothermal electrical power plants, to harness the spent fluids that contains enough amount of heat for direct use appliances. [1]

Compared to geothermal electricity generation in power plants, direct heating appliances of geothermal energy require lower temperatures and is more efficient. Therefore, they do not have to be located at tectonic plate boundaries.

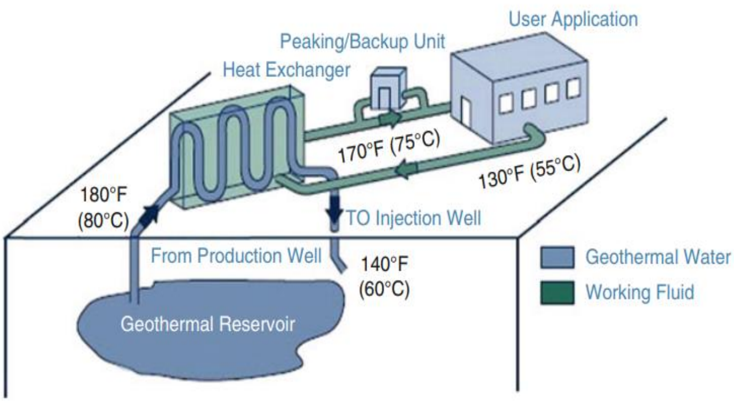

Figure 2.4 Geothermal direct-use schematic [1]

2.2.2 Geothermal Heat pump

Geothermal heat pump are the most common type of direct utilization of low temperature energy. It circulate water through pipes under the ground in a loop, the loop can be installed horizontally or vertically, depending on the available area.

Using an electric compressor and heat exchanger, during winter, it pulls heat from underground through the loop and distribute it throughout the building by the duct system. During summer, the process is reversed, it extracts heat away from the building and returns it back into the underground loop. Since the electricity needed for this process is only for collecting and delivering heat, geothermal heat pump reduces the consumption of electricity 30-60% compared with traditional heating and cooling system. [2]

Heat pumps can be installed almost everywhere compared to other geothermal technologies. There are four types of ground loop system. Horizontal, vertical and pond are classified as closed loop system, while the forth type of the ground loop is the open loop system. The type of ground loop installed depends on the climate, soil conditions, land availability and the cost of installations. [3]

Compared to other traditional heating and cooling system, geothermal heat pump are very quiet and are more durable, with operation about 50 years. Also the installation of this system takes up less space, with great control for adjustment of temperature in different parts of the house. And most importantly it does not emit carbon dioxide or other greenhouse gases, which makes it more eco-friendly.

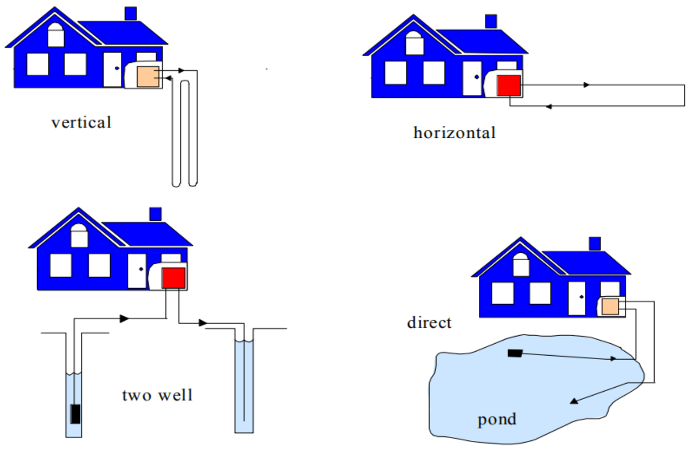

Figure 2.5 Types of Geothermal heat pump diagram [2]

2.3 Advantages and Disadvantages of Geothermal Energy

First, the process of extraction of the geothermal energy is done without burning fossil fuels such as coal, oil and gas. Geothermal energy produces little to no greenhouse gases emissions that can be harmful to the atmosphere and that's why it's more environmentally friendly than other fossil fuels. And the use of geothermal energy doesn't require large fields like other renewable energy sources, which uses damming of rivers or mining. Compared to other energy sources like wind and solar, geothermal energy is available, 365 days a year. Solar panels production of electricity is only possible when there is sunlight and wind turbines production of electricity is only possible only when there is enough wind.

Although the advantages of geothermal energy are far more than its disadvantages, still it has drawbacks which has to be considered. The main concern is the availability of geothermal energy, which is limited to areas near tectonic plate boundaries. Another concern is that the process of extracting from underground reservoirs may unintentionally release hydrogen sulphide and carbon dioxide to the atmosphere. Lastly, the ways of accessing the geothermal energy may harm the amount of energy that is effectively available at some locations. The improper re-injection might damage the geothermal resources within a geographic area.

3 Hydropower

Hydropower is the world's largest source of renewable electricity. It generates electricity by converting the energy of flowing water. Historically, one of the first uses of hydro power was for agriculture and wheat grinding. Today, modern hydro plants produce electricity using turbines and generators. [5] In Norway, about 99 percent of all power generation is hydropower.

Since the water cycle is endless, constantly recharging system, it's considered as a renewable energy source. Flowing water generated by the rivers and streams flows downwards because of the gravity. This water flow contains kinetic energy that can be extracted and used to spin the turbine, which drives a generator that produces electricity.

3.1 Classification of Hydropower plants

The hydropower plants can be broadly subdivided into different categories based on:

- Operation regime

- Installed capacity

- Head availability

3.1.1 Classification by operation

There are three types of hydropower stations. The different types serve different purposes for electricity generation and demand meeting power production.

- **Run-of-river station:**

  Where electricity is generated through the immediate use of water flow through a canal to spin a turbine. As a result, this scheme are subject to weather and seasonal variations, which results in variable power generation. Thus they produce electricity only during particular seasons when abundant flow of water is available. Most run-of-river schemes have no storage capacity, or limited storage.

Figure 3.1: Run of river station [7]

- **Storage station**:

  It’s the most common type of hydropower plant which uses a dam to store river water in a large reservoir during high-flow periods. Electricity is generated during low-flow periods, by releasing water from a reservoir which passes through turbines in a dam, which activates a generator. [5]

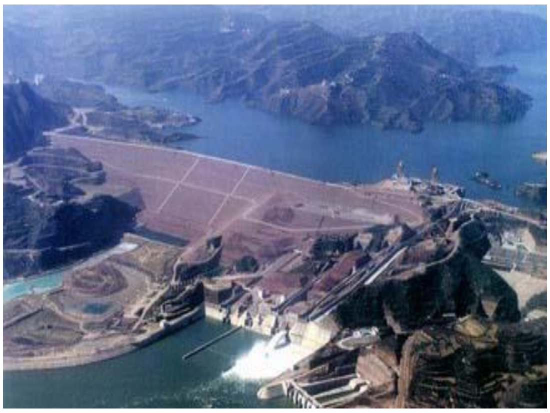

Figure 3.2: Storage station [8]

- **Pump Storage station**:

  It stores water by pumping it from a lower reservoir to a higher reservoir at times of low demand. When electricity demand is high, stored water is released from the higher reservoir to produce electricity in the same process as conventional hydropower station. These process creates efficiencies of up to 80% and are very good for load balancing. [6]

Figure 3.3: Pump Storage station [9]

3.1.2 Classification by installed capacity

Hydropower plant facilities can be categorized into three sizes.

- Large hydropower are facilities that have a capacity of more than 10 MW. It's always connected to a large grid.

- Small hydropower are facilities that have a capacity from 100 kW up to 10 MW. Most small HPPs are run-of-river type that are connected to the power distribution grid of low voltage or medium voltage.

- Micro hydropower has capacity of up to 100 kW. It usually used to supply electricity for a small remote community. All Micro HPPs are run-of-river type and are connected to houses or small industries.

3.1.3 Classification by head size

Hydropower plant schemes are divided depending upon on the quantity of available water and the surrounding areas.

- High head power plants are the types in which the working head of water is usually more than 100 m. These type of hydropower plants has a large reservoir to store water in the dams at very high heads, mainly during rainy seasons to be able to generate electricity throughout the year.

- Medium head power plants are the types in which the working head of water is usually between 30 m up to 100 m. They are usually located in the mountainous regions where there is a waterfall from high heights.

- Low head power plants are the types in which the working head of water is less than 30 meters. This system usually doesn't contain a dam at all and generation of electricity is dependent on the naturally occurring tidal flow that will have a minimal impact on the environment. Francis, Kaplan or propeller turbines are used for this type of hydropower plants.

3.2 Hydropower plant components

- **Dam:** A dam stores water upstream in a reservoir and releases water in a controllable manner down to the turbines.
- **Reservoir:** It stores the water that is held back by a hydroelectric dam. This water has a set amount of potential energy, when water flows down through a turbine, this potential energy is converted to kinetic energy that makes the turbine blades rotate.
- **Intake:** It takes water directly from the water flow and divert it to the penstock.
- **Penstock:** are pipes or long channels made of steel that carries water down from the reservoir to the turbines.
- **Turbine:** It converts the energy stored in the water flowing down into mechanical energy by rotating the turbine blades.
- **Generator:** It converts mechanical energy into electrical energy using an excitation system.
- **Transformer station** with switch gear

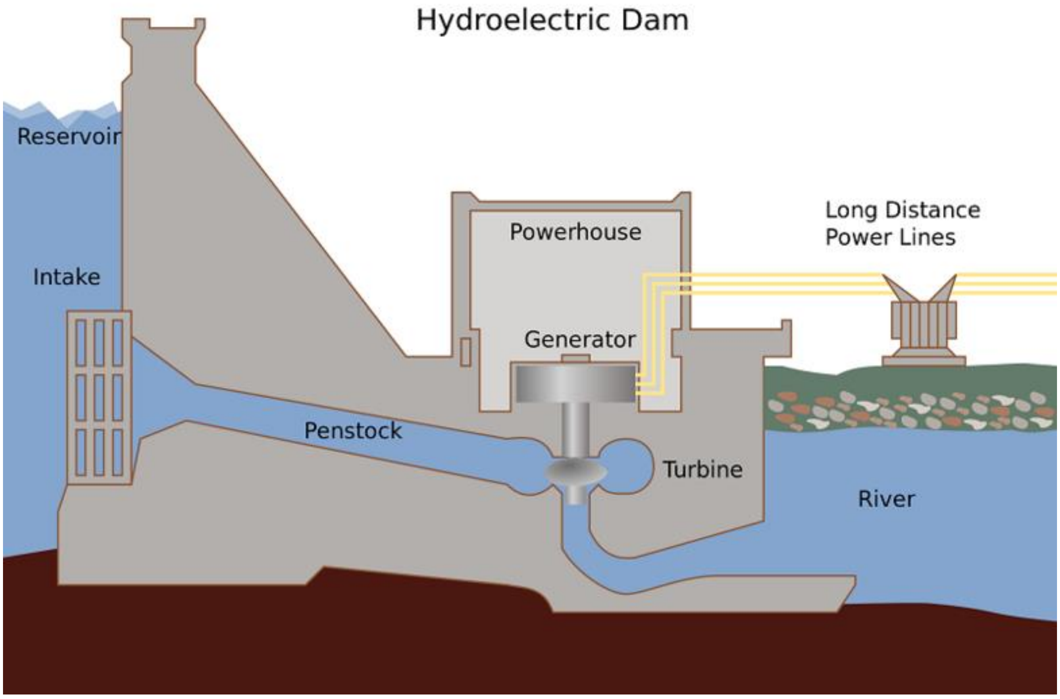

Figure 3.4: Components of Hydropower plant [10]

3.3 Calculation of Hydropower

The power available from falling water can be calculated by considering the flow and the head of the river. The flow is the volume of water which is used to drive the turbines and the head is the distance from the water reservoir to the generator. The higher the water level or head, the more energy is available for conversion to electricity.

$$P = \eta \rho Q g h$$

P is power in watts [W]
η is the dimensionless efficiency of the turbine [ ]
ρ is the density of water in kilograms per cubic metre [kg/m^3]
Q is the flow in cubic metres per second [m^3/s]
g is the acceleration due to gravity [m/s^2]
h is the height difference between inlet and outlet in metres [m]

3.4 Hydropower and the environment

Hydropower is the cheapest way to generate electricity, despite high initial building costs. It's a clean source of renewable energy and reliable source of electricity compared to other renewable sources, because it has technologies that stores water to be used another time. [5]

However, hydropower plants that use the large reservoirs technologies might destroy or disrupt habitats for wildlife and the surrounding area. The presence of the hydroelectric dams obstruct fish migration patterns and affect their populations. Also, building dams requires a large piece of land, which might results in clearing of large part of forests and this greatly impacts the natural ecosystems. Plus, it might force relocation of people in the surrounding area.

Lastly, the prices of the electricity depend mostly on the available water. In case there is a drought, which results in no or less generation of electricity. Thus, the prices of the electricity will increase considerably.

4 Wind Energy

Historically, people have been using wind as a form of energy for a thousands of years to power sailboats and windmills. From the propelled boats along the Nile River as early as 5000 B.C., to the simple windmills for pumping water in 20 B.C. in China. [13]

Humans have used the power of the wind for millennia. Without the power of wind, our ancestors would have struggled to travel across oceans, trade with other nations and explore the wonders of the world.

Today, it is most commonly used to create electricity. Wind-powered generators operate in every size range, from small turbines for battery charging at isolated residence to large, near-gigawatt- size offshore wind farms. Generation of electricity by wind energy has the potential to reduce environmental impacts caused by use of fossil fuels to generate electricity because, unlike fossil fuels, wind energy does not generate atmospheric contaminants or thermal pollution, thus being attractive to society.

4.1 Wind power generation

Wind is air in motion. It is caused by uneven temperatures on the Earth's surface when heated by the sun because the air over the land heats up more quickly than the air over the water, the warm air rises and the heavier cooler rushes to take its place, creating wind. While this process is not as predictable as the rising and setting of the sun, it's just as renewable.

Wind flow patterns depend on the earth's terrain and oceans. The wind flow is harvested by wind turbines to generate electricity. Wind Turbines converts the kinetic energy in the moving air into the mechanical power, which then then rotates a shaft to generate electricity. Similar to solar arrays wind farms connect individual wind turbines together to generate electricity on a large scale, these wind farms can be built both on land and water.

4.2 Types of Wind Turbines

There are different styles and many different sizes of wind turbines to fulfil different needs.

- **Horizontal-axis wind turbine:**

  The most common type is the horizontal-axis design, the axis of the blades are horizontal to the ground. On this type of wind turbine, two or three blades spin upwind of the tower. It's more common because it produces more electricity than vertical- axis turbine from a given amount of wind.

  However, it still has some drawbacks, one of them is that it doesn't produce well in turbulent winds. Because wind direction isn't constant, modern HAWTs use a yaw-adjustment system to position the rotor blades in the correct direction. This system usually consists of sensor and motor, sensor is used to monitor wind direction and motor to adjust turbine direction.

- **Vertical-axis wind turbine:**

  The other type is the vertical-axis turbines, the Savonius and the Darrieus wind turbines. The Darrieus wind turbine, named after the French engineer Georges Darrieus who invented it in the 1930s, this type is often called as eggbeater. It has vertical blades that rotate into and out of the wind. The Savonius wind turbine looks like S-shaped when viewed from above. It has a slow rotational speeds which is why it's not usually used for generating electricity and is mostly used for grinding grain or pumping water.

  VAWT are powered by wind coming from all 360 degrees and are more ideal than horizontal-axis turbines for installations in places where wind conditions are consistent.

a) Horizontal-axis wind turbine *b) Vertical-axis wind turbine*

Figure 4.1: Types of wind turbines [11][12]

4.3 Wind Turbines Components

A wind turbine is basically a collection of operating systems that convert energy from wind to produce electricity. The major components in wind turbine are shown in figure 5.2:

- **Blade:** catches the wind and spins. The more blades it contains, the more torque you will get but slower speed. Most turbines have three blades, using more than three blades results in many complications, like material strength problems with very thin blades. Nowadays, most rotor blades are built from glassfiber-reinforced-plastic (GRP).
- **Rotor hub:** made from iron cast, the hub holds the blades in position as they turn.
- **Nacelle:** contains the low-speed and high-speed shaft, gearbox, generator, brake and controller.

- **Low speed shaft:** turn the low-speed shaft at about 30-60 rate per minute.
- **Gearbox:** is used to increase the rotational speed from the low-speed shaft to the high-speed shaft needed to drive the generator.
- **High speed shaft:** derives the generator
- **Generator:** is a device designed to convert mechanical energy into electrical energy. It uses the principle of electromechanical induction.
- **Tower:** supports the structure of the turbine.

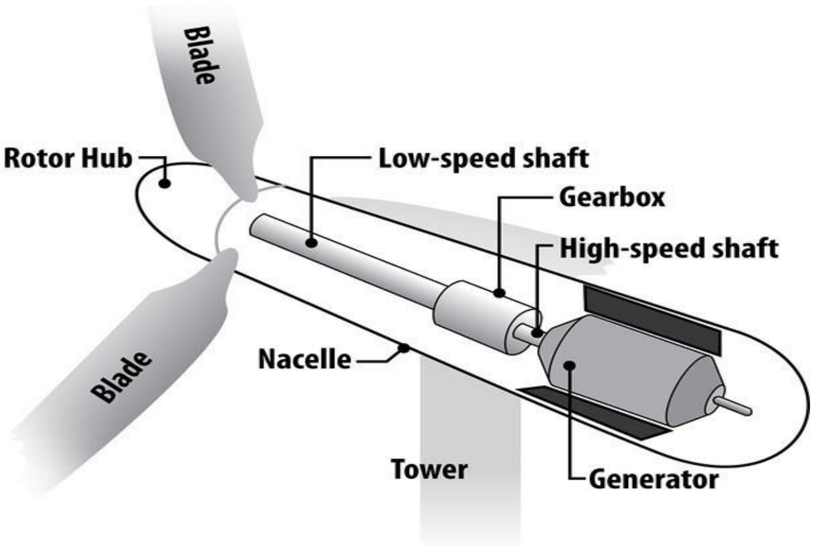

Figure 4.2: Wind turbine diagram [14]

4.4 Calculation of wind power

Wind turbines work by converting the kinetic energy in the wind first into rotational energy in the turbine and then electrical energy. The energy available for conversion mainly depends on the wind speed and the swept area of the turbine.

$$\mathbf{P} = \frac{1}{2}\rho A V^3$$

P = power output [W]

ρ = density of air [kg/m^3]

A = rotor swept area, cross sectional area of the rotor interacting with the air parcel and the velocity of air are critical in determining the power production [m^2]

V = wind speed in meters [mph]

4.5 Advantages and Disadvantages of wind power

First and foremost, wind itself is a renewable resource, unlimited. As long as the sun still shines, we will be able to harness wind energy on earth. Also, wind energy is a safe and clean source of energy because it does not release any harmful pollutants or greenhouse gases, which is why it’s considered more eco-friendly than fossil fuels.

Since wind is a natural occurrence, the process of generating electricity by the wind turbines from the kinetic energy of wind doesn't affect the wind cycle at all. It is considered one of the cheapest source of energy, because once the turbines are installed, the cost of maintaining and generating the electricity is very low but one might argue that the upfront investment is extremely expensive.

On the other hand, wind energy has some drawbacks which has to be considered. The main disadvantage of wind power is that the wind does not blow steadily. Therefore, the production of electricity is not consistent and that's why some people argue that wind farm can't be total replacement for fossil fuel or nuclear power plants.

Another drawback is the noise pollution that the wind turbine generate. The slower the wind's speed, the louder is the sound produced. Lastly, wind turbines can't be installed anywhere. You need to install them in a place where speed of wind is high and they are often located in remote locations, far from the cities that need the electricity. This means there will be a need of transmission lines, which require more investment.

5 Solar Energy

5.1 Introduction

Solar energy is the main source of all energy on Earth. It drives the mechanism of the earth to warm the atmosphere and land, generate wind, push the cycle of water circulation, warm the oceans and help plants growth.

Throughout history, humans have benefited from the energy of solar radiation directly in many applications such as drying grains and heating houses. In the Babylonian era, priests used golden vessels, polished like mirrors, to obtain fire from the sunlight. Some scientists also used the sunlight to melt materials, generate water vapour, and cook food.

In the beginning of this century, the world's first solar power thermal station, was established in Maadi, Egypt. Humans have long tried to harness the solar energy and exploit it. Nowadays, with the great development of technology and scientific advancement, it opened new scientific horizons in the field of solar energy exploitation. In addition, solar energy is relatively simple and uncomplicated compared to the technology used in other energy sources.

5.2 Solar cells

Solar cells are one of the most important inventions that have emerged in the modern era, which enable humans to secure a good part of their daily energy needs by converting solar light into electricity. They are semi-conductive, light sensitive and surrounded by a front and back-end electrical enclosure. It is one of the most common uses of solar energy. A simple photovoltaic cells function is to convert photons in light rays into forms of energy that humans can use and are usually made from chemically treated silicon.

Many techniques have been developed for the production of solar cells through a series of chemical, physical and electrical treatments. Various semiconductor materials have been developed for the manufacture of solar cells in the form of elements such as silicon or as compounds with gallium arsenic, cadmium carbide, indium phosphide, copper sulphide and other promising materials.

Photovoltaic cells have been used in many aspects of daily life, one of them is to supply satellites with electricity, where the sun provides satellites with electric power. These cells are an ideal source of electricity production because they do not cause environmental damage and do not produce toxic chemical residues and gases. This type of clean energy production from renewable sources has taken a great turn and has been of great importance to organizations and governments interested in preserving the environment.

The solar panels have a life span of approximately 25 years and their cost has recently become acceptable and affordable, with the growth of the quality of its manufacture and production. The amount of energy produced depends on the size of the solar panel and quantity of solar cells. In typical solar panels, the average production capacity of one panel is about 250 watts. The production capacity of a single sheet can be known, from the data sheet that is attached to the panels when purchased from the manufactured company.

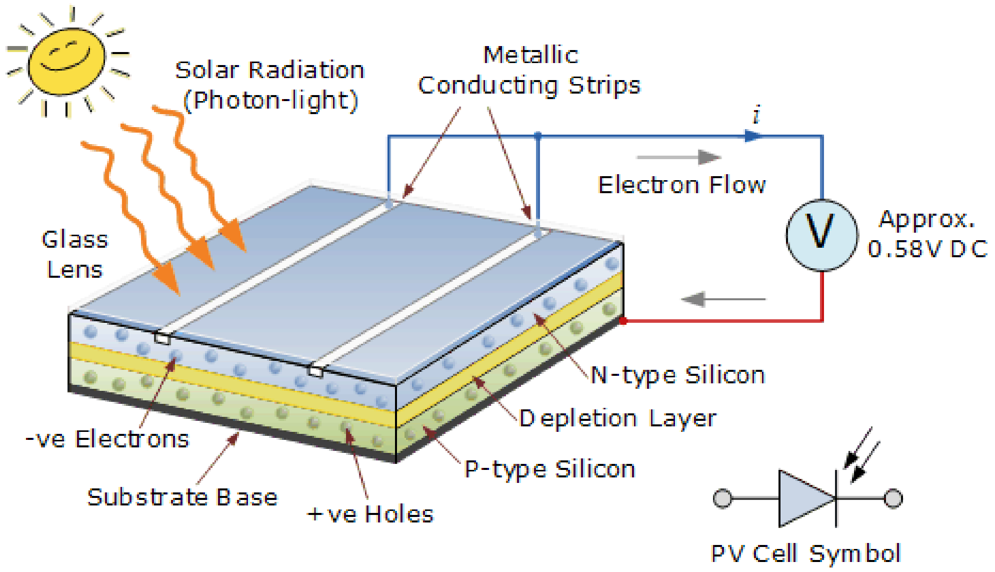

Figure 5.1: Solar cell construction [15]

5.2.1 Working principle of solar cell

Every day the sun shines, it releases a large energy in the form of photons covering each part of the surface. And the amount of this energy reaches to at least one thousand watts per square meter of every exposed land, which the solar panels harness this energy. Each solar panel are arranged in a series of rows and each row contains solar cells. These panels are assembled into a very large arrays to form solar plants that power cities and factories in many parts of the world. [16]

The principle of working solar cells is to absorb photons and drop them onto a crystalline surface formed by one of the chemical elements. The crystalline properties indicate that the atoms of this element are arranged together at the molecular level in a very fixed bound structure. Silicon is the most popular element used in this process, because it is a type of material known as a semiconductor, which has some properties of metals and insulators. Thus playing a fundamental role in the solar cell formation. When photons collide with the surface of silicon, they lead to the ionization of its atoms (an electrical charge is transferred to it), which results in the release of some electrons of their atomic bonds. The charge can move from one atom to the other freely, and become the basis of energy that the solar cell will produce from sunlight.

A silicon solar cells has two different layers of silicon, an N-type and P-type. The electrons within the solar cell then begin to move as a result of their acquisition of the electric charge, forming an electric field. Because of the electric field in the P/N junction, it will push the electron to the N-type and the hole to the P-type. Then the electrons are released from the silicon crystal and assembled in the form of electrical energy sent by the solar cell to the transformer. At this stage, electricity is produced in the form of direct current (DC), which is an electricity that can be generated from a chemical reaction, such as batteries, but it cannot be used in its current form to meet the needs of human's daily life. Therefore, it is necessary to use a solar inverter to convert this electricity From DC to AC, so that electricity is ready to run homes and buildings. [16]

5.2.2 Solar cell modulation

- **Series circuits:**

  Considering the low generation of electricity by a cell, they are usually aligned in series to obtain an output proportional to the load voltage used. Since the cells are connected in series, the current passing through all the cell is the same.

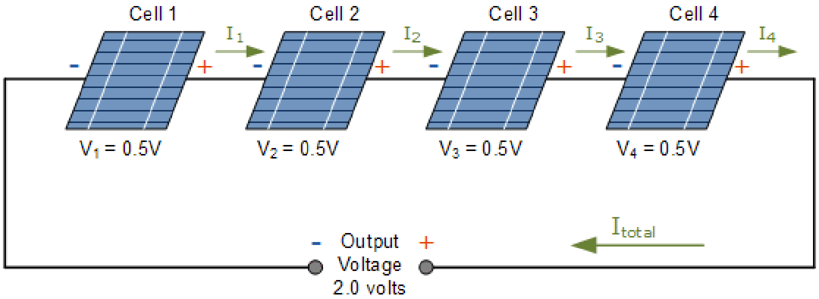

Figure 5.2: Series connection [17]

The drawback of this type of connection is that if any cell in the circuit is broken or shaded, it will stop the flow of the current and results in a complete loss of the power output. So, in order to solve this problem, a bypass diodes is added to every cell in the panel in parallel with opposite polarity.

In normal operation, the bypass diode is reverse biased acting as an open circuit and every cell in the panel is forward-biased, allowing the current to pass through them. If the solar cell is reversed biased due to a mismatch, the bypass diode will begin to conduct current through itself, therefore allowing the current from the broken cell to flow in the external circuit. The maximum reverse bias across the broken cell is reduced to around a single diode drop, thus limiting the current and preventing overheating, which occurs when the working solar cell is causing a huge amount of power to be dissipated into the faulty cell. [17]

However, another concern arises which is the huge price of adding the bypass diodes to every cell. So, practically it is usually inserted to a group of solar cells.

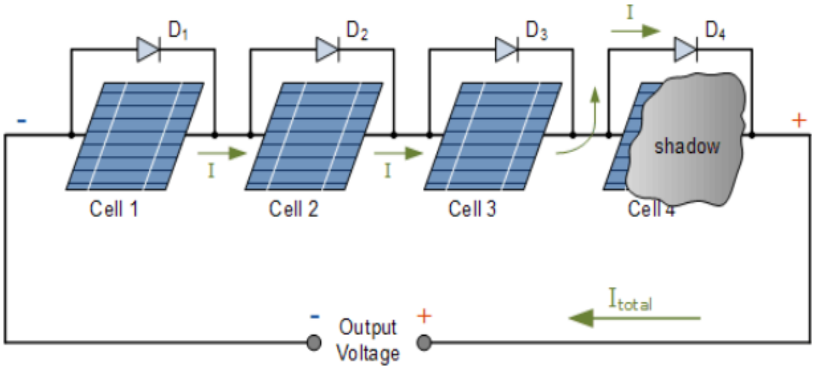

Figure 5.3: Bypass diodes [17]

- **Parallel circuits:**

  The current of a single cell is very small and might not be compatible with the existing loads. To obtain a large current, the cells are aligned in parallel.

  In this case, the load voltage and the voltage generated is the same but the current is the sum of all the cells current. Compared to the series circuit, if any cell is broken within the circuit, it will not affect the other cells in the circuit. Thus, the current will continue to flow.

  Although the damage of one solar cell in the panel does not result in a complete loss of the power output, like series circuit, but, as current flowing in the panel increase, the faulty cell will stop the generation of power. Thus, it will affect the solar panel by reducing the output voltage.

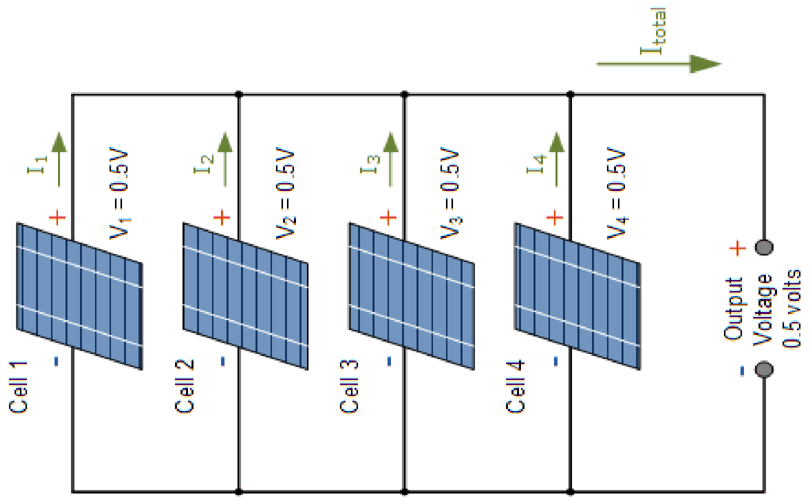

Figure 5.4: Parallel connection [17]

5.2.3 Types of solar panels

Solar cells are made of different materials, but most of these materials are rare to be found in nature. The characteristics of the solar cell vary according to their quality and most importantly the efficiency of the boards. The most popular types available in the market nowadays are monocrystalline silicon, polycrystalline silicon and thin film.

- **Monocrystalline silicon:**

  Monocrystalline panels have a symmetrical appearance that proves the purity of silicon crystals. Cells forming the monocrystalline panels are silicon alloys that have been sliced into pieces. Compared to other types, they occupy less space when installed and are the most expensive type, because it is made of pure silicon crystals with efficiency 15-20% and a life span of at least 25 years. [18]

Figure 5.5: Monocrystalline silicon [18]

- **Polycrystalline silicon:**

  This type of solar panels are made by melting raw silicon and the cells are arranged in squares. Unlike the monocrystalline silicon, their edges are not cut and they don't undergo the Czochralski process. Also compared to monocrystalline silicon, the process of manufacturing the polycrystalline silicon is cheaper and produces less waste. Thus, resulting in a lower price and efficiency 13-16%. [18]

Figure 5.6: Polycrystalline silicon [18]

- **Thin film:**

  This type of solar panels is thin and takes the form of the surface on which it is installed. The manufacture of this type is done by placing one or more thin films of photovoltaic material onto a substrate. Most of the researches currently underway are based on development in this particular type because it has a smooth, low weight and thickness. Compared to other types, it has less efficiency 7-13% and with a lifespan of around 15 years. [18]

Figure 5.7: Thin film [18]

Depending on the photovoltaic materials placed, thin films can be subdivided into different types.

- Amorphous silicon (a-Si):

This type uses a triple layered technology, to increase the efficiency. And compared to other types of silicon solar panels, it has lower cost. They are widely being used in technologies that require low power, like pocket calculator.

- Cadmium telluride (CdTe):

It is the second most common type after crystalline silicon. The cost of manufacturing is low and with an efficiency up to 17%. This type is well known for being toxic, when inhaled.

- Copper indium gallium selenide (CIS/CIGS):

It contains less cadmium than Cadmium telluride, which is toxic. Because of this type material properties, it absorbs more solar radiation, which results in higher efficiency. It has highest efficiency of all the types of thin film solar panels, which is up to 20%.

- Organic photovoltaic cells (OPC):

It produces electricity at lower than other types of solar panels and has the lowest efficiency.

5.3 Concentrated solar power

The concentrated solar technology uses the lenses or mirrors to focus light from the sun's rays and convert them into high-temperature heat and direct them through a conventional generator.
The process of concentrating the sun can be done in one of the following ways.

- **Solar towers:**

  It uses a group of flat mirrors to concentrate the sunlight towards a receiver, located at the top of the tower. The receiver usually uses molten salts, the liquid medium transfers the heat to the water that turns into steam that drives the turbines and generates electricity. Solar energy can be stored using the molten salts at elevated temperatures using dissolved salts. Salts are an efficient storage medium because they have low cost, have high thermal capacity and can produce heat at appropriate temperatures for conventional energy systems, which means during cloudy days or after the sun goes down, it can still generate electricity.

- **Parabolic dishes:**

  They are the most used solar thermal power plant. It uses its parabolic shaped mirrors as reflectors to focus the sunlight onto a receiver that is placed at the focal point, which transfers heat that drives traditional turbines and generates electricity. It has a tracking system which follows the sun, to harness a maximum amount of solar radiated. Compared to other concentrated solar power, the parabolic dishes has the highest concentration.
  The largest solar thermal power plant is located at Abu Dhabi, with production capacity up to 100 megawatts.

- **Trough:**

  It uses the large parabolic mirror to focus the sunlight onto a receiver pipe, which is filled with oil at the focal point. It uses the oil as a heating fluid, to generate electricity in the same manner as a conventional steam generator. This system is used to generate electricity in a large scale, by putting many trough in an arranged manner as a collector field. Thus, allowing it to track the sun from east to west and generate electricity largely. [1]

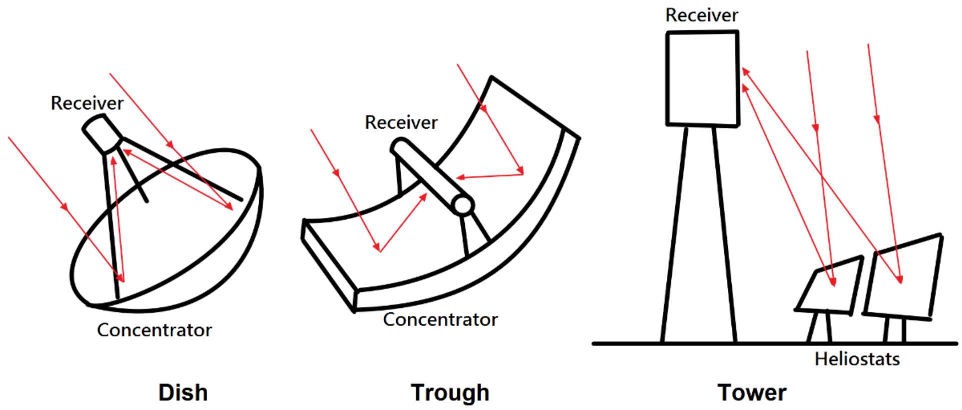

Figure 5.8: Types of Concentrated solar power [19]

5.4 Solar heating

Solar heaters harness the sunlight to generate hot water without concentrating devices, using a solar collector. It can be manufactured in several sizes to utilize the solar energy according to the required water temperatures, whether warm (below 50 ° C) for swimming pools or heated (60-80 ° C) for home usage.
Solar collectors for water's heat depend on the capacity and design of solar heater. There are three major types of solar collectors.

- **Flat plate solar collector:**

  The simplest of these solar collectors is the flat plate solar collector, which is a metal insulated box with a cover of ordinary glass or transparent plastic, and inside it is a dark heat absorbing panel. Often in black, to absorb the heat of the sun as much as possible. And the absorbing plate is of copper or aluminium or an alloy of them. Because they have a great ability to deliver heat, fast and with high efficiency. Copper is remarkable for its resistant to corrosion, although it is more expensive. The box is insulated to prevent heat leakage. Hot water is stored in heat-insulated tanks inside. It can be glass or fiber glass to contain the water's heat and for usage during the night. The drawback of this type of solar collector is its shape, which is flat. This means that when the sun is not directly above it, the efficiency will be reduced hugely compared to when the sun is directly above it. [20]

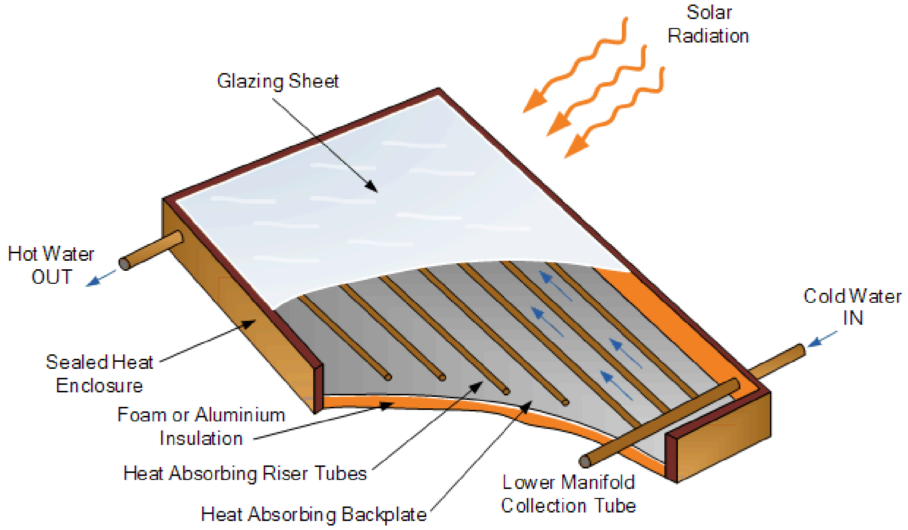

Figure 5.9: Flat plat collector [20]

- **Evacuated tube solar collector:**

  It is used to heat the water inside to a high degree, where the sun enters through the glass surface to be stored on transparent glass tubes, air is completely removed and closed. Also inside it is the heat pipe filled with water that is heated by contact. Water is stored in a tank. The vacuum tubes around the heat-absorbing pipes are cylindrical in shape, which allows it to produce with high efficiency almost all the time, during the day. And they don't lose heat, because the vacuum is not connected to the heat and also there is no air that passes the heat, carries it or goes through it. The tube can store the water, making it unnecessary for storage devices next to it. [20]

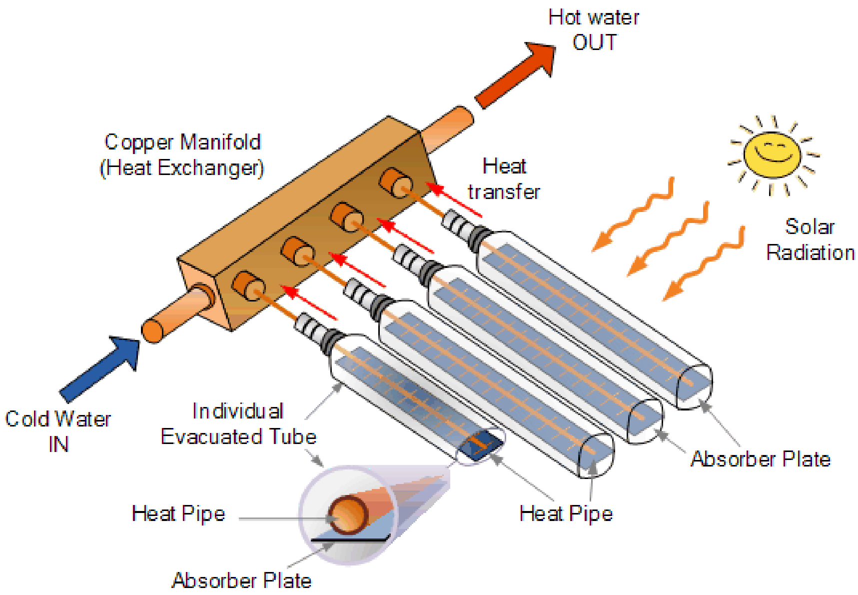

Figure 5.10: Evacuated tube collector [20]

- **Integral collector storage:**

  It operates in the same manner as flat plate storage. The collector and tank are combined into one unit, making it unrequired to have pumps, controllers and generates hot water without using electricity. Thus, they are categorized as passive systems. They are usually referred as batch systems, containing one or more black tubes. It preheats the cold water that passes through the solar collectors. The major problem of the batch collector system is its weight, which limits the installation to roof mounted system only to building that withstand its weight and another problem is that it has a very low resistant to cold weather. [20]

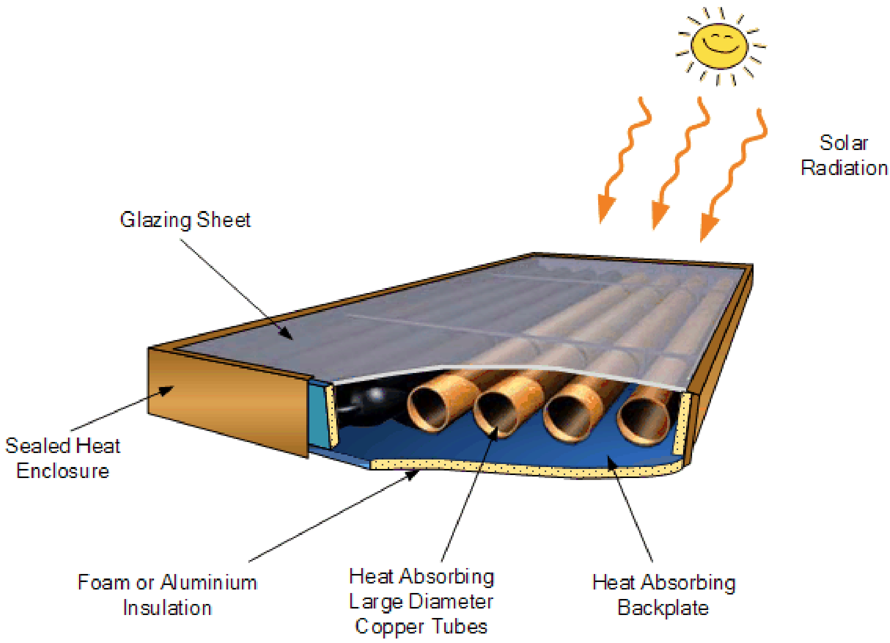

Figure 5.11: Integral collector storage [20]

5.5 PV versus CSP

Both photovoltaic and solar thermal harness the energy emitted from the sun. Photovoltaic systems uses the solar cells through the photovoltaic effect to directly convert the sunlight to electricity, while the solar thermal systems uses the sunlight to heat a fluid, which is then either transferred to electricity or stored as heat. Since the energy is free during the day, there is no cost associated with the actual fuel.

The main concern is the cost of these technologies, which is quite expensive. As long as the sun shines, there is a source of power for all solar power technologies. But, since humans require a certain base load or consistent delivery of power for daily usage, another concern rises, which is production of electricity when the sun goes down.

Both technologies use a storage system. Photovoltaic stores the energy in electrical energy form in batteries and solar thermal stores the energy in heat form using salt or other fluid. The latter storage system is much cheaper, because heat is stored using the same fluid that collects the solar radiated.

Heat is mostly delivered in the hottest part of the world, where there is no population in desert areas and with low water availability. So, we must build grids to transmit that power, which is costly and using non-water cooling projects will also increase the costs.

And PV technologies are easy to install and the initial cost of installation is low, compared to solar thermal technologies, where the initial investment cost reaches around 80% of the total cost. Those factors may lead investors to choose photovoltaic rather than solar thermal technologies.

5.6 Solar power drawbacks

The most important problem faced by researchers in the fields of solar energy is the presence of dust. Ongoing research has proven that more than 50% of the effectiveness of solar energy is lost, if the device for sunlight receiver is not cleaned for around a month.

The second problem is storing solar energy and making use of it during the night, cloudy days or dusty days. Solar storage depends on the nature and quantity of solar energy, used type and most importantly the total cost of the storage method. The best storage batteries of solar energy does not cause the release of harmful gases, but remains the issue of the high price of this type of batteries. Although there are cheap storage batteries, these batteries are dangerous when used because of the toxicity of the gases inside them, which can be emitted. It is preferable not to use storage devices to reduce the cost. The topic of solar energy storage is one of the topics that needs more scientific research and new discoveries.

The third problem in the use of solar energy is the occurrence of corrosion in solar technologies because of the salts found in the water, which was used in the heating cycles. Closed cycles and the use of salt-free water are the best solutions to reduce the problem of corrosion and rust in solar technologies.

Lastly, all solar power plant require a backup because the sun is intermediate and produces little during the winter, when it’s needed the most. Therefore, some reliable source of energy is needed to cover for it. This backup plans are usually fossil fuels.

6 The rules for connecting dispersed energy sources to the distribution system

While renewable energy systems are capable of powering houses and small businesses without any connection to the electricity grid, many people prefer the advantages that grid-connection offers.

Using renewable energy, a grid-connected system can power your home or small business when the sun is shining, the water is running, or the wind is blowing. Any excess electricity you produce is fed back into the grid. When renewable resources are unavailable, electricity from the grid supplies your needs, eliminating the expense of electricity storage devices like batteries.

In addition, power providers (i.e., electric utilities) in most states allow net metering, an arrangement where the excess electricity generated by grid-connected renewable energy systems "turns back" your electricity meter as it is fed back into the grid. If you use more electricity than your system feeds into the grid during a given month, you pay your power provider only for the difference between what you used and what you produced.

Connection conditions:

Connection of small power plant (distributed sources) to the distribution network may be at low voltage level (0.4 kV) and at medium level (22, 35 kV), depending on the total power of the power plant, the nominal power of the generator, the circumstances of the distribution network , the power plants operation mode and other factors.

Connection to a low-voltage network:

- A power plant up to 50 kW - at the low voltage line or low voltage buses of 22 / 0.4 kV substation,
- A power plant up to 100 kW - at the medium-voltage network (22, 35 kV):
- A power plant up to 1000 kW - at the medium voltage line,
- A power plant over 1000 kW - at the medium or high voltage line, input-output system.

A possible way of connecting the power plant to the distribution network is determined by a detailed techno-economic analysis to define the optimal solution in terms of connection costs and the impact of production facilities on the distribution system.

The final evaluation of the capabilities and mode of connection of distributed sources to the distribution network has been adopted with regard to the state and expected development of the distribution network, and after calculation of voltage drops, load flow, short circuit current and total harmonic voltage distortion.

Defining the conditions for connection to the distribution network ensures reliability of the electric power system and user facility, and avoids at the same time unacceptable detrimental effects between them. Technical requirements for connection of generating units to the distribution network are delivered by the distribution system operator. The Grid System Rules define the basic features at the connection point to the distribution network and general requirements for the connection of system users to the distribution system, as well as special conditions to be met by all generating units connected to the distribution system under normal operating conditions. The distribution system operator defines the basic technical information relevant to the design of manufacturing plants:

- Available capacity
- Data for insulation coordination
- Concept of protection (fault clearance time in the user's facility with the primary and backup protection)
- Maximum and minimum short circuit power
- Terms of parallel operating with electric power systems
- The share of higher harmonics and flickers towards the principles for determining the effect on the system
- Breaking capacity for the corresponding nominal voltage of the transmission network
- Way of earthling,
- Maximum and minimum continuous operating voltage, the duration and level of short-term overdraft,
- Typical load profiles,
- Nature and extent of reactive power exchange, and installed reactive power reserve into the user's facility, for the production and delivery of energy, power plant must generate a sufficient quantity of reactive power. Production of reactive power should be in the range of cos φ = 0.85 inductively to cos φ = 1, except for solar power plants, where such a claim does not arise, and wind farms with asynchronous generators for which it is expressed in additional terms of Grid System Rules,
- Stake in the plan of the defence system (under frequency load shedding, under voltage shedding, manual and automatic control)
- Share in securing ancillary services,
- Behaviour in large-scale disturbances (the ability to pass through a state of failure)
- The method of measurement and calculation
- Integration into the remote control system
- Integration into the telecommunication system

6.1 Criteria for connecting electricity generating plants to the distribution network ČEZ supplier.

Way to connect electricity generating plants to the distribution network determines the network operator. When connecting to evaluate the effects of backward production plant to the distribution system of low or high voltage. They will cover the following feedback effects:

- Change Voltages when operating an electricity generating plant
- Change Stress during switching
- long term flicker
- Current harmonics
- Influence to device ripple control (HDO)
- Influence to short-circuit conditions

For photovoltaic plants are judged mainly voltage changes in the operation of the electricity generating plant, issued by harmonic currents and the effect on ripple control devices.

Voltage changes in the operation of the electricity generating plant.

PPC variations in voltage caused by connecting or disconnecting the electricity generating plant must not be at the medium voltage level (22 kV) exceed. Voltage change in the distribution of medium voltage by connecting electricity generating plant at the connection point (PCC) must not exceed 2%.

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

PPC variations in voltage caused by connecting or disconnecting the electricity generating plant must not be connected to low voltage (0.4 kV) exceed 2%.

These limits apply only to the case where switching is more frequent as once every 1.5 min., Which is at most plants using RES respected.

Most mass-produced dispersion of resources should have in their technical dossier factor information flicker. The amount of this quality parameter depends on the uniformity of the equipment operation. Generally, machines with great energy of rotating masses have little flicker factor and therefore not a source of flicker, for example: turbo generators and hydro generators. Problematic are the production of electricity from renewable sources, where it reaches a factor of flicker to 40. The highest values achieved without wind power converters and a small number sheets. Photovoltaic plants are generally deemed to be devices with very low duty flicker.

From the perspective of long-term rates flicker at each connection point to observe the following limits:

Term flicker effect can be determined by short-circuit power networks and rated apparent power of the connected source.

When flicker factor is declared by the equipment manufacturer.

6.2 Power Quality Parameters

Power quality is a characteristic of electricity at a certain point of the power system and it is usually considered as continuity of supply (availability of electricity) and voltage quality. Ideally, the best electrical supply would be a constant magnitude and frequency sinusoidal voltage waveform. However, because of the non-zero impedance of the supply system, of the large variety of loads that may be encountered and of other phenomena such as transients and outages, the reality is often different. The Power Quality of a system expresses to which degree a practical supply system resembles the ideal supply system.

- If the Power Quality of the network is good, then any loads connected to it will run satisfactory and efficiently. Installation running costs and carbon footprint will be minimal.
- If the Power Quality of the network is bad, then loads connected to it will fail or will have a reduced lifetime, and the efficiency of the electrical installation will reduce. Installation running costs and carbon footprint will be high and/or operation may not be possible at all.

The following main contributors to Low Voltage poor Power Quality can be defined:

- Reactive power, as it loads up the supply system unnecessary
- Harmonic pollution, as it causes extra stress on the networks and makes installations run less efficiently
- Load imbalance, especially in office building applications, as the unbalanced loads may result in excessive voltage imbalance causing stress on other loads connected to the same network, and leading to an increase of neutral current and neutral to earth voltage build-up
- Fast voltage variations leading to flicker

6.2.1 Parameters and Terminology of PQ

Reactive power and power factor ( )

In an AC supply, the current is often phase-shifted from the supply voltage. This leads to different power definitions (Figure 6.1):

- The active power P [kW], which is responsible of the useful work, is associated with the portion of the current which is in phase with the voltage.
- The reactive power Q [kvar], which sustains the electromagnetic field used to make e.g. a motor operate is an energy exchange (per unit of time) between reactive components of the electrical system (capacitors and reactors). It is associated with the portion of the current which is phase shifted by 90° with the voltage.
- The apparent power S [kVA], which gives a geometrical combination of the active and of the reactive powers, can be seen as the total power drawn from the network.

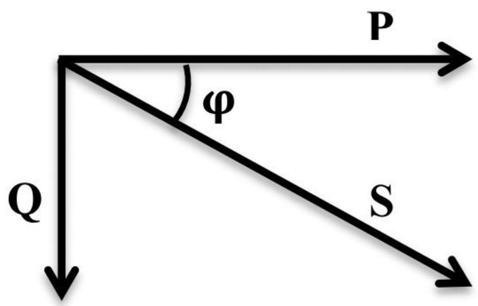

Figure 6.1: Basic Power in AC systems

The ratio between the active power and the apparent power if often referred to as the displacement power factor or cos(φ), and gives a measure of how efficient the utilization of the electrical energy is. A cos(φ) that equals to 1 refers to the most efficient transfer of useful energy. A cos(φ) that equals to 0 refers to the most inefficient way of transferring useful energy.

Harmonic Distortion

The harmonic pollution is often characterized by the Total Harmonic Distortion or THD which is by definition equal to the ratio of the RMS harmonic content to the fundamental:

$$THDV = \frac{\sqrt{V_{RMS}^2 - V_1^2}}{V_1} = \frac{\sqrt{\sum_{k=2} V_k^2}}{V_1}$$

where V_k is the k-th harmonic component of the signal V.

This quantity, expressed in %, is very useful when the fundamental value component is implicitly given or known. Consequently, the THD is particularly relevant information for the voltage (as the rated voltage is known). In order to be able to gauge THD of the current, it is imperative that a fundamental frequency current reference be defined.

Voltage unbalance

A normal three phase supply has the three phases of same magnitude but with a phase shifted by 120°. Any deviation (magnitude or phase) of one of the three signals will result in a negative phase sequence component and/or a zero phase sequence component. The definition of voltage unbalance is usually expressed as the ratio between the negative phase sequence component and the positive phase sequence component. This parameter is expressed in %.

Flicker

According to the International Electro technical Vocabulary (IEV) of the International Electro technical Committee (IEC), flicker is defined as 'Impression of unsteadiness of visual sensation induced by a light stimulus whose luminance or spectral distribution fluctuates with time'. From a more practical point of view one can say that voltage fluctuations on the supply network cause change of the luminance of lamps, which in turn can create the visual phenomenon called flicker. While a small flicker level may be acceptable, above a certain threshold it becomes annoying to people present in a room where the flicker exists. The degree of annoyance grows very rapidly with the amplitude of the fluctuation. Further on, at certain repetition rates of the voltage fluctuation, even small fluctuation amplitudes can be annoying. The influence of the flicker phenomenon on people is complex to analyse given that it depends not only on technical aspects like the lamp characteristics to which the fluctuating voltage is applied but also on the appreciation of the phenomenon by the eye/brain of each individual.

Operation of PVPP isn’t supposed to impact on flicker to distribution network. This parameter is not fully studied yet.

7 Case study for the selected part of the medium voltage distribution network.

In this case study, two photovoltaics power plant was connected in to distribution network in Central Bohemia region. The PVPP's are connected to medium voltage network (22 kV). Both PPV1 and PPV2 has installed capacity 2000 [kW] and 1000 [kW], respectively. Using eVlivy software, we were able to calculate the voltage profile of every node in the medium voltage network before and after PVPP connected to network.

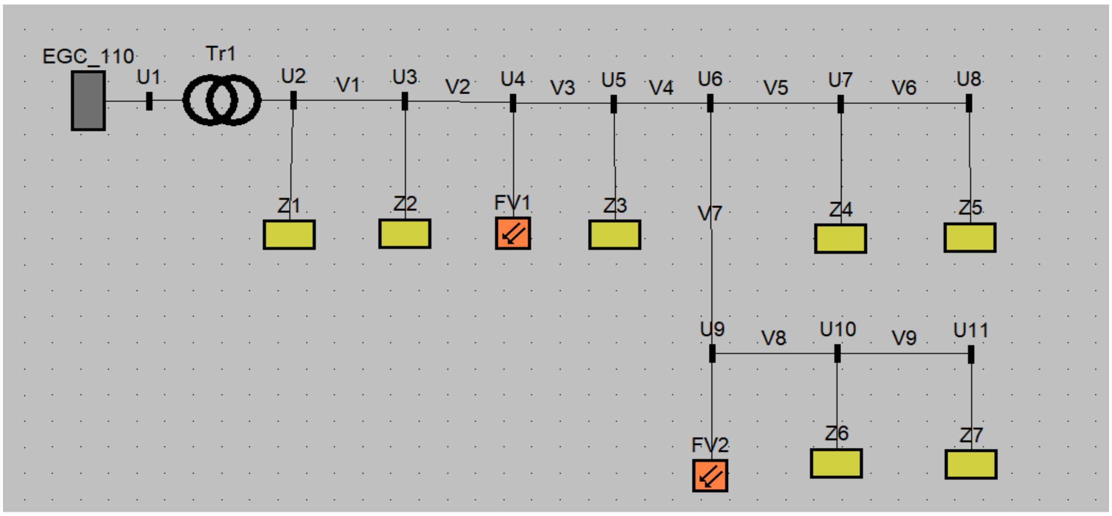

Figure 7.1: Network topology

Overhead line

Line Name	Wire type	Resistance [R/km]	Inductive reactance [X/km]	Nominal current [A]
V1 – V9	95 AlFe 6	0,301	0,375	290

Transformer

Type	Un1 (kV)	Un2 [kV]	S [MVA]	Pk [kW]
8 ERH 31 M-O	110	23	25	140

PVPP parameters

Name	Voltage [kV]	Power factor [-]	Active power [kW]	Reactive power [kVAr]	Apparent power [kVA]
FV1	22	1	2000	0	2000
FV2	22	1	1000	0	1000

Overhead line parameters

Line's Name	Starting Point	End Point	Distance [km]
V1	U2	U3	4
V2	U3	U4	10
V3	U4	U5	5
V4	U5	U6	3
V5	U6	U7	5
V6	U7	U8	4
V7	U6	U9	5
V8	U9	U10	4
V9	U10	U11	3

Consumption on overhead line

Consumption's Name	Node Name	Power factor [-]	Installed power [kVA]
Z1	U2	0,95	12000
Z2	U3	0,95	630
Z3	U5	0,95	400
Z4	U7	0,95	250
Z5	U8	0,95	630
Z6	U10	0,95	400
Z7	U11	0,95	630

- **Calculation results**

Condition before and after PVPP1 operation

Node Name	dU before [%]	dU after [%]	Voltage difference
U2	-3.722	-3.890	-0.173
U3	-3.006	-3.662	-0.659
U4	-1.722	-3.600	-1.879
U5	-1.079	-2.969	-1.891
U6	-0.791	-2.687	-1.896
U7	-0.427	-2.330	-1.903
U8	-0.218	-2.125	-1.907
U9	-0.674	-2.572	-1.898
U10	-0.333	-2.237	-1.905
U11	-0.176	-2.084	-1.908

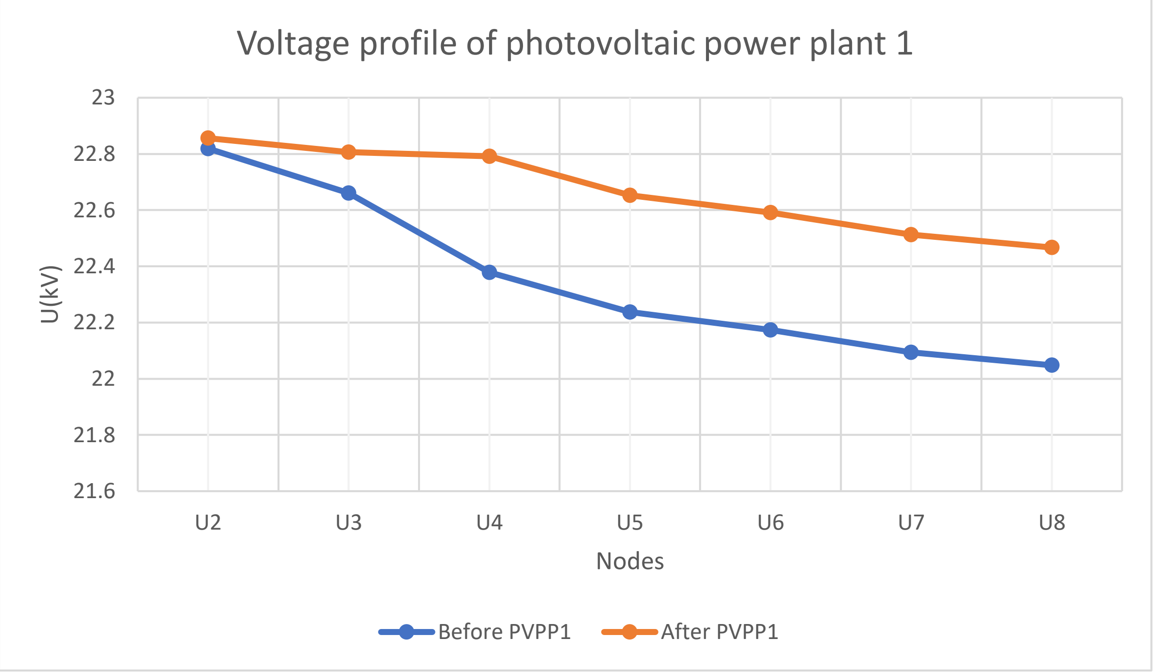

Figure 7.2: Voltage profile of PVPP1

Condition before and after PVPP2 operation

Node Name	dU before [%]	dU after [%]	Voltage difference
U2	-3.799	-3.890	-0.093
U3	-3.320	-3.662	-0.343
U4	-2.627	-3.600	-0.974
U5	-1.674	-2.969	-1.295
U6	-1.202	-2.687	-1.486
U7	-0.839	-2.330	-1.491
U8	-0.631	-2.125	-1.494
U9	-0.776	-2.572	-1.797
U10	-0.435	-2.237	-1.803
U11	-0.278	-2.084	-1.805

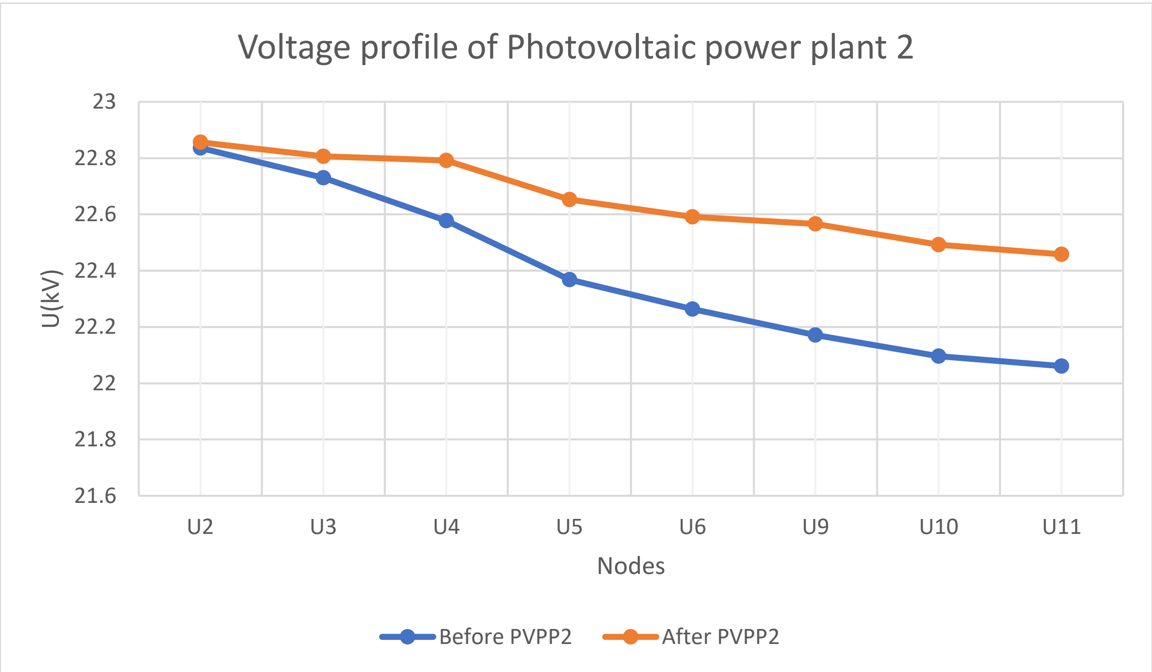

Figure 7.3: Voltage profile of PVPP2

- **Harmonics**

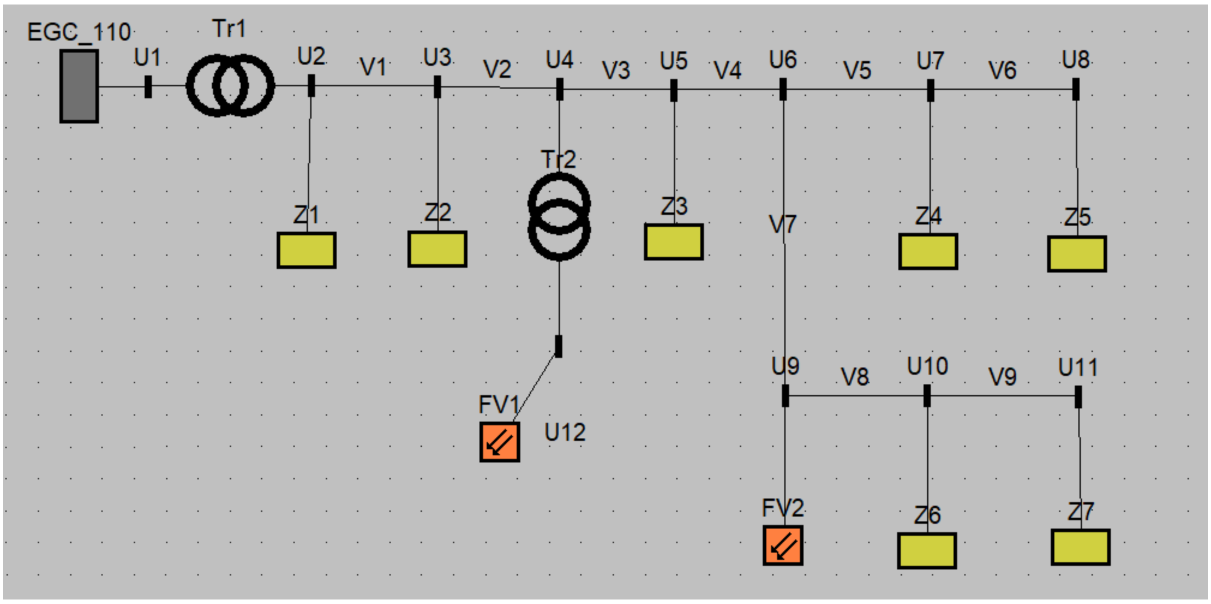

Figure 7.4: Network topology for harmonics

Harmonic Parameters

	11		**7**		**5**	
Node Name	**Uh [V]**	**uh[%]**	**Uh [V]**	**uh[%]**	**Uh [V]**	**uh[%]**
U2	17.411	0.079	26.292	0.120	30.240	0.137
U4	56.853	0.258	81.309	0.370	91.889	0.418
U6	55.510	0.252	79.571	0.362	89.995	0.409
U8	55.264	0.251	79.158	0.360	89.504	0.407
U12	2.905	0.726	3.888	0.972	4.271	1.068

8 Conclusion

Using the eVlivy app, I calculated the voltage response before and after the photovoltaic power plants operation in every node in the medium voltage distribution network (22kV). By comparing the voltage difference before and after the PVPP's connection, I was able to verify that the maximal voltage difference has not exceeded the limits given by Czech distribution network code (2%), which was 1.908% for PVPP1 and 1.805% for PVPP2.

In the harmonics part, I calculated the impact on the PVPP1 in every node on the same line by the 11, 7, and 5 harmonics. Thus, by checking the results, I was able to verify that it has not exceeded the limits given by Czech distribution network code and found out that the transformer reduces the harmonics almost to half. Also, nodes near the voltage source has very low harmonics and nodes far from the source almost has the same harmonics.

Therefore, I conclude that our calculation proved that this PVPP does not have bad impact on power quality in the distribution network.

In the theoretical part, I gave a review of the types of renewable energy sources, solar power was discussed in details. The generation of power using the solar energy, nowadays, is the most promising renewable energy source. Solar energy has a very bright future given the recent growth in the development of its power plant technologies, with the improvement of its efficiency.

Nonetheless, more improvement in performance is a must, to fulfill the energy demands by humans and substitute the non-renewable energy sources, to reduce the harmful gases they cause to the environment.

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