Czech Technical University in Prague

Faculty of Electrical Engineering

Department of Electrical Power Engineering

Integrace obnovitelných zdrojů do distribuční sítě

Integration of renewable energy sources in the distribution network

Bachelor's Thesis

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BACHELOR'S THESIS ASSIGNMENT

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1. General review on renewable energy sources
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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III. Assignment receipt

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Acknowledgement

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Abstract

This thesis will provide general information about renewable energy sources, types of power plants and their working principles. The thesis is focused on wind power plants (principles, types, components, advantages and disadvantages). It also includes the rules for connecting dispersed energy sources to the distribution system. In practical part, a case study demonstrates voltage characteristics before and after connection of a wind power plant to a distribution network with two different values of power factor.

Keywords

Renewable energy sources, Power generation, Hydropower energy, Solar energy, Wind energy, Power plants, Distribution System

Abstrakt

Tato práce uvádí obecné informace o obnovitelných zdrojích energie, typech elektráren a jejich pracovních principech. Práce je zaměřena na větrné elektrárny (principy, typy, komponenty, výhody a nevýhody). Obsahuje také pravidla pro připojování rozptýlených zdrojů energie k distribuční soustavě. V praktické části je řešena případová studie, která demonstruje napěťové charakteristiky pro síť vysokého napětí před a po připojení větrné elektrárny do distribuční sítě se dvěma různými hodnotami účiníku.

Klíčová slova

Obnovitelné zdroje energie, Výroba energie, Vodní energie, Solární energie, Větrná energie, Elektrárny, Distribuční soustava

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1 General Overview

In the last century, it was observed that the consumption of non-renewable energy sources caused more environmental destruction than any human activity. Electricity generated from fossil fuels has increased the concentration of harmful gases in the atmosphere. Despite the harmful effects, the price of fuel pushed up without restrictions. The reason is that demand for millions of barrels of oil is rising daily.

Today, the world encounters the challenge of how to balance sustainable development with environmental conservation. We are all responsible for climate change and we are responsible for working towards finding a solution. Human beings have come a long way in the field of technical sciences, but they still depend on traditional sources of energy for power generation. They are unable to find cheap alternatives to these non-renewable energy sources, which are already under the threat of depletion, not to mention the damage caused by these traditional energies which results in air pollution, heat, radiation and noise that affects the environment and human health.

Renewable energy is energy that is generated from natural processes that are continuously replenished. This energy cannot be exhausted and is constantly renewed. Scientists have guided several renewable sources of nature in the following conditions: Wind, sun, hydro, biomass, and geothermal. Although there are many issues that need to be addressed, switching to clean and renewable energy is a big step forward in combating climate change and pollution.

2 Geothermal Energy

Geothermal energy is the thermal energy generated and stored in the Earth. The geothermal energy beneath the surface of the earth originates from the original formation of the planet, geological process such as natural heat loss, volcanic activity, or from perfectly normal and safe processes such as radioactive decay of natural minerals like uranium and potassium. Traditionally, it was used for bathing and heating purposes but today it is also for practical purposes, such as heating buildings or generating electricity.

2.1 Geothermal Resource [1]

The real source of heat for the generation of geothermal energy is deep inside the earth's core. The earth's core is composed of three layers; the outer silicate and solid crust, a highly viscous mantle, and a liquid outer core. The outer core consists of extremely hot magma or melted rock wrapping around a solid iron center known as the inner core. The slow decay of radioactive material continually generates extremely high temperatures inside the earth. Wrapping around this outer core is a layer called the mantle. The mantle is mainly composed of magma and rock. The crust is the outermost layer of the earth's core. The crust forms the bulk of continents and ocean floors.This crust is split into numerous parts known as plates. At the edges of these plates, magma finds a way near the surface of the earth. Volcanoes are prevalent in these areas. When a volcano occurs, lava erupts from underneath. This lava is partly magma.

Besides, underneath the earth's surface, the water and rocks absorb heat from the magma.The temperatures of the underground water and rocks increases as the depth increases. Individuals across the world take advantage of the underground energy to heat their homes and generate electricity by digging up deep wells and subsequently pumping the hot underground water or steam to the earth's surface.

2.2 Conversion of geothermal energy to electricity [1]

The conversion of geothermal energy into electricity occurs through a geothermal power plant. The power plant harnesses the steam from the hot water beneath the earth's surface to turn turbines. This turbine activates a generator to produce electricity. Some geothermal power plants utilize steam to directly turn the turbine, while others utilize the steam to heat a liquid that is used to turn the turbine.

2.3 Types of geothermal power plants [1]

There are three types of geothermal power plants: dry steam, flash steam, and binary cycle. Despite their differences in design, all three control the behaviour of steam and use it to drive electrical generators, and the excess water vapour at the end of each process is condensed and returned to the ground, where it is reheated for later use.

- Dry steam power plant

  In a geothermal dry steam power plant, two separate wells are drilled into the ground to the extremely hot water reservoir underneath the earth's surface. These wells are called production well and injection well. The production well extracts hot steam with a temperature typically above 235°C (455°F) from the hot water reservoir below and directs it to the turbine. The steam turns the turbine, which turns a shaft connected to a generator. While turning, the generator converts the energy into electricity, which goes through power lines to a power grid and eventually supplied to consumers. The used steam goes to the condenser, where it's converted into water and sent back down to the hot water reservoir through the injection well and the cycle continues.

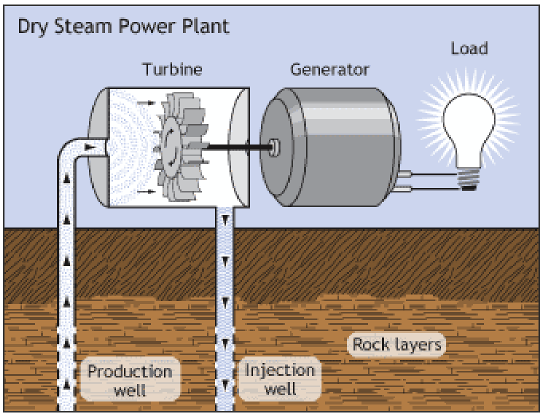


Figure 2.1 - Dry steam power plant [2]

- Flash steam power plant

  Flash steam power plants are the most common types of geothermal power plants in the modern world. This kind of geothermal power plant utilizes water at temperatures above 182°C (360°F) from geothermal reservoirs and has the addition of a flash tank over the dry steam design. As the water is pumped from the reservoir to the power plant, the reduction of pressure in the flash tank causes the water to vaporize into steam. The steam is then directed to turn turbines, which turns a shaft connected to a generator leading to production of electricity. Any water not flashed into steam is injected back into the reservoir for reuse, as is the water that is captured from the steam after it has moved the turbines.

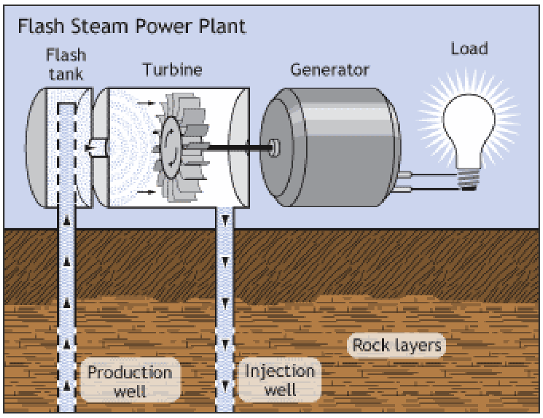


Figure 2.2 – Flash steam Power Plant [2]

- Binary cycle power plant

In a binary cycle power plant, hot water from the hot reservoir is pumped through the production well into the heat exchanger. On the other hand, a separate fluid with a lower boiling point known as the binary fluid, normally a pentane hydrocarbon or butane, is contained within a closed loop of pipe that passes through the heat exchanger. In the heat exchanger, the binary fluid is vaporized due to the heat exchanged from the hot water. Then, the vapor is directed to turn a turbine, which turns a shaft connected to a generator and electricity is generated. The vapor used to turn the turbine is then condensed and piped back to the heat exchanger.

Compared to the flash steam and dry steam power plants, this geothermal power plant is advantageous because it requires slightly cooler water (as low as 57°C (135°F) to heat a binary fluid that has a lower boiling point. However, the binary cycle power plants have an efficiency rate of just 10-13%.

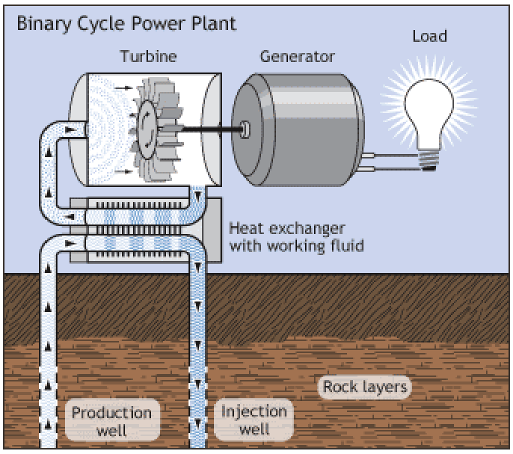


Figure 2.3 – Binary cycle power plant [2]

2.4 Advantages and disadvantages of geothermal energy

- Advantages

For as long as the Earth exists, there will be geothermal energy to harness. This puts it in the renewable category because the hot reservoirs used to extract geothermal energy are natural resources within the Earth. Unlike fossil fuels such as coal and natural gas, they are naturally replenished.

Geothermal energy’s impact on the environment is minimal. Producing geothermal energy does create some pollution. However, compared to the fossil fuel energy production, its carbon footprint is tiny.

Geothermal energy is able to be produced with minimal interruption, which means that geothermal energy is acceptable for meeting base load energy demand.

- Disadvantages

  The major disadvantage to geothermal energy is that for the most efficient use, they are geographically limited. The best use is from areas close to tectonic plate boundaries and areas of high volcanic activity. Near these areas, limitless supply of energy can be produced that will not deplete. While, in other areas, it may not be particularly intensive or profitable.

  While the harnessing of geothermal energy does not produce greenhouse gases, we must remember that a large volume of carbon, methane and other harmful gases do exist beneath the surface. During the digging process, these gases are often released into the atmosphere.

  There’s a heavy upfront cost. Building large geothermal power plant can be expensive and intense, and maintenance costs may be high. However, in the long run, it will still be a cheaper alternative than dwindling fossil fuel sources.

3 Hydropower Energy

On Earth, water evaporates from the oceans, forming into clouds, falling out as rain and snow, gathering into streams and rivers, and flowing back to the sea. This constant movement of water, known as the hydrologic cycle, provides an opportunity to harness a useful and renewable form of energy. Today, harnessing the power of moving water to generate electricity is known as hydroelectric power or hydropower and is done by a hydroelectric power plant. In fact, humans have been taking advantage of this source of energy for centuries. Farmers, since the ancient Greeks, have used water wheels to grind wheat into flour. Placed in a river, a water wheel picks up flowing water in buckets located around the wheel. The kinetic energy of the flowing river turns the wheel and is converted into mechanical energy that runs the mill. [3]

3.1 Working principle and components of a hydroelectric power plant

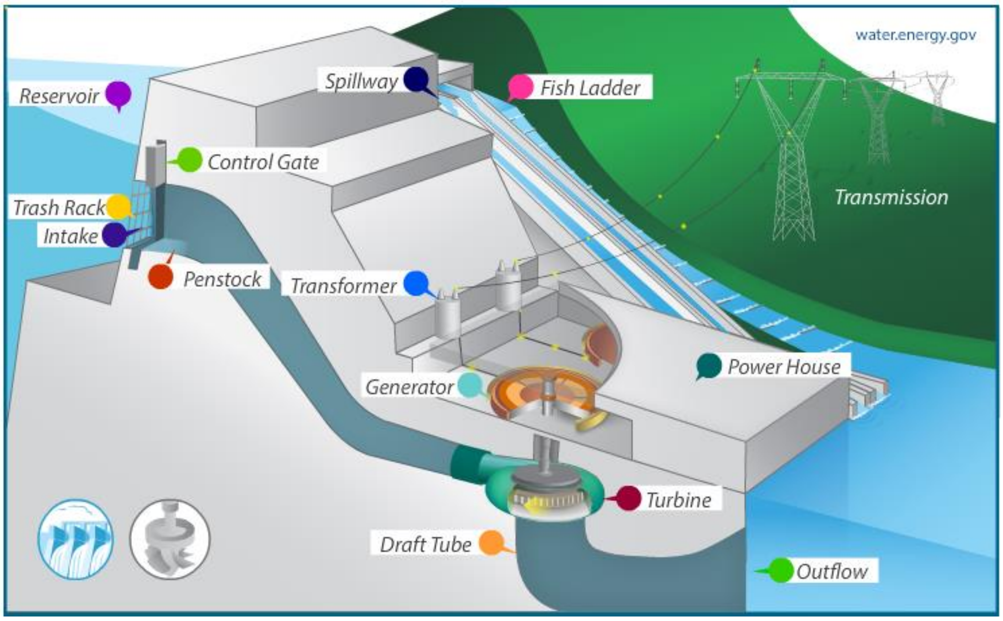


Figure 3.1 – Hydroelectric power plant [4]

Reservoir: The body of water that builds up behind many dams. The stored energy that is contained in the reservoir is converted into kinetic energy once the control gate opens and the water flows through it.

Trash Rack: A screen typically comprised of metal or concrete bars that prevents debris from entering the penstock.

Intake: The section of the reservoir immediately in front of the control gate where water is drawn into the penstock.

Penstock: Water travels into this channel from the intake, forcing it to run through the turbine.

Control Gate, Turbine: As water runs through the blades of the turbine, it forces them to spin, turning a shaft that is connected to the generator. Pictured is Francis, the most common type of hydropower turbine. Kaplan and Pelton are the other major hydropower turbine types.

Spillway: This structure allows water to be released in a controlled fashion from the dam downstream into the river, controlling flood situations – "a safety valve" for the facility.

Fish Ladder: This structure allows fish to migrate past a dam by providing them a series of steps to swim and leap up to reach the other side of the dam.

Transformer: Here, the electricity produced is converted to a higher voltage to travel into the transmission grid.

Generator: As the turbine runner is moved by water the connected shaft spins the generator producing the electricity.

Power House: This section houses the generators, turbines, and the controls.

Draft Tube: After water exits the turbine the draft tube slows down the water to keep the turbine under a more constant pressure, which increases turbine efficiency.

Outflow: The measure of water released from the dam during a certain period, typically expressed as acre-feet per day or cubic feet per second.

Transmission: Here, the electricity produced is converted to a higher voltage to travel into the transmission grid.

3.2 Calculation of the hydroelectric power

The total power generation capacity of the hydroelectric power plant depends on the flowing water which possesses two types of energy: The kinetic energy due to flow of water and the potential energy due to the height of the water. Therefore, the formula for total power that can be generated in a hydroelectric power plant is:

$$\mathbf{P} = \boldsymbol{\eta} \cdot \boldsymbol{\rho} \cdot \boldsymbol{Q} \cdot \boldsymbol{g} \cdot \boldsymbol{h}$$

Where,

$\mathbf{P}\ [\mathbf{W}]$:	Power
$\boldsymbol{\eta}$ [%]:	Efficiency of the turbine
$\boldsymbol{\rho}\ [\boldsymbol{kg/m^3}]$:	Density of water
$\boldsymbol{Q}\ [\boldsymbol{m^3/s}]$:	Flow rate
$\boldsymbol{g}\ [\boldsymbol{m/s^2}]$:	Acceleration due to gravity
$\boldsymbol{h}[\boldsymbol{m}]$:	Height difference between inlet and outlet

3.3 Types of hydroelectric power plants

There are three main types of hydropower facilities: storage, run of river and pumped storage hydropower. The main difference between these 3 types of hydropower is the method at which the water is stored and used to pass the turbine.

- Storage Hydropower [5]

  It's the most common type of hydroelectric power plant which is also often called impoundment facility. Typically a large hydropower system, an impoundment facility uses a dam to store river water in a reservoir. Water released from the reservoir flows through a turbine, spinning it, which in turn activates a generator to produce electricity. The water may be released either to meet changing electricity needs or to maintain a constant reservoir level.

Figure 3.2 – Storage hydroelectric power plant [6]

- Run Of River Hydropower

  Normally, it does not need a storage reservoir because it uses the natural current of the river to rotate a turbine. A separate canal or penstock is constructed in the river in order to divert some of the water flow to be used to generate electricity. As a result, it generates a continuous supply of electricity. During times of low electrical use, water flow is limited in the canals.

Figure 3.3 – Run of river hydroelectric power plant [6]

- Pumped Storage Hydropower [7]

  Two reservoirs are used to reuse the same supply of water. One reservoir is placed at a higher elevation and another at a lower elevation. During peak hours of electrical use, the higher elevated reservoir is opened to allow water to flow through a turbine towards the lower reservoir. During times of low use such as dawn, water is pumped back to the higher elevated reservoir from the lower reservoir for future use.

Figure 3.4 – Pumped storage hydroelectric power plant [6]

3.4 Working principle and basic components of hydroelectric turbine

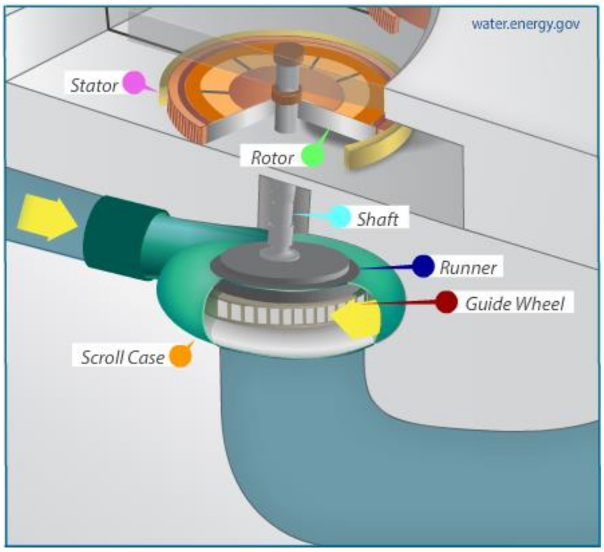


Figure 3.5 – Hydroelectric turbine [8]

Stator: Often made of a series of magnets, is the stationary part of a rotary generator system. The water moves the runner, which spins the shaft and the conductive rotor inside the stationary magnetic stator producing an alternating electric current.

Rotor: Often made of copper wire or other conductive material, is the spinning part of a rotary generator system.

Shaft: Connects the turbine with generator.

Runner: The Blades of Turbine are known as the runner, and their shape determines the flow of water and amount of energy extracted.

Guide Wheel: Is used to focus the flow of water directly onto the turbine blades, which are also called the runner.

Scroll Case: Allows water to travel smoothly from the penstock through the turbine.

3.5 Advantages and Disadvantages of hydropower energy

- Advantages

  Hydroelectric power is widely considered both a reliable and efficient electricity source. Hydroelectricity production can be constant and some countries have been successful in producing a large proportion of their total electricity capacity from it.

  It is both clean and renewable. No fossil fuels have to be burnt to produce hydroelectricity and therefore there are no harmful emissions as a result. Water is a renewable energy source that will never run out. This also allows countries to become less reliant on external supplies of fossil fuels such as coal, oil and natural gas.

  Hydroelectric dams have a degree of flexibility when it comes to meeting real-time energy demands. When high or low volumes of electricity are required, operators of a hydroelectric dam can change the water intake to increase or decrease the flow of water into the dam thus generating the right level of electricity. This alteration can be completed in a very short space of time when compared to other traditional power stations.

  Hydroelectric power is very economical to produce once the initial hydroelectric dam has been constructed. Hydroelectric dams have very low operating and maintenance costs when compared to those of more traditional power stations.

- Disadvantages

  As mentioned previously, when a hydroelectric dam is built, a reservoir is formed behind one face of the dam wall. Depending on the size of the dam, this can have an impact over a large area as land is flooded as the reservoir fills which brings disastrous consequences for wildlife, fish and even plants. Changes in river levels, flow patterns and water temperature all contribute to how severe this impact will be.

  Hydroelectric dams are expensive to build. Lots of planning, engineering and construction is required before a dam can start producing power to start paying for itself. This process takes many years and results in a long pay back or return on investment.

  As hydroelectric dams have to be built in areas with the perfect conditions, the majority of these places have already been used for hydroelectric dam construction. Nowadays, there are limited places where we can build new dams that will provide the highest reliability and efficiencies.

4 Solar Energy

Solar energy is energy created by the heat and light of the sun. Solar power is produced when this energy is converted into electricity either directly using photovoltaics (PV) or indirectly using concentrated solar power.

4.1 Components and working principle of photovoltaic cells (PV) [9]

The mojer components of a PV cell are two layers of semiconductor material commonly composed of silicon crystals. Crystallized silicon is not a good conductor of electricity, but when impurities are intentionally added—a process called *doping*—the stage is set for creating an electric current.

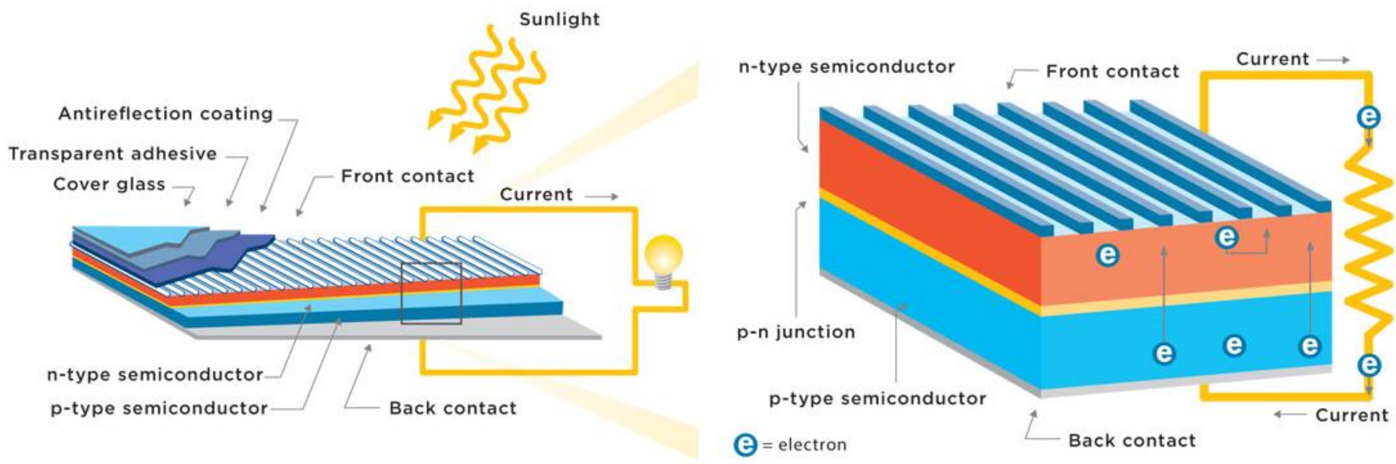


Figure 4.1 – Components of a photovoltaic cell [9]

The bottom layer of the PV cell is usually doped with boron, which bonds with the silicon to facilitate a positive charge (P), while the top layer is doped with phosphorus, which bonds with the silicon to facilitate a negative charge (N). The surface between the resulting "p-type" and "n-type" semiconductors is called the *P-N junction* (see diagram below). Electron movement at this surface produces an electric field that allows electrons to flow only from the p-type layer to the n-type layer.

When sunlight enters the cell, its energy knocks electrons loose in both layers. Because of the opposite charges of the layers, the electrons want to flow from the n-type layer to the p-type layer. But, the electric field at the P-N junction prevents this from happening. However, the presence of an external circuit provides the necessary path for electrons in the n-type layer to travel to the p-type layer. The electrons flowing through this circuit—typically thin wires running along the top of the n-type layer—provide the cell's owner with a supply of electricity.

Most PV systems are based on individual square cells a few inches on a side. Alone, each cell generates very little power (a few watts), so they are grouped together as *modules* or *panels.* The panels are then either used as separate units or grouped into larger *arrays*.

4.2 Types of semiconductors used in solar cells [10]

There are a variety of different semiconductor materials used in solar cells. Silicon, thin-film, and organic are the most commonly-used materials.

- Silicon

  Silicon is the most common material used in solar cells, representing approximately 90% of the modules sold today. It is also the second most abundant material on Earth (after oxygen) and the most common semiconductor used in computer chips. Crystalline silicon cells are made of silicon atoms connected to one another to form a crystal lattice. This lattice provides an organized structure that makes conversion of light into electricity more efficient.

  Solar cells made out of silicon currently provide a combination of high efficiency, low cost, and long lifetime. Modules are expected to last for 25 years or more, still producing more than 80% of their original power after this time.

- Thin-Film Photovoltaics

  A thin-film solar cell is made by depositing one or more thin layers of PV material on a supporting material such as glass, plastic, or metal. There are two main types of thin-film PV semiconductors on the market today: cadmium telluride (CdTe) and copper indium gallium diselenide (CIGS). Both materials can be deposited directly onto either the front or back of the module surface.

Cadmium telluride (CdTe) is the second-most common PV material after silicon and enables low-cost manufacturing processes. While this makes it a cost-effective alternative, its efficiency still isn't quite as high. CIGS cells have favourable electronic and optical properties, though the complexity is involved in combining four elements. Both CdTe and CIGS require more protection than silicon to enable long-lasting operation outdoors.

- Organic Photovoltaics

  Organic PV, or OPV, cells are composed of carbon-rich polymers and can be tailored to enhance a specific function of the cell, such as sensitivity to a certain type of light. This technology has the theoretical potential to provide electricity at a lower cost than silicon or thin-film technologies. OPV cells are only about half as efficient as crystalline silicon and have shorter operating lifetimes, but could be less expensive to manufacture in high volumes. They can also be applied to a variety of supporting materials, making OPV able to serve a wide variety of uses.

4.3 Types of solar cells [9]

There are three basic types of solar cells:

- Single-crystal cells

  They are made in long cylinders and sliced into thin wafers. While this process is energy-intensive and uses more materials, it produces the highest-efficiency cells. These cells are able to convert the most incoming sunlight to electricity. Modules made from single-crystal cells can have efficiencies of up to 23 percent. Single-crystal accounts for a little over one third of the global market for PV.

- Polycrystalline cells

  They are made of molten silicon cast into ingots then sliced into squares. While production costs are lower, the efficiency of the cells is lower too—with top module efficiencies close to 20 percent. Polycrystalline cells make up around half of the global PV market.

- Thin film cells

  They involve spraying or depositing materials (amorphous silicon, cadmium-telluride, or others) onto glass or metal surfaces in thin films, making the whole module at one time instead of assembling individual cells. This approach results in lower efficiencies, but can be lower cost. Thin film cells are around 10 percent of the global PV market.

4.4 Concentrating solar power

Concentrating solar power (CSP) technologies use mirrors to reflect and concentrate sunlight onto a single point where it is collected and converted into heat. This thermal energy can then be used to produce electricity.

Concentrating solar power systems are generally used for utility-scale projects. The mirrors in CSP plants focus sunlight onto a receiver that heats a high-temperature fluid, which is used to spin a turbine or power an engine that drives a generator. The final product is electricity.

4.5 Types of concentrating solar power systems [11]

- Linear concentrating solar power

Linear concentrating solar power (CSP) collectors capture the sun's energy with large mirrors that reflect and focus the sunlight onto a linear receiver tube. The receiver contains a fluid that is heated by the sunlight and then used to heat a traditional power cycle that spins a turbine that drives a generator to produce electricity. Alternatively, steam can be generated directly in the solar field, which eliminates the need for costly heat exchangers.

Linear concentrating collector fields consist of a large number of collectors in parallel rows that are typically aligned in a north-south orientation to maximize annual and summer energy collection. With a single-axis sun-tracking system, this configuration enables the mirrors to track the sun from east to west during the day, which ensures that the sun reflects continuously onto the receiver tubes.

Linear systems may incorporate thermal storage. In these systems, the collector field is oversized to heat a storage system during the day so the additional steam it generates can be used to produce electricity in the evening or during cloudy weather. There are two different types of linear concentrator power plants

The first linear concentrator technology is the parabolic trough system. The most common CSP system is the linear concentrator that uses parabolic trough collectors. In such a system, the receiver tube is positioned along the focal line of each parabola-shaped reflector. The tube is fixed to the mirror structure and the heat transfer fluid flows through and out of the field of solar mirrors to where it is used to create steam (or, in the case of a water/steam receiver, it is sent directly to the turbine).

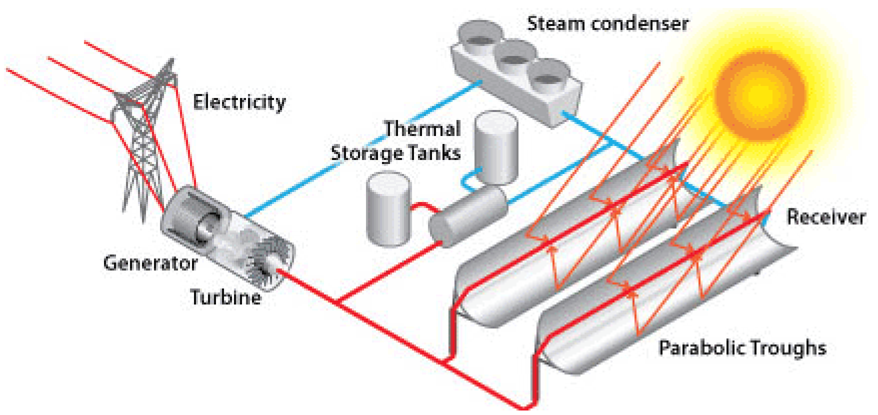


Figure 4.2 – Parabolic trough system [11]

A second linear concentrator technology is the linear Fresnel reflector system. Flat or slightly curved mirrors mounted on trackers on the ground are configured to reflect sunlight onto a receiver tube fixed in space above the mirrors. A small parabolic mirror is sometimes added atop the receiver to further focus the sunlight.

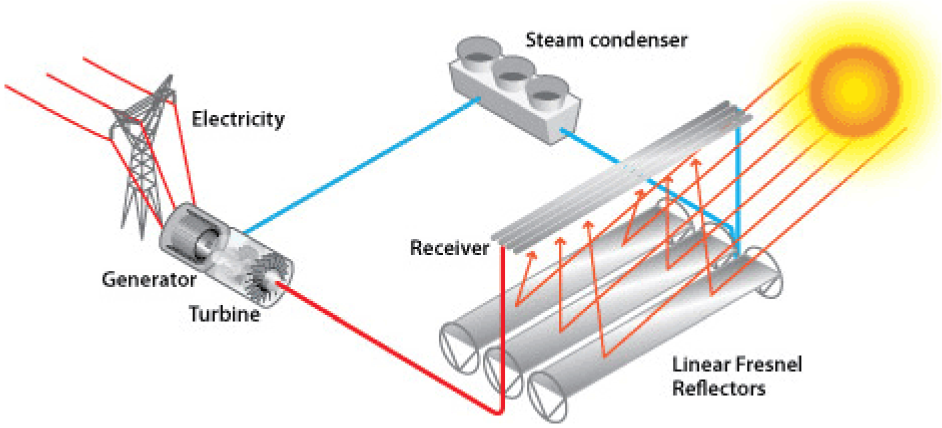


Figure 4.3 – Linear Fresnel reflector system [11]

- Dish/engine system concentrating solar power

Dish/engine systems use a parabolic dish of mirrors to direct and concentrate sunlight onto a central engine that produces electricity. The dish/engine system is a concentrating solar power (CSP) technology that produces smaller amounts of electricity than other CSP technologies—typically in the range of 3 to 25 kilowatts—but is beneficial for modular use. The two major parts of the system are the solar concentrator and the power conversion unit.

The solar concentrator, or dish, gathers the solar energy coming directly from the sun. The resulting beam of concentrated sunlight is reflected onto a thermal receiver that collects the solar heat. The dish is mounted on a structure that tracks the sun continuously throughout the day to reflect the highest percentage of sunlight possible onto the thermal receiver.

The power conversion unit includes the thermal receiver and the engine/generator. The thermal receiver is the interface between the dish and the engine/generator. It absorbs the concentrated beams of solar energy, converts the energy to heat, and transfers the heat to the engine/generator. A thermal receiver can be a bank of tubes with a cooling fluid—usually hydrogen or helium—that typically is the heat-transfer medium and also the working fluid for an engine. Alternate thermal receivers are heat pipes, where the boiling and condensing of an intermediate fluid transfers the heat to the engine.

The engine/generator system is the subsystem that takes the heat from the thermal receiver and uses it to produce thermal to electric energy conversion. The most common type of heat engine used in dish/engine systems is the Stirling engine. A Stirling engine uses the heated fluid to move pistons and create mechanical power. The mechanical work, in the form of the rotation of the engine's crankshaft, drives a generator and produces electrical power.

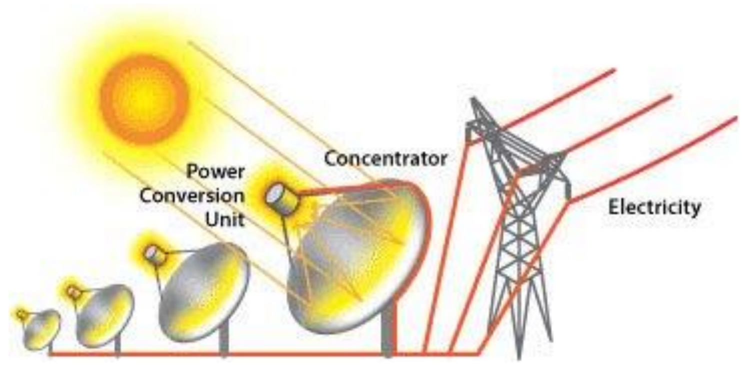


Figure 4.4 - Dish/engine system concentrating solar power [11]

- Power tower system concentrating solar power

  In power tower concentrating solar power systems, a large number of flat, sun-tracking mirrors, known as heliostats, focus sunlight onto a receiver at the top of a tall tower. A heat-transfer fluid heated in the receiver is used to heat a working fluid, which, in turn, is used in a conventional turbine generator to produce electricity. Some power towers use water/steam as the heat-transfer fluid. Other advanced designs are experimenting with high temperature molten salts or sand-like particles to maximize the power cycle temperature.

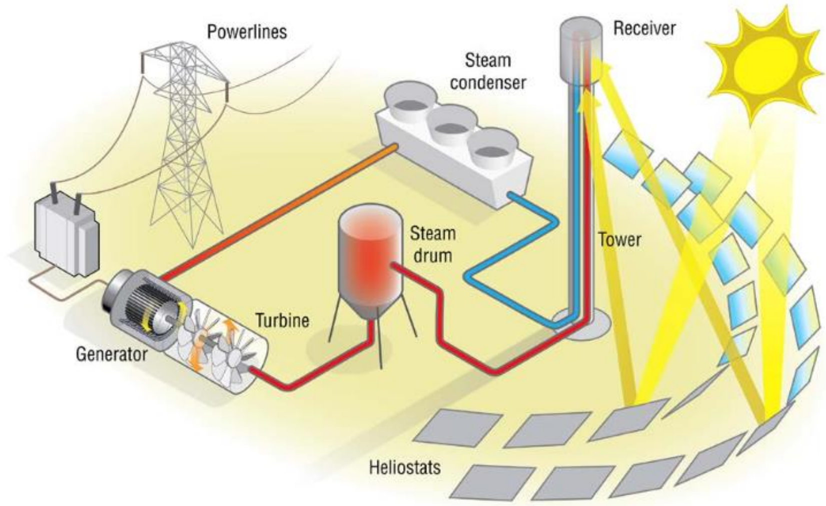


Figure 4.5 – Power tower system concentrating solar power [11]

4.6 Advantages and disadvantages of solar energy

- Advantages

  Solar energy which converts the sun's light and heat into electricity is renewable and inexhaustible until the death of the sun. Solar panels are fitted with photovoltaic cells that convert the ever abundant sun's rays into electrons and turn it into electricity.

  Once solar lights are installed, it does not cost much to maintain them. Good quality solar cells last for decades without the need to service or maintain them.

  Solar Energy is generally associated with lighting up houses, streets, communities, villages, towns and so on. However, solar energy is not only restricted to this. There are multiple other uses such as heating water at home, keeping houses warm, powering vehicles, powering airplanes, cooking, powering calculators, watches, clocks and many more.

Water is an ingredient that is used to generate electricity. There is, however, a shortage of fresh water throughout the world. The use of solar energy does not require the use of water. Since the energy from the sun is plentiful, solar energy indirectly helps in the conservation of water.

- Disadvantages

  The cost of setting up a solar power plant is high. This is due to the demand and supply curve. As the demand for solar energy increases, the cost would also decrease in time. However, since the energy generated after installation is absolutely free, in the long run, it works out to be the most inexpensive option for power generation.

  Though there is no shortage of sunlight on our planet, there are places in where the sun's rays barely reach the surface. It is also possible that more than one solar panel may be required to light up a house depending on the amount of sunlight available. Some parts of the world are too cloudy, shady or windy to effectively generate solar energy and light, which reduces the effectiveness of solar energy.

  Solar energy is very dependable. However, not all solar panels work at night. If the solar panels are not charged enough during the day, the efficiency is reduced. It would then not be reliable enough to provide a good amount of power to sustain an entire household or village.

  Installing solar panels at home or in corporate and IT parks require a good deal of empty land. This land should also be exposed to the sun. Due to this factor, not too many companies or houses have installed solar panels.

  Most solar panels are not 100% efficient. A good amount of electricity is generated using solar energy but 60% of energy ends up being wasted. Only 40% is actually utilized. To counter this, one has to conduct proper research and make sure that the solar panel being used is set up right and manages to harness most of the sun's rays in order to produce a good amount of electricity and increase its efficiency.

5 Wind Energy

Wind is created by the sun's uneven heating of the atmosphere, the earth's irregular surfaces (mountains and valleys), and the planet's revolution around the sun. Since wind is in plentiful supply, it is a sustainable resource for as long as the sun's rays heat the planet. Wind flow patterns are modified by the earth's terrain, bodies of water, and vegetative cover. Humans use this wind flow, or motion energy, for many purposes: sailing, flying a kite, and even generating electricity. This wind flow, or motion energy, when "harvested" by wind turbines, can be used to generate electricity. The ability to generate mechanical power or electricity using the wind flow that occur naturally in the earth's atmosphere is called wind power.

5.1 Conversion of wind energy

Wind turbines are used for the conversion of kinetic energy into electricity. They operate by using the kinetic energy of the wind, which pushes the blades of the turbine and spins a motor that converts the kinetic energy into electrical energy for consumer use. A wind farm is a set of wind turbines that are linked together to supply electricity to a local community or to an electricity grid for a larger population. Wind farms are often located along coastlines where the winds are strong.

5.2 Working principle of wind turbines [12]

Wind Turbines operate on a system comprised of many critical components that allow kinetic wind energy to be transformed into electrical energy. No matter the type of wind turbine system, they all work off the same principle that allows a generator to produce electricity. This principle is that if magnets are rotated around a coil of wire, or a coil of wire rotates within a magnetic field fast enough, electricity is produced.

5.3 Components of wind turbine [13]

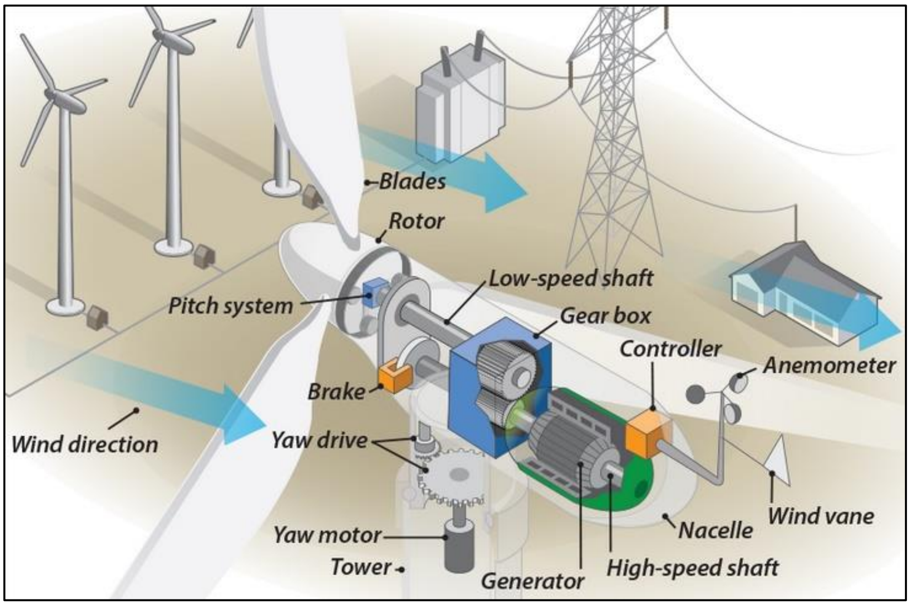


Figure 5.1 – Components of wind turbine [13]

Wind direction: Determines the design of the turbine.

Tower: Made from tubular steel, concrete, or steel lattice. Supports the structure of the turbine. Because wind speed increases with height, taller towers enable turbines to capture more energy and generate more electricity.

Blades: Lifts and rotates when wind is blown over them, causing the rotor to spin. Most turbines have either two or three blades.

Rotor: Blades and hub together form the rotor.

Pitch system: Turns blades out of the wind to control the rotor speed, and to keep the rotor from turning in winds that are too high or too low to produce electricity.

Brake: Stops the rotor mechanically, electrically, or hydraulically, in emergencies.

Low-speed shaft: Turns the low-speed shaft at about 30-60 rpm.

High-speed shaft: Drives the generator.

Gear box: Connects the low-speed shaft to the high-speed shaft and increases the rotational speeds from about 30-60 rpm, to about 1000 - 1800 rpm; this is the rotational speed required by most generators to produce electricity. The gear box is a costly and heavy part of the wind turbine. Engineers are exploring "direct-drive" generators that operate at lower rotational speeds and do not need gear boxes.

Generator: Produces 50 - cycle AC electricity; it is usually an off-the-shelf induction generator.

Controller: stars up the machine at wind speeds of about 13 to 26 kilometers per hour (km/h) and shuts off the machine at about 88 km/h. Turbines do not operate at wind speeds above 88 km/h because they may be damaged by the high winds.

Anemometer: Measures the wind speed and transmits wind speed data to the controller.

Wind vane: Measures wind direction and communicates with the yaw drive to orient the turbine properly with respect to the wind.

Nacelle: Sits atop the tower and contains the gear box, low- and high-speed shafts, generator, controller, and brake. Some nacelles are large enough for a helicopter to land on.

Yaw motor: Powers the yaw drive.

Yaw drive: Orients upwind turbines to keep them facing the wind when the direction changes. Downwind turbines don't require a yaw drive because the wind manually blows the rotor away from it.

5.4 Step by step process of operation of wind turbine

- Tower is constructed that puts the wind turbine system at the correct altitude where wind travels at a higher and more constant rate.
- Rotor blades are exposed to wind which forces them to start turning.
- As the rotor spins, the low-speed shaft, which is connected to a gearbox, spins at the same rate.
- The gearbox takes this slow rotational speed and through correct gearing turns it into a faster rotational speed.
- The high-speed shaft, which is on the outgoing end of the gearbox and connected to a generator, spins at a higher rate of speed.
- The generator spins at this high rate of speed which spins magnets around a coil of metal wire and generates electricity.
- The electricity travels from the generator through wires to the necessary applications.

5.5 Calculation of the wind power

The output of a wind turbine depends on the turbine's size and the wind's speed through the rotor.

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

Where,

$\boldsymbol{P}\ [\boldsymbol{W}]$: Output Power
$\boldsymbol{\rho}\ [\boldsymbol{kg/m^3}]$: Density of air
$\boldsymbol{A}\ [\boldsymbol{m^2}]$: Swept area of turbine
$\boldsymbol{V}\ [\boldsymbol{m/s}]$: Wind speed

5.6 Types of wind turbines

Basically, the wind turbines are divided into two types. On the basis of axis of rotation of the blades, it is divided into two parts; Horizontal axis wind turbine (HAWT) and vertical axis wind turbine (VAWT). Both types have their own advantages and disadvantages.

- ### Horizontal axis wind turbine (HAWT)

  Horizontal axis wind turbines are the common style of wind turbines. A HAWT has a similar design to a windmill, it has blades that look like a propeller that spin on the horizontal axis.

  Horizontal axis wind turbines have the main rotor shaft and electrical generator at the top of a tower, and they must be pointed into the direction of the wind. Small turbines are pointed by a simple wind vane placed square with the blades, while large turbines generally use a wind sensor coupled with a servo motor to turn the turbine into the wind. Most large wind turbines have a gearbox, which turns the slow rotation of the rotor into a faster rotation that is more suitable to drive an electrical generator.

  Since a tower produces turbulence behind it, the turbine is usually pointed upwind of the tower. Wind turbine blades are made stiff to prevent the blades from being pushed into the tower by high winds. Additionally, the blades are placed a considerable distance in front of the tower and are sometimes tilted up a small amount.

  Downwind machines have been built, despite the problem of turbulence, because they don't need an additional mechanism for keeping them in line with the wind. Additionally, in high winds the blades can be allowed to bend which reduces their swept area and thus their wind resistance. Since turbulence leads to fatigue failures, and reliability is so important, most horizontal axis wind turbines are upwind machines.

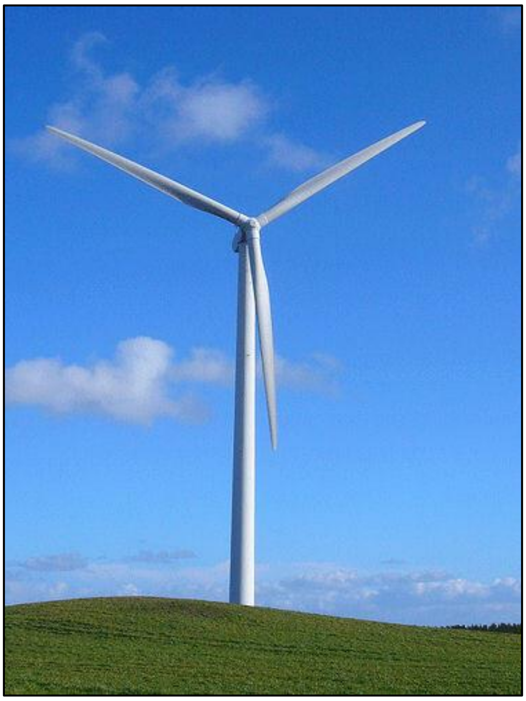


Figure 5.2 – Horizontal axis wind turbine [14]

- Advantages of HAWTs

  The tall tower base allows access to stronger wind in sites with wind shear. In some wind shear sites, every ten meters up the wind speed can increase by 20% and the power output by 34%.

  They have a high efficiency, since the blades always move perpendicularly to the wind, receiving power through the whole rotation. In contrast, all vertical axis wind turbines, and most proposed airborne wind turbine designs, involve various types of reciprocating actions, requiring airfoil surfaces to backtrack against the wind for part of the cycle. Backtracking against the wind leads to lower efficiency.

- Disadvantages of HAWTs

  Massive tower construction is required to support the heavy blades, gearbox, and generator.

  Their height makes them obtrusively visible across large areas, disrupting the appearance of the landscape and sometimes creating local opposition.

  Downwind variants suffer from fatigue and structural failure caused by turbulence when a blade passes through the tower's wind shadow.

  HAWTs require an additional yaw control mechanism to turn the blades toward the wind.

  HAWTs generally require a braking or yawing device in high winds to stop the turbine from spinning and damaging itself.

- Vertical axis wind turbines (VAWT)

  Vertical axis wind turbines have the main rotor shaft arranged vertically. The main advantage of this arrangement is that the wind turbine does not need to be pointed into the wind. This is an advantage on sites where the wind direction is highly variable or has turbulent winds.

  With a vertical axis, the generator and other primary components can be placed near the ground, so the tower does not need to support it, also makes maintenance easier. The main drawback of a VAWT is it generally creates drag when rotating into the wind.

  It is difficult to mount vertical-axis turbines on towers, meaning they are often installed nearer to the base on which they rest, such as the ground or a building rooftop. The wind speed is slower at a lower altitude, so less wind energy is available for a given size turbine. Air flow near the ground and other objects can create turbulent flow, which can introduce issues of vibration, including noise and bearing wear which may increase the maintenance or shorten its service life. However, when a turbine is mounted on a rooftop, the building generally redirects wind over the roof, thus doubling the wind speed at the turbine. If the height of the rooftop mounted turbine tower is approximately 50% of the building height, this is near the optimum for maximum wind energy and minimum wind turbulence.

Figure 5.3 – Vertical axis wind turbine [14]

- Advantages of VAWTs

  - They can produce electricity in any wind direction.
  - Strong supporting tower in not needed because generator, gearbox and other components are placed on the ground.
  - Low production cost as compared to horizontal axis wind turbines.
  - As there is no need of pointing turbine in wind direction to be efficient so yaw drive and pitch mechanism is not needed.
  - Easy to transport from one place to other.
  - Low maintenance costs.
  - They can be installed in urban areas.
  - Low risk for human and birds because blades moves at relatively low speeds.
  - They are particularly suitable for areas with extreme weather conditions, like in the mountains where they can supply electricity to mountain huts.

- Disadvantages of VAWTs

  - As only one blade of the wind turbine works at a time, efficiency is very low compared to horizontal axis wind turbines.
  - They need an initial push to start; this initial push that to make the blades start spinning on their own must be started by a small motor.
  - When compared to horizontal axis wind turbines they are very less efficient because of the additional drag created when their blades rotate.
  - They have relative high vibration because the air flow near the ground creates turbulent flow.

5.7 Sizes of wind turbines [15]

Utility-scale turbines range in size from 100 kilowatts to as large as several megawatts. Larger wind turbines are more cost effective and are grouped together into wind farms, which provide bulk power to the electrical grid.

Offshore wind turbines are larger, can generate more power, and do not have the same transportation challenges of land-based wind installations, as the large components can be transported on ships instead of on roads.

Single small turbines below 100 kilowatts are used for homes, telecommunications dishes, or water pumping. Small turbines are sometimes used in connection with diesel generators, batteries, and photovoltaic systems. These systems are called hybrid wind systems and are typically used in remote, off-grid locations where a connection to the utility grid is not available.

5.8 Advantages and disadvantages of wind energy

- ### Advantages

  It's a clean fuel source. Wind energy doesn't pollute the air like power plants that rely on combustion of fossil fuels, such as coal or natural gas. Wind turbines don't produce atmospheric emissions that cause acid rain or greenhouse gasses.

  It's sustainable. Wind is actually a form of solar energy; winds are caused by the heating of the atmosphere by the sun, the rotation of the earth, and the earth's surface irregularities. For as long as the sun shines and the wind blows, the energy produced can be harnessed to send power across the grid.

  Wind power is cost effective. It is one of the lowest-priced renewable energy technologies available today.

  Wind turbines can be built on existing farms or ranches. This greatly benefits the economy in rural areas, where most of the best wind sites are found. Farmers and ranchers can continue to work the land because the wind turbines use only a fraction of the land. Wind power plant owners make rent payments to the farmer or rancher for the use of the land providing landowners with additional income.

- ### Disadvantages

  Depending on how energetic a wind site is, the wind farm may or may not be cost competitive. Even though the cost of wind power has decreased in the past 10 years, the technology requires a higher initial investment than fossil-fuel generators.

  Good wind sites are often located in remote locations, far from cities where the electricity is needed. Transmission lines must be built to bring the electricity from the wind farm to the city.

  Wind resource development may not be the most profitable use of the land. Land suitable for wind turbine installation must compete with alternative uses for the land, which may be more highly valued than electricity generation.

  Turbines may cause noise and visual pollution. Although wind power plants have relatively little impact on the environment compared to other conventional power plants, there is some concern over the noise produced by the rotor blades.

The turbine blades may damage local wildlife. Sometimes birds have been killed by flying into the rotors. Most of these problems have been resolved or greatly reduced through technological development.

6 Rules for connecting dispersed energy sources to the distribution network

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

6.3 Parameters and Terminology of PQ

1) Reactive power and power factor (cos φ)

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.

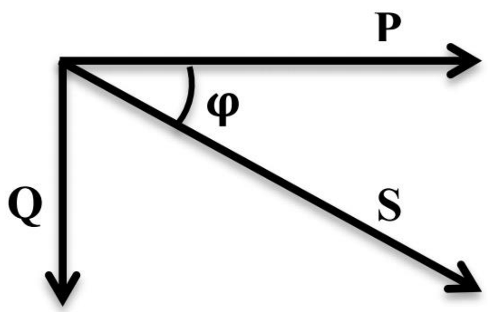


Figure 6.1: Basic Power in AC systems

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.

2) 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.

3) 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 %.

4) 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.

7 Case Study

In this case study, we are testing the impact of wind power plant with installed capacity 1000 kW to distribution network 22 kV in Southern part of Central Bohemia region. We are also demonstrating the voltage characteristics before and after connection of wind power plant to distribution network with two different power factor values ($\cos\varphi = 0.95$ and $\cos\varphi = 0.98$).

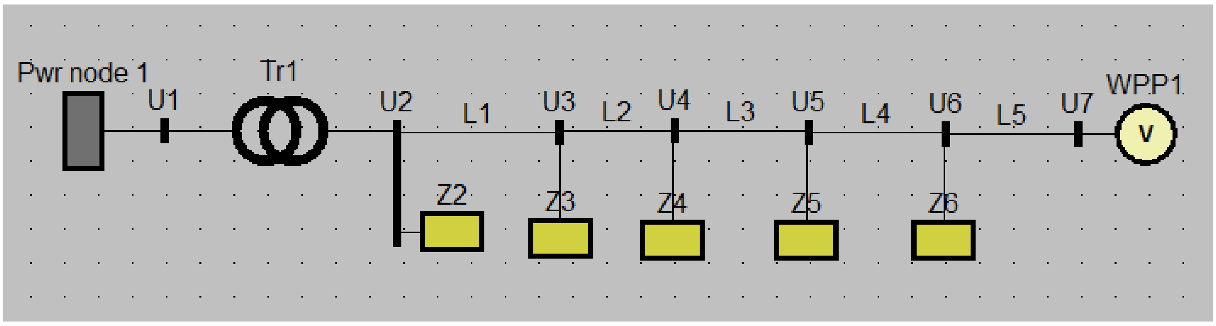


Figure 7.1 – Network Topology [16]

- Transformer (Tr1) parameters

Manufacturer	Type	$U_{n1}[kV]$	$U_{n2}[kV]$	$S\ [MVA]$
Škoda	8 ERH 33 M-O	110	23	40

Table 7.1

- Overhead lines

Name of the line	Start of the Line	End of the Line	Distance [km]
L1	U2	U3	5
L2	U3	U4	4
L3	U4	U5	6
L4	U5	U6	4
L5	U6	U7	5

Table 7.2

- Overhead lines parameters

Name of Line	Type	$R\ [\Omega/km]$	$X\ [\Omega/km]$	$B\ [\mu S/km]$	$I_{max}[A]$
L1 – L5	110/22AlFe6	0,259	0,368	1,46	318

Table 7.3

- Consumption

Consumer	Node number	Load [kVA]
Z2	U2	25000
Z3	U3	100
Z4	U4	100
Z5	U5	100
Z6	U6	100

Table 7.4

7.1 Calculation results [16]

The input data is used in application E-Vlivy that enables calculation of influence of a wind power plant into a distribution network.

- Voltage difference before and after connection of Wind Power Plant (WPP1) with power factor ($\cos\varphi = 0.95$) into distribution network

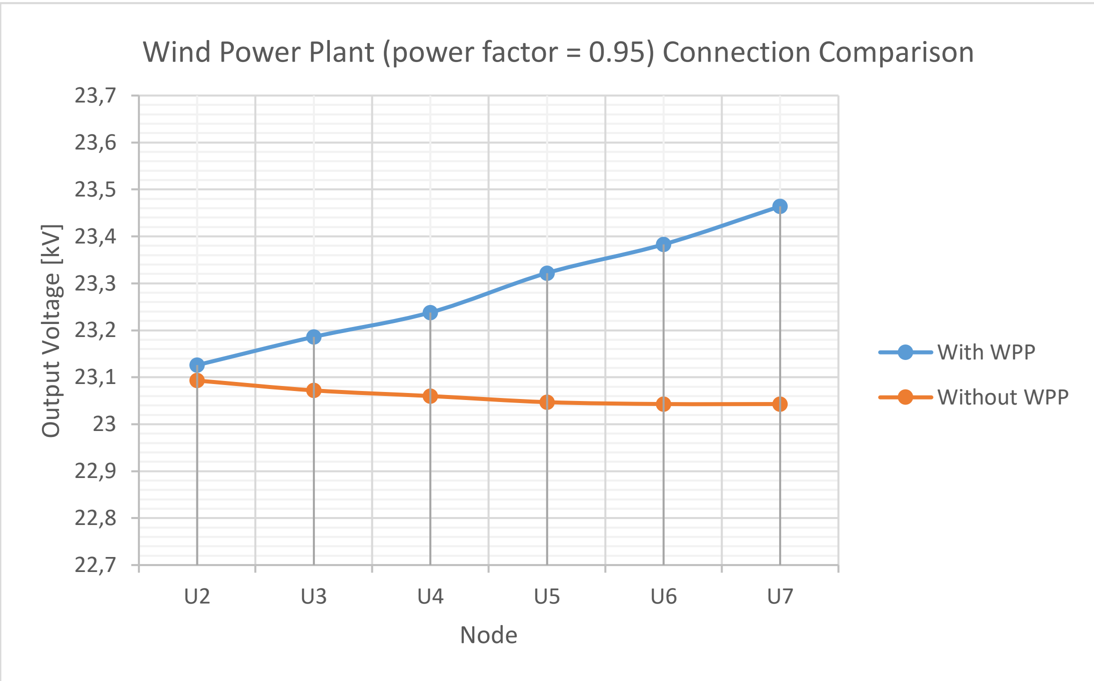
Node	dU before [%]	dU after [%]	Difference
U2	-4,970	-5,120	-0,150
U3	-4,874	-5,391	-0,518
U4	-4,817	-5,627	-0,812
U5	-4,759	-6,010	-1,253
U6	-4,740	-6,286	-1,547
U7	-4,741	-6,654	-1,915

Table 7.5

- Output voltage difference before and after connection of Wind Power Plant (WPP1) with power factor ($\cos\varphi = 0.95$) into distribution network

	WPP1 Connected	WPP1 NOT Connected	
	U [kV]		Sk [MVA]
U2	23,126	23,093	282,257
U3	23,186	23,072	127,220
U4	23,238	23,060	86,954
U5	23,322	23,047	58,745
U6	23,383	23,043	48,263
U7	23,464	23,043	39,449

Table 7.6



Graph 7.1

- Voltage difference before and after connection of Wind Power Plant (WPP1) with power factor ($\cos\varphi = 0.98$) into distribution network

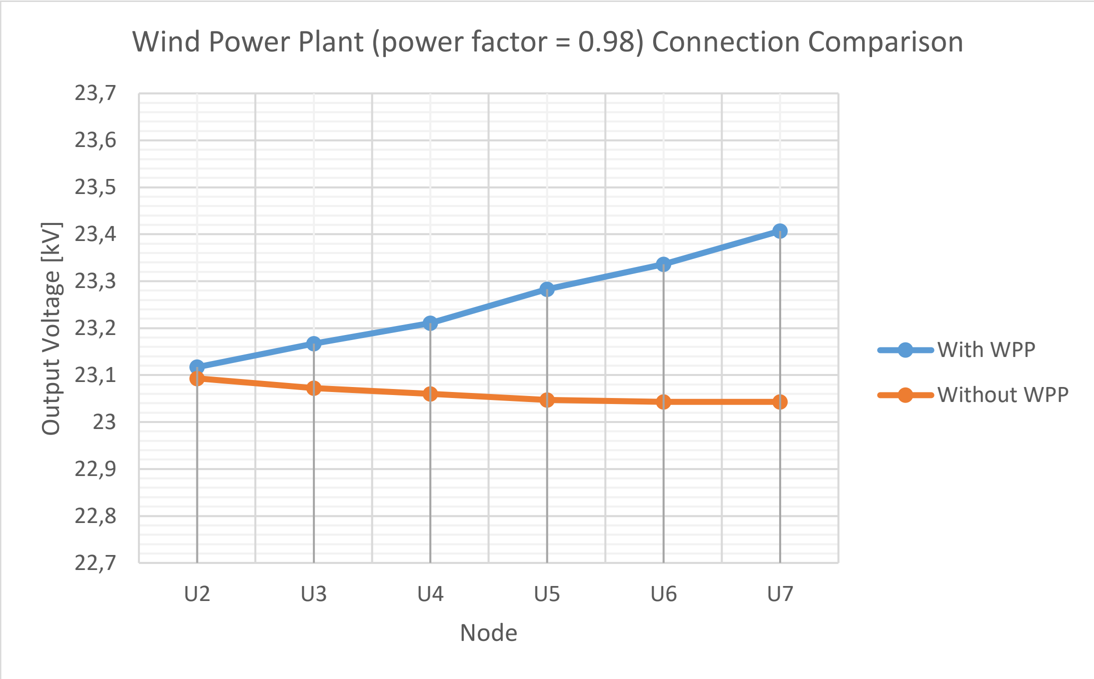
Node	dU before [%]	dU after [%]	Difference
U2	-4,970	-5,076	-0,107
U3	-4,874	-5,303	-0,430
U4	-4,817	-5,503	-0,688
U5	-4,759	-5,833	-1,076
U6	-4,740	-6,073	-1,335
U7	-4,741	-6,397	-1,659

Table 7.7

- Output voltage difference before and after connection of Wind Power Plant (WPP1) with power factor ($\cos\varphi = 0.98$) into distribution network

	WPP1 Connected	**WPP1 NOT Connected**	
	U [kV]		**Sk [MVA]**
U2	23,117	23,093	282,257
U3	23,167	23,072	127,220
U4	23,211	23,060	86,954
U5	23,283	23,047	58,745
U6	23,336	23,043	48,263
U7	23,407	23,043	39,449

Table 7.8



Graph 7.2

8 Conclusion

First, using the data from tables 7.5 and 7.6 and graph 7.1, we can conclude, that such a wind power plant with the given parameters when connected to the distribution network, that the maximal voltage difference (node U7) before and after connection of WPP1 (power factor: $\mathbf{cos\,\varphi = 0.95}$) into distribution network is $\mathbf{1.915}\%$. This difference does not exceed the limit, which is $\mathbf{2}\%$ by Czech standards.

Second, using the data from tables 7.7 and 7.8 and graph 7.2, we can conclude, that such a wind power plant with the given parameters when connected to the distribution network, that the maximal voltage difference (node U7) before and after connection of WPP1 (power factor: $\mathbf{cos\,\varphi = 0.98}$) into distribution network is $\mathbf{1.659}\%$. This difference does not exceed the limit, which is $\mathbf{2}\%$ by Czech standards.

Therefore, we can finally conclude that the connection of the wind power plant of power factor either $\mathbf{cos\,\varphi = 0.95}$ or $\mathbf{cos\,\varphi = 0.98}$ into the distribution network is fully acceptable since it does not cross the limits of the Czech standards.

9 References

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