Czech Technical University Prague

Faculty of Electrical Engineering

Department of Electrical Power Engineering

Diploma Thesis

Electricity quality issues when connecting renewable sources to a distribution network

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MASTER'S THESIS ASSIGNMENT

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1. General overview of RES
2. Description of WPP (principle, types, installed capacity)
3. Rules for connection of RES to a distribution network
4. Case study (Connection of WPP to 22 kV overhead line)

Bibliography / sources:

[1] Energy outlook 2017
[2] Distribution network code
[3] CSN EN 50 160
[4] eVlivy application manual

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III. Assignment receipt

The student acknowledges that the master's thesis is an individual work. The student must produce her thesis without the assistance of others, with the exception of provided consultations. Within the master's thesis, the author must state the names of consultants and include a list of references.

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Czech Technical University in Prague
Faculty of Electrical Engineering

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DIPLOMA THESIS ASSIGNMENT

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2. Description of WPP (principle, types, installed capacity)
3. Rules and standards for connection of RES to distribution network
4. Case study (Connection of WPP to 22 kV overhead line)

Bibliography/Sources:

[1] Energy world outlook 2018
[2] Distribution network code
[3] CSN EN 50 160
[4] E-Vlivy application manual

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Prague, February 22, 2019

Declaration

I declare that I have worked on my diploma thesis titled "Electricity quality issues when connecting renewable sources to a distribution network" by myself and I have used only the sources mentioned at the end of the thesis. As the author of the diploma thesis, I declare that the thesis does not break copyrights of any their person.

In Prague on___________________________

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I would like to thank everyone for their kind support and help for the completion of my thesis assignment. I am highly grateful to my supervisor Ing. František Vybíralík, CSc. for his guidance and constant supervision as well as providing all necessary information. After him, I express deepest thanks to my mentor Ing. Jan Kyncl, Ph.D for his entire support during my master course at Czech technical University in Prague.

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Problematika kvality elektřiny v distribuční síti při připojení obnovitelného zdroje

Abstrakt

Zvýšené povědomí o životním prostředí podpořilo využívání obnovitelných zdrojů energie jako alternativních zdrojů pro výrobu čisté a zelené energie. Větrná energie je v posledních letech významnou obnovitelnou energií.V diplomové práci je prezentován vliv výrobny elektřiny využívající obnovitelné zdroje energie připojené na distribuční síť. Tato diplomová práce předkládá kompletní simulační analýzu napěťového rozvodu 22kV pomocí simulačního softwaru E-Vlivy před a po připojení větrné elektrárny do distribuční soustavy v Libereckém kraji. Graficky byla charakterizována analýza zatížení a profil napětí v každém uzlu distribučního systému vysokého napětí.

Klíčová slova:

Obnovitelné zdroje energie, větrné elektrárny, větrné turbíny, fotovoltaické systémy, profil napětí, distribuční síť vysokého napětí, kvalita elektrické energie, vliv připojení výrobny elektřiny na distribuční síť

Electricity quality issues when connecting renewable sources to a distribution network

Abstract

Increased environmental awareness has encouraged the exploitation of renewable energy as the alternative sources to produce clean and green energy. Wind energy is the significant renewable energy in the recent years. The Impact of renewable energy sources connected to distribution network has been presented in detail. This master thesis presents a complete simulation analysis of medium voltage distribution line 22 kV with the help simulation software E-Vlivy before and after connection of WPP into the distribution system in Liberecký Region. The load flow analysis and voltage profile at each node of medium voltage distribution system has been characterized graphically.

Keywords: Renewable energy sources, Wind power plant, Photovoltaic system, Wind Turbine, Voltage Profile, Medium voltage distribution network, Power quality, Impact of wind power plant connecting to distribution network.

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List of Abbreviation

IEA	International Energy Agency
RES	Renewable Energy Sources
PV	Photovoltaic
DC	Direct Current
AC	Alternating Current
HAWT	Horizontal Axis Wind Turbine
VAWT	Vertical Axis Wind Turbine
WTG	Wind Turbine Generator
MV	Medium Voltage
LV	Low Voltage
DG	Distributed Generation
PCC	Point of Common Coupling
DOD	Department of Defense
IPP	Independent Power Producer
WPP	Wind Power Plant
PF	Power Factor
OH	Overhead
AC	Alternating Current
DC	Direct current
IG	Induction Generator

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1. INTRODUCTION

1.1. Current Energy Demand statistics

The population in the world is currently experiencing exponential growth and it is estimated to reach 8.5 billion by the end of 2030. Therefore, the demand of energy also increases, and the cost and availability of energy crucially affect the quality of life and economic balances of a country. World energy demand is continuously growing and the consumption of energy is expected to reach above 700 quadrillion Btu by 2030 [1]. Currently around 65% of world energy consumption is based on natural fuel sources like coal, oil and gas. Researchers predict that the fossil fuel will be depleted within 54 years based on current consuming rates. If we rely only on fossil fuels, the world will experience massive energy crisis and high price in near future. Moreover, the fossil fuels generates large amount of CO_2 emission which causes climate change. Therefore, long lasting, green and resourceful alternative sources have received considerable attention in the past decade (Figure 1).

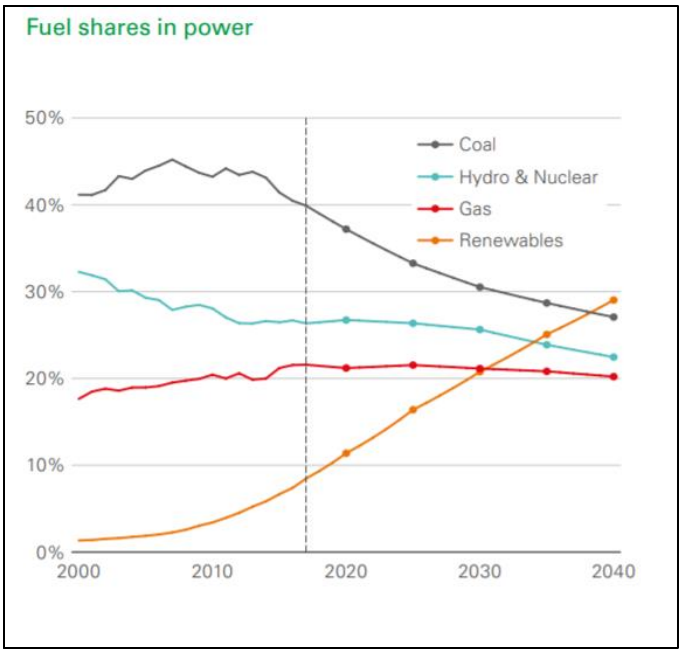


Figure 1. Forecasting of World renewable energy and fuel share till 2040 [2]

1.2. Advantages and disadvantages of renewable energy

Research and developments are enormously progressing on renewable energy systems like hydropower, tidal, wind power and solar energy to attain clean and green environment. They are produced from natural resources, and therefore can be reproduced or replaced by ecological processes in a short-term period. The main advantages of these renewable energy sources are, it is abundantly available, reproduced with in limited time and require low maintenance compared to conventional sources. Moreover, energy produced from renewable sources are clean and green, it reduces the contribution of greenhouse gases in the global warming. These energies can be generated in large scale as well as small scale and hence can be produced independently for individual household [3].

However, renewable energies are mostly produced on lower scale when compared to other resources. Most of these alternative sources are rely on the weather conditions. For instance, the wind energy production depends on the sites, availability, speed and wind direction. Similarly, solar power production efficiencies are much lower in cloudy days and cannot be generated during night. Due to high initial investment for renewable energy installation, most of the people won't be able to afford it. Various programmes and subsidies are available in many countries to promote the production of renewable energy system [3].

1.3 Renewable Energy in the World

The global renewable energy capacity amount reached to 2351 GW at the end of 2018 according to international renewable energy agency (IRENA) 2018 report [2, 4]. The installed capacity of hydro power plant is 1172 GW which is the largest share of the world total energy. Wind and solar energy are the next leading energies in the world with 564 GW and 486 GW installed capacities, respectively. Other renewable energies like biomass (115 GW), geothermal energy (13 GW) and marine energy (500 MW) are also hold a minimal share in the world renewable energy market. Renewable capacity elaborates continues to be driven mostly by new installations of solar and wind energy.

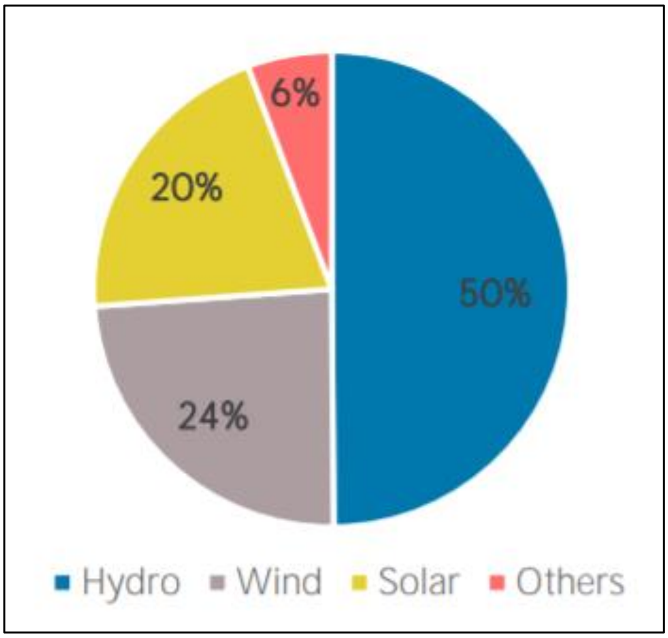


Figure 2. Renewable energy capacity in the world by energy sources [5]

Therefore, the the contribution of renewables in the growth of electricity has increased from 25% in 2001 to 63% in 2018 and the amount of total renewable energy production reached to 2.351 GW in 2018 [6]. The corresponding percentage contribution of energy sources in the renewable energy production is shown in Figure 2. The contribution of renewables in total production of electricity capacity has also increased from 22% to 33% over the same period.

2. TYPES OF RENEWABLE ENERGY SOURCES

Renewable energy is the energy generated from a source that do not diminish or can be naturally refilled within short period. It can be produced from various natural resources such as water, sunlight, tidal, wind and geothermal are considered as green and clean energy. The energy obtained from these sources is designated as according to their origin.

2.1. Wind energy

It is the highly developed renewable energy which produces energy from wind, where the kinetic motion of air converts in to mechanical energy with the help of wind turbines to produce electrical energy. The available quantity of power energy in the wind is related to the cube of the wind speed (v) and to the air density and it functions according to the temperature and altitude. The air density at the sea level at 15 ^oC is 1.225 kg m^{-3} and it decreases with increasing altitude.The efficiency of wind turbine determines the rotor area and the rotor power coefficient (C_p). Detail description about wind energy is provided in chapter 3.

2.2. Solar Energy

Sunlight is the most abundant renewable energy sources available in the nature. The radiant light from the sun is converted to various forms of energies such as solar energy, electric energy (photovoltaics) and solar thermal energy using different technologies [7]. The energy from the sun is converted to electricity with the help of solar panels are made up of photovoltaic cells. This amount of solar energy is more than that the world's anticipated energy requirements. Since the 21st century the solar energy attracted as renewable energy.

2.2.1. Solar power system generation and utilization

A solar power system consists of multiple PV panels, power converter and a rack system to hold PV panels. Solar light is a type of quantum mechanical particles which is known as photon. Solar cell (Figure 3) in the PV system is made up of semiconducting materials (Eg: Silicon) which absorbs photons and generate electron hole pair and thus produce electricity by photovoltaic effect. A typical solar cell and solar panel is shown in Figure 3. This energy can be used for various applications such as heating, cooling, and lighting. The first commercial solar power plant was constructed in 1980s and the biggest solar power plant in the world is located in the Mojave Desert of California which produces 392 MW of electricity [8].

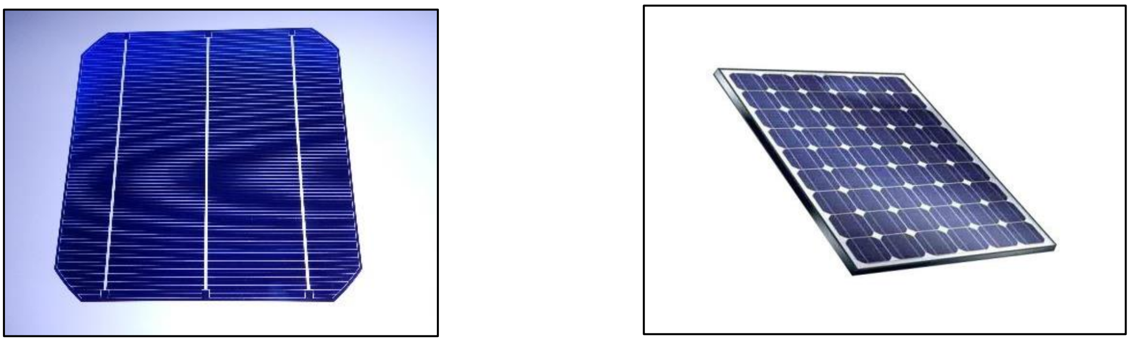


Figure 3. Photographs of typical Solar cell and Solar Panel

Photovoltaic system has many advantages than any other energy systems. They use only sunlight as fuel and hence the electricity produced by solar clean and noiseless. Also this system does not make any harmful to environment and never deplete natural resources. There are no moving parts and silicon used in the PV system is abundantly available in nature. Because of these reasons, PV energy is the most widely encouraged energy system today. The cost of PV systems is largely decreased in recent years because of the huge demand of photovoltaics. Different types of solar cell technologies are using to generate electricity such as crystalline technology, thin film and organic solar cell. The photovoltaic system can be functioned in two different ways, stand-alone system and grid connected system.

2.2.2. Principle of Operation of Solar Cell

The main semiconducting material used in the photovoltaic cell is silicon. Usually, the silicon is doped with other material and it becomes P-type silicon. When connected to n-type material the electrons flow from n-type to p-type materials and holes move from p-type to n-type. When photon hits the panel, it creates a thin potential barrier between them. This generated current by the movement of this process called diffusion current. The electric field is increasing due to movement of charge carriers. Drift current is generated by this process. At the beginning the diffusion current is higher than the drift current. After that potential difference higher caused by diffusion current and drift current is increase. The current does not flow when drift current and diffusion current are same [9] .

2.2.3. Types of Photovoltaic Systems

Grid Connected PV Systems

In grid connected systems, PV systems connected to utility grid where the excess power generated in the PV panel are transferred to the grid and receive power from the grid when generated power is lower than the demand of load. Therefore, grid connected systems do not require any energy storage devices. PV system produces large amount of power during maximum solar irradiance hours. Since the local grid supply utilizes the excess generated power, fewer conventional plants are required to work during this time [10]. The system generally employed of solar panels, one or several inverters, and equipment for grid connection. This type of PV system can be design for housings as well as large scale solar plant for commercial systems. A typical grid connected PV system is shown in Figure 4.

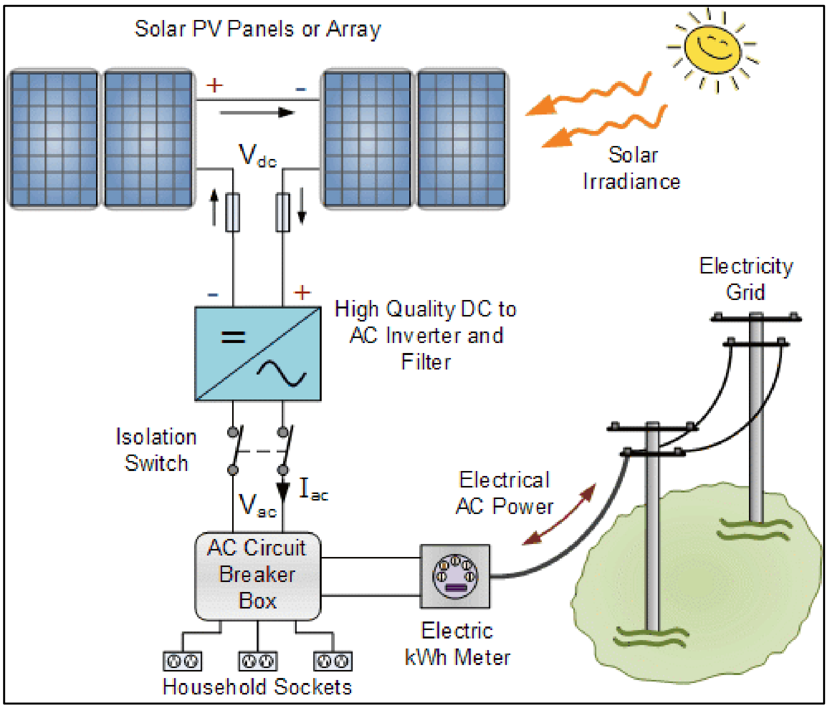


Figure 4. Structure of grid connected PV system [9] .

In grid connected solar system, the main component is the inverter for converting DC power from PV array to AC to the feeding grid or deliver power to domestic load. Two-way energy meters can be used to record grid and solar energy.

The solar radiation is different in each country and its intensity is depending on the weather. Figure 5 shows the solar radiation in the Czech Republic. The Photovoltaic installed capacity in the Czech Republic is around 2.08 GW. The Czech Republic energy sector are planning to generate 13.5% of total electricity capacity from the renewable sources by 2020 [8, 11].

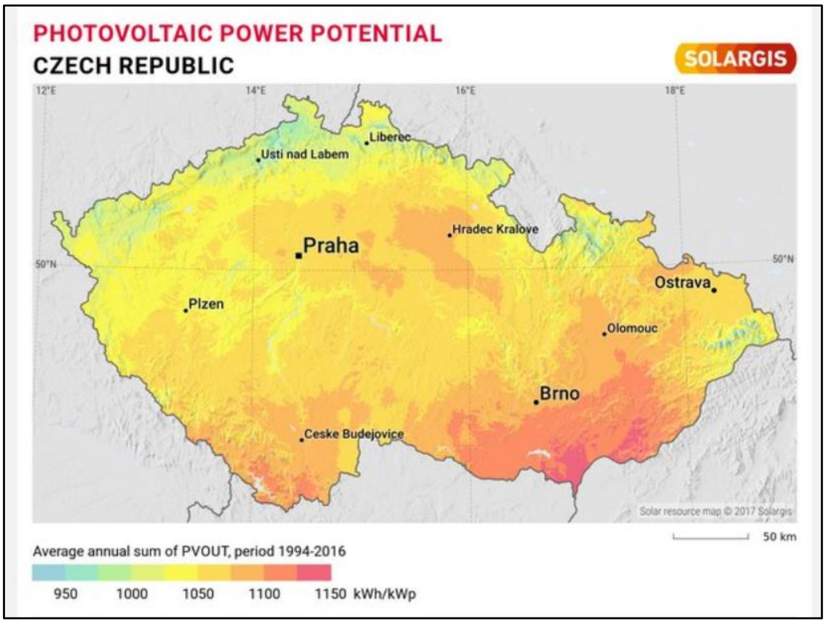


Figure 5. Photovoltaic power potential in the Czech Republic from 1994-2016 [12]

Stand-Alone System

Stand-alone PV system works without connecting to electric utility grid. Generally, this solar system is used in house hold and commercial operation. A typical structure of stand-alone PV system is shown in Figure 6.

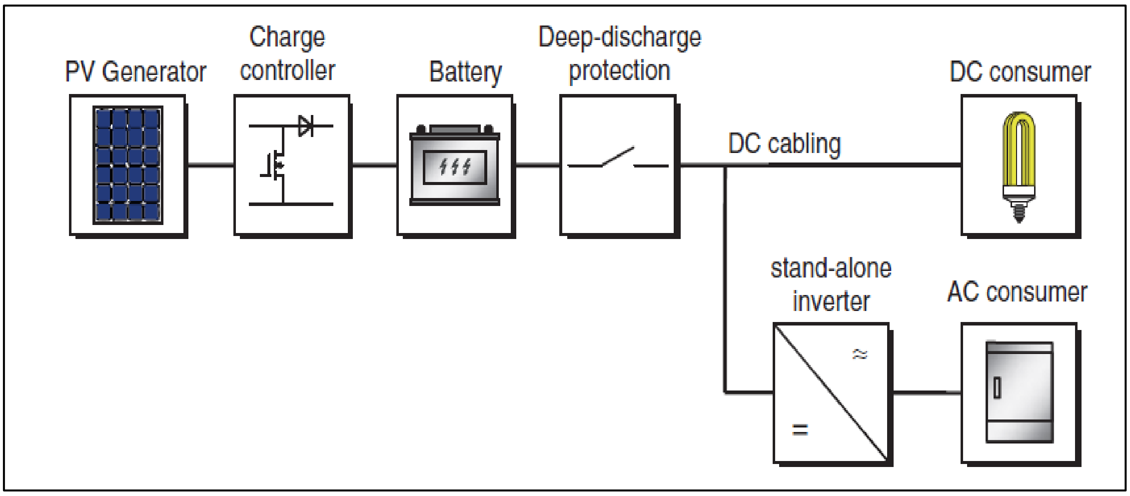


Figure 6. Structure of Stand-alone PV system [9] .

The charge controller in this system controls the overload condition and deep-discharge protects the battery. Since the load is not coupled, it prevents the damage of battery when voltage decreases below critical level. For DC loads the energy is given by DC cabling whereas for AC load is taken from stand-alone inverter.

The main element of stand-alone system is the energy storage i.e. batteries. The electrical energy stored in batteries can be used when the power generation from the PV systems is not obtainable. The different types of batteries are used to store the electricity such as lead batteries, nickel metal hydrate batteries, lithium-ion batteries, lithium-polymer batteries. The lead batteries are mostly used in standalone PV system [7].

The flow rate of electricity from the PV array to the load and battery is controlled by the charge controller. It controls the battery charging optimally to avoid over-charging. The controller permits the electricity flow from the PV array to either battery, load or both. As well as if the battery is completely charged, the controller limits or stops the flow of the charge from the array. In solar panels an DC equipment load can be used with charge controller. It delivers a controlled DC output energy and allows storing the excess energy as well as allows observing the battery voltage to avoid under or over charging. The maximum power point tracking task is performed by charge controller. Using the inverter in standalone system, AC equipment can operate by converting to DC voltage.

2.3. Hydro power

In hydro power plant, the potential energy of falling water is converted into kinetic energy using turbine and thus generate electricity though generator. The generated energy depends up on the product of pressure head and flow rate [13]. To calculate the power output for any hydropower system is given below[13, 14]

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

P generated mechanical power at the turbine shaft (W)

η turbine's hydraulic efficiency

ρ density of water (kg/m^3)

g acceleration due to gravity (m/s^2)

Q volume flow rate through the turbine (m^3/s)

H pressure head of water across the turbine (m)

An efficiency of 80 to above 90 % can be achieved with best turbines. The water is stored in a dam from the river, which is built across the river. The water reaches through the penstock from reservoir to the turbine blade. The penstock is a pipe which carry the water and this kinetic of water convert potential energy in penstock. The quantity of power generated by turbine relies on the potential energy of water. The flow of water in penstock is controlled by the intake gate. The water flow rate striking to the turbine blades regulated by the intake gate or sluice gate. To shut down or maintenance the turbine the sluice gate can be closed which is located at the top of the penstock. Water reversibly flows to the river when the sluice gate valve is closed. In case of flood, heavy rain, the spillway protects the dam from damage by over flooded water discharge and keep the safe water level of reservoir. The water coming from reservoir contains mud and impurities which purify by trash rack is located between the reservoir and turbine somewhere between the lengths of penstock. In hydro power plant, surge tank is the imported safety part which is mounted on the penstock. It protects the penstock from water hammering. When the pressure of water hitting on the turbine decreases rapidly then the flow of water to the turbine shuts down by gates controlling suddenly, it generate a high pressure in penstock.

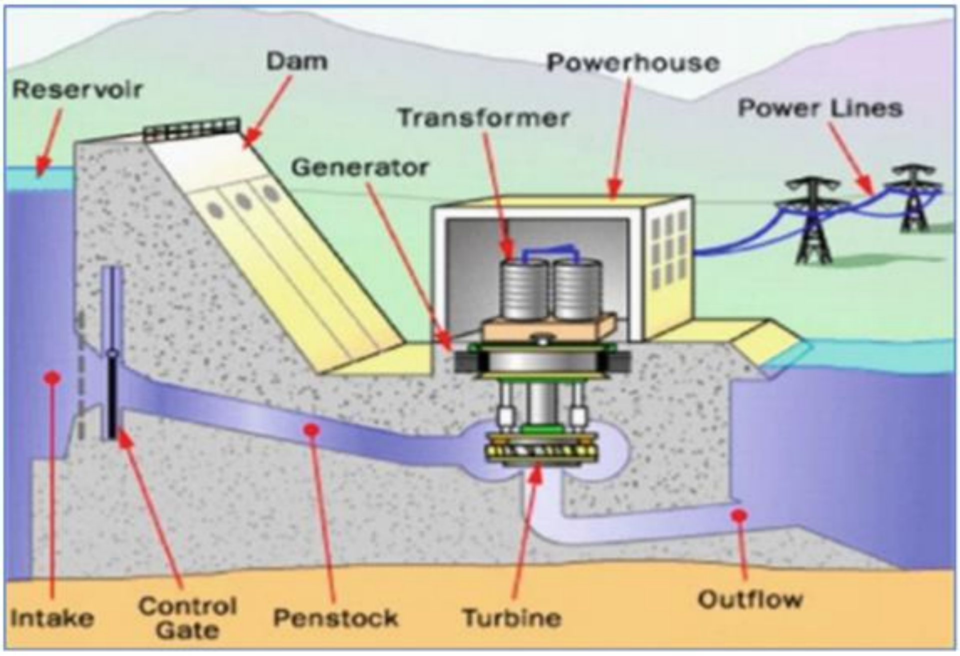


Figure 7. Components of hydro power plant [13]

High pressure of water leads to exploding the penstock, this high-pressure water is diverted to the surge tank for protect from collapsing the penstock. A turbine rotates when water hitting on it which rotate the shaft the produce electricity by generators. The selection of the turbine depends the location of the site, water flow rate etc. The different kinds of turbines are using hydrelectric plant which are impulse turbine and reaction turbine. The components of hydro power plant shown in Figure 7.

Impulse Turbine:

The function of impulse turbine is driven the turbine blades by kinetic energy of water and release to atmospheric temperature. It is normally used with high head and low flow. There are three types of impulse turbines are used in the hydropower systems namely Pelton, cross flow and Turgo. In this, Pelton turbines are used with the large water head.

Reaction turbine:

In this type of turbine the electricity produces from the mutual action of pressure and by moving water [15]. The rotor present in the reaction turbine is completely immersed in water by bounding in a pressure case. Unlike impulse turbine, these are commonly suitable for lower head and higher flows locations. These types reaction turbine are generally using which are Propeller, Francis and Kinetic. Francis is the widely used turbines in hydro power plants.

Different types of hydro Power Plant

The hydro power plant classified in to four which are Run-of-river hydropower, off shore hydro power, storage pumped-storage hydropower.

Run of river hydro power

This type of hydro power plants is mostly used in world wide. This type of hydro power plant is diverse in their appearance, engineered design, and impact from conventional large hydropower plants. The water reservoir is not used in this power plant except small head pond capacity [16]. The diverted water return back to the river stream below the power house and the environmental impact is very less in this type. The initial cost and design of the equipment is high. The water scarcity will affect the fluctuation of the production of electricity.

Storage hydropower

This is used to produce large scale electricity production. The water stored in the reservoir of the river is called dam. Electricity is generated by water discharging from the reservoir through a turbine triggers a generator. According to the requirement of the peak load the stored power delivers base load as well as helps to shut down or started up with minimal time. Because of enough storage capacity, it can operate independently of the hydrological inflow for many weeks. [17].

Pumped-storage hydropower

It is a vital solution for grid reliability. This type of hydropower store and produce electricity by moving water between two reservoirs at different potential. If the demand of electricity is minimal, the maximum energy is used to pump water to an upper reservoir [17]. The stored water in the reservoir will be released while the demand of electricity is high and while the water flowing from upper to lower reservoir generates electricity. When water flowing to uphill the turbine act as a pump [16].

Offshore hydropower

It is not popular one which is use the tidal current or tidal power to produce electricity from seawater [17].

2.4. Biomass Energy

Any source of heat energy produced from non-fossil materials are called biomass energy. This energy can be considered to any source of heat energy produced from non-fossil fuel biological material. It can be getting from ocean, fresh water habitat and land. The wood fire is the one of the biomass energy sources that was the important energy source before the industrial revolution. The plants utilize the solar energy energy by photosynthesis. The electricity produced from biomass burning which have same efficiency as fossil fuels [18].

2.5. Tidal Energy

The tides are produced by the interaction of the gravity of the sun earth and moon. In some cases, more than 12 month the rise and fall of the tides generates potential energy. In Europe, the tidal energy has been found around the 700 year before. Today, new technologies have developed considerably over the past few years and there are many new demonstration projects are introducing.

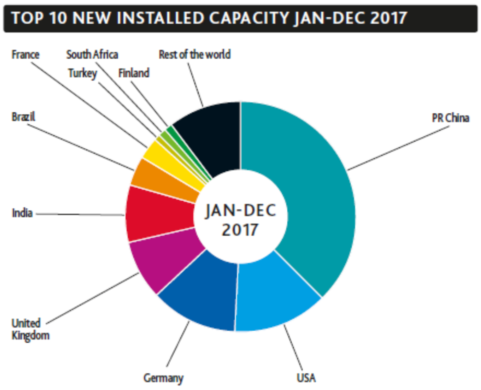
2.6. Geothermal Energy

This energy is heat which is produced from within earth surface. Due to rainfall water filled in the earth surface which is produce heat continuously. This heat energy can be used as renewable energy. High thermal energy (300 to 700 degrees Fahrenheit) is required for the geothermal plants which are come from either dry steam wells or hot water wells. This type of energies are utilized by drilling wells into the earth and piping the steam or hot water to the surface [19, 20].

3.WIND ENERGY GENERATION

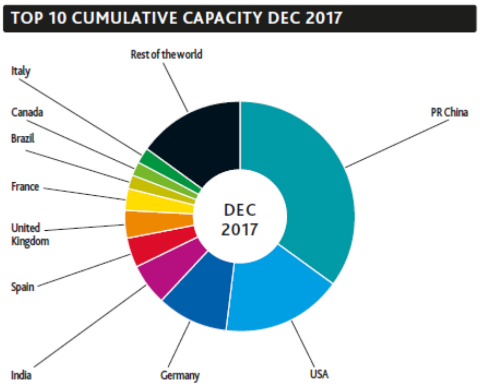
3.1. World wind energy

The global wind power market keeps on growing and global wind industry has installed more than 50 GW of each year since 2014. China detained the major market since 2009 and new annual installation made between 40-50% of global market. European Union maintained annual installation between 30-40% with 10 GW and above installation in each year and EU will probably increase the installation up to 12-14 GW annually till 2023 [21]. The total global installation brings to 539.1 GW with addition of 52.5 GW wind installations in 2017. It was 3.8% down on 2016's in annual market where as the cumulative total was increased 11% over 2016's year-end total of 487.3 GW [6]. In offshore market, it was record growth with 4.3 GW of installation and cumulative capacity 30% progress was done shown in Figure 8.



Country	MW	% Share
PR China	19,660	37
USA	7,017	13
Germany	6,581	12
United Kingdom	4,270	8
India	4,148	8
Brazil	2,022	4
France	1,694	3
Turkey	766	1
South Africa	618	1
Finland	535	1
Rest of the world	5,182	10
Total TOP 10	**47,310**	**90**
World Total	**52,492**	**100**

Source: GWEC



Country	MW	% Share
PR China	188,392	35
USA	89,077	17
Germany	56,132	10
India	32,848	6
Spain	23,170	4
United Kingdom	18,872	4
France	13,759	3
Brazil	12,763	2
Canada	12,239	2
Italy	9,479	2
Rest of the world	82,391	15
Total TO P10	**456,732**	**85**
World Total	**539,123**	**100**

Source: GWEC

Figure 8. Installed capacity of wind power in 2017 [6]

According to survey of world wind agency, the global energy market has only 8% growth in offshore, but it will be expected to increase very quickly in the upcoming years (Figure 8). In India, new installation of 4.1 GW was added in 2017 and became the second largest market place in Asia. The dramatic increases are expected in Indian market after 2019. Indian government target is to meet 175 GW of renewable capacity by 2022, with 60 GW of energy from wind [6] . After china, USA is the second largest market in terms of total installed capacity. Figure 8 shows the installed capacity of wind all over the world comparison in January – December 2017 and December 2017.

3.2. Europe wind energy

The aim of European Union (EU) is to become the global leader in renewable energy technology and reduce conventional energy system 2050 to ensure a green, inexpensive and reliable energy supply for all European citizens and businesses. EU is promoting the renewable energy in all part of the life such as heating, cooling, transport etc. In European power system wind energy will be most dominant energy system. Wind energy capacity in the EU could increase by 2030 from 160 GW to 323 GW which becomes close to 30% of the EU's power demand [22]. Moreover, the societal benefits and supplying consumers with safe clean and emission free energy at reasonable costs, this growth could also give job opportunities in Europe and also increase the EU's GDP.

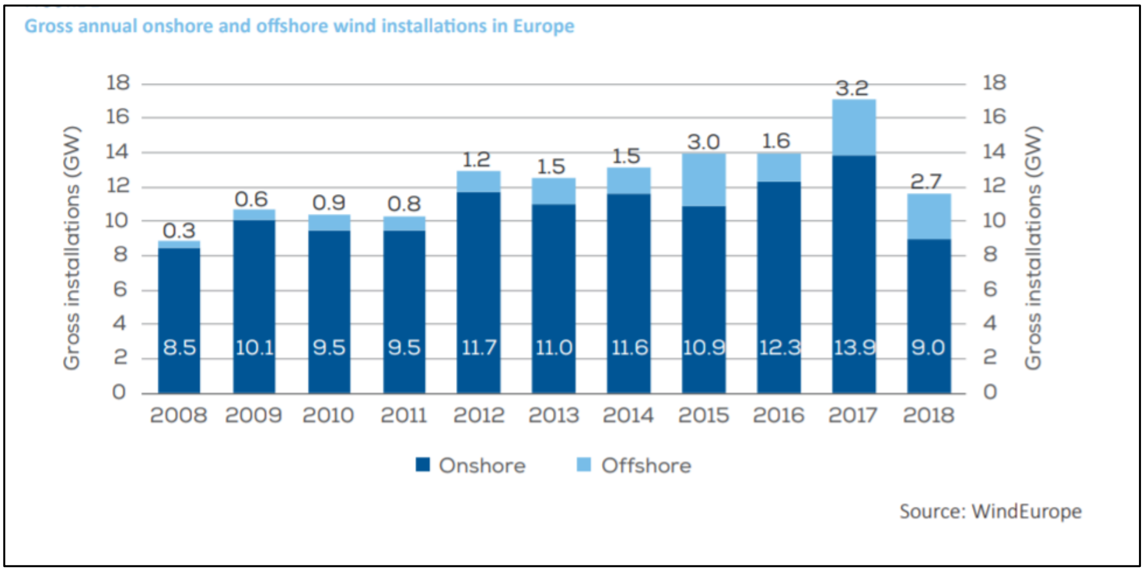


Figure 9. The gross annual off shore and on shore wind installation in Europe [22]

To achieve this goal, further strengthening and more commitment to wind power are required from the EU side. New policies should be welcomed to support this strategic sector by encouraging the ongoing cost reduction trend for the onshore and offshore wind energy and ramping up the production of variable renewable energy systems and its core. Further improvements are possible by supporting research and innovation. The electricity from wind met 14% of the EU's electricity demand in 2018 which is a 2% share higher than in 2017 rate. In Europe, Denmark (41%), Ireland (28%) and Portugal (24%) are the countries producing the highest amount of energy from wind. Followed by Germany, Spain and the UK with 21%, 19% and 18% respectively (Figure 10). The wind capacity in the Czech Republic is 278MW according to the survey of EUROPEUM. But, its growth will be more in 2030. In future, one third of the electricity consumption could cover from wind power plant based on the analysis of the Chamber of RES. The offshore and onshore wind gross installation is shown in Figure 9.

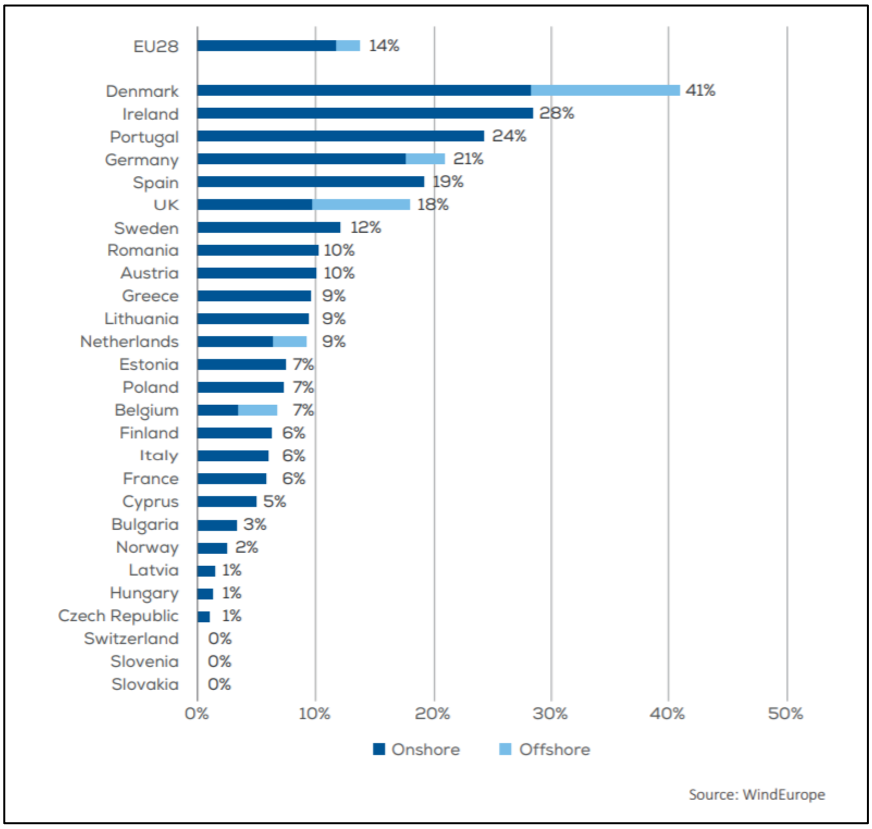


Figure 10. Onshore and offshore wind capacity in European countries [22]

3.3. Wind generation principle

Atmospheric pressure gradients cause the movement of air from higher pressure to lower pressure regions which results in the realization of wind. The factors influencing the creation of atmospheric pressure gradients are uneven solar heating, the formation Coriolis force as a result of earth rotation and geographical conditions [23]. The uneven solar heating is triggered by i) the revolution of earth around the sun the heat absorption is more in the equatorial region and less in polar region, ii) revolving of earth its own axis creates the temperature gradients by yearly cycle seasonal weather and iii) the unequal heat absorption of topographic surface by the variation of solar radiation. These above temperature changes make the difference in wind speed and direction. Another factor is Coriolis effect which creates by the self-rotation of earth. This self-rotation causes the variation of the air temperature, and then air is flowing from the equator toward the poles.

The wind direction and speed influence the result of Coriolis effect. The average wind speed is the wind potential at given wind site. Generally, anemometer is using to determine wind speed and wind direction. Today, anemometers with different conventional sensing mechanisms, such as mechanical, hotline, sonic, and optical techniques are using. The anemometer is made up with cup or blade. The wind speed determined by the rotation of cup or blade. The wind speed is 5m/s or above that site viable and also check the consistency of wind in a year ideally 12 month or more will be choose. The wind availability is less than 6 months required to apply a seasonal adjustment factor as wind speed varies by season.

3.4. Wind Power generation

The technology of transforming the kinetic energy of the wind into electrical energy through a wind turbine is commonly referred to as wind power generation. Wind turbines collects and transform the wind power into rotational mechanical energy, which further produces electricity with the help of a generating unit. This technology power generation from the wind has been around in the word more than a century. However, due to the lack of technology and economic benefits limited the wind power generation. The technological advancements and innovation of power electronics in the 21st century boost the wind power technology into a moderately mature with 640 TWh production of electricity per year [24].

3.5. Parameters of Wind Power Generation

Wind Power Equation

$$\mathbf{P_w = 0.5\rho\pi R^2 V_w^3 CP(\lambda, \beta)}$$

Where,

P_w the extracted power from the wind

ρ air density, which is approximately 1.2 kg/m^3 at 20 ^oC at sea level

R blade radium in meter, which varies from 40 to 60 m

V_w velocity of wind (m/s), it can be controlled between 3 to 30 m/s

Cp power coefficient, which is a function of both tip speed ratio (λ)

β is the blade pitch angle (deg)

On basis of the wind power equation, high wind speed, blade with longer length and higher air density are required for obtaining high wind power.

Blade swept area

The area of the circle created by the blades as they sweep through the air is known as swept area (Figure 11).

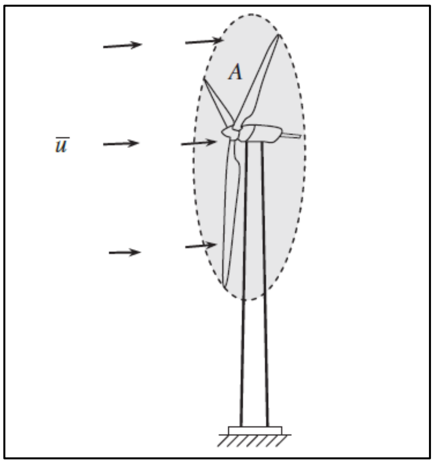


Figure 11. Blade Swept area of wind turbine

Air density (ρ)

The density of air influences the wind power generation, which is determine by this equation

$$\rho = P/RT$$

P local pressure of the air

T temperature in K

R gas constant

Capacity factor

The conversion of wind energy to electrical energy involves primarily two stages in the first stage the kinetic energy of wind is converted into mechanical energy to drive the shaft of a wind generator and wind blades are used as the converting the devices in this stage. Wind blades are required to design carefully to maximize the power capture from the wind. The converting efficiency is determined in the first stage by the power coefficient Cp which is the ratio of the mechanical power captured by blades to the available wind power. Due to various aerodynamic losses in wind turbine systems the Cp falls in the range of 30 to 45% are much lower than its theoretical limit.

Power conversion coefficient and output

Further in the second stage, the wind generators convert the captured mechanical energy by wind blades in to electrical energy and here the converting efficiency is determined by numerous factors.

Gearbox efficiency

Two types of power losses occur in the gearbox such as load-dependent and non-load power losses. The load-dependent losses come from the gear tooth friction and bearing losses. Whereas the non-load losses come from the oil churning, windage and shaft seal losses. Higher power transmission efficiencies in wind turbines can be obtained by using planetary gearboxes.

Generator efficiency

It is depending all electrical and mechanical losses in a wind generator, such as windage, copper, iron, load, friction, and other miscellaneous losses.

Electric efficiency

The electric efficiency includes all electric power losses in the converter, switches, controls, and cables.

Lanchester–Betz limit

The effectiveness of the wind turbine was theoretically calculated by Lanchester and Bertz in 1915 and 1920, respectively. According to Lanchester–Betz law, the turbomachines are able to convert the wind kinetic energy into mechanical energy is about 59.26% only.

Power coefficient (CP)

The ration of the out power and the available power from the wind is known as the power coefficient. Compared to many other energy sources the effects of the turbines on nature are very low, if the wind turbines are positioned well. Wind energy is considered as primary energy and is cost effective for the production technology and governmental sectors. Generally, the fossil fuel power plants produce energy continuously and therefor these conventional plants have higher capacity factor. But, the wind energy is mostly depending on the velocity and direction of the wind, hence it cannot function at maximum production condition and the capacity factor for wind turbine is around 40-45% only. The construction of the wind turbine can be engineered to improve the reliability of the wind power plants.

3.6. Wind characteristics

According to the geography, season, weather and height from the surface, the changes will occur in the wind speed and direction. Therefore, developing of measuring techniques and engineering of turbines and selecting of locations will support to convert the maximum power from wind into mechanical energy.

Wind speed

The important parameter influence the wind power production is the wind speed. The wind speed changes with time and space. The speed of wind is calculated by many factors such as weather conditions and geographic. Because of its random speed, the data of the wind speed mostly controlled using statistical tools. The Weibull distribution function can be using for describing wind speed variation at a particular site.

Wind turbulence

Wind speed often changes in small intervals for horizontal component and this fluctuation is known as wind turbulence.

Wind gust

In another case wind velocity occurs rapid change in short time period is called wind gust. The harsh change in wind speed, turbulence, and its shear may due to this turbulent gust. The sudden turbulent gust leads to reducing rotor imbalance and also effect the output of wind power. Owing to the wind shear rise, the gusts also influence the tower fore-aft and side-to-side bending moments and the prediction of this wind gust are preferred for the high quality production of wind plant.

Wind direction

Another important characteristic for the good quality wind production is the direction of the wind. Therefore, statistical predictions for long period, location and wind turbine design for very important for the high quality production of the wind energy.

Wind shear

Wind shear is a related to the wind gradient where the wind speed increases with the height. The Hellmann power equation is generally used to estimate the wind shear. Owing to roughness on the earth's surface, the wind varies its velocity and direction.

3.7. Types of Modern Wind Turbine

Different types of turbine designs are used for the energy production and important part in these designs are rotor. According to their orientation of the rotor shaft they are classified as vertical axis and horizontal axis machines.

3.7.1 Vertical Axis Wind Turbine

The ancient wind mill was constructed as vertical axis rotation which is shown in Figure 12. In this type, the rotor is connected to the blade situated perpendicular to the ground. The advantages of this design is the turbine does not require the yaw control and hence it can receive wind from any direction.The components of the turbines such as wind generator and gearbox are usually placed on the ground. Shorter construction of wind tower design significantly reduces the cost of the turbine. However, an external energy source is required during initial process to rotate the blades. The length of the wind turbine is limited in this design due to the wind turbine axis. Even though the construction cost is low, due to its low power efficiency the usage of vertical axis wind turbine is very low.

Figure 12. Vertical axis wind turbine [25]

3.7.2. Horizontal Axis Wind Turbine

Nowadays, the wind turbine used in wind industry is horizontal axis wind turbine (Figure 13). In this design, the wind turbine employed the generator and main rotor shaft which are pointed in to the wind at top of the tower. The small turbine creates with a simple wind vane and wind sensors are employed with large turbines. The gear box used in most of the wind turbine provides fast rotation of the slow rotation of the blade. That is appropriate to drive electrical generator. This type of wind turbine has high efficiency, higher power density, reliable wind speeds, and low cost for unit production compared to horizontal axis turbine. Therefore, this type of turbines is widely used in industrial purpose.

Figure 13. Horizontal axis wind turbine [25]

The multi-blade wind turbine was used for pumping water. This type of wind mill has high rotating torque so this type of turbine is suitable for this purpose. The amount of captured power depends on the number of rotor blade. The selection of blade number is restricted to 2 or 3 in this design to reduce kinetic energy losses. A three bladed turbine is optimized as more efficient, larger dynamic balance and less noise compared to two blades. The most of modern wind turbine is made with 3 turbine blades.

The wind turbine is usually made up of with wood or fibre glass material due to their high strength and low weight. It helps them to start quickly even at low wind speed. The carbon fibre is used for making turbine blade, but it is quite expensive. Whereas the consistency and efficiency of the carbon fibres are higher when compare to glass fibre blades. They are twice as strong and therefore produce very low noise during high wind speed conditions.

3.8. Wind Turbine Parts

The wind turbine consists of mechanical, electrical and controller parts. The main components of turbines are described briefly. The components of wind turbine are shown in Figure 14.

Tower

In modern wind turbine the tower made up of steel with round tubular shape. Modern turbine typically 100 meters and higher depends the size of turbine and site.

Rotor

It is a rotating part employed to 3 or 2 bladed turbines. Its midpoint usually attached to the hub and the kinetic energy of the wind is transferred to the shaft. The main function of rotor is to take the surface area of wind in order to rotate the most comfort way.

Hub

The role of the hub is to hold the blades which are connected to gear box through main shaft.

Wind turbine blade

The wind turbine blade is two styles which are lifting style wind turbine blade and drag style wind turbine blade. The lifting style wind turbine blade is more efficient design for capturing strong energy and fast wind. Whereas, the drag style wind turbine blade are not efficient and which is more used in water mills like Dutch windmills. The blades are corrosion-resistant material, light weight, durable. The best materials for making the blade are fiberglass and reinforced plastic.

Gear box

The gear box is placed directly between the rotor and the generator. A gear box amplifies the energy output of the rotor. Because of this, the shaft on the generator side is called "high-speed shaft."

Nacelle

It is an enclosure situated on the top of the turbine consist all internal equipment of the turbine on the top. The function of nacelle is protecting the internal equipment from surrounding environment.

Brake

It is used to control the rotational speed of wind turbine in emergency which is connected to high speed shaft.

Yaw

It is a horizontal moving part of turbine which moves depend up on the orientation of the wind. The important parts of the yaw are motor and the drive. When the wind direction changes the yaw, drive helps to keep the rotor towards facing the wind and the yaw motor helps to move the yaw.

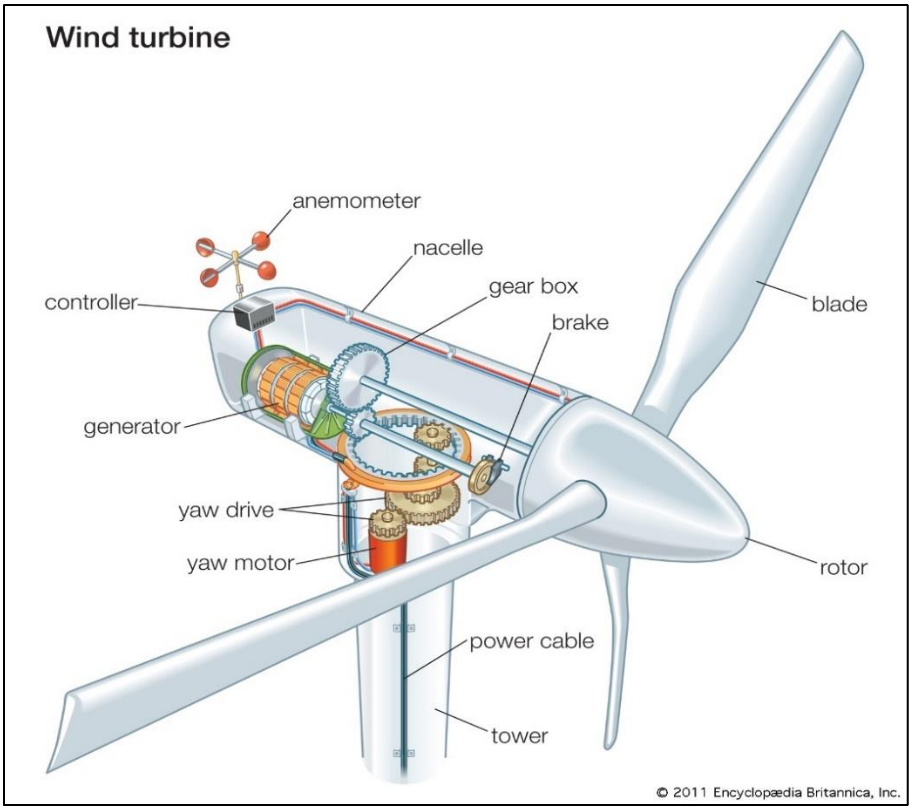


Figure 14.Components of wind turbine [26]

The wind vane

This sensor is used to determine the wind direction. To operate yaw control system, the wind direction is a significant element.

Generator

Commonly used generators in wind turbines are Induction generators (IG) and doubly fed induction generators (DFIG) and permanent magnet synchronous generators (PMSG).

Induction generators (IGs)

When we are using IG in wind turbine, the external torque from wind is applied to the grid connected IGs and rotating. Here, the rotor speed increases due to the extra rotational energy, which is higher than the rotating magnetic field produced by the grid frequency, which makes a negative slip to produce the current which is fed back to the grid. The advantages of the IG are permits the generator fit in with variations in wind speed around the design speed and helps to reduce gear box wear. The disadvantages are it creates reactive power on the grid. Moreover, the generator can only work at or close to the grid frequency. This type of generators is not used in main utility grid.

Double -Fed Induction generators

It is advanced version of the induction generator, which is mostly used in large wind turbine. In the double fed induction generator, the rotor has three phase windings, it is connected to the grid supply through power electronic DC/AC converters. The double fed induction generator is used in modern wind turbine up to 5 MW turbine. The schematic diagram of double fed induction generator is shown in Figure 15.

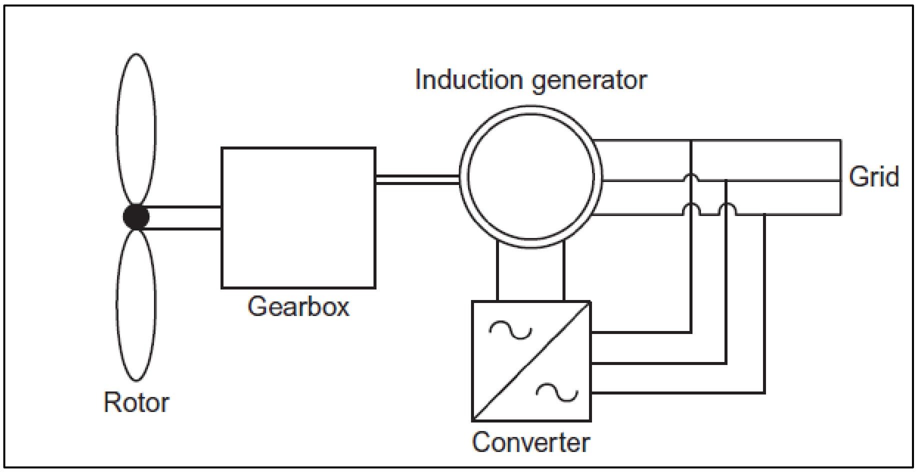


Figure.15. Schematic diagram of double fed induction generator

Permanent magnet Synchronous generators [PMSG]

This type synchronous generator is mostly used in modern wind turbine instead of conventional type synchronous generator. It is lighter than conventional type and they need no excitation. But it can only work at or near to its synchronous speed. Otherwise it creates the power loss. To overcome this, the power electronics converters is using with it. The variable speed generators are the advanced type in this. It gives many advantages than conventional types.

Controller

The condition of wind turbine is observing continuously and controls the pitch and the yaw systems to capture optimum power from the wind.

3.9. Wind turbine control methods

The control of wind turbine is the important factor to improve wind energy capture and enduring the safe and reliable wind turbine operation. There are many methods are using to control the wind turbine. The main methods are using in modern wind turbine are pitch control, stall control and yaw control.

1. Pitch control:

In modern wind turbine, there are two methods using in pitch control that are hydraulic system and electric control system. The hydraulic actuator is used to drive the rotating the blade with respect to its axial centreline. It has many advantages which large driving power is no need of gear box and robust back up power. Another pitch-controlled system s electric pitch control system. This has high efficiency compared to the hydraulic system and reduces the environmental pollution by hydraulic fluid. This type of controlled system is used in large wind turbines.

2. Stall control

Stall control is the method used to protecting and controlling a wind turbine. When reached the rated speed the power is controlled through stalling blades. In this method, there are two types of control methods that is active and passive control method. The passive stall control is used in which the blades are bolted to the hub at a fixed installing angle. The power control is depends on the aerodynamics function of the blades in passive stall control system. Usually the turbine operated near maximum efficiency in low and medium wind speed. In high wind speed, the turbine has to control by stalled blades to protect the wind turbine. This passive system provides high reliability for controlling the turbine and also it is a simple structure. Even though it has some drawbacks that it can use only in small and medium turbine due to its low efficiency, need of external equipment at the turbine start.

In recent years, most of the wind turbines are multi megawatt wind turbine therefore pitch control is an important factor in wind power control. In large wind turbine, active stall control is using. Active control gives exact control on power output and keep rated power at high wind velocity than stall control. But, the use of active stall control with addition of pitch control is increasing turbine cost and reduces the reliability of turbine operation.

3. Yaw control

The yaw control is divided by two approaches one is hydraulic and electrical approach. In modern wind turbine, the yaw mechanism is working by electrically. The yaw control mechanism generally involves an electrical motor connected with speed reducing gear box, a bull gear which is attached to the tower., the wind direction information attains by wind vane. The yaw deck is controlled the turbine a yaw deck and when reach required location the break is locked the wind turbine properly in yaw. For a large wind turbine with high driving loads, the yaw control system may use two or more yaw motors to work together for driving a heavy nacelle.

3.10. Types of wind power plants

3.10.1. Onshore wind power plants

Onshore wind denotes to turbines located on land which can implement based on the wind availability. The onshore wind turbine can be connected to the grid or used as standalone.

Standalone system

In the stand-alone wind energy system turbines are not connected to an established electrical grid, whereas the energy produced from the turbines are directly delivered to an independent unit. The advantage of this system is that it can be placed any areas where the electricity supply from the grid are economically unsustainable. The energy produced from this system is stored in the battery banks and a diesel generator is used to run the turbine and therefore it can be in various electrical vehicles.

Grid connected systems

In the grid connected system, wind energy is connected to the grid system and therefore it cannot be stored using batteries. It is mainly used for house hold applications, so the generated power directly used and the remaining power exported to the grid. The advantage of the grid connected system is that the power can be imported from the grid if there is a low wind flow time or during the higher power consumption than the power generation. In addition, the grid efficiently acts as an energy store, if the power generation and consumption are equals and therefore the expenses for maintaining batteries. However, during the event of power cuts, this system does not act as a back-up power supply.

3.10.2. Off-Shore Wind Energy

In 1991, the first offshore wind project installed in Denmark. Today offshore wind farm is being operated worldwide mostly in Europe. Simplified off-shore wind farm is shown in figure.17. The world largest off shore wind turbine situated in Scotland.

The offshore wind turbine operating principle is same as all wind turbines. The wind blowing is more and uniformly in coastal areas than on land. If wind average speed 16mph the turbine would generate 50% more electricity than at the site with same turbine. Because of this the developers are interesting to invest offshore wind energy.

The turbine captures the energy is higher which is the difference from on shore wind turbine. Usually offshore wind turbine is horizontal axis with 3 blades. Offshore wind turbine made up of tubular steel sections. The foundation is different from on shore. The main factor is environmental conditions in off shore wind turbine installations. Special modifications are need for offshore wind turbines to prevent corrosion, to withstand the harsh environment of the ocean, including storm waves, hurricane-force winds, and even ice flows. Foundation for Offshore wind turbine is shown in figure.16.

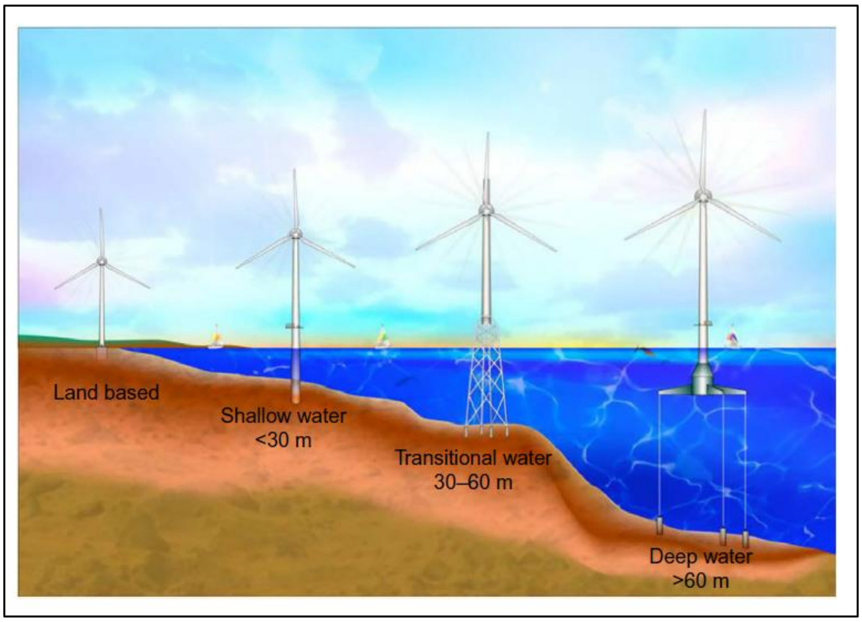


Figure.16. Foundation for Offshore wind turbine [27, 28]

The design of offshore wind turbines depends on site-specific conditions. Mainly it depends on the following factors.

- water depth
- seabed geology
- wave loading

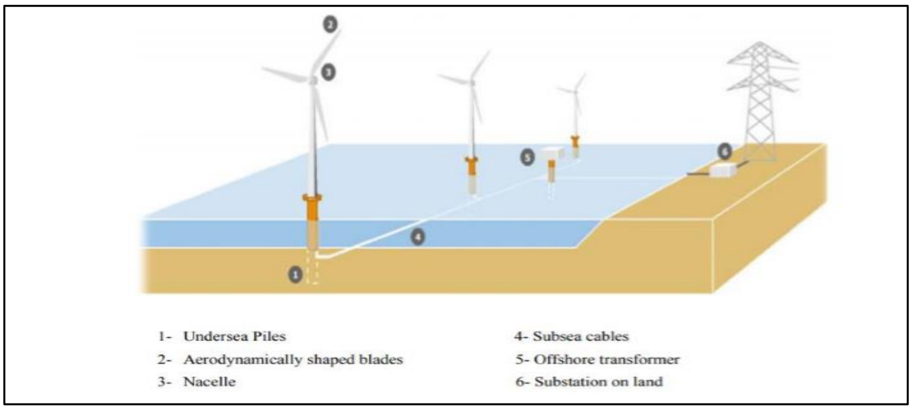


Figure 17. Simplified Off-shore Wind Farm

Modern off-shore turbines are built with technological advancements. These modifications protect to the turbine from waves or ice flows, protection of the electrical equipment's from the corrosion and easy navigation safety and maintenance access by brightly coloured access platforms.The turbine consist with lubricates bearings and blades and cooling systems to maintain gear oil temperature within a specified range, which is reduce the daily service cost. Lightning protection systems are using to protect from lightning in some offshore locations.

Offshore Installation and Operation steps

- ❖ Suitable selection of site.
- ❖ At the selected areas, Piles are driven into the seabed.
- ❖ Erosion protection systems must ensure at the base of piles.
- ❖ The top is painted brightly for easy ship navigations.

- To detect the wind direction, sensors are using on the turbine and turn the nacelle into the direction of wind flow.
- The turbines are placed at the proper places. It permits the proper working of the rotor at the rated wind speed.
- Inside the nacelle, the rotor is connected to a shaft which is further connected to a gearbox and it provide the speed around 1200-1500 rpm[29].
- The generator connected with wind turbine system runs at the above speed and generates power.
- Subsea cables are used to carries the power to an offshore transformer set. It will convert to high voltages, and then fed to the grid substation.

Transport of Wind-Generated Energy

The generated wind power need to transmit to shore and connected to the power grid. All turbines are connected to an electric service platform (ESP) by a power cable in Figure 18. The function of ESP is serves as a common electrical collection point for all the wind turbines like a substation. ESP's also provide the facility to helicopter landing pad, communications station, crew quarters, and emergency backup equipment.

Figure 18. An Electric Service Platform (ESP) for an offshore wind facility [29]

Development of Offshore Wind Turbine

Various advances of offshore wind turbines listed below:-

1. **Small scale 500 kW -class prototype:** In the northern European countries like Denmark, Netherland and Germany, the first research of offshore wind turbines was started in 1970's. They developed a small scale 500 kW prototypes wind turbine.
2. **The First Generation (Megawatt-class Prototype Wind Turbine**): Megawatt-class type offshore wind turbines were installed and tested in early 2000's. Development in ship maintenance with modified anti corrosion features was carried out and implemented.
3. **Second Generation (Megawatt-class Prototype Wind Turbine):** It consisted of turbines with rating of 3-5 MW and 90-115 m long turbine rotor. It provides the higher energy efficiency and high dependability. It has special features for anti-corrosion in the off-shore wind turbine.
4. **Third Generation (Megawatt-class Prototype Wind Turbine):** It has turbines having ratings greater than 5 MW and diameter typically in the range of 120 m. Due to larger turbines, higher energy yields have been obtained. It is more cost effective. Several manufactures of offshore wind power generation like Nordex (Germany), Repower (Germany), GE Wind Energy (USA), Bonus (Denmark), Vestas (Denmark), Enercon (Germany) etc.

4. Power quality issues of grid connected wind energy systems

Electrical distribution systems are the crucial part in any kind of power systems and they are designated for energy transmission from the power systems to consumer's place. Similar to other energy sources wind power generation also facing lots of challenges in the power distribution. To reduce the unfavorable impact of the wind power energy in the distribution and utilize the maximum potential benefits, it is very important to understand the power quality issues from the wind turbine [30].

The major technical challenges of the integration of wind energy in to existing distribution networks are voltage regulation, harmonic distortion, power system stability etc. These power quality issues can occur at the generation, transmission and distribution levels and should be confined to IEC and IEEE standards.

4.1. Voltage Regulation

The voltage fluctuation can affect the high-quality wind power generation. Various factors may cause the voltage variation like voltage rise occurs when they integrate power into the grid and the variation of wind speed can also affect the voltage fluctuations. Therefore, to achieve the higher wind power penetration the voltage fluctuations must be regulated and it is achieved by using voltage regulation equipment such as capacitor banks and voltage regulators [30].

4.2. Voltage Sags

The integration of wind power into the grid is becoming more popular because of its high efficiency, economics benefits, reliability, and balanced production and distribution of electricity [30]. However, power quality becomes a major issue when the wind generators are penetrated into the grid as it is highly influenced by the voltage drops. Voltage sag is a decrease in rms voltage between 0.1 and 0.9 p.u. and decrease in the current at the frequency of 0.5 cycles to less than a minute [31]. As the fault occurs in the distribution network, the grid voltage will decrease to lower levels and during this time the feeder connected to wind generators experience a voltage sag condition. The reasons for the voltage sag conditions are due to the different types of faults in the grid such as symmetrical faults, asymmetrical faults and phase-angle jump in the power network [32]. To overcome this, the power electronic converter using a series compensator can be used. It can restore the voltage at the load side and requires very less active power.

4.3. Real and Reactive Power

Power quality from the wind turbine is measured by different parameter such as power factor, transient over voltage and harmonic distortion. Power factor is one of the crucial parameters for determining the power quality when the system connected to the grid [33]. The power factor (PF) is defines as the following equation [34].

$$PF= \frac{P}{S}$$

$$S^2 = P^2 + Q^2$$

$$P = S|\cos \emptyset|$$

P the active power in Watts (W)

S the apparent power in volt-amperes (VA)

Q the reactive power in reactive volt-amperes (VAr)

ϕ the phase angle between the current and the voltage

Wind energy offers lots of technical challenges when it is integrated in to existing distribution system and it requires considerable attention on voltage regulation and power quality issues. Importantly the voltage variations are directly connected to the active and reactive power variation. Reactive power production and consumption are often regulated by the generators and permits the network operator to control the voltage in the system.

A generator used in the wind turbines follow some specific rules when they are connected to grid is called “grid code”. The requirements are executed by the transmission system operator (TSO) through these grid codes [35]. For instance the reactive power regulations are controlled by the three modes reactive power control mode, Power factor control mode and Voltage control mode. One way to control the voltage variation is the regulation of its reactive power consumption or production. Alternatively, the simplest way is the wind farm operates at a fixed power factor to 1 when generating the power. This fixed value may change at different occasions such as winter and summer, or peak and no-load periods. Therefore the verification of the power factors is required at integration intervals.

Wind turbines often consume reactive power due to their dispersed location in the distributed network systems. The reduced flow of reactive power from the main grid increases the active power supply to the substation transformers. It also induces the reactive and active power losses in the distribution system. In order to get the economic benefits the network operators must be able to set the power factor. Consequently, it is essential to quantify the power losses by the power factor setting in advance to estimate the economic benefits and long run.

4.4. Rules for connection of RES to a distribution network ČEZ supplier.

The network operator determines the techniques of connecting the electricity generating plants to the distribution network. The network operator evaluates the effects when connecting RES to medium or low distribution network. These effects are voltage changes, stress during switching, long term flicker, current harmonics, influence on device ripple control (HDO), and influence to short-circuit conditions. Voltage changes in the operation of the electricity generating plant.

The voltage stability, frequency stability, power quality and losses are main issues when wind power plant connecting to distribution grid. Voltage variation in the medium voltage distribution network by connecting electricity generating plant at the connection point (PCC) must not exceed 2%. Variation in voltage distribution in low voltage network by connecting electricity generating plant at the connection point (PCC) must not exceed 3%. When switching electricity generating plant, voltage change is 3%. The voltage variations in PPC caused by connecting or disconnecting the electricity generating plant must not be connected to low voltage (0.4 kV) exceed 2%. The most plants is connecting to RES, these parameters apply only to the case where switching is more frequent as once every 1.5 min.

5. Case study: Overview and Description

In this case study, wind power plant has been connected in medium voltage network of distribution system (22 kV) with different power factor wind generator. For analyzing the voltage profile and current at each branches and nodes on the medium network, E-Vlivy software has been used. This software gives the best possible data for the connection of WPP to the distribution network. After calculation the result we can obtained all network parameters (voltage profile, current in branches, and so on).

5.1. Wind power plant connection to 22 kV overhead lines

The wind power plants operated different power factor is connected to medium voltage distribution line 22 kV. The line is fed from distribution transformer 110/23 kV with the capacity 40 MVA. The distribution line modelled as distribution line 22 kV at Liberecký region.

Scheme of the medium voltage distribution line

In this scheme, one 1.8 MW wind turbine with different power factors (0.96 -1 and -0.98, -0.99) is connected to 22 kV medium voltage distribution line in the 14-kilometer (km) distance from distribution transformer as shown in Figure1 9. Different loads are connected every 2 km in the distribution line which are designated as Z1 to Z8. The corresponding load parameters such as voltage, power factor and apparent is provided in the Table 4. Voltage at each nodes and branches are calculated with and without working of wind turbine has been carried out using E-Vlivy software. According to the Czech Republic standard, the voltage differences at each nodes and branches should not be higher than 2% of nominal voltage of network when wind turbine is connected to medium voltage network.

Calculating Scheme and input data

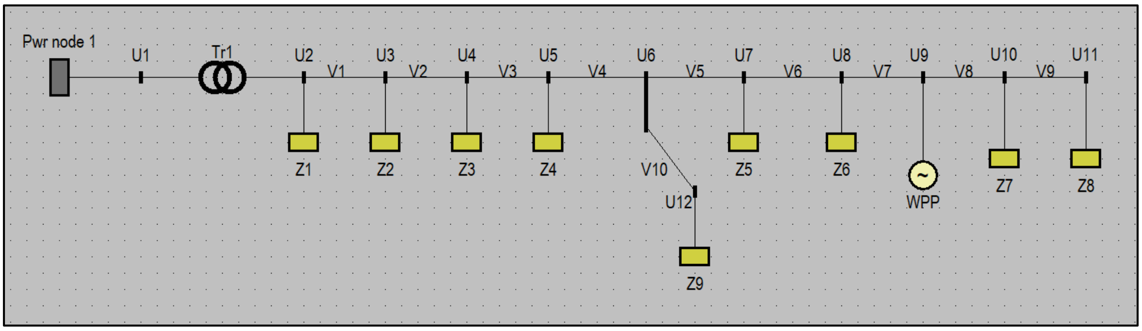


Figure.19. Schematic diagram of WPP connected to medium voltage OH.

Table 1. Input data of 110 kV OH

Name	Un (kV)	Uop (kV)	Izkr (kA)	Szkr (MVA)
110kV	110	110	11.02	2100

Table 2. Parameters of distribution transformer 110/23 kV

Name	U_{n1} (kV)	U_{n2} (kV)	S_K (MVA)	P_K (kW)	Primary connection	Secondary Connection	I_{n1} (A)	I_{n2} (A)
TR1	110	23	40	210.7	YN	YN	210	1005

Table 3. Parameters of 22 kV OH

Name	Type	Un (KV)	R (Ω/km)	X (Ω/km)	B (µS/km)	Length (km)	Imax (A)
V1	120AlFe6	22	0.225	0.36	1.47	2	357
V2	120AlFe6	22	0.225	0.36	1.47	2	357
V3	120AlFe6	22	0.225	0.36	1.47	2	357
V4	120AlFe6	22	0.225	0.36	1.47	2	357
V5	120AlFe6	22	0.225	0.36	1.47	2	357
V6	120AlFe6	22	0.225	0.36	1.47	2	357
V7	120AlFe6	22	0.225	0.36	1.47	2	357
V8	120AlFe6	22	0.225	0.36	1.47	2	357
V9	120AlFe6	22	0.225	0.36	1.47	2	357

Table 4. Loads consumption parameters on overhead line 22 kV

Name	Un (kV)	cosφ	S (kVA)
Z1	22	0.95	2400
Z2	22	1	630
Z3	22	1	500
Z4	22	0.95	400
Z5	22	0.96	300
Z6	22	0.98	300
Z7	22	1	200
Z8	22	0.92	300

Wind power plant (WPP) parameters

Table 5. WPP parameters

Name	Un (KV)	cosφ	P (kW)	S (kVA)	X”d [%]
WPP	22	0.96	1728	1800	14

5.2. Calculation Results

5.2.1. Network operation without wind power plant

Table 6. Voltage in network nodes before connection of WPP

Name	U [kV]
U1	109.922
U2	22.887
U3	22.813
U4	22.752
U5	22.701
U6	22.662
U7	22.632
U8	22.611
U9	22.598
U10	22.585
U11	22.576

The voltage at U1 is higher than voltage at U11 node when before connecting WPP.

Table 7. Currents and power in network nodes before WPP

Name	Node	I (A)	P (kW)	Q (kVAr)	S (kVA)
Z1	U2	60.544	2280	749.4	2400
Z2	U3	15.944	630	0	630
Z3	U4	12.688	500	0	500
Z4	U5	10.173	380	124.9	400
Z5	U7	7.653	288	84	300
Z6	U8	7.66	294	59.699	300
Z7	U10	5.113	200	0	200
Z8	U11	7.672	276	117.576	300

Table 8. Values of current and power in network branches after WPP

Name	Node	I [A]	P [kW]	Q [kVAr]	S [kVA]
Pwr node 1	U1	28.61	-5241.22	-1483.01	5446.98
Tr1	U1	28.60	5241.21	1482.89	5446.95
V1	U2	74.77	2919.74	511.51	2964.21
V2	U3	59.13	2282.20	500.84	2336.51
V3	U4	46.81	1777.48	494.71	1845.04
V4	U5	36.67	1394.50	366.51	1441.86
V5	U6	27.79	1060.11	257.17	1090.85
V10	U6	8.90	332.62	107.97	349.70
V6	U7	20.15	771.04	172.95	790.20
V7	U8	12.51	476.50	113.89	489.92
V8	U9	12.51	476.29	115.04	489.98
V9	U10	7.657	276.073	116.19	299.52

5.2.2. Network operation with wind power plant operated at 0.96 PF IND

Table 9. Voltage in network nodes after WPP operated at PF 0.96

Voltage in nodes	U [kV]
U1	109.95
U2	22.93
U3	22.90
U4	22.89
U5	22.89
U6	22.90
U7	22.92
U8	22.95
U9	22.99
U10	22.98
U11	22.97

Table 10. Currents and power in network nodes after WPP operated at PF 0.96

Name	Node	I (A)	P (kW)	Q (kVAr)	S (kVA)
Z1	U2	60.42	2280	749.40	2400
Z2	U3	15.87	630	0	630
Z3	U4	12.60	500	0	500
Z4	U5	10.08	380	124.9	400
Z5	U7	7.55	288	84	300
Z6	U8	7.54	294	59.70	300
WPP	U9	45.19	-1728	-504	1800
Z7	U10	5.02	200	0	200
Z8	U11	7.53	276	117.57	300

Table 11. Currents and power in network branches after WPPs operated at PF 0.96

Name	Node	I [A]	P [kW]	Q [kVAr]	S [kVA]
Power node 1	U1	18.97	-3496.7	-912.79	3613.86
Tr1	U1	18.97	3496.68	912.77	3613.85
V1	U2	29.64	1177.21	-16.37	1177.32
V2	U3	13.76	546.02	-16.75	546.28
V3	U4	1.21	45.76	-15.62	48.36
V4	U5	9.12	-334.24	-139.00	362
V5	U6	17.91	-666.91	-245.48	710.65
V10	U6	8.81	332.63	107.95	349.71
V6	U7	25.44	-955.41	-328.75	1010.39
V7	U8	32.921	-1250.24	-388.22	1309.12
V8	U9	12.301	476.27	114.91	489.94
V9	U10	7.52	276.09	116.17	299.54

When connecting the WPP with 0.96 power factor with inductive nature, the voltage in each load was calculated. The current, active power, reactive power and apparent power was also calculated.

5.2.3. Network operation with wind power plant operated at 0.97 PF IND

Table 12. Voltage in network nodes after WPP operated at PF 0.97

Voltage in nodes	U [kV]
U1	109.94
U2	22.92
U3	22.90
U4	22.89
U5	22.88
U6	22.89
U7	22.91
U8	22.94
U9	22.97
U10	22.96
U11	22.95

Table 13. Currents and power in network nodes after WPP operated at PF 0.97

Name	Node	I (A)	P (kW)	Q (kVAr)	S (kVA)
Z1	U2	60.44	2280	749.4	2400
Z2	U3	15.88	630	0	630
Z3	U4	12.61	500	0	500
Z4	U5	10.09	380	124.9	400
Z5	U7	7.55	288	84	300
Z6	U8	7.55	294	59.70	300
WPP	U9	12.32	476.30	114.95	489.97
Z7	U10	5.02	200	0	200
Z8	U11	7.54	276	117.57	300

In this case the voltage at node U2 is 22.92 kV. From node U2 to U6 the voltage is decreasing and the U6 to U10 the voltage is increasing because of connection of the WPP. When comparing the node voltage in case of the WPP operated at 0.96 PF, voltage in U2 is little bit lower than node U10.

5.2.4. Network operation with wind power plant operated at 0.98 PF IND

Table 14. Voltage in network nodes after WPP operated at PF 0.98

Voltage in nodes	U [kV]
U1	109.94
U2	22.92
U3	22.9
U4	22.89
U5	22.88
U6	22.89
U7	22.92
U8	22.95
U9	22.98
U10	22.97
U11	22.96

Table 15. Currents and power in network nodes after WPP operated at PF 0.98

Name	Node	I (A)	P (kW)	Q (kVAr)	S (kVA)
Z1	U2	60.44	2280	749.4	2400
Z2	U3	15.88	630	0	630
Z3	U4	12.61	500	0	500
Z4	U5	10.09	380	124.9	400
Z5	U7	7.55	288	84	300
Z6	U8	7.54	294	59.699	300
WPP	U9	45.22	-1764	-358.20	1800
Z7	U10	5.028	184	78.38	200
Z8	U11	8.829	332.5	109.28	350

5.2.5. Network operation with wind power plant operated at 0.99 PF IND

Table 16. Voltage in network nodes after WPP operated at PF 0.99

Voltage in nodes	U [kV]
U1	109.94
U2	22.91
U3	22.88
U4	22.86
U5	22.85
U6	22.86
U7	22.87
U8	22.90
U9	22.93
U10	22.91
U11	22.91

Table 17. Currents and Power in network nodes after WPP operated at PF 0.99

Name	Node	I (A)	P (kW)	Q (kVAr)	S (kVA)
Z1	U2	60.47	2280	749.4	2400
Z2	U3	15.89	630	0	630
Z3	U4	12.62	500	0	500
Z4	U5	10.10	380	124.9	400
Z5	U7	7.57	288	84	300
Z6	U8	7.56	294	59.70	300
WPP	U9	45.32	-1782	-253.92	1800
Z7	U10	5.03	200	0	200
Z8	U11	7.56	276	117.57	300

5.2.6. Network operation with wind power plant operated at 1 PF IND

Table 18. Voltage in network nodes after WPP operated at PF 1

Voltage in nodes	U [kV]
U1	109.92
U2	22.89
U3	22.85
U4	22.83
U5	22.82
U6	22.81
U7	22.82
U8	22.83
U9	22.85
U10	22.84
U11	22.83

Table 19. Currents and power in network nodes after WPP operated at PF 1

Name	Node	I (A)	P (kW)	Q (kVAr)	S (kVA)
Z1	U2	60.52	2280	749.4	2400
Z2	U3	15.91	630	0	630
Z3	U4	12.64	500	0	500
Z4	U5	10.12	380	124.9	400
Z5	U7	7.59	288	84	300
Z6	U8	7.58	294	59.70	300
WPP	U9	45.46	-1800	0	1800
Z7	U10	5.05	200	0	200
Z8	U11	7.58	276	117.57	300

When connecting WPP with unity power factor to distribution grid, the voltage variation is 1%.

5.2.7. Network operation with wind power plant operated at 0.98 PF CAPA

Table 20. Voltage in network nodes after WPP operated at PF 0.98 CAPA

Voltage in nodes	U [kV]
U1	109.90
U2	22.86
U3	22.82
U4	22.78
U5	22.75
U6	22.74
U7	22.73
U8	22.74
U9	22.75
U10	22.73
U11	22.72

Table 21. Currents and power in network nodes after WPP operated at PF 0.98 CAPA

Name	Node	I (A)	P (kW)	Q (kVAr)	S (kVA)
Z1	U2	60.58	2280	749.4	2400
Z2	U3	15.94	630	0	630
Z3	U4	12.67	500	0	500
Z4	U5	10.15	380	124.9	400
Z5	U7	7.62	288	84	300
Z6	U8	7.61	294	59.70	300
WPP	U9	45.68	-1764	358.19	1800
Z7	U10	5.07	200	0	200
Z8	U11	7.62	276	117.57	300

5.2.8 Network operation with wind power plant operated at 0.99 PF CAPA

Table 22. Voltage in network nodes after WPP operated at PF 0.99 CAPA

Voltage in nodes	U [kV]
U1	109.91
U2	22.87
U3	22.83
U4	22.79
U5	22.77
U6	22.76
U7	22.75
U12	22.75
U8	22.76
U9	22.78
U10	22.76
U11	22.75

Table 23. Current and power in network nodes after WPP operated at PF 0.99 CAPA

Name	Node	I (A)	P (kW)	Q (kVAr)	S (kVA)
Z1	U2	60.56	2280	749.4	2400
Z2	U3	15.93	630	0	630
Z3	U4	12.66	500	0	500
Z4	U5	10.14	380	124.9	400
Z5	U7	7.61	288	84	300
Z6	U8	7.61	294	59.70	300
WPP	U9	45.62	-1782	253.92	1800
Z7	U10	5.072	200	0	200
Z8	U11	7.61	276	117.57	300

5.2.9. Voltage Profile Analysis

The voltages in each node and voltage profile at wind power plant operated at power factor range 0.96 IND to 0.99 CAPA and without WPP are shown in below.

Table 24. Node Voltages after WPP operated at different PFs and without WPP

Power factor	0.96 IND	0.97 IND	0.98 IND	0.99 IND	1.0 IND	0.98 CAPA	0.99 CAPA	without WPP
Nodes	Voltage (kV)	Voltag e (kV)	Voltage (kV)	Voltage (kV)	Voltage (kV)	Voltag e (kV)	Voltage (kV)	Voltage (kV)
U2	22.93	22.92	22.92	22.91	22.89	22.86	22.87	22.88
U3	22.90	22.90	22.90	22.88	22.85	22.82	22.831	22.81
U4	22.89	22.89	22.88	22.86	22.83	22.78	22.79	22.75
U5	22.89	22.88	22.88	22.85	22.82	22.75	22.77	22.70
U6	22.90	22.89	22.89	22.86	22.81	22.73	22.76	22.66
U7	22.92	22.91	22.91	22.87	22.82	22.73	22.75	22.63
U8	22.95	22.94	22.94	22.9	22.83	22.73	22.76	22.61
U9	22.99	22.97	22.98	22.93	22.85	22.74	22.78	22.59
U10	22.98	22.96	22.97	22.917	22.84	22.73	22.76	22.58
U11	22.97	22.95	22.96	22.90	22.83	22.72	22.75	22.57

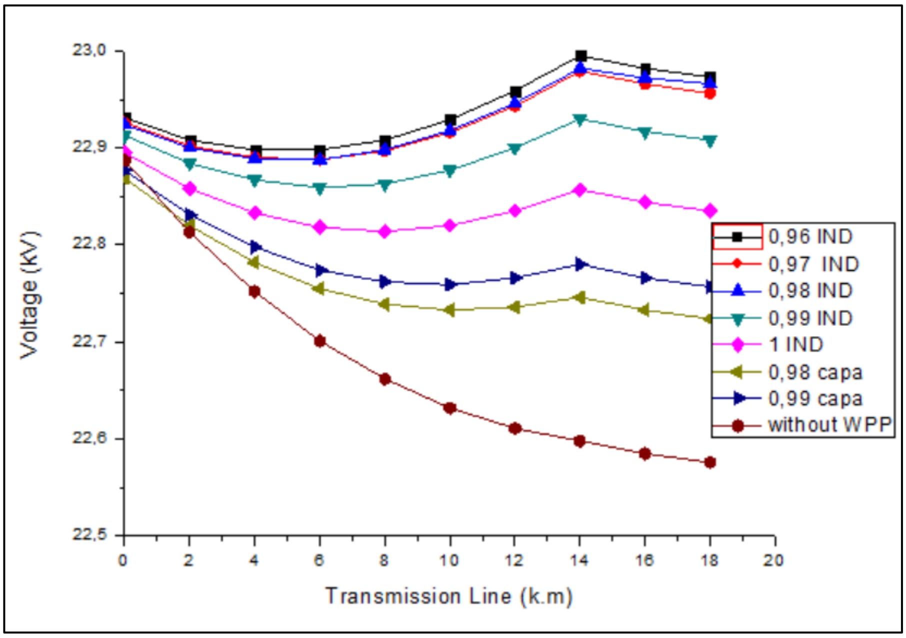


Figure 20. Voltage profile of wind power plant operation at different PFs and without WPP

Analysis of calculation results

The voltage variation at each node of the distribution line is calculated with and without connecting wind power plant. The power factor influences in the voltage stability have been studied while penetrating WPP in to the utility grid. It can see from the Figure.20 that the voltage in the distribution line without connecting WPP is gradually decreased over distances from distribution transformer. When the power factor is assumed as unity, the voltage variation from node U2 to U11 was low while it maintained above nominal voltage. Then the power factor is decreased until 0.96 IND (lagging) i.e. the reactive power is absorbed by the equipment and studied the voltage profile. In this case, the voltage variation from the nominal voltage was high compared to without WPP operation. Whereas the voltage variation from nominal voltage was lower when WPP operated at leading power factor i.e. the reactive power provided by equipment. The voltage variation was decreased if the leading power factor of the WPP is decreased to 0.98 (CAPA). The voltage variation exceeds the Czech standard limit (2%), if the leading power factor is further decreased. Therefore, it is not advisable to go beyond 0.98 leading power factor. From the above analysis, optimization of power factor is very important to receive better power quality while penetrating WPP in to the utility grid.

6. Conclusion

In this thesis, different types of renewable energy sources (RES) and supply has been discussed in detail. Major renewable energy such as solar energy, wind energy and hydroelectric energy and their utilization aspects has also been described. From the International Renewable Energy Agency (IRENA) it is very clear that solar and wind power generation are the most dominant RES in the past decade. A brief discussion about the current challenges and impact of RES when connected to distribution network and rules for connecting RES with distribution grid has been provided.

Penetration of wind power systems (WPP) into the distribution network affect the overall power system performance like voltage profile, network power losses, etc. The value of voltage profiles at each node in the distribution line before and after connection of WPP into the Medium voltage distribution line was measured. The analysis and calculation of network parameters using E-Vlivy software is clearly show that the important of power factor maintenance in the distribution network when connecting to the RES. In this thesis, the voltage difference in network was lower than 2% of nominal voltage. It has been observed that, voltage Profile at each node increase slightly after integration of WPP compare to before integration of WPP with different PF into distribution network.

References

[1] J. G. OPEC, "World Oil Outlook 2010," 2010.

[2] B. P. Magazine. (2019). *Power*. Available: https://www.bp.com/en/global/corporate/energy-economics/energy-outlook/demand-by-sector/power.html

[3] R. Ploetz, R. Rusdianasari, and E. Eviliana, "Renewable Energy: Advantages and Disadvantages," in *Proceeding Forum in Research, Science, and Technology (FIRST) 2016*, 2016.

[4] IRENA, "International Renewable Energy Agency- Renewable Capacity Statistics," ed, 2018.

[5] IRENA. (2018). *Renewable Energy Capacity by Energy Source*. Available: https://www.irena.org/newsroom/infographics?irena_topic=d50ed9fa16654bff98c75c3a6377184d

[6] S. Sawyer, Q. Liming, and L. Fried, *GLOBAL WIND REPORT - Annual Market Update 2017*, 2018.

[7] N. Kannan and D. Vakeesan, "Solar energy for future world:-A review," *Renewable and Sustainable Energy Reviews,* vol. 62, pp. 1092-1105, 2016.

[8] M. Wasfi, "Solar energy and photovoltaic systems," *Journal of Selected Areas in Renewable and Sustainable Energy (JRSE),* 2011.

[9] K. Mertens, *Photovoltaics: fundamentals, technology, and practice*: John Wiley & Sons, 2018.

[10] M. Obi and R. Bass, "Trends and challenges of grid-connected photovoltaic systems–A review," *Renewable and Sustainable Energy Reviews,* vol. 58, pp. 1082-1094, 2016.

[11] (2010). *World Energy Resources: 2010 survey*. Available: https://www.worldenergy.org/data/resources/country/czech-republic/solar/

[12] SOLARGIS. (2019). *Solar Resource Maps of Czech Republic*. Available: https://solargis.com/maps-and-gis-data/download/czech-republic

[13] A. Bobat, "Thermal pollution caused by hydropower plants," in *Energy systems and management*, ed: Springer, 2015, pp. 19-32.

[14] K. M. Takal, A. R. Sorgul, and A. T. Balakarzai, "Estimation of Reservoir Storage Capacity and Maximum Potential Head for Hydro-Power Generation of Propose Gizab Reservoir, Afghanistan, Using Mass Curve Method," *International Journal of Advanced Engineering Research and Science,* vol. 4.

[15] O. Paish, "Small hydro power: technology and current status," *Renewable and sustainable energy reviews,* vol. 6, pp. 537-556, 2002.

[16] D. Egré and J. C. Milewski, "The diversity of hydropower projects," *Energy Policy,* vol. 30, pp. 1225-1230, 2002.

[17] (2018). *International Hydropower Association-Types of hydropower*. Available: https://www.hydropower.org/types-of-hydropower

[18] C. B. Field, J. E. Campbell, and D. B. Lobell, "Biomass energy: the scale of the potential resource," *Trends in ecology & evolution,* vol. 23, pp. 65-72, 2008.

[19] T. Lay, J. Hernlund, and B. A. Buffett, "Core–mantle boundary heat flow," *Nature geoscience,* vol. 1, p. 25, 2008.

[20] M. Hossain, N. Madlool, N. Rahim, J. Selvaraj, A. Pandey, and A. F. Khan, "Role of smart grid in renewable energy: An overview," *Renewable and Sustainable Energy Reviews,* vol. 60, pp. 1168-1184, 2016.

[21] R. Lacal-Arántegui, "Globalization in the wind energy industry: contribution and economic impact of European companies," *Renewable Energy,* vol. 134, pp. 612-628, 2019.
[22] (2018). *WIND ENERGY IN EUROPE IN 2018*. Available: https://windeurope.org/about-wind/statistics/european/wind-energy-in-europe-in-2018/
[23] W. Tong, *Wind power generation and wind turbine design*: WIT press, 2010.
[24] Z. Liu, *Global energy interconnection*: Academic Press, 2015.
[25] M. Mustafa, V. Sunil, and U. Bhasker, "Hybrid Power Generation By Solar Tracking and Vertical Axis Wind Turbine (Design and Analysis)," *International Research Journal of Engineering and Technology (IRJET),* vol. 4, 2017.
[26] S. Simani, "Overview of modelling and advanced control strategies for wind turbine systems," *Energies,* vol. 8, pp. 13395-13418, 2015.
[27] P. Breeze, "Offshore Wind," *Paul Breeze Wind Power Generation. UK: Academic Press. p75-84,* 2015.
[28] L. Moffi Ebite, "Modelling of the structural performance of arctic offshore wind turbines," 2016.
[29] (2017). *Offshore wind energy in USA*. Available: http://easywindenergy.blogspot.com/2013/03/offshore-wind-energy-in-usa.html
[30] K. Kumar, S. Venkateshwarlu, and G. Divya, "A review on power quality in grid connected renewable energy system," *CVR JOURNAL OF SCIENCE & TECHNOLOGY,* vol. 57, 2013.
[31] D. Kadam and B. Kushare, "Mitigation of Voltage Sag in Grid Connected Large Scale Wind Farm."
[32] M. Mohseni, S. M. Islam, and M. A. Masoum, "Impacts of symmetrical and asymmetrical voltage sags on DFIG-based wind turbines considering phase-angle jump, voltage recovery, and sag parameters," *IEEE Transactions on power electronics,* vol. 26, pp. 1587-1598, 2010.
[33] A. Kusiak and H. Zheng, "Optimization of wind turbine energy and power factor with an evolutionary computation algorithm," *Energy,* vol. 35, pp. 1324-1332, 2010.
[34] F. D. Bianchi, H. De Battista, and R. J. Mantz, *Wind turbine control systems: principles, modelling and gain scheduling design*: Springer Science & Business Media, 2006.
[35] T. Ayodele, A. Jimoh, J. Munda, and J. Agee, "Challenges of grid integration of wind power on power system grid integrity: A review," *world,* vol. 3, 2020.