REVIEW OF WIND POWER AND ITS IMPACTS ON A DISTRIBUTION SYSTEM

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ABSTRACT

Wind power growth significantly worldwide, the installed wind power capacity globally shown that there is an increase from just 283GW in 2012 to 369,55GW as at the end of 2014.And there will be more expectation in future years. This was achieved as a result of government policies on energy consumption from renewable resources. The government is doing an effort to reduce the emission of greenhouse gases to the atmosphere and over dependence of imported petroleum by some countries and using coal to produce energy.

To supply electricity to potential consumers, the substantial amount of wind power requires to be connected to the power system. Wind power system poses different qualities that differentiate their integration from other conventional power plants. The size of wind power mostly varies from a kilowatt(KW) range single turbine to hundreds of megawatt(MW) wind farm. Wind power are connected to the grid at various voltage level. The required power during normal operation of conventional power plants can be generated at any time, provided the power demand is within the technical constrain of the plant. And therefore the power output is controllable and predictable.On the other hands, the wind power output depend mainly on the wind power condition and location of the area as well as fluctuations of the wind. The production of electrical energy by conventional sources uses synchronous generator. Wind power plants however, uses different type of generator system which includes induction generators, double fed induction generators, and induction or synchronous generator with full power converters. Every one of this generator system is having various opportunities and challenges to the power grid.

Keywords: Wind, wind power, wind turbines, overvoltage, overloading.

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1. INTRODUCTION

Wind power connected to an electrical distribution system stances different types of reliability issues and power quality. Depending on the technology of the wind turbine, location and the characteristics of the distribution system. These integrated issues of the wind power comprises of overloading of the system components, overvoltage, malfunction of protection system, voltage flickers and harmonics. This paper is dedicated to the discussion of these integrated issues that arises due to the introduction of wind power. Hence the paper starts with the discussion of the characteristics of wind power in term of the nature of the source of energy, that is the wind, and the generator system that converts the kinetics energy extracted from the wind in to electrical energy. The different integration issues of wind power are discussed in term of how they are qualified and assessed, how their effect differ depending on the turbine generator technology.

The wind

Wind fluctuates both temporally and spatially. The temporal fluctuation ranges from a time scale of less than one second to several days. In this respect three peaks are identified: turbulent peak, diurnal peak, and synoptic peak [2]. The turbulent peak is caused mainly by wind gusts in the sub-seconds to minute range. The diurnal peak is the result of daily wind speed variation caused by such factors as land breeze and sea breeze, which happens due to temperature differences between land and sea. On most of the globe this peak occurs in the early afternoon [3]. The synoptic peak is the result of changing weather patterns, which typically vary daily to weekly but includes also seasonal cycles[2]. On this regard, particularly in Europe, the wind speed tends to be higher in winter than in summer [4]. This is ideal because the electricity consumption has also a similar seasonal pattern in this region.

From a wind turbine’s point of view, the diurnal, synoptic fluctuations of the wind are used together with the mean wind speed to predict the energy yield for a site. The knowledge about turbulence and gustiness is required, first of all, for the load calculation of the wind turbine [5]. From the power system’s point of view, the diurnal and the synoptic peaks mainly affect the operational aspect of the power system. The short term variation, and hence the turbulent peak, is the one that is given greater attention in terms of power quality, though its effect depends on the technology of the wind turbine connected to the system.

The spatial variations range from some millimeters to several kilometers [5]. The knowledge of these variations and the correlation between different sites is vital in the planning and operation of the power system. In this regard, a study carried out using two-year wind data with a three-hour resolution obtained from 142 synoptic stations in Sweden shows that the distance at which the correlation between wind speeds from two location drops to approximately 0.37 ranges from 38 to 530 km [6]. Since the area covered by a typical radial distribution system is not that large, the study implies that wind power in distribution systems can have a high level of correlation. In fact, we have observed a correlation that ranges from 0.82 to 0.95 among an hourly time series wind power data of one year. The data are obtained from 10 sites in a distribution system where there is a maximum of distance of around 10 km among the sites. Hence in a distribution system of such size full correlation can be assumed between wind turbine sites for planning studies.

2. STOCHASTIC NATURE OF WIND POWER

2.1 Wind Power

Wind power is the kinetic energy of wind, harnessed and redirected to perform a task mechanically or to generate electrical power.

With the development of electric power, wind power found new applications in lighting buildings remote from centrally-generated power. Throughout the 20th century parallel paths developed small windstations suitable for farms or residences, and larger utility-scale wind generators that could be connected to electricity grids for remote use of power. Today wind powered generators operate in every size range between tiny stations for battery charging at isolated residences, up to near-gigawatt sized offshore wind farms that provide electricity to national electrical networks.

2.2 Wind Energy Yield Determination

In wind power planning studies it is vital to know the energy available from a wind turbine. To this end, the power output of a wind turbine at a given time depends on the power curve of the wind turbine and the wind speed. Fig. 2.1 shows the power curve of a typical fixed speed and variable speed wind turbine. Below the cut in speed, since the wind is too low for useful energyproduction, the wind turbine is shut down. Then, once operating, the power output increases following a broadly cubic relationship with wind speed (although modified by the variations in power coefficient CP) until rated wind speed is reached. Above the rated wind speed, the rotor is arranged to limit the mechanical power extracted from the wind [7]. Above the cut-out wind speed, the turbine is shut down to avoid mechanical damage on the wind turbine.

Based on the power curve of the wind turbine PWT, and the probability distribution the wind speed at a given site f(v), the total energy yield of the wind turbine, ETWT, can be calculated using

$$E_{\mathrm{TWT}} = T\int_{0}^{\infty} f(v)P_{\mathrm{WT}}(v)\,dv \qquad (2.1)$$

Where T is the time period of interest, e.g. a year. The energy yield is usually expressed in terms of the capacity factor (CF) of the wind turbine at that particular site, which is calculated using

$$C^F = \frac{E_{TWT}}{8760 P_{rat}} \tag{2.2}$$

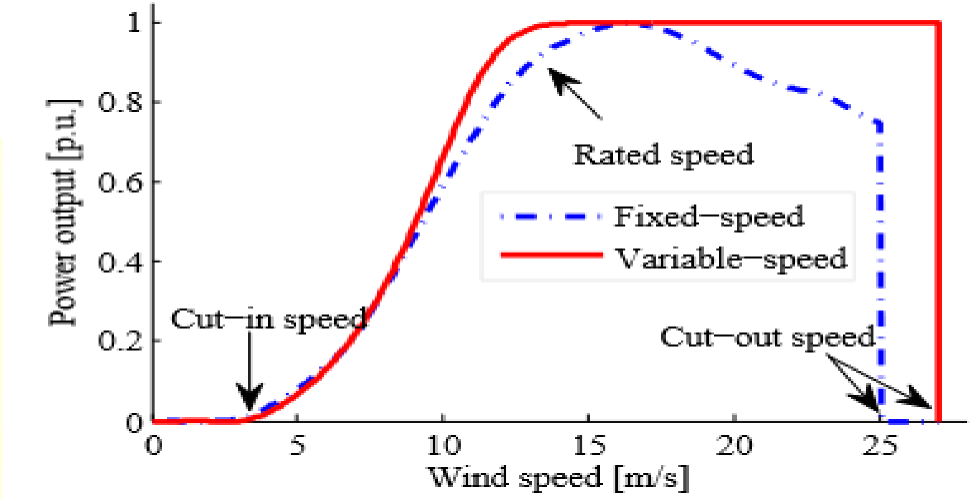


Fig. 2.1: power curves of a typical fixed and variable speed wind turbines

Where P_{rat} is the rated power of the wind turbine and 8760 is the number of hours per year. In practice this capacity factor lies in the range about 0.20 to 0.40 [11]. It is sometimes convenient to represent the capacity factor as the utilization time t_{util} in hours per year, calculated as

$t_{util} = 8760C^F$.

It can be seen from Figure 2.1 that wind turbines are generally designed to start running at a specific minimum wind speed. This wind speed is called the Cut-in wind speed. The generated power increases non-linearly as shown in Figure 2.1 with the increase in the wind speed from Cut-in speed to the rated wind speed. A wind turbine generator generates the rated power at therated wind speed. Wind turbines are designed to stop at high wind speed in order to avoid mechanical damaging on the wind turbine. This maximum allowable wind speed is called Cut-out wind speed.

2.3The Wind Turbines

A wind turbine is composed of various components: the turbine blades, the tower, the generator system, etc. However, my aim in this paper is to investigate the impact of wind power on power quality and reliability of an electrical distribution system. Thus, it is of interest to study the characteristic of the power output from the wind turbine which is governed by the characteristic of the generator system. In this respect, today's commercial wind turbines can be classified into four major groups depending on their ability to control the rotational speed, hence the power output, of the wind turbine [2].

2.3.1 Fixed speed wind turbines

Wind turbines equipped with squirrel-cage induction generators (SCIGs) are generally known as fixed speed wind turbines since these wind turbines work at almost constant speed, with slip order of 2% at rated power [2]. A typical fixed wind speed turbine has the configuration given in Fig. 2.2 Since there is a large inrush current during starting the induction generator, which can be as high as 6 to 8 times the current at rated operation [5], these wind turbines are equipped with soft-starters to limit the inrush current and bring the drive train slowly to the operational speed [7]. These wind turbines also consume a substantial amount of reactive power during idling as well as operation, as long as they are connected to the grid; the higher the power output is, the higher is the reactive power consumption as shown in Fig. 2.3 Consequently, these wind turbines are equipped with capacitor banks to provide a reactive support. However, these capacitor banks only shift the reactive power consumption curve downward.

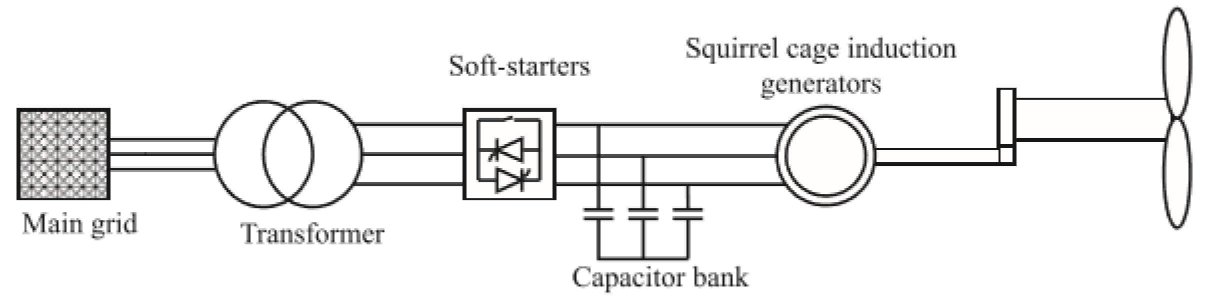


Fig. 2.2 schematic of fixed speed wind turbine

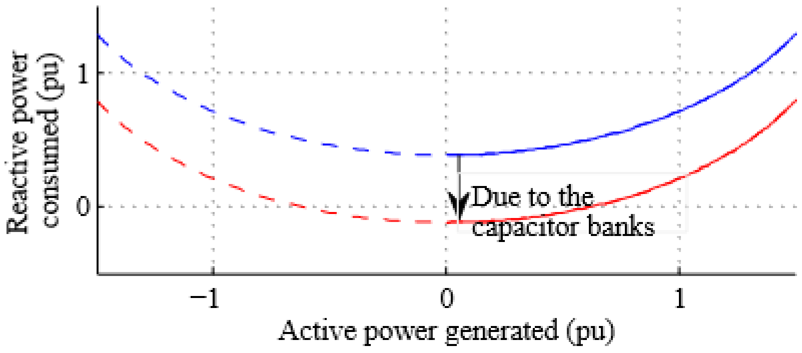


Fig. 2.3: PQ curve of a typical fixed speed wind turbine

Fixed speed wind turbines constitute most of the early generation utility scale wind turbines. In the year 2000, these wind turbines still represented 39 % of the total installed wind turbines in the world [8]. The main reason for the use of SCIGs is the damping they provide for the drive train. The damping is provided by the difference in speed between the rotor and the stator magneto motive force (MMF), i.e. the slip speed. Additional benefits include the simplicity and robustness of their construction and the lack of requirement for synchronizing [9]. However, regardless of the power control principle (active or stall), the wind fluctuation are converted to mechanical fluctuations and consequently into electrical power fluctuation. The electrical power fluctuation can yield voltage fluctuation and flicker emission in weak grids while the mechanical fluctuation increases the stress on the drive train.

2.3.2 Limited variable speed wind turbines

One of the disadvantages of fixed wind speed turbines is that during wind gusts and high wind speeds, the drive train is exposed to high mechanical stresses. If a larger slip is allowed temporarily, the drive train will be relieved. Moreover during high wind speeds, a smoother increase in power output is possible. This is done by varying the resistance of the rotor circuit. Such control of rotor circuit resistance is possible in wound rotor induction generators (WRIG) as they allow access to the rotor winding via slip rings and brushes. By connecting electronically controlled variable resistance to the terminals of the rotor winding it is possible to vary rotor circuit resistance. Using this approach a brief increase in rotational speed up to 20% has been achieved [5]. At normal wind speeds, the additional variable resistor is shorted out for maximum efficiency. During strong wind the variable resistors are manipulated to get the required torque. Hence during wind gusts the additional wind power is dissipated in the resistors, which needs additional cooling consideration. Whenever necessary, pitching can be combined with varying the rotor circuit resistance to get an optimum performance. To this end, varying the rotor circuit resistance is convenient whenever fast response is required while pitching can be used to reduce the power extracted from the wind rather than dissipating it in the resistors. Apart from this improved power controllability described, the characteristic of limited variable speed wind turbine can be considered similar to fixed speed wind turbines.

2.3.3 Double fed induction generators

Though limited variablewind turbines have improved some of the drawbacks of their counterparts that is fixed speed wind turbines, they have their own shortcomings. One of this is the fact that the speed variability achieved is at the expense of increased power loss in the rotor circuit. Besides, the achieved variability in speed is not sufficient enough to ensure maximum energy extraction under varying wind speed condition. The next generation of wind turbines with improved performance are double fed induction generator (DFIG), wind turbines.

Fig. 2.4 presents the schematic diagram of this type of wind turbine. The rotor windings, that are accessible through slip rings, are connected back to the grid through a back to back AC/DC/AC power converter. This converter circuit, through injecting a controllable voltage at the rotor frequency, realizes a variable speed operation of the wind turbine [10]. Moreover, the energy that used to be dissipated in the external resistors in limited variable speed wind turbines is now fed back to the grid through machine-side converter. The power converters can also be used for smooth connection of the wind turbines to the grid as well as to provide the required reactive power compensation. During faults, the crowbar switches the rotor circuit to an external resistor to protect the machine side converter from excessive current [12]. Similarly, the DC-link crowbar activates to protect the DC-link capacitor from overvoltage [11, 13].

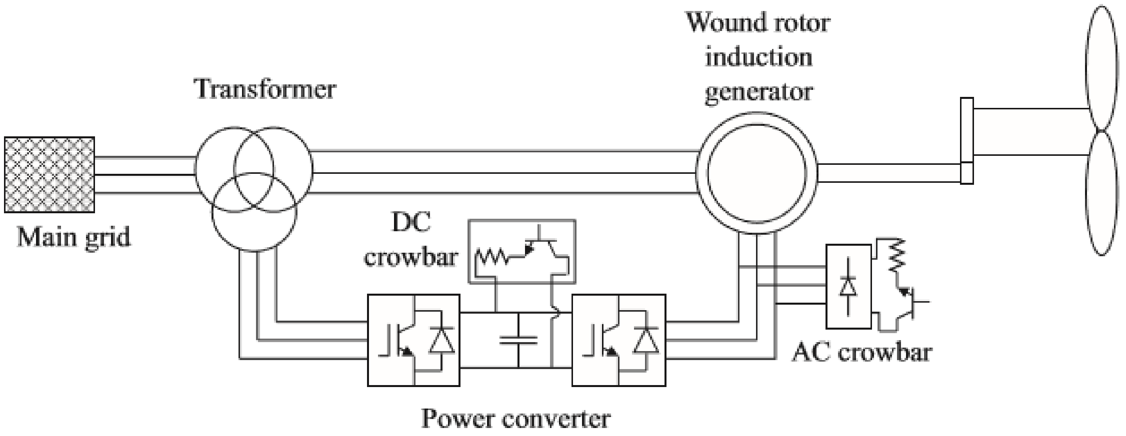


Fig. 2.4: Schematic diagram of DFIG wind turbines [11]

The extent of speed variability achieved and the amount of wind power absorbed or delivered by the rotor depend on the size of the power converter used. Considering also the economic aspect of the converter, it is usually sized to be around 30% of the rated power of the wind turbine. And the usual speed range of operation of these wind turbines is between −40% to +30% of the synchronous speed [2].

The reactive power capability of a DFIG wind depends on the stator current limit, the rotor current limit, and the rotor voltage. In general, the rotor current limits the reactive power production capacity of the machine while the stator current limits reactive power absorption capacity. The rotor voltage becomes a limiting factor only at high slips [14]. The grid side converter can provide additional reactive power support when it is not fully used for active power transfer. A typical reactive power curve of a DFIG wind turbine is shown in Fig. 2.5 [14, 15]. This is assuming that the wind turbine is always connected to the grid. However, at zero power output, the wind turbine is switched off. Hence reactive power support would only be available from the grid side converter. The magnitude of this reactive support will then depend on the ratings of the converter [15].

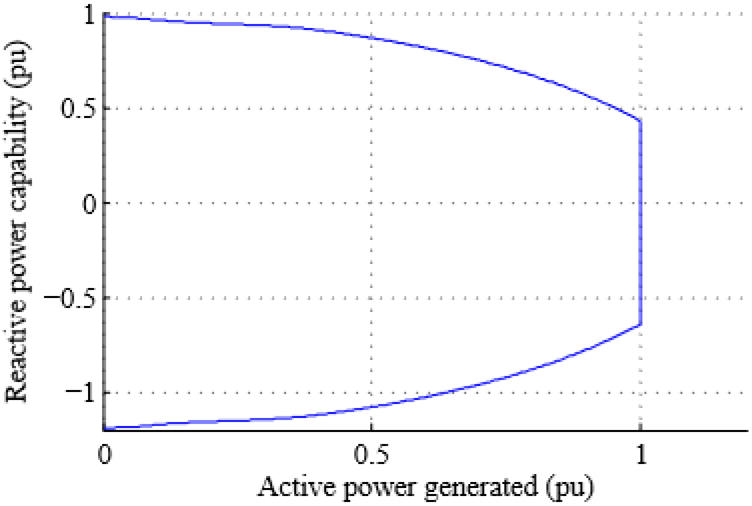


Figure 2.5:A reactive power capability diagram of a typical DFIG wind turbine

2.3.4 Full power converter wind turbines

In this wind turbine type the converter is rated to handle the full capacity of the wind turbine. That is, it completely decouples the wind turbine generator from the grid, giving the opportunity to vary the frequency of the generator as required. This also makes it possible to employ different types of generators such as induction, wound rotor synchronous, and permanent magnet synchronous generators [16]. The schematic diagram of a full power converter wind turbine is shown in Fig. 2.6.

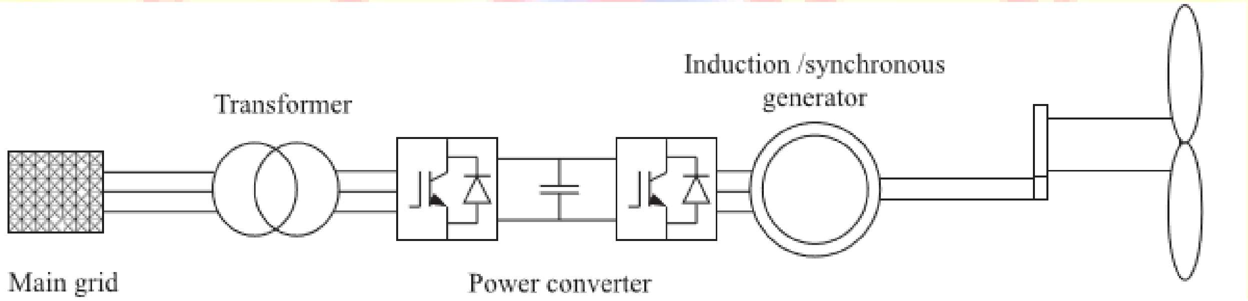


Fig. 2.6 Schematic diagram of full power converters

These wind turbines can provide a wider range of speed variability than the DFIG wind turbines. The converter is used for smooth connection of the wind turbine as well as for providing the required reactive power support.

2.4 Wind Turbine Siting

The power available in wind increase rapidly with wind speed. Therefore, the main consideration for locating a wind power generation plant is the availability of strong and persistent wind [1]. A suitable site should preferably have some of the following features:

I. No tall obstructions for some distance (about 3 km) in the upwind direction (i.e., the direction of incoming wind) and also as low a roughness as possible in the same direction.
II. Wide and open views that is, open plain, open shoreline or offshore locations.
III. An island in a lake or the sea
IV. A narrow mountain gap through which wind is channeled
V. Site reasonably close to power grid.
VI. Soil condition must be such that building of foundation of the turbines and transport of road-construction materials loaded in heavy trucks is feasible.
VII. Production results of existing wind turbines in the area to act as a guide to local wing conditions etc.

2.5 Types of Wind Turbine

Wind turbines are broadly classified into two categories. When the axis of rotation is parallel to the air stream (i.e., horizontal), the turbine is said to be Horizontal Axis Wind Turbine (HAWT), and when it is perpendicular to the air stream (i.e., vertical) it is said to bea Vertical Axis Wind Turbine (VAWT) [1]

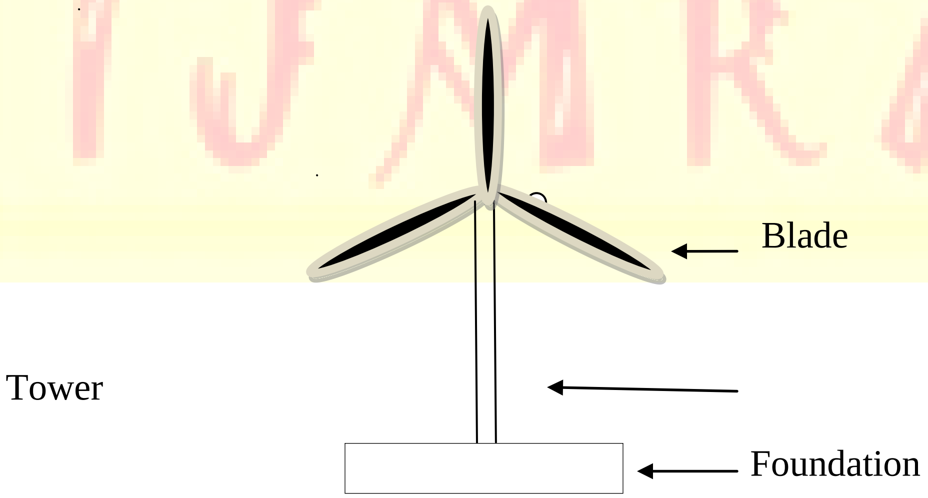


Figure: 2.7 Horizontal axis wind turbine

Horizontal-axis wind turbines (HAWT) have the main rotor shaft and electrical generator at the top of a tower, and must be pointed into the wind. Small turbines are pointed by a simple wind vane, while large turbines generally use a wind sensor coupled with a servo motor. Most have a gearbox, which turns the slow rotation of the blades into a quicker 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. 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 forward into the wind a small amount.

Downwind machines have been built, despite the problem of turbulence (mast wake), because they don’t need an additional mechanism for keeping them in line with the wind, and because in high winds the blades can be allowed to bend which reduces their swept area and thus their HAWTs are wind resistance. Since cyclic (that is repetitive) turbulence may lead to fatigue failures most upwind machines.

2.5.1.1Advantages of Horizontal axis wind turbine

1. Variable blade pitch, which gives the turbine blades the optimum angle of attack. Allowing the angle of attack to be remotely adjusted gives greater control, so the turbine collects the maximum amount of wind energy for the time of day and season.

2. The tall tower base allows access to stronger wind in sites with wind shear. In some wind shear sites, the wind speed can increase by 20% and the power output by 34% for every 10 meters in elevation.

3. High efficiency, since the blades always move perpendicular to the wind, most receiving power through the whole rotation. In contrast, all vertical axis wind turbines, and t 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 inherently lower efficiency.

4. The face of a horizontal axis blade is struck by the wind at a consistent angle regardless of the position in its rotation. This result in a consistent lateral wind loading over the course of a rotation, reducing vibration and audible noise coupled to the tower or mount.

2.5.1.2 Disadvantages of Horizontal axis wind turbine

1. HAWTs are Tall difficult to install, needing very tall and expensive cranes and skilled operators.
2. Massive tower construction is required to support the heavy blades, gearbox, and generator.
3. Their height makes them obtrusively visible across large areas, disrupting the appearance of the landscape and sometimes creating local opposition.
4. HAWTs require an additional yaw control mechanism to turn the blades and nacelle toward the wind.

2.5.2 Vertical axis wind turbine

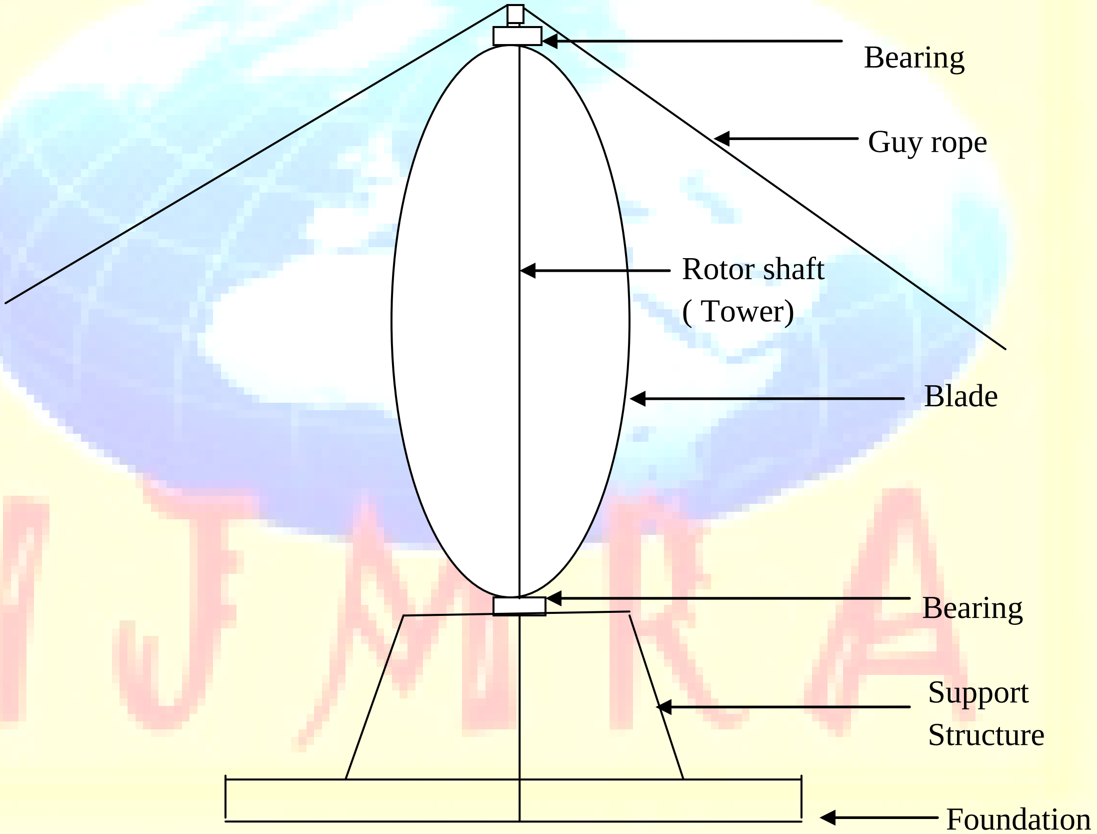


Figure: 2.8 Vertical axis wind turbine

Vertical-axis wind turbines (or VAWTs) have the main rotor shaft arranged vertically. Key advantages of this arrangement are that the turbine does not need to be pointed into the wind to be effective. This is an advantage on sites where the wind direction is highly variable.

With a vertical axis, the generator and gearbox can be placed near the ground, so the tower doesn't need to support it, and it is more accessible for maintenance. Drawbacks are that some designs produce pulsating torque.

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 the service life. However, when a turbine is mounted on a rooftop, the building generally redirects wind over the roof and this can double 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.

2.5.2.1Advantages of Vertical Axis Wind Turbine

1. A massive tower structure is less frequently used, as VAWTs are more frequently mounted with the lower bearing mounted near the ground.
2. Designs without yaw mechanisms are possible with fixed pitch rotor designs.
3. The generator of a VAWT can be located nearer the ground, making it easier to maintain the moving parts.
4. VAWTs have lower wind startup speeds than HAWTs. Typically, they start creating electricity at 6 m.p.h. (10 km/h).
5. VAWTs may be built at locations where taller structures are prohibited.

2.5.2.2Disadvantages of Vertical Axis Wind Turbine

1. A VAWT that uses guy-wires to hold it in place puts stress on the bottom bearing as all the weight of the rotor is on the bearing. Guy wires attached to the top bearing increase downward thrust in wind gusts. Solving this problem requires a superstructure to hold a top bearing in place to eliminate the downward thrusts of gust events in guy wired models.
2. The stress in each blade due to wind loading changes sign twice during each revolution as the apparent wind direction moves through 360 degrees. This reversal of the stress increases the likelihood of blade failure by fatigue.
3. While VAWTs' components are located on the ground, they are also located under the weight of the structure above it, which can make changing out parts very difficult if the structure is not designed properly.
4. Having rotors located close to the ground where wind speeds are lower due to the ground's surface drag, VAWTs may not produce as much energy at a given site as a HAWT with the same footprint or height.

2.6 Major Application of Wind Power

Wind turbines have been built-in power output range from a kilowatt to a few MW to suit a wide range of applications. Major application may be grouped in three categories [1].

2.6.1 Application requiring mechanical power

1.Wind pumps Low power turbines are used for producing mechanical power for pumping water in remote areas. These are also known as wind pumps. Simple and reliable traditional reciprocating pump or centrifugal pumps are used. Wind pump are used to supply water for livestock, small-scale irrigation, theselow head pumping for aquatic breeding and domestic water supply. Mechanical power also used to operate farm appliances.

2.Heating the direct dissipation of mechanical power produces heat with 100% efficiency using paddle wheel and other turbulent fluid system. The available hot water is used as such or employed for space heating.

3.Sea transports the old square- rigged sailing ships were inefficient as they were operated by drag forces. Modern racing yachts, with a subsurface keel, harness lift forces and the much more efficient and sail faster than the wind. Large cargo ships requiring power in MW range, driven by improve efficiency sails, are now been designed. Also, wind turbine are installed onboard to power propeller in ferries operating on short routes

2.6.2 As off- grid electrical power source

1. Machines of low power with a rotor diameter of about 3 m and 40-1000W rating can generate sufficient electrical energy for space heating and cooling of homes, water heating and for operating domestic appliances such as fan, light and small tools.
2. Applications for somewhat more powerful turbines of about 50KW are producing electrical power for navigation signal (e.g., lighthouse), remote communication, weather stations and offshore oil-drilling platforms.
3. Intermediate power range, roughly 100 to 250 KW aero-generators can supply power to isolated populations, farm cooperation, commercial refrigeration, desalination and to other small industries. The generation may operate in a stand-alone mode or may be connected to the grid system.
4. For lifting water to a hill, aero-generator is installed on the top of hill and electric energy is transmitted to a pump fixed at a lower level. The same principle is utilized to store excess generated power using a pumped storage system to be utilized later during no wing periods.

2.6.3 As Grid Connected Electrical Power Source

Large aero-generators in a range of a few hundred KW to a few MW are planned for supplying power to a utility grid. Large arrays of aero-generators, known as wind farms, are being deployed in an open plain or offshore in shallow water for this purpose.

3. Impacts of wind power on a distribution system

3.1 Voltage regulation in a distribution system

In an electrical distribution system there are one or more transformers through which electricity is supplied to the consumers in the network. The purpose of these transformers is to step down the voltage from transmission or sub-transmission systems. These transformers are also equipped with on-load tap changers (OLTC) that regulate the voltage at the secondary side of the transformer so as to keep the voltage in the distribution system within, for example, ±10% of the nominal voltage. These range is not continuous, it is divided into steps of, for example, 1.67% so that each change represents a specific voltage increment. Moreover, tap changers have adjustable dead bands and time delays. The dead band is the voltage range around the reference value within which the tap changer does not take action. The time delay is the duration during which the voltage should be outside this dead band before the tap changer takes action.

The tap changers can accomplish the voltage regulation in two ways [17]. One way is through maintaining the voltage at the secondary side of the transformer at a given dead band around a constant voltage set point. In the second alternative, the voltage set-point is augmented with line drop compensation, i.e. the voltage set-point changes depending on the voltage drop on the user adjusted internal impedance. This internal impedance is chosen to give the required voltage boost from low to high loading condition.

Though many regulators have a bidirectional capability, to give the required boost depending on the direction of the power flow, the change in power factor of the load complicates the application of the method. Many regulators are, thus, set up without line drop compensation. It is obviously easier and less prone to mistakes, but at the expense of losing some significant capability [17].

3.2 Wind turbines contribution to overvoltage

Whichever is used, the above voltage regulation approaches have been utilized and was found effective in passively operated distribution systems for many years. But due to the introduction of wind power, or any distributed generation for that matter, voltage regulation has become a challenge. Wind power introduces a reverse power to the external grid. With the voltage at the transformer being held almost constant, these results in a higher voltage at the point of common connection (PCC) compared to that at the substation. Depending on the amount of reverse power flow, the voltage at the PCC could be above the allowed voltage level in the distribution system this can cause an overvoltage in the network.

3.2 Overloading

The components of a distribution system, such as cables and transformers, can continuously carry only up to a given current level. This limit is based on their thermal rating. The introduction of wind power can have both positive and negative effect on the loading level of distribution system components. If the capacity of the wind power is relatively low compared to the load in the system, it can reduce the power flow through network thereby relieving the thermal stress on the system components. It may also decrease the system loss. On the other hand, if the installed wind power in the distribution system is relatively high there will be a substantial reverse power flow. This reverse power flow can also be higher than the forward power flow that used to flow through the system before the introduction of wind power. This of course will increase both the thermal stress in the network components and the system loss. Under special cases, this reverse power flow can even exceed the thermal rating of the network components, resulting in an overloading situation.

3.3 Voltage flickers

Voltage flickers are the rapid fluctuation of voltage which may cause a perceptible light flicker depending on the magnitude and frequency of the fluctuation. Large voltage flickers can also cause malfunctioning of sensitive equipment. Hence a measurement system was developed by IEC [18] to quantify and put a limit on the allowed level of these disturbances. Based on this standard two quantities are identified for flicker measurement: the short term flicker severity factor P_{st} and the long term flicker severity factor P_{lt}. The former is based on measurements over 10 minute period while the latter is based on 2 hour measurements [19]. Using this flicker emission quantification, flicker emission limits are imposed on each installation to ensure that the cumulative effect of the emissions at various voltages will not be disturbing to the customers located on the low voltage side. The IEC standard provides a strategy of allocating these emission limits accounting for the capacity of the installation compared to the total system capacity.

A flicker severity index exceeding unity will be felt disturbing to the majority of individuals; a flicker severity index between 0,7 and 1,0 is noticeable, but not disturbing [31]. Hence compatibility level of these flicker emissions at LV are given near unity (Pst= 1 and Plt= 0.8) [32]. That is, the flicker emission levels that occur in low voltage systems should be below this value with 95% probability based on a statistical distribution representing both time and spatial variations. From the compatibility levels the system operator can assign different flicker emission planning levels for different voltage levels in the system. Some indicative values of planning level for MV and HV are shown in Table 3.1 where the flicker transfer coefficients between the different voltage levels–HV to MV, MV to LV–are assumed be unity.

Table 3.1: Indicative values of planning levels for flicker in MV, HV, and EHV power systems [33]

	Planning level	
	MV	HV-EHV
P_{st}	0.9	0.8
P_{lt}	0.7	0.6

Wind turbines introduce two types of flicker: flicker emission during continuous operation and flicker emission during switching operation. The flicker emission during continuous operation is caused by wind turbulence, the wind gradient and tower shadow effect, and the mechanical properties of the wind turbine [2, 20]. The voltage flicker that occur due to switching operation are induced by a change in power production due to startupand shut down of the wind turbines. More over switching between generators or generator windings causes switching voltage flicker [2].

In general, the flicker emission from variable speed wind turbines can be considered fairly low during both continuous and switching operation, whereas the flicker emission from fixed speed wind turbines depends on the control mechanism: stall or pitch [2]. The flicker emission from stall controlled wind turbines is average during continuous operation. However, due to limited controllability of the torque input of the turbine, the flicker emission is high during switching operation. With better controllable turbine torque input, the flicker emission from pitch controlled wind turbines during switching operation can be considered average. However, due to limited bandwidth of the pitching system, their flicker emission during continuous operation is high [21]

Moreover, flicker emission from wind turbines depend on the short circuit capacity of the network relative to the capacity of the wind turbines, measured by short circuit ratio (SCR), the angle of the Thevenin impedance of the grid seen from the point of connection of the wind turbine, and the average wind speed. Hence wind turbine manufacturers supply different coefficients which can be used to assess the level of flicker emission from the turbine under continuous as well as switching operation. Using these flicker emission coefficients and the grid characteristic at the point of connection, the flicker emission from a given wind turbine installation can be determined.

3.3.1 Flicker emission during continuous operation

Flicker emission from a wind turbine under continuous operation is characterized by a flicker coefficient $c(\psi_k, v_a)$ which is specified for different average wind speeds v_a and impedance angles ψ k. Based on the average wind speed at a particular site and the impedance angle of the grid, the flicker emission from the wind turbine is calculated using

$$P_{st} = P_{lt} = c(\psi_k, v_a)\frac{S_n}{S_k} \qquad (3.1)$$

Where S_n is the rated apparent power of the wind turbine and S_K is the short circuit level of the distribution system at the point of connection.

3.3.2 Flicker emission during switching operation

For a given wind turbine, two factors are stated to characterize the wind turbine during switching operation: voltage change factor ku (ψ k) and flicker step factor kf (ψ k) [22]. Similar to the flicker coefficients, these factors are functions of the grid impedance angle ψ k.

A voltage change occurs at the PCC due to switching operation of a wind turbine installation. The magnitude of this voltage change in percent is given as [22]

$$\Delta V = k_u(\psi_k)\frac{S_n}{S_k}\cdot 100 \qquad (3.2)$$

The flicker emission during switching operation can be calculated using

$$P_{st} = 18 \times N_{10m}^{0.31} \times k_f(\psi_k)\frac{S_n}{S_k} \qquad (3.3)$$

Where N10m is the maximal number of switching operations that may occur during 10 minute.

3.4 Harmonics

Harmonics are sinusoidal voltage or currents having frequencies that are integer multiple of the frequency at which the supply system is designed to operates (termed fundamental frequency; (usually 50 or 60 Hz).

3.4.1 Individual harmonic distortion: Individual harmonic distortion (IHD) is the ratio between the roots means square (RMS) value of the individual harmonic and the RMS value of the fundamental for example, assume that the RMS value of the third harmonic current in a nonlinear load is 20A, the RMS value of the fifth harmonics current is 15A, and the RMS value of the fundamental is 60A. Then, the individual third harmonic is:

$$IHD_3 = 20/60 = 0.333 \text{ or } 33.3\%$$

And the individual fifth harmonic distortion is:

$$IHD_5 = 15/60 = 0.25 \text{ or } 25.0\%$$

Under this definition, the value of IHD1 is always 100%. This method of quantifying the harmonics is known as harmonic distortion based on the fundamental. This is the convention used by the institute of international electrical and electronics engineers (IEEE) in the U.S.

3.4.2 Total harmonic distortion: Total harmonic distortion (THD) is a term used to describe the net deviation of a non-linear waveform from ideal sine waveform characteristics. Total harmonic distortion is the ratio between the RMS value of the harmonics and the RMS value of the fundamental. For example, if a nonlinear current has a fundamental component of V_1 and harmonics components of V_2, V_3, V_4 …Vn, then the RMS value of the harmonics is:

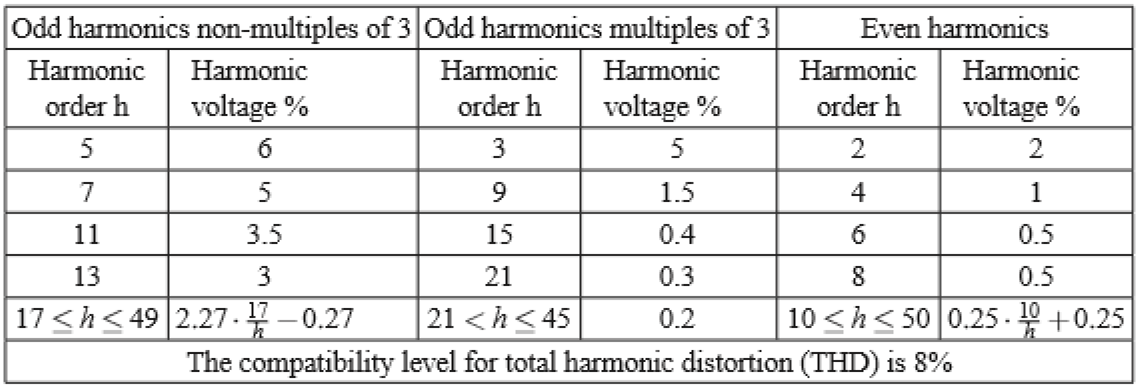
$$V_H = \sqrt{(V_2^2 + V_3^2 + V_4^2 + \cdots + V_n^2)}$$

$$THD = \frac{\sqrt{(V_2^2 + V_3^2 + V_4^2 + \cdots + V_n^2)}}{V_1} * 100\%$$

The individual harmonic distortion indicates the contribution of each harmonic frequency to the distorted waveform, and the total harmonic describes the net deviation due to all the harmonics [34].

Harmonics are produced by nonlinear loads such as power electronic devices, rectifiers and inverters. They can cause overheating and equipment failure, faulty operation of protection devices, nuisance tripping of sensitive devices and interference with communication circuits [2]. Hence standards specify the harmonic emission limits which will ensure normal operation of the power system. Table 3.2 presents the harmonic voltage emission limits at low and medium voltage networks specified by the IEC standard [23, 24]

Table 3.2: Compatibility levels for individual harmonic voltages in low and medium voltage networks (percent of fundamental component) [23, 24]



Odd harmonics non-multiples of 3		Odd harmonics multiples of 3		Even harmonics	
Harmonic order h	Harmonic voltage %	Harmonic order h	Harmonic voltage %	Harmonic order h	Harmonic voltage %
5	6	3	5	2	2
7	5	9	1.5	4	1
11	3.5	15	0.4	6	0.5
13	3	21	0.3	8	0.5
$17 \le h \le 49$	$2.27 \cdot \frac{17}{h} - 0.27$	$21 < h \le 45$	0.2	$10 \le h \le 50$	$0.25 \cdot \frac{10}{h} + 0.25$
The compatibility level for total harmonic distortion (THD) is 8%					

Harmonics with magnitudes below 0.1% of the nominal current may not be reported according to the IEC 61400-21 standard.

CONCLUSION

This paper discussed the stochastic nature of wind power and the impacts of wind power integration on a distribution systems. For wind power planning power curve can be used to assess the expected energy yield of a given wind power installation.

The introduction of wind power in a given distribution system poses a number of known power quality and reliability concerns. Overvoltage and overloading can occur more or less independent of the generator technology. However, other impacts of wind power–such as flicker and harmonic emission, increased fault level–depend on the technology of the generator system of the wind turbine. Flicker emission, for example, is higher in fixed speed wind turbines while voltage harmonics are introduced mainly due to variable speed wind turbines. The fault current contribution is highest with fixed speed wind turbines while significant fault currents are also injected by limited variable speed wind turbine and double fed induction generators wind turbines. The full power converter wind turbines, on the other hand, have a low level of fault current contribution as determined by the overcurrent capability of the converter system.

Flicker emission is directly related to the stochastic nature of wind power and harmonics is indirectly related to it since power electronic converters are used to avoid the negative impact of the stochastic nature. The other integration issues can arise due to any type of DG and are not specific to DGs with intermittent output.

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