

# Wind Power Generation: An Overview

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**Abstract** - In this paper, components of wind power generation including the wind turbine, wind generators, the gear box, pitch control, and yaw control are discussed with emphasis on grid connected systems. Also, real life implementation issues are discussed to realize a viable wind power system. The objective of the paper is to develop end user understanding by utilizing analogies and simple language.

**Index Terms** - wind turbine, tip speed ratio, induction generator, doubly fed induction generator, permanent magnet generator, synchronous generator, pitch control, yaw control, gear box, gearless systems, logistics of wind power systems, standards of wind power systems.

## I. INTRODUCTION

With the ever increasing demand on power, there is a great interest in developing renewable energy and increase energy conservation efforts. Because of that, technological research is being directed toward utilizing wind energy. Figure 1a shows the rapid increase of wind power use as more technological breakthroughs are achieved. Figure 1b shows major manufacturers of wind power systems of the 2008 installed capacity of 28.190 GW.

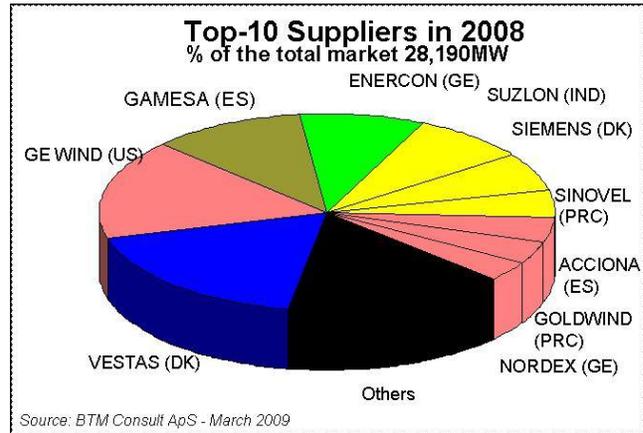


Fig. 1b. Top 10 manufacturers in 2008 [16].

The goal of this paper is to map all industrial wind power generation systems with the endeavor to develop intuitive user understanding. That understanding will help a user appreciate the capabilities of wind power systems. Also, that user will be able to communicate intelligently with wind power systems manufacturers to satisfy his needs.

The first section of this paper will examine the basics of wind power systems in an intuitive and understandable way. Manufacturing and complex control schemes are avoided as possible. The wind turbine and various types of generators are discussed in this section. The second section discusses stand-alone wind power systems, and the third section discusses some real life practical considerations.

## II. BASICS OF WIND POWER SYSTEMS

### A. The Wind Turbine:

To understand wind power systems, it is very important to conceive the wind turbine. A turbine like the one shown in Figure 2 will be able to capture a fraction of the available power from the wind. Power available from the wind is given by:

$$P_w = 0.5 A D V^3 \quad (1)$$

where  $A$  is the swept area of the turbine,  $D$  is air density and  $V^3$  is the cube of wind speed flowing through the turbine. The fraction of power that a turbine can capture is referred to as coefficient of power ( $C_p$ ). This gives the equation:

$$P_t = C_p P_w \quad (2)$$

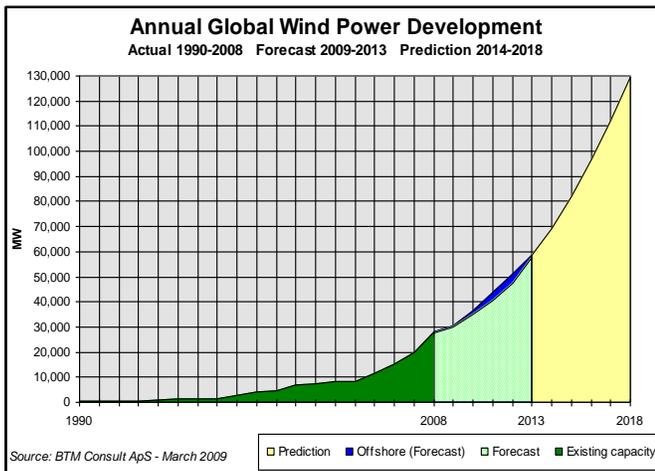


Fig. 1a. The rapid growth of wind power systems [16].

where  $P_t$  is turbine power.  $C_p$  depends on the turbine design. It has been proven mathematically that the maximum fraction that a wind turbine can capture is less than 59% of the available wind power. That value is referred to as the Betz limit [1].



Fig. 2. A typical wind power system utilizing three blades turbine design.

$C_p$  depends on the turbine design and other factors including wind speed and turbine rotation speed. Turbine design includes factors like the number of blades, area of each blade and pitch angle of the blades.

While it is easy to understand that  $C_p$  depends on the turbine design, it is not readily clear its dependence on wind and turbine speeds. That dependence is shown in Figure 3. The y-axis can also be labeled as  $C_p$  multiplied by wind velocity of each curve.

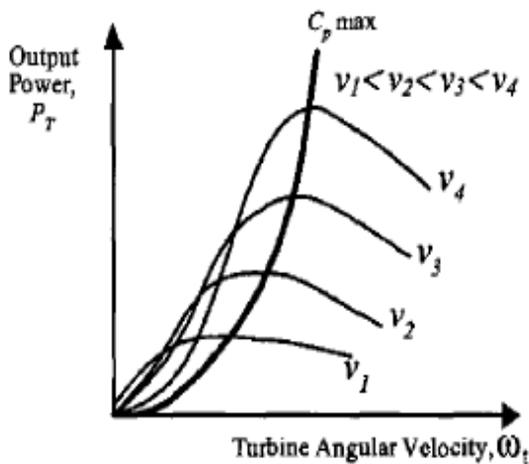


Fig. 3. Turbine output dependence on wind and turbine speeds [2].

From Figure 3, we can see that available power from the turbine or  $C_p$  is changing with wind speed and turbine speed. Furthermore, maximum power available is also changing with the wind and turbine speeds. It has to be noted that curves in Figure 3 are for a single pitch angle and the shape of the curve would vary with pitch angle.

In modern wind power systems, the generator loading is constantly adjusted for the turbine to operate at  $C_p$ -max with the varying wind speed [9]. This is done for wind speeds below those rated. Beyond rated wind speeds, pitch control

will be utilized to limit the speed of the turbine and in turn keep the power generated at rated power. This way, the turbine is protected against high destructive speeds and the generator against overload [3, 4].

Of course, it is assumed for the previous two ways of control that we are connected to the grid where power can be absorbed. This is compared to the standalone systems where it is more difficult to capture maximum power. Section III of this paper will discuss this case.

Figure 4 shows a typical wind generation system output power vs. wind speed. The rated power for this system is 2 MW.

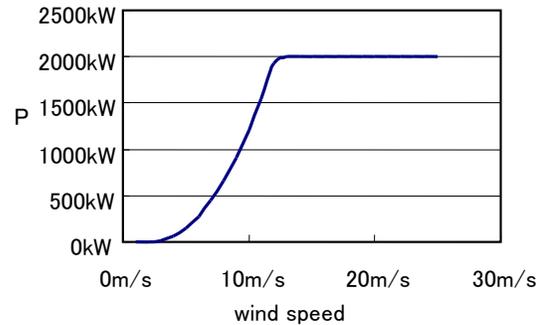


Fig. 4. Wind turbine output power vs. wind speed.

Another concept worth mentioning is the tip speed ratio. Figure 3 can be represented by only a single curve representing the same data. That can be done by defining the tip speed ratio (TSR) which is " $(\omega_t R)/V$ " where  $\omega_t$  is turbine angular velocity,  $R$  is the radius of the turbine and  $V$  is the wind speed. In other words, TSR is the ratio of blade tip speed to wind velocity. Figure 5 shows the other way of representing the turbine available power by using TSR.

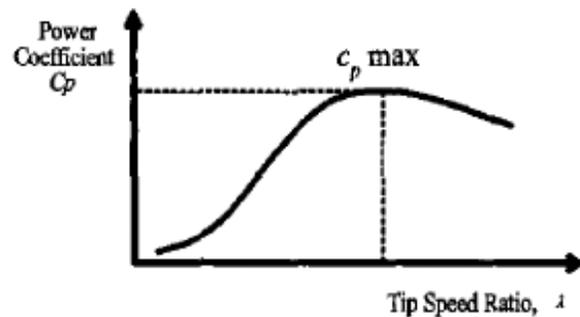


Fig. 5. TSR vs.  $C_p$  [2].

The drop of power or  $C_p$  after a certain tip speed ratio in Figure 4 can be explained by noting wind turbulence behind the turbine blades at high turbine speeds or TSR.

Similar to Figure 3, Figure 4 shows only a single pitch angle and the shape of the curve would change with the changing pitch angle. Figure 6 depicts this fact.

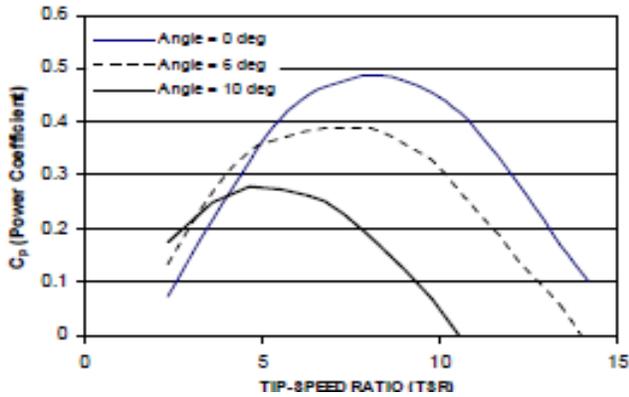


Fig. 6. TSR vs.  $C_p$  for different pitch angles [4].

### B. The Wind Generator:

The other major part of a wind generation system is the generator, which can be squirrel cage induction, wound rotor induction permanent magnet and synchronous. However, there are other types like field modulated or Roesel generators, which are rarely used in industry and therefore out of scope of this paper.

#### 1. Squirrel Cage Induction Generator:

The squirrel cage induction generator is the most used type. This is due to its simplicity, reliability, low weight, low cost and low maintenance cost [6]. This type of generator doesn't need slip rings or an excitation system. However, the disadvantage is the need for a reactive power source to establish the rotor magnetic field [5]. Fortunately, this is easily solved by the use of modern power electronics along with a single capacitor to provide all the reactive power needed for its operation [7, 8]. Also, those power electronic devices can even inject reactive power back to the network if needed. This type of generator needs to be rotated above synchronous speed (3,600 rpm for a 60 Hz network and 2 pole generator) for it to generate power [10]. That requirement is not necessary for the other types discussed below.

Even for the squirrel cage induction generator, with the use of modern power electronic devices (drive), the generator can produce power at sub-synchronous speeds. This is done by the action of the drive that will make the network seem to be running at a lower frequency.

The use of the drive is very important to realize variable speed wind power generation. Without such devices, the squirrel cage induction generator will generate power only when the generator rotor is rotated above synchronous speed; and if the wind speed is low, the generator will act as motor consuming instead of producing electric power. It has to be noted that the drive in this case should be rated for 100% of the generator. This is compared with only 30% of the doubly fed induction generator mentioned below [13]. Figure 7 shows a squirrel induction wind generator coupled with a drive.

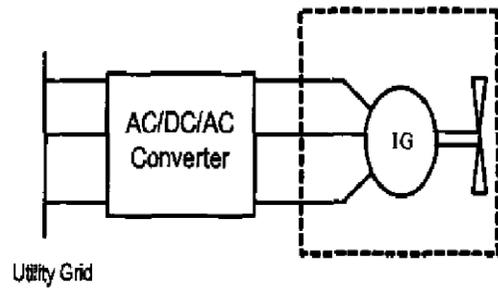


Fig. 7. Squirrel cage induction wind generator.

#### 2. Wound Rotor Induction Generator (Doubly Fed):

This is an interesting type of generator where the stator and rotor can give power simultaneously at certain speeds [12]. Figure 8 shows this type of wind generator. The rotor is connected to the drive while the stator terminal is directly connected to the grid or network.

Since the stator is connected directly to the grid, the magnetic field rotation speed is fixed in the stator windings. The rotor side drive function is to adjust the rotation of the magnetic field in the rotor to match the stator one. This is exactly the operation principle of a synchronous generator where there is no slip between rotation of the stator and rotor magnetic field.

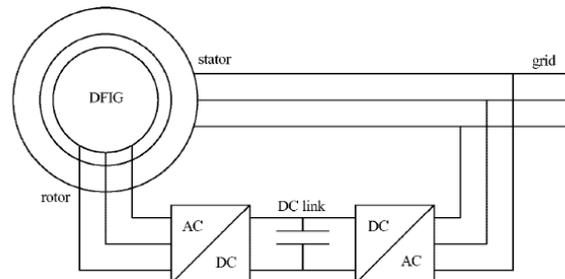


Fig. 8 Wound rotor or Doubly Fed IG

At sub-synchronous rotor speeds, due to low wind, the drive will adjust the frequency fed to the rotor to make the rotor magnetic field seem like it is running faster at synchronous speed. This action requires borrowing real power from the grid. The stator will add that power to the power from the turbine. In total, the wind system at this condition will be exporting power to the network.

At super synchronous rotor speeds, due to high wind, the opposite takes place. Here, the rotating magnetic field in the rotor will run in a direction opposite to the physical rotation of the rotor. The result is zero relative speed between stator and rotor magnetic field. This way, both the rotor and stator produce real power.

At rotor speed of exactly synchronous speed, DC current is fed to the rotor. That means the generator will be acting as a synchronous generator, which will be discussed.

To visualize the operational concept of the wound rotor

generators, the pedestrians' horizontal escalator in an airport, for example, can be utilized, Figure 9. Assuming a pedestrian wants to keep his speed constant at certain value relative to the ground, he will walk along that escalator to maintain his target speed if the escalator is slower than the target speed (low wind speed). On the other hand, when the escalator is faster (high wind speed), that pedestrian should walk backward to slow himself down. When the escalator is running at the exact target speed, he should stop. The escalator is the rotor, the pedestrian is the rotor magnetic field and the target speed is the synchronous speed of the stator.

This type of generator can't be realized without the use of power electronics or drives. If this type of generator is to be utilized without a drive, the rotor windings need to be shorted directly or through a resistor. In this case, it will act like a squirrel cage induction generator.



Fig. 9. Pedestrians' horizontal escalator [18].

### 3. Permanent Magnet Generator (PMG):

Unlike the squirrel cage induction and the doubly fed generators, the permanent magnet generator (PMG) doesn't need any external source to establish the rotor magnetic field. Instead, permanent magnets provide all the field requirement of the generator [13].

Without a drive, this generator will only produce power when wind speed is high enough to attempt running the rotor at a speed higher than the network stator magnetic field rotation. That will increase the rotor speed and in turn the power system frequency by a small fraction. That increase will be sensed and other generators in the power system will cut power exactly equal to that of the wind generator power production to bring the frequency back to the network frequency, typically 50 Hz or 60 Hz. When wind speed is too low, the PMG will act as a motor consuming power from the network.

The analogy of the multi-person bicycle can be used to render this concept intuitive. Assuming that bicycle is intended to run at a constant speed all the time, a child riding with his family on that bicycle will not contribute in pushing the bicycle unless he pedals fast enough. The speed of the bicycle will increase a little but the other riders should relax to reduce the speed back into desired speed. The speed

of the bicycle is the system frequency while the child is the wind generator. The other riders are the main network generators, which are fossil fuel or nuclear based. Figure 10 shows that analogy.



Fig. 10. Multi-person bicycle (tandem) analogy [19].

With a drive, the PMG can produce power at a wider range of wind speeds. This is achieved by the drive making the network seem to run at a lower frequency during low wind speeds. When the wind speed is high, the opposite takes place. The analogy of the drive is the multi-ratio gear connecting the child pedals to the wheels of the bicycle.

### 4. Synchronous Generator (SG):

While the PMG employs permanent magnets in the rotor, the synchronous generator (SG) employs Direct Current (DC) windings to provide the rotor magnetic field. The operation of this type of generator is very similar to the PMG. The only difference is that the rotor DC field is controllable in the SG while it is not in the PMG.

That controllable DC field in the rotor offers control on the output voltage for the SG. This advantage is not very important since the inverter or drive can easily regulate the output voltage in the PMG. The only advantage of the SG is its familiarity as it is the preferred type of generator for fossil fuel or nuclear-based generation.

#### C. The Gearbox:

To optimize material use, torque and speed characteristics, almost all major wind generation system manufacturers adapt the three blade wind turbine. That design offers rotation speed around 15 revolutions per minute (RPM). Size and cost limitation of generators mandates the number of poles around six, which have a rated speed of 1,200 RPM assuming a 60 Hz frequency rating. To match the turbine with the generator speed, an up speed gearbox is usually used to increase rotation speed of the turbine from 15 RPM to 1,200 RPM.

It has to be noted that new expensive design concepts exists where a large number of poles are utilized to do without the gearbox [13]. This in turn increases the overall efficiency and reliability of the wind system. For example, the wind system [14] utilizes a 60-pole permanent magnet 1.5 MW generator, which gives a speed of 100 RPM with the 50 Hz network. The drive will match that network frequency with the low speed wind turbine of 18 RPM. For example, the generator is seeing

a drive generated frequency of 9 Hz with the wind turbine speed at 18 RPM. To give a prospective, the generator for this system weighs 37 metric tons while the doubly fed 1.5 MW generator would weigh only 8 metric tons.

#### D. Yaw and Pitch Control:

Industrial wind power systems incorporate active yaw and pitch control. Yaw control is responsible for directing the wind turbine in the direction of the wind. This is achieved by a wind direction sensor that actuates the yaw control. An important function of the pitch control is to prevent the wind turbine from over speeding in order not to exceed its mechanical limits and generator power rating [4].

The pitch control system should be failsafe, which means that control will work during a network outage to prevent turbine over speed during high wind periods. It should be noted that during such periods, the generator will be electrically disconnected from the grid while the pitch angle is set completely out of the wind. Also, the wind turbine will be left to rotate freely to prevent pending of blades, as wind may change direction quickly. The yaw control will be deactivated as tracking wind direction is not useful in this case.

Figure 11 shows various parts of a wind generation system. All the components in the Figure are mentioned above with the exception of the Nacelle and brakes. The Nacelle is the outer cover sheltering all mentioned components while the brake's function is to stop the turbine during maintenance.



Fig. 11. Various components of a wind power system [17].

### III. STAND-ALONE WIND SYSTEMS

Due to the changing nature of wind, most wind power systems are not relied on as a primary power source. Instead, wind power systems are used as a supplement for the electrical network or grid.

When the wind is high enough, the wind power system will feed the local load and the access will be fed to the grid. When wind speed is too low, the local load is fed from the grid. This way, the electric bill for those loads will be reduced or even eliminated if good winds blow long enough.

Although being connected to the grid has its benefits, in some areas where power lines are too far, a stand-alone wind power system can provide some of the electrical needs of that remote area. Such a system will face many challenges. Those include: unreliability of the wind and load characteristics not matching the wind turbine [15]. As mentioned in part II of this paper, that match is needed to ensure optimum power extraction from the wind.

To mitigate for wind unreliability, energy storage can be used. Batteries, water heating or pumping water uphill can be used for example. The other problem of wind turbine power optimization is mitigated by load control. For example, water heaters can be inserted or removed depending on wind speeds. Another method is to utilize loads that inherently match the turbine load characteristics like a pump. Another scheme that can be very effective is to use diesel generators along the wind system. Those systems are referred to as Hybrid Wind-Diesel [11].

### IV. WIND POWER SYSTEM IMPLEMENTATION ISSUES

In this section, real life implementation issues are discussed. Those issues should be thoroughly considered to realize a viable wind power system.

#### A. Economical Considerations:

Wind average speed in the area that a wind power system will be installed is the most important factor in deciding the utilization of such a system. A wind system shall be installed in an area where average annual wind speed guarantees power production. That power production should compensate for the initial cost and maintenance cost.

To give a prospective, a 1.5 MW wind power system is estimated to have a turnkey cost of U.S. \$4 million [16]. This cost, along with the maintenance cost and production power revenue, based on wind speed average, should be considered to make an intelligent decision. Even if wind power systems are utilized to protect the environment, they should make long-term economic sense.

#### B. Logistics:

An industrial wind power system of 1.5 MW, for example, can face very challenging logistics problems. Such a system can weigh more than 320 metric tons. This includes a 200 ton tower, 100 ton nacelle and 20 tons for the three turbine blades. Moving those heavy and long components on roads that may have weight limitation is one of these challenges. Also, a very heavy crane is needed to hoist the components

in place. For example, a 550 ton crane was needed to install a 2 MW wind system [15].

### C. Wind System Standards:

To achieve a successful implementation of any project, the use of industry standards is a must. This is the case since standards harbor long industry experience to increase reliability and reduce cost.

The International Electrotechnical Commission (IEC) developed the IEC-61400, which is the most widely utilized wind power standard. To name a few, the standard addresses safety, performance, noise and blade structural testing. IEC61400-24 deals with lightning protection which is a very important issue to ensure a long lasting wind power system.

## V. CONCLUSION

Although wind power suffers from low reliability if compared with fossil fuel or nuclear power, its main advantage is renewability and environment acceptance. With the new advances on blade, gearbox, generator and power electronics technologies, wind power can play an even wider role in providing clean power.

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## VII. BIOGRAPHIES



**Salah Al-Majed** was born in Dammam, Saudi Arabia, on January 17, 1971.

After working for the Saudi consolidated Electric Company in the Eastern Province (SCECO EAST) for five years as a Relay Technician, Salah joined King Fahd University of Petroleum and Minerals (KFUPM) in Dhahran, Saudi Arabia. In 1998, Salah earned his Bachelor degree in Electrical Engineering.

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