ANALYSIS OF WIND AND PV SYSTEMS

4.1 Wind Energy Conversion Systems (WECS)

A wind energy conversion system (WECS) is composed of blades, an electric generator, a power electronic converter, and a control system, as shown in Fig. 4.1.The WECS can be classified in different types, but the functional objective of these systems is the same: converting the wind kinetic energy into electric power and injecting this electric power into the electrical load or the utility grid.

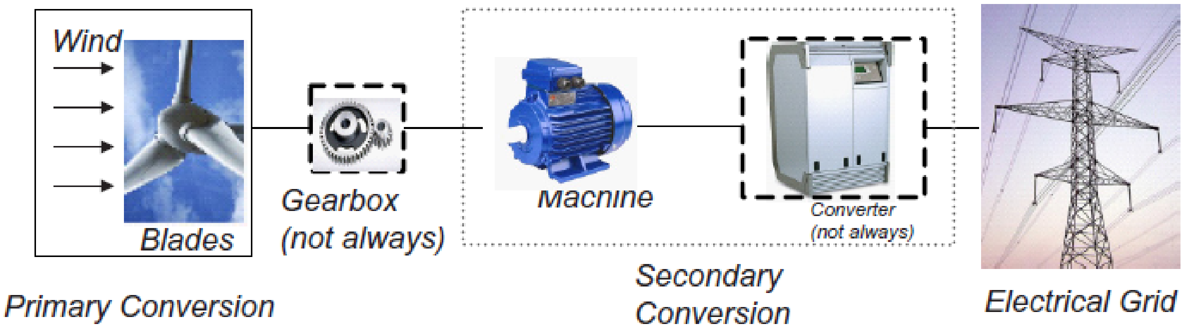


Fig. 4.1. Block diagram of a WECS.

4.2 Classification of wind turbine rotors

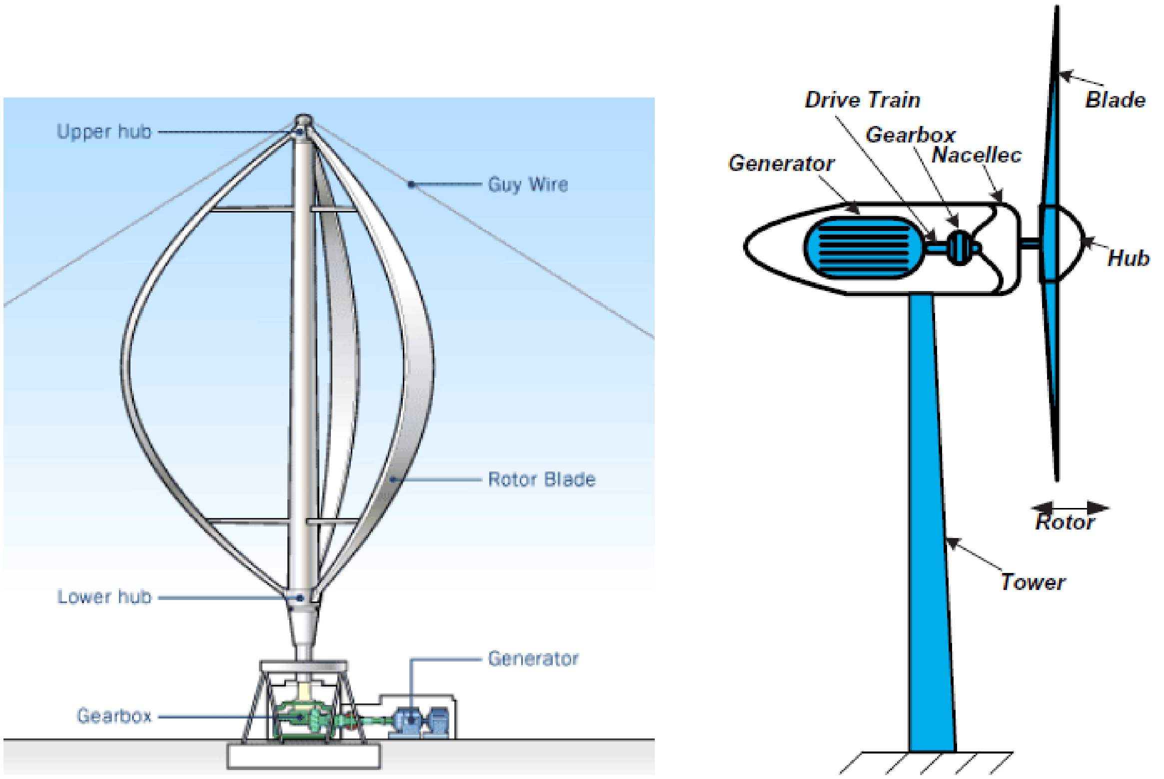
Wind turbines are usually classified into two categories, according to the orientation of the axis of rotation with respect to the direction of wind, as shown in Fig. 4.2

- ✓ Vertical-axis turbines
- ✓ Horizontal-axis turbines

4.2.1 Vertical-axis wind turbine (VAWT)

The first windmills were built based on the vertical-axis structure. This type has only been incorporated in small-scale installations. Typical VAWTs include the Darrius rotor, as shown in Fig. 4.2(a). Advantages of the VAWT are:

- ✓ Easy maintenance for ground mounted generator and gearbox,
- ✓ Receive wind from any direction (no yaw control required), and
- ✓ Simple blade design and low cost of fabrication.



(a) (b)

Fig. 4.2. (a)A typical vertical-axis turbine (the Darrius rotor) (b) a horizontal-axis wind turbine

Disadvantages of a vertical-axis wind turbine are:

- ✓ Not self starting, thus, require generator to run in motor mode at start,
- ✓ Lower efficiency (the blades lose energy as they turn out of the wind),
- ✓ Difficulty in controlling blade over-speed, and
- ✓ Oscillatory component in the aerodynamic torque is high.

4.2.2 Horizontal-axis wind turbines (HAWT)

The most common design of modern turbines is based on the horizontal-axis structure. Horizontal-axis wind turbines are mounted on towers as shown in Fig. 2.2(b). The tower's role is to raise the wind turbine above the ground to intercept stronger winds in order to harness more energy.

Advantages of the HAWT:

- ✓ Higher efficiency,
- ✓ Ability to turn the blades, and

- ✓ Lower cost-to-power ratio.

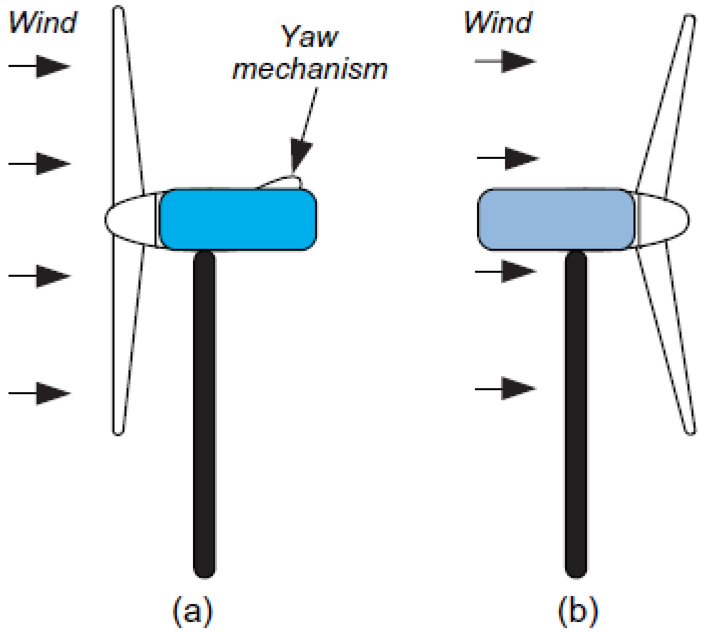


Fig. 4.3. (a) Upwind structure, (b) downwind structure

Disadvantages of the horizontal-axis:

- ✓ Generator and gearbox should be mounted on a tower, thus restricting servicing, and
- ✓ More complex design required due to the need for yaw or tail drive.

The HAWT can be classified as upwind and downwind turbines based on the direction of receiving the wind, as shown in Fig. 4.3. In the upwind structure the rotor faces the wind directly, while in downwind structure, the rotor is placed on the lee side of the tower. The upwind structure does not have the tower shadow problem because the wind stream hits the rotor first. However, the upwind needs a yaw control mechanism to keep the rotor always facing the wind. On the contrary, the downwind may be built without a yaw mechanism. However, the drawback is the fluctuations due to the tower shadow.

4.3 Common generator types in wind turbines

The function of an electrical generator is providing a means for energy conversion between the mechanical torque from the wind rotor turbine, as the prime mover, and the local load or the electric grid. Different types of generators are being used with wind turbines. Small wind turbines are equipped with DC generators of up to a few kilowatts in capacity. Modern wind turbine systems use three-phase AC generators. The common types of AC generator that are possible candidates in modern wind turbine systems are as follows:

- ✓ Squirrel-Cage rotor Induction Generator (SCIG),
- ✓ Wound-Rotor Induction Generator (WRIG),
- ✓ Doubly-Fed Induction Generator (DFIG),
- ✓ Synchronous Generator (with external field excitation), and
- ✓ Permanent Magnet Synchronous Generator (PMSG).

For assessing the type of generator in WECS, criteria such as operational characteristics, weight of active materials, price, maintenance aspects and the appropriate type of power electronic converter, are used.

Historically, the induction generator (IG) has been extensively used in commercial wind turbine units. Asynchronous operation of induction generators is considered an advantage for application in wind turbine systems, because it provides some degree of flexibility when the wind speed is fluctuating.

There are two main types of induction machines: squirrel-cage (SC), and wound rotor (WR). Another category of induction generator is the DFIG; the DFIG may be based on the squirrel-cage or wound-rotor induction generator.

The induction generator based on SCIG is a very popular machine because of its low price, mechanical simplicity, robust structure, and resistance against disturbance and vibration.

The wound-rotor is suitable for speed control purposes. By changing the rotor resistance, the output of the generator can be controlled and also speed control of the generator is possible. Although the WRIG has the advantage described above, it is more expensive than a squirrel-cage rotor.

The DFIG is a kind of induction machine in which both the stator windings and the rotor windings are connected to the source. The rotating winding is connected to the stationary supply circuits via power electronic converter. The advantage of connecting the converter to the rotor is that variable-speed operation of the turbine is possible with a much smaller and therefore much cheaper converter. The power rating of the converter is often about 1/3 the generator rating.

Another type of generator that has been proposed for wind turbines in several research articles is a synchronous generator. This type of generator has the capability of direct connection (direct-drive) to wind turbines, with no gearbox. This advantage is favorable with respect to lifetime and maintenance. Synchronous machines can use either electrically excited or permanent magnet (PM) rotor.

The PM and electrically-excited synchronous generators differ from the induction generator in that the magnetization is provided by a Permanent Magnet pole system or a dc supply on the rotor, featuring providing self-excitation property. Self-excitation allows operation at high power factors and high efficiencies for the PM synchronous. It is worth mentioning that induction generators are the most common type of generator use in modern wind turbine systems.

4.4 Mechanical gearbox

The mechanical connection between an electrical generator and the turbine rotor may be direct or through a gearbox. In fact, the gearbox allows the matching of the generator speed to that of the turbine. The use of gearbox is dependent on the kind of electrical generator used in WECS. However, disadvantages of using a gearbox are reductions in the efficiency and, in some cases, reliability of the system.

4.5 Control Method

With the evolution of WECS during the last decade, many different control methods have been developed. The control methods developed for WECS are usually divided into the following two major categories:

- ✓ Constant-speed methods, and
- ✓ Variable-speed methods.

4.5.1 Variable-speed turbine versus constant-speed turbine

In constant-speed turbines, there is no control on the turbine shaft speed. Constant speed control is an easy and low-cost method, but variable speed brings the following advantages:

- ✓ Maximum power tracking for harnessing the highest possible energy from the wind,
- ✓ Lower mechanical stress,
- ✓ Less variations in electrical power, and
- ✓ Reduced acoustical noise at lower wind speeds.

In the following, these advantages will be briefly explained.

Using shaft speed control, higher energy will be obtained. A comparison was made between the power extracted for a real variable-speed wind turbine system, with a 34-m-diameter rotor, against a constant-speed wind turbine at different wind speeds. The results are illustrated in Fig. 4.4. The figure shows that a variable-speed system outputs more energy than the constant-speed system. For example, with a fixed speed system, for an average annual wind speed of 7 m/s, the energy produced is 54.6 MWh, while the variable-speed system can produce up to 75.8 MWh, under the same conditions. During turbine operation, there are some fluctuations related to mechanical or electrical components. The fluctuations related to the mechanical parts include current fluctuations caused by the blades passing the tower and various current amplitudes caused by variable wind speeds. The fluctuations related to the electrical parts, such as voltage harmonics, is caused by the electrical converter. The electrical harmonics can be conquered by choosing the proper electrical filter.

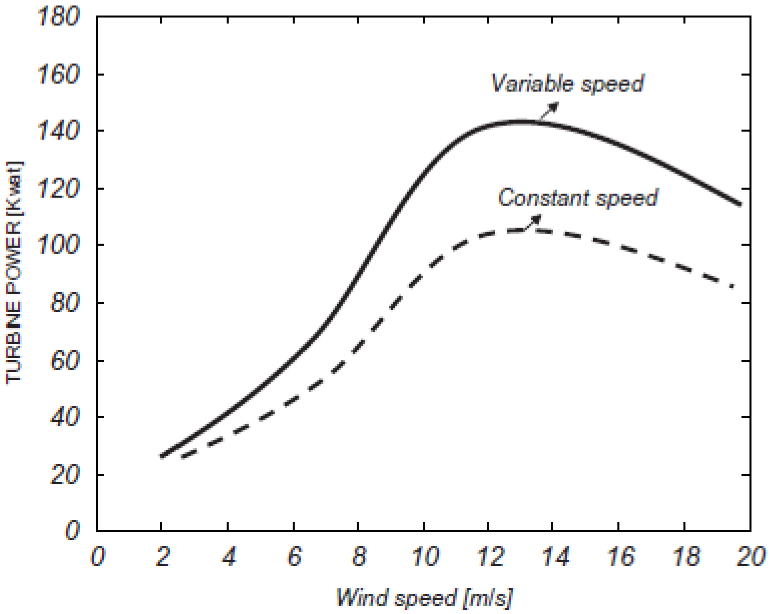


Fig. 4.4. Comparison of power produced by a variable-speed wind turbine and a constant speed wind turbine at different wind speeds.

However, because of the large time constant of the fluctuations in mechanical components, they cannot be canceled by electrical components. One solution that can largely reduce the disturbance related to mechanical parts is using a variable-speed wind turbine. The figure 4.5 illustrates the ability of the variable-speed system to reduce or increase the shaft speed in case of torque variation. It is important to note that the disturbance of the rotor is related also to the mechanical inertia of the rotor.

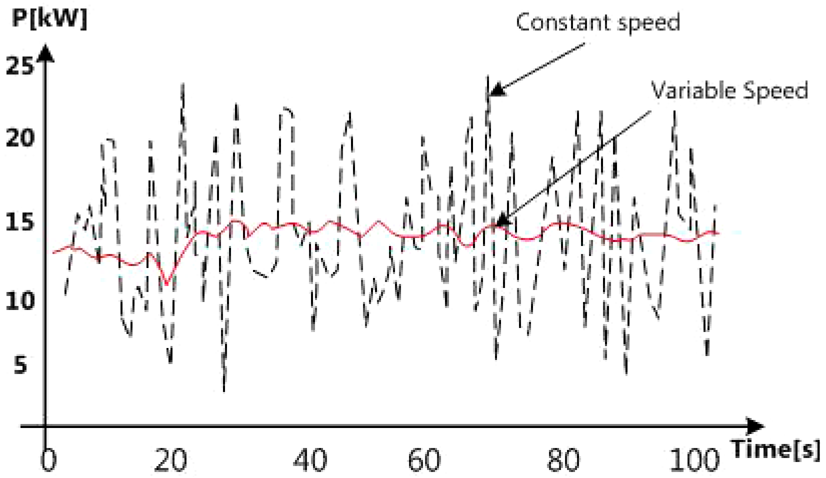


Fig. 4.5. Power output disturbance of a typical wind turbine with constant-speed method and variable-speed methods.

Although a variable-speed operation is adopted in modern wind turbines, this method has some disadvantages, such as additional cost for extra components and complex control methods.

4.6 Fixed Speed Wind Energy Conversion Systems

Fixed-speed WECS operate at constant speed. That means that, regardless of the wind speed, the wind turbine rotor speed is fixed and determined by the grid frequency. Fixed-speed WECS are typically equipped with squirrel-cage induction generators (SCIG), soft starter and capacitor bank and they are connected directly to the grid, as shown in Figure 4.6. This WECS configuration is also known as the "*Danish concept*" because it was developed and widely used in Denmark.

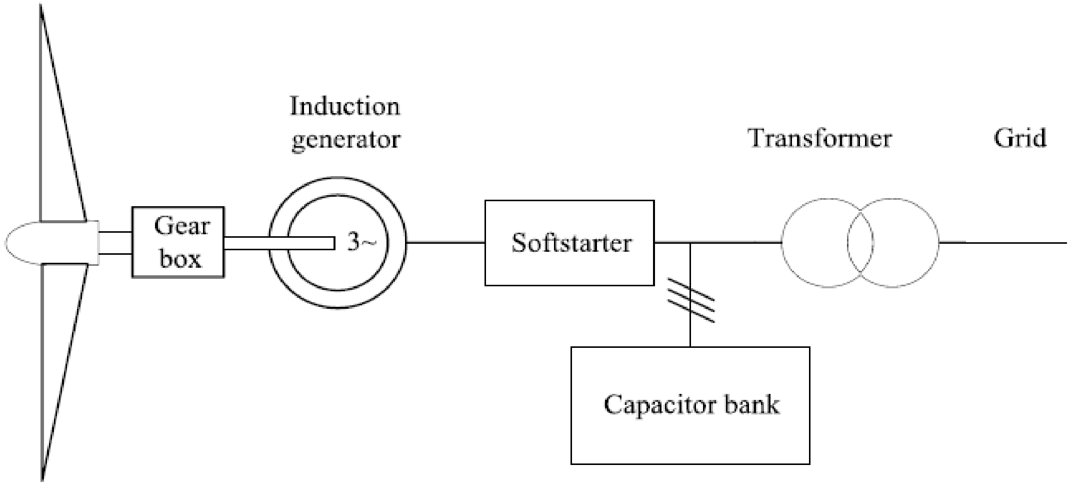


Fig 4.6. General structure of a fixed-speed WECS

Initially, the induction machine is connected in motoring regime such that it generates electromagnetic torque in the same direction as the wind torque. In steady-state, the rotational speed exceeds the synchronous speed and the electromagnetic torque is negative. This corresponds to the squirrel-cage induction machine operation in generation mode. As it is directly connected to the grid, the SCIG works on its natural mechanical characteristic having an accentuated slope (corresponding to a small slip) given by the rotor resistance. Therefore, the SCIG rotational speed is very close to the synchronous speed imposed by the grid frequency. Furthermore, the wind velocity variations will induce only small variations in the generator speed. As the power varies proportionally with the wind speed cubed, the associated electromagnetic variations are important.

SCIG are preferred because they are mechanically simple, have high efficiency and low maintenance cost. Furthermore, they are very robust and stable. One of the major drawbacks of the SCIG is the fact that there is a unique relation between active power, reactive power, terminal voltage and rotor speed. That means that an increase in the active power production is possible only with an increase in the reactive power consumption, leading to a relatively low full-load power factor. In order to limit the reactive power absorption from the grid, SCIG based WECS are equipped with capacitor banks. The soft starter’s role is to smooth the inrush currents during the grid connection.

SCIG-based WECS are designed to achieve maximum power efficiency at a unique wind speed. In order to increase the power efficiency, the generator of some fixed-speed WECS has two winding sets, and thus two speeds. The first set is used at low wind speed (typically eight poles) and the other at medium and large wind speeds (typically four to six poles).

Fixed-speed WECS have the advantage of being simple, robust and reliable, with simple and inexpensive electric systems and well proven operation. On the other hand, due to the fixed-speed operation, the mechanical stress is important. All fluctuations in wind speed are transmitted into the mechanical torque and further, as electrical fluctuations, into the grid. Furthermore, fixed-speed WECS have very limited controllability (in terms of rotational speed), since the rotor speed is fixed, almost constant, stuck to the grid frequency.

An evolution of the fixed-speed SCIG-based WECS are the limited variable speed WECS. They are equipped with a wound-rotor induction generator (WRIG) with variable external rotor resistance; see Figure 4.7. The unique feature of this WECS is that it has a variable additional rotor resistance, controlled by power electronics. Thus, the total (internal plus external) rotor resistance is adjustable, further controlling the slip of the generator and therefore the slope of the mechanical characteristic. Obviously, the range of the dynamic speed control is determined by how big the additional resistance is. Usually the control range is up to 10% over the synchronous speed.

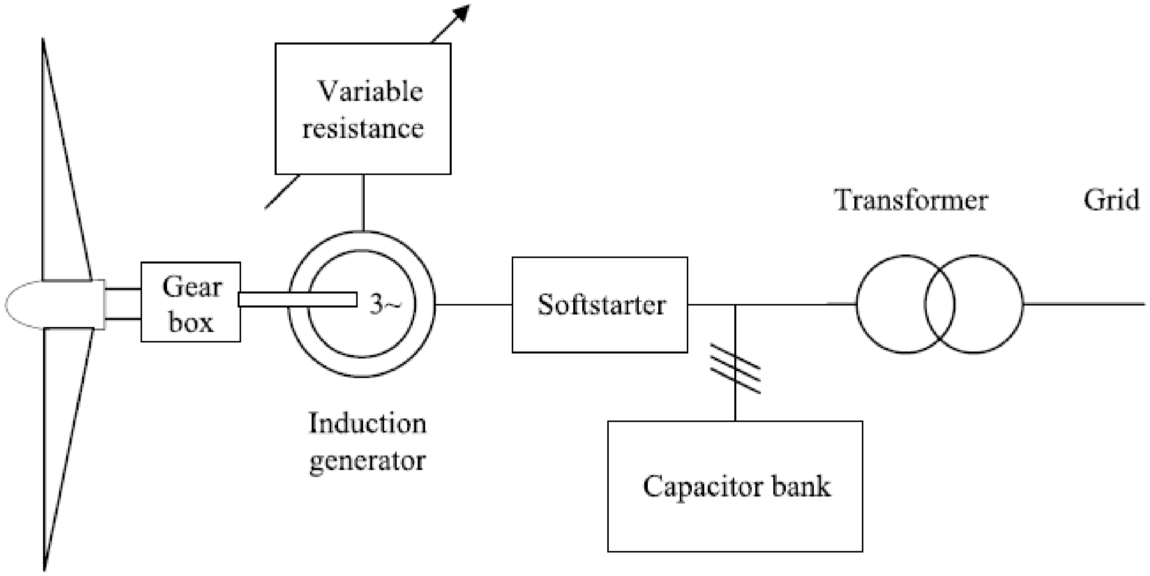


Fig 4.7. General structure of a limited variable-speed WECS.

4.7 Variable-speed Wind Energy Conversion System

Variable-speed wind turbines are currently the most used WECS. The variable speed operation is possible due to the power electronic converters interface, allowing a full (or partial) decoupling from the grid.

The doubly-fed-induction-generator (DFIG)-based WECS (Figure 4.8), also known as improved variable-speed WECS, is presently the most used by the wind turbine industry.

The DFIG is a WRIG with the stator windings connected directly to the three phases, constant-frequency grid and the rotor windings connected to a back-to-back (AC–AC) voltage source converter. Thus, the term “doubly-fed” comes from the fact that the stator voltage is applied from the grid and the rotor voltage is impressed by the power converter. This system allows variable-speed operation over a large, but still restricted, range, with the generator behavior being governed by the power electronics converter and its controllers.

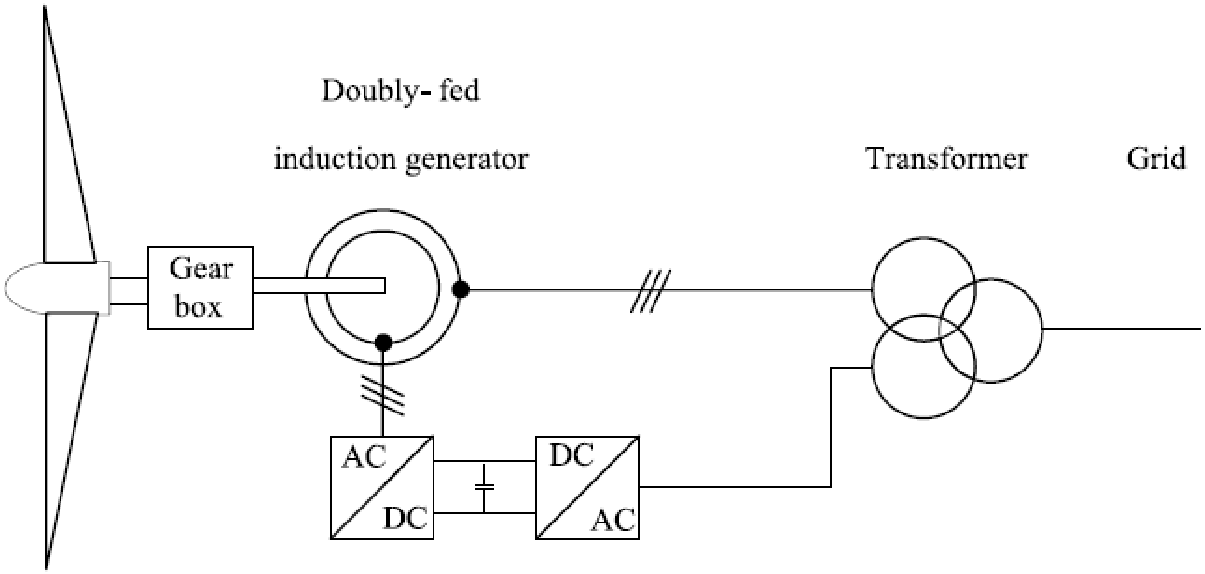


Fig 4.8. General structure of an improved variable-speed WECS

The power electronics converter comprises of two IGBT converters, namely the rotor side and the grid side converter, connected with a direct current (DC) link. Without going into details about the converters, the main idea is that the rotor side converter controls the generator in terms of active and reactive power, while the grid side converter controls the DC-link voltage and ensures operation at a large power factor.

The stator outputs power into the grid all the time. The rotor, depending on the operation point, is feeding power into the grid when the slip is negative (over synchronous operation) and it absorbs power from the grid when the slip is positive (sub-synchronous operation). In both cases, the power flow in the rotor is approximately proportional to the slip.

The size of the converter is not related to the total generator power but to the selected speed variation range. Typically a range of ±40% around the synchronous speed is used.

DFIG-based WECS are highly controllable, allowing maximum power extraction over a large range of wind speeds. Furthermore, the active and reactive power control is fully decoupled by independently controlling the rotor currents. Finally, the DFIG-based WECS can either inject or absorb power from the grid, hence actively participating at voltage control.

Full variable-speed WECS are very flexible in terms of which type of generator is used. As presented in Figure 4.9, it can be equipped with either an induction (SCIG) or a synchronous generator. The synchronous generator can be either a wound-rotor synchronous generator

(WRSG) or a permanent-magnet synchronous generator (PMSG), the latter being the one mostly used by the wind turbine industry. The back-to-back power inverter is rated to the generator power and its operation is similar to that in DFIG-based WECS. Its rotor-side ensures the rotational speed being adjusted within a large range, whereas its grid-side transfers the active power to the grid and attempts to cancel the reactive power consumption. This latter feature is important especially in the case of SCIG-equipped WECS.

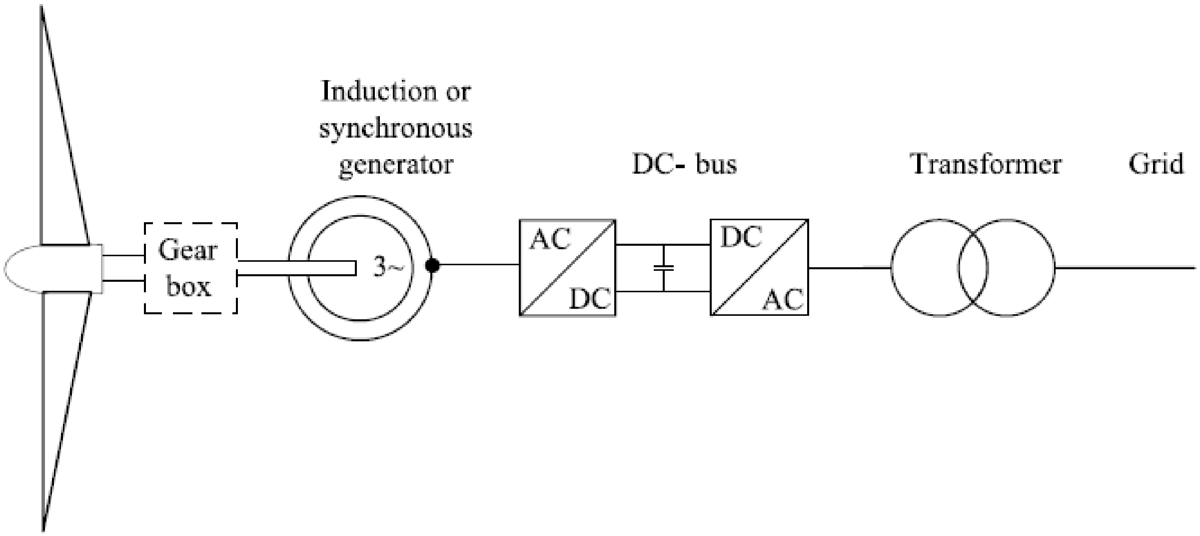


Fig 4.9. General structure of a full variable-speed WECS

The PMSG is considered, in many research articles, a good option to be used in WECS, due to its self-excitation property, which allows operation at high power factor and efficiency.

PMSG does not require energy supply for excitation, as it is supplied by the permanent magnets. The stator of a PMSG is wound and the rotor has a permanent magnet pole system. The salient pole of PMSG operates at low speeds, and thus the gearbox (Figure 4.9) can be removed. This is a big advantage of PMSG-based

WECS as the gearbox is a sensitive device in wind power systems. The same thing can be achieved using direct driven multipole PMSG with large diameter.

The synchronous nature of PMSG may cause problems during start-up, synchronization and voltage regulation and they need a cooling system, since the magnetic materials are sensitive to temperature and they can loose their magnetic properties if exposed to high temperatures.

4.8 Grid Connected Permanent Magnet Synchronous Generator (PMSG) Based Wind Energy Conversion Systems.

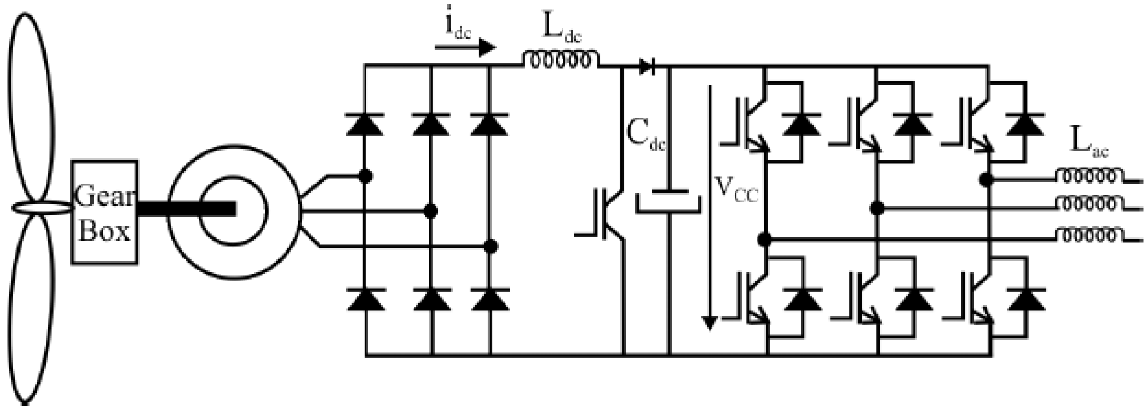


Fig 4.10. PM Synchronous generator with the rectifier, boost chopper, and the PWM line-side Converter

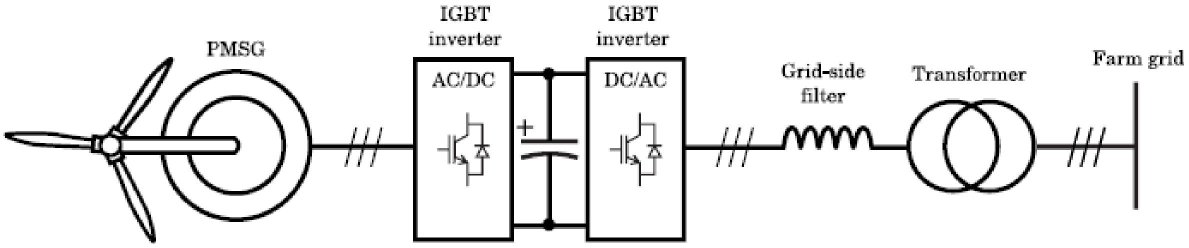


Fig 4.11. PM Synchronous generator with two back-to-back PWM converters.

A typical power electronics topology that is used for a permanent magnet synchronous generator is shown in Figure 4.10. The three-phase variable voltage, variable frequency output from the wind turbine is rectified using a diode bridge. With the change in the speed of the synchronous generator, the voltage on the DC side of the diode rectifier changes. To maintain a constant DC-link voltage of the inverter, a step-up chopper is used to adapt the rectifier voltage. As viewed from the DC inputs to the inverter, the generator/rectifier system is then modeled as an ideal current source. This rectified output signal from the diode bride is filtered into a smooth DC waveform using a large capacitor. The DC signal is then inverted through the use of semiconductor switches into a three-phase, 50 Hz waveform. This waveform can then be scaled using a transformer to voltage levels required by the utility's AC system. The generator is decoupled from the grid by a voltage-sourced DC-link; therefore, this PE interface provides excellent controllable characteristics for the wind energy system. The power converter to the grid enables a fast control of active and reactive power. However, the negative side is a more complex system where more sensitive power electronic parts are required.

The diode rectifier is the most commonly used topology in power electronic applications. For a three-phase system it consists of six diodes. It is shown in Fig. 4.10. The diode rectifier can only be used in one quadrant, it is simple and it is not possible to control it. It can be used in some applications such as pre-charging.

Figure 4.11 shows the scheme of a full power converter for a wind turbine. The machine-side three-phase converter works as a driver controlling the torque generator, using a vector control strategy. The grid-side three-phase converter permits wind energy transfer into the grid and enables to control the amount of the active and reactive powers delivered to the grid. It also keeps the total-harmonic-distortion (THD) coefficient as low as possible, improving the quality of the energy injected into the public grid. The objective of the dc link is to act as energy storage, so that the captured energy from the wind is stored as a charge in the capacitors and may be instantaneously injected into the grid. The control signal is set to maintain a constant reference to the voltage of the dc link Vdc. An alternative to the power-conditioning system of a wind turbine is to use a synchronous generator instead of an induction one and to replace a three-phase converter (connected to the generator) by a three phase diode rectifier and a chopper, as shown in Fig. 4.10. Such choice is based on the low cost as compared to an induction generator connected to a VSI used as a rectifier. When the speed of the synchronous generator alters, the voltage on the dc side of the diode rectifier will change. A step-up chopper is used to adapt the rectifier voltage to the dc-link voltage of the inverter. When the inverter system is analyzed, the generator/rectifier system can be modeled as an ideal current source. The step-up chopper used as a rectifier utilizes a high switching frequency, so the bandwidth of these components is much higher than the bandwidth of the generator. Controlling the inductance current in the step-up converter can control the machine torque and, therefore, its speed.

Based on the control design for the back-to-back PWM converter system, various advantages can be obtained such as:

- ✓ The line-side power factor is unity with no harmonic current injection (satisfies IEEE 519);

- ✓ Wind generator output current is sinusoidal;
- ✓ There are no harmonic copper losses;
- ✓ The rectifier can generate programmable excitation for the induction generator based system.
- ✓ Continuous power generation from zero to the highest turbine speed is possible.
- ✓ Power can flow in either direction, permitting the generator to run as a motor for start-up (required for vertical turbine). Similarly, regenerative braking can quickly stop the turbine; and
- ✓ Islanded operation of the system is possible with a start-up capacitor charging the battery.

4.8.1 Principle of Operation

Figure 4.12 shows the structure of the PWM line side converter. Power flow in the PWM converter is controlled by adjusting the phase angle δ between the source voltage U_1 and the respective converter reflected input voltage V_{s1}. When U_1 leads V_{s1} the real power flows from the ac source into the converter. Conversely, if U_1 lags V_{s1}, power flows from the converter's dc side into the ac source. The real power transferred is given by the Eq. (4.1).

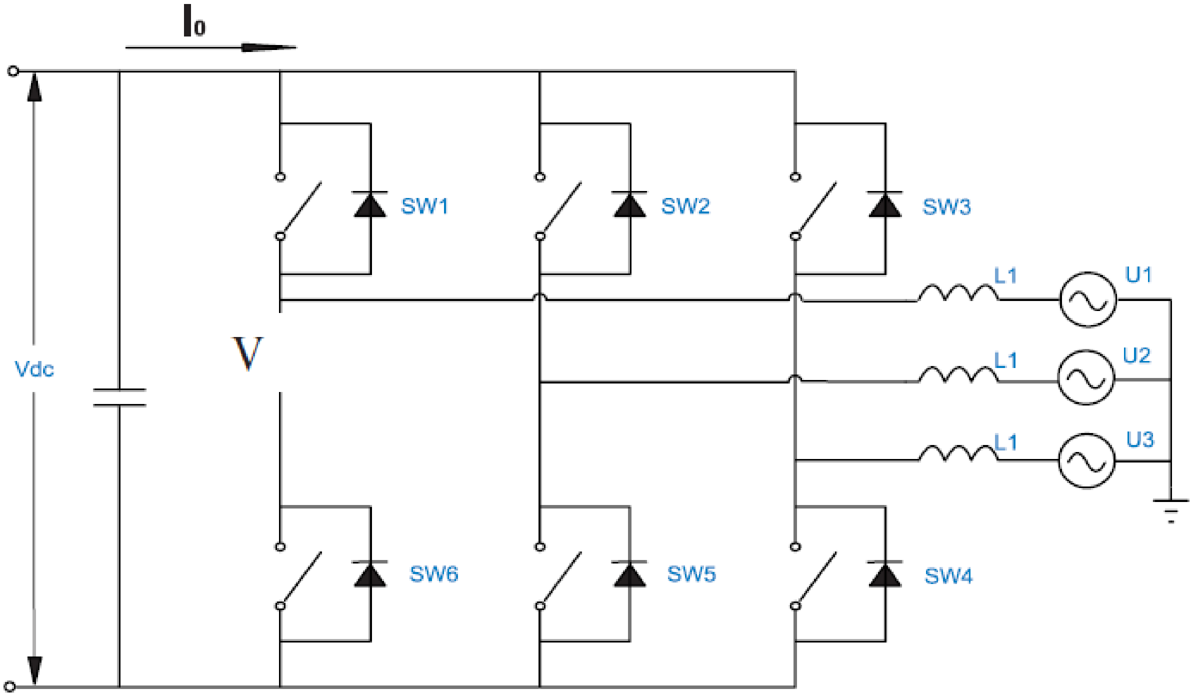


Fig. 4.12. PWM converter.

$$P = \frac{V_{S1} U_1}{X_1} \sin(\delta) \text{------- (4.1)}$$

The ac power factor is adjusted by controlling the amplitude of the converter synthesized voltage V_{s1}. The per phase equivalent circuit and phase diagrams of the leading, lagging and unity power factor operation is shown in Fig. 4.13 (a). The phasor diagram in Fig. 4.13 (b) shows that to achieve a unity power factor, V_{s1} has to be,

$$V_{s1} = \sqrt{U_1^2 + (X_1 I_1)^2} \text{----- (4.2)}$$

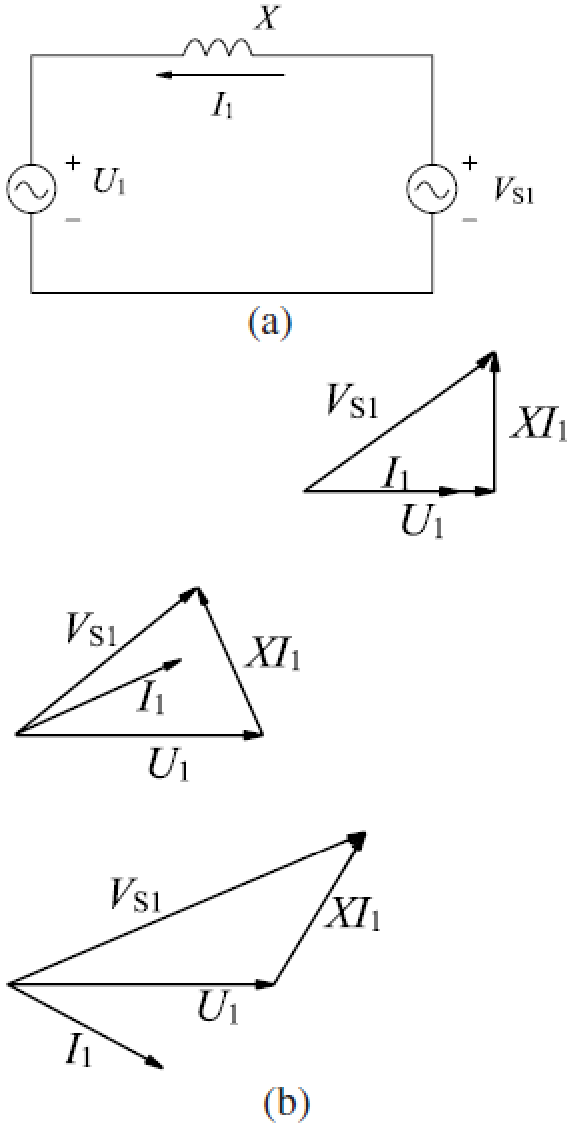


Fig. 4.13. (a) Per-phase equivalent circuit of the line side converter, (b) phasor diagrams for unity, leading and lagging power factor operation

4.9 Grid Connected Squirrel Cage Induction Generator (SCIG) Based Wind Energy Conversion Systems.

4.9.1 Fixed Speed System

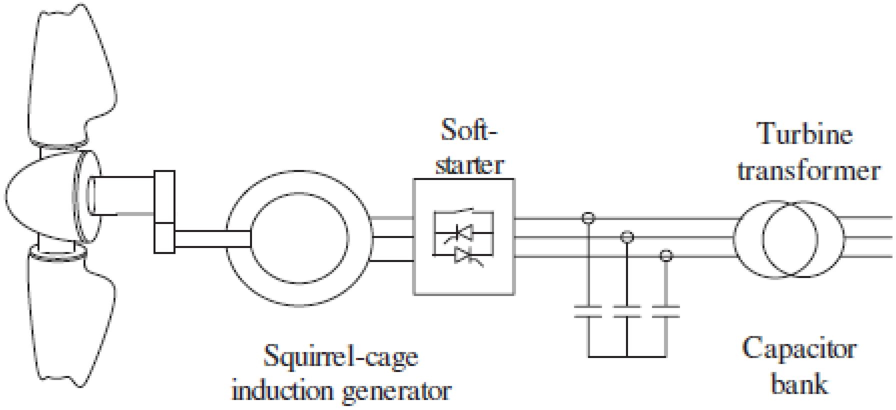


Fig 4.14 SCIG Connected to Grid

Fixed-speed wind turbines are electrically fairly simple devices consisting of an aerodynamic rotor driving a low-speed shaft, a gearbox, a high-speed shaft and an induction (sometimes known as asynchronous) generator. From the electrical system viewpoint they are perhaps best considered as large fan drives with torque applied to the low-speed shaft from the wind flow.

It consists of a squirrel-cage induction generator coupled to the power system through a turbine transformer. The generator operating slip changes slightly as the operating power level changes and the rotational speed is therefore not entirely constant. However, because the operating slip variation is generally less than 1%, this type of wind generation is normally referred to as fixed speed. Squirrel-cage induction machines consume reactive power and so it is conventional to provide power factor correction capacitors at each wind turbine.

The function of the soft-starter unit is to build up the magnetic flux slowly and so minimize transient currents during energization of the generator. Also, by applying the network voltage slowly to the generator, once energized, it brings the drive train slowly to its operating rotational speed.

4.9.2 Variable Speed System

The typical configuration of a Variable Speed Grid Connected SCIG based fully rated converter wind turbine is shown in Figure 4.15. This type of turbine may or may not include a gearbox and a wide range of electrical generator types can be employed, for example, induction, wound-rotor synchronous or permanent magnet synchronous. As all of the power from the turbine goes through the power converters, the dynamic operation of the electrical generator is effectively isolated from the power grid. The electrical frequency of the generator may vary as the wind speed changes, while the grid frequency remains unchanged, thus allowing variable-speed operation of the wind turbine.

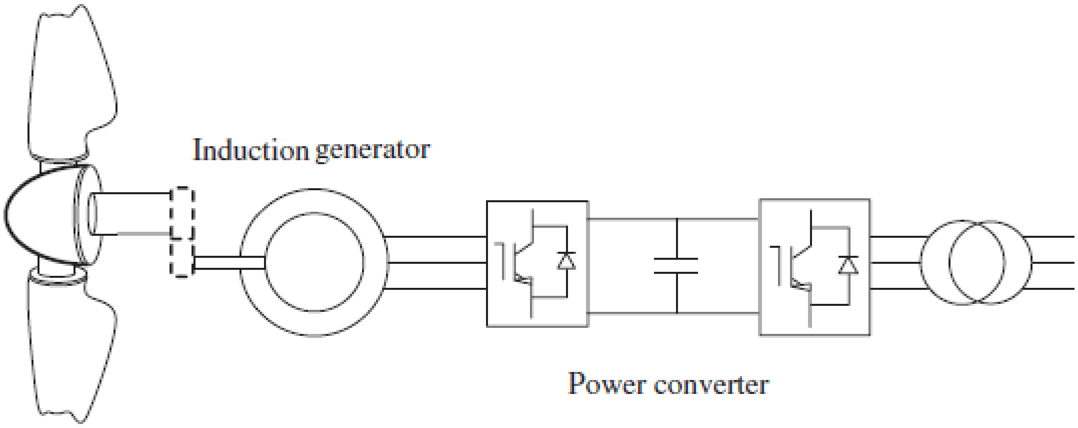


Figure 4.15 Typical configuration of a fully rated converter-connected wind turbine

The power converters can be arranged in various ways. Whereas the generator-side converter (GSC) can be a diode rectifier or a PWM voltage source converter (VSC), the network-side converter (NSC) is typically a PWM VSC. The strategy to control the operation of the generator and the power flows to the network depends very much on the type of power converter arrangement employed. The network-side converter can be arranged to maintain the DC bus voltage constant with torque applied to the generator controlled from the generator-side converter. Alternatively, the control philosophy can be reversed. Active power is transmitted through the converters with very little energy stored in the DC link capacitor. Hence the torque applied to the generator can be controlled by the network-side converter. Each converter is able to generate or absorb reactive power independently.