

UNIT-II

WIND GENERATOR TOPOLOGIES

Introduction

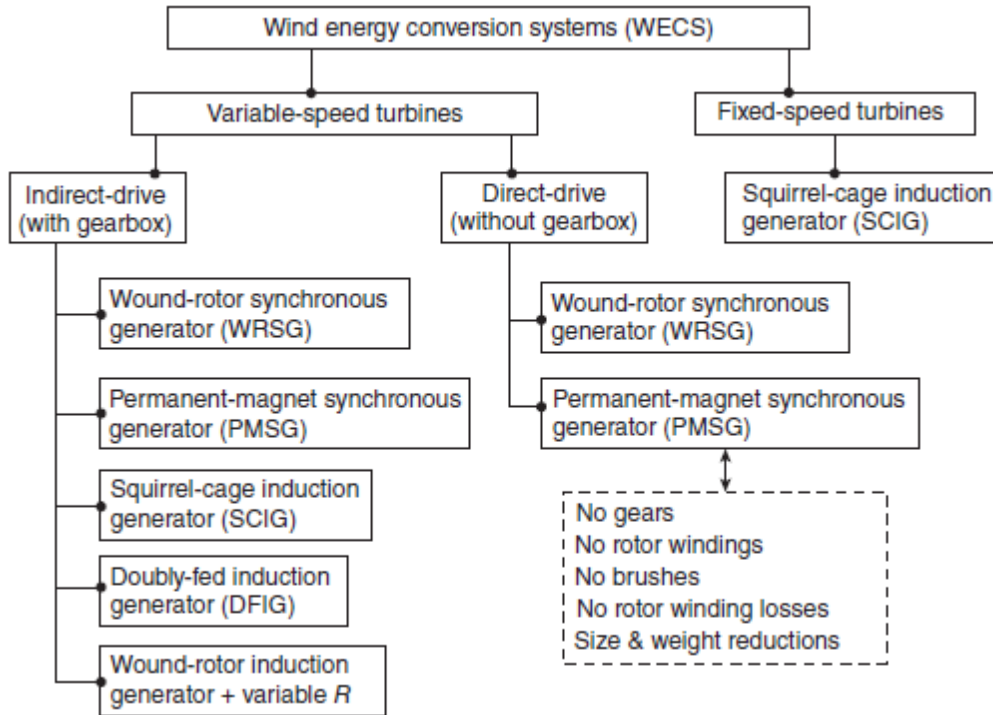
- Wind turbines capture the power from the wind by means of aerodynamically designed blades and convert it into rotating mechanical power.
- Wind turbine blades use airfoils to develop mechanical power.
- Recent advances in technology and performance have resulted in current wind turbine designs being increasingly efficient, cost effective, and reliable.

Wind Turbine Generators

- One of limiting factors in wind turbines lies in their generator technology.
- There is no consensus among academics and industry on the best wind turbine generator technology.
- Traditionally, there are 3 main types of wind turbine generators (WTGs) for the various wind turbine systems, these being direct current (DC), alternating current (AC) synchronous and AC asynchronous generators.
- In principle, each can be run at fixed or variable speed.
- Due to the fluctuating nature of wind power, it is advantageous to operate the WTG at variable speed which reduces the physical stress on the turbine blades and drive train, and which improves system aerodynamic efficiency and torque transient behaviors.
- The primary distinguishing characteristics include whether the turbines are fixed or variable speed whether the generators are synchronous or inductive, and whether there is a gearbox or not.

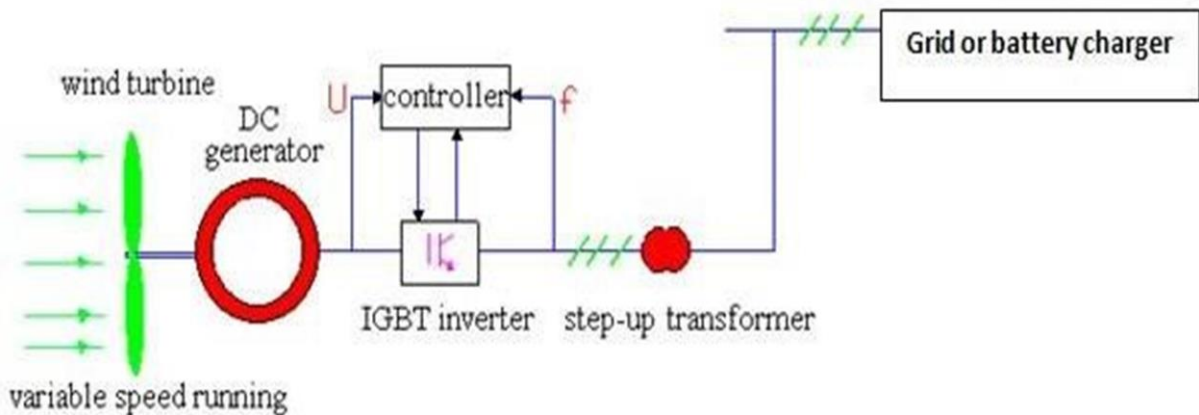
One way to categorize wind energy systems is by whether their rotors rotate at a fixed or variable speed.

System configuration for wind turbine system is shown below



DC Generator Technologies

- In conventional DC machines, the field is on the stator and the armature is on the rotor.
- The stator comprises a number of poles which are excited either by permanent magnets or by DC field windings.
- If the machine is electrically excited, it tends to follow the shunt wound DC generator concept.
- The DC wind generator system is shown in below Fig.



The primary distinguishing characteristics include whether the turbines are fixed or variable speed, whether the generators are synchronous or inductive, and whether there is a gearbox or not. The most advanced system shown is a variable speed turbine, without a gearbox, that uses a permanent magnet synchronous generator (PMSG)

Fixed-Speed Synchronous Generators

fixed-speed generators rotational speed determined by the number of poles on the rotor p and the frequency f (Hz) of the three-phase armature voltage provided by the grid.

$$N(\text{rpm}) = \frac{120 f}{P}$$

Armature currents create a rotating magnetic field within the generator that interacts with a second magnetic field created on the rotor itself. The rotor field can be created either with permanent magnets (PMSG) on the rotor or with a field current delivered through slip rings to windings on the rotor itself. The latter configuration is referred to as having a wound rotor Synchronous generator (WRSG).

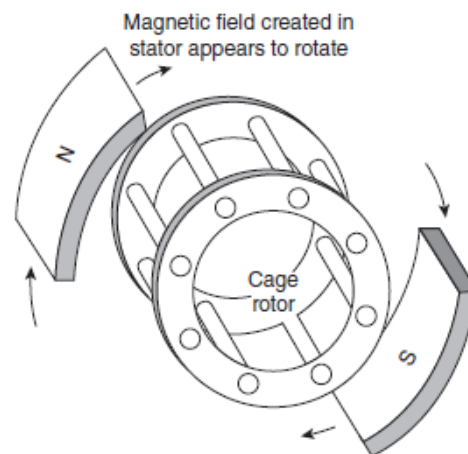
The Squirrel-Cage Induction Generator

Most of the world's wind turbines use induction generators rather than the synchronous machines just mentioned. In contrast to a synchronous generator (or motor), induction machines do not turn at a fixed speed, so they are often described as *asynchronous* generators. While induction generators are uncommon in power systems other than wind turbines, their counterpart, induction motors, are the most prevalent motors—using almost one-third of all the electricity generated worldwide. In fact, just as is the case for synchronous machines, an induction machine can act as a motor or generator depending on whether shaft power is being put into the machine (generator) or taken out (motor). Both modes of operation—as a motor during start-up and as a generator when the wind picks up—take place in wind turbines with induction generators.

Induction generators rely on a rotating magnetic field created in the armature windings, but their speed is allowed to vary somewhat from the fixed speed of the rotating magnetic field.

There are two categories of induction machines: those that have wound rotors (wound rotor induction generators (WRIGs)), and those that have what are often called “squirrel”-cage

rotors (squirrel-cage induction generators (SCIGs)), or more simply, cage rotors. Cage rotors consist of a number of copper or aluminium bars shorted together at their ends, forming a cage not unlike the one you might have to give your pet rodent some exercise. The cage is then imbedded in an iron core consisting of thin (0.5 mm) insulated steel laminations to help control eddy current losses. The key advantage of SCIGs is that their rotors do not require the exciter, brushes, and slip rings that are needed by WRIGs.



Above Figure shows the basic relationship between stator and rotor, which can be thought of as a pair of magnets in the stator spinning around the cage rotor. To understand how the rotating stator field interacts with the cage rotor, consider Figure 2.2a. The rotating stator field is shown moving toward the right, while the conductor in the cage rotor is stationary. Looked at another way, the stator field can be thought to be stationary and, relative to it, the conductor appears to be moving to the left, cutting lines of magnetic flux as shown in Figure 2.2 b. Faraday's law of electromagnetic induction says whenever a conductor cuts flux lines, an electromotive force (emf) will develop along the conductor and, if allowed to, a current will flow. In fact, the cage rotor has thick conductor bars with very little resistance, so lots of current can flow easily. That rotor current, labelled i_R in Figure 2.2 b, will create its own magnetic field, which wraps around the conductor. The rotor's magnetic field then interacts with the stator's magnetic field producing a force that attempts to drive the cage conductor to the right.

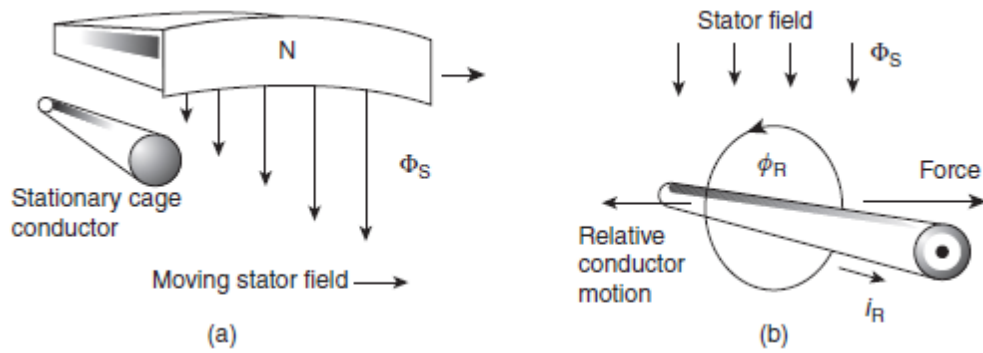


Fig 2.2 In (a), the stator field moves toward the right while the cage rotor conductor is stationary.

As shown in (b), that is equivalent to the stator field being stationary while the conductor moves to the left, cutting the lines of flux. The conductor then experiences a force toward the right that tries to make the rotor want to catch up to the stator's rotating magnetic field.

In other words, the rotor wants to spin in the same direction (in this case, clockwise), and at the same speed, as that of the rotating stator field. When the stator of an induction machine is provided with three-phase excitation current and the shaft is connected to a wind turbine, as the wind begins to blow the machine will start operation by motoring up toward its synchronous speed. When the wind speed is sufficient to force the generator shaft to exceed synchronous speed, the induction machine automatically becomes a three-phase generator delivering electrical power back to its stator windings. The relative speed between the stator magnetic field and the rotor itself is called the slip speed s , defined as

$$s = \frac{N_S - N_R}{N_S} = 1 - \frac{N_R}{N_S}$$

where N_S is the no-load synchronous speed. N_R is the rotor speed. Slip is defined to be positive when the rotor is moving at a slower speed than the stator's rotating magnetic field; that is, when the machine is acting as a motor. When the rotor moves faster than the rotating magnetic field, slip is negative, and the machine becomes a generator.

The Doubly-Fed Induction Generator

The cage induction generator, with no electrical connections to the rotor, has the significant advantage of simplicity and robustness. On the other hand, it is pretty much a fixed-speed

machine whose rotation rate differs only modestly from that of a synchronous generator. Even that modest variation, though, helps when it comes to absorbing shocks caused by rapidly fluctuating winds. The added complexity of a wound rotor induction generator, which needs slip rings to energize the rotor, are often more than justified by the additional flexibility in rotor speed control that they can provide. One of the most popular wind turbine configurations is based on what is referred to as a wound-rotor, doubly-fed induction generator (DFIG). As shown in Figure 2.3, the stator part

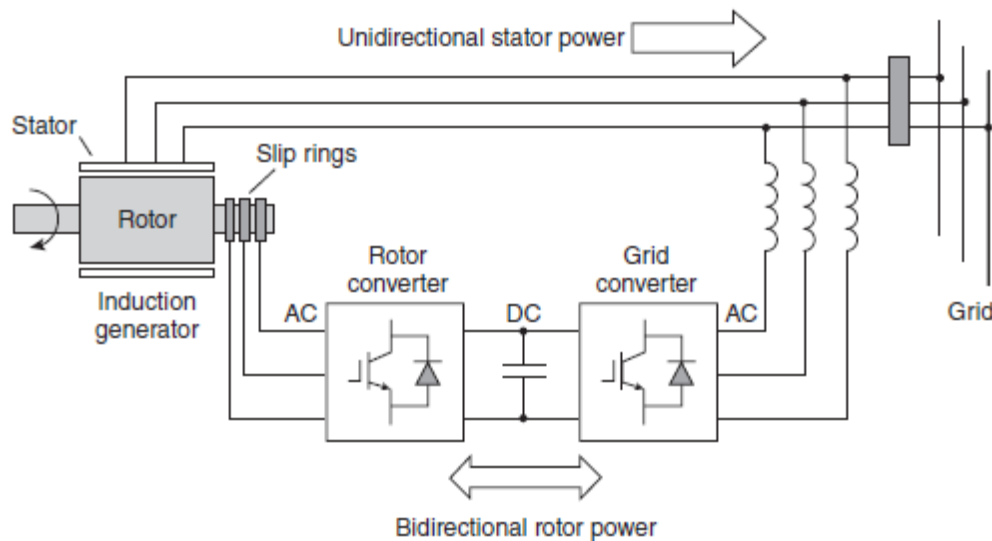


FIGURE 2.3 A wound-rotor, doubly-fed induction generator (DFIG).

of a DFIG system is conventional. That is, the grid provides three-phase voltages that create the stator's rotating magnetic field. Power generated in the stator is fed back to the grid in the normal way. The difference is that the rotor is set up to allow bidirectional power flow to or from the grid. When the rotor spins at less than the synchronous frequency (sub-synchronous), the machine acts like a motor, slowing down the turbine and absorbing power from the grid. When it operates in super-synchronous mode, going faster than synchronous speed, power is generated from the rotor itself and sent back to the grid. As shown, the key is a modestly sized back-to-back voltage converter that makes it possible to deliver AC voltages to the rotor at the slip frequency. If those voltages oppose the rotor emf, the generator will spin faster and power will be delivered from the rotor to the network (super-synchronous). When they add to rotor emf, power will be absorbed by the rotor and it will run slower (sub-synchronous). The usual range of speed control is from about 40% below synchronous speed up to about 20% above synchronous speed. In addition to speed control,

the converters also allow control of both real power P and reactive power Q flows from the stator to the grid independently of the generator's turning speed.

Variable-Speed Synchronous Generators

The DFIG configuration just described uses a relatively small voltage converter, which might be rated at about 30% of the full power of the turbine. And, it is capable of about the same magnitude of speed adjustments. The next step up is to gain complete control of speed with a full-capacity converter powering a synchronous generator (Fig.2.4). The generator can be either a wound-rotor type, in which case slip rings and an exciter circuit are needed, or it can be built with a permanent-magnet rotor that avoids those complications. When a PMSG is provided with a large enough number of poles, the gearbox

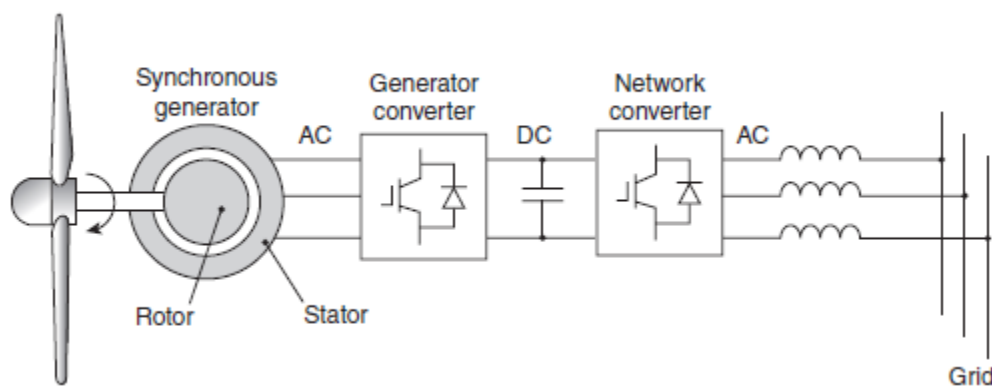


FIGURE 2.4 A gearless, variable-speed synchronous generator with full-capacity converters.

as well can be eliminated. Permanent magnets, however, use rare earth materials such as neodymium, which have some issues of their own. The resource base for rare earth materials, especially in the United States, is an issue of some concern, as is as the materials' propensity to permanently lose magnetic field strength when exposed to high temperatures.

The gearless configuration shown in Figure 2.5 has considerable impact on the shape of the wind turbine's nacelle. It does not need to be as long since there is no gearbox, but it does need a larger diameter nacelle to be able to house the multi-pole, permanent-magnet generator. The increased sophistication of these systems increases their cost, but decreases their maintenance requirements. They are making their first inroads into the market using very large turbines for use in offshore systems

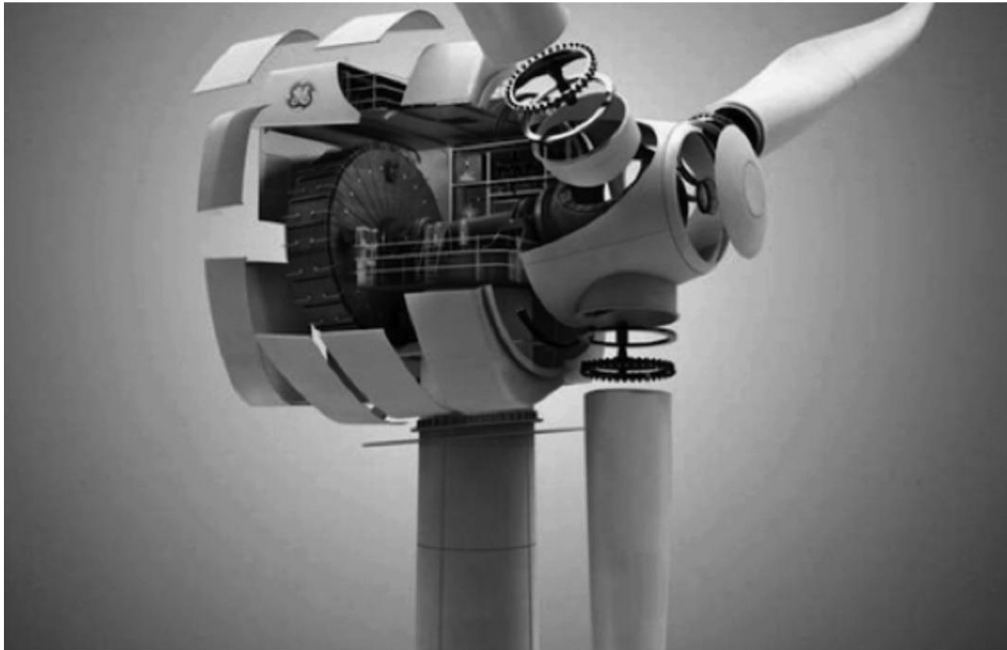


Fig2.5 The GE 4.1-MW, 113-m, direct-drive, permanent-magnet, variable-speed, synchronous generator. Reproduced with permission from General Electric.

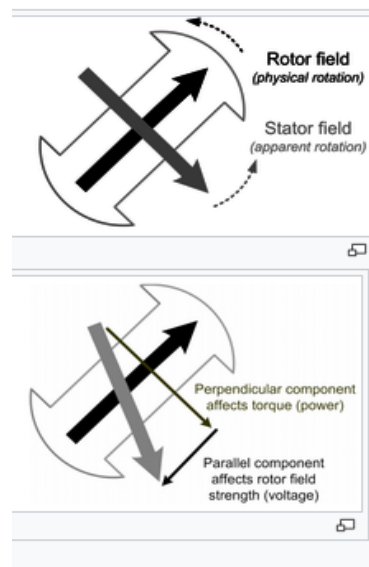
Permanent magnet synchronous generator

A **permanent magnet synchronous generator** is a [generator](#) where the excitation field is provided by a permanent magnet instead of a coil. The term synchronous refers here to the fact that the rotor and magnetic field rotate with the same speed, because the magnetic field is generated through a shaft mounted permanent magnet mechanism and current is induced into the stationary armature.

Synchronous generators are the majority source of commercial electrical energy. They are commonly used to convert the mechanical power output of [steam turbines](#), [gas turbines](#), [reciprocating engines](#) and [hydro turbines](#) into electrical power for the grid. Some designs of [Wind turbines](#) also use this generator type.

In the majority of designs the rotating assembly in the center of the generator—the "[rotor](#)"—contains the magnet, and the "[stator](#)" is the stationary armature that is electrically connected to a load. As shown in the diagram, the perpendicular component of the stator field affects the torque while the parallel component affects the voltage. The load supplied by the generator determines the voltage. If the load is inductive, then the angle between the rotor and stator fields will be greater than 90 degrees which corresponds to an increased generator voltage. This is known as an overexcited generator. The opposite is true for a generator supplying a capacitive load which is known as an underexcited generator. A set of three

conductors make up the armature winding in standard utility equipment, constituting three phases of a power circuit—that correspond to the three wires we are accustomed to see on transmission lines. The phases are wound such that they are 120 degrees apart spatially on the stator, providing for a uniform force or torque on the generator rotor. The uniformity of the torque arises because the magnetic fields resulting from the induced currents in the three conductors of the armature winding combine spatially in such a way as to resemble the magnetic field of a single, rotating magnet. This stator magnetic field or "stator field" appears as a steady rotating field and spins at the same frequency as the rotor when the rotor contains a single dipole magnetic field. The two fields move in "synchronicity" and maintain a fixed position relative to each other as they spin.



They are known as synchronous generators because f , the frequency of the induced voltage in the stator (armature conductors) conventionally measured in [hertz](#), is directly proportional to RPM, the rotation rate of the rotor usually given in revolutions per minute (or angular speed). If the rotor windings are arranged in such a way as to produce the effect of more than two magnetic poles, then each physical revolution of the rotor results in more magnetic poles moving past the armature windings. Each passing of a north and south pole corresponds to a complete "cycle" of a magnet field oscillation. Therefore, the constant of

proportionality is $\frac{P}{120}$, where P is the number of magnetic rotor poles (almost always an even number), and the factor of 120 comes from 60 seconds per minute and two poles in a single magnet

$$F(\text{Hz}) = \frac{\text{RPM } P}{120}$$

The power in the prime mover is a function of RPM and torque. $P_m = T_m \cdot \text{RPM}$ where P_m is mechanical power in Watts, T_m is the torque with units of N-m/rad, and RPM is the rotations per minute which is multiplied by a factor of $2\pi/60$ to give units of rad/sec. By increasing the torque on the prime mover, a larger electrical power output can be generated.

In practice, the typical load is inductive in nature. The diagram above depicts such an arrangement. E_i is the voltage of the generator, and V_a and I_a are the voltage and the current in the load respectively and θ is the angle between them. Here, we can see that the resistance, R , and the reactance, X_d , play a role in determining the angle δ . This information can be used to determine the real and reactive power output from the generator.

In this diagram, V_t is the terminal voltage. If we ignore the resistance as shown above, we find that the power can be calculated.

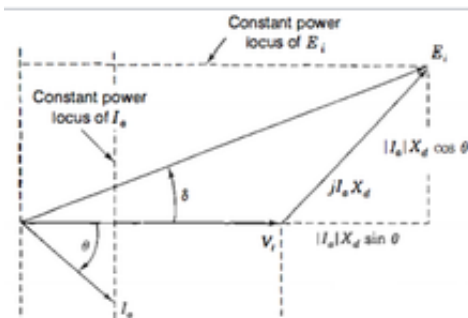
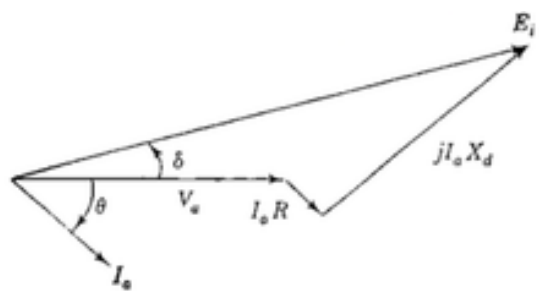
$$I_a = \frac{|E_i| \angle \delta - |V_t|}{jX_d}$$

$$S = P + jQ = V_t I_a^* = \frac{|V_t| |E_i| \angle(-\delta) - |V_t|^2}{-jX_d} = \frac{|V_t| |E_i| (\cos(\delta) - j\sin(\delta)) - |V_t|^2}{-jX_d}$$

Breaking the apparent power into Real and Reactive power, we get:

$$P = \frac{|V_t| |E_i|}{X_d} \sin(\delta)$$

$$Q = \frac{|V_t|}{X_d} (|E_i| \cos(\delta) - |V_t|)$$



Power Electronics converters

The power electronic circuits in wind and photovoltaic power systems basically perform the following functions:

- convert AC into DC.
- convert DC into AC.
- control voltage.
- control frequency.
- convert DC into DC.

These functions are performed by solid state semiconductor devices periodically switched on and off at desired frequency. In terms of applications, no other technology has brought greater change in power engineering, or holds greater potential of bringing improvements in the future, than the power electronic devices and circuits. In this chapter, we review the power electronic circuits used in modern wind and photovoltaic power systems.

Basic Switching Devices

A great variety of solid state devices is available in the market. Some of the more commonly used devices are as follows:

- bipolar junction transistor (BJT).
- metal-oxide semiconducting field effect transistor (MOSFET).
- insulated gate bipolar transistor (IGBT).
- silicon controlled rectifier (SCR), also known as the thyristor.
- gate turn off thyristor (GTO).

For specific application, the choice depends on the power, voltage, current, and the frequency requirement of the system. A common feature among these devices is that all are three-terminal devices as shown in their generally

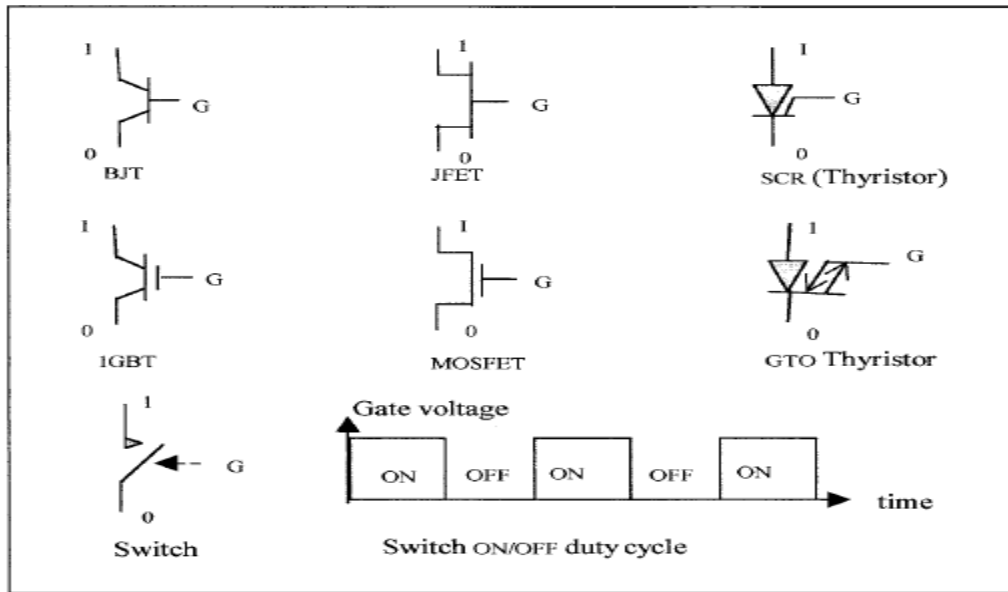


FIGURE 2.6 Basic semiconductor switching devices.

used circuit symbols in [Figure 2.6](#). The two power terminals 1 and 0 are connected in the main power circuit, and one control terminal G. In normal conducting operation, terminal 1 is generally at higher voltage than terminal 0. Terminal G, known as the gate terminal, is connected to the auxiliary control circuit. Since the devices are primarily used for switching power on and off as required, they are functionally represented by the gate-controlled switch shown in (f). In absence of the control signal at the gate, the device resistance between the power terminals is large, with the functional equivalence of an open switch. When the control signal is applied at the gate, the device resistance approaches zero, making the device behave like a closed switch. The device in this state lets the current flow freely through its body. The voltage and current ratings of the switching devices available in the market vary. The presently available ratings are listed in [Table 1-1](#). The switch is triggered periodically on and off by a train of gate signals of suitable frequency. The gate signal may be of rectangular or other wave shape, and is generated by a separate triggering circuit, which is often called the firing circuit

Device	Voltage Rating, Volts	Current Rating, Amperes	Remark
BJT	1500	200	Requires large current signal to turn on
IGBT	1200	100	Combines the advantages of BJT, MOSFET and GTO
MOSFET	1000	100	Higher switching speed
SCR	6000	3000	Once turned on, requires heavy turn-off circuit

TABLE 1-1 Maximum Voltage and Current Ratings of Power Electronic Switching Devices

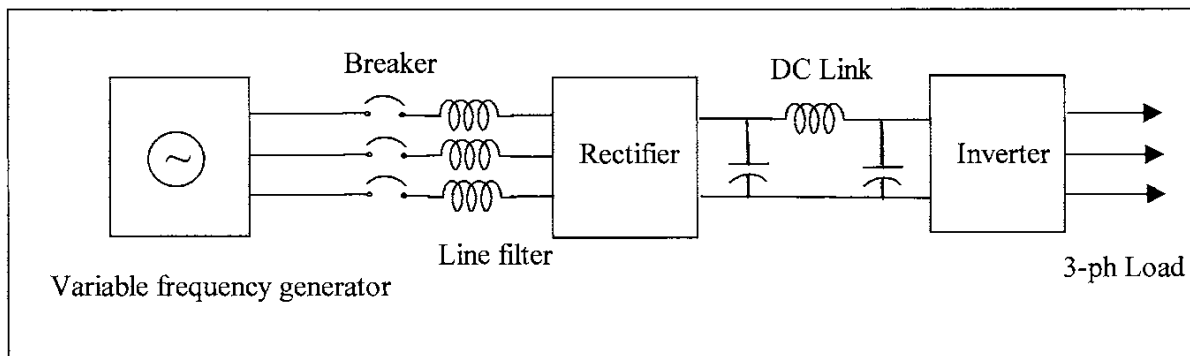


FIGURE 2.7 Variable-speed constant-frequency wind power system schematic

Although it has a distinct identity and many different design features, it is generally incorporated in the main power electronic component assembly. In wind power system operating at variable speed for maximum annual energy production, the output frequency and voltage of the induction generator vary with the wind speed. The variable-frequency, variable-voltage output is converted into fixed voltage 60 Hz or 50 Hz terminal output to match with utility requirement. In modern plants, this is accomplished by power electronics scheme shown in [Figure 2.7](#). The variable frequency is first rectified into DC, and the DC is then inverted back into the fixed frequency AC. The increase in the energy production from the variable speed wind turbine over the plant life more than offsets the added cost of the power electronics.

In photovoltaic power systems, the DC power produced by the pv modules is inverted into 60 or 50 Hz AC power using the inverter. The inverter circuit in the pv system is essentially the same that is used in the variable speed wind power system.

The main power electronic components of the wind and pv power systems are, therefore, the rectifier and the inverter. Their circuits and the AC and DC voltage and current relationships are presented in the following sections.

AC to DC Rectifier

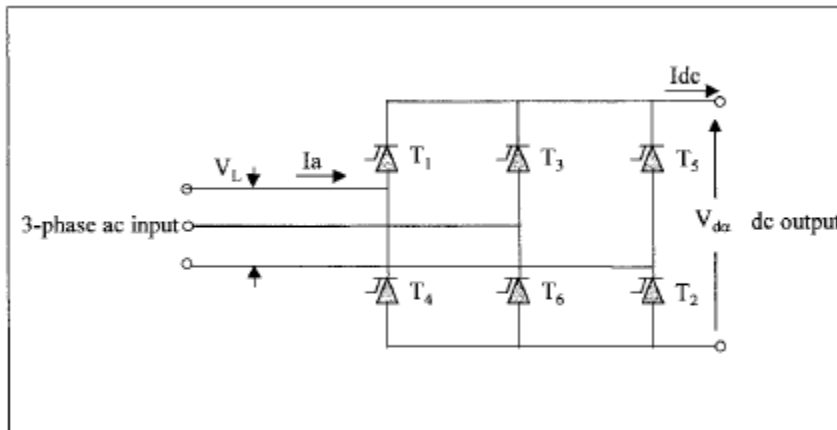


FIGURE 2.8 Three-phase full bridge AC to DC silicon-controlled rectifier circuit.

The circuit diagram of the full-bridge, three-phase, AC to DC rectifier is shown [Figure 2.8](#). The power switch generally used in the rectifier is the silicon-controlled rectifier. The average DC output voltage in this circuit is given by the following:

$$V_{dc} = \frac{3\sqrt{2}}{\pi} V_L \cos \alpha$$

where V_L = line-to-line voltage on three-phase AC side of the rectifier
 α = angle of firing delay in the switching.

The delay angle is measured from the zero crossing in the positive half of the AC voltage wave. Below Equation shows that the output DC voltage is controllable by varying the delay angle α , which in turn controls the conduction (on-time) of the switch.

The load determines the DC side current:

$$I_{DC} = \frac{\text{DC load power}}{V_{DC}}$$

In the steady state operation, the balance of power must be maintained on both AC and DC sides. That is, the power on the AC side must be equal to the sum of the DC load power and the losses in the rectifier circuit. The AC side power is therefore:

$$P_{AC} = \frac{\text{DC load power}}{\text{rectifier efficiency}}$$

the three-phase AC power is given by the following: where $\cos \phi$ is the power factor on the AC side. With a well-designed power electronic converter, the power factor on the AC side is approximately equal to that of the load

$$P_{AC} = \sqrt{3} \cdot V_L \cdot I_L \cdot \cos \phi$$

DC to AC Inverter

The power electronic circuit used to convert DC into AC is known as the inverter. The term “converter” is often used to mean either the rectifier or the inverter. The DC input to the inverter can be from any of the following sources:

- rectified DC output of the variable speed wind power system.
- DC output of the photovoltaic power modules.
- DC output of the battery used in the wind or photovoltaic power system.

Figure 2.9 shows the DC to three-phase AC inverter circuit diagram. The DC source current is switched successively in a 60 Hz three-phase time sequence such as to power the three-phase load. The AC current contains significant harmonics . The fundamental frequency (60 or 50 Hz) phase-to-neutral voltage is as follows:

$$V_{ph} = \frac{2\sqrt{2}}{\pi} \cos\left(\frac{\pi}{6}\right) \cdot V_{DC}$$

The line-to-line AC voltage, as will be seen in the next chapter, is given by $\cdot \sqrt{3} V_{ph}$. Unlike in BJT, MOSFET, and IGBT, the thyristor current, once switched on, must be forcefully switched off (commutated) to cease conduction. If the thyristor is used as the switching device, the circuit must incorporate additional commutating circuit to perform this function. The commutating circuit is a significant part of the inverter circuit. There are two main types of inverters, the line commutated and the forced commutated.

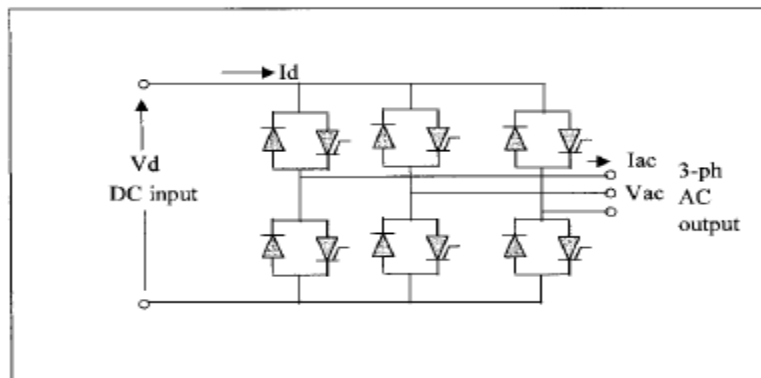


FIGURE 2.9 DC to three-phase AC inverter circuit.

The line-commutated inverter must be connected to the AC system into which they feed power. The design method is matured and has been extensively used in the high-voltage DC transmission line inverters. Such inverters are simple and inexpensive and can be designed in any size. The disadvantage is that they act as a sink of reactive power and generate high content of harmonics. Poor power factor and high harmonic content in line commutated inverters significantly degrade the quality of power at the utility interface. This problem has been recently addressed by a series of design changes in the inverters. Among them is the 12-pulse inverter circuit and increased harmonic filtering. These new design features have resulted in today's inverters operating at near unity power factor and less than 3 to 5 percent total harmonic distortion. The quality of power at the utility interface at many modern wind power plants exceeds that of the grid they interface. The force-commutated inverter does not have to be supplying load and can be free-running as an independent voltage source. The design is relatively complex and expensive. The advantage is that they can be a source of reactive power and the harmonics content is low.

Grid Interface Controls

At the utility interface, the power flow direction and magnitude depend on the voltage magnitude and the phase relation of the site voltage with respect to the grid voltage. The grid voltage being fixed, the site voltage must be controlled both in magnitude and in phase in order to feed power to the grid when available, and to draw from the grid when needed. If the inverter and phase control of the site voltage is done with the same inverter with no additional hardware cost. The controls are accomplished as follows: is already included in the system for frequency conversion, the magnitude

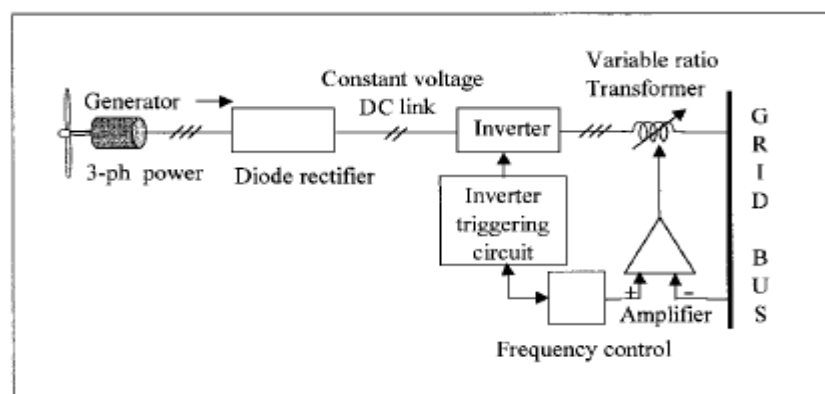


FIGURE 2.10 Voltage control by means of uncontrolled rectifier and variable ratio tap-changing transformer.

Frequency Control

The output frequency of the inverter solely depends on the rate at which the switching thyristors or transistors are triggered into conduction. The triggering rate is determined by the reference oscillator producing a continuous train of timing pulses, which are directed by logic circuits to the thyristor gating circuits. The timing pulse train is also used to control the turnoff circuits. The frequency stability and accuracy requirements of the inverter dictate the selection of the reference oscillator. A simple temperature compensated R-C relaxation oscillator gives the frequency stability within 0.02 percent. When better stability is needed, a crystal-controlled oscillator and digital counters may be used, which can provide stability of .001 percent or better. The frequency control in a stand-alone power system is an openloop system. The steady state or transient load changes do not affect the frequency. This is one of the major advantages of the power electronics inverter over the old electromechanical means of frequency controls.

Voltage Control

For interfacing with the utility grid lines, the renewable power system output voltage at the inverter terminals must be adjustable. The voltage is controlled by using one of the following two methods: 1. By controlling the alternating voltage output of the inverter using tap-changing autotransformer at the inverter output (Figure 2-10). The tap changing is automatically obtained in a closed-loop control system. If the transformer has a phase-changing winding also, a complete control on the magnitude and phase of the site voltage can be achieved. The advantages of this scheme are that the site output voltage waveshape does not vary over a wide range, and high input power factor is achieved by using uncontrolled diode rectifiers for the DC link voltage. The added cost of the transformer, however, can be avoided by using the method discussed below. 2. Since the magnitude of the alternating voltage output from the static inverter is proportional to the direct voltage input from the rectifier, the voltage control can be achieved by operating the inverter with the variable DC link voltage. Such a system also maintains the same output voltage, frequency and wave shape over a wide range. However, in circuits deriving the load current from the commutating capacitor voltage from the DC link, the commutating capability decreases when the output voltage is reduced. This could lead to an operational difficulty when the DC link voltage varies over a wide range, such as in motor drives controlling **Fig 2-10** Voltage control by means of uncontrolled rectifier and variable ratio tap-changing transformer the speed in

ratio exceeding four to one. In renewable power applications, such commutation difficulty is unlikely as the speed varies over a narrow range.

The variable DC link voltage is obtained two ways:

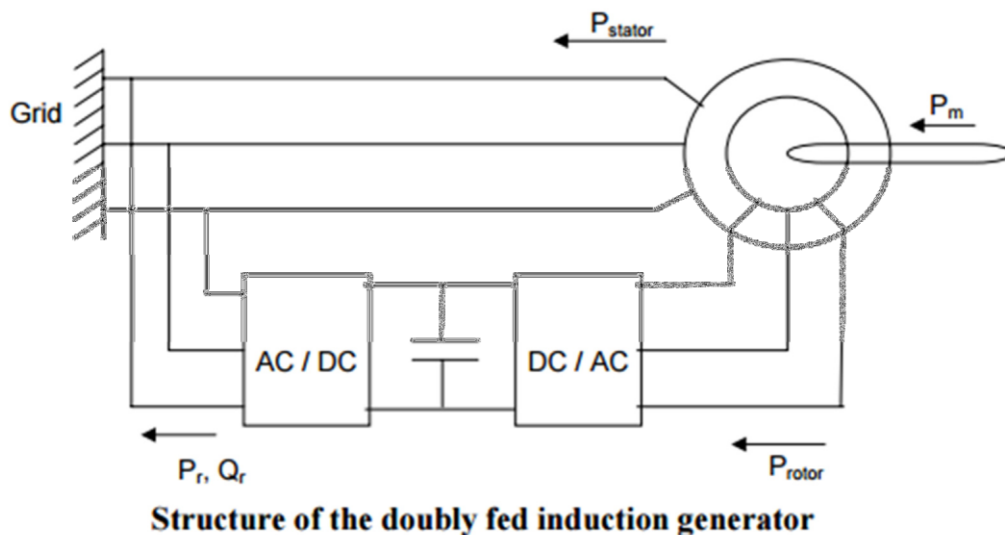
- one way is to connect a variable ratio transformer on the input side of the rectifier. The secondary tap changing is automatically obtained in a closed-loop control system.
- the other way is to use the phase-controlled rectifier in place of the uncontrolled rectifier

At reduced output voltage, this method gives poor power factor and high harmonic content, and requires filtering the DC voltage before feeding to the inverter.

Doubly fed induction motors

One of the most recent rotor-side-control schemes is the doubly fed induction generator. The method uses bi-directional AC-AC converters in the rotor circuit to control the currents injected into the rotor. The converters, being bi-directional, can be used to feed the rotor power back to the grid, reducing rotor power losses and surmounting the main drawback of the rotor resistance control.

Doubly-fed electric machines are electric motors or electric generators where both the field magnet windings and armature windings are separately connected to equipment outside the machine. By feeding adjustable frequency AC power to the field windings, the magnetic field can be made to rotate, allowing variation in motor or generator speed. This is useful, for instance, for generators used in wind turbines.



Doubly fed electrical generators are similar to AC electrical generators, but have additional features which allow them to run at speeds slightly above or below their natural synchronous speed. This is useful for large variable speed wind turbines, because wind speed can change suddenly.

When a gust of wind hits a wind turbine, the blades try to speed up, but a synchronous generator is locked to the speed of the power grid and cannot speed up. So large forces are developed in the hub, gearbox, and generator as the power grid pushes back. This causes wear and damage to the mechanism. If the turbine is allowed to speed up immediately when hit by a wind gust, the stresses are lower and the power from the wind gust is converted to useful electricity.

One approach to allowing wind turbine speed to vary is to accept whatever frequency the generator produces, convert it to DC, and then convert it to AC at the desired output frequency using an inverter. This is common for small house and farm wind turbines. But the inverters required for megawatt-scale wind turbines are large and expensive.

Doubly fed generators are one solution to this problem. Instead of the usual field winding fed with DC, and an armature winding where the generated electricity comes out, there are two three-phase windings, one stationary and one rotating, both separately connected to equipment outside the generator. Thus the term "doubly fed".

When the machine is operating in the generating mode, the mechanical power P_m gets converted into electrical power in the stator (P_{stator}) and in the rotor (P_{rotor}). The rotor power is processed by the PWM converters and the grid side converter can be controlled to feed this power as both real and reactive powers (P_r and Q_r). Thus, the induction generator system is capable of generating a limited amount of reactive power, unlike the pitch control or rotor resistance controlled wind energy systems. The system can usually be made to operate at a unity power factor with a ± 10 % control range on the power factor for the entire system.

The principle of the DFIG is that rotor windings are connected to the grid via slip rings and back-to-back voltage source converter that controls both the rotor and the grid currents. Thus rotor frequency can freely differ from the grid frequency (50 or 60 Hz). By using the converter to control the rotor currents, it is possible to adjust the active and reactive power fed to the grid from the stator independently of the generator's turning speed. The control principle used is either the two-axis current vector control or direct torque control (DTC). DTC has turned out to have better stability than current vector control especially when high reactive currents are required from the generator.

The doubly-fed generator rotors are typically wound with 2 to 3 times the number of turns of the stator. This means that the rotor voltages will be higher and currents respectively lower. Thus in the typical ± 30 % operational speed range around the synchronous speed, the rated current of the converter is accordingly lower which leads to a lower cost of the converter.

The drawback is that controlled operation outside the operational speed range is impossible because of the higher than rated rotor voltage. Further, the voltage transients due to the grid disturbances (three- and two-phase voltage dips, especially) will also be magnified. In order to prevent high rotor voltages - and high currents resulting from these voltages - from destroying the IGBTs and diodes of the converter, a protection circuit (called crowbar) is used.

1. What is meant by frequency control of IM?

The speed of IM can be controlled by changing the supply freq because the speed is directly proportional to supply frequency. This method of speed ctrl is called freq control.

2. What is meant by V/F control?

When the freq is reduced the i/p voltage must be reduced proportionally so as to maintain constant flux otherwise the core will get saturated resulting in excessive iron loss and magnetizing current. This type of IM behavior is similar to the working of dc series motor.

3. What are the advantages of V/F control?

- Smooth speed control
- Small i/p current and improved power factor at low freq. start
- Higher starting torque for low case resistance

3. What is meant by stator current control?

The 3 phase IM speed can be controlled by stator current control. The stator current can be varied by using current source inverter.

5. What are the 3 modes of region in the adjustable-freq IM drives characteristics?

- Constant torque region
- Constant power region
- High speed series motoring region

6. What are the two modes of operation in the motor?

The two modes of operation in the motor are, motoring and braking. In motoring, it converts electrical energy to mechanical energy, which supports its motion. In braking, it works as a generator converting mechanical energy to electrical energy and thus opposes the motion.

7. How will you select the motor rating for a specific application?

When operating for a specific application motor rating should be carefully chosen that the insulation temperature never exceed the prescribed limit. Otherwise either it will lead to its immediate thermal breakdown causing short circuit and damage to winding, or it will lead to deterioration of its quality resulting into thermal breakdown in near future.

8. What is braking? Mention its types.

The motor works as a generator developing a negative torque which opposes the motion is called braking.

- It is of three types. They are
- a. Regenerative braking.
 - b. Dynamic or rheostat braking.
 - c. Plugging or reverse voltage braking.

9. What are the three types of speed control?

The three types of speed control are,

- a. Armature voltage control
- b. Field flux control
- c. Armature resistance control.

10. What are the advantages of armature voltage control?

The advantages of armature voltage control are,

- a. High efficiency
- b. Good transient response
- c. Good speed regulation.

11. What are the methods involved in armature voltage control? When the supply is in A.C.

- a. Ward-Leonard schemes
- b. Transformer with taps and an uncontrolled rectifier bridge.
- c. Static Ward Leonard scheme or controlled rectifiers when the supply is in D.C.
- d. Chopper control.

12. Give some drawbacks and uses of Ward-Leonard drive.

The drawbacks of Ward . Leonard drive are.

- a. High initial cost
- b. Low efficiency

The Ward-Leonard drive is used in rolling mills, mine winders, paper mills, elevators, machine tools etc.

13. Give some advantages of Ward-Leonard drive.

The advantages of Ward-Leonard drive are,

- a. Inherent regenerative braking capability
- b. Power factor improvement.

14. What is the use of controlled rectifiers?

Controlled rectifiers are used to get variable D.C. Voltage from an A.C. Source of fixed voltage.

15. What is known as half-controlled rectifier and fully controlled rectifier?

The rectifiers provide control of D.C. voltage in either direction and therefore, allow motor control in quadrants I and IV. They are known as fully-controlled rectifiers.

The rectifiers allow D.C. Voltage control only in one direction and motor control in quadrant I only. They are known as half-controlled rectifiers.

16. What is called continuous and discontinuous conduction?

A D.C. motor is fed from a phase controlled converter the current in the armature may flow in discrete pulses in called continuous conduction.

A D.C. motor is fed from a phase controlled converter the current in the armature may flow continuously with an average value superimposed on by a ripple is called discontinuous conduction.

17. What are the three intervals present in discontinuous conduction mode of single phase half and fully controlled rectifier?

The three intervals present in half controlled rectifier are,

- a. Duty interval
- b. Free, wheeling interval
- c. Zero current intervals.

The two intervals present in fully controlled rectifier are

- a. Duty interval
- b. Zero current intervals.

18. What is called inversion?

Rectifier takes power from D.C. terminals and transfers it to A.C. mains is called inversion.

19. What are the limitations of series motor? Why series motor is not used in traction applications now a days?

1. The field of series cannot be easily controlled. If field control is not employed, the series motor must be designed with its base speed equal to the highest desired speed of the drive.
2. Further, there are a number of problems with regenerative braking of a series motor. Because of the limitations of series motors, separately excited motors are now preferred even for traction applications.

20. What are the advantages of induction motors over D.C. motors?

The main drawback of D.C. motors is the presence of commutator and brushes, which require frequent maintenance and make them unsuitable for explosive and dirty environments. On the other hand, induction motors, particularly squirrel-cage are rugged, cheaper, lighter, smaller, more efficient, require lower maintenance and can operate in dirty and explosive environments.

21. Give the applications of induction motors drives.

Although variable speed induction motor drives are generally expensive than D.C. drives, they are used in a number of applications such as fans, blowers, mill run-out tables, cranes, conveyors, traction etc., because of the advantages of induction motors. Other applications involved are underground and underwater installations, and explosive and dirty environments.

22. How is the speed controlled in induction motor?

The induction motor speed can be controlled by supplying the stator a variable voltage, variable frequency supply using static frequency converters. Speed control is also possible by feeding the slip power to the supply system using converters in the rotor circuit, basically one distinguishes two different methods of speed control.

- a. Speed control by varying the slip frequency when the stator is fed from a constant voltage, constant frequency mains.
- b. Speed control of the motor using a variable frequency variable voltage motor operating a constant rotor frequency.

23. How is the speed control by variation of slip frequency obtained?

Speed control by variation of slip frequency is obtained by the following ways.

- a. Stator voltage control using a three-phase voltage controller.
- b. Rotor resistance control using a chopper controlled resistance in the rotor circuit.
- c. Using a converter cascade in the rotor circuit to recover slip energy.
- d. Using a cycloconverter in the rotor circuit.

24. Mention the effects of variable voltage supply in a cage induction motor.

When a cage induction motor is fed from a variable voltage for speed control the following observations may be made.

- a. The torque curve beyond the maximum torque point has a negative slope. A stable operating point in this region is not possible for constant torque load.
- b. The voltage controlled must be capable of withstanding high starting currents. The range of speed control is rather limited.
- c. The motor power factor is poor.

25. Classify the type of loads driven by the motor.

The type of load driven by the motor influences the current drawn and losses of the motor as the slip varies. The normally occurring loads are

- a. Constant torque loads.
- b. Torque varying proportional to speed.
- c. Torque varying proportional to the square of the speed.

26. What are the disadvantages of constant torque loads?

The constant torque loads are not favored due to increase in the losses linearly with slip and becoming maximum at $s = 1.0$. This is obvious from the variation of flux as the voltage is varied for speed control. To maintain constant torque the motor draws heavy current resulting in poor torque/ampere, poor efficiency and poor power factor at low speeds.

27. In which cases, torque versus speed method is suitable.

Torque versus speed method is suitable only for the following cases.

- a. For short time operations where the duration of speed controls is defined.
- b. For speed control of blowers or pumps having parabolic or cubic variations of torque with speed. This is not suitable for constant torque loads due to increases and heating.

28. How is the speed of a squirrel cage induction motor controlled?

The speed of a squirrel cage induction motor can be controlled very effectively by varying the stator frequency. Further the operation of the motor is economical and efficient, if it operates at very small slips. The speed of the motor is therefore, varied by

varying the supply frequency and maintaining the rotor frequency at the rated value or a value corresponding to the required torque on the linear portion of the torque-speed curve.

29. Why the control of a three-phase induction motor is more difficult than D.C. motors.

The control of a three-phase induction motor, particularly when the dynamic performance involved is more difficult than D.C. motors. This is due to a. Relatively large internal resistance of the converter causes voltage fluctuations following load fluctuations because the capacitor cannot be ideally large.

b. In a D.C. motor there is a decoupling between the flux producing magnetizing current and torque producing armature current. They can be independently controlled. This is not the case with induction motors.

c. An induction motor is very poorly damped compared to a D.C. motor.

30. Where is the V/f control used?

The V/f control would be sufficient in some applications requiring variable torque, such as centrifugal pumps, compressors and fans. In these, the torque varies as the square of the speed. Therefore at small speeds the required torque is also small and V/f control would be sufficient to drive these loads with no compensation required for resistance drop. This is true also for the case of the liquid being pumped with minimal solids.

31. What are the components of the applied voltage to the induction motor?

The applied voltage to the induction motor has two components at low frequencies. They are

a. Proportional to stator frequency.

b. To compensate for the resistance drop in the stator.

The second component deepens on the load on the motor and hence on rotor frequency.

32. What is indirect flux control?

The method of maintaining the flux constant by providing a voltage boost proportional to slip frequency is a kind of indirect flux control. This method of flux control is not desirable if very good dynamic behaviour is required.

33. What is voltage source inverter?

Voltage source inverter is a kind of D.C. link converter, which is a two stage conversion device.

34. What is the purpose of inductance and capacitance in the D.C. link circuit?

The inductance in the D.C. link circuit provides smoothing whereas the capacitance maintains the constancy of link voltage. The link voltage is a controlled quality.

35. What are the disadvantages of square wave inverter in induction motor drive?

Square wave inverters have commutation problems at very low frequencies, as the D.C. link voltage available at these frequencies cannot charge the commutating capacitors sufficiently enough to commutate the thyristors. This puts a limit on the lower frequency of operation. To extend the frequency towards zero, special charging circuits must be used.

36. What is slip controlled drive?

When the slip is used as a controlled quantity to maintain the flux constant in the motor the drive is called slip controlled drive. By making the slip negative (i.e., decreasing the output frequency of the inverter) The machine may be made to operate as a generator and the energy of the rotating parts fed back to the mains by an additional line side converter or dissipated in a resistance for dynamic braking. By keeping the slip frequency constant, braking at constant torque and current can be achieved. Thus braking is also fast.

37. What are the effects of harmonics in VSI fed induction motor drive?

The motor receives square wave voltages. These voltage has harmonic components. The harmonics of the stator current cause additional losses and heating. These harmonics are also responsible for torque pulsations. The reaction of the fifth and seventh harmonics with the fundamental gives rise to the seventh harmonic pulsations in the torque developed. For a given induction motor fed from a square wave inverter the harmonic content in the current tends to remain constant independent of input frequency, with the range of operating frequencies of the inverter.

38. What is a current source inverter?

In a D.C. link converter, if the D.C. link current is controlled, the inverter is called a current source inverter, The current in the D.C. link is kept constant by a high inductance and the capacitance of the filter is dispensed with. A current source inverter is suitable for loads which present a low impedance to harmonic currents and have unity p.f.

39. Explain about the commutation of the current source inverter.

The commutation of the inverter is load dependent. The load parameters form a part of the commutation circuit. A matching is therefore required between the inverter and the motor. Multimotor operation is not possible. The inverter must necessarily be a force commutated one as the induction motor cannot provide the reactive power for the inverter. The motor voltage is almost sinusoidal with superimposed spikes.

40. Give the features from which a slip controlled drive is developed.

The stator current of an induction motor operating on a variable frequency, variable voltage supply is independent of stator frequency if the air gap flux is maintained constant. However, it is a function of the rotor frequency. The torque developed is also a function of rotor frequency. The torque developed is also a function of rotor frequency only. Using these features a slip controlled drive can be developed employing a current source inverter to feed an induction motor.

41. How is the braking action produced in plugging?

In plugging, the braking torque is produced by interchange any two supply terminals, so that the direction of rotation of the rotating magnetic field is reversed with respect to the rotation of the motor. The electromagnetic torque developed provides the braking action and brings the rotor to a quick stop.

42. Where is rotor resistance control used?

Where the motors drive loads with intermittent type duty, such as cranes, ore or coal unloaders, skip hoists, mine hoists, lifts, etc. slip-ring induction motors with speed control by variation of resistance in the rotor circuit are frequently used. This method of speed control is employed for a motor generator set with a flywheel (Ilgner set) used as an automatic slip regulator under shock loading conditions.

43. What are the advantages and disadvantages of rotor resistance control?

Advantage of rotor resistance control is that motor torque capability remains unaltered even at low speeds. Only other method which has this advantage is variable frequency control. However, cost of rotor resistance control is very low compared to variable frequency control.

Major disadvantage is low efficiency due to additional losses in resistors connected in the rotor circuit.

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46. How is the resistance in the output terminals of a chopper varied?

The resistance connected across the output terminals of a chopper can be varied from O to R by varying the time ratio of the chopper. When the chopper is always OFF, the supply is always connected to the resistance R . The time ratio in this case is zero and the effective resistance connected is R . Similarly when the chopper is always ON, the resistance is short circuited. The time ratio in the case is unity and the effective resistance connected is 0 . Hence by varying the time ratio from 0 to 1 , the value of resistance can be varied from R to O .

47. What is the function of inductance L and resistance R in the chopper resistance circuit?

A smoothing inductance L is used in the circuit to maintain the current at a constant value. Any short circuit in the chopper does not become effective due to L .

The value of R connected across the chopper is effective for all phases and its value can be related to the resistance to be connected in each phase if the conventional method has been used. The speed control range is limited by the resistance.

48. What are the disadvantages and advantages of chopper controlled resistance in the rotor circuit method?

The method is very inefficient because of losses in the resistance. It is suitable for intermittent loads such as elevators. At low speeds, in particular the motor has very poor efficiency. The rotor current is non-sinusoidal. The harmonics of the rotor current produce torque pulsations. These have a frequency which is six times the slip frequency. Because of the increased rotor resistance, the power factor is better.

49. How is the range of speed control increased?

The range of speed control can be increased if a combination of stator voltage control and rotor resistance control is employed. Instead of using a high resistance rotor, a slip ring rotor with external rotor resistance can be used when stator voltage control is used for controlling the speed.

50. Why the static scherbius drive has a poor power factor?

Drive input power is difference between motor input power and the power fed back. Reactive input power is the sum of motor and inverter reactive power. Therefore, drive has a poor power factor throughout the range of its options.
