EE3014 POWER ELECTRONICS FOR RENEWABLE ENERGY SYSTEMS

UNIT II

ELECTRICAL MACHINES FOR WIND ENERGY CONVERSION

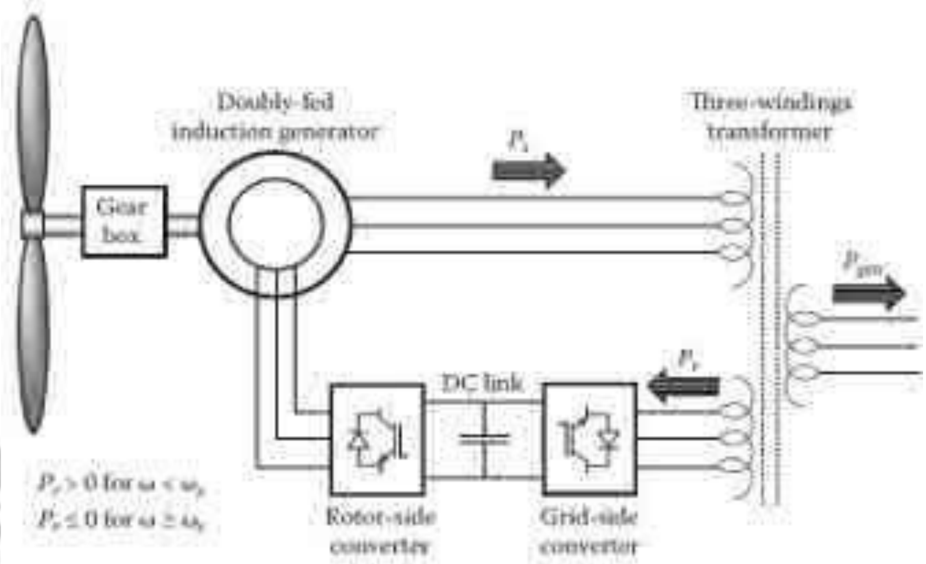
2.5- DFIG

DOUBLY FED INDUCTION GENERATORS (DFIG)

Constructional features

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. Therefore 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 stressesare lower and the power from the wind gust is converted to useful electricity. One approach toallowing 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 formegawatt-scale wind turbines are large and expensive. Doubly fed generators are one solution tothis problem. Instead of the usual field winding fed with DC, and an armature winding where thegenerated electricity comes out, there are two three-phase windings, one stationary and onerotating, both separately connected to equipment outside the generator. Thus the term "doublyfed". One winding is directly connected to the output, and produces 3-phase AC power at thedesired grid frequency. The other winding (traditionally called the field, but here both windingscan be outputs) is connected to 3-phase AC power at variable frequency. This input power isadjusted in frequency and phase to compensate for changes in speed of the turbine.



Wind turbine–powered DFIG with transformer-based utility connection

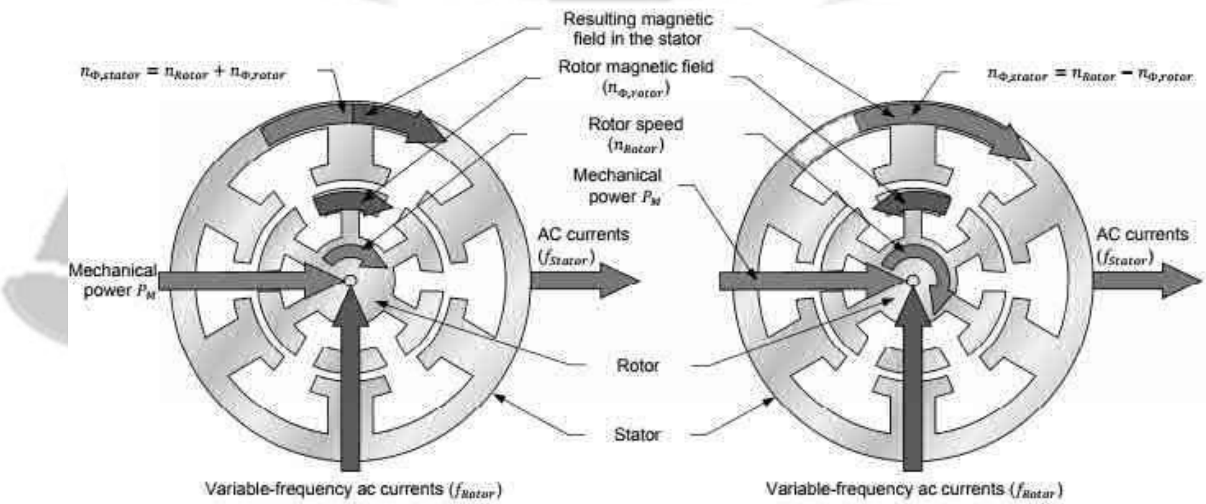
The doubly-fed generator rotors are typically wound with 2 to 3 times the number of turns of the stator. This means that the rotor voltages will be higher and currents respectively lower. Thus in the typical ± 30% operational speed range around the synchronous speed, the rated current of the converter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

The crowbar will short-circuit the rotor windings through a small resistance when excessive currents or voltages are detected. In order to be able to continue the operation as quickly as possible an active crowbar has to be used. The active crowbar can remove the rotor short in a controlled way and thus the rotor side converter can be started only after 20-60 ms from the start of the grid disturbance when the remaining voltage stays above 15% of the nominal voltage. Thus it is possible to generate reactive current to the grid during the rest of the voltage dip and in this way help the grid to recover from the fault. For zero voltage ride throughit is common to wait until the dip ends because with zero voltage it is not possible to know the phase angle where the reactive current should be injected.

Principle of operation

The principle of the Doubly-Fed Induction Generator (referred to as DFIG) is that rotor windings are connected to the grid via slip rings and back-to-back voltage source converters that control both the rotor and the grid currents. Thus, rotor frequency can freely differ from the grid frequency (50 or 60 Hz). Double Fed Induction Generator, a generating principle widely used in wind turbines. It is based on an induction generator with a multiphase wound rotor and a multiphase slip ring assembly with brushes for access to the rotor windings. It is possible to avoid the multiphase slip ring assembly but there are problems with efficiency, cost and size.

A doubly-fed induction machine is a wound-rotor doubly-fed electric machine and has several advantages over a conventional induction machine in wind power applications. First, as the rotor circuit is controlled by a power electronics converter, the induction generator is able to both import and export reactive power. This has important consequences for power system stability and allows the machine to support the grid during severe voltage disturbances. Second, the control of the rotor voltages and currents enables the induction machine to remain synchronized with the grid while the wind turbine speed varies. A variable speed wind turbine utilizes the available wind resource more efficiently than a fixed speed wind turbine, especially during light wind conditions. Third, the cost of the converter is low when compared with other variable speed solutions because only a fraction of the mechanical power, typically 25-30%, is fed to the grid through the converter, the rest being fed to grid directly from the stator. The efficiency of the DFIG is very good for the same reason. Doubly-fed electric machine is connected to a selection of resistors via multiphase slip rings for starting. However, the slip power was lost in the resistors. Thus means to increase the efficiency in variable speed operation by recovering the slip power were developed.



(a) When the stator and rotor magnetic fields rotate in the same direction

(b) When the stator and rotor magnetic fields rotate in opposite directions

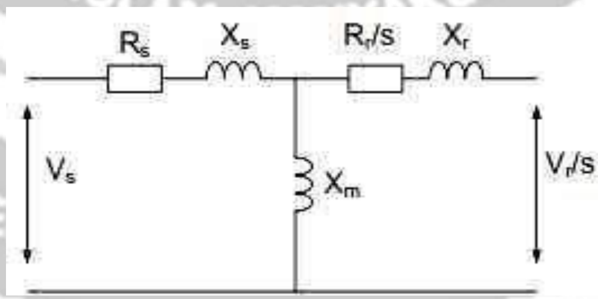
Interaction between the rotor speed and the frequency of the rotating magnetic fieldcreated in the rotor windings of a doubly-fed induction generator.

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. Direct torque control has turned out to have better stability than current vector control especially whenhigh reactive currents are required from the generator.

Equivalent Circuit of DFIG

A doubly fed induction generator is basically a wound rotor induction generator fed by both stator and rotor, in which the stator winding is directly connected to the grid and the rotor winding is connected to the grid through AC/DC/AC converters. These converters are divided into two components: the rotor side converter and the grid side converter. A capacitor between the converters plays a role of a DC voltage source. A coupling inductor is used to link the grid side converter to the grid.

The operation principle of DFIG is fundamentally the same as that of a transformer. Thus, DFIG can be represented as a transformer‘s per phase equivalent circuit, where R_r and X_r represent rotor resistance and reactance referred to the stator side. But the equivalent circuit of induction machine differs from a transformer‘s primarily with respect to varying rotor frequency on the rotor voltage. In case of DFIG, there is a voltage injected to the rotor winding, so an equivalent circuit of classic induction machine needs to be modified by adding a rotor injected voltage as shown in Figure. In this figure, *s* is the rotor slip, *V* the voltage, *I* the current, *R* and *X* represent resistance and reactance, respectively. The subscripts *r*, *s* and *m* stand for rotor, stator and mutual, respectively.



The Equivalent Circuit of DFIG

Real and reactive power in the stator side like P_s and Q_s delivered to the connected grid can bederived from I_s and *Vs* as in (1):

$$P_s = 3Re(V_s I_s^*)$$

$$Q_s = 3Im(V_s I_s^*) \qquad (1)$$

Real and reactive power in the rotor side, P_r , Q_r , referred to stator side is derived from I_r and V_r/s, as in (2):

$$P_r = 3Re\left(\frac{V_r}{s} I_r^*\right)$$

$$Q_r = 3Im\left(\frac{V_r}{s} I_r^*\right) \quad (2)$$

It is possible to express the electromechanical torque, T_e , as in (3):

$$T_e = \frac{3}{2}\frac{p}{2} Re\left(j\Psi_s I_s^*\right) = \frac{3}{2}\frac{p}{2} Re\left(j\Psi_r I_r^*\right) \quad (3)$$

where

$$\Psi_s = \frac{X_s I_s + X_m I_r}{\omega_s};\ \Psi_r = \frac{X_r I_r + X_m I_s}{\omega_S}$$

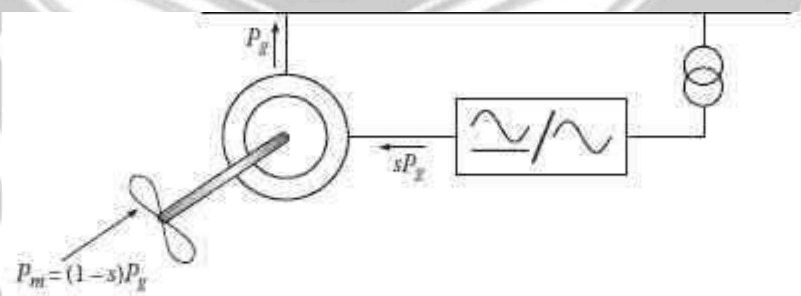
□$_s$ and □$_r$: the stator and the rotor flux,

respectively.p: the number of poles per phase.

I_s^*, I_r^* : the complex conjugates of the stator and the rotor current, respectively.

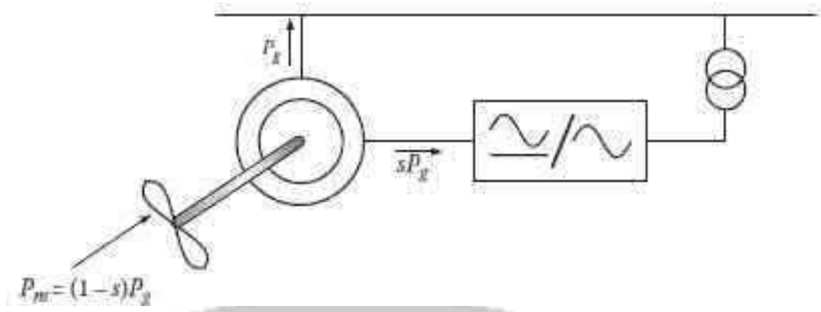
Sub- and Super-synchronous modes

Figure (a) shows the power balance in a DFIG at sub-synchronous generation where $s > 0$ and the power flow into the rotor by a current-controlled inverter. A step-up transformer is usually connected between the low-frequency low-voltage requirements and the grid in order to alleviate the rotor converter ratings.

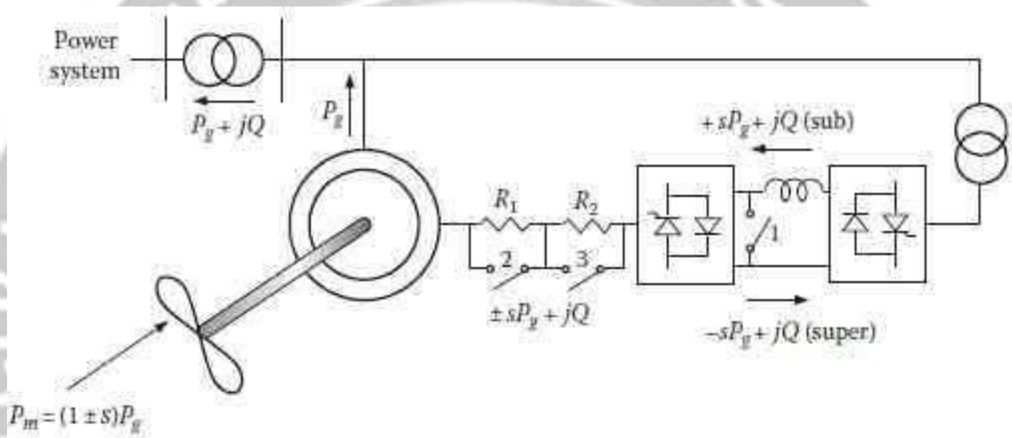


(a) Sub-synchronous generating mode ($s > 0$).

Figure (b) shows the super-synchronous generating mode where the mechanical speed is greater than the electrical synchronous speed, so the slip is negative ($s < 0$). The rotor voltages will have their phase sequence reversed; since $Pg < 0$ and $Pr < 0$, the rotor circuit contributes in generating power to the line with improved efficiency.



(b) Super-synchronous generating mode (*s* < 0).

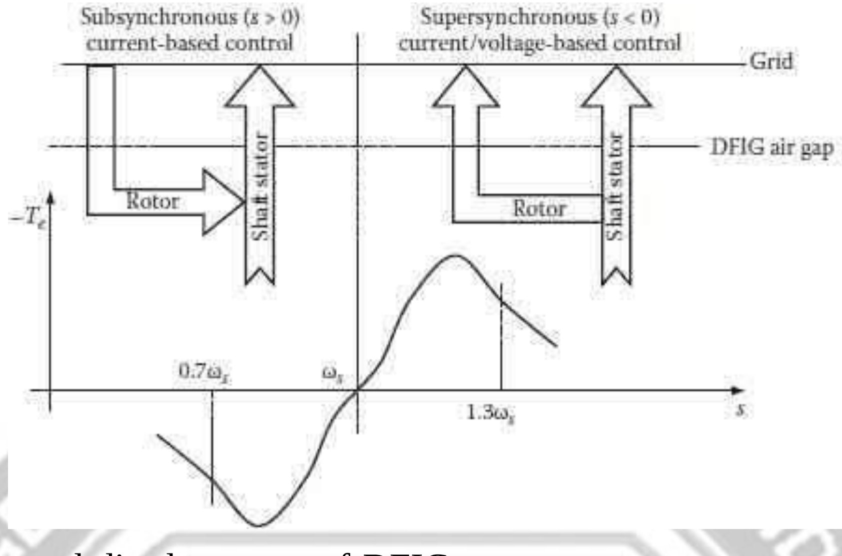


(c) Sub-synchronous mode back-to-back double converter.

It is important to note that the shaft incoming power indicates $Pm = (1 + s)Pg$ to showthe extra capability of the power conversion, but the slip is actually negative. Thus, very efficient generating systems can be achieved using the super-synchronous region. Because the operating region is limited, the main drawback is the starting-up sequence of the system. One possible way around this is to use auxiliary resistors in the rotor circuit as indicated in Figure (c), then drive the machine in motoring mode, and, just after the cut-in speed, plug in the controller, which imposes regenerative operation.

Torque-slip curve for DFIG in sub- and super-synchronous modes.

For high-power machines, the stator resistance is neglected, and the stator terminalpower is *Pg*. Considering that the power flowing out of the machine is negative (generatingmode), the induction generator has a power balance in accordance with the torque-slip curveindicated in Figure. The power distribution for the generator operating at sub-synchronous andsuper-synchronous regions is indicated in the operating region from 0.7ω*s* to 1.3ω*s*. Foroperation at the sub-synchronous region, the slip is positive, and therefore, the rotor circuitreceives power from the line, whereas for the super-synchronous region, the slip is negative, and the rotor power supplements extra generating power to the grid.



Advantages and disadvantages of DFIG

Advantages

- DFIG is a variable speed generator and therefore has the variable speed advantagescompared to fixed speed generators.
- It more fully converts the available wind power over a wider range of wind speeds with lessmechanical complexity but more electrical and electronic complexity.
- DFIG provides variable speed with a smaller power converter compared to other variable-speed generators.
- Only the rotor power needs to be converted. That is typically about 30% of the total power.
- Reduced power conversion means reduced losses and increased efficiency. However the converter must be designed to transfer power in either direction, making it more complex than power converters for other types of variable-speed generators.
- The overall equipment, installation and maintenance cost is apparently lower for DFIG systems for some range of power levels.

Disadvantages

- A disadvantage of the DFIG compared to the permanent magnet synchronous generatoris that the DFIG requires a speed increasing gearbox between the wind turbine and the generator whereas the PMSG can be constructed with a sufficient number of poles to allow direct drive.