



## Basic Concepts of Doubly Fed Induction Generator Driven by Wind Energy Conversion System

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**Abstract:** With increased production capacity in wind farms, their role in power system stability has become important. The inertia response of a generator is influenced by the sensitivity of the generator's electromagnetic torque to changes in the power system frequency. DFIG has low inertia response. Inertia response of DFIG can be improved by adding feedback parameter as a function of the rate of the change of the grid frequency to reference electromagnetic torque. At any mode of operation, rotational speed of the turbine must be changed and thus active and reactive power of the generator must be changed.

**Keywords:** Active Power, Doubly Fed Induction Generator, Reactive Power, Wind Turbine.

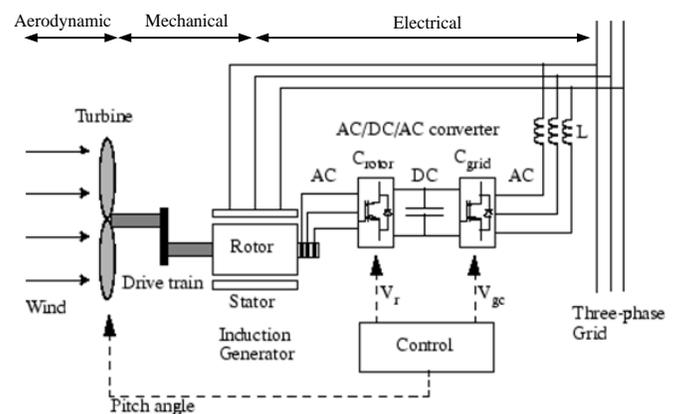
### I. INTRODUCTION

Wind industry is becoming one of the world's fastest growing energy sectors nowadays, helping to satisfy global energy demand, offering the best opportunity to unlock a new era of environmental protection, and starting the transition to a global economy based on sustainable energy. Wind turbines based on doubly fed induction generators have attracted particular attention because of their advantages such as variable speed constant frequency operation, reduced flicker and independent control capabilities for active and reactive powers. Active power from the generator is determined by the turbine control and must of course be within the capability of the turbine generator system. Voltage is primarily determined by the reactive power injection into the node, and since the generator must operate within its reactive capability curve it is not possible to control the voltage outside certain limits. The reactive capability of a generator depends on a number of quantities, such as active power, bus voltage and other operating conditions. The doubly fed induction generator construction caused a good performance when the voltage reduction occurs in these conditions, without losing any dynamic balance; it will remain connected to the power system. DFIGs are variable speed generators with advantages than others, they are used more in wind turbine because its control is easier and energy efficiency is higher than other generators and power quality is improved in this type of generator, controlled power electronic converters are used for improving the efficiency.

### II. WIND ENERGY CONVERSION SYSTEM

The development in wind turbine systems has been steady for the last 25 years and four to five generation of wind turbine exist. The main components of a wind turbine system,

including the turbine rotor, gearbox, generator, transformer, and possible power electronics, are illustrated in Fig.1.



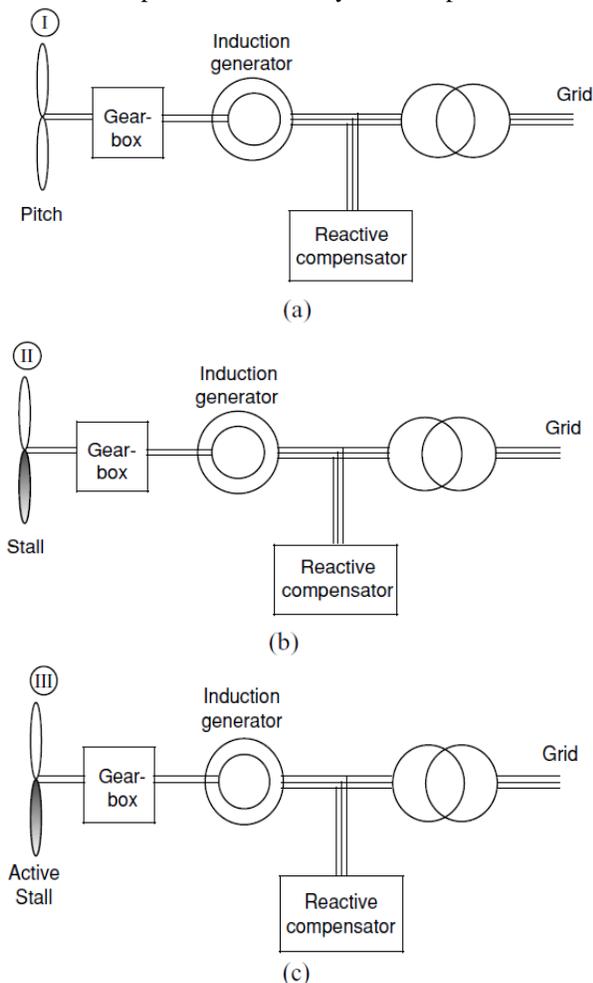
**Fig.1. Wind Energy Conversion System with Three Types of Components.**

The turbine rotor converts the fluctuating wind energy into mechanical energy, which is converted into electrical power through the generator, and then transferred into the grid through a transformer and transmission lines. Wind turbines capture the power from the wind by means of aerodynamically designed blades and convert it to rotating mechanical power. The number of blades is normally three and the rotational speed decreases as the radius of the blade increases. For megawatt range wind turbines the rotational speed will be 10-15 rpm. The weight-efficient way to convert the low-speed, high-torque power to electrical power is to use a gearbox and a generator with standard speed. The gearbox adapts the low speed of the turbine rotor to the high speed of the generator. The gearbox may be not necessary for multipole generator systems. The generator converts the

mechanical power into electrical energy, which is fed into a grid through possibly a power electronic converter, and a transformer with circuit breakers and electricity meters. The connection of wind turbines to the grid is possible at low voltage, medium voltage, high voltage, and even at the extra high voltage system since the transmittable power of an electricity system usually increases with increasing the voltage level. While most of the turbines are nowadays connected to the medium voltage system, large offshore wind farms are connected to the high and extra high voltage level.

**III. GENERATOR SYSTEMS FOR WIND TURBINES**

Both induction and synchronous generators can be used for wind turbine systems. Induction generators can be used in a fixed-speed system or a variable-speed system, while synchronous generators are normally used in power electronic interfaced variable-speed systems. Mainly, three types of induction generators are used in wind power conversion systems: cage rotor, wound rotor with slip control by changing rotor resistance, and doubly fed induction generators. The cage rotor induction machine can be directly connected into an ac system and operates at a fixed speed or uses a full-rated power electronic system to operate at



**Fig.2. Wind turbine systems without power converter, but with aerodynamic power control.(a) Pitch controlled (System I), (b) stall controlled (System II), and (c) active stall controlled (System III).**

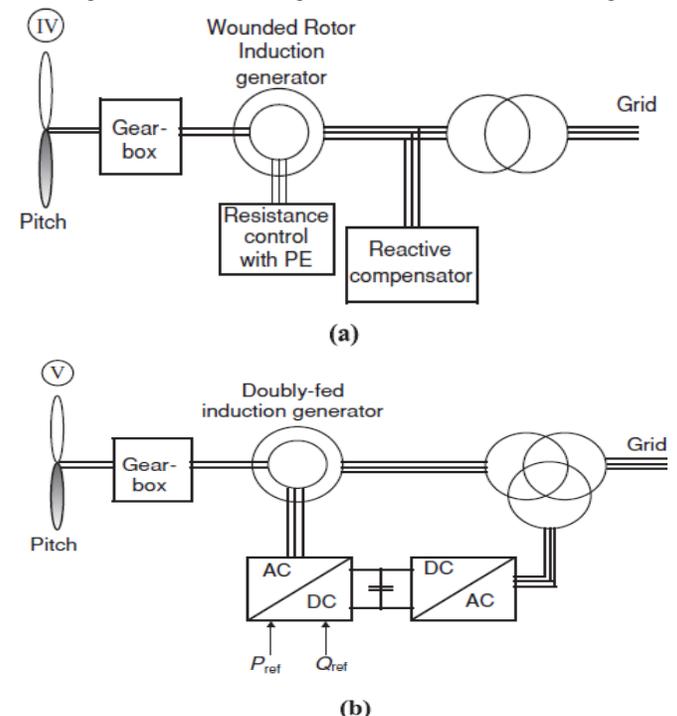
variable speed. The wound rotor generator with rotor-resistance-slip control is normally directly connected to an ac system, but the slip control provides the ability of changing the operation speed in a certain range. The doubly fed induction generators provide a wide range of speed variation depending on the size of power electronic converter systems. In this paper we first discuss the systems without power electronics except the thyristor soft starter, and then discuss the variable-speed wind turbine systems, including those with partially rated power electronics and the full-scale power electronic interfaced wind turbine systems.

**A. Fixed-Speed Wind Turbines**

In fixed-speed wind turbines, the generator is directly connected to the mains supply grid. The frequency of the grid determines the rotational speed of the generator and thus of the rotor. The generator speed depends on the number of pole pairs and the frequency of the grid. The basic configurations of three different fixed speed concepts are shown in Fig.2. The advantage of wind turbines with induction generators is the simple and cheap construction. In addition, no synchronization device is required.

**B. Variable Speed Wind Turbines**

In variable-speed systems the generator is normally connected to the grid by a power electronic system. For synchronous generators and for induction generators without rotor windings, a full-rated power electronic system is connected between the stator of the generator and the grid, where the total power production must be fed through the power electronic system. For induction generators with rotor windings, the stator of the generator is connected to the grid



**Fig.3. Wind turbine topologies with partially rated power electronics and limited speed range. Rotor-resistance converter (System IV) and doubly-fed induction generator (System V).**

## Basic Concepts of Doubly Fed Induction Generator Driven by Wind Energy Conversion System

directly. Only the rotor of the generator is connected through a power electronic system. This gives the advantage that only a part of the power production is fed through the power electronic converter. This means the nominal power of the converter system can be less than the nominal power of the wind turbine. In general the nominal power of the converter may be 30% of the power rating of the wind turbine, enabling a rotor speed variation in the range of 30% of the nominal speed. By controlling the active power of the converter, it is possible to vary the rotational speed of the generator and thus of the rotor of the wind turbines. The generator for wind turbine systems shown in Fig.3 is an induction generator with a wounded rotor.

### IV. DOUBLY FED INDUCTION GENERATOR

Doubly-fed electric machines are basically electric machines that are fed ac currents into both the stator and the rotor windings. Most doubly-fed electric machines in industry today are three-phase wound-rotor induction machines. Although their principles of operation have been known for decades, doubly-fed electric machines have only recently entered into common use. This is due almost exclusively to the advent of wind power technologies for electricity generation. The primary advantage of doubly-fed induction generators when used in wind turbines is that they allow the amplitude and frequency of their output voltages to be maintained at a constant value, no matter the speed of the wind blowing on the wind turbine rotor. Because of this, doubly-fed induction generators can be directly connected to the ac power network and remain synchronized at all times with the ac power network. Other advantages include the ability to control the power factor, while keeping the power electronics devices in the wind turbine at a moderate size. A more detailed picture of the DFIG system with a back-to-back converter can be seen in Fig.4. The back-to-back converter consists of two converters, i.e., machine-side converter and grid-side converter that are connected back-to-back. Between the two converters a dc-link capacitor is placed, as energy storage, in order to keep the voltage variations (or ripple) in the dc-link. With the machine-side converter it is possible to control the torque or the speed of the DFIG and also the power factor at the stator terminals, while the main objective for the grid-side converter is to keep the dc-link voltage constant.

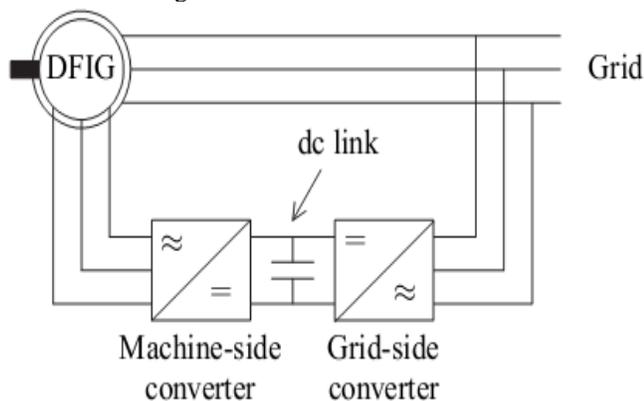


Fig.4. DFIG system with a back-to-back converter.

### V. OPERATING PRINCIPLE OF WOUND-ROTOR INDUCTION MACHINE

A wound-rotor induction machine can be operated as a doubly-fed induction machine (DFIM) when a power converter is present in its rotor circuit. This converter directs the power flow into and out of the rotor windings. Because the DFIM can operate as either a motor or a generator at sub-synchronous and super-synchronous speeds. When the machine runs above synchronous speed, this operation is termed super-synchronous operation. Similarly, operation below synchronous speed is called sub-synchronous operation. In both sub- and super-synchronous operation, the machine can be operated either as a motor or a generator. In the motoring mode of operation, the torque produced by the machine is positive. On the other hand, during generating operation, the machine needs mechanical torque as input; thus, the torque is negative during generating operation. So, basic concepts of slip and frequency is yields:

$$\begin{aligned} \text{Slip} = s &= \frac{\omega_s - \omega_m}{\omega_s} \\ &= \frac{n_s - n_m}{n_s} \\ n_s &= \frac{60f_s}{p} \text{ rpm} \\ n_m &= n_s (1-s) \\ \omega_m &= \omega_s (1-s) \end{aligned} \quad (1)$$

The induced rotor voltages have frequency of:

$$\begin{aligned} \omega_r &= \omega_s - \omega_m \\ s &= \frac{\omega_r}{\omega_s} \\ \omega_r &= s\omega_s \\ f_r &= sf_s \end{aligned} \quad (2)$$

Where,

- $n_s$  = synchronous speed of machines
- $f_s$  = stator frequency or supply frequency
- $p$  = number of pole pairs

Synchronous speed induces an emf in the rotor windings according to:

$$e_{\text{ind}} = (\bar{v} \times \bar{B}) \cdot \bar{L} \quad (3)$$

Where,

- $e_{\text{ind}}$  = induced emf in one conductor of rotor
- $v$  = velocity of conductor relative to stator flux rotation
- $B$  = stator magnetic flux density vector
- $L$  = length of conductor

**VI. POWER AND TORQUE EXPRESSION OF DFIG**

Power balance relation:

$$P_{mech} = P_s + P_r - P_{loss,s} - P_{loss,r} \tag{4}$$

Where,

$P_s$  and  $P_r$  are powers entering the machine through stator and rotor windings,  $P_{loss,s}$  and  $P_{loss,r}$  are the stator and rotor winding losses

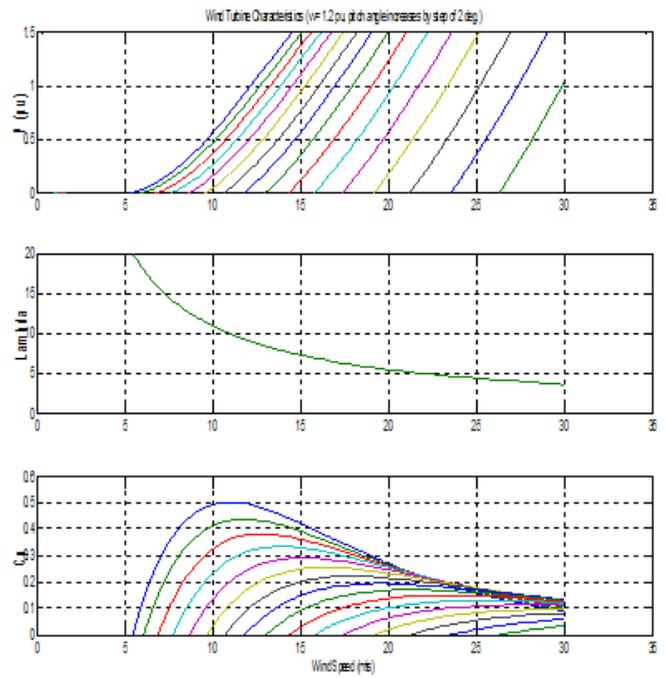
$$\begin{aligned} P_{mech} &= 3|I_r|^2 (R_{eq}) - 3\text{Re}\{V_{eq} I_r^*\} \\ &= 3|I_r|^2 \left(\frac{R_r(1-s)}{s}\right) - 3\text{Re}\left\{V_r \left(\frac{1-s}{s}\right) I_r^*\right\} \\ &= 3|I_r|^2 \left(\frac{R_s(1-s)}{s}\right) - 3\left(\frac{1-s}{s}\right) \text{Re}\{V_r I_r^*\} \end{aligned} \tag{5}$$

Since,

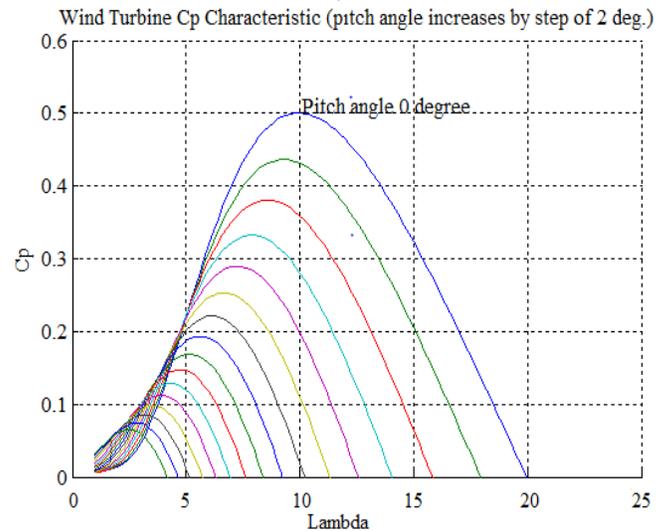
$$\begin{aligned} P_{mech} &= T_{em} \omega_m \\ &= T_{em} \frac{\omega_m}{p} \\ T_{em} &= P_{mech} \frac{p}{\omega_m} \\ &= 3 \frac{p}{\omega_m} |I_r|^2 \left(\frac{R_r(1-s)}{s}\right) - 3 \frac{p}{\omega_m} \text{Re}\left\{V_r \left(\frac{1-s}{s}\right) I_r^*\right\} \\ T_{em} &= 3 \frac{p}{\omega_m} |I_r|^2 \left(\frac{R_r \omega_m}{\omega_r}\right) - 3 \frac{p}{\omega_m} \left(\frac{\omega_m}{\omega_r}\right) \text{Re}\{V_r I_r^*\} \\ &= \frac{3p|I_r|^2 R_r}{\omega_r} - \frac{3p}{\omega_r} \text{Re}\{V_r I_r^*\} \\ &= \frac{3p|I_r|^2 R_r}{\omega_r} - \frac{3p}{\omega_r} V_r I_r \cos(\phi_v - \phi_i) \end{aligned} \tag{6}$$

**VII. CHARACTERISTIC OF DFIG IN SIMULINK**

The characteristics of DFIG model is shown in Fig.5 and Fig.6. There are three axes in Fig.5. The first axis illustrates the power output in per unit versus wind speed in meter per second. Since the cut in wind speed is 5 m/s and cut out wind speed is 30 m/s, the curves are drawn for power versus wind speed with pitch angle increased by step of two degree. The second axis is described Lambda versus wind speed. As shown in Fig.5, Lambda value is decreased as the wind speed increased. The last axis is displayed the Power Coefficient (Cp) versus wind speed. In this axis, the power coefficient is expressed for various pitch angles as in first axis. Since the designed rated wind speed of built in DFIG is 11 m/s, the power coefficient is maximum at this wind speed. Fig.6. is illustrated the detail characteristics of power coefficient versus wind speed.



**Fig.5. Characteristics of DFIG.**



**Fig.6. Detail Characteristics of Power Coefficient versus Wind Speed.**

**VIII. CONCLUSION**

Various wind turbine systems with different generators and power electronic converters have been described. Different types of wind turbine systems will have quite different performances and controllability, which was discussed with some results from study examples. The wind farms with different turbines may need different configurations for best use of the technical merits; therefore, electrical topologies of wind farms with different wind turbines have been briefed. In general, the connection of DFIG improve the stability of the system and the load voltage. Wind power generation with DFIG provides better performance for terminal voltage recovery after the load connects suddenly.

## Basic Concepts of Doubly Fed Induction Generator Driven by Wind Energy Conversion System

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