Conference Paper

Performance of Control Dynamics of Wind Turbine Based on Doubly Fed Induction Generator under Different Modes of Speed Operation

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There are many solar power and wind stations installed in the power system for environmental and economic reasons. In fact, wind energy is inexpensive and the safest among all sources of renewable energy, it has been recognized that variable speed wind turbine based on the doubly fed induction generator is the most effective with less cost and high power yield. Therefore, this paper has chosen doubly fed induction generator for a comprehensive study of modeling, analyzing, and control. DFIG in wind turbine has to operate below and above the synchronous speed, which requires smooth transition mode change for reliable operation, specially, close to synchronous speed where the DFIGWT instability starts to appear. Furthermore, its output electric power has to be controlled to provide stability for the power system; hence its performance depends on the generator itself and the converter operation and control system. This paper presents completed mathematical model of DFIG with its AC/DC/AC converter driven by DC machine. A new vector control technique is designed and modeled, which allows to evaluate the dynamic performance of the controller under (below, above, and through synchronous speed). The simulation results demonstrate the accuracy and high performance of the new control system of DFIG for wind turbine, which provides smooth transition mode without using any extra circuit.

1. Introduction

The electric power generation using wind farms is subject to considerable attention in the world due to the increase of electricity demand and consumption, which led to the depletion of existing energy sources such as fossil fuels, coal, and oil. Furthermore, there are many countries unable to generate hydroelectric power or nuclear energy. Indeed, wind power is environmentally and economically acceptable and the safest source among renewable energy sources [1]. Large wind turbines can be operated at a constant speed or variable speed using different types of generators that can be either directly connected to the network or connected through a power electronic converter.

In recent years more development has been carried out to improve the performance of variable speed wind turbines

to overcome the problem of the necessity to operate above, below, and through synchronous speed; as the result of this development the wind energy industry ended up with doubly-fed induction generator wind turbine (DFIGWT), which is the most efficient generator in wind energy conversion system so far. In fact, DFIG it is one of the most important generators in high-power applications; it is a form of three-phase asynchronous machine with its rotor windings also connected to the grid through the power electronic converter [2]. Indeed, DFIG offers a number of features when it is compared with other generators: its ability to operate at ($\pm 30\%$) of synchronous speed, its converter has only to handle rotor circuit power, high efficiency, maximum power extracted, and independent control of active and reactive powers. On other hand, DFIG has some disadvantages such as its sensitivity to unbalanced fault condition which can

heat the stator winding hence reduce the machine lifetime. Furthermore limited rang speed, control complicity, and the cost of maintenance due to the slip rings assembly [3], are among its disadvantages.

In general, the control system of active and reactive powers of DFIG is achieved by controlling the injected rotor currents, using each of d - q rotor currents to regulate the active and reactive powers independently of each other. In fact, vector control technique is the most effective control system; it is used for both rotor-side and grid-side inverters using either stator voltage- or stator flux-orientated frames [4]. The control dynamic performance of DFIGWT is not only based on the induction generator but also on the power electronic converter and its control system. However, modern DFIGWTs are designed with self-commutated back-to-back voltage source inverters also called AD/DC/AC converter. The converter rate depends on the rotor circuit power allowing the machine to operate in sub- and supersynchronous speed and even at synchronous speed [5]. It has been shown in different papers that the instability of the DFIG wind turbine system appears closely to the synchronous speed; this is due to the reduction of the rotor voltages and frequency when the slip is small. To overcome this situation some people have used battery storage linked to DC/DC converter in order to fix the dc link voltage. This paper deals with DFIG control system for wind turbine applications; it investigates the dynamics performance of DFIGWT under different speed operations (subsynchronous, synchronous and supersynchronous speed). the wind turbine is modeled using Matlab/Simulink. The vector control system based on stator voltage-oriented frame is designed and modeled. The stated state and transient models are used.

2. Wind Conversion System Description

The wind turbines with doubly fed induction generator have long been the preferred choice for wind farms due to their noticeable features such as adjustable speed operation, reduced noise and mechanical stress, and high power quality and performance. Figure 1 shows the phase diagram of modern DFIGWT; the turbine consists of fixed three blades on rotor turbine, which are coupled to the rotor of three-phase wound rotor induction generator via a gearbox to allow a different level of speed between the two rotors [6, 7].

As the variable speed operation existed, this means that variable frequency also existed. Therefore, the power electronic converter must be used to link the variable frequency with grid frequency. The three-phase stator windings of the generator are directly connected to the infinity bus voltage and the rotor three-phase windings are also connected to the same infinity bus voltage but through AC/DC/AC converter; it is basically a back-to-back inverter, which is represented as rotor-side and grid-side converters; both inverters are based on forced commuted IGBTs. The capacitor is used to link the DC side of both inverters and acts as a DC voltage source; the inductor line is needed to connect the converter with the grid [8]. The captured wind by the blades of the turbine is converted to mechanical power based on the aerodynamic theory; this mechanical power is transmitted to

the generator, which converts it to electrical power and then transfers it to the grid. The power flow from the generator to the grid has two paths: either the stator windings or the rotor windings through the converter. The direction of the power flow depends on the generator operation speed wither above or below synchronous speed as shown in Figure 2. While the generator operates in supersynchronous speed, the rotor power flows towards the electrical grid, whereas in subsynchronous speed the power flows from the grid to the rotor windings [9]. The control system of DFIGWT has to generate two commanded signals in order to control the electrical power flow between the turbine and the power system. The first controlled signal for the rotor-side inverter to regulate the active and reactive powers; the second controlled signal for the grid-side inverter in order to keep the DC-like constant [10].

3. Dynamic Model of DFIG in Excitation Frame

A typical d - q model of the doubly-fed induction generator in the excitation frame is illustrated in a detailed diagram in Figure 3. Traditionally, it is a three-phase asynchronous machine model but the three phase rotor voltages are considered due to connecting the slip rings to the grid through bidirectional converter [9].

It can be seen that the Park transformation is used in order to link the three-phase stator and rotor voltages to d - q generator model. The starting point to build the model is the mathematical equations of wound rotor induction machine, in which the steady state and transient responses are taken into account; these equations are expressed using the sink convention, which means that the values with (+) sign go in the machine and with (-) sign go out of the machine. The following section represents the stator and rotor equations of d - q equivalent circuits of DFIG.

The equations of stator voltages and flux linkage are as follows:

$$\begin{aligned} V_{ds}^e &= R_s I_{ds}^e + \frac{d}{dt} \psi_{ds}^e - \omega_e \psi_{qs}^e, \\ V_{qs}^e &= R_s I_{qs}^e + \frac{d}{dt} \psi_{qs}^e - \omega_e \psi_{ds}^e, \end{aligned} \quad (1)$$

where $\psi_{ds}^e = L_s I_{ds}^e + L_m I_{dr}^e$ and $\psi_{qs}^e = L_s I_{qs}^e + L_m I_{qr}^e$.

The equations of rotor voltages and flux linkage are as follows:

$$\begin{aligned} V_{dr}^e &= R_r I_{dr}^e + \frac{d}{dt} \psi_{dr}^e - (\omega_e - \omega_r) \psi_{qr}^e, \\ V_{qr}^e &= R_r I_{qr}^e + \frac{d}{dt} \psi_{qr}^e + (\omega_e - \omega_r) \psi_{dr}^e, \end{aligned} \quad (2)$$

where $\psi_{dr}^e = L_r I_{dr}^e + L_m I_{ds}^e$ and $\psi_{qr}^e = L_r I_{qr}^e + L_m I_{qs}^e$.

The torque generation in DFIG depends on the misalignment fields of the stator and rotor flux; hence the electromagnetic torque can be expressed using stator or rotor d - q flux:

$$T_{em} = \frac{3}{2} \left(\frac{P}{2} \right) (\psi_d I_q - \psi_q I_d). \quad (3)$$

FIGURE 1: The phase diagram of wind turbine with DFIG.

FIGURE 2: DRG power flow.

FIGURE 3: Detailed diagram of DFIG model.

And the power flows in the rotor and stator circuits are as follows:

$$\begin{aligned}
 P_s &= \frac{3}{2} (V_{ds} I_{ds} + V_{qs} I_{qs}), \\
 Q_s &= \frac{3}{2} (V_{qs} I_{ds} - V_{ds} I_{qs}), \\
 P_r &= \frac{3}{2} (V_{dr} I_{dr} + V_{qr} I_{qr}), \\
 Q_r &= \frac{3}{2} (V_{qr} I_{dr} - V_{dr} I_{qr}).
 \end{aligned} \tag{4}$$

FIGURE 4: AC/DC/AC converter for DFIGWT.

4. PWM AC/DC/AC Converter Model

To modify three-phase wound rotor induction machine to be used as DFIG the power electronic converter is required; it connects the rotor circuit to the grid that allows isolated feeding of the stator circuit. There are a number of converter topologies used but PWM voltage source inverters linked back to back by dc capacitor have long been an appropriate choice for variable speed DFIG [11, 12].

In fact, using this arrangement offers a number of features; it allows variable speed operation below, above, and through synchronous speed, allows to import and export electric power between the rotor and the grid, and allows independent control of active and reactive powers. Figure 4 shows typical AC/DC/AC converter; it uses IGBTs devices in both inverters that offer high control switching; the left-side inverter is connected to the rotor circuit via slip rings and it

FIGURE 5: Grid filter model in AC/DC/AC converter.

is known as a rotor-side converter (RSC), whereas the right-side inverter is connected to the grid and it is known as a grid-side converter (GSC). However, this paper uses the converter average model, in which the modulation index is considered as a unity mode. Therefore, the injected three-phase rotor voltage and converter voltage are directly proportional to the controllers output voltages. For simplicity the switching loss is ignored; hence dc model is based on the converter power balance, in which the capacitor charging power should be equal to the capacitor discharging power in either the power flow towards the machine or towards the grid so the dc-link voltage can be calculated as follows:

$$\begin{aligned} P_{ch} &= I_{ch} V_{dc} \quad \text{so} \quad I_{ch} = \frac{P_{ch}}{V_{dc}}, \\ P_{dis} &= I_{dis} V_{dc} \quad \text{so} \quad I_{dis} = \frac{P_{dis}}{V_{dc}}. \end{aligned} \quad (5)$$

Dc-link voltage is

$$V_{dc} = \frac{1}{c} \int \frac{P_{ch}}{V_{dc}} - \frac{P_{dis}}{V_{dc}} dt. \quad (6)$$

For simulation purpose the RL filter is connected to the grid-side converter as shown in Figure 5 in order to calculate the converter current as well as to synchronize it with stator current. The voltages crossing the inductors and resistances can be calculated as follows:

$$\begin{bmatrix} V_a \\ V_b \\ V_c \end{bmatrix} = R \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} i_a \\ i_b \\ i_c \end{bmatrix} + \begin{bmatrix} V_{a1} \\ V_{b1} \\ V_{c1} \end{bmatrix}. \quad (7)$$

The previous equation can be rewritten in d - q reference frame in order to be easy to calculate and control the power of the grid using converter currents [13]:

$$\begin{bmatrix} V_d \\ V_q \end{bmatrix} = R \begin{bmatrix} i_d \\ i_q \end{bmatrix} + L \frac{d}{dt} \begin{bmatrix} i_d \\ i_q \end{bmatrix} + \omega_s L \begin{bmatrix} -i_q \\ i_d \end{bmatrix} + \begin{bmatrix} V_{d1} \\ V_{q1} \end{bmatrix}. \quad (8)$$

5. Vector Control System Design in Stator Voltage-Oriented Frame (SVOF)

The dynamic performance of variable speed DFIGWT is highly dependent on the performance of the induction generator and accuracy of the control system. The controller is designed to regulate the power flow between the turbine and the power system. In fact, the active power is controlled in order to extract maximum power under different conditions

of wind speed; the reactive power is controlled in order to improve the stability of the grid by getting the desired power factor.

Figure 6 illustrates the whole control system of DFIG wind turbine; it can be recognized that there are three controllers which participate: pitch angle controller that controls the speed of rotor blades by controlling their angle of facing wind to follow the maximum power tracking characteristic, rotor-side controller that regulates the stator apparent power by controlling the rotor currents via PWM voltage source inverter at the machine side, and the grid-side controller that keeps the dc-link voltage constant and regulates the reactive power of the grid-side converter; this can be done by controlling the inverter currents. The control mechanism is based on PI feedback control, which increases the system robustness and reliability. Nonetheless, this work ignores the pitch angle control system because the DFIG is driven by DC machine instead of wind turbine; it just concentrates on control of power flow. Therefore, both rotor-side and grid-side controls have been presented and implemented using Matlab/Simulink, the following sections explain vector control technique using SVOF.

5.1. Rotor-Side Converter Controller. Control system of the rotor-side converter is designed to control the power flow between the stator and the infinity bus voltage; it requires measurements of three-phase stator voltage, stator current, rotor current, and rotor position. In general, the rotor-side controller consists of two closed-loop control as shown in Figure 7. In fact, the outer loop control (power control) computes the rotor current reference using the error of comparing the actual and reference powers:

$$\begin{aligned} i_{dr}^{e\#} &= PI(P_{ref} - P_{act}), \\ i_{qr}^{e\#} &= PI(Q_{ref} - Q_{act}), \end{aligned} \quad (9)$$

while in the inner loop (rotor current control) the actual rotor current is compared with the reference value in order to generate the rotor demanded voltages:

$$\begin{aligned} V_{dr}^{e\#} &= PI(i_{dr}^{e\#} - i_{dr}^e), \\ V_{qr}^{e\#} &= PI(i_{qr}^{e\#} - i_{qr}^e). \end{aligned} \quad (10)$$

However, in this paper the outer loop control is replaced by a mathematical model to calculate the rotor current references from power reference using steady-state equations. In the voltage orientation frame, the stator voltage vector is aligned along with d -axis of the excitation reference frame as shown in Figure 8. Assuming that the stator applied voltage is not varying and the voltage drop on stator resistance is small, hence d -axis of stator voltage is constant and equal to stator voltage vector and the q -axis is zero. Hence in SVOF the equations of the stator active and reactive powers can be rewritten as a function of rotor current, in which the real

FIGURE 6: Control system of wind turbine.

power becomes affected directly by the d -axis rotor current and the reactive power by the q -axis rotor current:

$$\begin{aligned} P_s &= \frac{3}{2} V_{ds}^e \quad i_{ds}^e = \frac{3}{2} V_{ds}^e \left(\frac{-L_m}{L_s} i_{dr}^e \right), \\ Q_s &= -\frac{3}{2} V_{ds}^e \quad i_{qs}^e = -\frac{3}{2} V_{ds}^e \left(\frac{\psi_{qs}^e}{L_s} - \frac{L_m}{L_s} i_{qr}^e \right). \end{aligned} \quad (11)$$

5.2. Grid-Side Converter Control. The controller of the grid-side converter control has to balance the active power exchanged between the rotor circuit and power system by controlling the dc-link voltage. As the reactive power flow between the RSC and GSC is decoupled due to exciting of the dc-link, hence the reactive power inverter of the grid side can be controlled independently. Similar to the control system of the rotor-side converter, the vector control technique requires the instant values of the dc-link voltage, three-phase converter currents, and three-phase stator voltages.

A typical two-stage feedback control for GSC is shown in Figure 9. The outer loop control keeps dc-link voltage constant by producing demanded d - q converter currents, which generates the demanded converter voltages. The feed forward term helps the controller to act fast with step change and improve the response of the demanded GSC voltages:

$$\begin{aligned} i_{dgc}^{e\#} &= PI(V_{dc}^{\#} - V_{dc}), \\ i_{qgc}^{e\#} &= PI(Q_{gc}^{\#} - Q_{gc}), \\ V_{dgc}^{e\#} &= PI(i_{dgc}^{e\#} - i_{dgc}^e) + (\omega_e L i_{qc}^e + V_{ds}^e), \\ V_{qgc}^{e\#} &= PI(i_{qgc}^{e\#} - i_{qgc}^e) - (\omega_e L i_{dc}^e). \end{aligned} \quad (12)$$

6. Control Dynamics under Different Speed Operations

Variable speed wind turbine is one of the most common applications for doubly fed induction generator, for this reason the DFIG has to operate at different wind speeds; it can be above or under and even at the synchronous speed but within a limited range ($\pm 30\%$ of synchronous speed). Practically, the three-phase wound rotor induction machine is unable to generate electric power below synchronous speed because a motoring torque is produced. However, in case of DFIG this torque can be used by regulating the injected voltages in the rotor circuit, in which they must be correctly controlled to obtain reliable and constant transient operation during mode changes. Therefore, the rotor-side control plays important role to provide system stability and provide smooth transition mode. Therefore, this paper presents the control dynamic of DFIG in three different modes of speed operation with high stability and liner transition response using vector control technique. The time simulation is three seconds; each second presents one mode as shown in Figure 10. At starting the reference speed is set at 800 r.p.m that illustrates subsynchronous mode, then at $t = 1$ s the rotor speed is changed to 1000 r.p.m to equalize the machine synchronous speed, after that at $t = 2$ s the rotor speed is increased to 1200 r.p.m to create supersynchronous mode.

6.1. DFIG Active and Reactive Powers Flow. The states of the active and reactive powers flow during the three modes are presented in Figure 11. The positive power indicates that the power goes towards the machine, whereas the negative value indicates that it goes towards the grid. However, the stator active power reference is set at -7500 W while the reactive power is set at zero through all simulation time. From Figure 11(a) while the rotor speed is changed from one region to another, it is clear that after the initial transient state

FIGURE 11: DFIG power flow under sub- and supersynchronous speeds.

FIGURE 12: Controlled rotor-converter and grid-converter voltages.

FIGURE 13: Controlled RSC and GSC voltage vectors positions.

and effective in wind energy conversion systems. It has been seen that the direction of the rotor power can be controlled using rotor voltages in order to allow the DFIG to generate electric energy below and at the synchronous speed, where the induction generators are usually not used to generate electricity in these modes. In fact, under synchronous mode the generator has to excite its rotor circuit by using part of the stator power through the bidirectional back-to-back converter, while under the synchronous speed the DFIG is transferred to the synchronous generator that only needs dc

FIGURE 14: Three-phase stator and rotor voltages and currents.

FIGURE 15: Transmitted active and reactive powers between DFIGWT and the grid.

current in the rotor circuit. Therefore, the two VSCs of the machine side and grid side are adjusted to operate once as a rectifier and once as an inverter depending on the direction of the power flow; this is done by the control system ability to change the phase sequence of the rotor voltages. Indeed, the results illustrate that the system of DFIG with designed vector control technique is performed very well during the transition from mode to another; it offers the high dynamic performance and smooth transition response without using any extra circuit.

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