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Study of Stabilty Analysis of a Grid Connected Doubly Fed Induction Generator Based on Wind Energy Application

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Abstract

The present paper formulates the state space modeling of doubly fed induction generator (DFIG) based wind turbine system for the purpose of the stability analysis. The objective of this study is to discuss the various modes of operation of the DFIG system under different operating conditions such as voltage sags with reference to variable wind speed and grid connection. The proposed control methodology exploits the potential of the DFIG scheme to avoid that grid voltage unbalances compromise the machine operation, and to compensate voltage unbalances at the point of common coupling (PCC), preventing adverse effects on loads connected next to the PCC. This methodology uses the rotor side converter (RSC) to control the stator current injected through the machine and the GSC to control the stator voltage to minimize the electromagnetic torque oscillations. The proposed control methodology is validated by simulation results.

***Keywords**: doubly fed induction generator, wind energy conversion, nonlinear stability, power system control*

1. Introduction

In recent years, wind energy has witnessed a large surge in research and development. The drawback of wind energy is that electrical energy is obtained only when the wind blows. Although in modern wind turbines, power can be regulated and stabilized at their rated capacity but the power generated by them varies during the whole day. To accommodate the change in wind generation, many installations have established for utility system, as they change their output to accomplish the demand. Before taking reliability of a system as an issue, it’s been predicted that wind energy can fulfill up to 30% of the present energy demand. Atmospheric air’s energy is used to generate kinetic energy. Generation of kinetic energy is done by utilizing the atmospheric air’s energy. Wind energy had been used for centuries to perform many different functions such as grain grinding, sailing and for irrigation purposes. The main function of wind power system is conversion of kinetic energy present in the wind into various sources of power. In ancient times, milling and irrigation were also done by wind power systems. During the twentieth century, wind power started to generate electricity. Similarly, windmills were used in several countries to pump water from the ground. Wind turbines can be used as a single unit as well as in groups (also known as wind farms). Wind turbines, which are smaller in size are also called as aero generators. These can be used for charging large sized batteries. Five countries in the world have greater than 80% of the installed global wind energy capacity, among them India is at the 5th position [1].

For a variable speed turbine can be improved by 2-6% output power as compared to a fixed speed turbine. According to the condition of site and design consideration of the variable-speed turbine may fluctuate by 3-28% as compared to the fixed-speed [2-4]. The energy capture is enhanced by 20% in case of doubly fed induction generator (DFIG) when compared to variable speed turbine using a cage bar induction machine and by nearly 60% from the fixed speed system. As the assumptions used while performing the study of DFIG varies vastly from one person to another, therefore, the results may also vary accordingly. The controlling of DFIG is far more tedious than controlling any other machine. The rotor current in the DFIG is controlled by power converters. It is controlled by using vector control techniques. Till date,

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various vector control techniques have been suggested for the controlling of DFIG. The stator flux orientation can be used to control the rotor currents according to the system parameters [4, 5] According to the eigenvalues of the DFIG are poorly damped having a corresponding natural frequency close to the line frequency.

In the past, as the penetration of wind power was very low, the wind turbine connection requirements were focused mainly on the turbine protection and, in case of disturbances, the wind turbines were simply disconnected from the grid. This scenario has changed and, currently, wind turbines should remain connected during system disturbances and, in some cases, wind turbines are required to actively support the grid. Among the possible disturbances, voltage unbalance is responsible for a poor wind generator performance and it is an important cause of partial or total disconnection of wind parks [6-8]. As a consequence, some strategies for the operation of wind turbines under unbalanced voltage conditions have already been proposed and are still evolving towards an effective solution.

Among current techniques used to convert wind energy, the DFIG and one of the mainly used in recent years due to its flexible operation. When this induction generator is concerned with a small disturbance in the grid voltage, stator and rotor current is highly disturbed [9, 10]. These unbalanced current are responsible for oscillations in the torque of the machine. Analyzed by the grid operation, when machine operation is unstable due to its inequitable the grid voltage [11, 12].

The improved awareness of individuals towards renewable energy support from governmental establishments and speedy advancement within power industries, which form the core of wind power generation systems, are the foremost contributing factors for its expansion. As a result, the share of wind power generation with respect to total installed power capacity is increasing worldwide. Particularly, grid-connected wind generation system plays an important role in the development [13]. As the use of wind turbine is increasing, the wind turbine is required to remain connected during the fault and contribute to the stability of the system. The variable speed system, which utilizes wind energy, is the main type of grid-connected wind generation system. Different PI controllers installed in the studied power system model of the present work requires optimal tuning for proper functioning of the model. Recently, computational intelligence based algorithms have been applied to different fields of power engineering applications.

2. Mathematical Modeling of DFIG

DFIG model represents a complete system of four equations; the d-q synchronous reference frame is considering the variables of the induction machine. The equation for stator and rotor windings with torque equations can be given in (1)-(4) as follows:

$$u_{ds} = r_s i_{ds} - \omega_s \lambda_{qs} + \dot{\lambda}_{ds} \tag{1}$$

$$u_{qs} = r_s i_{qs} + \omega_s \lambda_{ds} + \dot{\lambda}_{qs} \tag{2}$$

$$u_{dr} = r_r i_s - (\omega_s - p\omega_r)\lambda_{qr} + \dot{\lambda}_{dr} \tag{3}$$

$$u_{qr} = r_r i_s + (\omega_s - p\omega_r)\lambda_{dr} + \dot{\lambda}_{qr} \tag{4}$$

The equation of flux can be described in d-q reference frame as follows:

$$\lambda_{ds} = l_s i_{ds} + l_m i_{dr} \tag{5}$$

$$\lambda_{dr} = l_r i_{dr} + l_m i_{ds} \tag{6}$$

$$\lambda_{qs} = l_s i_{qs} + l_m i_{qr} \tag{7}$$

$$\lambda_{qr} = l_r i_{qr} + l_m i_{qs} \tag{8}$$

In these equations; u_{ds}, u_{qs}, u_{dr}, u_{qr} : d and q axis voltages of stator and rotor, i_{ds}, i_{qs}, i_{dr}, i_{qr} : d and q axis of currents of stator and rotor, λ_{ds}, λ_{qs}, λ_{dr}, λ_{qr} : d and q axis magnetic fluxes of stator and rotor, ω_s : angular speed of stator, s: slip r_s and r_r : resistance of stator and rotor, l_s and l_r : inductance of stator and rotor, l_m : magnetic inductance, P_s, Q_s, P_r, Q_r active and reactive power of stator and rotor respectively.

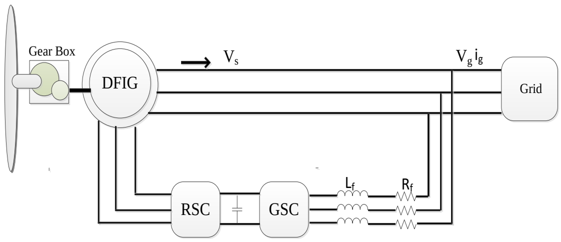

Figure 1. Schematic Diagram of Wind Energy based on DFIG System

Through (1)-(8), the following nonlinear dynamic model can be acquired for the DFIG.

$$\frac{d}{dt} i_{ds} = g_1 i_{ds} + g_2 i_{qs} + g_3 i_{dr} + g_4 i_{qr} + g_5 \omega_r - g_6 V_{dr} + u_{ds} \tag{9}$$

$$\frac{d}{dt} i_{qs} = -g_2 i_{ds} - g_1 i_{qs} - g_4 i_{dr} + g_3 i_{qr} - g_5 \omega_r - g_6 V_{qr} + u_{qs} \tag{10}$$

$$\frac{d}{dt} i_{qr} = g_7 i_{ds} + g_1 i_{qs} - g_8 i_{dr} - g_3 i_{qr} + g_9 \omega_r + g_{10} V_{qr} - u_{qs} \tag{11}$$

$$\frac{d}{dt} i_{dr} = g_1 i_{ds} - g_7 i_{qs} - g_3 i_{dr} + g_8 i_{qr} - g_9 \omega_r + g_{10} V_{dr} - u_{ds} \tag{12}$$

$$\frac{d}{dt} \omega_r = -g_{11} i_{qr} + g_{11} i_{dr} - g_{12} \omega_r - T_m \tag{13}$$

Where, $g_1 = \frac{r_s}{\sigma l_s}$, $g_2 = \omega_s l_s$ $g_3 = \frac{r_r l_m}{\sigma l_s l_r}$, $g_4 = \frac{p\omega_r l_m}{\sigma l_s}$, $g_5 = \frac{p l_m^2 i_{qs}}{\sigma l_s l_r}$, $g_6 = \frac{l_m}{l_r}$, $g_1 = \frac{r_s}{\sigma l_s}$, $g_7 = \frac{p\omega_r l_s}{\sigma l_s}$
$g_3 = \frac{r_r l_m}{\sigma l_s l_r}$, $g_8 = \frac{\omega_s l_r}{l_s}$, $g_9 = \frac{p l_r l_s i_{dr}}{\sigma l_s l_m}$, $g_{10} = \frac{l_s}{l_m}$, $g_{11} = \frac{3}{2}\frac{p l_m}{J}$, $g_{12} = \frac{b}{J}$

3. State Space Modelling of DFIG

The internal model control state-feedback approach is proposed in this paper in order to control the DFIG, which keeps the smooth control signal of the classical PI controller and, at the same time, provides robustness to external disturbances automatically, eliminating the need of feed-forward compensation.

As already discussed, for controlling the RSC and the GSC of the DFIG scheme, the variables are modeled in the positive and negative sequences and the control is performed independently for each sequence. The controls using the variables in the positive sequence have the objective to maintain the main functions of the DFIG, which are the active and reactive power output and the dc link voltage. The controls using the negative sequence of the variables are responsible for the negative sequence current injection and for minimizing the effect of the unbalanced currents in the machine torque. The dynamic model of the doubly fed induction generator is given in the (9-13) which is summarized as:

$$\dot{X} = AX + B_1U + B_2d \quad (14)$$

$$A = \begin{bmatrix} g_1 & g_2 & g_3 & g_4 & g_5 \\ g_2 & g_1 & g_4 & g_3 & g_5 \\ g_1 & g_7 & g_3 & g_8 & g_9 \\ g_7 & g_1 & g_8 & g_3 & g_9 \\ g_{11} & g_{11} & 0 & 0 & g_{12} \end{bmatrix}, \ B_1 = \begin{bmatrix} g_6 & 0 \\ 0 & g_6 \\ g_{10} & 0 \\ 0 & g_{10} \\ 0 & 0 \end{bmatrix}, \ U = \begin{bmatrix} V_{dr} \\ V_{qr} \end{bmatrix}, \ B_2 = \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ -1 & 0 & 0 \\ 0 & -1 & 0 \\ 0 & 0 & -1 \end{bmatrix}, \ d = \begin{bmatrix} u_{ds} \\ u_{qs} \\ T_m \end{bmatrix}$$

4. Wind Turbine Model

The captured mechanical power from a wind turbine is given as follows:

$$p_m = c_p(\lambda, \beta).\frac{1}{2}\rho A_1 v_\omega^3 \quad (15)$$

$$\lambda = \frac{r_{blade}.\omega_r}{v_\omega} \quad (16)$$

Where p_m denotes the mechanical output power (W) and it depends upon the performance coefficient, air density (ρ), turbine swept area (A) and wind speed υ_ω. In (12), the term $\frac{1}{2}\rho A_1 v_\omega^3$ denotes the kinetic energy contained in the wind at a particular speed and the term $c_p(\lambda, \beta)$ denotes the performance coefficient which depends on tip speed ratio (λ) and blade pitch angle (β). It decides how much of the kinetic energy of the wind can be captured by the wind turbine system. In (13), r_{blade} denotes the blade radius. A nonlinear model describes $c_p(\lambda, \beta)$ as given in:

$$c_p(\lambda, \beta) = c_1(c_2 - c_3\beta - c_4\beta - c_5)e^{c_6} \quad (17)$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \quad (18)$$

A typical wind turbine characteristic and turbine power attribute curve is depicted in Figure 2(a) which corresponds to the maximum energy to be captured from the wind. When speed of the induction generator is higher than the rated value, the location of the generator speed is set to the small value or rated value, respectively.

5. Voltage Oriented Control Techniques

In the case studied, where the Voltage oriented control method is used, the stator voltage is chosen in d-q synchronous reference frame, which means that $u_{ds} = 0$. The first two equations is using at steady state conditions and voltage oriented control is adopted, exactly hold the following equations:

$$r_s i_{ds} - \omega_s \lambda_{qs} = 0 \quad (19)$$

$$r_s i_{qs} + \omega_s \lambda_{ds} = u_{qs} \quad (20)$$

Rating of the induction machine in MW, it is valued at the range of stator resistance in $m\Omega$, while ω_s = $100\pi rad/\sec$.the stator flux q-axis component value very small in steady state condition, and stator flux d-axis component it hold that:

$$\lambda_{qs} = \frac{r_s}{\omega_s} i_{ds} \tag{21}$$

$$\lambda_{ds} = \frac{r_s i_{qs} - u_{qs}}{\omega_s} \tag{22}$$

$$\lambda_{ds} = \frac{u_{qs}}{\omega_s} \tag{23}$$

The nonlinear dynamic model of the DFIG wind turbine equation of electromagnetic torque model is given as follows:

$$T_e = -\frac{3}{2}\rho \frac{l_m}{l_s} \lambda_{ds} i_{qr} \tag{24}$$

6. Controllers' Design and Analysis

The rotor input v_{dr} is proposed for inner loop current for the DFIG.

$$v_{dr} = k_{pd}[i_{dr}^{ref} - i_{dr}] \tag{25}$$

Where the reference input i_{dr}^{ref} is selected to be zero for simplicity with no generality loss, the system damping is to determine at preferred level. k_{pd} is the proportional gain of the controller. The reference current i_{dr}^{ref} is then compared with i_{dr} and the obtained value is fed into the PI controller which changes it to v_{dr} as given in:

$$v_{qr} = k_{pq}[i_{qr}^{ref} - i_{qr}] \tag{26}$$

The reference input is present by the PI controller accountable for operation of maximum power points, as follows:

$$i_{qr}^{ref} = -k_p\omega_r + k_{i\omega}\int_0^t [\omega_r^{ref} - \omega_r]dt \tag{27}$$

All integral and proportional gain k_{pq} , $k_{p\omega}$, $k_{i\omega}$ are the positive scalars and ω_r^{ref} is given by.

7. Rotor Speed Control Design

Since the voltage oriented technique utilized outcomes in stator flux which is fairly constant, as shown in III-A, the electromagnetic torque expression (9) can be written as:

$$T_e = -\frac{3l_m}{2l_s}\rho\lambda_{ds} i_{qr} \tag{28}$$

And is rotor current directly depends on the *q*-axis component. The outer loop current controller to be lesser then inner loop, then once can considering $i_{qr} = i_{qr}^{ref}$ by using the time scale assumption. Thus, the simplified block diagram of Figure 2 is valid.

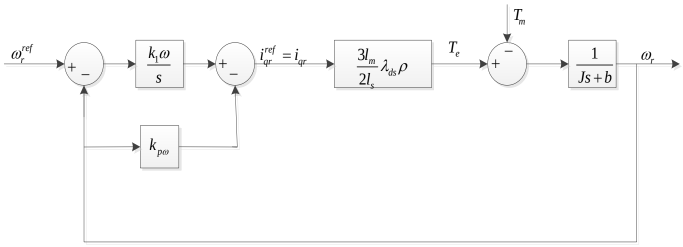

Figure 2. Control Block Diagram of Angular Speed

$$\frac{\omega_r}{\omega^{ref}_r} = \frac{\dfrac{3\rho l_m}{2Jl_s}\lambda_{ds}k_{i\omega}}{s^2 + \left[\dfrac{b}{J} + \dfrac{3\rho l_m}{2Jl_s}\lambda_{ds}k_{\rho\omega}\right]s + \left[\dfrac{3pl_m}{2Jl_s}\lambda_{ds}k_{i\omega}\right]} \tag{29}$$

As a disturbance of the mechanical torque T_m for a close loop system is obtained by the following transfer function.

$$\frac{\omega_r}{\omega_r^{ref}} = \frac{\omega_n^2}{s^2 + 2\zeta\omega_n s + \omega_n^2} \tag{30}$$

Where, $\omega_n^2 = \dfrac{3}{2}\dfrac{pl_m}{Jl_s}\lambda_{ds}k_{i\omega}$ and $2\zeta\omega_n = \dfrac{b}{J} + \dfrac{3\rho l_m}{2Jl_s}\lambda_{ds}k_{\rho\omega}$

Applying the 2% criterion [11], settling time of the desired T_s is associated to ζ and ω_n through $T_s = 4/\zeta\omega_n$. Also, for the desired damping factor *of* the outer-loop controller gains are calculated as:

$$k_{p\omega} = \frac{2J}{3p}\left[\frac{8}{T_s} - \frac{b}{J}\right]\frac{l_s}{l_m}\frac{1}{\lambda_{ds}} \tag{31}$$

$$k_{i\omega} = \frac{2Jl_s}{3}\frac{1}{\lambda_{ds}}\frac{16}{T_s^2\zeta_{ds}^2} \tag{32}$$

8. Simulation Results

The effects of DFIG on the behavior of power system when operated under different wind speed conditions is assessed through Figure 1. The strength of the transmission network also affects the dynamic performance of the power system. Therefore, the effect of strong and weak transmission network are studied with short circuit level of 20 MV A and 8 MV A, respectively. Matlab / Simulink are used to implement the model of the present work.

Moreover, wind is always varied from time to time, so due to uncertain wind conditions, we are considering a step change around in between 10 m/s to 12 m/s and can be easily visualized in Figure 2. The angular speed of the generator rotor versus its reference, ω_r clearly track the reference speed is depicted in Figure 3. The stator fluxes of the d-axis and q-axis components are presented. The d-axis component of the stator flux is almost constant but q-axis component of stator flux is nearly zero shown in Figure 4. The stator current is responsible for compensating the voltage unbalance at the PCC. Figure 5 shows, until 2s, the d-q component of the stator current caused by the unbalanced voltage at the stator terminal. After that, the RSC control injects a current in order to reduce the unbalance at the PCC. In this case the current reached the values of the 0.14 p.u. It is worth to mention that the line impedance value used in the simulation associated to the source were defined to need a current injection, which required the entire converters power capability. Figure 6 illustrates the voltage at the stator terminals. Rotor current is exactly the same of the PCC. The DFIG control induces a voltage, resulting in a stator voltage that eliminates the oscillations in the electromagnetic torque, even if the machine is injecting a current from its stator. According to Figure 6, the control was effective for all different angles of rotor current. The DFIG control changes the rotor voltage according to the injected current avoiding the increase of the oscillation in the electromagnetic torque.

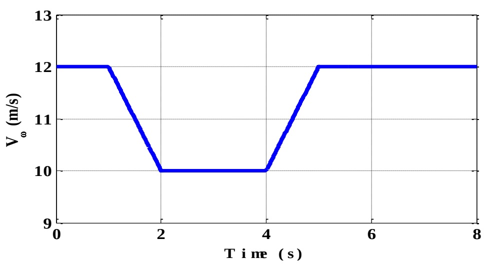

Figure 2. Wind Speed Versus Time

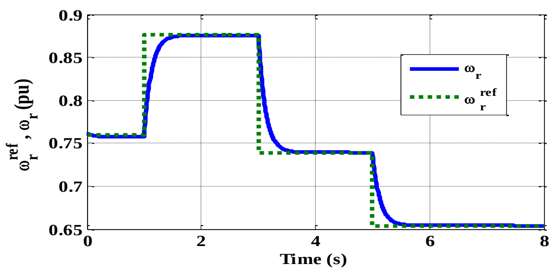

Figure 3. Angular Speed of Generator Vesus Time

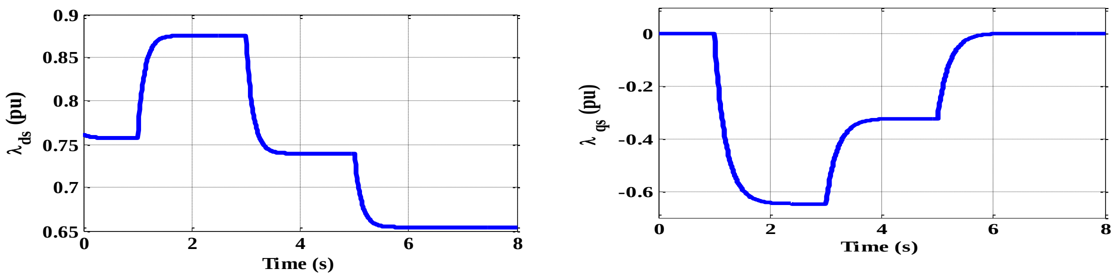

Figure 4. Stator Flux λ_{ds} And λ_{qs} Versus Time

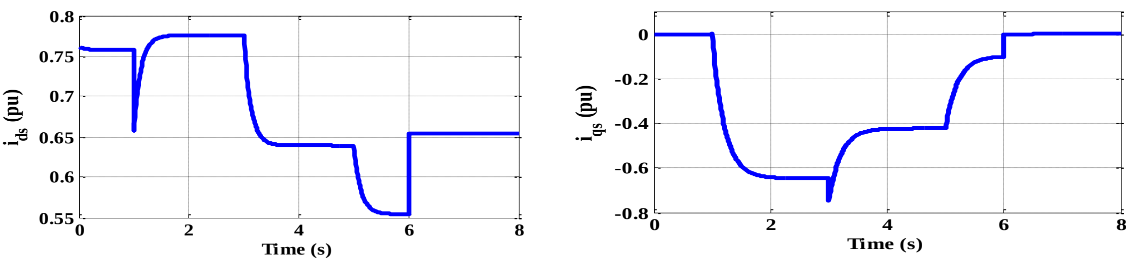

Figure 5. Stator Current i_{ds} And i_{qs} Versus Time

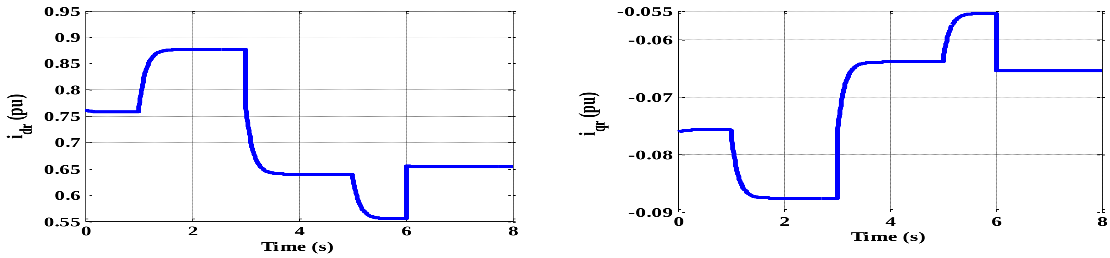

Figure 6. Rotor Current i_{dr} And i_{qr} Versus Time

9. Conculsion

Taking consideration of the restraints due to the limited nonrenewable energy sources and with the ever increasing demand of electricity, it has become an absolute necessity to integrate the wind power systems in the grid, for which a complete and detailed study of wind power generation models as well as the grid codes are required, in which simulation studies under various expected operating conditions are highly needed to prevent any harmful impact of the power system network to the grid where it is connected. In this paper, a dynamic model of DFIG and the controllers used with the reduced order illustration is presented which is helpful for the steady state as well as the transient stability analysis of the power system. It is, finally, observed that optimization of controller gains of the DFIG model by using linearization is much better technique for the studied power system model under different scenarios considered.

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Appendix

Table 1. 1,5 MW DFIG Wind Turbine Parameters

Symbol	Quantity	Values	Symbol	Quantity	Values
R_s	Stator Resistance	1.4 m Ω	R_f	Grid Filter Resistance	0.04 Ω
R_r	Rotor Resistance	0.99 m Ω	l_f	Grid Filter Inductance	0.001H
l_s	Stator Inductance	0.08998 mH	F	Frequency	50Hz
l_r	Rotor Inductance	0.08208 mH	P	Pole Pairs	3
l_m	Mutual Inductance	1.526 mH	V_ω	Wind Speed	12m/s