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Design and Simulation of Wind Energy Conversion System Synchronized with Electrical Grid Using DFIG

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Abstract**—**The aim of this paper is to show the modeling design and simulation of wind energy conversion system driven by doubly-fed induction generator that feeds ac power directly to the electrical grid. Doubly Fed Induction Generator (DFIG) is the basis on which the variable speed wind generation system works. The doubly fed Induction generator has its stator directly connected to the electrical grid. While DFIG has the rotor connected to the grid with the help of back-to back power converters which will reduce the harmonics that arises in the system voltage or current using the sinusoidal PWM technique. The Voltage Source Converters (VSC) are used for connecting the wind energy systems to the grid so that the variable speed operation should be possible. Early detection and isolation of the fault is very important in this context thus the protections of the whole system have paid much attention. For the control purposes of the system basically two power converters Rotor side converter and Grid side converter are used, which are known as back to back converters. The GSC (grid side converter) controls the flow of power between the DC bus and the AC side also allows the system to operate in sub-synchronous and super synchronous operational modes. This conversion system model has been designed and simulated in the MATLAB Simulink in a manner that response can be studied for different type of grid connections.

Keywords*- DFIG, VSC, Dc link, Pulse width modulation (PWM), Back to Back Converters,PLL.*

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I. INTRODUCTION

For independent operations mostly single induction generator or parallel operated induction generators works according to available studied references. The induction generator operated by the prime movers uses capacitor bank excitation to generate required voltage through self-excitation. Thus the magnitude of the output voltage and its frequency can be determined by the rotor speed and the capacitive bank excitation [1]. To feed the power to the load we need to control the voltage as well as the frequency. Single output and double output generators are the two types which are used for the grid connected operations. If the machine will run at a speed more than synchronous speed then only we will be able to feed the active power to the grid, the synchronous speed is referred to the rotating magnetic field of the generator, thus slip should be negative. In the single output generator active power can be supplied to the grid through stator only while in double output generators the active power can be supplied to the generator through the stator as well as the rotor connections. Thus the double output generators are also called static Kramer or double-fed induction generators [1]. The generator can generate more than the rated power without overheating, although this kind of power generation generally creates problems in the utility grid as it is very complicated to control the flow of active and reactive power between the generator and the grid. In wind power generations if turmoil in the wind occurs then the wind turbines are disconnected and resumed when normal operating conditions arrives thus wind turbines do not take part in control of voltage and frequency. Now wind power entrance is continually increasing thus major concerns are shifting to the power stability problems created by the wind turbine connections from the early power quality issue. Thus now it has become more important to understand the impact of wind power on the power system operation and planning.

In this paper we tried to develop a model of induction machine that can be simulated as doubly fed generating machine with testing control strategies. With this model we can develop an understanding for the power generation with different induction generator configurations and different kind of connections with the grid. The induction generator is modeled in the synchronous reference frame. At a given wind speed to maximize the power generation the speed is adjusted by the turbine pitch control method. Whole simulation model is developed for such generating systems under variable speed operation using MATLAB Simulink.

II. SUBSYSTEM MODELS

A. PLL Technique

PLL that is Phase – Locked Loop is a phase tracking algorithm extensively applied in the field of communication technology, PLL is able to provide the output signal which will be synchronized with its reference input in both phase and frequency and [2]. To extract the phase angle of the grid voltages the Phase – Locked Loop technique is used here.

The PLL is enforced in dq synchronous reference frame. This framework needs to correspond the transformation from abc to dq axis modeling and the reference should be settled to zero. A Proportional Integral controller is employed to manage the variable. This frame will provide much needed frequency of the grid and the grid voltage angle that will be used for proper interconnection of wind mill with the grid [2].

B. Pitch Controller

For each blade of the turbine there is a pitch control system. With sufficient damping to make the pitch chase a pre provided reference, each pitch control system is designed as a servo loop. For compensating the dead band and for providing limitations in the proportional valve a pitch controller is provided which is a non-linear controller. When the velocities of the wind velocities are more than the rated wind velocities, the maximum energy that has to be captured must be controlled by modifying blade pitch angle β that is using pitch control, the pitch angle can be adjusted till the machine can be set at the rated speed [3].

C. Wind Speed Model

To understand the behavior of wind we need to develop a model which shows the space effect of wind involving gusting, rapid and background noise component. This wind speed model can be expressed as the sum of these four components [2] listed above.

$$V_w(t) = V_b(t) + V_r(t) + V_g(t) + V_n(t) \qquad (1)$$

The components used are-

Vb= base component of or constant wind component,

Vr = ramp component of wind,

Vg = gust component of wind and

Vn = base noise component of wind.

All of them expressed in meter/second. Our present work considers a constant wind speed of 12 meter/second.

D. Wind Turbine Model

We have used here a horizontal axis wind turbine having three-bladed structure and design with the corresponding pitch controller. The mechanical output power that is available from a wind turbine can be shown through the following equations [4].

$$P_m = C_p(\lambda, \beta)\frac{\rho A V^3}{2} \qquad (2)$$

Components used are- ρ = air density, V = Wind Speed, Cp = power coefficient or Coefficient of Performance of the wind turbine, A = Area swept by the rotor blades of the wind turbine.

The Coefficient of Performance Cp is depends on the tip-speed ratio = **λ**, and blade pitch angle = **β** can expressed by given equation [2],

$$\lambda = \left(\frac{R\omega_m}{v}\right) \qquad (3)$$

Where, ωm = Angular speed of the turbine rotor,

R = Turbine blade Radius

Further the power coefficient Cp can be expressed as [3,5]

$$C_p(\lambda, \beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right) exp\left(\frac{-C_5}{\lambda_i}\right) + C_6\lambda \quad (4)$$

Where as

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \qquad (5)$$

The torque of the wind turbine can be calculated as

$$T = \frac{1}{2}C_t(\lambda, \beta)\rho A V^3 \qquad (6)$$

With, $C_t\ (\lambda, \beta)$ is called as the torque coefficient of wind turbine.

E. Drive Train Model

In this paper two mass drive train models are utilized. The equations providing the mechanical dynamics are presented as follows [6]

$$2H_t\frac{d\omega_t}{dt} = T_m - T_{sh} \qquad (7)$$

$$\frac{1}{\omega_{elb}}\frac{d\theta_{tw}}{dt} = \omega_t - \omega_r \qquad (8)$$

$$2H_g\frac{d\omega_r}{dt} = T_{sh} - T_g \qquad (9)$$

Where, Ht = inertia constant of the turbine,

Hg = inertia constant of the generator,

θtw = shaft twist angle,

ωt = per unit angular speed of the wind turbine,

ωr = per unit rotor speed of the generator,

ωelb = electrical base speed, and

Tsh = shaft torque

Shaft Torque is expresses as [7],

$$T_{sh} = K_{sh}\theta_{tw} + D_t\frac{d\theta_{tw}}{dt} \qquad (10)$$

Where, Ksh = shaft stiffness and

Dt = damping coefficient.

III. MODELING OF DOUBLY FED INDUCTION GENERATOR

The wind turbine and the doubly-fed induction generator are shown in Figure 1.

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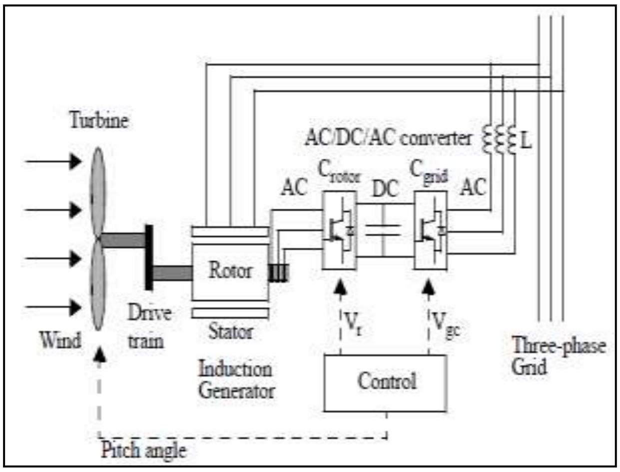

Figure.1. Wind Turbine with DFIG Sysytem

In the Following Figure1 the AC/DC/AC converter is separated into rotor side and grid side components [8]. As Crotor - the rotor-side converter and the grid-side converter – Cgrid. Crotor and Cgrid converters are Voltage-Sourced converters; to synthesize an AC voltage from a DC voltage source they enforced IGBTs as forced-commutated power electronic devices. As a DC voltage source a capacitor is connected on the DC side. From the figure to connect Cgrid to the grid a coupling inductor L is used. Slip rings and brushes are utilized to connect the Crotor with the three-phase rotor winding and the three-phase stator winding is directly connected with the grid [8]. By the help of induction generator the wind power trapped by the turbine is converted into electrical power and further by the rotor and the stator windings it is transmitted to the grid. For controlling the DC bus voltage, the voltage at the grid terminals and power of the wind turbine the control system triggers the following commands 1.pitch angle command 2.voltage command signals Vr and Vgc for rotor side converter and grid side converter. A controlled current source is used to simulate the DC bus, this source is feeding the DC capacitor. Based on the principle of instantaneous power conservation the current source is computed. This principle stats that the power which flows inside the two AC-sides of the converter is equal to the power absorbed by the DC capacitor [8].

A. Operating Principle Of The Wind Turbine Doubly-fed Induction Generator

For understanding of operation of DFIG we need to describe the flow of active and reactive power which has been shown in the following figure 2.

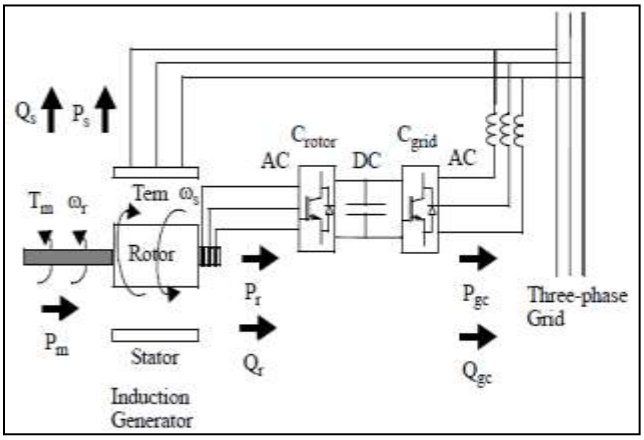

Figure.2. Active and Reactive Power Flow

Figure 2 shows the power flow [8], which is used to describe the principle of operation for Doubly Fed Induction Generator.

The parameters used in the equations for the calculations of the mechanical power and electrical powers are defined here [9]:

P_m = Mechanical power transmitted to the rotor by wind turbine,
T_m = Mechanical torque applied to rotor,
T_{em} = Electromagnetic torque applied to the rotor by the generator,
J = Combined moment of Inertia of rotor and wind turbine,
Ps = Stator active power output,
Qs = Stater reactive power,
Pr = Rotor active power output,
Qr = Rotor reactive power,
Qgc = Cgrid reactive power,
Pgc = Cgrid active power output,
ώr = Rotational speed of rotor, and
ώs= Rotational speed of the magnetic flux of the generator .

Now we can use the principle of operations to develop the calculations of mechanical power and electrical power output of rotor and stator, also the mechanical and electromagnetic torque developed are described [9] as follows:

$$P_m = T_m \omega_r \tag{11}$$

This equations shows Mechanical power transmitted to the rotor by wind turbine

$$P_s = T_{em} \omega_s \tag{12}$$

Equation 12 shows Stator active power output

The mechanical equation for a lossless generator is:

$$J\frac{d\omega_r}{dt} = T_m - T_{em} \tag{13}$$

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Equations 13 shows the relation between rotor's mechanical torque and electromagnetic torque applied to rotor.

For a a lossless generator in steady-state condition and at fixed speed

$$T_m = T_{em} \text{ and } P_m = P_s + P_r \quad (14)$$

Equations 14 shows here mechanical and electromagnetic torque became equal

Also:

$$P_r = P_m - P_s = T_m \omega_r - T_{em} \omega_s = -sP_s \quad (15)$$

Whereas

$$s = (\omega_s - \omega_r) / \omega_s \quad (16)$$

S is known as the slip of the generator.

Usually the practical slip value is very much less than 1 and thus from equation (15) we can say that rotor's active power (P_r) is a fraction of active power of stator (P_s).

With equation (15) for power generation mechanical torque applied to the rotor is positive and for constant frequency grid voltage ω_s is constant and positive, thus sign of P_r will change according to the sign of slip. For super-synchronous speed operation that is for negative slip P_r is positive that means P_r is transmitted to DC bus capacitor and will participate to raise the DC voltage. And for sub-synchronous speed operation that is for positive slip P_r is negative, which means active power is flown out of DC bus capacitor and results in decreasing of the DC voltage.

To keep the DC voltage constant Grid side Converters are employed and it is done by absorbing or generating grid side converter's active power (Pgc). For a lossless set of converters in a steady-state condition Pgc is equal to Pr and the wind turbine speed can be determined by Crotor whether it absorbs or generates Pgc [9].

Further For the power control Explanation, for the sub-synchronous speed operation the phase-sequence of the AC voltage generated by rotor side converter will be positive and the phase-sequence of the same voltage will be negative for super-synchronous speed operation.

The frequency of the AC voltage generated by rotor side converter is equal to the product of the value of the slip and the grid frequency. Rotor side converter and grid side converter have the potential to generate or absorb reactive power and thus could be utilized to control the reactive power or the voltage at the grid terminals [8].

B. *Rotor Side Converter Control For DFIG*

The rotor-side converter controller is used for controlling the stator voltage (or reactive power) and output active power of the wind turbine independently. The converter operates in a stator-flux qd-reference frame; the rotor current broke down into an active power in the q-axis component and a reactive power in the d-axis component. When speed of the wind speed changes there will be a change in the active and reactive power of the generator also. As (actual P) that is actual active power of the generator is compared with reference value of P (ref P) which is determined by the wind speed. The variations between these two values will be provided to a Proportional Integral (PI) controller which will generate (ref I) that is the required value of q-axis rotor current. Similarly, a Proportional Integral controller is used in the reactive power side to generate (ref I) the required d-axis rotor current [10].

C. *Grid Side Converter Control For DFIG*

The role of the grid-side converter is to control the value of the DC-link voltage by controlling it to constant and it is also utilized for generating or absorbing the reactive power. The voltage of DC link is used as well, with the q-d reference frame aligned along the stator currents and stator voltages, sets up separate control of the active and reactive power between the converters and the grid. The compensation and decoupling procedures of a typical grid-side converter control can be seen in system model. The (DC actual E) that is actual DC link voltage is compared with (DC ref E) that is reference value. The variations between these two values will go to two Proportional Integral controllers which are utilized to generate the required value of d-axis stator voltage. Also the difference between the actual reactive power that is actual Q and reference value that is ref. Q will go to another two Proportional Integral controllers to generate value of the q-axis stator voltage which will be required [10].

IV. SIMULATION MODEL

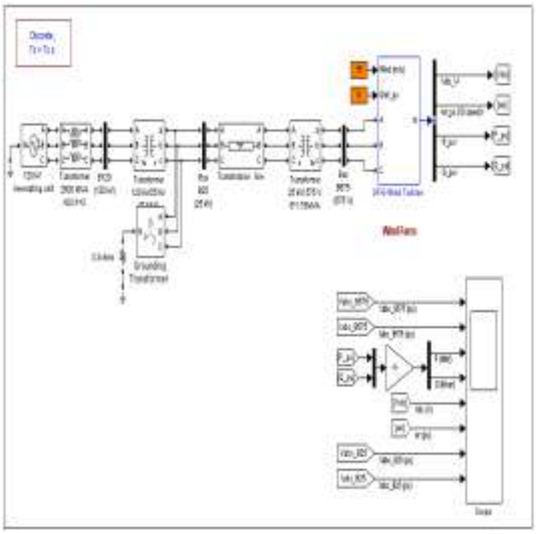

Figure 3 Simulation model of wind farm connection with 120 kv electrical grid

In the following simulation model (Figure-3) a wind mill of a capacity of generating 9 MW is connected to a electrical grid. The wind mill is connected to a transformer which step ups the generating power for a 25 kv distribution. Through a 30 km transmission line this distribution network is connected to a 120 kv Grid. In between the distribution system another step up distribution transformer is used to step up the voltage level to 120 kv, with this star delta connected transformer a grounding transformer is used for providing path for zero sequence current. Wind turbine used here will be using a wound rotor induction generator and IGBT-based converters. The stator of DFIG is directly connected to grid while the rotor is connected through AC/DC/AC Converters.

V. RESULT ANALYSIS

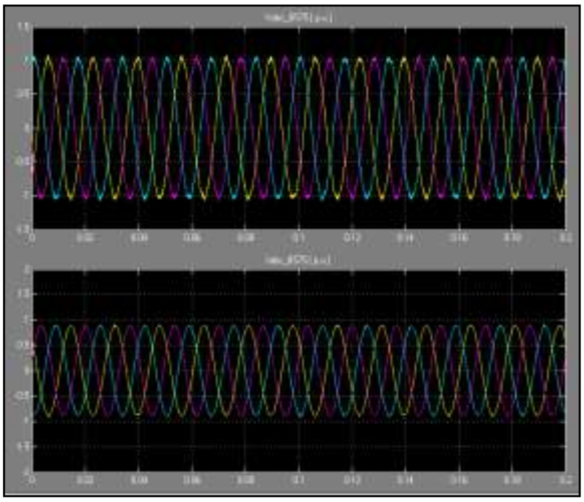

Figure 4 Waveform for three phase output Voltage and current output of wind farm

This Figure 4 shows the three phase voltage and three phase current output of the wind farm. Both voltage and current are sinusodial in nature and synchronized with the grid requirements. Vabc is output voltage and Iabc is output current of wind farm in per unit representation varing upto 1 p.u.

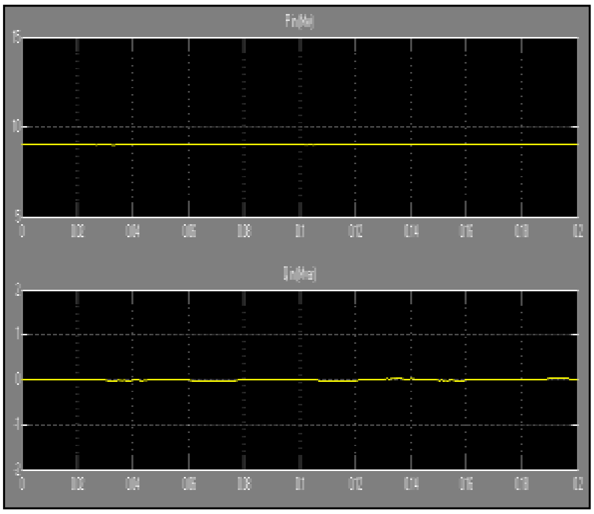

Figure 5 Waveform for active and reactive power flow in wind farm

This Figure 5 Shows the flow of active and reactive power within the system. In figure active power shows the capacity of the wind plant as of “P =9 MW”. While Reactive power flow is maintained almost at “Q = 0 Mvar”.

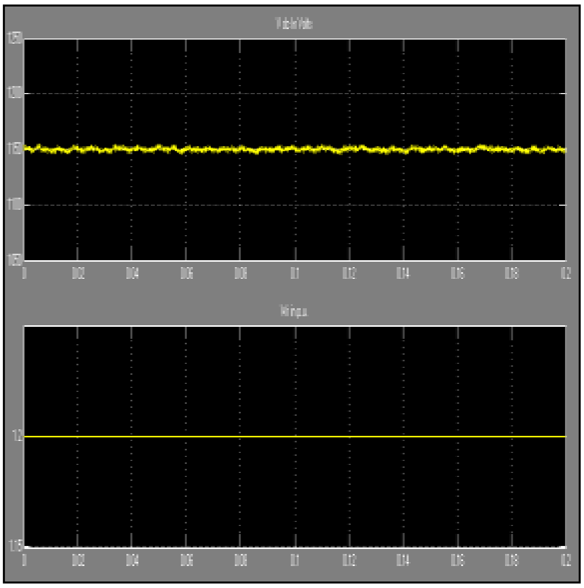

Figure 6 Waveform for Dc Voltage and rotor speed

The value of the DC voltage in volts and the rotor speed is shown in Figure 6. In this model the wind speed is maintained constant at 15 m/s. The control system uses a torque controller in order to maintain the rotor speed at 1.2 pu. Same is shown in the figure also the nominal value of the Dc voltage is 1150 volts.

From above waveform the result drawn is that by using DFIG in wind farm the efficiency can be improved and maximum power can be extracted and maintained constant for the whole time period.

VI. VI. CONCLUSION AND FUTURE SCOPE

From the above study of the simulation model we understand that using doubly fed induction generator wind energy conversion can be made more reliable and efficient. By changing blade angle and pitch control maximum control on the generation can be obtain. Also by controlling the torque the speed of the rotor can be controlled up to desired extent. In the wind energy conversion system the usage of power electronic converters have made it possible to synchronize the generated power with the electrical grid. Further study of turbine characteristics can help in modification of the system design such that the quality of the output can be improved more.

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