ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
Volume 3, Issue 1, July 2013

Wind Energy Using Doubly Fed Induction Generator

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Abstract*— Wind power as an important and promising renewable resource, is widely studied. Recently doubly fed induction generator (DFIG) becomes more popular in wind power due to its various advantages over other types of wind turbines, such as variable speed, lower power electronic cost and so on [7].It is a standard, wound rotor induction machine with its stator windings directly connected to the grid and its rotor windings connected to the grid through an AC/DC/AC PWM converter. In this paper, a model of DFIG-based wind power system is derived in complex form. The present form focuses on the analysis of traditional decoupled d-q vector control approaches for control of DFIG wind turbines. Then; detailed study is performed to investigate the power control characteristics of DFIG converter using d-q control approaches. A simulation study is performed to examine the power control characteristics of DFIG.

***Index Terms*—wind energy, doubly fed, induction generator, power system.**

I. INTRODUCTION

The use of the doubly fed induction machines was subject of many investigations in research and especially in generator mode for the wind turbine [1, 2].It is important that the generator can function at variable speed but the presence of converters between the generator and the network harms the global efficiency of the installation. The DFIG proposes a good compromise between the variation speed range which it authorizes and the converters size compared to the machine nominal power. Several control strategies were established to control the power exchange between the machine and the network which is connected to [3, 4]. A two-stage AC-DC-AC inverter is used with the induction generator, The rectifier and the inverter are used to modulate the alternating power of variable frequency into that of constant frequency to be used by load .Thereby, the issue that the output amount of power varies with rotating speed and the load of the induction generator can be effectively solved[5]. In doubly-fed machine, it is possible to control both of active power and reactive power through modifications of magnitude and phase in excitation currents, while only the magnitude of terminal voltage can be controlled as a vector by means of modification of excitation currents in doubly-fed machine [6]. The development of the wind turbine system has experienced three stages [6]:

- Fixed speed stall controlled induction generator.
- Variable speed pitch controlled synchronous generator.
- Variable speed, pitch controlled doubly-fed induction generator (DFIG).

DFIG can be suitable for the variable nature of wind. FIG can be operated in any desired power factor through power electronic converter control .Moreover, the special connection of rotor windings results in a lower converter cost and also a lower loss [7]. The stator of DFIG is directly connected to the grid while the rotor is indirectly to the grid through back-to-back converters. Which are capable of providing 10-40% of the generators rated power the back-to-back converters are controlled by pulse width modulation (PWM). in this paper, the mathematical model of the DFIG wind power system is derived in section 2 .In section 3,the decoupled method is introduced for DFIG system control-based on which, the active and reactive power can be controlled independently. Control strategy is proved to be effective by the simulation results. The use of a DFIG is preferred option for large- scale electromechanical conversion of wind power to mechanical power. The DFIG requires a two-sided controller, a rotor-side controller (RSC) to control the speed of operation and the reactive power, and a grid-side controller(GSC) using a grid- side voltage-source converter, which is responsible for regulating the dc-link voltage as well as the stator terminal voltage[8].So the RSC objectives are:

- ❖ Regulate the reactive power and hold the stator output voltage frequency constant by a form of current control.
- ❖ Regulate the rotor speed to maintain stable operation.
- ❖ Alter the speed set point to ensure maximum wind power capture.

The objective of the GSC is to ensure regulation of the dc-voltage bus, and thereby indirectly control the stator terminal voltage [8]. Doubly-fed wound rotor induction machines with d-q vector control are attractive to the high performance and are commonly used by the wind turbine industry today[9].There are several reasons for using variable-speed DFIG wind turbines, among those are possibilities to:

- ▪ Reduce stresses of the mechanical structure.
- ▪ The back-to-back PWM converter, connected between the grid and the induction machine rotor circuit, only to handle a fraction(20-30%) of the total system power[9]

The general control technique for the grid-side converter control, which is widely used in wind power industry, is a

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ISO 9001:2008 Certified
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decoupled d-q control approach that uses the direct axis current component for real power control and quadrature axis current component for reactive power control [9]. In the sections that follow, the paper first introduces the DFIG wind power system model, the DFIG model equations and the fundamental converter control principles .Then, power control relationship, models, and equivalent circuit are developed for steady-state evaluation associated with the decoupled d-q control approach. A simulation study is performed to examine the power characteristic of the DFIG.Finally the paper is summarized in the conclusion section. By controlling the converters on both sides, the DFIG characteristics can be adjusted so as to achieve maximum of effective power conversion or capturing capability for a wind turbine and to control its power generation with less fluctuation.

II. DFIG WIND POWER SYSTEM MODEL.

The overall DFIG-based wind power system, as shown in Figure1, consists of wind power model and DFIG model.

II.1 Wind turbine model equations:

The wind power can be expressed as a function of wind speed

$$p_w = 0.5\rho C_p(\lambda,\theta) A_R V_W^3 \quad (1)$$

Where:

ρ: is the air density [Kg/m3];

A_R : is the area swept by the rotor [m3];

V_W : is the upstream wind speed;

C_p : is the performance coefficient with respect to the speed ratio λ and the pitch angle θ [10].

Where λ_i can be approximated by a function of the tip speed ratio λ [8],which is given by:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda} + 0.002$$

The mechanical torque is given by:

$$T_{mech} = P_m/\omega_w \quad (2)$$

II.2 DFIG model equations:

The basic equations of the doubly-fed induction machine can be established by considering the equivalent circuit of a single stator phase and a single rotor phase, and the mutual coupling the stator and the rotor phases. The voltage vector consisting of the voltages drops across the resistances of these phases, and the rate of change of the fluxes linking the stator and rotor phases. The fluxes in turn are related to the current vector via a matrix of inductances, which are not constant but period functions of time with the period equal to the rotor's electrical speed $\omega_e = P\omega_m$,which is the product of the number of pole pairs P and the rotor's mechanical speed ω_m .When all of the stator and rotor quantities are transformed to a stationary frame(the d-q frame),using Park transformation, in terms of the stator's and rotor's voltage-pulsation frequencies ω_s and ω_r ,respectively, The basic equations reduce to a set of four with constant coefficients. Moreover=ω_s-ω_e and can be found by measuring ω_s and ω_e ,and the slip frequency(the ratio $s=\omega_r/\omega_s$ is the slip).Thus ,the phase angles relating the direction of the d-q frame and the phase angles of the first of the three stator phases,A,B, and C ,θ_s and the first of the three rotor phases, a,b, and c, θ_r satisfy the relation $\theta_r=\theta_s-\theta_e$, where θ_e is the rotor's electrical angle[8]. The four equations of the DFIG with constant coefficient in the d-q frame are:

$$V_{ds} = R_s i_{ds} + \frac{d\phi_{ds}}{dt} - \omega_s \phi_{qs} \quad \& \quad V_{qs} = R_s i_{qs} + \frac{d\phi_{qs}}{dt} + \omega_s \phi_{ds} \quad (3)$$

$$V_{dr} = R_r i_{dr} + \frac{d\phi_{dr}}{dt} - \omega_r \phi_{qr} \quad \& \quad V_{qr} = R_r i_{qr} + \frac{d\phi_{qr}}{dt} + \omega_r \phi_{dr} \quad (4)$$

The stator fuxes are related to the stator and rotor currents in the $d-q$ frame as:

$$\phi_{ds} = L_s i_{ds} + L_m i_{dr} \;\&\; \phi_{qs} = L_s i_{qs} + L_m i_{qr} \quad (5)$$

The rotor fuxes are related to the stator and rotor currents in the *d-q* frame as:

$$\emptyset_{dr} = L_r i_{dr} + L_m i_{ds} \;\&\; \emptyset_{qr} = L_{qr} i_{qr} + L_m i_{qs} \quad (6)$$

Where, R_s , R_r , L_s , *and* L_r are the resistances and self-inductances of the stator and rotor windings, and L_m is the mutual inductance between a stator and a rotor phase when they are fully aligned with each other.

The vector control strategy applied to the DFIG consists on making the stator flux in quadrature with the q-axis of the Park reference frame, therefore,

$$\emptyset_s = \emptyset_{ds} \text{ and } \emptyset_{qs} = 0 \quad (7)$$

Equations (3) and (4) can be simplified as:

$$\frac{d\emptyset_{ds}}{dt} = -R_s i_{ds} + V_{ds} \quad (8)$$

$$V_{qs} = R_s i_{qs} + \omega_s \emptyset_{ds} \quad (9)$$

$$\frac{d\emptyset_{dr}}{dt} = -R_r i_{dr} + \omega_r \emptyset_{qr} + V_{dr} \quad (10)$$

$$\frac{d\emptyset_{qr}}{dt} = -R_r i_{qr} - \omega_r \emptyset_{dr} + V_{qr} \quad (11)$$

From Eq.(5)

$$i_{qs} = -L_m/L_s i_{qr} \quad (12)$$

and

$$i_{ds} = (\emptyset_{ds} - L_m i_{dr})/L_s \quad (13)$$

By replacing Eq (12) and Eq (13) in Equations (6), we obtain

$$\emptyset_{dr} = (L_r - L_m^2) i_{dr} + L_m/L_s \emptyset_{ds} \quad (14)$$

$$\emptyset_{qr} = L_r(1 - L_m^2/(L_s L_r)) i_{qr} \quad (15)$$

By introducing the leakage coefficient σ with:

$$\sigma = 1 - L_m^2/(L_s L_r) \quad (16)$$

then:

$$\emptyset_{dr} = L_r \sigma i_{dr} + L_m/L_s \emptyset_d \quad (17)$$

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ISO 9001:2008 Certified
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$$\emptyset_{qr} = L_r \sigma i_{qr} \quad (18)$$

Substituting equations (17) and (18) in Eqs (10) and (11), we obtain:

$$V_{dr} = R_r i_{dr} + L_r \sigma d i_{dr}/dt + \frac{L_m}{L_s} d\emptyset_{ds}/dt - \omega_r L_r \sigma i_{qr} \quad (19)$$

$$V_{qr} = R_r i_{qr} + L_r \sigma d i_{qr}/dt + \omega_r L_r \sigma i_{dr} + L_m/L_s \omega_r \emptyset_{ds} \quad (20)$$

Assuming that the stator flux is stationary in the $d-q$ frame (the d-axis is aligned with the stator-flux-linkage vector $\emptyset_s$) and neglecting the stator's resistive voltage drop,so:

$$\emptyset_{ds} = \emptyset_s \text{ and } \quad \emptyset_{qs} = 0 \quad (21)$$

and

$$V_{ds} = 0 \text{ and } \quad V_{qs} = V_s \quad (22)$$

From Equation (3):

$V_{qs} = V_s = R_s i_{qs} + \omega_s \emptyset_s$, from which

$$\emptyset_s = (V_s - R_s i_{qs})/\omega_s \quad (23)$$

From Equation (5):

$$\emptyset_{ds} = \emptyset_s = L_s i_{ds} + L_m i_{dr} = \frac{V_s - R_s i_{qs}}{\omega_s} = L_m i_{ms}$$

Where i_{ms} is defined as :

$$i_{ms} = \left(\frac{V_s - R_s i_{qs}}{\omega_s L_m}\right) = \frac{V_s}{\omega_s L_m} - \left(R_s\left(-\frac{L_m}{L_s i_{qr}}\right)\right)/(\omega_s L_m) \quad (24)$$

Then, the rotor voltage equations given by Eqs(19) and (20) are expressed as:

$$V_{dr} = R_r i_{dr} + L_r \sigma \frac{d i_{dr}}{dt} + L_m/L_s \frac{d\emptyset_{ds}}{dt} - s\omega_s L_r \sigma i_{qr} \quad (25)$$

$$V_{qr} = \left(R_r + \frac{s L_m^2}{L_s^2 R_s}\right) i_{qr} + L_r \sigma \frac{d i_{qr}}{dt} + s\omega_s L_r \sigma i_{dr} + s L_m/L_s V_s \quad (26)$$

Furthermore, the active and reactive components of the power at stator terminals are given by:

$$P_s = V_{ds} i_{ds} + V_{qs} i_{qs} \quad \& \quad Q_s = V_{qs} i_{qs} - V_{ds} i_{qs} \quad (27)$$

The active and reactive components of the power at rotor terminals are given by:

$$P_r = V_{dr} i_{dr} + V_{qr} i_{qr} \quad \& \quad Q_r = V_{qr} i_{qr} - V_{dr} i_{qr} \quad (28)$$

The electromagnetic reaction torque may be expressed as:

$$T_{el} = \emptyset_{ds} i_{qs} - \emptyset_{qs} i_{ds} \quad (29)$$

From Eqs (21),(22),(23), and (24):

$$T_{el} = -L_m^2/L_s\left(\frac{V_s}{\omega_s L_m} + \frac{R_s}{\omega_s L_s} i_{qr}\right) i_{qr} \quad (30)$$

And the active power at the stator terminal:

$$P_s = V_s i_{qs} = -L_m/L_s V_s i_{qr} \quad (31)$$

The reactive power at the stator terminals:

$$Q_s = V_s i_{ds} = \omega_s L_m^2/L_s\left(\frac{V_s}{\omega_s L_m} + \frac{R_s}{\omega_s L_m} i_{qr}\right)\left(\frac{V_s}{\omega_s L_m} + \frac{R_s}{\omega_s L_m} i_{qr} - i_{dr}\right) \quad (32)$$

If the stator resistance Rs is neglected, then Eq(31) can be expressed as :

$$Q_s = -\frac{L_m}{L_s V_s i_{dr}} + V_s^2/(\omega_s L_s) \quad (33)$$

III. RESULTS AND DISCUSSION

With the increased penetration level of wind power in the power system, wind turbines have to contribute not only to active power generation but also to the reactive power. The main advantages of DFIG wind turbine its ability to control reactive power and decouple control of active and reactive power by independently controlling the rotor excitation current. The DFIG can produce or absorb an amount of reactive power to or from the grid within its capacity, to regulate the terminal voltage. To assist its further integration into the modern power system, it is therefore important to assess its dynamical behavior, steady state performance, and impacts on the interconnected power network with regard to its reactive power capability and voltage control. The optimum speed of the generator should be selected based on annual wind speed distribution and the size of the power converter. It is not always possible to operate wind turbine in maximum power point tracking mode and constant pitch control only. For maintaining regulated frequency and voltage in the power system, the generated power should be equal to the demanded power, when the load decreases, the power output from the turbine should reduced to match the load. When the speed is less than the rated speed, the pith angle is always kept at zero and λ is varied and corresponding Cp is calculated to obtain demanded power output from the wind turbine.

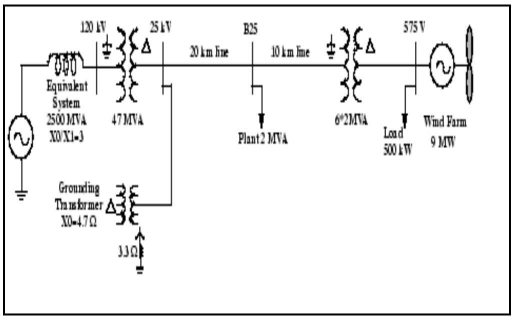

Fig.1. Single-line diagram of the wind farm connected to a distribution system.

The case described in this section illustrates application of SimPower System software to study the steady-state and dynamic performance of 9MW wind farm connected to a distribution system. The wind farm consists of six 1.5MW wind turbines connected to a 25KV distribution system exporting power to a 120KV grid through a 30Km 25KV feeder. A 23KV,2MVA plant consisting of a motor load(1.68MW induction motor at 0.93 PF) and of a 200KW resistive load is connected on the same feeder at bus B25. A 500KW load is also connected on the 575V bus of the wind

ISSN: 2277-3754
ISO 9001:2008 Certified
International Journal of Engineering and Innovative Technology (IJEIT)
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farm. The single-line diagram of this system is illustrated in Figure.1.If the wind speed is set at 8 m/s, then at t = 5s, wind speed increases suddenly to 14 m/s. the wind turbine voltage, current, generated active and reactive powers, DC bus voltage is presented in Figure.2.At t = 5 s, the generated active power starts increasing smoothly (together with the turbine speed) to reach its rated value of 9 MW in approximately 20 s. Over that time frame the turbine speed will have increased from 0.8 PU to 1.21 PU. Initially, the pitch angle of the turbine blades is zero degree. Then the pitch angle is increased from 0 deg to 0.76 deg in order to limit the mechanical power. We also observed the voltage and the generated reactive power. The reactive power is controlled to maintain a 1 PU voltage. At nominal power, the wind turbine absorbs 0.68 Mvar (generated Q = -0.68 Mvar) to control voltage at 1PU

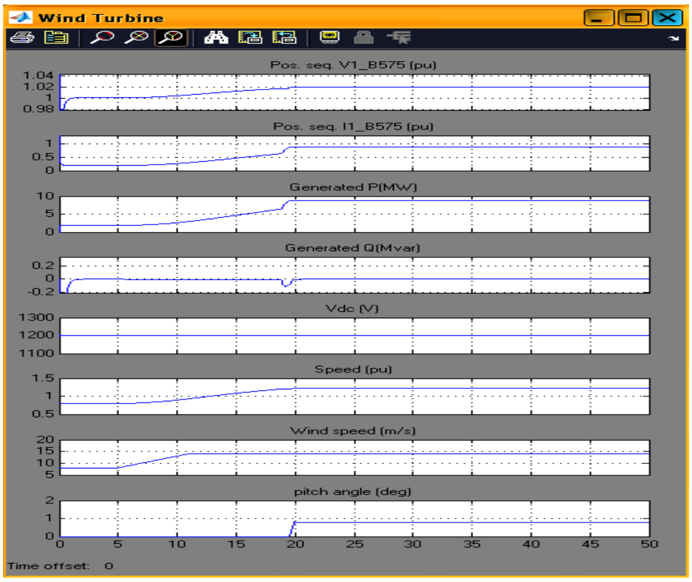

Fig.2 the Turbine Response to a Change in Wind Speed

When the mode of operation is set to control parameters, as shown in Figure.3 then we see that for grid the active power starts decreasing after 5 s and becomes nearly 5 MW while the reactive power becomes positive and starts increasing to nearly 2MW before becoming constant turbine speed remains constant for 7 s then it increases and again becomes constant at 20 s.

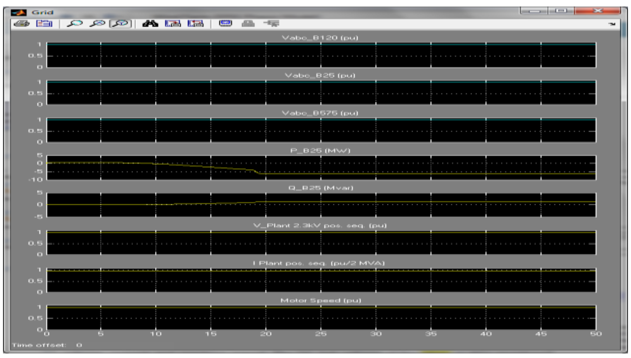

Fig.3. Simulation of wind turbine and grid parameters when the mode of operation is set to control parameters.

In the grid side simulation the active power generated starts increasing as the voltage increases and reaches to nearly 9 MW as the voltage reaches to 1 Pu. The reactive power requirement is less initially but gradually it increases to few MWs. The wind turbine speed remains constant for 7 s then it increases and again becomes constant at 20 s.

IV. CONCLUSION

The variation of wind turbine causes change of operation mode in the wind turbine system. when the wind is less than rated speed, wind turbine is operating in maximum power point tracking mode so Cp=0.48 and tip speed ratio=8.1 with pitch angle=0.when the wind speed is more than rated speed, pitch control starts operating as a result,Cp<0.48,tip speed ratio<8.1 and pitch angle>0.The detailed modeling of DFIG has been carried out for a wind energy conversion system. The DFIG has been found capable to work for a wide speed range and it is clear that power fed to the grid can be controlled by controlling the rotor current's components. The vector control allows decoupled or independent control of both active and reactive power of DFIG.

V. ACKNOWLEDGMENT

This work has been carried out during sabbatical leave granted to Ali Dalabeeh from Al-Balqa' Applied University (BAU) during the academic year 2011/2012.

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