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Analysis of Wind Turbine Driven DFIG Under Abnormal Condition

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***Abstract*—This paper describes the study undertaken to assess the steady state and dynamic behavior of a doubly fed induction generator (DFIG) driven by wind turbine after its disconnection from the grid. The machine side converter provides good decoupling between the active and reactive power and the network side converter controls the power flow between the DC bus and the AC side and allows the system to be operated in sub-synchronous and super synchronous speed. The induction machine runs at a specific speed with the stator disconnected from the grid (Is=0), the rotor is suddenly excited with slip-frequency voltages derived from voltage regulators so as to produce commended open-circuit stator terminal voltage. Behavior under varying input power typically observed in wind turbines is also reported. A MATLAB computer simulation study was undertaken and results on 1.5 kW wind turbine are presented indicating grid abnormalities and varying input power.**

***Keywords*— Doubly fed Induction Generator (DFIG), Wind Energy Conversion Systems (WECS), Dynamic d-q modeling, Grid abnormalities**.

I. INTRODUCTION

V_{qs}, V_{ds} are the three-Phase supply voltages in d-q reference frame, respectively i_{qs} ,i_{ds} are the three-Phase stator currents in d-q reference frame, respectively λ_{qs}, λ_{ds} are the three-Phase stator flux linkages in d-q reference frame, respectively V_{qr}, V_{dr} are the three-Phase rotor voltages in d-q reference frame, respectively i_{qr} ,i_{dr} are the three-Phase rotor voltages in d-q reference frame, respectively λ_{qr}, λ_{dr} are the three-Phase rotor voltages in d-q reference frame, respectively r_s ,r_r are the stator and rotor resistances of machine per phase, respectively L_{ls}, L_{lr} are the leakage inductances of stator and rotor windings, respectively T_e *is* the electromagnetic torque P_s, Qs are the stator-side active and reactive powers respectively P is the Number of poles.

Wind generators play an important role among all possible renewable energy resources, they considered as the most promising in terms of competitiveness in electrical power production. Energy of the wind is user for more than thousand years for water pumping, grinding grain, and other low-power applications. There were several early attempts to build large-scale wind powered systems to generate the electrical energy. The first production of electrical energy with wind power was done in 1887 by Charles Brush in Cleveland, Ohio. The rated Power of the used dc-generator was 12kW and was designed to charge batteries. The induction machine was used at the first time in 1951. Recently Enercon constructed a wind turbine of 4.5 MW and rotor diameter of more than 112.8 meters. Today, it is one of the rapidly growing technologies in markets. By the end of 2010[WWEA] the total installed capacity of wind energy is estimated to be more than 160 GW all around the world.

In a grid connected wind energy conversion system with squirrel cage induction machine, the grid can be connected in three ways, such as direct grid connection method, grid connection via direct-current intermediate circuit method (with thyristor converter, with pulse inverter) and grid connection via direct a.c converter method. If the machine is a wound rotor induction machine, the control scheme includes dynamic slip control method, over synchronous static Kraemer system method and doubly fed induction machine method. Double fed configuration is best suited for variable speed generation since it can be controlled from rotor side as well as stator side. This is possible since rotor circuit is capable of bidirectional power flow. The doubly-fed machine can be operated in generating mode in both sub-synchronous and super-synchronous modes. The rotor will observe slip power from the in sub-synchronous operation and can feed slip power back to grid in super-synchronous operation. The rotor converter needs thus only to be rated for a fraction 25% (Slip Power) of the total output power. All these advantages make the DFIG a favorable candidate for variable speed operation. In recent years, DFIG have received increased attention and they have been widely employed as suitable isolated power sources and grid-connected in small hydroelectric and wind energy applications.

For stand alone or autonomous operation, mostly single induction generator or parallel operated induction generators are focused according to available analyzed references. These induction generator driven by the individual prime movers employed excitation capacitor bank to buildup desired voltage via self-excited phenomena. Hence the value of the excitation capacitor bank and the rotor speed determine the magnitude of the generated voltage and its frequency. Both voltage and frequency need to be controlled to feed the power to the load. But for grid connected operation, there are two types of generators are used (i.e., single output and double outputs).In order to feed the active power to the grid, the machine should run at a speed greater than the synchronous speed of the revolving magnetic field. (i.e. slip should be negative).The single output generator feeds active power to the grid via only stator side and double output generator feeds electrical power to the grid via both stator as well as rotor side. The latter is also called static Kramer, double-fed or double outputs induction generators. This is only the generator which generates the power more than rated power without overheating. Besides, this kind of power generation usually causes problems in the utility grid system. Because the control on active and reactive power of the machine is complex one. Wind turbines often do not take part in voltage and frequency control and if a disturbance occurs, the wind turbines are disconnected and reconnected when normal operation has been resumed. As the wind power penetration continually increases, power utilities concerns are shifting focus from the power quality issue to the stability problem caused by the wind power connection. In such cases, it becomes important to consider the wind power impact properly in the power system planning and operation. This paper will focus on the grid-connected induction generator feeding power with DOIG during steady state and transient conditions.

This paper presents steady state and transient analysis of a double-output induction generator based on dynamic d-q modeling which is used to derive the dynamic equations of an induction generator feeding to the utility grid. This paper is organized as follows. Section II introduces the derivation of dynamic equations of the studied system. Section III describes the steady-state analyses results under variation of rotor speed. Section IV shows the transient responses due to grid disconnection phenomena. Section V addresses the conclusion part of this paper.

II. BASIC STUDY OF SYSTEM

Wind turbine converts the kinetic energy present in the wind into mechanical energy by means of producing torque. Since the energy contained by the wind is in the form of kinetic energy, its magnitude depends on the air density and the wind velocity. The wind power developed by the turbine is given by the following equations.

$$P=1/2C_p\lambda \quad A\,V^3 \qquad (1)$$

where C_p is the power co-efficient, _ is the air density in kg/m3, A is the area of the turbine blades in m^2 and V is the wind velocity in m/sec.

The power coefficient C_p gives the fraction of the kinetic energy that is converted into mechanical energy by the wind turbine. It is a function of the tip speed ratio _ and depends on the blade pitch angle for pitch-controlled turbines. The tip speed ratio may be defined as the ratio of turbine blade linear speed and the wind speed.

$$\lambda = \frac{R\omega}{V} \qquad (2)$$

Substituting (2) in (1), we have:

$$P = \frac{1}{2} C_p(\lambda)\rho A \left(\frac{R}{\lambda}\right)^3 \omega^3 \qquad (3)$$

There is a value of the tip speed ratio at which the power coefficient is maximum [2-3]. Variable speed turbines can be made to capture this maximum energy in the wind by operating them at a blade speed that gives the optimum tip speed ratio. This may be done by changing the speed of the turbine in proportion to the change in wind speed.

Fig. (1) shows how variable speed operation will allow a wind turbine to capture more energy from the wind. As one can see, the maximum power follows a cubic relationship. For variable speed generation, an induction generator is considered attractive due to its flexible rotor speed characteristic in contrast to the constant speed characteristic of synchronous generator.

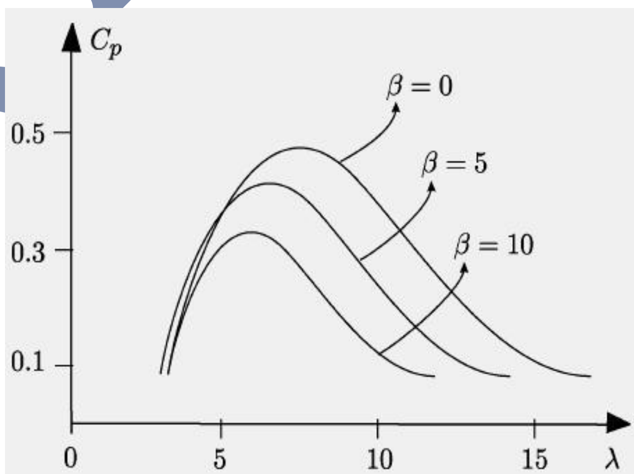

Fig. 1. Maximum power capture of wind turbine by optimizing Cp as a function of λ

A commonly used model for induction generator converting power from the wind to serve the electric grid is shown in Fig.2.The stator of the wound rotor induction machine is connected to the low voltage balanced three-phase grid and the rotor side is fed via the back-to-back IGBT voltage-source inverters with a common DC bus. The grid side converter controls the power flow between the DC bus and the AC side and allows the system to be operated in sub-synchronous and super synchronous speed. The proper rotor excitation is provided by rotor side converter.

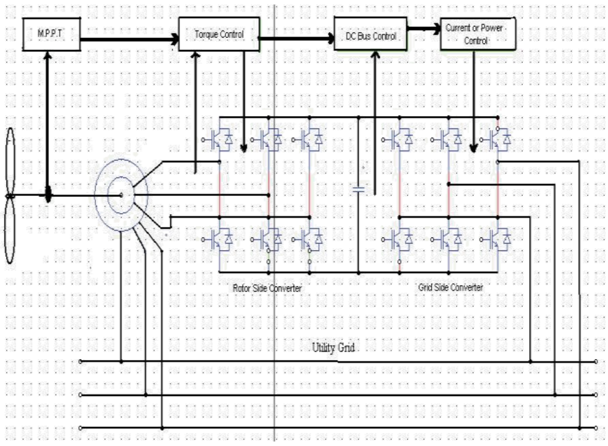

Fig. 2. Doubly Fed Induction Generator Wind Turbine

The general model for wound rotor induction machine is similar to any fixed-speed induction generator as follows

Voltage Equations:

$$Vqs = p\lambda qs + \omega\lambda ds + r_s i_{qs} \quad (4)$$

$$Vds = p\lambda ds - \omega\lambda qs + r_s i_{ds} \quad (5)$$

Power Equations:

$$P_s = \frac{3}{2}(V_{ds}i_{ds} + V_{qs}i_{qs})$$

$$Q_s = \frac{3}{2}(V_{qs}i_{ds} + V_{ds}i_{qs}) \quad (6)$$

Torque equation:

$$T_e = -\frac{3}{2}\frac{P}{2}(\lambda_{ds}i_{qs} - \lambda_{qs}i_{ds}) \quad (7)$$

Flux Linkage Equations:

$$\lambda_{qs} = (L_{ls} + L_m)i_{qs} + L_m i_{qr}$$

$$\lambda_{ds} = (L_{ls} + L_m)i_{ds} + L_m i_{dr} \quad (8)$$

III. STEADY STATE ANALYSIS

How the rotor speed of induction generator involves on the power flow of the studied system is discussed below. Fig. 3 shows the plot between active power of induction generator and its rotor speed. It is observed that the induction machine. synchronous speed. The negative sign of active power means that the power absorbed by the induction machine, while the rotor runs at a speed more than synchronous speed of the revolving magnetic field and the active power is supplied from induction generator to the grid. The reactive power always absorbed by the induction machine, despite its operating mode. Fig. (4) shows the reactive power of the stator, rotor, output side and Grid side respectively. It is observed that the grid side absorbed the reactive power when the induction machine operated in motor mode, since the rotor side converter provided the amount of reactive power which the induction motor cannot absorb completely. Fig. (5) plots the active power at the stator side of IG and rotor side and grid side respectively. It is evident that the both are almost equal, except the losses of the transmission lines. From the above observations, the motor mode has higher efficiency than the machine operated in generator mode, since the stator of the machine sinks more reactive power in the generator mode. The correlation with the steady-state analysis results are seems to be fair. In fact at the higher speeds the DOIG produces slightly more power. The benefits would therefore appear to lie in the rotor converter ratings. The overall rating of the converter is related to the required speed range, typically 30% of the generator rating as mentioned previously. However the VA converter rating would be translated into maximum current and voltage ratings of the switching devices in the converter.

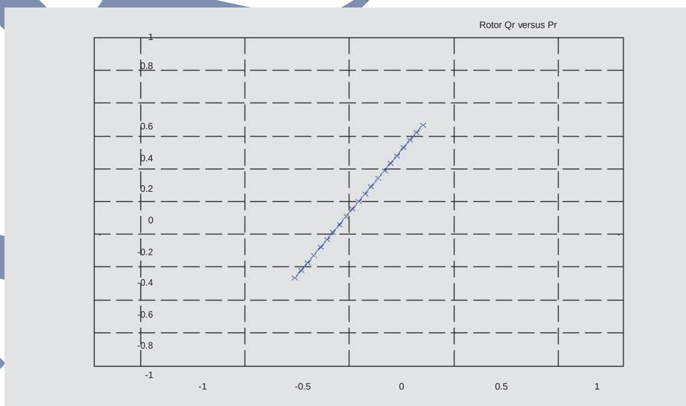

Fig. 3. Response of rotor active power with respect to reactive power

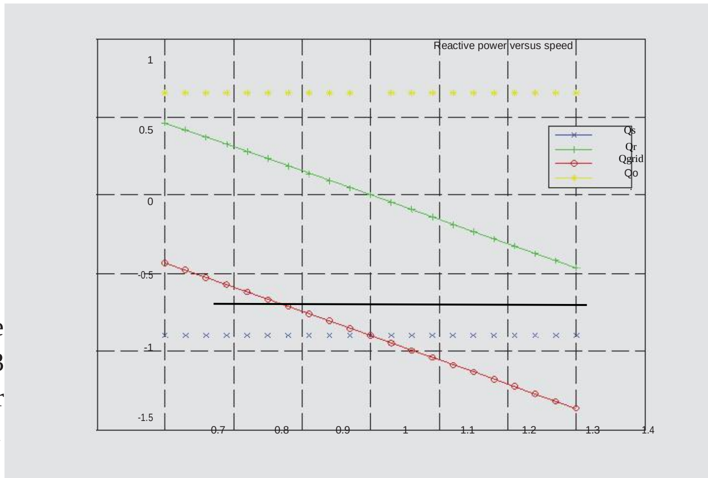

Fig. 4. Response of reactive power of the stator, rotor, grid output

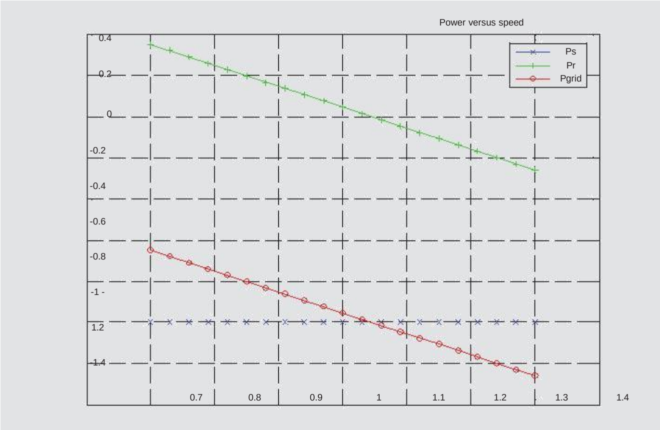

Fig. 5. Response of active power of stator, rotor and grid

IV. TRANSIENT ANALYSIS DURING GRID DISCONNECTION

Fig.(6) shows the three phase stator voltages under normal operating conditions. When the induction machine is running at a particular speed while the stator disconnected from the grid. So the rotor is suddenly got excited due to slip frequency rotor voltages from the voltage regulators in order to produce the commended stator terminal voltage. Since the variation of speed of the rotor, torque also could be varied on the machine. Fig. (7) shows the transient response of the stator voltage of induction generator under torque disturbance. It is found that the voltage of the stator becomes slightly small value after disturbance. The stator current of the induction generator is also plotted in Fig. (8). It is found that stator current has a step change following the torque and then carry the additional power to the grid. Fig. 9 shows the transient response of the active power of the induction generator during disconnecting. When induction generator is disconnected from the grid, the active powers supplied from induction generator decreases and quickly recover to original value after re-closed to the grid. The changes in a reactive power are also shown in Fig. (10). It is observed that the reactive power absorbed by the induction is also decreases rapidly, but the part of reactive power would be supplied by rotor side converter for compensation during re-closed to the grid.

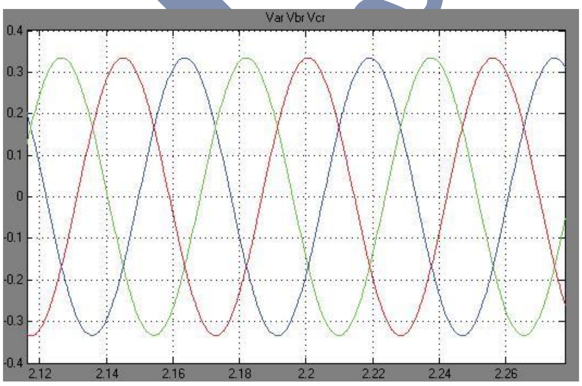

Fig. 6. Three phase stator voltage under normal condition

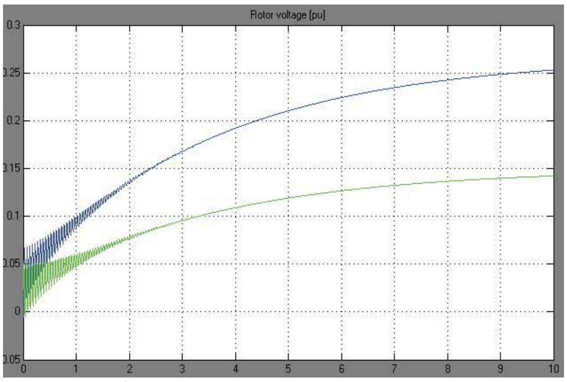

Fig. 7. Transient response of stator voltage and stator current under grid disconnection

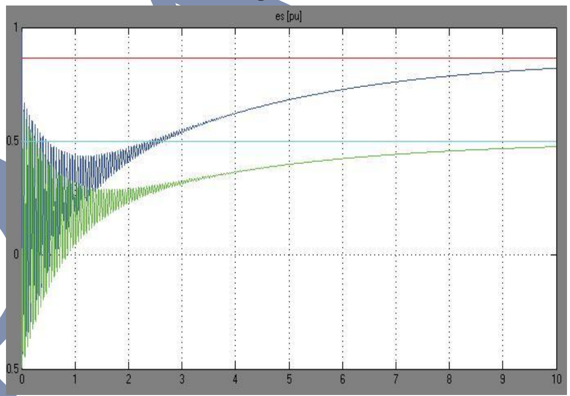

Fig. 8. Transient response of rotor voltage under grid disconnection

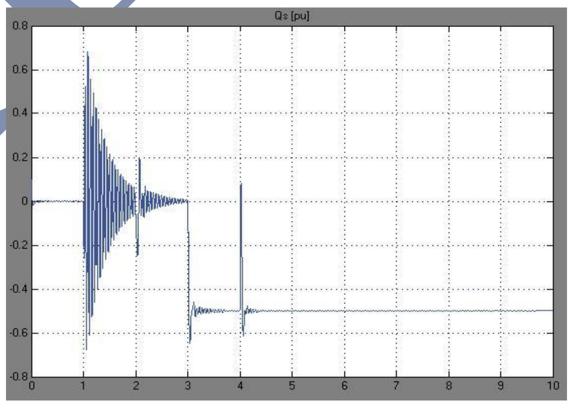

Fig. 9. Transient response of active power during grid disconnection

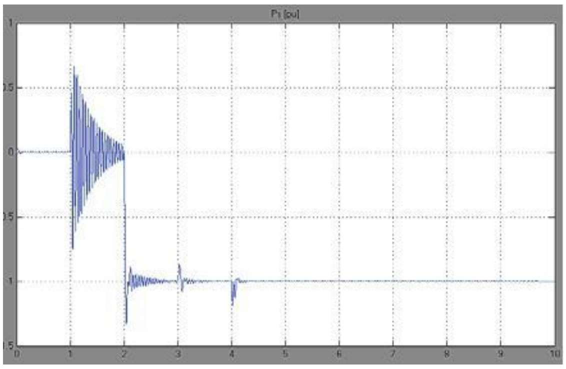

Fig. 10. Transient response of reactive power during grid disconnection.

V. CONCLUSION

In this paper, steady state and dynamic characteristics of double-out induction generator has been studied during normal and abnormal conditions. For this, dynamic d-q model was used to derive the dynamic equations of such machine in a synchronous reference frame. The choice of synchronous rotating reference frame makes it particularly favorable for the simulation of double-output configuration in transient conditions. During steady state conditions, the DOIG feeds active power to the grid and reactive power is supplied to the machine through rotor side converter. And the rotor speed of the machine highly influence on the active power production on the machine. In fact active power produced by the machine is higher at higher speeds and VA rating decides the converter rating on rotor and grid side respectively (normally rating of converter is 30% of machine rating). When the stator is disconnected from the grid, the rotor is suddenly got excited due to slip frequency rotor voltages from the voltage regulators in order to produce the commended stator terminal voltage. So active and reactive power of the machine has been decreases rapidly. For reactive power compensation during these conditions, rotor side converter has to supply necessary reactive power.

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