Mathematical Analysis and Simulation of Complete Wind Farm which is Directly Connected to Grid

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Abstract

The statistical data conveys that Doubly-fed Induction Generator (DFIG) based wind turbine with variable speed is the most common wind turbine in the growing wind farm market. [1] This machine is usually used on the grid connected wind energy conversion system. For wind farm reactive power compensation is essential because DFIG requires reactive power for creating its own magnetic flux, which weakens the power factor and reduced the voltage regulation of wind farm. [2] This paper describes the study undertaken to assess the steady state current of a doubly fed induction generator (DFIG) driven by wind turbine of a wind farm which is directly connected to the grid. The rotor side converter (RSC) and the grid side converter (GSC) provide the power flow between the DC bus and the AC side. [3] The induction machine runs at above synchronous speed and rotor is attached to wind blade. Various reactive power compensation devices compensate the reactive power and with the help of reactive power compensation we reduce the different current which flow in the different line of wind farm. Behaviour under slip is typically observed in wind turbines. A MATLAB computer simulation study was undertaken and results on 4 kW wind turbine are presented indicating current before and after compensation and sending end voltage before and after compensation keeping receiving end voltage constant.

Key Words- Wind farm, doubly fed induction generator, rotor side convertor, grid side convertor, slip, and grid

1. Introduction

Due to depletion of fossil fuels and increase of polluted emissions, renewable energy production is rapidly growing. 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. Today, it is one of the rapidly growing technologies in markets. By the end of 2011 [(EWEA) The European wind energy association] the total installed capacity of wind energy is estimated to be more than 150 GW all around the world [4].

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 AC converter method. If the machine is a wound rotor induction machine, doubly fed induction machine method are used. Double fed configuration is best suited for variable speed generation, because nature of the wind in variable. The doubly-fed machine can be operated in generating mode in super-synchronous modes. In this mode the rotor speed is much higher than the stator magnetic flux speed. A gear system is attached in between wind blade and rotor which maintain the rotor speed is above synchronous speed. The slip power requires for doubly fed induction generator is fraction of 30 % (Slip Power) of the total output power. [6] All these advantages make the DFIG a favourable 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 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 build-up 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. This is only the generator which generates the power more than rated power without overheating. 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. [5] 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 directly grid-connected induction generator feeding power with DFIG during steady state conditions.

This paper presents steady state condition of a double-output induction generator (DFIG) based on mathematical modelling which is used to show the power flow of an induction generator feeding power to the utility grid. This paper is organized as follows- Section II introduces the nomenclature of the studied system. Section III explain the basic study of the system Section IV describe the steady-state analyses of DFIG with the help of torque-slip characteristics. Section V shows the steady state response of current before and after compensation and voltage regulation of the system after reactive power compensation. Section VI addresses the conclusion part of this paper.

2. Nomenclature

$P_{m1-\Phi}$ is prime mover electrical power per phase.
P_g is air gap power.
Q_C_bank1 is reactive power supplied by capacitor bank.
γ is propagation constant.
δ is load angle of inverter voltage.

3. 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 equation.

$$P = 1/2C_p \ \rho \ A \ V3 \qquad (1)$$

Where C_p is the power co-efficient, ρ 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 λ 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. 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.

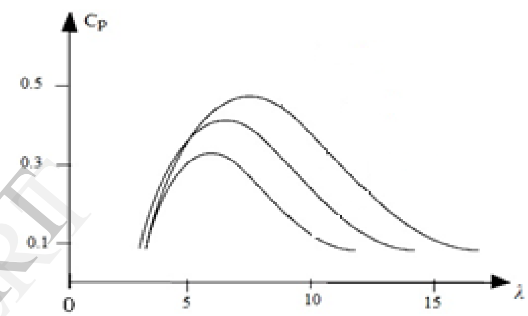

Fig-1 Power Coefficient (C_p) & Tip Speed Ratio (λ) Curve

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 (by eq(1)). 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. A commonly used model for induction generator converting power from the wind to serve the electric grid is shown in Fig.2. And the rotor side is fed via the back-to-back converter. In the given fig 2 the wind blade is directly connected to the rotor and stator is connected to the grid. The transformer is used to increase or decrease the voltage level where it requires. The gear box is required to rotate the rotor above synchronous speed. For rotating the rotor above synchronous speed low speed shaft and high speed shaft are placed in the gear box system. This system is rotating the rotor above synchronous speed, when the wind velocity is below the rated speed. With the help of high speed shaft the rotor is rotates higher speed in comparison of stator magnetic field. Thus induction motor is operated in generating mode.

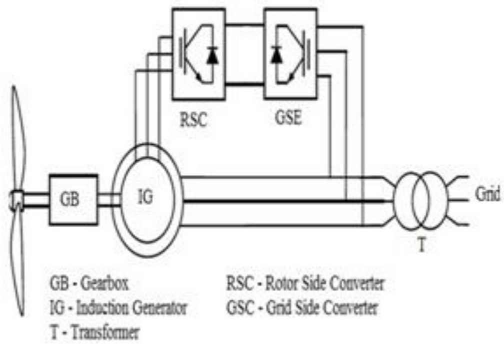

Fig. 2. Induction generator connected to grid

The stator of the wound rotor induction machine is connected to the balanced three-phase grid. The grid side converter controls the power flow between the DC bus and rotor and allows the system to be operated in super synchronous speed.

The mathematical equation for wound rotor induction generator is as follows-

Prime mover power which is converted into electrical power in per phase = $P_{m1-\Phi}$

Air gap power = $P_g = \frac{P_{m1-\Phi}}{(1-s)}$ (2)

Reactive power supplied per phase by capacitor bank 1 = $(Q_C\_bank1) = \frac{\left(V_{t12}/\sqrt{3}\right)^2}{X_{c1}}$ (3)

Propagation constant is given by

$(\gamma) = \sqrt{z * y}$ (4)

Load angle of inverter voltage

$$(\delta) = \sin^{-1}\left[\left(\frac{P_{rg} * X}{|V_{inv}| * |V_{r\_bus\_bar}|}\right) * 10^{-3}\right]$$

(5)

Reactive power of inverter output side

$= (Q_{rg})$
$= \frac{V_{r\_bus\_bar}}{X} * (V_{r\_bus\_bar} * \cos\delta)$ (6)

Reactive power drawn from synchronous condenser

$(Q_{sy}) =$

$\frac{|V_{r\_bus\_bar}|}{|X_s|}\left[E * \cos\delta - \left(|V_{r\_bus\_bar}|\right)\right]$ (7)

Voltage regulation between sending end voltage and receiving end voltage (VR) =

$\left(\frac{|V_{s\_bus\_bar}| - |V_{r\_bus\_bar}|}{|V_{r\_bus\_bar}|}\right) * 100$ (8)

4. 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 torque slip characteristic of induction motor.

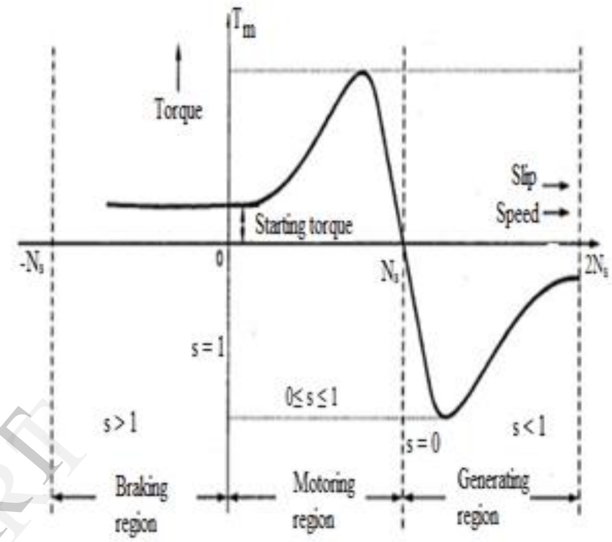

Fig. 3. Torque slip characteristics

It is observed that the induction machine operated as generator mode when the rotor is driven above the 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 Motoring mode. From the characteristics it is clear that when machine is in motoring mode the speed of rotor is less the stator magnetic field speed. In motoring mode the machine has absorbing active as well as reactive power while in generating mode machine has absorbs reactive power (for creating its own magnetic field) and supplies active power.

5. Steady State Response

In this section the study of current are observed, with and without reactive power compensation.
For compensating the reactive power various reactive power compensators devises are employed. Fig-4 shows the plot between current of line-1(line between grid and stator) before and after

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compensation of reactive power. It is clearly shows that after compensation of reactive power the current level is reduced.

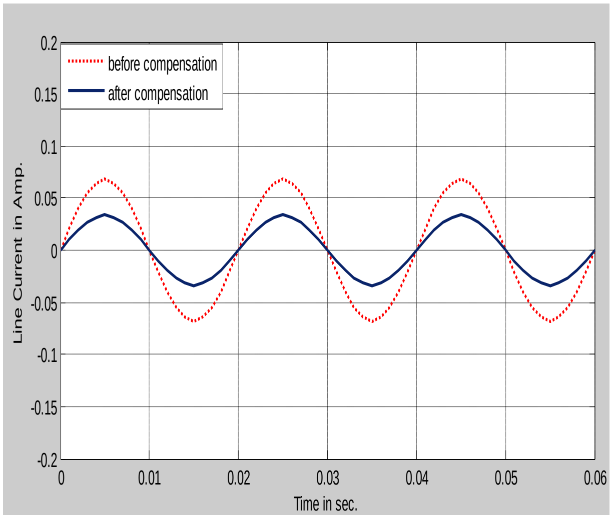

Fig. 4. Plot between current in line before and after compensation

Fig. (5) Shows the rotor circuit current before and after compensation of reactive power. It is observed that the reactive power absorbed by the induction is also decreases rotor current rapidly after compensation.

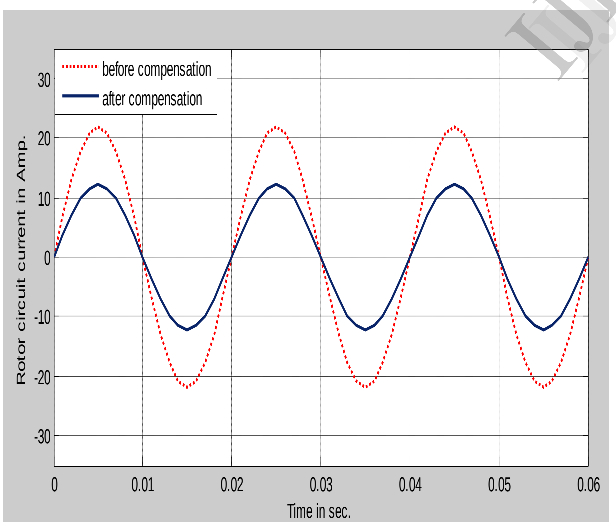

Fig. 5. Response of rotor current before and after compensation

Fig. (6) Shows the receiving end voltage at load side. In this paper the receiving end voltage are kept constant.

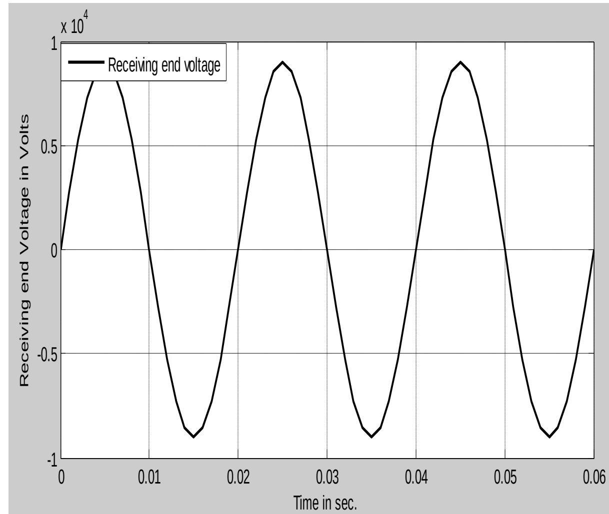

Fig. 6. Plot of receiving end voltage

Fig. (7) Shows the comparison between receiving end voltage and sending end voltage after compensation of the reactive power. It is clear that the amount of voltage will reduced after compensation of reactive power.

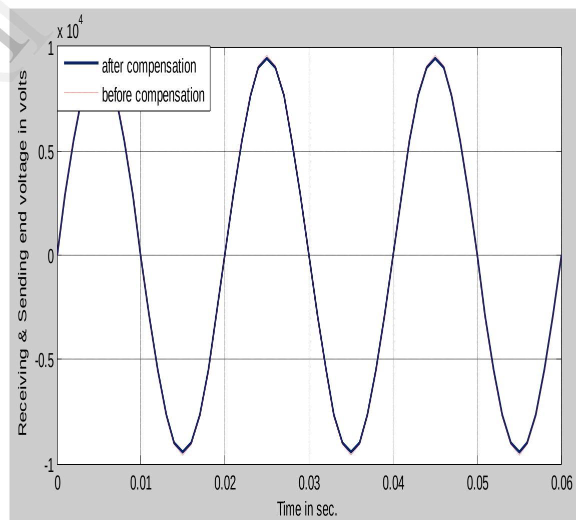

Fig. 7. Comparison of receiving end voltage and sending end voltage

6. Conclusion

In this paper, steady state characteristics of double-out induction generator have been studied during normal conditions. This paper shows the mathematical modelling of wind turbine driven doubly-fed induction generator which feeds active power to the utility grid and draw reactive power from the grid. During steady state conditions, the DFIG feeds active power to the grid and reactive power is supplied to the machine 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). In this paper the power factor of wind farm as well as voltage regulation of load side is analyse and overall behaviour of power and power flow in wind farm is observed.

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