Modelling,Simulation And Analysis Of Doubly Fed Induction Generator For Wind Turbines

Amarendra Singh[1], Er.Pratibha Tiwari[2],

Department of Electrical and Electronics Engineering (SSET), SHIATS, Allahabad, India

Abstract: This paper refers to modeling, simulation and analysis of doubly fed induction generator for wind turbines. This paper presents the modelling of DFIG based WT system and the simulation results performed for the system developed in Simulink environment of MATLAB . A gird connected wind energy generation model is developed and simulated for normal operation and for some faults in the grid. the analysis, modeling, and control of the doubly-fed induction generator (DFIG) for wind turbines. The variable speed wind turbine generator with doubly-fed induction generator (DFIG) is today widely used concept. control system of the doubly-fed induction generator wind turbine with focus on the control strategies and on active power reference value choice Different rotor current control methods are investigated with the objective of eliminating the influence of the back electromotive force (EMF), which is that of, in control terminology, a load disturbance, on the rotor current.

Keywords: Doubly-fed induction generator, wind turbine, wind energy, current control, voltage sag, power quality, simulation, MATLAB.

I.   INTRODUCTION

Turbine (wts)can either operate at fixed speed or variable speed for a fixed speed wind turbine the generator is directly connected to the electrical grid for a variable speed wind turbine the generator is controlled by power electronic equipment. There are several reasons for using variable-speed operation of wind turbines among those are possibilities to reduce stresses of mechanical structure, a coustic noise reduction and the possibility to control active and reactive power [11]. Most of the major wind turbine manufactures are developing new larger wind turbines in the 3-to-5-mw range [3]. These large wind turbines are all based on variable-speed operation with pitch control using a direct driven synchronous generator (without gearbox) or a doubly-fed induction generator (dfig).fixed-speed induction generators with stall control are regards as unfeasible [3] for these large wind turbines today, doubly-fed induction generators are commonly used by the wind turbine industry (year 2005) for large wind turbines [19, 29,]. The major advantage of the doubly –fed induction, which has made it popular is that the power electronic equipment only has to handle a fraction (20–30%) of the total system power [36, 68,]. This means that the losses in the power electronic equipment can   1be reduced in comparison to power electronic equipment that has to handle the total system power as for a direct-driven synchronous generator apart from the cost saving of using a smaller converter.

II.   WIND ENERGY SYSTEM

II.I. Wind Energy Conversion

In this section, properties of the wind, which are of interest in this thesis, will be described. First the wind distribution, i.e., the probability of a certain average wind speed, will be presented. The wind distribution can be used to determine the expected value of certain quantities, e.g. produced power. Then different methods to control the aerodynamic power will be described. Finally, the aerodynamic conversion, i.e., the so-called $Cp(\lambda, \beta)$-curve, will be presented. The interested reader can find more information in, for example, [11, 53].
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II.II. Wind Distribution

The most commonly used probability density function to describe the wind speed is the Weibull functions [53]. The Weibull distribution is described by the following probability density function

$$f(w) = \frac{k}{c}\left(\frac{w}{c}\right)^{k-1} e^{-(w/c)^k} \tag{2.1}$$

where k is a shape parameter, c is a scale parameter and w is the wind speed. Thus, the average wind speed (or the expected wind speed), $\overline{w}$, can be calculated from

$$\overline{w} = \int_0^\infty w f(w) dw = \frac{c}{k}\Gamma\left(\frac{1}{k}\right) \tag{2.2}$$

where Γ is Euler's gamma function, i.e.,

$$\Gamma(z) = \int_0^\infty t^{z-1} e^{-t} dt. \tag{2.3}$$

If the shape parameter equals 2, the Weibull distribution is known as the Rayleigh distribution. For the Rayleigh distribution the scale factor, c, given the average wind speed can be found from ($k=2$, and $\Gamma(\frac{1}{2}) = \sqrt{\pi}$)

$$c = \frac{2}{\sqrt{\pi}}\overline{w}. \tag{2.4}$$

In Fig. 2.1, the wind speed probability density function of the Rayleigh distribution is plotted.The average wind speeds in the figure are 5.4 m/s, 6.8 m/s, and 8.2 m/s. A wind speed of 5.4 m/s correspond to a medium wind speed site in Sweden [100], while 8–9 m/s are wind speeds available at sites located outside the Danish west coast [24].
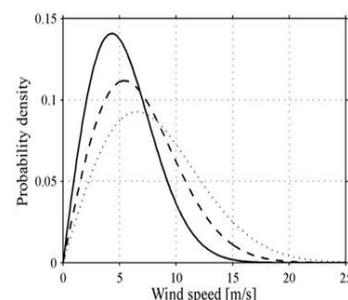

Fig. 2.1. Probability density of the Rayleigh distribution. The average wind speeds are 5.4 m/s (solid), 6.8 m/s (dashed) and 8.2 m/s (dotted).

II.III. Aerodynamic Power Control

At high wind speeds it is necessary to limit the input power to the wind turbine, i.e., aerodynamic power control. There are three major ways of performing the aerodynamic power control, i.e., by stall, pitch, or active stall control. Stall control implies that the blades are designed to stall in high wind speeds and no pitch mechanism is thus required [11].

II.IV. Aerodynamic Conversion

Some of the available power in the wind is converted by the rotor blades to mechanical power acting on the rotor shaft of the WT. For steady-state calculations of the mechanical power from a wind turbine, the so called $Cp(\lambda, \beta)$-curve can be used. The mechanical power, Pmech, can be determined by [53].

$$P_{\text{mech}} = \frac{1}{2}\rho A_r C_p(\lambda, \beta)w^3$$

$$\lambda = \frac{\Omega_r r_r}{w}$$

III. DOUBLY FED INDUCTION GENERATOR

The DFIG is an induction machine with a wound rotor where the rotor and stator are both connected to electrical sources, hence the term 'doubly-fed'. The rotor has three phase windings which are energised with three-phase currents. These rotor currents establish the rotor magnetic field. The rotor magnetic field interacts with the stator magnetic field to develop torque. The magnitude of the torque depends on the strength of the two fields (the stator field and the rotor field) and the angular displacement between the two fields. Mathematically, the torque is the vector product of the stator and rotor fields. Conceptually, the torque is developed by magnetic attraction between magnet poles of opposite polarity where, in this case, each of the rotor and stator magnetic fields establish a pair of m agnet poles. The AC/DC/AC Converter is divided to two components: the rotor side converter and the grid side converter. These converters are voltage sourced converters that use force commutated power electronic devices to synthesize an AC Voltage from
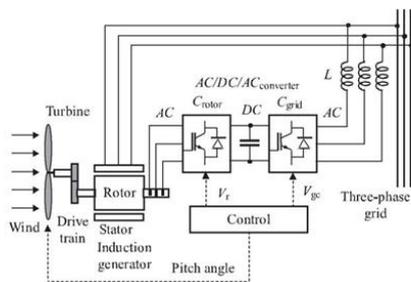

Fig. 1. Wind Energy Conversion System The power output from a wind turbine is given by the equation [7]

a DC source. A capacitor connected on the DC side acts as the DC voltage source. A coupling inductor is used to connect the grid side converter to the grid. The three phase rotor winding is connected to the rotor side converter by slip rings and brushes and the three phase stator windings are directly connected to the grid. The control system generates the pitch angle command and the voltage command signals Vr and Vgc for the rotor and grid side

converters respectively in order to control the power of the wind turbine, the DC voltage and the reactive power or the voltage at the grid terminals [13].

IV. POWER FLOW in DFIG

Figure 2 shows the Power flow in a DFIG. Generally in the DFIG system the value of slip is much lower than 1 and consequently the rotor electrical power output Pr is only a fraction of stator real power output Ps . Since the electromagnetic torque Tm is positive for power generation and since Ws is positive and constant for a constant frequency grid voltage, the sign of Pr is a function of the slip sign Pr is is negative for positive slip (speed lower than synchronous speed). The machine is operated in the sub-synchronous mode, at, ωm < ωs., if and only if its speed is exactly ωm = ωs - ωr >0 and both the phase sequences of the rotor and stator mmf's are the same and in the positive direction, as referred to as as positive phase sequence (ωr > 0) [6]..and it is positive for negative slip (speed greater than synchronous speed).The machine is operated in the super-synchronous mode, i.e., ωm > ωs, if and only if its speed is exactly ωm = ωs – (-ωr) = ωs + ωr >0, and the phase sequence in the rotor rotates in opposite direction to that of the stator, negative phase sequence (ωr<0) [6].This condition takes place during the condition of high wind speeds. . For sub synchronous speed operation, Pr is taken out of the DC bus capacitor and tends to decrease the DC bus voltage For super synchronous speed operation, Pr is transmitted to DC bus capacitor and tends to raise the DC voltage. The grid side converter is used to generate or absorb the grid electrical power Pgc in order to keep the DC voltage constant. In steady state for a lossless AC/DC/AC converter Pgc is equal to Pr and the speed of the wind turbine is determined by the power Pr absorbed or generated by the rotor side converter. By properly controlling the rotor side converter, the voltage measured at the grid terminals can be controlled by controlling the grid side converter DC bus voltage of the capacitor can be regulated.
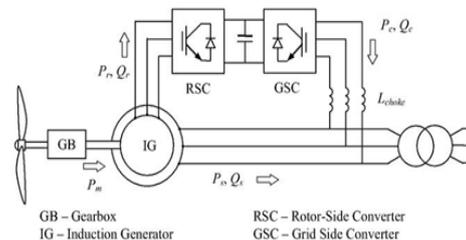

GB – Gearbox   RSC – Rotor-Side Converter
IG – Induction Generator   GSC – Grid Side Converter

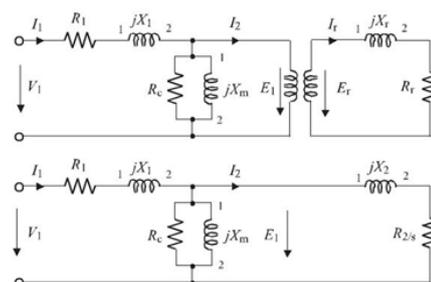Fig.2 doubly-fed induction generator system power flow

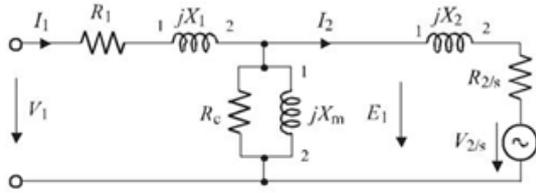Fig. 3. Conventional induction machine equivalent circuit

Fig. 4. Equivalent circuit of DFIG

V.   TORQUE SPEED CHARACTERISTICS

To understand the operating characteristics of a DFIG is to investigate DFIG characteristic curves through simulation. Unlike a traditional induction machine, these characteristics depends on the applied stator voltage and on the injected rotor voltage V2 . The amplitude and angle of this equivalent injected rotor voltage changes as the real and reactive power control signals from the rotor side converter varies.When a traditional fixed-speed induction machine is used for wind power generation the operating speed or slip is affected only by the wind speed whereas when a
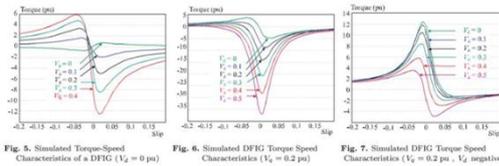

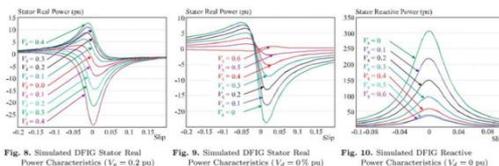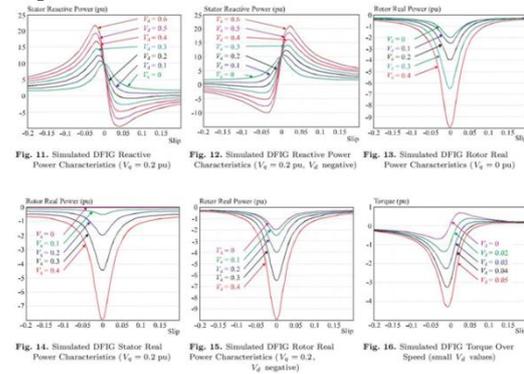**Fig. 5.** Simulated Torque-Speed Characteristics of a DFIG ($V_d = 0$ pu) **Fig. 6.** Simulated DFIG Torque Speed Characteristics ($V_d = 0.2$ pu) **Fig. 7.** Simulated DFIG Torque Speed Characteristics ($V_q = 0.2$ pu , V_d negative)

Fig. 8. Simulated DFIG Stator Real Power Characteristics ($V_d = 0.2$ pu) **Fig. 9.** Simulated DFIG Stator Real Power Characteristics ($V_d = 0\%$ pu) **Fig. 10.** Simulated DFIG Reactive Power Characteristics ($V_d = 0$ pu)

DFIM is used as a generator in a wind turbine system, the operating slip of a DFIM is affected by the injected rotor voltage. Hence, the traditional fixed-speed induction machine have different output power and electromagnetic torque characteristics from DFIGs . This peculiar behaviour of DFIG can be simulated in MATLAB and presented as different characteristic curves. As it is known, a conventional fixed-speed induction machine operates in motoring mode for $0 < s \leq 1$ and generating mode for $1 < s \leq 0$. The common operating slips of a fixed-speed induction machine lie within a very narrow slip range around ±2%. The normal motoring region lies between 98% and 100% of synchronous speed, while the normal generating region lies between 100% and 102% of synchronous speed. Rated power is usually about 50% of peak powers. DFIG work s at both over and below the synchronous speed to generate electricity but fixed-speed wind turbine is not woks at both synchronous speed. The generating mode of DFIG corresponding to negative torque values extends from the negative slip (super synchronous speed) to positive slip (sub-synchronous speed) region. Through the phase angle and amplitude of the equivalent injected rotor voltage we modified the DFIG torque-speed characteristics. For simulation, the real and imaginary components of the injected rotor voltage are varied to observe the variation in the torque speed

characteristics. For practical operating characteristics of the DFIG, the simulation study is performed corresponding to the decoupled DFIG control concepts, assumed that Vq keeps positive for real power control but Vd can be positive or negative for reactive power control. Figure 5 presents the DFIM torque-speed characteristics as the imaginary component, Vq , of the injected voltage changes from 0 to 0.5 pu when the real component, Vd , is fixed at 0 pu, from the figure when both the real and imaginary components are 0, the DFIM torque-speed characteristic is the same as the traditional induction machine torque- speed characteristic, and the DFIM operates in generating mode only above the synchronous speed. When we increasing Vq while keeping Vd constant, the DFIM torque-speed characteristics shift more from over-synchronous to sub-synchronous range to generate electricity, and the DFIG becomes more stable because the pushover torque increases too. The variation in the real component of rotor injected voltage, Vd , also affects the DFIG torque characteristics. Fig. 6. shows the DFIM torque-speed characteristics as a function of

Fig. 11. Simulated DFIG Reactive Power Characteristics ($V_q = 0.2$ pu) **Fig. 12.** Simulated DFIG Reactive Power Characteristics ($V_q = 0.2$ pu, V_d negative) **Fig. 13.** Simulated DFIG Rotor Real Power Characteristics ($V_q = 0$ pu)

Fig. 14. Simulated DFIG Stator Real Power Characteristics ($V_q = 0.2$ pu) **Fig. 15.** Simulated DFIG Rotor Real Power Characteristics ($V_q = 0.2$, V_q negative) **Fig. 16.** Simulated DFIG Torque Over Speed (small V_q values)

synchronous range for its stable generating mode and the DFIG becomes more stable because the pushover torque increases for negative values of Vd . In Fig. 7 under a constant Vq at 0.3 pu, the DFIG torque-speed characteristics for its generating mode shrink while Vd is negative and the absolute value of Vd increases. Figure 7 shows the simulated DFIG torque-speed characteristics ,the real component of the injected rotor voltage, Vd , is positive and changes from 0 to 0.6 pu while Vq is fixed at 0.3 pu. The increase of Vd shifts the DFIM torque-speed characteristics more to sub- synchronous range for its stable generating mode and the DFIG becomes more stable because the pushover torque increases for negative values of Vd .Shown in Fig. 7 under a constant Vq at 0.3pu, the DFIG torque-speed characteristics for its generating mode shrink while Vd is negative and the absolute value of Vd increases. Figure 7 shows the simulated DFIG torque-speed characteristics(Vq = 0.3pu).

VI.   STATOR POWER

DFIM has stator power generator which include the active and reactive power that is send to the grid with help of DFIM stator winding. When grid is drive at a speed above the synchronous speed then a conventional fixed-speed induction generator sends real power to the grid, but it also draws inductive reactive power from the grid for magnetizing and leakage reactive power needs characteristics of DFIG can be change, when DFIG is

with an injected rotor voltage. This characteristic may be changed. The simulation study is conducted by keeping the value of either Vq or Vd component constant while varying the other one. Figure 8 shows the power supply system of the DFIG from which real power taken as Vd increases from −0.6 pu to 0.6 p.u while Vq is kept constant at 0.4 pu. Figure 9 shows the DFIG real power as Vq increases from 0 pu to 0.6 p.u while Vd is kept constant at 0 pu More simulation results show that DFIG torque-speed characteristics can be shifted or expanded by varying the amplitude of the rotor-injected voltage when both Vq and Vd are positive. It can be concluded:

1) The component of the rotor injected voltage either vq or vd increases positively, the DFIG real power generation characteristics shift more into sub-synchronous speed range.

2) The generation pushover power of a DFIG rises too through by vq or vd increases positively, showing increased DFIG stability and power generation capability.

3) vd changes from negative to positive DFIG real power changes slowly from flowing into induction machine. In the traditional induction machine it takes inductive reactive power from the power supply system for its leakage and magnetizing reactive power need sunder both motoring and generating modes. But it is not happened in the DFIG system due to injected rotor voltage. Through study the torque, reactive power and real power characteristics as well as many other simulation results. It is obtained that
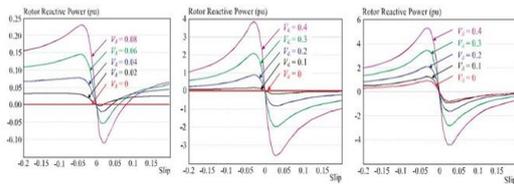

Fig. 17. Simulated DFIG Rotor Reactive Power Over Speed (small *Vq* values)   **Fig. 18.** Simulated DFIG Rotor Reactive Power Over Speed (*Vq* = 0.2 pu)   **Fig. 19.** Simulated DFIG Rotor Reactive Power Over speed (*Vq* = 0.4 pu)

4) In the generating mode, if we increase Vq can result in the expansion of DFIG torque and real power characteristics, also results in more inductive reactive power needed by the DFIG,

5) if we increase Vd, it shifted DFIG real power and torque characteristics to its generating mode but also reduce the DFIG inductive reactive power and even could change it to capacitive, and

6) if we increase of Vd negatively it shrinks the DFIG torque and real power characteristics in generating mode and results in more inductive reactive power need.

7) conclusion of above analysis that proper coordination between both Vd and Vq components of the DFIG injected rotor voltage results in optimal operation of DFIG in terms of real power torque, and reactive power.

VII. ROTOR POWER CHARACTERISTICS

The rotor windings of a 1 fixed-speed wound rotor induction machine are normally shorted by the slip rings so that there is no power output from the rotor of the induction machine. The rotor power under both generating and motoring modes are rotor copper loss. For a DFIG, owever, the rotor power means not only the rotor copper loss but also real and reactive power passing to the rotor, which is fed to the grid through the DFIG frequency converter. Figures 13 to 15 show the simulated real power passing to the DFIG rotor, under the conditions of a) Vq = 0 pu and Vd = 0 to 0.5 pu, b) Vd = 0.3 pu and Vq = 0 to 0.5 pu, and c) Vq = 0.3 pu and Vd = 0 to 0.5 pu From the figures, as well as the simulation analysis, it is found that 1) the DFIG sends an additional real power through its rotor to the grid in both motoring and generating as shown in Figs. 13–15. 2) The power sent to the grid through DFIG rotor is mainly dependent on the amplitude of the injected rotor voltage as shown in Figs. 13–15. 3) The real power delivered by the DFIG rotor is maximum at high values of the injected rotor voltages, synchronous speed at which the DFIG rotor is equivalent. To a short circuit. A proper control of Vq and Vd is essential to prevent high currents flowing in the rotor and 4) A comparison between DFIG stator and rotor real power shows that the rotor power is normally smaller than the stator power and the difference between the two really depends on the Vq and Vd values and the slip. There is also reactive power passing to the DFIG rotor. Fig. 16. shows the simulated DFIG torque-speed .

CONCLUSIONS

In this paper a simulation study on the operating characteristics of a doubly fed induction generator is conducted using MATLAB. From the simulation analysis it has been made clear that the DFIG characteristics are affected by its injected rotor voltage. By changing the amplitude and phase angle of the rotor injected voltage, the DFIG torque speed characteristics are shifted from the over-synchronous to sub-synchronous speed range to generate electricity and also increases the DFIG pushover torque, therefore improving the stability of operation. The simulated stator real power characteristics of the DFIG shows that with the increase in the rotor injected voltage, the DFIG real power characteristics shifts more in to the sub-synchronous speed range and the pushover power of the DFIG rises. The increase of Vq results in the expansion of the DFIG torque and real power characteristics for its generating mode, but at the same time increase the inductive reactive power demand from the grid. Whereas, the increase of Vd can not only expand DFIG torque and real power characteristics for its generating mode but also reduces the DFIG inductive power demand and may even change its capacitive. For both motoring and generating modes, the DFIG sends additional real power through its rotor to the grid Unlike the stator power, the characteristics of rotor power are mainly affected by the rotor injected voltage. A comparison of the stator and rotor real power shows that the rotor power is normally smaller than the stator power and the difference between the two depends on the values

of Vd and Vq and slip. It can also be seen that the DFIG rotor power is capacitive when the DFIG operates in the generating mode under a sub synchronous speed and is inductive otherwise.

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BIOGRAPHIES

Amarendra singh Belong to allahabad received her Bachelor of Technology degree from U.P.T.U University, ghaziabad in 2012. He is pursuing his M.Tech in Electrical Engg. (Power System) from SHIATS, Allahabad, UP-India.

Er pratibha Tiwari. Belong to Allahabad, Received his Bachelor of Engineering degree from the VPS Purvanchal in 2002, He obtained his M.Tech in Electrical Engg. (Control & Instrumentation.) from MNNIT Allahabad, India.in 2006 . Presently he is working as Assi. Prof. in Electrical Engg. Dept. SSET, SHIATS (Formally Allahabad Agriculture Institute, Allahabad-India).