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Interpretation of the Operation Modes of the Doubly Fed Induction Machine in Wind Energy Systems

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Abstract: *Over the last years, there has been a strong penetration of renewal energy sources into the power supply network. Wind energy generation has played and will continue to play a very important role in this area for the coming years. Doubly fed induction machine (DFIM) based wind turbines have undoubtedly arisen as one of the leading technologies for wind turbine manufacturers, demonstrating that it is a cost effective, efficient and reliable solution. This machine, a key element of the wind turbine, presents many similarities with themostly used and popular squirrel cage induction machine (SCIM).However, despite the parallelism of both machines, the DFIM requires its own specific study for an adequate understanding.*

In this paper, the steady state characteristics of a doubly fed induction machine, used as wind turbine generator, is analyzed. Analysis is performed to investigate a variety of DFIM characteristics, including torque-speed, real and reactive power over speed characteristics. Based on the analysis, it can be seen that the DFIM can operate under different conditions depending on the power and the speed.

Keywords-*Doubly fed induction machine, rotor power, stator power, sub-synchronous, super-synchronous, torque-speed characteristic*

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I. Introduction

Both induction and synchronous machines can be used for wind turbine systems. Induction machines can be used in a fixed-speed system or a variable-speed system, while synchronous machines arenormally used in power electronic interfaced variable-speed systems. Mainly, three types of induction machines are used in wind power conversion systems: cage rotor, wound rotor with slip control by changing rotor resistance, and doubly fed induction machines. The cage rotor induction machine can be directly connected into an AC system and operates at a fixed speed or uses a full-rated power electronic system to operate at variable speed. The wound rotor machine with rotor-resistance-slip control is normally directly connected to an AC system, but the slip control provides the ability of changing the operation speed in a certain range. The doubly fed inductionmachines provide a wide range of speed operation from sub-synchronous to super-synchronous speeds.This paper is focused on the standard doubly fed induction machine considering only the steady state [1, 2].This is confirmed by the fact and that the standard doubly fed induction machine is the mostly one used today by the major wind turbine manufacturers.

To understand the behaviour of DFIM, it is essential to investigate a variety of DFIM characteristics [3-6]. In this paper, a detailedperformance evaluation of the machine,used as wind turbine generator,is carried out depending on the specificoperating conditions of the machine. First, the doubly fed induction machine concept is introduced. Then, the steady state electric circuit of the machine is developed, deriving the steady state model electric equations along with its physics. Next, by means of these model equations, the modes of operation of the machine are presented and analyzed. Finally, based also on the model equations, a variety of DFIG characteristics including torque-speed, and active and reactive power outputs of stator and rotor sides with respect to rotor slip variations are analyzed.

II. Doubly Fed Induction Machine

A doubly-fed induction machine is basically a standard, wound rotor induction machine equipped with slip rings. Fig.1 shows a principle diagram of the doubly-fed induction machine.It consists of two three-phase windings need to be supplied independently and also both windings can be bidirectionally energy supplied. The stator circuit is connected directly to the grid while the rotor circuit is controlled by an inverter via slip rings.When the three stator windings are supplied by a balanced three-phase voltage of frequency f_s, the stator flux is induced. This stator flux rotates at constant speed. That is, the synchronous speed (n_s).According to Faraday's law, this rotational stator flux induces an emf in the rotor windings.Due to this induced voltage in the rotor windings and the voltage that can be injected externally through the brushes, a current is induced in the rotor windings. This current, according to Laplace's law, creates an induced force in the rotor of the machine.

The induced voltage in the rotor depends on the relation between the stator flux rotational speed and the rotational speed of the rotor [7].

The angular frequency of the induced rotor voltages and currents is given by the relation:

$$\omega_r = \omega_s - \omega_m \quad (1)$$

The relation between the speed of the stator and the rotor angular frequency is the slip, s:

$$s = \frac{\omega_s - \omega_m}{\omega_s} \quad (2)$$

The relation between the slip,the stator, and the rotor angular frequency is given by:

$$\omega_r = s\omega_s \quad (3)$$

Equivalently, the relation between the frequencies can also be derived:

$$f_r = sf_s \quad (4)$$

Depending on the sign of the slip, it is possible to distinguish three different operating modes for the machine:

$$\omega_m < \omega_s \Rightarrow \omega_r > 0 \Rightarrow s > 0 \Rightarrow Subsynchronous\ operation$$
$$\omega_m > \omega_s \Rightarrow \omega_r < 0 \Rightarrow s < 0 \Rightarrow Hypersynchronous\ operation$$
$$\omega_m = \omega_s \Rightarrow \omega_r = 0 \Rightarrow s = 0 \Rightarrow Synchronous\ operation$$

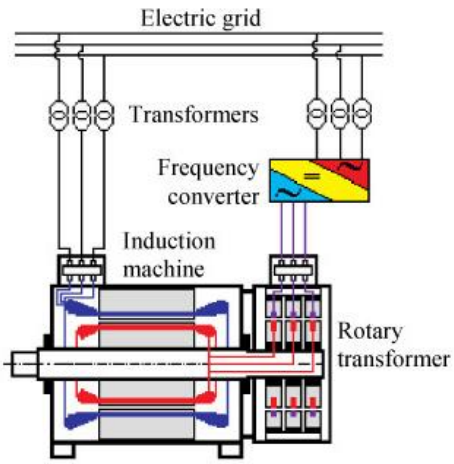

Figure 1. Grid connection of the doubly fed three-phase induction machine

III. Dfim Steady State Model

Figure 2 shows a diagram over the steady-state equivalent circuit of the short-circuited induction machine.Most induction machines have a short-circuited rotor,but to be able to influence the rotor circuit, the induction machine must be equipped with a wound rotorequipped withsliprings. In the case of doubly fed induction machines, however there is a voltage injected in to the rotor windings sothat the normal induction machine equivalent circuit of Fig.2 needs to be modified by adding a rotor injected voltage.The equivalent circuit with the inclusion of an external rotor voltage can be seen in Fig.3[8,9].

From the equivalent circuit, for a doubly fed induction machine the real and reactive power of stator P_s, Q_s and rotor P_r, Q_r, the mechanical power and the torque developed T_{em} can be derived as follows:

$$P_s = 3R_s|I_s|^2 + 3Re\{j\omega_s L_m I_r \cdot I_s^*\} \quad (5)$$

$$P_r = 3R_r|I_r|^2 + 3Re\{js\omega_s L_m I_s \cdot I_r^*\}(6)$$

$$Q_s = 3\omega_s L_s|I_s|^2 + 3Im\{j\omega_s L_m I_r \cdot I_s^*\}(7)$$

$$Q_r = 3s\omega_s L_r|I_r|^2 + 3Im\{js\omega_s L_m I_s \cdot I_r^*\}(8)$$

$$P_{mec} = 3\omega_m L_m \cdot Im\{I_r^* \cdot I_s\}(9)$$

$$T_{em} = 3pL_m \cdot Im\{I_r^* \cdot I_s\}(10)$$

where$V_s$is the stator voltage,$I_s$stator current,V_r rotor voltage related to stator side,$I_r$rotor current related to stator side, $R_s$stator winding resistance,$R_r$rotor resistance related to stator side, $L_{\sigma s}$ stator leakage inductance, $L_{\sigma r}$ rotor leakage inductance related to statorside, L_m magnetizing inductance and$s$is theslip.

By neglecting the copper power losses in the stator and rotor resistances,the relation between the stator and rotorpower becomes:

$$P_r \cong -sP_s \quad (11)$$

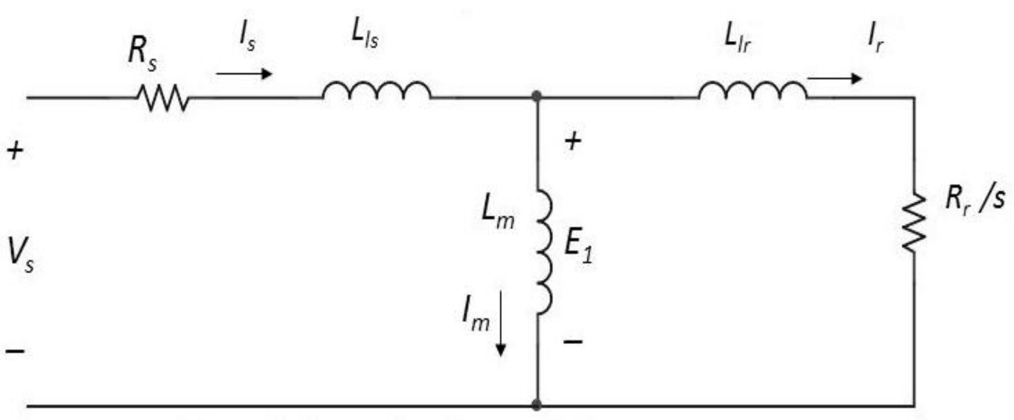

Figure 2. Conventional induction machine equivalent circuit

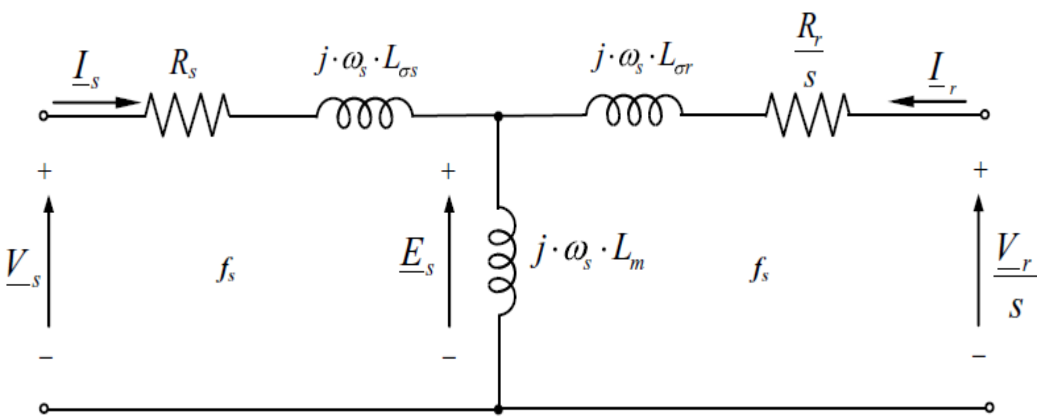

Figure 3. Equivalent circuit of the induction machine with inclusion of rotor voltage

IV. Power Flow in DFIM

The DFIM can operate under different conditions depending on the power and the speed.Hence,the DFIM can operate likely as motor or generator.Fig.4 graphically illustrates the four quadrant operation modes.When the DFIM operates like motor at sub-synchronous speed, Fig.4-a, the power P_r is provided by the rotor. If speed increases so that the motor operates into super-synchronous speed, Fig.4-b, the power P_r is absorbed by the rotor. While DFIM operates in generator at sub-synchronous speed, Fig.4-c, the power P_r is then absorbed by the rotor. If speed increases so that the generatoroperates at super-synchronous speed, Fig.4-d, the power P_r changes directionand the rotor provides a possible recovery power [10].

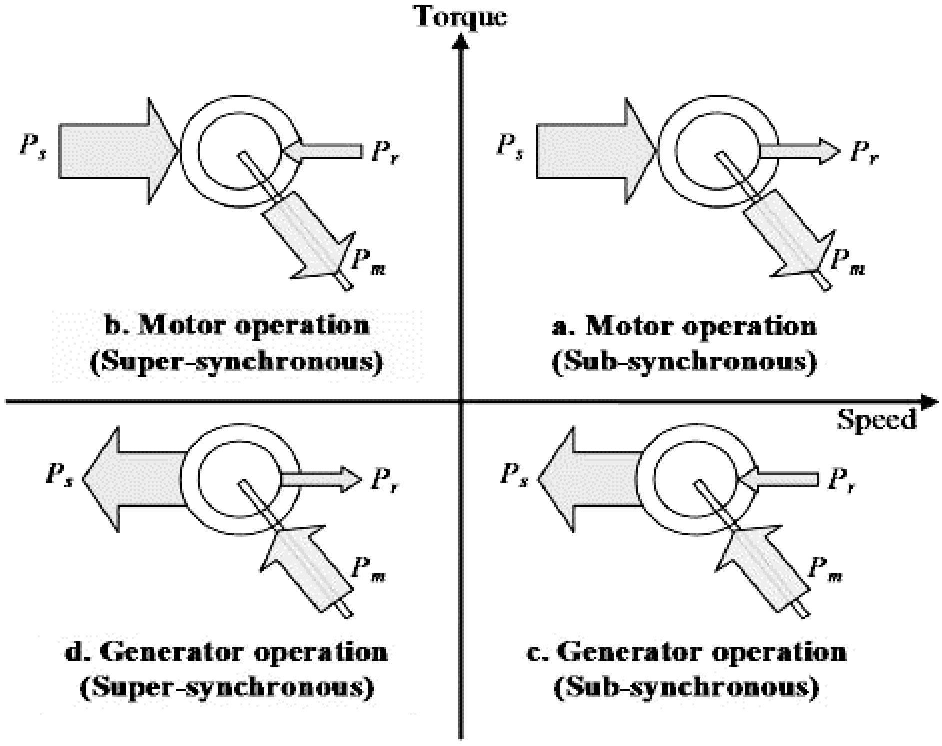

Figure 4: Operational modes characteristic of the DFIM

V. Steady-State Operational Characteristics of the Doubly-Fed Induction Machine

5.1 Electromechanical Torque-Speed Characteristics

Unlike a traditional induction machine, the operating characteristics of a DFIG not only depend on the applied stator voltage, but also depend on the injected rotor voltage V_r. Moreover, the possibility of changing both the amplitude and phase of the rotor voltage V_r provides an additional degree of freedom for control. For the doubly-fed induction machine the applied rotor voltage, V_r, can be adjusted to get the desired slip or torque.

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 whenaDFIM is usedas a generator ina wind turbine the operating slip of a DFIM is also affected by the injected rotor voltage.Hence,the turbine output power and electromagnetic torque characteristics of DFIGs are different from traditional fixed-speed induction machine. As it is known, a conventional fixed-speed induction machine operates in generating mode for $-1 \leq s < 0$ and motoring mode for $0 < s \leq 1$.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.Unlike a traditional fixed-speed induction machine, a DFIG can run both over and below the synchronous speed to generate electricity. 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. The DFIG torque-speed characteristics can be modified by varying the amplitude and phase angle of the equivalent injected rotor voltage. Fig.5 illustrates the torque-speed characteristics of the doubly-fed induction generator with different applied rotor voltages.

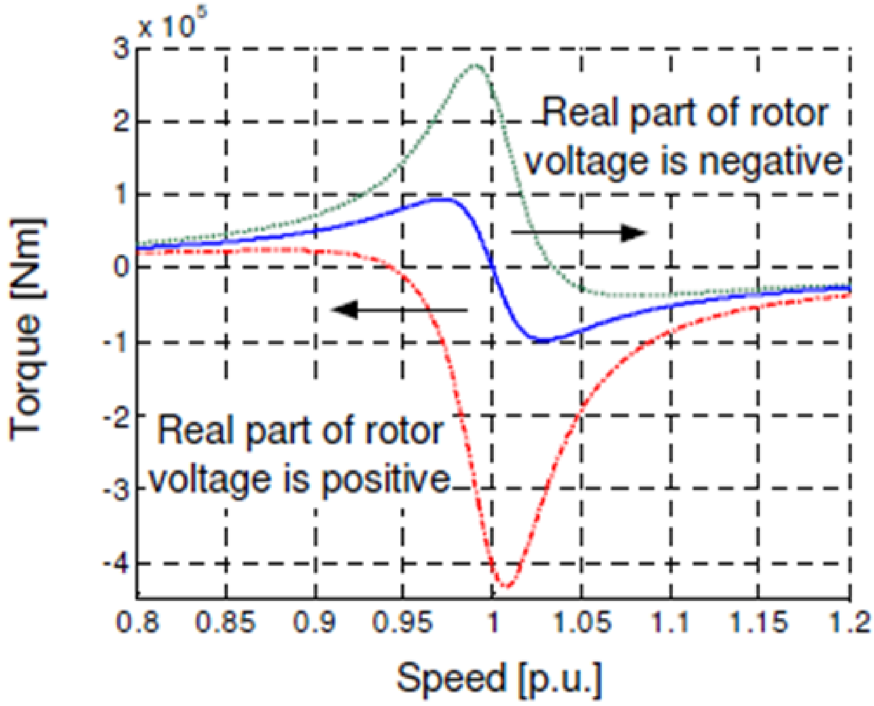

Figure 5: Torque-speed characteristic for a doubly-fed induction generator with three different applied rotor voltages

From the figure, it can be seen that, the overall behavior of DFIG is essentially same as that of SCIG. However, depending on the supplied rotor voltage, DFIG performs differently from SCIG. When the injected rotor voltage V_r=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.

If the rotor voltage is positive the torque-speed characteristic is displaced to the left;to the sub-synchronous region.Additional power is then fed into the rotor of the DFIG. This means that the positive increase of the rotor voltage 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 too.In contrast,if the rotor voltage is negative the torque-speed characteristic is displaced to the right;to super-synchronousregion. The rotor power is then fed from the rotor into the grid. So, when the rotor voltage is negative the DFIG torque-speed characteristics for its generating mode shrink.

Clearly,inorder to adjust the rotor speed,electromechanical torque can be easily changed by changing the sign of rotor voltage. Likewise, a deviation of mechanical torque input in SCIG can lead a significant change in the rotor speed whereas for DFIG, by adapting rotor voltage, electromechanical torque can be accommodated to mechanical torque to keep the rotor speed in the stable region.

5.2 Active Power Characteristics

When DFIG is used as a generator in wind turbine,the power outputdepends not only on mechanical power input transmitted by the shaft of wind turbine but also on the behavior of AC/DC/AC converter connected between the rotor winding and the grid.

A traditional induction generator (SCIG) generally exchanges energy with the interconnected grid via only the stator winding while the rotor winding is short-circuited.In DFIG, energy can be exchanged with the linked network by not only the stator winding but also the rotor winding.

A vast proportion of active power that DFIG exchanges with the interconnected grid comes from the stator winding but this active power output also depends on the rotor speed and the rotor voltage(V_r).Fig.6(a)and(b)illustrate the stator active power (P_s)and rotor active power(P_r) of DFIG with respect to varying rotor side voltage, with SCIG's that corresponds to the V_r=0 curve. The points '*x*' and '*y*' represent the rated operating points of DFIG for the sub-synchronous and super-synchronous modes, respectively.

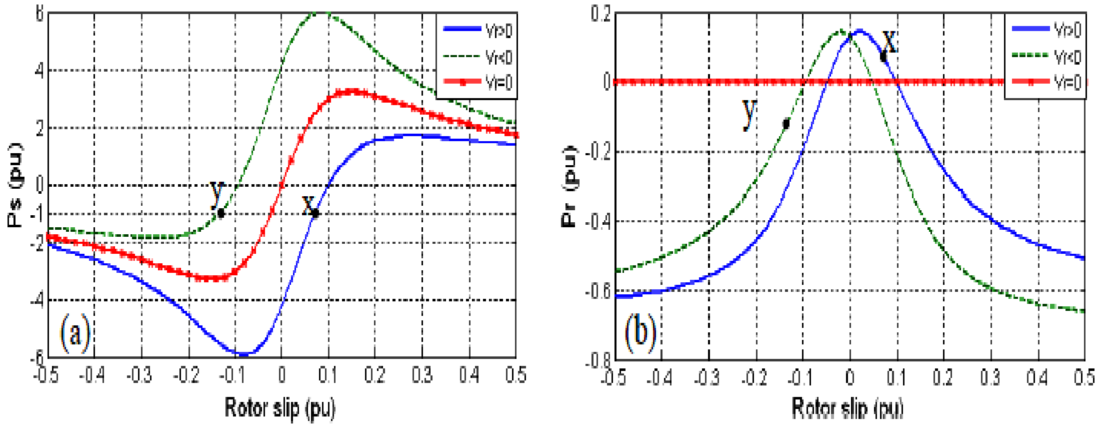

Figure 6:. Active power output of DFIG for the stator side (a), and the rotor side (b)

As can be seen from Fig.6 (a),SCIG only supplies active power to the linked grid when rotor speed is oversynchronous speed. Unlike SCIG,the stator winding of DFIG can deliver active power to the connected grid in sub-synchronous region if a positive voltage is applied to rotor winding. For SCIG, an increase in rotor speed leads to a rise of stator active power but for DFIG, same active power can be produced at different rotor speeds by controlling rotor voltage.

One superior feature of DFIG compared with SCIG is that the rotor winding is connected to the system via AC/DC/AC converter while in SCIG, it is shorted. Therefore, active power in the rotor side of SCIG is always equal to zero whereas the rotor winding in DFIG contributes to the additional energy exchange between DFIG and grid. Thisenergy exchange is almost directly proportional to the product of minus rotor slip and active power in the stator side. In generating mode, rotor winding supplies activepowerto the connected grid forV_r<0 and power flow is reversed forV_r>0.This is resulted from changein the sign of rotor slip.

5.3 ReactivePower Characteristics

Figure 7 (a) and (b) illustrate the stator reactive power (Q_s) and rotor reactive power (Q_r) of DFIG with respect to varying rotor side voltage. The points '*x*' and '*y*' represent the rated operating points of DFIG for the sub-synchronous and super-synchronous modes,respectively, which are the same as those in Fig.6.In SCIG, to create magnetizing flux in generator, it must receive reactive power from the interconnected grid and it requires a higher reactive power to produce a higher active power, which are shown in V_r=0 curve in Fig.7(a).Contrarily,the magnetizingflux in generatorcan be generated by stator or rotor winding in DFIG.Therefore,DFIG can absorb reactive power in the rotor or stator side depending on the behavior of converter.

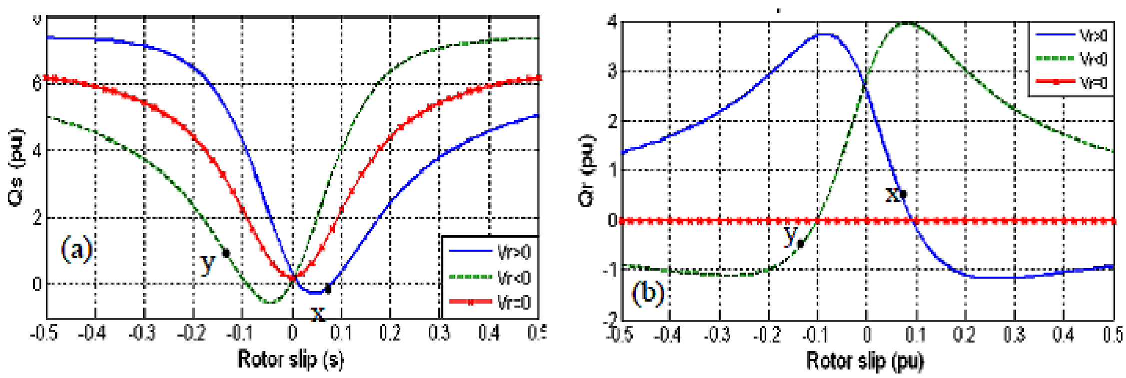

Figure: 7. Reactive power output of DFIG for the stator side (a), and the rotor side (b)

Since rotor winding is short-circuited, reactive power in the rotor side of SCIG is equal to zero as shown in V_r=0 curve in Fig.7 (b).However,the rotor winding of DFIG can absorb reactive power from the grid or supply a part of reactive power to the grid.The figure reveals that the rotor winding can compensate reactive power exchanged by the stator side to the grid.

Another thing drawn from Fig.7 is that reactive power atpoint '*y*' absorbed by the stator side is much higher than that delivered by the rotor side. By contrast,reactive power at point '*x*' absorbed by the rotor side is much higher than that supplied by the stator side. The reactive power output in the rotor side is completely opposite to that in the stator side for the rated generating mode.Therefore, DFIG can magnetize either the stator winding or the rotor winding and total reactive power absorbed from the grid is less than that in SCIG.

VI. Conclusion

This paper concentrates on analyzing the operating characteristics of a doubly fed induction generator including torque-speed and real and reactive power over speed characteristics.

From the analysis,it is clear that the DFIG characteristics are affected by its injected rotor voltage.By varying the amplitude and phase angle of the rotor injected voltage, the DFIG offers a wide range of torque-speed curve depending on the rotor voltagecontrol.Thus,in order to adjust the rotor speed,electromechanical torquecan be easily changed by changing the sign of rotor voltage.This allows DFIG to be able to operate with variable speed.

Depending also on the supplied rotor voltage, DFIG is able to generate active power as rotor speed is sub-synchronous or super-synchronous.In addition, reactive power output of DFIG heavily depends on the mechanical power input and the magnitude of V_r. Thus, a proper coordination of the DFIG injected rotor voltage results in optimal operation of DFIG in terms of torque, real power and reactive power.

References

[1]. T.Ackermann,*Wind power in power systems*(Royal Institute of Technology,John Wiley & Sons,Ltd, 2005).

[2]. F. Blaabjerg, Z. Chen, *Power electronics for modern wind turbines* (Institute of Energy Technology, Morgan & Claypool Publishers, 2006).

[3]. G. Michalke, *Variable speed wind turbines-modelling, control and impact on power systems*, PhD thesis, Technische Universitat Darmstadt, Denmark, 2008.

[4]. M. G. S. Zaghloul, *Modelling and analysis of wind farms*, Master of Science, Ain Shams University, Egypt, 2012.

[5]. B. Babypriya, Modelling, simulation and analysis of doubly fed induction generator for wind turbines, *Journal of Electrical Engineeing, Vol. 60, No. 2, 2009, 79-85*.

[6]. R. Muthu, Doubly fed induction generator for wind energy conversion system-A survey, IEEE Conference Paper, 2013, 617-628.

[7]. G. Abad, J. Lopez, M. A. Rodriguez, L. Marroyo, G.Lwanski, *Doubly fed induction machine:modeling and control for wind energy generation*(Institute of Electrical and Electronics Engineers, Inc., John Wiley & Sons, 2011).

[8]. A. Petersson, *Analysis, modelling and control of doubly-fed induction generators for wind turbines*, Master of Science, Chalmers University of Technology, Sweden, 2003.

[9]. M. R. M. Altimania,*Modeling of doubly-fed induction generators connected to distribution system based on eMEGASim real-time digital simulator*,Master of Engineering, University of Tennessee, Chattanooga, 2014.

[10]. S. Drid, M. S. N. Said, M. Tadjine,The doubly fed induction generator robust vector control based on Lyapunov method,Researchgate, Transactions on Systems, Signals & Devices, Vol.4,No.2,pp.237-249.

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