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Performance of Double Fed Induction Machine at Sub- and Super-Synchronous Speed in Wind Energy Conversion System

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ABSTRACT

In this paper two modes of operating a wound rotor induction machine as a generator at sub-and super-synchronous speeds in wind energy conversion systems are investigated. In the first mode, known as double fed induction generator (DFIG), the rotor circuit is fed from the ac mains via a controlled rectifier and a forced commutated inverter. Adjusting the applied rotor voltage magnitude and phase leads to machine operation as a generator at sub-synchronous speeds. In the second mode, the machine is operated in a slip recovery scheme where the slip energy is fed back to the ac mains via a rectifier and line commutated inverter. This mode is described as double output induction generator (DOIG) leading to increase the efficiency of the wind-to electrical energy conversion system. Simulated results of both modes are presented. Experimental verification of the simulated results are presented for the DOIG mode of operation, showing larger amount of power captured and better power factor when compared to conventional induction generators.

Keywords: Double Fed Induction Machine, Wind Energy, Power generation, Grid-connection

1. Introduction

With increased penetration of wind power into electrical grids, wind energy conversion systems utilizing double fed induction generators (DFIG) are largely deployed due to their ability to operating at variable speeds. For wind mills above 2 MW, the DFIG is the most widely used generator concept (e.g. GE Wind Energy, Vestas, RE Power, Nordex, NEG Micon) [1,2]. The rotor circuit of the DFIG is connected to the grid via a controlled rectifier and controlled inverter. Hence a voltage, at slip frequency, with controlled magnitude and phase angle could be applied to the rotor circuit. This leads to power generation at sub-synchronous speeds, i.e. it extends the speed range within which the induction machine operates as a generator.

This feature allows utilization of wind power at lower wind speeds, leading to a higher efficiency wind energy conversion system. The sub-synchronous generation speed range depends on the magnitude and phase angle of the rotor applied voltage.

Operating the induction machine at super-synchronous speeds is also studied. In this case the rotor circuit is connected to the grid via a diode rectifier followed by a three-phase inverter. This mode of operation is known in the literature as double output induction generator (DOIG).

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In the case of operation as DOIG, varying the inverter firing angle controls the amount of power delivered from the rotor to the grid, saving the power lost in the rotor circuit resistance, thus increasing efficiency in the wind energy conversion system.

In this paper the effect of rotor voltage magnitude and phase angle on the power generated at sub-synchronous speeds is investigated through simulation. Also the magnitude of power generated at super-synchronous speeds compared to the rated power of the induction machine is investigated theoretically. Theoretical results are proved experimentally at super-synchronous speeds, showing that the total power generated from both stator and rotor circuits exceed the rated power of the employed induction machine. It also demonstrates a higher power factor as compared to a conventional induction generator.

2. Modeling Double Fed Induction Generator (DFIG)

A DFIG is a wound rotor induction generator whose rotor is fed from a three-phase variable-frequency source, thus allowing DFIG to operate at variable speeds. This ability to vary operating speed is important in wind generation because it allows for an optimization of the transfer of power from the wind to the turbine blades. A general structure of the model is depicted in Fig. 1.

The variable-frequency supply to the DFIG rotor is attained via the use of two voltage-source converters linked by a capacitor. The rotor-side converter feeds the DFIG rotor circuit with voltage at slip frequency. The main objective of the stator-side converter is to maintain control of the voltage level on the dc bus capacitor.

Phase "a" of the 3-phase stator and rotor voltages is given respectively by:

$$V_{as} = V_s \sin \omega_s t \quad (1)$$

$$V_{ar} = V_r \sin (s\, \omega_s.t - \varphi) \quad (2)$$

where φ is the phase shift between stator and rotor voltages, and s is the slip.

The three phase voltage equations of the DFIG are transformed into d,q axes reference frames rotating at a synchronous frequency ω_s. Neglecting saturation, the d,q terminal voltage equations are given by: [3]

$$V_{ds} = R_s I_{ds} + p\, \Psi_{ds} - \omega_s \Psi_{qs} \quad (3)$$

$$V_{qs} = R_s I_{qs} + p\, \Psi_{qs} + \omega_s \Psi_{ds} \quad (4)$$

$$V_{dr} = R_r I_{dr} + p\, \Psi_{dr} - (\omega_s - \omega_r) \Psi_{qr} \quad (5)$$

$$V_{qr} = R_r I_{qr} + p\, \Psi_{qr} - (\omega_s - \omega_r) \Psi_{dr} \quad (6)$$

Flux linkage equations:

$$\Psi_{ds} = L_s I_{ds} + M I_{dr} \quad (7)$$

$$\Psi_{qs} = L_s I_{qs} + M I_{qr} \quad (8)$$

$$\Psi_{dr} = L_r I_{dr} + M I_d \quad (9)$$

$$\Psi_{qr} = L_r I_{qr} + M I_{qs} \quad (10)$$

Torque equation:

$$Te = 1.5\, n_p M (\Psi_{qs} I_{dr} - \Psi_{ds} I_{qr}) / L_s \quad (11)$$

The stator active and reactive powers are:

$$P_s = 1.5 (V_{ds} I_{ds} + V_{qs} I_{qs} + V_{dr} I_{dr} + V_{qr} I_{qr}) \quad (12)$$

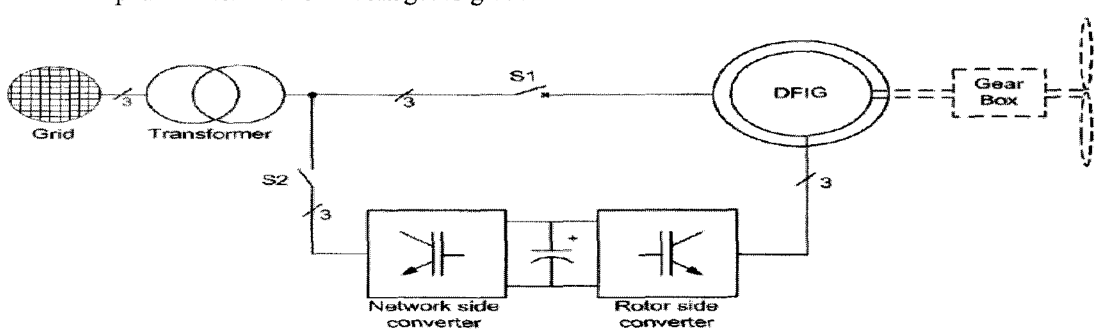

Fig. 1. Double Fed Induction Generator Schematic.

$$Q_s = 1.5\,(V_{ds}\,I_{qs} + V_{qs}\,I_{ds} - V_{dr}\,I_{qr} - V_{qr}\,I_{dr}) \qquad (13)$$

Where, sufixes s and r stand for stator and rotor parameters respectively, V is the voltage, I is the current, Ψ is the flux linkage, M is the magnetizing inductance, L is the self inductance, R is the resistance per phase, ω_s is the synchronous speed, n_p is the number of pole pairs, and "p" is the d/dt operator.

3. DFIG Control Scheme

To achieve vector control of stator active and reactive power, a d-q reference frame synchronized with the stator flux is chosen. Setting the stator flux vector to align with the d-axis of reference frame gives:

$$\Psi_{ds} = \Psi_s \quad \text{and} \quad \Psi_{qs} = 0 \qquad (14)$$

This leads to following current relation:

$$I_{qs} = -\,M\,I_{qr} / L_s \qquad (15)$$

Hence the electrical torque is:

$$T_e = -\,1.5\,n_p\,M\,\Psi_{ds}\,I_{qr}/L_s \qquad (16)$$

For a medium power induction generator used in wind energy conversion system stator resistance can be neglected, giving the simplified stator voltage equation:

$$V_s = p\,\Psi_s \qquad (17)$$

The stator voltage vector is consequently in quadrature advance with the stator flux vector. Therefore the d,q components of stator voltage are:

$$V_{ds} = 0, \text{ and } V_{qs} = V_s \qquad (18)$$

Thus equations (2) through (8) can now be written as follows:

$$V_{ds} = 0, \qquad V_{qs} = V_s = \omega_s\,\Psi_{ds} \qquad (19)$$

Manipulating equations (14) to (20) gives the following expressions for rotor fluxes and voltages:

$$\Psi_{dr} = (L_r - M^2/L_s)\,I_{dr} + M\,V_s/\,\omega_s\,L_s \qquad (20)$$

$$\Psi_{qr} = (L_r - M^2/L_s)\,I_{qr} \qquad (21)$$

$$V_{dr} = R_r\,I_{dr} + (L_r - M^2/L_s)\,p.I_{dr} - s\,\omega_s\,(L_r - M^2/L_s)\,I_{qr} \qquad (22)$$

$$V_{qr} = R_r\,I_{qr} + (L_r - M^2/L_s)\,p.I_{qr} + s\,\omega_s\,(L_r - M^2/L_s)\,I_{dr} + s\,\omega_s\,M\,V_s/\,\omega_s\,L_s \qquad (23)$$

4. Simulation Results at Sub-Synchronous Speeds DFIG

The performance of the DFIG at sub-synchronous speeds when varying the magnitude and phase of the voltage applied to the rotor circuit at slip frequency is investigated. Fig. 2 demonstrates the effect of varying the rotor voltage magnitude with constant phase angle ($\varphi = 0^o$) on the electrical torque at different speeds. With positive torque indicating motoring action and negative torque indicating generation, it is noted that applying a rotor voltage Vr of magnitude 10% of stator voltage Vs results in negative torque at sub synchronous speed down to slip

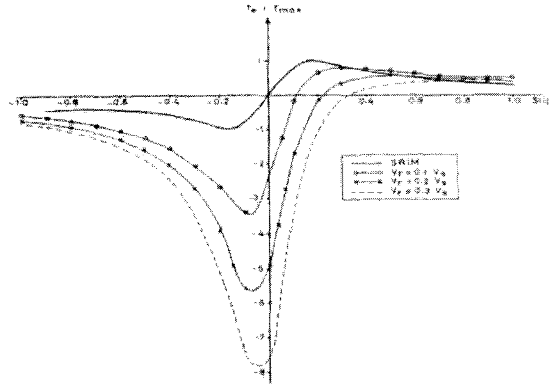

Fig. 2. Variation of Electric Torque with Slip for Different Values of V_r and $\varphi = 0^o$.

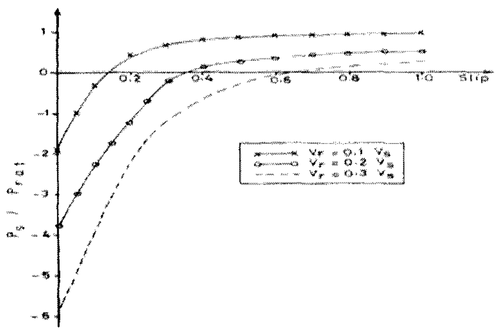

Fig. 3. Variation of Stator Active Power with Slip for Different Values of V_r & $\varphi = 0^o$.

s=0.1. Increasing the magnitude of the rotor voltage widens the speed range within which negative torque (generation mode) is obtained. It is noted that generation is possible up to s=0.4 at Vr=30% of Vs.

The stator generated active power at $\varphi = 0^{\circ}$ and different values of V_r are shown as a percentage of rated induction machine power in Fig. 3. It is noted that twice rated power is generated at s=0.2 at $V_r = 20\%$ of V_s.

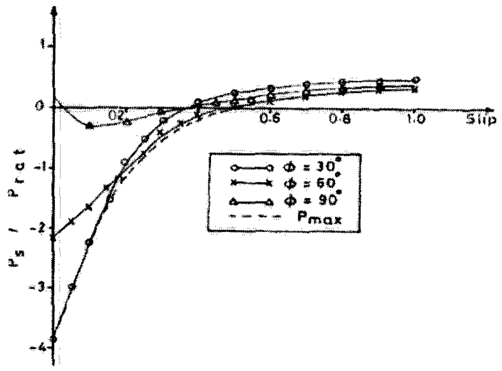

Fig. 4. Variation of Stator Active Power with Slip for Different Values of φ at Vr = 20%Vs.

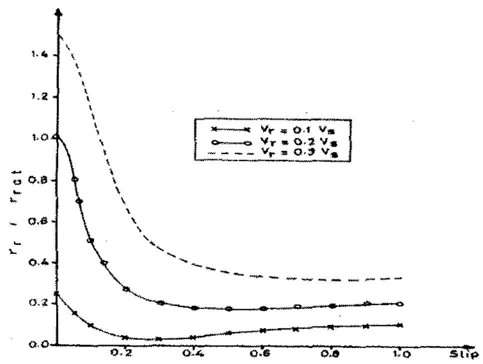

Fig. 5. Variation of Rotor Active Power with Slip at Different Values of Vr at φ = 0°.

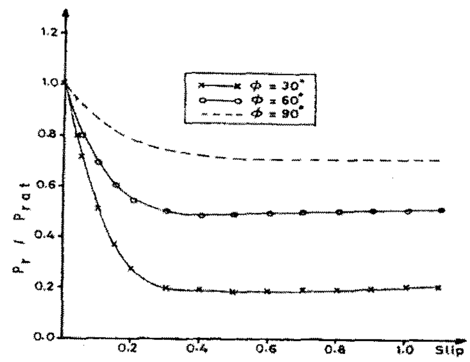

Fig. 6. Variation of Rotor Active Power with S for Different Values of φ atV_r=20%V_s.

Fig. 4 shows the effect of varying the phase angle of the applied rotor voltage at a constant magnitude ($V_r = 20\%\ V_s$). On the same plot the line tracking maximum power P_{max} at each slip is plotted. It is noted that power generation at sub-synchronous speeds is possible for values of $\varphi < 90^{\circ}$. Also the generated power may exceed the rated power at certain values of φ with 20% applied rotor voltage only.

To fairly evaluate the process of power generation at sub-synchronous speed, it is essential to calculate the power consumed by the rotor via applied voltage V_r. This is demonstrated in Fig. 5, where the active power consumed by the rotor as a percentage of rated power is plotted at $\varphi = 0^{\circ}$ and different V_r magnitudes. The consumed power limits the value of V_r that can be applied to 20% of the stator voltage; otherwise the consumed rotor power may exceed the generated stator power. Fig. 6 shows the consumed rotor power at constant Vr magnitude (20% of stator Vs), while varying the phase angle φ. It is concluded that φ should be less than 60° in order to generate higher stator power than is consumed by the rotor.

Taking the consumed power factor into consideration is another important factor for evaluating power generation at sub-synchronous speeds. Hence the DFIG power factor is plotted at a constant phase angle and different values of V_r in Fig. 7. As speed decreases, the power factor also decreases irrespective of values of V_r. This is the drawback of subsynchronous power generation. However, using power factor correction devices could improve low p.f.

5. Super-Synchronous Operation of DFIG

Operating the DFIG at super-synchronous speeds, defined in this paper as a double output induction

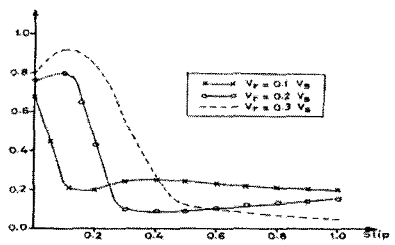

Fig.7. Variation of Power Factor of DEIG with Slip for Different Values of V_r.

generator (DOIG), is investigated. The converter connected to the rotor is operated as a rectifier, while the converter connected to the grid inverts the rotor power to the grid at the grid frequency. This generator scheme supplies real power to the grid from the stator as well as the rotor and reduces the reactive power burden on the connected grid under the variable speed prime mover

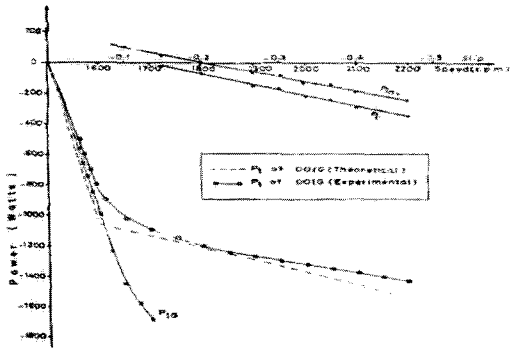

Fig. 8. Variation of DOIG and IG Generated Active Power with Speed at Rated Voltage.

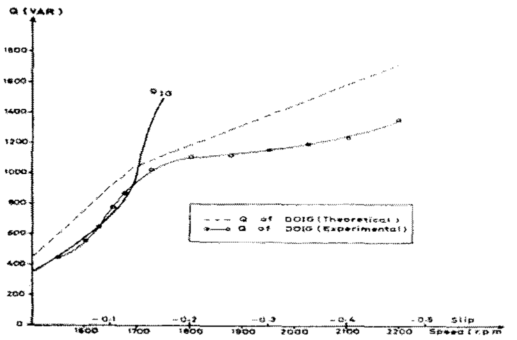

Fig. 9. Variation of DOIG and IG Reactive Power with Speed at Rated Voltage.

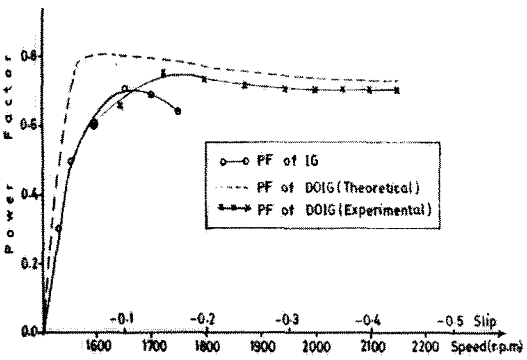

Fig. 10. Variation of DOIG and IG Power Factor with Speed at Rated Voltage.

condition [4-7]. The d-q model derived earlier is applied.

The DOIG performance is investigated by varying the firing angle ά of the line inverter, i.e. varying the equivalent rotor resistance. Varying ά allows variable speed operation of the DOIG to track the varying wind speeds. It also affects the power generated from rotor. The experimental setup implemented to study DOIG performance composed of a 1.5HP, 4 pole slip ring induction machine (SRIM) coupled to a variable speed dc motor representing the wind turbine. The stator was connected directly to the mains, while the rotor was connected to the mains via a diode rectifier, a dc link, and a line commutated inverter built with thyristors. Variable wind energy was implemented with a variable speed DC motor. Digital control circuits were built to fire the thyristors with different values of ά according to rotor speed. The control circuitry included measuring devices to monitor the amount of energy and its direction of flow as described in [7].

6. Experimental Results for Super-Synchronous Operation

Varying the inverter firing angle with wind speeds changed the value of active power generated from both the stator and rotor circuits. Fig. 8 shows the variation of total active power generated as function of rotor speed in the super synchronous range. The power is compared to that generated from conventional induction generators (short circuited rotor). The plot also includes theoretical and experimental results for the sake of comparison. Results show the wide speed range within which the machine generates active power compared to the IG range of generation.

Fig. 9 shows the theoretical and experimental reactive power consumed by IG and DOIG. The lower reactive power consumption of DOIG when compared to IG is clear. The superiority of DOIG over IG is also obvious from the plot of power factors shown in Fig. 10.

The difference between theoretical and experimental results may be due to measuring device and component errors. However, the generation of more power than the rated level of machine power is clear, which is the main objective of the paper.

Evaluating DOIG performance necessitates calculating the efficiency as shown in Fig. 11. Although the DOIG has a lower efficiency than the IG, its wider range of operating speeds as a generator results in the generation of more active power.

7. Conclusion

In this paper two modes of operating a wound rotor induction machine as a generator at sub-and super-synchronous speeds in wind energy conversion systems are described and investigated. First operating the machine as a double fed induction generator DFIG at sub-synchronous speed, the rotor circuit is fed from the ac mains via a controlled rectifier and a forced commutated inverter. It was concluded that adjusting the rotor voltage magnitude and phase leads to machine operation as a generator at sub-synchronous speeds. This widens the range of wind speeds at which power could be extracted from the wind. It was concluded also that at certain values of V_r and ϕ, the generated current exceeds the rated value of the employed induction machine. This necessitates limiting the magnitude of applied rotor voltage to 20% of stator voltage, and the rotor voltage phase angle to less than 60^o. The power generation of DFIG at sub-synchronous speed leads to higher efficiency in a wind energy conversion system. This advantage overrides the drawback of its relatively lower power factor which could be remedied by correction devices such as STATCOM and SVC. Also operating the induction machine at super-synchronous speed, defined as a double output induction generator (DOIG) is investigated both theoretically and experimentally. Experimental verification of simulation results presented for the DOIG mode of operation, revealed a larger amount of power captured from wind and a better power factor when compared to conventional induction generators. Consequently better efficiency is obtained on the average.

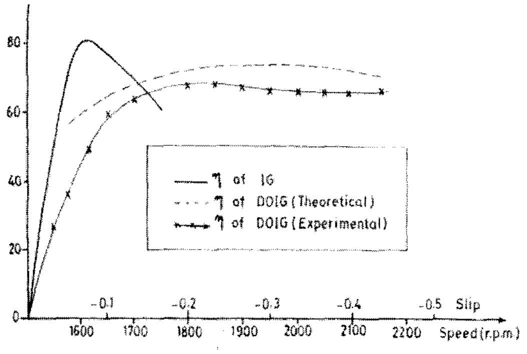

Fig. 11. Variation of DOIG and IG Efficiency with Speed at Rated voltage.

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