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Performance Control of a Wind-Driven Double-Fed Induction Generator to Meet Grid Requirements

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Abstract

Double fed induction generator (DFIG) is widely used nowadays in the wind Energy Conversion systems to track the maximum wind power point. This paper deeply investigates the performance of a DFIG subject to a developed control strategy through adjusting both the magnitude and phase of the rotor injected voltage. A set of two converters has been inserted in the rotor to control the injected voltage such that the turbine extracts the maximum wind power which is the basic control, and at the same time to control the generator power factor or maximize its output active power to meet the grid requirements. Mathematical models for the turbine and generator have been developed. Two computation algorithms have been designed to determine the DFIG performance characteristics. The first has been based on a novel direct analytical technique to determine the performance characteristics when employing the basic control strategy, while the second has been based on efficient iterative techniques to compute the performance characteristics with the suggested control strategy. The suggested control strategy has been evaluated against the basic control one through comparing the resulted performance characteristics. The comparison has revealed that the DFIG could be controlled through controlling both the magnitude and phase of the rotor injected voltage to meet the network requirements. The generator could be controlled to the extent that it could deliver reactive power to the grid when required, or its output power could be maximized. The presented technique aids greatly in maximizing the benefits of wind energy.

Keywords: Induction Generator, Voltage injection, Maximizing wind energy, DFIG

List of Symbols

C_Q	Torque coefficients
C_P	Power coefficients
P_r	Wind-turbine power, W
P_{core}	Core losses, W
P_{cu}	Copper losses, W
P_m	Input mechanical power, W
Pf_s	Stator Power factor
Pf_r	Rotor Power factor
Q_s	Stator Reactive power
Q_r	Rotor Reactive power
R_T	Thevinin's equivalent resistance
R	Turbine blades radius, m
V	Wind speed, m/s
T, τ	Torque, N.m
V_T	Thevinin's equivalent circuit voltage
X_T	Thevinin's equivalent reactance
V_r	Rotor injected voltage, V
β	Pitch angle, Degree
λ	Tip-speed ratio
ρ	Air density, Kg/m^3
Ω_r	mechanical angular speed of the turbine, rad/s
ψ_s	Stator Voltage phase Angle
φ_s	Stator Current phase Angle
Ψ_r	Rotor Voltage phase Angle
Φ_r	Rotor Current phase Angle

I. INTRODUCTION

The utilization of wind energy is very important and finds nowadays great interest. This interest has become vital as many energy experts have expected the rapid exhaust of the conventional energy resources. Therefore, generation of the electrical power from the sustainable energy sources such as wind energy has become on the top of the solution priorities [1, 2]. Integration of wind-driven induction generators in the electrical network expands clearly [3].

As the wind speed varies from time to time, the performance of induction generator powered by the wind-turbine is greatly affected. Thus, it is necessary to control the generator to guarantee a good performance irrespective of the wind speed. Ameliorating the performance of the network-connected induction generators can be realized through the use of semi-conductor converters in the stator side for single-fed generators [4-7], or through the use of a rectifier-inverter set in the rotor side for double fed generators [8-18].

Carlos [8] suggested a technique by which the current of the grid-connected induction generator is controlled while driven by a variable-speed wind-turbine. De Almeida and Lopes [9] have suggested a control technique which integrates a frequency regulator, depending on the frequency deviation, into the control loop of active power of the DFIG using the frequency deviation. This technique gives a more robust system with little frequency changes following any disturbance. Shaltout, et. al, [10] presented a basic control technique for the DFIG to enable harnessing the maximum possible mechanical power from the wind. The strategy is performed through adjusting the rotor injected voltage resulting from a rectifier-inverter set. Abdel-halim, et. al [11] presented a control method for the double fed induction generators to trace the maximum wind power and at the same time the power factor is adjusted at unity. The optimization technique is based on an approximate circuit model which neglects the iron losses and fixes the magnetizing current.

Many publications based their control on the generalized model of the generator. Some authors used the stator flux oriented control, where the q-axis rotor current controls the active power while the d-axis rotor current component handles the reactive power [12-14]. Others used the stator voltage control where the d-axis rotor current is utilized for active power control and the q-axis rotor current is used for reactive power control [15].

Boumassata et. al. [16] used a cycloconverter in the stator side to control a DFIG incorporated in a wind energy conversion system. Abdel-halim used a cycloconverter in the stator side and a dc chopper in the rotor side to be very close to the maximum wind-power points [17].

Laafou et. Al. [18] proposed focused on the control of the active and reactive stator powers generated by a DFIG of a wind energy conversion system. This control is achieved by acting on the rotor side converter to extract the maximum power from the wind turbine while regulating the rotor currents. Furthermore, another control objective is achieved by acting on the grid side converter, in which the DC bus voltage is maintained constant and a unity power factor is ensured. To do that, a new robust control known as active disturbance rejection control (ADRC) has been proposed and applied to the WECS

The present paper aims at improving the performance of the wind-driven double-fed induction generators (DFIG) at the different wind speeds employing developed control techniques from the rotor side. The control is employed using a rectifier-inverter set in the rotor to inject a voltage of controlled magnitude and phase such that the generator turbine will track the maximum wind power point, and furthermore to meet the network requirements by adjusting the generator power factor to a pre-set value, or alternatively its output active power is maximized. The size of the rotor converts will be determined to comply with the suggested control strategy. The study will be performed through developing steady-state frequency domain circuit models and mathematical models for the system. Based on these models, computer programs will be developed to compute the performance characteristics of the DFIG. Then the performance will be compared to that of the DFIG which is controlled through the basic control strategy, where the rotor injected voltage is kept in-phase or in-phase-opposition to the rotor current.

II. SYSTEM DESCRIPTION AND CONTROL STRATEGY

II.I Studied System

The system under study (Fig. 1) comprises a variable-speed wind-driven grid-connected double-fed induction generator. The stator of the generator is directly connected to the grid. The generator slip-ring rotor is connected to the grid through a set of two controlled three-phase bridge converters.

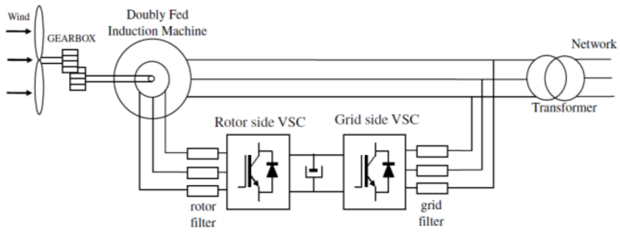

Fig. 1: DFIG system

II.II Control Strategy

The generator control is performed by adjusting both the magnitude and phase of the rotor injected voltage. The control strategy aims to regulate the speed of the generator to force the turbine to operate such that it will [19],

i. Limit the minimum speed of operation (region 1) at low wind speeds.
ii. Follow the curve of maximum power extraction from the wind with partial load (region 2) at intermediate wind speeds.
iii. Limit the maximum speed at partial load operation up to the rated generator power (region 3) at high wind speeds.

At the same time, the generator performance is controlled over the entire wind-speed range such that the power factor of the output current is adjusted at a pre-set value or the output electrical power is maximized.

III. SYSTEM MODELLING

III.I Wind-turbine Modelling

Commonly, the turbine torque and power are expressed in terms of non-dimensional torque (C_Q) and power (C_P) coefficients as follows [19]

$$T_r = \frac{1}{2}\rho\pi R^3 C_Q(\lambda,\beta)V^2, \tag{3.1}$$

$$P_r = C_P(\lambda,\beta)P_V = \frac{1}{2}\rho\pi R^2 C_P(\lambda,\beta)V^3, \tag{3.2}$$

The coefficients are written in terms of the pitch angle and the so-called tip-speed-ratio λ defined as

$$\lambda = \frac{\Omega_r R}{V}. \tag{3.3}$$

Figure 2 depicts typical coefficients $C_Q(\lambda)$ and $C_P(\lambda)$ of fixed pitch turbines in two-dimensional graphs.

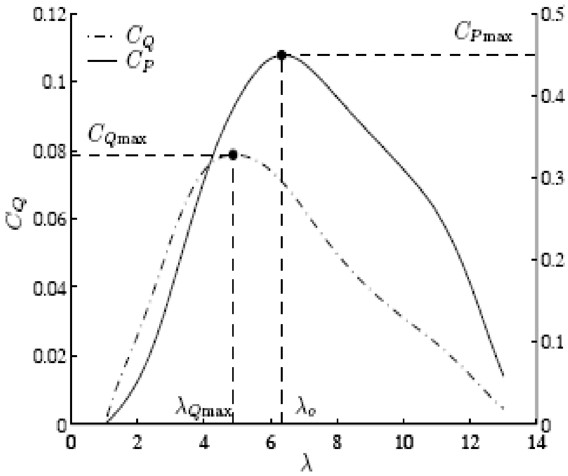

Fig. 2: Typical variations of C_Q and C_P for a fixed-pitch wind turbine

III.I Double Fed Induction Generator Modelling

Fig. 3 shows a frequency domain circuit model of the double fed 3-phase induction generator [3]. The stator terminal voltage is considered constant assuming a large network linking transformer. The injected voltage in the rotor is assumed pure sinusoidal due to the filters action.

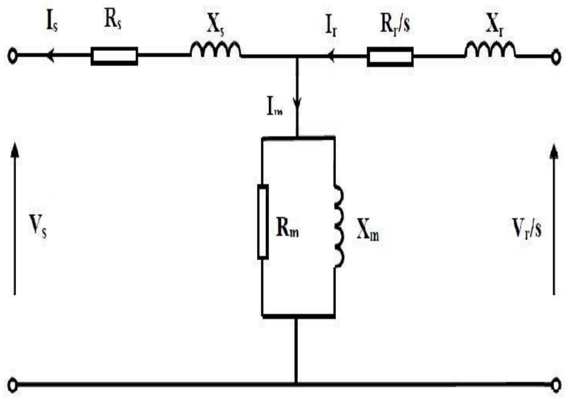

Fig. 3: Equivalent circuit of the DFIG

The generator different voltages and currents are determined using the conventional circuit theories [3]. The input mechanical power, active electrical and reactive electrical power components are calculated as follows:

$$P_m = (1\text{-}s)\,(-3\, I_r^2\, R_r/s + 3\, V_r/s\, I_r\, P.f_r) \qquad (3.4)$$

$$P_e = 3\, V_s\, I_s\, P.f_s - 3\, V_r\, I_r\, P.f_r \qquad (3.5)$$

$$P_{Loss} = P_{core} + P_{cu} = P_m - P_e \qquad (3.6)$$

$$Q_s = 3\, V_s\, I_s \sin(\psi_s - \varphi_s) \qquad (3.7)$$

$$Q_r = -3\, V_r\, I_r \sin(\psi_r - \varphi_r) \qquad (3.8)$$

In the case of the basic control strategy where the rotor injected voltage is in phase or in phase-opposition to the rotor current, the rotor injected voltage, $\mathbf{V_r}$, can be considered as a voltage drop on a positive or negative resistance added in the rotor circuit. The induced torque of the induction generator is related to the applied voltage, slip and the equivalent circuit parameters as follows [3]:

$$\tau = \frac{3\, V_T^2 R_{2t}/s}{\omega_s[(R_T + R_{2t}/s)^2 + (X_T + X_2)^2]} \qquad (3.9)$$

Where V_T, R_T and X_T are the Thevenin's equivalent circuit parameters of the stator, and R_{2t} is the total resistance of the rotor circuit and is given by

$$R_{2t} = R_2 + R_{add} \qquad (3.10)$$

Where R_{add} is the virtual added rotor resistance.

$$\mathbf{V}_r = -\,\mathbf{I_r}\, R_{add} \qquad (3.11)$$

Depending on the sign of the added rotor resistance, the rotor injected voltage will be in phase opposition to the rotor current when R_{add} is positive, while it will be in phase with the rotor current when R_{add} is negative.

IV. ALGORITHMS AND COMPUTATION METHODOLOGIES

IV.I Algorithm of the Basic Control Strategy

An analytical technique is used in case of the basic control strategy using the following algorithm:

i. At any wind speed, the generator speed and, hence the corresponding generator slip will be determined such that the turbine follows the 3-regions pattern explained above.
ii. At this wind speed, the turbine driving torque is determined using Fig. 2 and Eq. 3.1.
iii. At steady state the induced generator torque is equated to the turbine torque. Then, equation 3.17 is used to determine the virtual added resistance; R_{add} which corresponds to the rotor injected voltage. Two values of R_{add} will be obtained, and one proper value is chosen such that operation in the stable region is realized.
iv. Using the equivalent circuit of Fig. 3 replacing $\mathbf{V_r}$ by R_{add}, all the generator variables such as the stator current, rotor current, output electrical power, losses, efficiency, e.t.c are determined.

IV.II Algorithm of the Developed Control Strategy

It is difficult to develop closed form formulae for the magnitude and phase of the rotor injected voltage to realize the required electrical performance of the generator. An iterative technique will be followed to determine the phase and the value of the rotor injected voltage such that while the generator speed is regulated according to the intended mode of operation, the stator power factor is adjusted at a pre-set value or the output active power is maximized.

i. At a certain wind speed, the generator slip and the wind mechanical power are determined according to the region of operation.
ii. The phase angle of the rotor injected voltage is fixed at a value chosen in a range around zero for wind speeds below the base speed or around -180° for wind speeds above the base speed.
iii. The value of the rotor voltage is determined iteratively such that P_m calculated by Eq. 3.15 equals the value of the wind mechanical power.

iv. At this rotor injected voltage, the generator variables (currents, losses, power factors, active powers and reactive powers) are calculated using the equivalent circuit (Fig.3).

v. A new phase angle for the injected voltage is assumed, and the calculations are repeated starting from step (iii).

vi. The calculations continue for a range of rotor voltage phase angle around zero degree for wind-speeds below the base speed, and around -180° for wind-speeds above the base speed.

vii. From the different injected voltages at the different phase shift angles which enable operation at the required point in the specified region, points of the specified power factors and minimum losses (maximum output power) are determined.

V. RESULTS

A system consisting of a wind turbine driving a 2 MVA, DFIG has been studied. The specifications and parameters of the system are given in Appendix 1. The three regions of operation of the DFIG system is shown in Fig. 4 which gives the relation between the generator speed and the wind speed over the three regions.

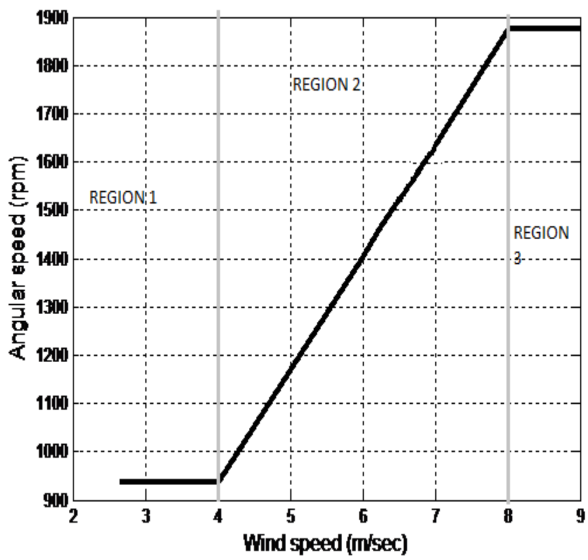

Fig. 4: DFIG speed versus wind speed for the 3-operation regions.

The generator input mechanical power at differen wind speeds over the 3 regions of operation is given in Appendix .2.

V.I Analytical Results in the Case of the Basic Control Strategy

The magnitudes of the rotor voltage which should be injected in phase or in phase-opposition to the rotor current such that the generator runs at speed enabling the turbine to extract the maximum mechanical power from the wind have been calculated at different wind-speeds using the algorithm presented in Section 4.1 The performance characteristics of the DFIG which is controlled using this basic control algorithm are shown in Figs 5-7.

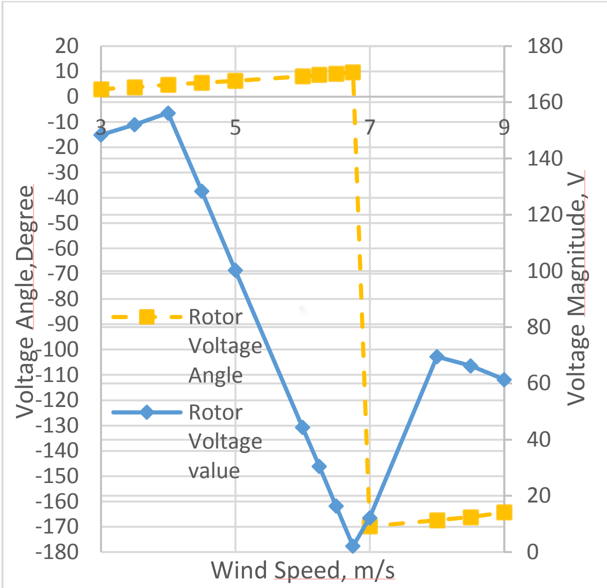

Fig. 5: Magnitude and Phase-angle (w. r. t the stator voltage) of the rotor injected voltage versus the wind speed when employing the basic control strategy

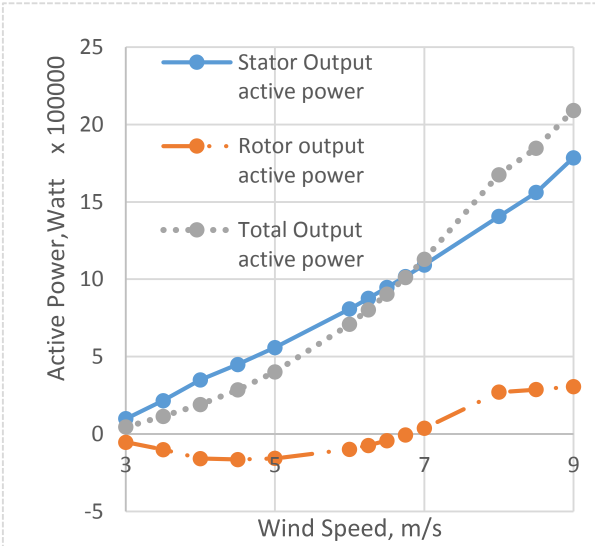

Fig. 6: Stator, rotor and total output active powers versus the wind speed when employing the basic control strategy

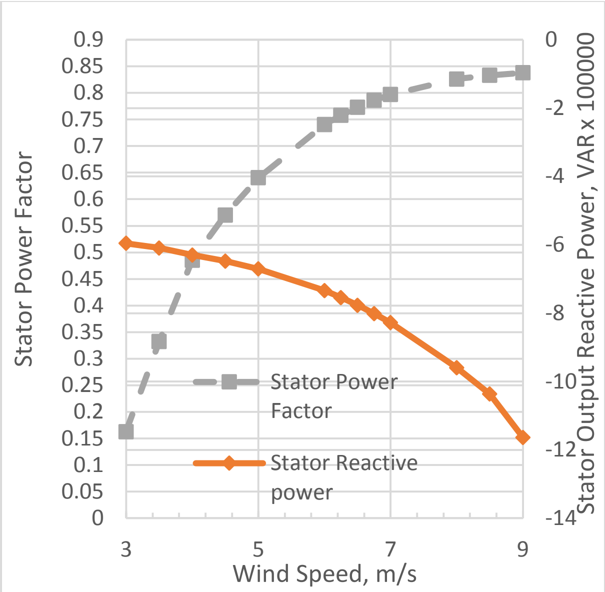

Fig. 7: Stator power factor and output reactive power versus the wind speed when employing the basic control strategy

V.II Results with the Developed Control Strategies

1) Stator Unity Power Factor Control Strategy

The performance characteristics of the DFIG which is controlled such that it traces the maximum wind power and at the same time its stator power factor is adjusted at unity are shown in Figs 8-10

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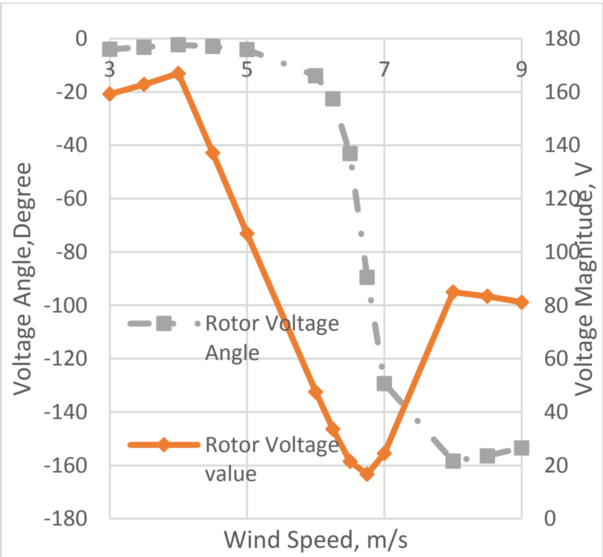

Fig. 8: Magnitude and Phase-angle (w. r. t. the stator voltage) of the rotor injected voltage versus the wind speed at unity power factor

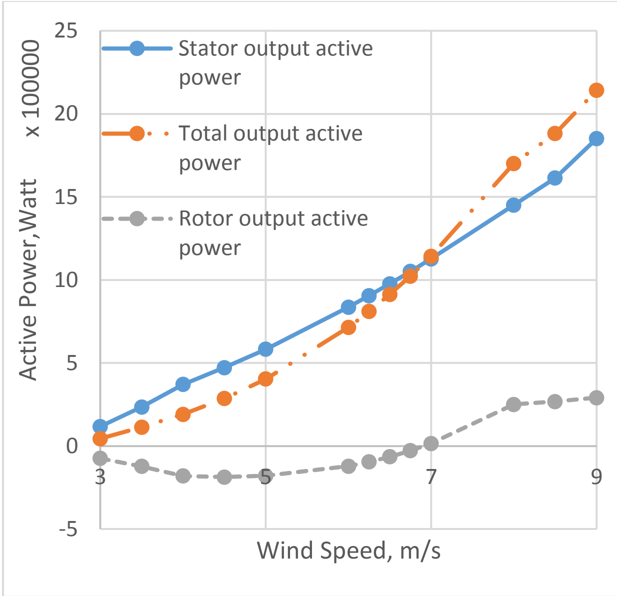

Fig. 9: Stator, rotor and total output active powers versus the wind speed at unity power factor

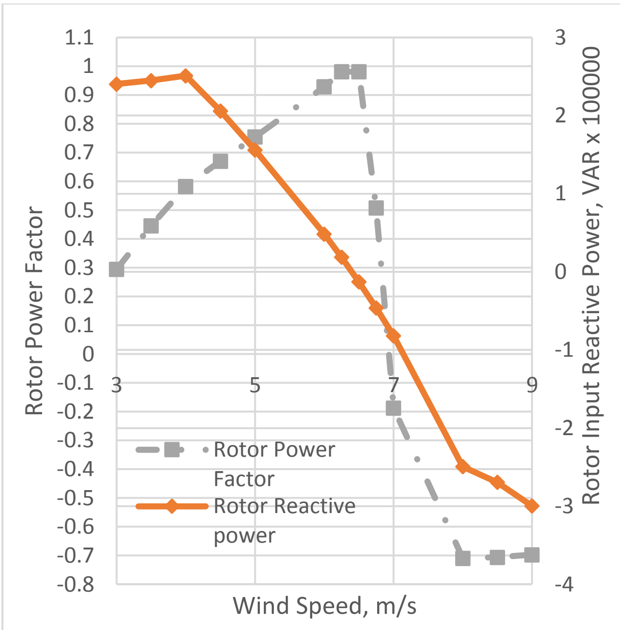

Fig. 10: Rotor input reactive power and power factor versus the wind speed at unity power factor

Comparing the DFIG performance characteristics when employing the unity Pf control strategy to the basic control strategy reveals the following:

The output active power of the generator is more or less the same as that of the basic control strategy. For example, at wind speed of 3.5 m/s, the total output active power is about 0.113642 MW, while it is 0.113645 MW for the basic control strategy. At wind speed of 9 m/s, the total output active power is 2.14189 MW while it is 2.09131 for basic control strategy (Figs. 6& 9).

The DFIG when employing the unity power factor strategy does not of course consume reactive power from the stator side. On the other hand, the DFIG when employing the basic control strategy consumes reactive power from the stator side ranging from 0.59565 up to 1.16322 MVAR, (Fig. 7).

The DFIG when employing unity power factor control strategy consumes from the rotor side a maximum reactive power of about 0.24 MVAR at wind speed of 3.5 m/s. No reactive power is required at speed slightly less than the base wind speed. At wind speeds higher than the base wind speed, the DFIG delivers reactive power which reaches about 0.295 MVAR at wind speed of 9 m/s (Fig. 10). On the other hand, DFIG employing basic control strategy does not consume reactive power from the rotor side.

The application of the unity power factor control strategy keeps the stator and rotor currents within their rated values.

2) Stator 0.9 Lagging Power Factor Control Strategy

The performance characteristics of the DFIG which is controlled such that it traces the maximum wind power and at the same time its stator power factor is adjusted to 0.9 lagging are shown in Figs 11-14.

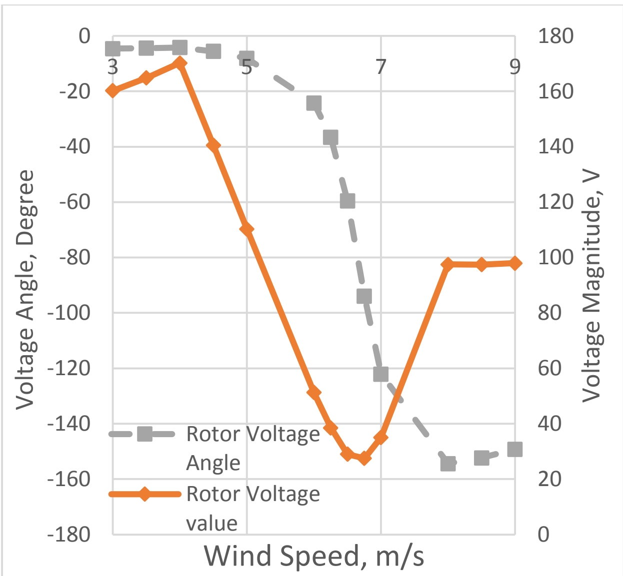

Fig. 11: Magnitude and phase-angle (w. r. t. the stator voltage) of the rotor injected voltage versus the wind speed at 0.9 lagging power factor

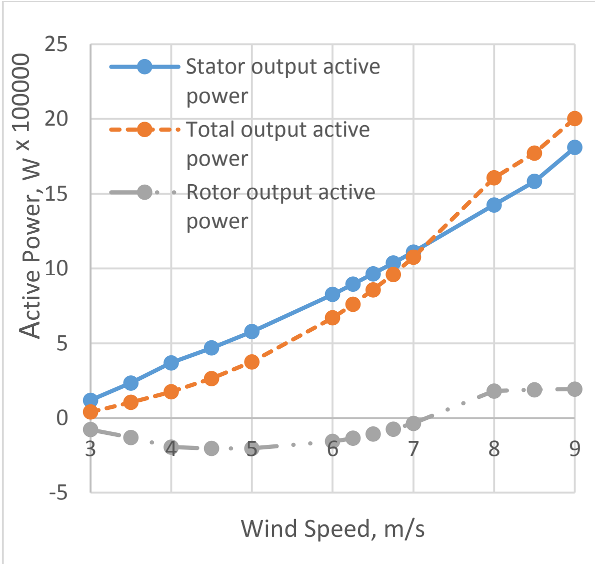

Fig. 12: Stator, rotor and total output active powers versus the wind speed at 0.9 lagging power factor

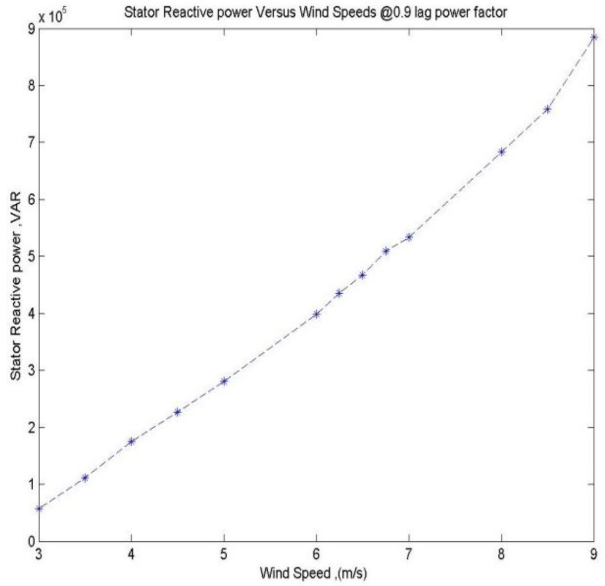

Fig. 13: Stator output reactive power versus the wind speed at 0.9 lagging power factor

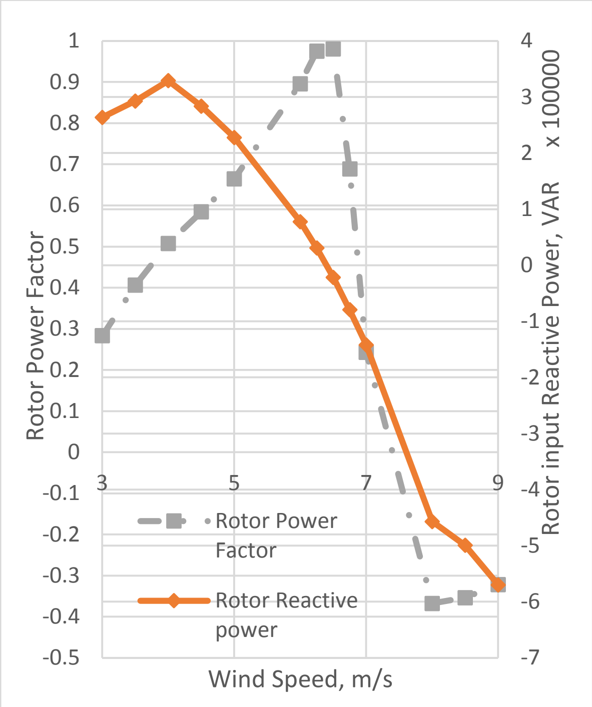

Fig. 14: Rotor input reactive power and power factor versus the wind speed at 0.9 lagging power factor

Comparing the performance characteristics of the DFIG when employing the 0.9 lagging power factor control strategy to that of other DFIG control strategies reveals the following:

The output active power of the generator is about 0.104371 MW at wind speed of 3.5 m/s which is less than that of the basic control strategy (0.113645 MW). As the wind speed increases, the total output active power increases. As long as the wind speed is less than 8.5 m/s, the stator and rotor currents are within their limits (the rated values). At wind speed of 8.5 m/s and higher, the control strategy should be modified such that the generator delivers reactive power keeping the rotor current at its rated value. In this case, the total output active power will be as given in Table 1. At wind speed of 9 m/s, the total output active power will be about 2.111 MW which is slightly higher than that of the basic control strategy (2.091308 MW) as shown in (Figs. 6 and 12).

The DFIG delivers reactive power to the grid from the stator side. At the lowest wind speed (3 m/s) it delivers about 0.264 MVAR to the grid. This reactive power increases as the wind speed increases and it reaches a maximum value of about 0.758 MVAR at wind speed slightly less than 8.5 m/s without violating the stator or the rotor current limits.

At higher wind speeds, it is recommended to turn the control strategy as explained. The results of this modification is given in Table 1. The results show that the reactive power should be decreased as wind speed increases to avoid over-currents.

The DFIG consumes from the rotor side a maximum reactive power of about 0.33 at a wind speed of about 4 m/s. No reactive power is required at a speed slightly less than the base wind speed. At wind speeds higher than the base wind speed, the DFIG delivers reactive power which reaches about 0.499 MVAR at wind speed of about 8.5 m/s (Fig. 13 and 19).

Table 1: Limits of reactive powers and power factors at high wind speeds

Wind speed, m/s	Reactive power, MVAR	Power factor	Total active power, MW
8.5	0.724	0.910	1.779
9.0	0.308	0.986	2.111

3) Maximum Output Power Control Strategy

The performance characteristics of the DFIG which is controlled such that it tracks the maximum wind power, and at the same time the total generator power losses are minimized are shown in Figs 15-17.

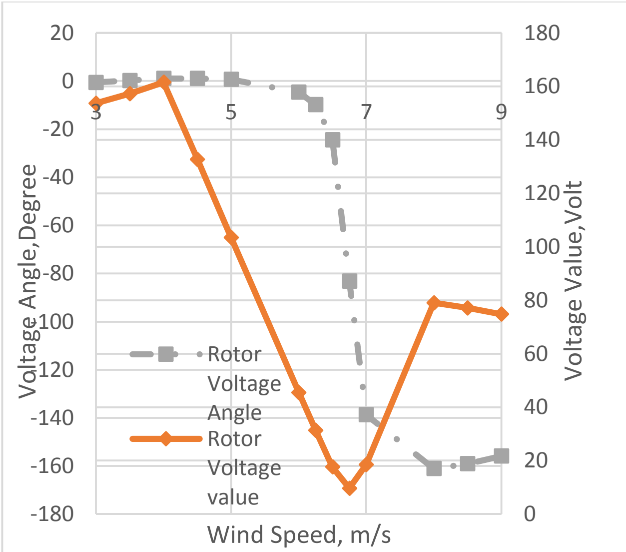

Fig. 15: Magnitude and Phase-angle (w. r. t the stator voltage) of the rotor injected voltage versus the wind speed when employing the minimum losses strategy

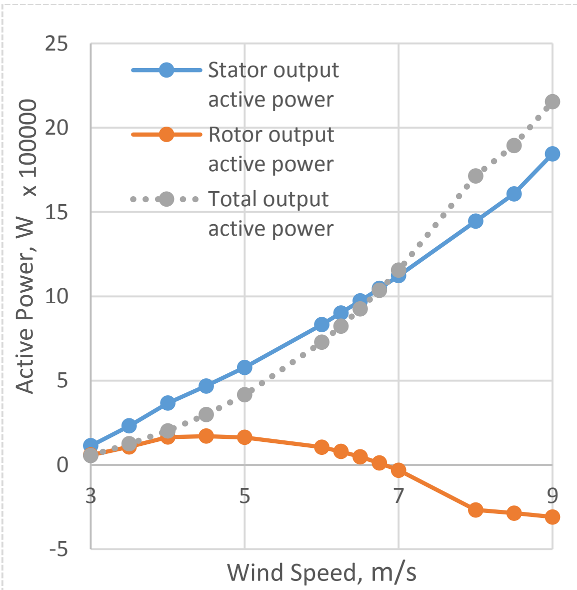

Fig. 16: Stator, rotor and total output active powers versus the wind speed when employing the minimum losses strategy

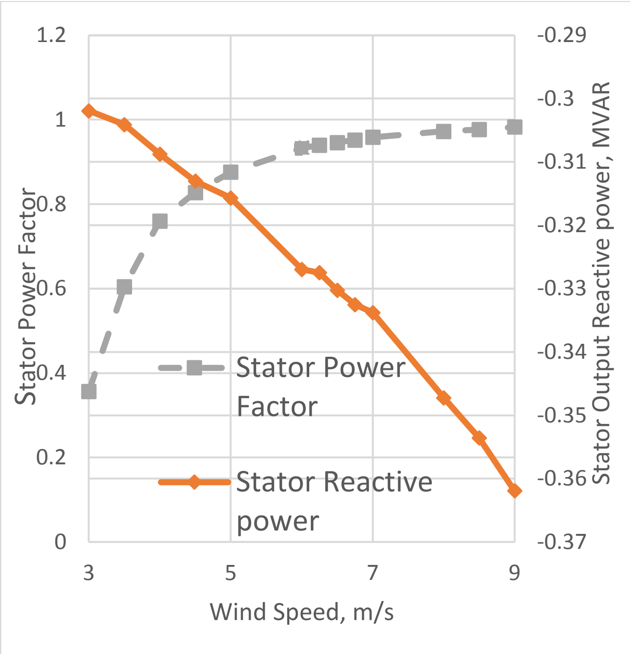

Fig. 17: Stator power factor and output reactive power versus the wind speed when employing the minimum losses strategy

Comparing the performance characteristics of DFIG in case of minimum power losses to the SFIG and DFIG employing the basic control strategy reveals the following:

The output active power of the generator is increased when employing the minimum losses control strategy especially at wind speeds far from the base speed. For example, at wind speed of 3.5 m/s the total output active power is about 0.124 MW, while for Basic control strategy gives at wind speed of 3.5 m/s total output active power of about 0.113645 MW. At wind speed of 9 m/s the total output active power is about 2.155 MW, while for the basic control strategy, the total active power is 2.091308 MW (Fig. 6& 16).

The DFIG in case of minimum power losses consumes reactive power from the stator side ranging from about 0.298 MVAR at a wind speed of 3 m/s up to a maximum value of about 0.3536 MVAR at a wind-speed of 8.5 m/s. These values are about half the reactive power consumed in the case of the basic control strategy (Figs. 7& 17).

VI. CONCLUSION

The present paper aimed at controlling the performance of the double-fed induction generators used with wind turbine at the different wind speeds employing control techniques from the rotor side. The inverter-rectifier set in the rotor circuit has been initially adjusted to inject a voltage in phase or in phase-opposition to the rotor current such that the generator runs at the speed which allows the wind turbine to extract the maximum mechanical power from the wind. Thereafter, the injected voltage has been shifted in phase to- according to the network requirements- either control the generator power factor or maximize the output active power

In case of control strategy resulting in unity power factor, the DFIG nearly does not consume reactive power even from the rotor side. In case of control strategy resulting in 0.9 lagging power factor, the DFIG delivers reactive power to the grid. The generator could be controlled such that its output is maximized, and its consumed reactive power is decreased to about half that consumed in the basic control case. The stator and rotor currents still within their rated values over most of the wind speeds range. At high speeds, and in order to keep the currents within the rated values the strategy may be turned to be delivering a certain amount of reactive power instead of keeping a certain power factor. The choice of the control strategy depends on the needs of the network.

The results show that the rotor injected voltage phasors required at each wind-speed depends on the chosen control strategy, and clearly vary as the wind speed changes.

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APPENDICES

Appendix 1: Generator and Turbine Data

The data and parameters of the studied induction generator and wind turbine are given in Tables 2 and 3.

Table 2: Main Characteristics of the Generator

Nominal stator power	2.0 MW	Speed range, rpm	900–2000
Nominal torque, Nm	12732	Pole pairs	2
Rated voltage	690 V	Magnetizing inductance	2.5 mH
Rotor to stator voltage ratio	2.6	Stator& rotor leakage inductance	0.087 mH
Nominal stator current	1760 A	Stator resistance	0.029 ohm
Nominal referred rotor current	1807 A	Rotor resistance	0.026 ohm
Nominal speed	1500 rpm	Core resistance	23.55 ohm

Table 3: Turbine Parameters

Radius	62 m	Optimum λ	6.3
Nominal wind speed	9 m/s	C_{p_max}	0.455

Appendix 2: Wind-turbine Mechanical Power

The mechanical power extracted from the wind at different wind speeds over the three regions of operation has been calculated and given in Table 4.

Table 4: Wind-turbine mechanical power at different wind speeds

Wind speed, m/s	3	3.5	4	4.5	5	6	6.25	6.5	6.75	7	8	8.5	9
Slip	0.375	0.375	0.375	0.2969	0.218	.062	.0234	-.0156	-0.0547	-0.094	-0.25	-0.25	-0.25
P_m, MW	.0873	0.1623	0.2505	0.35667	0.4893	0.8455	0.9556	1.075	1.20385	1.343	2.0043	2.246	2.6056