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Improving Light-Load Efficiency by Eliminating Interaction Effect in the Grid Connected Doubly-Fed Induction Generator

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ABSTRACT

A wind turbine equipped with doubly-fed induction generator (DFIG) is used in wind power plant industry. This paper studies the maximum power extraction of DFIG via evaluation of state-space equations in closed loop control condition for improving light-load efficiency. The DFIG state-space equations have been considered in the form of a multi-input- multi output (MIMO) system. Also, the tracing table has been used to determine the speed which the generated power will be proportional to the maximum load. The tracing table input is the generator speed, and its output is the optimum active power that has been considered as the reference power of the active power control system of the convertor. A controller is presented for the tracing table and the extracted power is able to follow the reference power with minimum ripple. Then, the results are compared with the single-input and single-output (SISO) case, for the values up to 0.2 times of the rated load. Therefore, in MIMO modeling, in the case that the DFIG connected to the grid, by eliminating the interaction effect, the efficiency in light-load can be increased.

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1. INTRODUCTION

Recently, the doubly-fed variable speed wind turbines have attracted much interest. The ability of variable speed, allows the turbine to work at its maximum efficiency in the wider range of wind speed. On the contrary, in single speed turbines, the wind fluctuation is absorbed by changing the rotor rotation speed and do not transmit to the network. [1, 2].

The generators used in these turbines are usually asynchronous, which are connected to the network by power electronic circuits. These power electronic circuits are back to back convertor, cycloconvertor, or matrix converter [3].

The variable speed wind turbines equipped with DFIG, has attracted much interest, by having lots of advantages such as:

- The possibility of mechanical speed control and maximum power extraction from wind turbine, as a result of constant network frequency and rotor frequency regulation.
- The degradation of mechanical apparatus will be decreased.
- The rated power of power electronic convertor used in DFIG is 25% more than the one used in synchronous generator.

Actually, DFIG is the same as induction generator with wound rotor which its stator is connected directly to the network, and its rotor is connected to the network via back to back power electronic convertor, as it can be seen in Figure 1 [4].

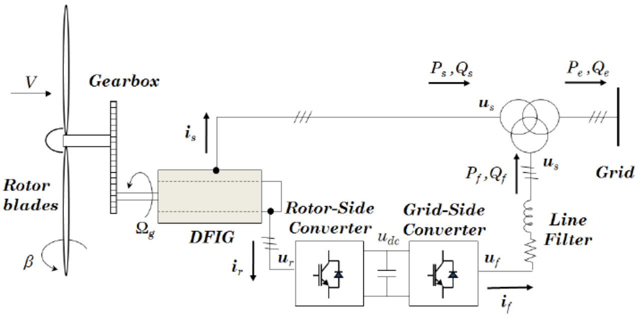

Figure 1. Total structure of DFIG connection to the network

The diagram in Fig. 1 shows that the network side convertor works with network frequency. The aim of controlling this convertor is to keep constant of the middle connection DC voltage. For this purpose, it should be operated independent of the power direction and magnitude, passing through the bidirectional convertor. The vector control is performed in the same direction with the stator voltage, considering the reference frame. Also, in the rotor side convertor, the frequency changes with variation of the turbine speed. The aim of controlling the rotor side convertor is controlling the electric torque and the rotor excitation current. In this convertor, the vector control is performed in the same direction with the stator flux vector, considering the reference frame [5].

Up to now, different methods have been proposed for wind turbine controlling. In Ref. [6], the constant power method along with the energy storage system has been used for wind turbine controlling. In this system, each wind turbine is equipped with an energy storage system which is controlling by a wind turbine initial controller that is connected with a wind farm secondary controller. In Ref. [7], a control system has been proposed, using a flywheel and fuzzy logic controller to reduce oscillations of output power of doubly-fed wind turbine and also regulating the turbine output voltage.

In Ref. [8] and [9], using vector control methods along the stator flux, the output active and reactive power are controlled by PI controller in SISO mode, such that the voltage magnitude of d and q axes are considered as system input reference voltage. According to the table of regulated power for extracting wind maximum power in different speeds, the maximum power in each moment is traced. This method has relatively low resistance, considering the relatively wide variations in internal characteristics of generator, such as variations in resistance value and rotor and stator inductance. In Ref. [10], a method has been proposed to maintain high efficiency in power convertor, over the whole range of loads and in circuits. The proposed method basically increases the convertor efficiency in light-load. This can be possible by minimizing the switching loss, semiconductor switches loss and also the magnetic component of core loss. This loss is minimized by controlling the turning on and turning off in power convertors, such that if the convertor is on, it works at maximum level of efficiency. In Ref. [11], a method has been proposed for efficiency improvement of light-load in synchronous buck convertor by loss reduction in gate trigger. Also, a novel technique for gate trigging has been proposed, such that the gate voltage is oscillating dynamically, along with the load current, in a way that the gate trigger loss is exchanged for conduction loss. The conduction loss is proportional with square current. The existence of an optimum gate oscillator shows that in light-loads, the magnitude of loss is smaller.

In Ref. [12] and [13], using torque control method, the stator active and reactive power magnitude are calculated and then, based on the hysteresis regulators, the stator voltage vectors are controlled. The basic problem of this method is the variation of the switching frequency of the rotor side power convertor, which changes with the output active and reactive power variations. Therefore, the power convertor and harmonic filters construction will become complicated and expensive.

Indeed, the vector control is controlling the flux maker and torque maker components of stator current in an arbitrary reference frame. These components are controlled in an arbitrary frame with magnitude, phase and frequency regulation of supply voltage. Since the flux variation with current control is very slow, the flux maker component of current should be kept constant for having fast speed and fast torque response. On the other hand, it is necessary to control the flux in order to avoid magnetic saturation and also flux mitigation in order to reducing the core loss in light-load. The rotor flux orientation method is sensitive with respect to the motor parameters and has a complicated decouple circuit, but the stator flux orientation method has less sensitivity with respect to motor parameters [14]. Therefore, the stator flux orientation method has been used.

There are processes that have lots of control variables and many measured variables. Such systems are called multi-input multi-output (MIMO) systems. Because of the interaction between the signals, it may be very difficult to control such systems by a combination of simple controllers. A simple way to control such systems is to use two single-loop controllers, each for one loop. To do this, it has to be decided how to connect these controllers in the first place. Figure 2 shows a procedure with two-input and two-output [15].

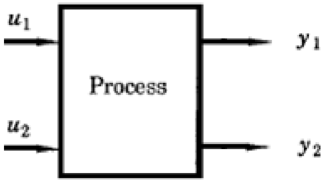

Figure 2. Block diagram of a system with two-input and two-output

In this paper, extraction of maximum power of DFIG via evaluating the state-space equations in the case of closed-loop control, for the purpose of light-load efficiency improvement has been studied. Considering the state-space equations of DFIG as a MIMO system, and proposing the decentralized control method for it, the obtaining results compared with the SISO system results per the values up to 0.2 times of the rated load. Therefore, in the MIMO modeling, the light-load efficiency of DFIG, when it is connected to network, can be increased by eliminating the interference effect and with the help of the proper controller.

2. THE WIND TURBINE MODEL EQUIPPED WITH THE DFIG

The wind turbine is a set of complicated equipment's which comprises lots of controllers. For removing this complexity, the wind turbines can be considered as combination of sub-systems, which can be modeled alone. The sub-system separated models can be turned into a full wind turbine after combination.

2.1. The Aerodynamic Model of the Wind Turbine

The wind turbine is a system that absorbs the wind energy using some vanes, and turns it to mechanical energy. The swept energy by the rotor is obtained as:

$$P_w = \frac{\rho}{2} C_p(\lambda,\beta) A_R v^3 \tag{1}$$

Where P_w is the extractable power of wind, ρ is the mass density of wind, v is the wind speed, A_R is the surface area swept by blades of turbine, C_p is the performance factor of the turbine which is obtained via equation (2).

$$\begin{aligned} C_p(\lambda,\beta) &= 0.5176\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)e^{-\frac{21}{\lambda_i}} + 0.0068\lambda \\ \frac{1}{\lambda_i} &= \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{\beta^3 + 1} \end{aligned} \tag{2}$$

Where λ is ratio of blade tip speed to wind speed, β is the blade pitch angle. Fig. 3 shows the diagram of the performance factor of the turbine in the terms of blade tip rotation to wind speed per different values of β.

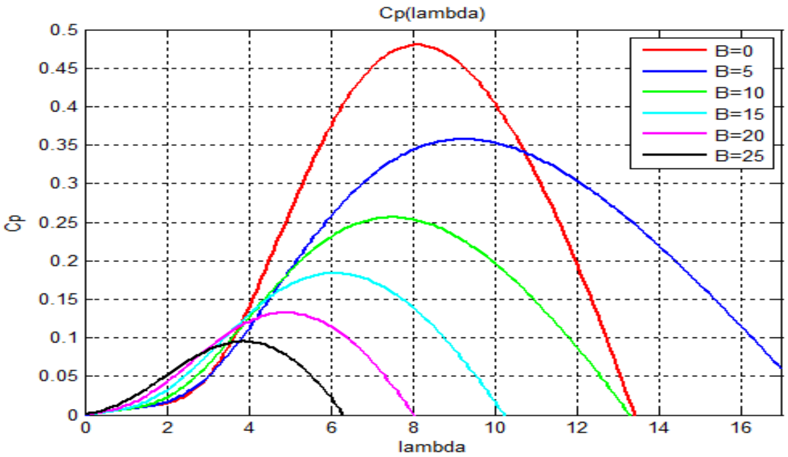

Figure 3. The turbine performance factor in terms of λ

Also Figure 4. Shows the performance factor of turbine in terms of blade pitch angle per different values of λ.

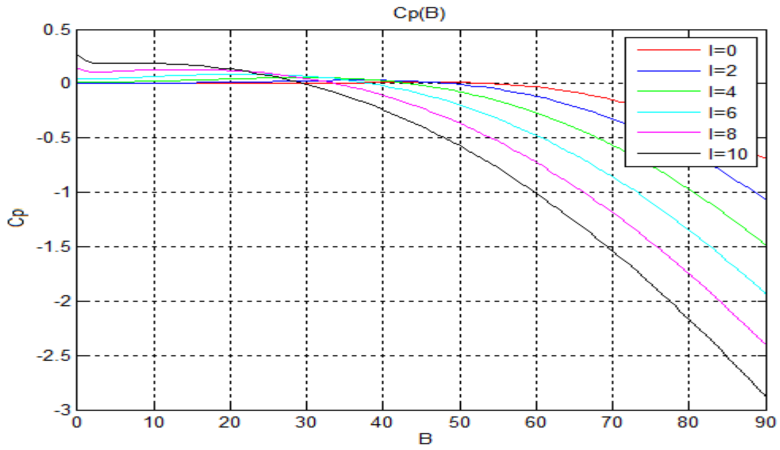

Figure 4. The turbine performance factor in terms of β

The rated speed for the used turbine is $13\ m/s$. This means that when the wind speed is equal to the rated speed, the rated real power is $2\ MW$. The minimum wind speed to extract the power is considered as $3\ m/s$. The maximum tolerable speed for turbine without being damaged is $20\ m/s$. Therefore, if the wind speed is more than $20\ m/s$, the turbine will be shut down with braking performance.

Table 1. The performance of the output active power of turbine for different wind speed

Output active power of turbine	Speed Range
Zero output power	Less than $3\ m/s$
Maximum power Extractable from wind	Between $8\ m/s$ and $20\ m/s$
Zero output power	More than $20\ m/s$

Thus, the diagram of active power in terms of wind speed is show in Figure 5.

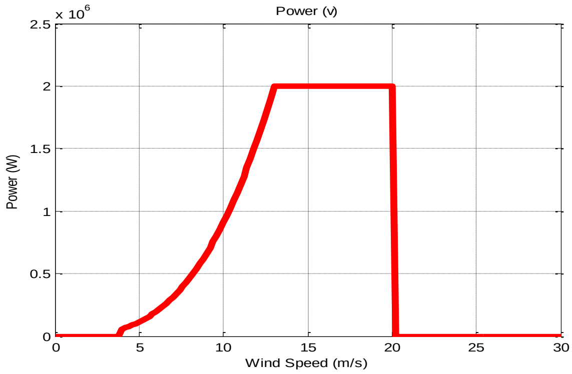

Figure 5. Diagram of active power in terms of wind speed

2.2. The DFIG Model

To model the DFIG, the dynamic model of fifth-order has been used. To show the electrical relation of DFIG in reference frame system, which rotates with synchronous speed along the stator flux d and q axes, using Park conversion, the following non-linear state-space equations will be used.

$$\begin{cases} \dfrac{dx}{dt} = Ax + Bu + Gd \\ \quad y = Cx \end{cases} \tag{3}$$

The states, system input and disturbance are shown as follow, respectively:

$$x = [i_s d i_s q i_r d i_r q]^T \tag{4}$$

$$u = [v_r d v_r q]^T \tag{5}$$

$$d = [v_s d v_s q]^T \tag{6}$$

$$A = \begin{bmatrix} -\dfrac{1}{\sigma\tau_s} & \dfrac{\omega_s - \omega_R k_m}{\sigma} & \dfrac{k_s}{\sigma\tau_r} & \dfrac{\omega_r k_s}{\sigma} \\ \dfrac{\omega_R k_m - \omega_s}{\sigma} & -\dfrac{1}{\sigma\tau_s} & -\dfrac{\omega_r k_s}{\sigma} & \dfrac{k_s}{\sigma\tau_r} \\ \dfrac{k_r}{\sigma\tau_s} & -\dfrac{\omega_r k_r}{\sigma} & -\dfrac{1}{\sigma\tau_r} & \dfrac{\omega_R - \omega_s k_m}{\sigma} \\ \dfrac{\omega_r k_r}{\sigma} & \dfrac{k_r}{\sigma\tau_s} & \dfrac{\omega_s k_m - \omega_R}{\sigma} & -\dfrac{1}{\sigma\tau_r} \end{bmatrix} \tag{7}$$

$$B = \begin{bmatrix} -k_I & 0 \\ 0 & -k_I \\ \dfrac{1}{\sigma L_r} & 0 \\ 0 & \dfrac{1}{\sigma L_r} \end{bmatrix}, G = \begin{bmatrix} \dfrac{1}{\sigma L_s} & 0 \\ 0 & \dfrac{1}{\sigma L_s} \\ -k_I & 0 \\ 0 & -k_I \end{bmatrix} \tag{8}$$

$$\begin{aligned}
&k_s = L_m / L_s , k_l = L_m / (\sigma L_s L_r) \\
&k_m = L_m{}^2 / (L_s L_r), k_r = L_m / L_r \\
&\tau_r = L_r / R_r , \tau_s = L_s / R_s , \omega_R = \omega_s - \omega_r \\
&\omega_s = 2\pi f_s , \omega_r = n_p . \Omega_g
\end{aligned} \tag{9}$$

In these equations, R_s‘L_s‘R_r‘L_r are resistance and self inductance of stator and rotor winding, respectively. L_m is the mutual inductance, ω_s is the generator synchronous speed, ω_r is the rotor synchronous speed, Ω_g is generator mechanical speed and n_p is rotor pole pair.

3. DFIG VECTOR CONTROL

In the vector control method, the doubly fed induction machine three phase model is converted to two perpendicular winding models and then, the currents of these windings are controlled. The purpose is controlling the stator active and reactive power. The reference power value is based on the maximum power extraction from the tracing table. The stator flux in the odq reference frame is widely used for DFIG vector control in the wind power plant. Therefore, the rotor side convertor is controllable using the stator flux of odq reference frame. The voltages of control variables are controlled via the rotor currents [16].

$$v_{dr} = R_r i_{dr} + \frac{d}{dt}\left(\sigma L_r i_{dr} + \frac{L_m}{L_s}\psi_s \right) - \left(\omega_s - \omega_r\right)\left(\sigma L_r i_{qr}\right) \tag{10}$$

$$v_{qr} = R_r i_{qr} + \frac{d}{dt}\left(\sigma L_r i_{qr}\right) + \left(\omega_s - \omega_r\right)\left(\sigma L_r i_{dr} + \frac{L_m}{L_s}\psi_s \right) \tag{11}$$

Assuming that that the d-axis is in the same phase with the stator voltage [17]:

$$\lambda_{ds} = \lambda_s \lambda_{qs} = 0 \tag{12}$$

The stator resistance can be ignored, considering the insignificant resistance of it. Consequently, the stator active and reactive powers are obtained by [18]:

$$P_s = -\frac{3}{2} V_s \frac{L_m}{L_s} i_{qr} \tag{13}$$

$$Q_s = \frac{3V_s}{2L_s}\left(\psi_s - L_m i_{dr}\right) \tag{14}$$

As it can be seen from equations (12) and (13), there are two procedures with two inputs (i_{dr}, i_{qr}) and two outputs (V_{dr}, V_{qr}) which can be mentioned as a MIMO system. The aim is controlling i_{dr} and i_{qr} values, such that the active and reactive powers reach to the desired values. The input reference currents can be obtained through the active and reactive powers.

4. ACTIVE AND RACTIVE POWER CONTROL

To control the active and reactive power of wind turbine equipped with DFIG, different schemes have been proposed. In these schemes, decoupled variable and SISO modeling have been performed.

In this paper, in the first step, it has been tried to control the system properly using PID controller. It should be mentioned that, because it is a two variable system, it is better to evaluate the input and output effects, for better controlling the system. The controller design in this system is performed using the decentralized control method.

4.1. The proposed Control System

In this section, the active and reactive control system of wind turbine have been introduced. The control system showed in Figure 6 has been considered as rotor side control system convertor.

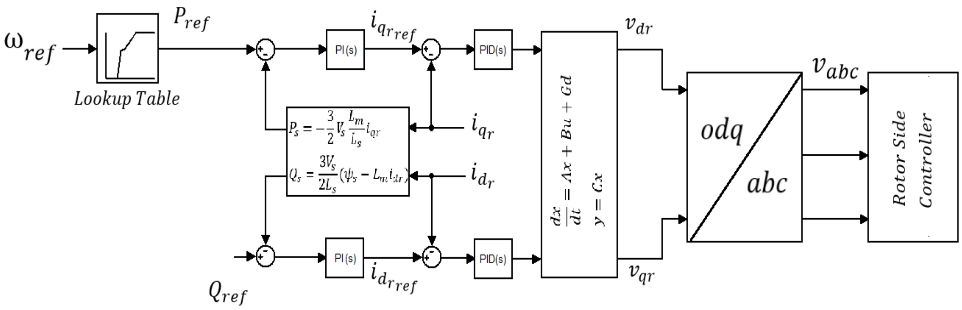

Figure 6. Block diagram of rotor side control system convertor

For this purpose, the tracing table has been used to determine the speed which the generated power will be proportional to the maximum load. The tracing table input is the generator speed, and its output is the optimum active power that has been considered as the reference power of the active power control system of the convertor. These characteristics have been obtained based on the aerodynamic information of wind turbine rotor and the points which are proportional to the turbine maximum power. Then, the desired $i_{q\ ref}$ has been obtained by controller and it is compared with the output current value.

5. SIMULATION RESULTS

In this section, the simulation results are represented in order to verify the effective performance of the proposed control method. The simulations are carried out based on the characteristics of a typical DFIG, which are shown in table 2 [19]. Also, the rotor side convertor was modeled by the proposed control system

Table 2. The Determined values for the parameters of the simulated system

Considered Value	Parameter
2 MW	P_{nom}
690 v	V_{nom}
50 Hz	f_{nom}
10.3 mΩ	R_s
8.28 mΩ	R_r
0.2801 mH	L_s
0.1177 mH	L_r
26.96 mH	L_m
1950 rpm	Ω_g
2	n_p

5.1. The Tracing Results of the Maximum Extractable Power from System

In Figure 7, the maximum extractable power has been shown by red diagram, which has been obtained per different wind speeds. The extracted power, which has been shown by blue diagram, could trace the maximum reference power with minimum ripple.

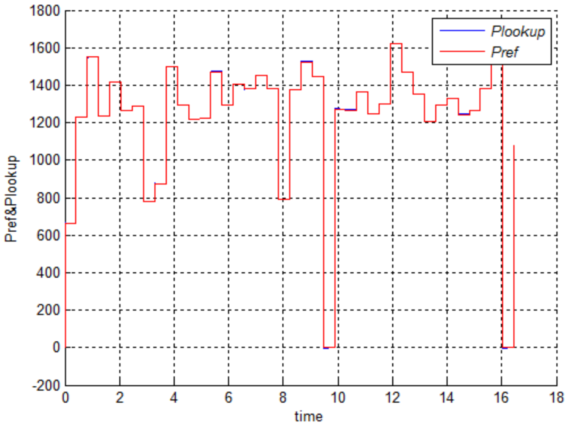

Figure 7.a. The reference power tracing diagram the of control system

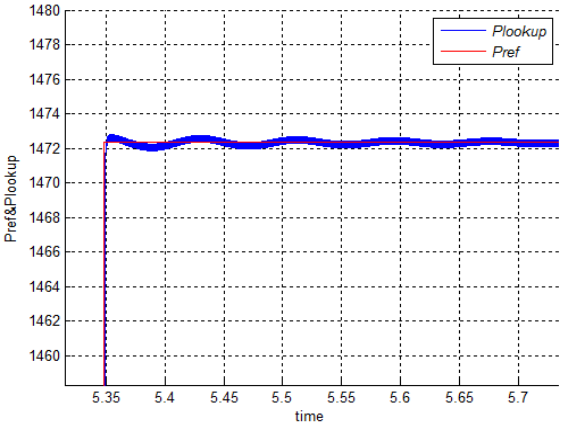

Figure 7.b. Resize of the reference power tracing diagram the of control system

5.2. The Efficiency Results Obtained in Light-Loads

In this section, the proposed control system in MIMO mode per 0.01, 0.025, 0.05, 0.1, 0.2 times of rated load, which have been considered as light-loads, has been simulated and the obtained results have been compared with the results obtained by the control system in SISO mode, as it has been shown in Figure 8.

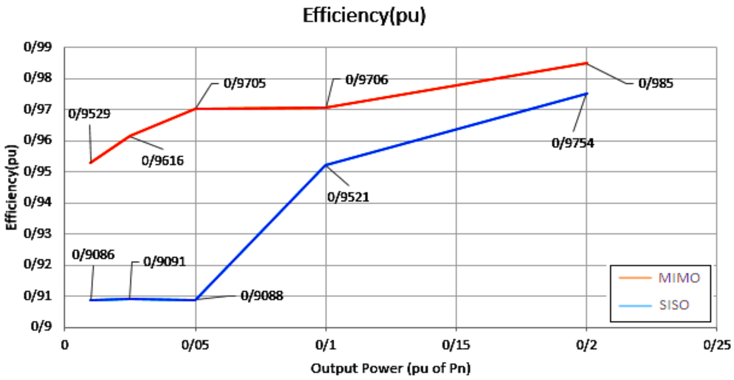

Figure 8. The output power efficiency diagram per light-loads

6. CONCLUSION

In this paper, a novel method has been proposed for efficiency improvement in light-loads. In this system, the optimum power value of the controller reference of turbine has been obtained using decentralized controller to increase the system efficiency. This has been done using the tracing table, which is obtained via the wind turbine technical characteristics. In the simulation of the proposed method, it has been shown that the proposed control model has been improved the quality of the reactive power. Moreover, the more the applied load getting away from the rated load, the more the efficiency will increase.

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