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Control of Active and Reactive Power of DFIG by Artificial Neural Networks

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Abstract: In this study, active and reactive power control of Doubly Fed Induction Generator (DFIG) has been proposed and suggested which a comparative study between two control strategies has been carried out, the first strategy uses a PI controller based on Field-oriented control; the second is based on Artificial Neural Networks (ANN) controller which the training data of ANN controller design are obtained using field oriented control. Modeling of DFIG and details of both control strategies have been presented. The proposed control methods have been tested on 3.6 MW DFIG generators. The performances in terms of power tracking, accuracy and robustness test under DFIG's parameter variations have been shown and compared. The simulation results and their comparison are presented in this study.

Key words: Active and reactive power control, artificial neural networks controller, comparative study, doubly fed induction generator, field oriented control

INTRODUCTION

Electrical energy is an important factor for the human life development in terms of improving living conditions and industrial activities. Therefore the growing energy consumption requires more and new energy conversion technologies with high efficiency. In this context, many factors can be studied for improving their efficiency such as the energy source (wind, sun, hydro, tidal wave, biomass, geothermal), generators, converters, control strategies, etc. Production of electricity from wind power as a renewable energy source is one of the most promising solutions and it is continually attracting the attention of investors, researchers and electrical utilities (Liu *et al*., 2015; Ekanayake *et al*., 2003).

A large number of generators have been used in wind energy conversion systems, the Foubly Fed Induction Generator (DFIG) is widely since it can be operates in wide range of speed variation around the synchronous speed ±30%, the independent control of active and reactive power, the opportunity measure of currents to the stator and rotor, unlike the asynchronous machine (Barbade and Kasliwal, 2012). In addition, the main area of application for the DFIG is in variable-speed generating systems such as wind power and hydro power (Abdeddaim and Betka, 2013).

Some years ago, many DFIG control strategies have been developed and implemented: the field-oriented control is widely used (Dendouga *et al*., 2007; Forchetti *et al*., 2002), nonlinear model predictive control, sliding mode control, artificial neural networks (Barbade and Kasliwal, 2012), neuro-fuzzy vector control, predictive control. The field-oriented control using PI controllers is the most commonly used control techniques, however it may be difficult to adjust PI gains properly due to the nonlinearity and system complexity. In addition, the obtained performances using PI controller depends heavily on accurate of the machine parameters.

Moreover, the PI-type control methods are not effective when the system to be controlled is characterized by strong nonlinearity and external disturbances. Therefore, to overcome these drawbacks, many techniques have been developed to replace PI-type controllers. Artificial neural networks is one of the best techniques that can offer many advantages such as aptitude to discover all possible interactions between predictor variables and the availability of multiple training algorithms, ability to implicitly detect complex nonlinear relationships between dependent and independent variables which they require less formal statistical training, etc.

MATERIALS AND METHODS

DFIG model: The basic diagram of DFIG is shown in Fig. 1 which the stator is connected directly to the network while the rotor is connected via an AC-AC

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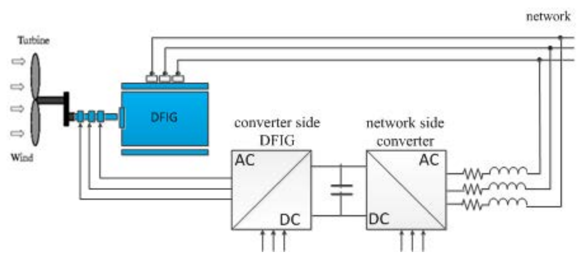

Fig. 1: Wind turbine system based on DFIG

converter. The general model of the DFIG using the park transformation can be described by the following equations which voltage relations on rotor and stator sides are given by the following equation:

$$\begin{bmatrix} V_{sd} \\ V_{sq} \end{bmatrix} = \begin{bmatrix} -R_s & 0 \\ 0 & -R_s \end{bmatrix} \begin{bmatrix} I_{sd} \\ I_{sq} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi_{sd} \\ \varphi_{sq} \end{bmatrix} + \begin{bmatrix} 0 & -\omega_s \\ \omega_s & 0 \end{bmatrix} \begin{bmatrix} \varphi_{sd} \\ \varphi_{sq} \end{bmatrix} \tag{1}$$

$$\begin{bmatrix} V_{rd} \\ V_{rq} \end{bmatrix} = \begin{bmatrix} R_r & 0 \\ 0 & R_r \end{bmatrix} \begin{bmatrix} I_{rd} \\ I_{rq} \end{bmatrix} + \frac{d}{dt} \begin{bmatrix} \varphi_{rd} \\ \varphi_{rq} \end{bmatrix} + \begin{bmatrix} 0 & -\omega \\ \omega & 0 \end{bmatrix} \begin{bmatrix} \varphi_{rd} \\ \varphi_{rq} \end{bmatrix} \tag{2}$$

The expressions of the rotor and stator flux are:

$$\begin{cases} \varphi_{sd} = -L_s I_{sd} + M I_{rd} \\ \varphi_{sq} = -L_s I_{sq} + M I_{rq} \\ \varphi_{rd} = L_r I_{rd} - M I_{sd} \\ \varphi_{rq} = L_r I_{rq} - M I_{sq} \end{cases} \tag{3}$$

The DFIG electromagnetic torque and its mechanical equations are given respectively by the following:

$$\begin{cases} C_{em} = pM\left(I_{sq} \times I_{rd} - I_{sd} \times I_{rq}\right) \\ C_e - C_r = j\dfrac{d\Omega}{dt} + f\,\Omega \end{cases} \tag{4}$$

The stator active and reactive powers of DFIG are expressed as follows:

$$\begin{cases} P_s = -V_{sd} \times I_{sd} - V_{sq} \times I_{sq} \\ Q_s = -V_{sq} \times I_{sd} + V_{sd} \times I_{sq} \end{cases} \tag{5}$$

Where:

s, r = Rotor and stator indices
V, I, ϕ = Voltage, current and flux
R_s, R_r = Stator and rotor resistances
L_s, L_r, M = Stator, rotor and mutual inductances
ω_s, ω_r = Stator and rotor pulsations
P_s, Q_s = Active and reactive powers
C_{em} = Electromagnetic torque

The DFIG system can be written as:

$$\frac{dX}{dt} = [L]^{1}[Z]X + [L]^{1}U \tag{6}$$

Where:

$$\begin{cases} [x] = \left[I_{sd}\ I_{sq}\ I_{rd}\ I_{rq}\right]' \\ [U] = \left[V_{sd}\ V_{sq}\ V_{rd}\ V\right]' \end{cases} \tag{7}$$

$$[L] = \begin{bmatrix} -L_s & 0 & M & 0 \\ 0 & -L_s & 0 & M \\ -M & 0 & L_r & 0 \\ 0 & -M & 0 & L_r \end{bmatrix} \tag{8}$$

$$[Z] = \begin{bmatrix} R_s & -\omega_s L_s & 0 & \omega_s M \\ \omega_s L_s & R_s & -\omega_s M & 0 \\ 0 & -(\omega_s - \omega)M & -R_r & (\omega_s - \omega)L_r \\ (\omega_s - \omega)M & 0 & -(\omega_s - \omega)L_r & -R_r \end{bmatrix} \tag{9}$$

Field-oriented control of DFIG: As mentioned previously, the double fed induction machine is widely used in wind turbine, since it can operates at variable speed to produce the maximum power under variable wind speed. In addition, for more efficiency, the produced active and reactive powers must be controlled perfectly. Therefore, this section presents the control of DFIG using field oriented control (Ahmed and Saad, 2013). Based on stator flux oriented, the following equations can be obtained:

$$\varphi_{ds} = \varphi_s \quad \text{and} \quad \varphi_{qs} = 0 \tag{10}$$

Therefore, the stator active and reactive power, can be written as:

$$\begin{cases} P_s = -V_s \dfrac{M}{L_s} I_{rq} \\ Q_s = \dfrac{V_s^2}{\omega_s L_s} - V_{sq} \dfrac{M}{L_s} I_{rd} \end{cases} \tag{11}$$

Equations showing the relationship between the rotor currents and voltages are established and are written by the following equations set:

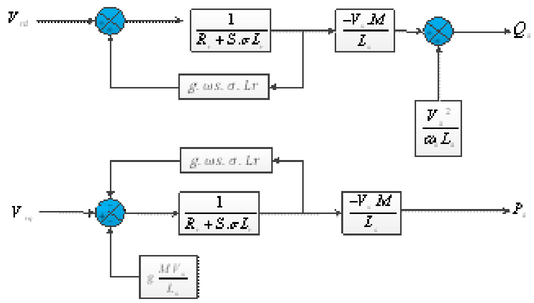

Fig. 2: Simplified DFIG model

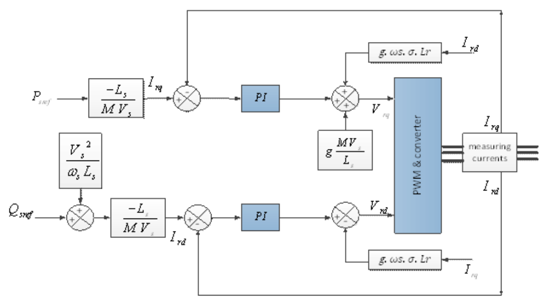

Fig. 3: Indirect field oriented control of DFIG

$$\begin{cases} V_{rd} = R_r I_{rd} + (L_r - \frac{M^2}{L_s})\frac{dI_{rd}}{dt} - g\omega_s (L_r - \frac{M^2}{L_s}) I_{rq} \\ V_{rq} = R_r I_{rq} + (L_r - \frac{M^2}{L_s})\frac{dI_{rq}}{dt} + g\omega_s (L_r - \frac{M^2}{L_s}) I_{rd} + g\frac{MV_s}{L_s} \end{cases} \quad (12)$$

The block diagram of the DFIG is illustrated in Fig. 2. The block diagram of DFIG indirect field oriented control is shown in Fig. 3. In this control strategy, active and reactive power are controlled independently. The quadrature component of the rotor current controls the stators active power and the direct component controls reactive power exchanged between the stator and the network.

RESULTS AND DISCUSSION

Simulation results of F.O.C: To validate the proposed method a 3.6 MW DFIG is used, parameters are listed in Table 1. Figure 4 and 5 show the performance of the active and reactive power control. It's clear that both active and reactive powers have been produced with good accuracy and they track their reference perfectly.

Artificial neural networks: Today, artificial neural networks are one of the most promising and powerful tools that can be used in many apllications such as: control, signal processing, vision, forecasting, modeling, decision support, robotics, bacteria identification, process control, modeling of physical systems, measurement, instrumentation, etc (Barbade and Kasliwal, 2012). Artifcial Neural Networks (ANNs) are a set of models inspired by biological neural networks and are used to calculate or approximate functions that can depend on a many inputs (Javad *et al*., 2012; Alizadeh *et al*., 2015; Djeriri *et al*., 2015; Ishak *et al*., 2015).

In this research, ANN controller is proposed to control active and reactive power of DFIG. The training data for ANN controller design are obtained from field oriented control. The neural network controller is

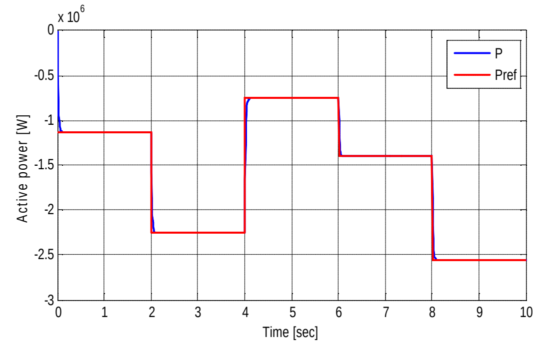

Fig. 4: Produced DFIG active power using field oriented control

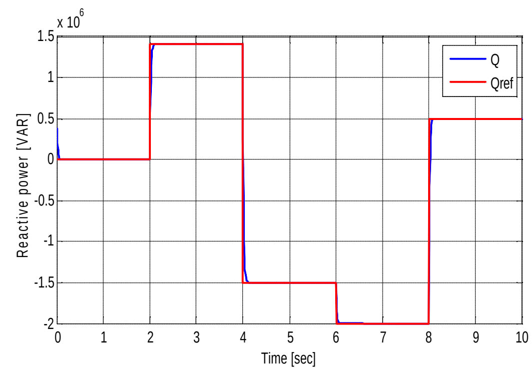

Fig. 5: Produced DFIG reactive power using field oriented control

Table 1: The 3.6 MW DFIG parameters

Parameters	Values
Nominal power	3.6 MW
Rated speed	1460 tr/min
Stator resistance	0.0079 Ω
Rotor resistance	0.025 Ω
Stator inductance	0.07937 H
Inductor rotor	0.40 H
Mutual inductance	4.4 mH
Even number of poles	2

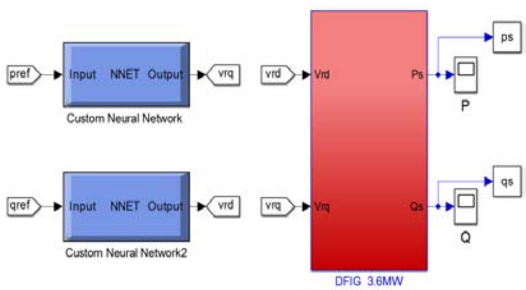

Fig. 6: Developed ANN controller for DFIG

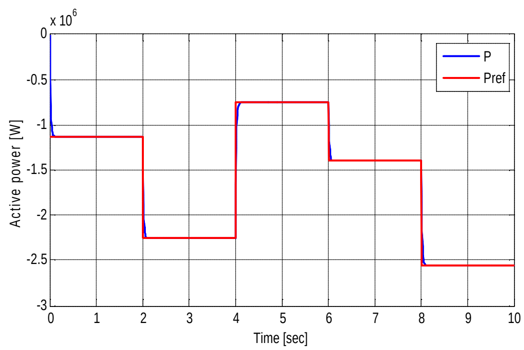

Fig. 7: Active power using ANN controller

developed in two steps: in the first step, the optimal structure (Inputs, outputs, number of layers, number of neurons in each layer, activation function and training algorithm) is chosen based on best results compared to training data calculated previously by field oriented control, the optimum number of neurons in hidden layer and the number of hidden layer is determined on heuristic basis so

that the prediction accuracy is acceptable. In the second step, the optimal ANN controller obtained in previous step is used in block Simulink of DFIG system which the field oriented controller is replaced by ANN controller.

The proposed neural network controller consists on feed-forward backpropagation with four hidden layers which active and reactive power have been chosen as inputs and V_{rd} and V_{rq} as outputs. The Developed ANN Controller of DFIG is shown in Fig. 6.

Simulation results: The simulation results using ANN controller are presented in Fig. 7 and 8 show the active and reactive power produced by DFIG using the neural controller. we can see that both power active and reactive have controlled with good accuracy.

Robustness tests: In order to study the robustness of the F.O.C based on PI and ANN controllers, the values of the

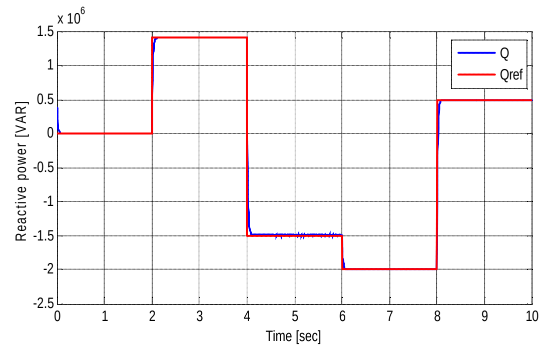

Fig. 8: Reactive power using

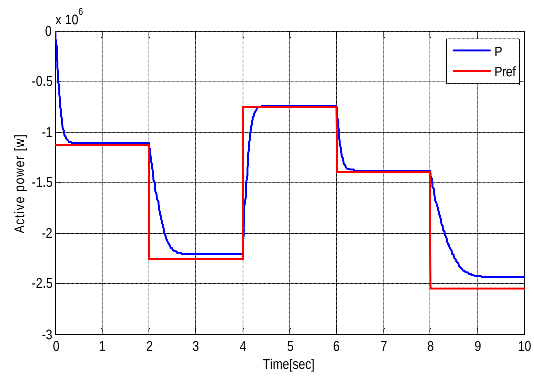

Fig. 9: Active power using F.O.C controller with DFIG parameters variation

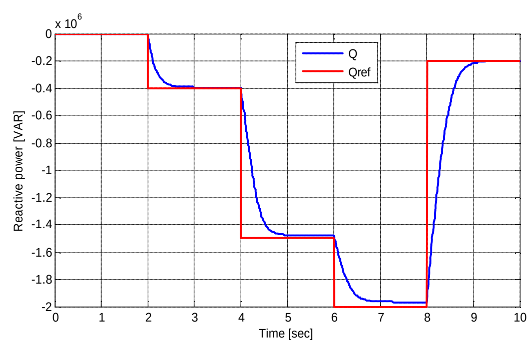

Fig. 10: Reactive power using F.O.C controller with DFIG parameters variation

rotor resistance and stator resistance have been increased by 15% of their nominal values. The values of stator inductance, rotor inductance have been increased by 10% of their nominal values and the value of mutual inductance has been decreased by 15% of its nominal value. The following figures present the simulation results for both control (FOC and ANN)under variation of parameters. From Fig. 9-12 the obtained results present

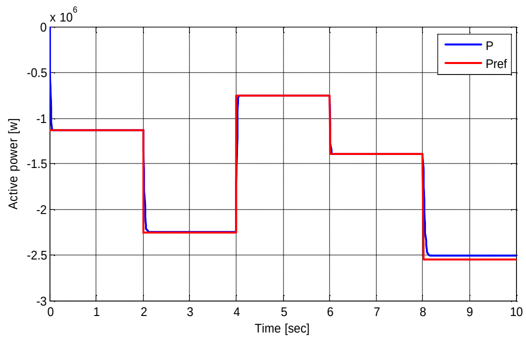

Fig. 11: Active power using

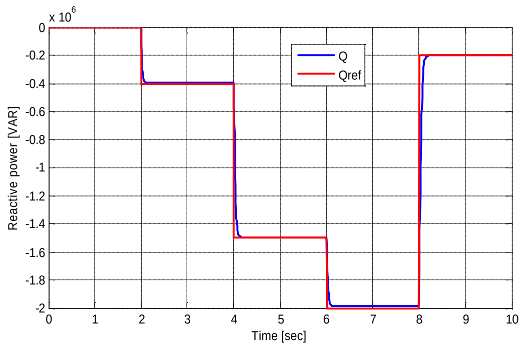

Fig. 12: Reactive power using ANN controller with DFIG parameters variation

good perfomances but it can be observed the superiority of the ANN controller compared to F.O.C. Thus, the neural controller has significant improvements over F.O.C. controller in terms of insensitivity to parameter variations.

CONCLUSION

In this study, two control strategies of DFIG have been presented and discussed, the first one using field oriented control and the second employing on artificial neural networks controller. In addition, robustness tests under variation of DFIG parameters have been studied. The obtained results for both control methods have been provided good and satisfied performances for active and reactive power control. Simulation results indicate that performance using artificial neural networks controller is significantly higher than field oriented control especially under variable DFIG parameters.

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