

Studying, Simulating and comparing Control Methods of Doubly Fed Induction Generator

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Abstract

The electrical energy generation from wind is done by several models of wind turbines with different generators, including wind turbines with doubly fed induction generators (DFIG). Due to its features and benefits, this type of wind turbine is mostly used and manufacturers have tended to the production of this type of turbine. In recent years, various control techniques as a definitive control solution for AC induction drives have been proposed. For this reason, in this paper, two control techniques are studied to control the doubly fed induction generator and the potential benefits of direct power control and fuzzy strategies are expressed. In this regard, the latest technologies in drivers of the doubly fed induction machine have been reported. In addition to controlling meet the main goals and according to the conditions, proper control model is selected. In this paper, both control methods, the direct power control and improved direct power control with fuzzy logics, are implemented based on stator flux oriented control requirements. Nevertheless the simulation is developed in Matlab/Simulink using accurate generator parameters.

Keywords: doubly-fed induction generator; back to back converter; direct power control; Fuzzy control.

1. Introduction

The wind power capacity has substantially grown worldwide during the last few years [1]. In the past two decades and the past few years, the developed countries increasingly focused on new energies. One of the energy sources in the nature is wind, which its energy is about 15 times more than the total fossil energy in the world. Wind energy is one of the most important of the renewable sources in the world. So that it is predicted that the share of electrical energy generation from the wind power by 2030 is reached to 23% of the required energy of the world. Increasing the excessive consumption of the fossil fuels, environmental considerations are the reasons for approaching the world to use this clean energy [2]. Nowadays, the use of DFIG is ideal due to flexibility, strength and being multi-capacity; thus, it becomes one of the most applicable methods for utilization of wind energy. Working according to DFIG technology, it still confronts with various challenges such as stability of the system, the quality of power [1], [3], low voltage, currency errors, phase imbalance [4] and Maximum Power Point Tracking (MPPT) [5]. When a large number of wind turbine generators are connected to the network and replace a significant number of conventional synchronous generators, have different effects on behavior of the power system including potential for the power system stability [6]. Nowadays, the control systems play an important role in modern wind turbines. A well-designed

control system can cause to increase the turbines efficiency and on the other hand, by reducing the mechanical and aerodynamic loads on the system, increases their working life, and will cause to reduce energy generation costs.

Investigating of two different control topologies of DFIG, as a source of the electric power generation is the most important and biggest generator in the power generation, is the main objectives of this article. The important advantage of DFIG is that power converters used in these generators have to bear only a fraction of the power generation of generators. In contrast, the main disadvantage of this technology are sliding rings, however, it seems that DFIG is one of the important generators of the wind power generation which is faced to the wind power consumers requirements.

2. Doubly Fed Induction Generator Model

As it shown in Figure 1, in the doubly-fed induction generator (DFIG), which is a wound rotor induction generator (WRIG), there are a direct connection from the stator to the three phase grid with constant frequency and a connection from the rotor with a supply voltage converter to the previous connection, consisted of the insulated-gate bipolar transistor (IGBT) switches in unidirectional back to back case.

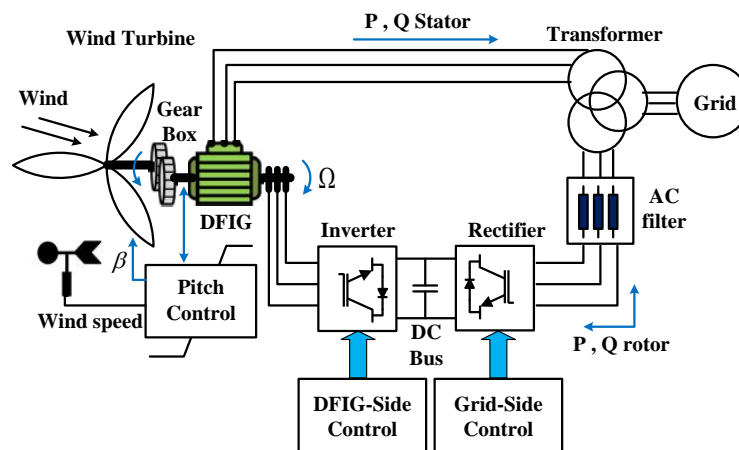


Figure 1: General DFIG supply system

Attention to the fact that the voltage for feeding load of the grid is supplied by the stator and the rotor voltage is created by the power converter, this generator is called the doubly fed. This system operates in a wide speed range but its operation is limit. For compensating the difference between the electrical and mechanical frequency of the converter, a variable frequency current is induced to the rotor. The back to back power converter and its controllers are used to set the generator behavior. This converter is composed of two separate converters, known as the grid side converter (GSC) and the rotor side converter (RSC) and connected by a dc coupled capacitor. The constant voltage of the dc link is kept by the grid side converter, while the torque or the DFIG speed and also the power factor at the stator terminals are controlled by the rotor side converter. For making the smoother voltage in the voltage variations time or small swings in the dc link voltage and storing the energy, the dc coupled capacitor is applied.

2.1. Wind Model

Power of kinetic Energy in wind can be calculated through (1) [7]:

$$P_v = \frac{1}{2} \rho A_1 V_w^3 \quad (1)$$

Where, P_v is the wind power, ρ is the air density, A_1 is the swept area, and V_w is the wind speed. Wind turbine can only recover some part of this power (2) [8]:

$$P_m = \frac{1}{2} \rho \pi R^2 C_p(\lambda, \beta) V_w^3 \tag{2}$$

Where, P_m is the output power, R is the radius of the turbine blades, λ is the blade tip speed ratio, and β is the blade pitch angle.

For a wind turbine, power coefficient of C_p is a function of wind speed, Wind turbine rotation speed, and Pitch angle (3) [8].

$$C_p = 0.22 \left(\frac{116}{\lambda_i} - 0.4\beta - 5 \right) e^{\frac{-12.5}{\lambda_i}} \tag{3}$$

C_p is often a function of the tip speed ration to the wind speed and λ_i is defined as (4) [8]:

$$\lambda_i = \left[\left(\frac{1}{\lambda + 0.008\beta} \right) - \left(\frac{0.035}{\beta^3 + 1} \right) \right]^{-1} \tag{4}$$

And λ is calculated thorough (5) [8]:

$$\lambda = \frac{\omega_m R}{V_w} \tag{5}$$

Where, ω_m is the turbine rotor angle speed.

Power coefficient curve $C_p(\lambda, \beta)$ for a specific speed is provided as λ . Constant Coefficients of C1 and C2 are given by the turbine builder. It should be noted that the amount of $C_p(\lambda, \beta)$ should not be exceeded from its maximum amount, $C_p^{max} = 0.59$, which is called Betz Limit. This coefficient is used for constant performance of turbine. Diagram block of above equations is shown in Figure 2. In this block, turbine blade angle is considered constant ($\beta = 0$) [7].

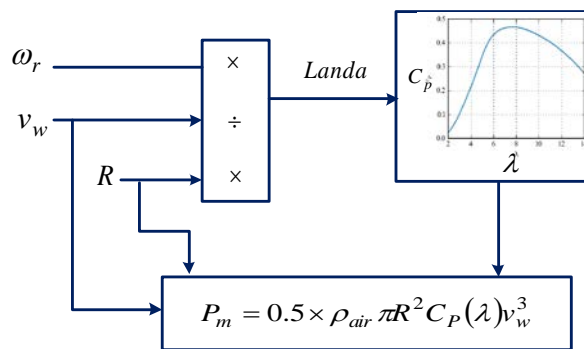


Figure 2: Dynamic model of wind turbine.

3. RSC controller based on sensing stator flux

The stator flux reference frame, d axis is in the direction stator flux linkage vector ψ_s , is shown in figure 3 by name $\psi_{ds} = \psi_s$ and $\psi_{qs} = 0$ [9].

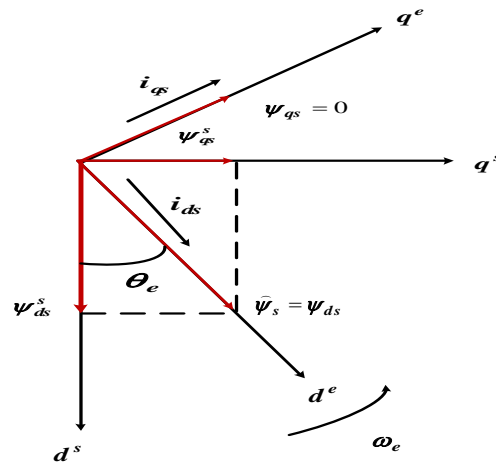


Figure 3: Phasor diagram by stator flux control .

Stator flux by using relevance machine in inertial reference system ($d^s - q^s$) in obtained by equation 6 and 7 [9].

$$\psi_{ds}^s = \int V_{ds}^s - R_s i_{ds}^s \quad (6)$$

$$\psi_{qs}^s = \int V_{qs}^s - R_s i_{qs}^s \quad (7)$$

Multiplying the dynamic equations of the induction machine in ω_b obtained dynamic equations in terms of flux [9].

$$V_{ds} = R_s i_{ds} - \omega_e \psi_{qs} + \frac{d\psi_{ds}}{dt} \quad (8)$$

$$V_{qs} = R_s i_{qs} - \omega_e \psi_{ds} + \frac{d\psi_{qs}}{dt} \quad (9)$$

$$V_{dr} = R_s i_{dr} - (\omega_e - \omega_r) \psi_{ds} + \frac{d\psi_{dr}}{dt} \quad (10)$$

$$V_{qr} = R_s i_{qr} + (\omega_e - \omega_r) \psi_{qs} + \frac{d\psi_{qr}}{dt} \quad (11)$$

Where

$$F_{ij} = \psi_{ij} \omega_b \quad (12)$$

$$\psi_{ds} = L_s i_{ds} + L_m i_{dr}$$

$$\psi_{qs} = L_s i_{qs} + L_m i_{qr}$$

$$\psi_{dr} = L_s i_{dr} + L_m i_{ds}$$

$$\psi_{qr} = L_s i_{qr} + L_m i_{qs}$$

If stator flux reference frame was Inertial, stator flux gives the following results:

$$\begin{aligned} \psi_{ds} &= \psi_s \\ \psi_{qs} &= 0 \end{aligned} \quad (13)$$

By substituting equation 12 in equation 7 to 11, new equations can be obtained from below:

$$\begin{cases} V_{ds} = R_s i_{ds} \\ V_{qs} = R_s i_{qs} + \omega_e \psi_{ds} \end{cases} \quad (14)$$

$$i_{qs} = \frac{-L_m}{L_s} i_{qr} \quad (15)$$

$$i_{qs} = \frac{-L_m}{L_s} (i_{ms} - i_{qr}) \quad (16)$$

Where

$$i_{ms} = \frac{V_{qs} - R_s i_{qs}}{\omega_e L_m} \quad (17)$$

$$P_s = \frac{3}{2} (V_{ds} i_{ds} + V_{qs} i_{qs}) \quad (18)$$

$$Q_s = \frac{3}{2} (V_{qs} i_{ds} + V_{ds} i_{qs}) \quad (19)$$

By substituting equations 14,15 and 16 in about 17 or 18 active and reactive power is calculated as follows.

$$P_s = \frac{-3 L_m^2}{2 L_s} \omega_e i_{ms} i_{qr} \quad (20)$$

$$Q_s = \frac{3 L_m^2}{2 L_s} \omega_e i_{ms} (i_{ms} - i_{dr}) \quad (21)$$

By substituting equations 15,11 and 16 in equation 9 and 10 have:

$$V_{dr} = R_r i_{dr} + \sigma L_r \frac{di_{dr}}{dt} - (\omega_e - \omega_r) \sigma L_r i_{qr} \quad (22)$$

$$V_{qr} = R_r i_{qr} + \sigma L_r \frac{di_{qr}}{dt} - (\omega_e - \omega_r) \left(\frac{\sigma L_r i_{qr} + L_m^2 i_{ms}}{L_s} \right) \quad (23)$$

Where

$$\sigma = 1 - \frac{L_m^2}{L_s L_r}$$

Equation 19 and 20 state that, P_s and Q_s can be set independently with the rotor current components i_{qr} and i_{dr} . thus the reference value i_{qr} and i_{dr} is calculated by output loop power control.

If the R_s were regardless, that was acceptable for high power machine; final active and reactive power equation is equaled to [9]:

$$P_s = \frac{-3 L_m}{2 L_s} i_{qr} \quad (24)$$

$$Q_s = \frac{3 L_m}{2 L_s} \left(\frac{V_{qs}}{\omega_e L_m} - i_{dr} \right) \quad (25)$$

Where v_{qs} is constant and equal to stator voltage Equation 21 and 22 is designed

By internal current control loop that using PI controller. Internal control loop design details are not explained here [10].

$$V_{dr} = \left(K_p + \frac{K_i}{s} \right) (i_{dr}^* - i_{dr}) - s \omega_e \sigma L_r i_{qr} \quad (26)$$

$$V_{qr} = \left(K_p + \frac{K_i}{s} \right) (i_{qr}^* - i_{qr}) - s \omega_e \left(\sigma L_r i_{qr} + \frac{L_m}{L_s} i_{ms} \right) \quad (27)$$

Ki and Kp are respectively integral coefficients and proportional of PI controllers.

4. Direct DPC power control

4.1. An introduction of direct power control DPC method

Due to the changes in machine parameters in the working time, non-linear inverters and limitation in the switching states, nonlinear control methods such as Direct Power Control (DPC) have been presented in recent decades. In this method, the momentary control of electromagnetic torque or active power and the size of flux or reactive power are based on selecting a voltage vector and an average control signal. Generally, the introduction of DPC theory is derived from DTC method in a way that in this method, the geometric relationships among stator and rotor fluxes were used and RSC in fact quite controls the rotor flux.

In DPC method, the impact that T_e and λ_r have on active and reactive power of stator is controlled rather than directly controlling them. These intangible changes in DPC control method causes to create a significant impact on the strength and ease of this strategy. The main features of this method include: 1) being independence from machine parameters, 2) reduction of measured electronic amounts and 4) no need to the changes in the frame of reference.

In general, DPC method uses (28-31) and Tables 29 to 31. (28) and (29) in $\alpha\beta$ reference frame is used for the calculation of active and reactive power [11].

$$P_s = \frac{3}{2} (V_{\beta s} i_{\beta s} + V_{\alpha s} i_{\alpha s}) \quad (28)$$

$$Q_s = \frac{3}{2} (V_{\beta s} i_{\alpha s} - V_{\alpha s} i_{\beta s}) \quad (29)$$

used for changes of the required active and reactive power [3]. Active ΔP and reactive ΔQ power threshold of error signals are used to limit switching frequency of RSC.

$$Q_+ \Rightarrow Q_{s \text{ error}} \geq \Delta Q \quad (30)$$

$$Q_- \Rightarrow Q_{s \text{ error}} \leq -\Delta Q$$

$$P_+ \Rightarrow P_{s \text{ error}} \geq \Delta P \quad (31)$$

$$P_- \Rightarrow P_{s \text{ error}} \leq -\Delta P$$

$$P_0 \Rightarrow \Delta P > P_{s \text{ error}} > -\Delta P$$

When the appropriate changes of active (P_+ or P_0 or P_-) and reactive (Q_+ or Q_-) powers dependent on the position of rotor flux are applied, optimal space vector is selected to be applied to the rotor using Table I [3]. The position of the rotor flux is estimated by Tables II and III [3].

4.2. DPC Schematic

Figure 4 shows the complete schematic of DPC circuit in which similar to DTC method, there is no transition stage among voltage space vectors. Also, RSC is required for DPC. Equations (30) and (31) are consistent with hysteresis controllers creating the confirmed outputs (update analog with the flux part) of Table 1.

Table 1: Selecting the optimal DPC vector

Reactive Power	Active Power	Sector					
		1	2	3	4	5	6
Q ₊	P ₊	v ₂	v ₃	v ₄	v ₅	v ₆	v ₁
	P ₌	v ₀	v ₇	v ₀	v ₇	v ₀	v ₇
	P ₋	v ₆	v ₁	v ₂	v ₃	v ₄	v ₅
Q ₋	P ₊	v ₃	v ₄	v ₅	v ₆	v ₁	v ₂
	P ₌	v ₇	v ₀	v ₇	v ₀	v ₇	v ₀

Table 2: Change in the stator reactive power

	v ₀	v ₁	v ₂	v ₃	v ₄	v ₅	v ₆	v ₇
Sector1	0	0	-1	1	0	-1	1	0
Sector2	0	1	0	-1	1	0	-1	0
Sector3	0	-1	1	0	-1	1	0	0
Sector4	0	0	-1	1	0	-1	1	0
Sector5	0	1	0	-1	1	0	-1	0
Sector6	0	-1	1	0	-1	1	0	0

Table 3: CHANGE IN THE STATOR REACTIVE POWER

	v ₀	v ₁	v ₂	v ₃	v ₄	v ₅	v ₆	v ₇
Sector1	=	-	-	+	+	+	-	=
Sector2	=	-	-	-	+	+	+	=
Sector3	=	+	-	-	-	+	+	=
Sector4	=	+	+	-	-	-	+	=
Sector5	=	+	+	+	-	-	-	=
Sector6	=	-	+	+	+	-	-	=

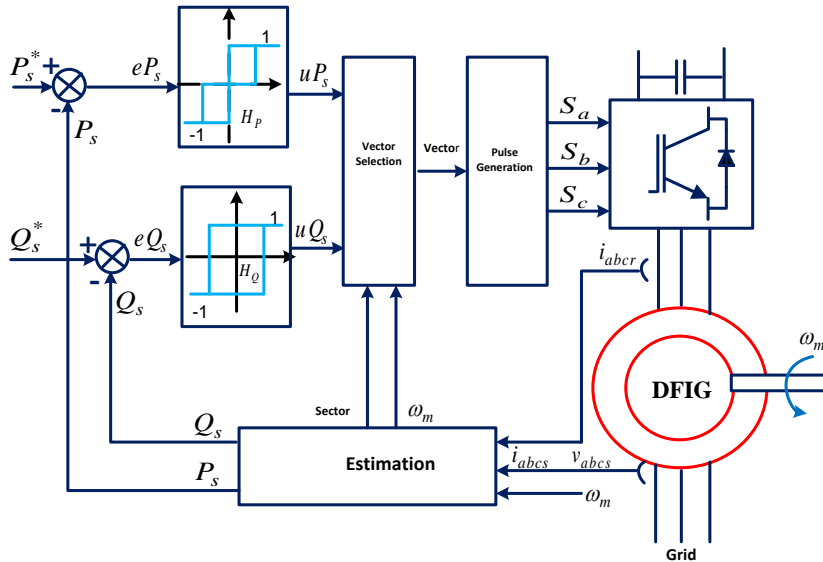


Figure 4: DPC schematic.

5. Fuzzy logic Control

5.1. Introduction to fuzzy logic

Fuzzy logic is one of the strongest control methods. Fuzzy control has 3 stages. Fuzzy function is deduction of fuzzy diagram. In the first part, functions are drawn based on specialized knowledge. There are two inputs, tracking line and integral of the tracking error, for each mode of d and q, and one rotor voltage output from each mode is received.

5.2. Fuzzy method schematic for DFIG

In fact, fuzzy control is vector control which fuzzy logic based on vector controller (Figure 5) is used to track possible created error in grid [12].

5.3. Stimulation of system with Fuzzy

Block diagram of fuzzy controller is as Figure 6. The values of stimulated DFIG have been presented in Table 4 and the stimulation has been done in dq reference.

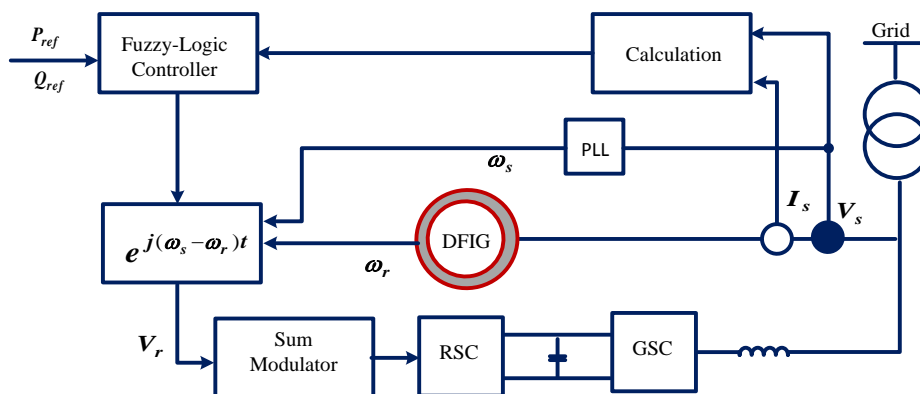


Figure 5: Fuzzy control schematic based on DFIG.

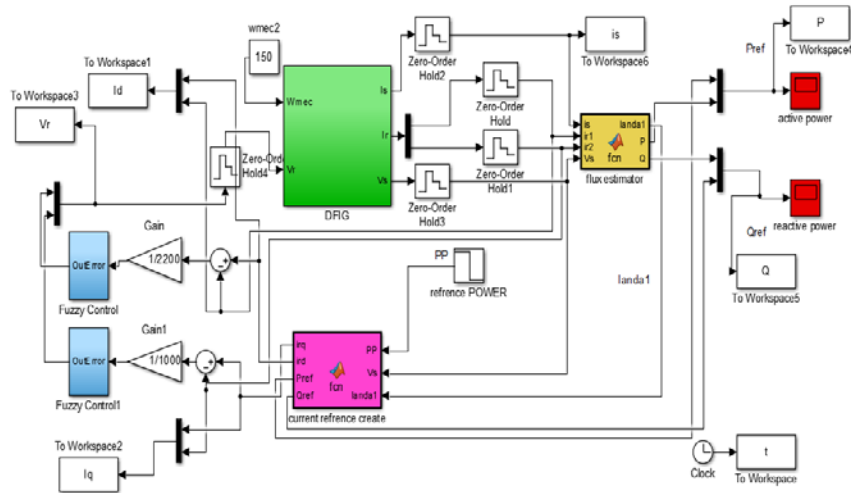


Figure 6: Fuzzy control block diagram based on Matlab simulation.

Table 4: VALUES OF SIMULATED DOUBLY-FED INDUCTION GENERATOR PARAMETERS

Induction generator power rating	3KW
Frequency	0-50 Hz
Stator resistance	$R_s = 12.5 \Omega$
Stator leakage inductance	$L_s=23.3 \text{ mH}$
Rotor resistance	$R_r = 3.9 \Omega$
Rotor leakage inductance	$L_r=23.3 \text{ mH}$
Magnetizing inductance	$L_m = 477 \text{ mH}$
Bipolar Machine	$P_p=2$
Line Voltage	DC=120 V
Maximum Power	$P_{MAX} = 0.75 \text{ kw}$

Blocks, that have been named fuzzy control, are fuzzy controllers, before the controllers, two subtractors have been placed included to subtract the reference rotor current, i_{rd} and i_{rq} , from the rotor currents in the d and q axes for calculating the tracking current error. Due to multiplying of errors by the fuzzy system efficiency, the currents may be obtained large values. Therefore, they are multiplied by gain so that their amplitudes value is reduced. The inside of fuzzy blocks is as Figure 7.

Fuzzy system (Figure 8) includes two inputs that one of them is the tracking error inputs which are multiplied by k_p (proportional gain) and another is the integral of the tracking error input which is multiplied by k_i (integral gain). Also, because the inputs are PI, this kind of fuzzy system is called PI-like-fuzzy system.

Simulation is done in Simulink/Matlab environment. At first, the simulation of the wind turbine induction generator is firstly separated from the grid in the Matlab software. The parameter values of doubly-fed induction generator.

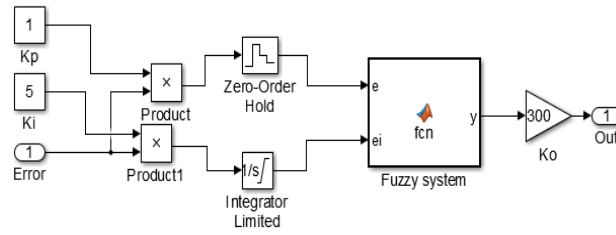


Figure7: The inside of Fuzzy control block.

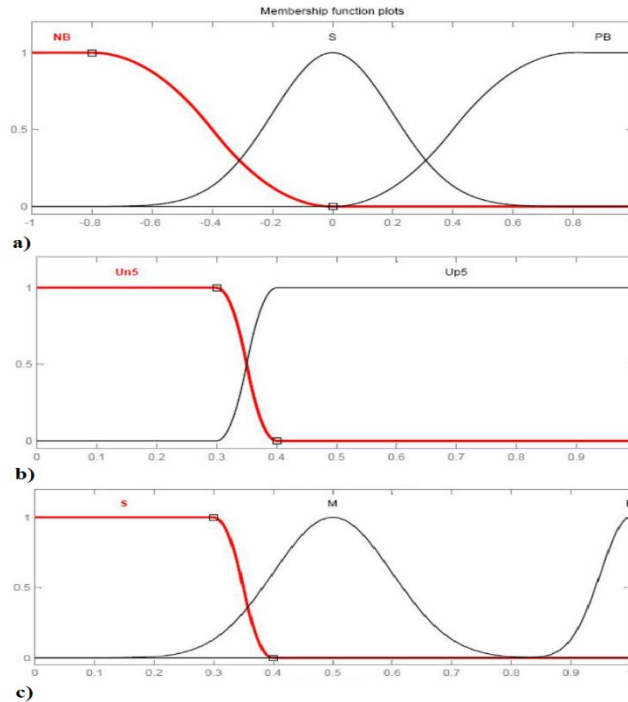


Figure 8: Fuzzy membership a) input 1 W b) input 2 delta c) output torque.

6. Simulation results

Simulation is done in Simulink/Matlab environment. In Figure 9, 10 and 11, the simulation results of the fuzzy controller and DPC controller are presented. At first, the simulation of the wind turbine induction generator is firstly separated from the grid in the Matlab software. The parameter values of doubly-fed induction generator, simulated in this paper, are presented in Table 4. Simulation is performed in the dq reference.

Figure 9 shows the results of stimulation for stator current parameter with two methods, DPC and fuzzy strategy. In Figure 12, the generator worked in nominal case. As it seen, stator current in fuzzy reached to the stability in 6 seconds, while in DPC method, generator worked in nominal without load. Nominal load applied in 0.1 second and in 2 second it decreased and stator current became stable.

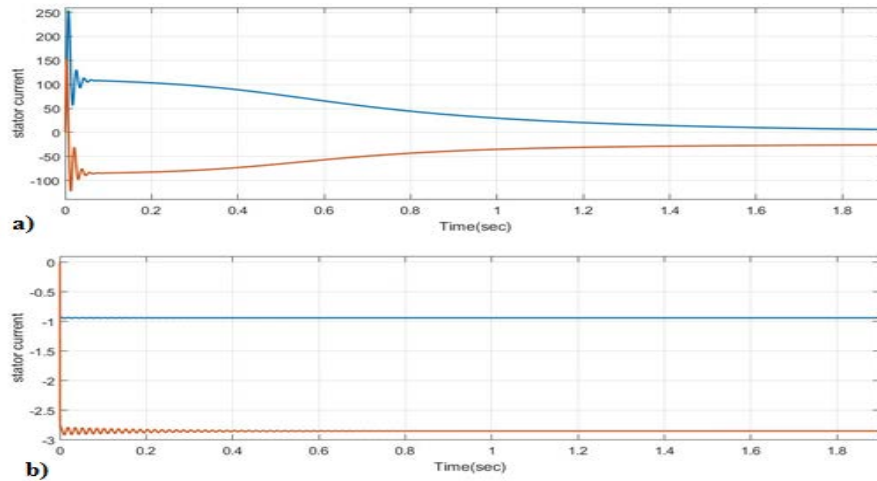


Figure 9: Stator Current a) fuzzy method b) DPC.

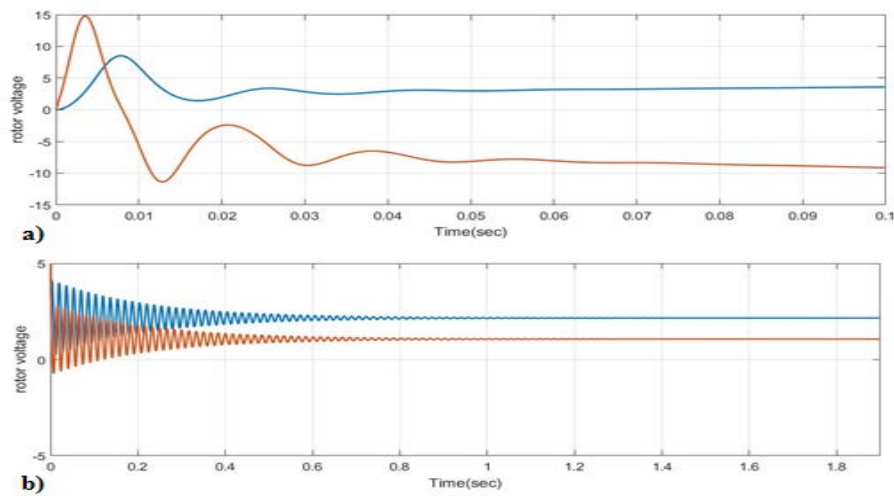


Figure 10: Rotor voltage a) fuzzy method b) DPC method.

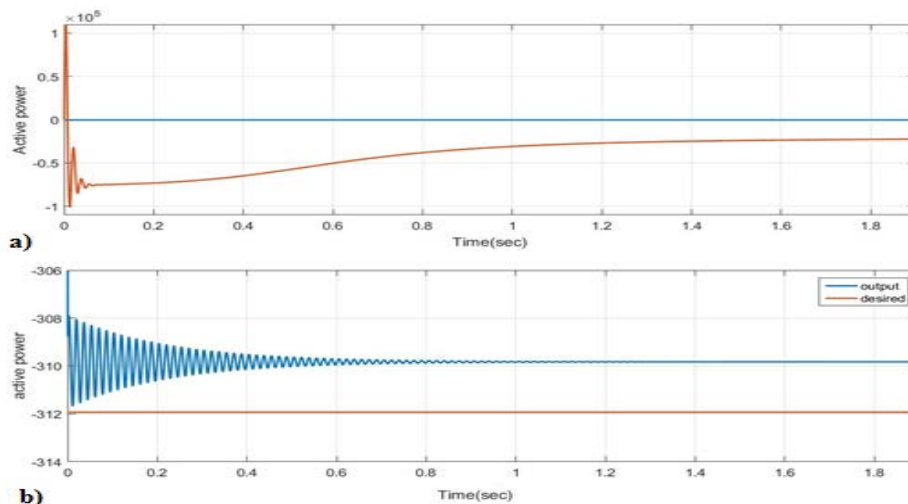


Figure 11: Active Power a) fuzzy method b) DPC method.

In Figure 10-a, rotor voltage after 7 second was stable that is not acceptable. In DPC, system had swing and the load was changed in 0-2 second. After 2 second it became stable.

In Figure 11, the active powers obtained from the fuzzy and DPC methods were provided. In Fuzzy method, it reach to zero at approximately 4.5 s, which is the favorite value, but in the DPC method, after passing 2 s, it is fixed at approximately -950 v.

Conclusions

In this paper, two methods are presented to control the doubly-fed induction generator wind turbine. The direct power control method does not need to measure the rotor quantities which have variable and sometimes very low frequency and create high latency. In addition, this control method is also very close to the behavioral nature of the induction machine in this machine. Due to the nonlinear behavior of the induction machine and wind turbine, using a fixed control factor will not have the favorable response. For this reason, the control factor of speed loop replaced the fixed factor as fuzzy, a proportionate with two variables, the speed and the speed loop error. Simulations showed that the fuzzy controller could present a proper response to startup and normal operation.

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