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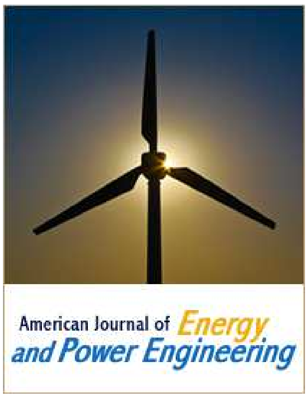

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Modeling and control of wind turbine powers by – A perspective PI and fuzzy logic controller

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Abstract
Utilization of the electrical energy is increasing day by day, and to satisfy the load demanded by the load centres has to satisfy the generating units. As the fossil fuels are depleting day by day, in order to save these fossil fuels we have to use the “Renewable energy sources”. Developing countries like Algeria, India, Nigeria, Ethiopia etc., are having tremendous wind energy, which is the most promising sources of energy. A case study has been conducted on the wind turbines that are controlled to provide constant active and reactive power during a certain period. In this paper, we model three different controllers of active and reactive power for horizontal axis wind turbine in order to compare their performance: the direct method with a PI and a Fuzzy Logic controller, and also the indirect method control with powers feedback. We aim to improve performance and reduce the number of controllers used. A series of simulation results obtained by Matlab / Simulink software are compared and analyzed.

1. Introduction

Fossil fuel dependency in the global economy and the environmental concerns hold attention for an alternative to current electricity generation methods. However, wind energy has proven the most promising sustainable energy resources [1]. Indeed, progress in wind technology is leading to lower costs compared to conventional methods [2]. In more than 80% of any country has a wind speed greater than or equal to 4 m / s [3].There are many fossil fuels in the environment like sunlight, wind, rain, tides, waves and geothermal heat. But the major source and more research work is going on the wind energy. And most of the wind energy is interlinked with the grid system. And lot of challenges are there for the industrial people who are linking renewable energy to the grids.

As known, in wind turbine installations, the generator mode of the doubly-fed induction machine (DFIM) attracts particular interest [4]. The wind turbine conversion system based on the doubly-fed induction generator (DFIG) is presented in Figure 1. The stator is directly connected to the grid (fig. 1); it operates synchronously at grid frequency, although the rotor is connected via a static converter that controls the active and reactive power of the generator.

The recent growth in wind power generation has reached a level where the influence of wind turbine dynamics can no longer be neglected. Regulations require normalization to make all stakeholders contribute to service system: control of active power, frequency, reactive power, voltage and tolerance of fault mode [5]. Control of the power quality is required then to reduce the adverse effects on the of WECS integration into the network. Thus, active control has an immediate impact on the cost of wind energy. Moreover, high performance and reliable controllers are essential to enhance the competitiveness of wind technology.

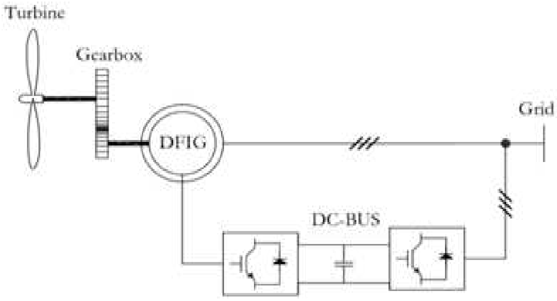


Fig. 1. *Overview of Wind Generation*

Several active and reactive power control strategies have been the subject of many researches. In the high wind speed range, the pitch control seems more relevant for controlling power margin [6]. To this end, the turbines incorporate either electromechanical or hydraulic devices to rotate the blades, and while in some countries the low wind speed range makes this type of setting useless view point price /additional needless inertia. The direct and indirect power control method presented in [7] seems to be more effective. The simulation results shown that the indirect control is more efficient than the direct one in terms of dynamics and responses to reactive power levels, but this method is more complicated due to the necessary regulator number and its very high cost.

This paper aims to improve the performance of direct control. To do this, we replace the conventional PI correctors by fuzzy logic controllers. Since the fuzzy logic approach is based on linguistic rules [8], the controller design doesn't require machine parameter to perform adjustment. In terms of robustness, this controller possesses a high robustness [9]. The simulation results obtained by the latter are compared with both direct and indirect methods to analyze the studied system dynamics. In the next section, we briefly describe the mathematical model of wind turbine essential elements.

2. Modeling of Variable Speed Wind Turbine

2.1. Energy Efficiency of a "Wind Sensor"

We can be found throughout the literature several models for power production capability of wind turbines that have been developed. Power in a wind turbine is proportional to the cube of the wind speed and may be expressed as [10]:

$$P_e = \frac{1}{2}\rho \mathrm{A} \tag{1}$$

Where ρ is air density, A is the area swept by blades and V is wind speed. A wind turbine can only extract part of the power from the wind, which is limited by the Betz limit (maximum 59%). This fraction is described by the performance coefficient of the turbine C_p, which is a function of the blade pitch angle and the tip speed ratio.

Therefore the mechanical power of the wind turbine extracted from the wind is:

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

The performance coefficient depends on both the pitch angle (β) and the tip speed ratio (λ). The tip speed ratio is calculated by using blade tip speed and wind speed upstream of the rotor, as in the following formula [11]:

$$\lambda = \frac{R\Omega}{V} \tag{3}$$

The relationship between performance coefficient (c_p), pitch angle (β) and tip speed ratio (λ) is established by the $c_p - \lambda$ approximation (3) for different blade pitch angle, as shows the simulation result obtained by MATLAB / SIMULINK software.

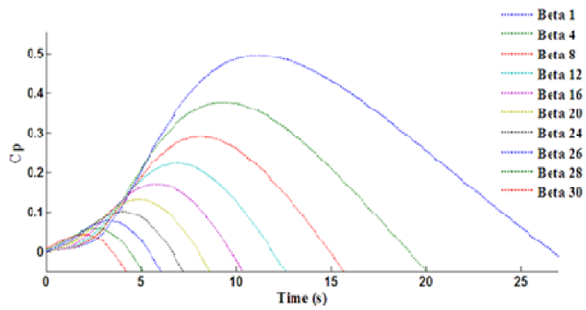


Fig. 2. *performance coefficient* (c_p)

2.2. Model of the Wind

The model of the wind is essential to obtain realistic simulations for the wind turbines power control. The model includes wind turbulence. But to exploit this energy, we must consider the following constraints [12]:

The wind speed may fluctuate by ± 25% over a several minutes period. The regularity of the wind direction and speed depends on the site. To determine the best wind resource, we must conduct surveys of speed and wind direction over a period of at least one year. The measurement of wind speed is generally carried out at 10 meters above the ground. However, it is often useful to be able to measure at interest altitudes such as the heights of wind turbines. Several empirical formulas allowing the vertical extrapolation of wind speed [4,13]. Speed v_1 is extrapolated from an altitude above sea level to a $z_1 z_2$, according to the formula (4)

$$V_2 = V_1 \left[\frac{Z_2}{Z_1}\right]^{\alpha_1} \quad (4)$$

With

$$\alpha_1 = \frac{1}{In\frac{Z}{Z_0}} - \left\{\frac{0.0881}{1-0.0881\, In\frac{Z_1}{10}}\right\} In\left(\frac{V_1}{6}\right) \quad (5)$$

Where

$$Z = \exp[\mathrm{In}(Z_1) + \mathrm{In}(Z_2)]/2 \quad (6)$$

Z: the roughness of the ground.

Wind speeds, the roughness of the place is available, were extrapolated at 10 meters height, and at 25 meters altitude. Table 1, defines the values of and according several surfaces type [14].

Table 1. *The values of Z_0 and $\alpha_1$according several surfaces type*

Surface type	Z0(mm)	α1
sand	0.2 to 0.3	0.1
mown grass	1 t0 10	0.13
high grass	40 to 100	0.19
suburb	1000 to2000	0.32

Figure 3 shows a realistic sample of variable wind speed simulated in 100s

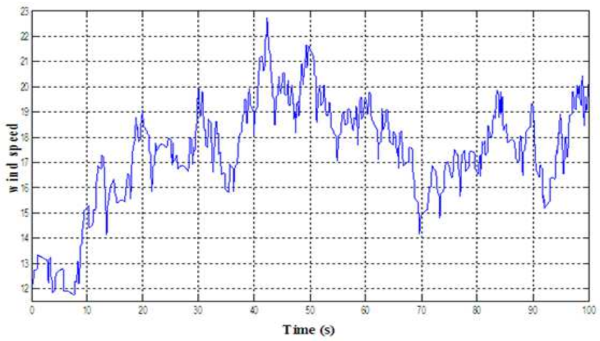


Fig. 3. *Wind speed sample (100s)*

2.3. DFIG Modeling

As cited before, we use in this study the DFIG, nowadays, most of the installed wind turbines are based on a doubly fed induction generator (DFIG), sharing the place with the wound rotor synchronous generators (WRSGs) and the permanent magnet synchronous generators (PMSGs) [15]. These generator choices allow variable speed generation. The DFIG is operableas a motor or generator independently from the rotation speed [16]. It allows access to the rotor voltages and currents [17]. The rotor voltages control gives the machine the ability to operate in super or sub synchronism of both motor and generator mode [18].

The general equations of the DFIG can be written in a three-phase landmark as a result [19] [20].The generalized reduced order machine modelwas developedbased on conditions and assumptions cited in [19].

$$\begin{bmatrix}[V_s]\\ [V_r]\end{bmatrix} = \begin{bmatrix}[R_s][I_S]\\ [R_R][I_r]\end{bmatrix} + \frac{d}{dt}\begin{bmatrix}[\phi_s]\\ [\phi_r]\end{bmatrix} \quad (7)$$

And the flux;

$$\begin{cases}[\phi_s] = L_s[I_s] + M[I_r]\\ [\phi_r] = M[I_s] + L_r[I_r]\end{cases} \quad (8)$$

$$L_s = I_s - M_s;\ L_r = I_r - M_r\ ;\ M = \frac{3M_{sr}}{2} \quad (9)$$

Taking into account (8), Park transformations applied to (7) provide:

$$\begin{cases}V_{sd} = R_s I_{sd} + \frac{d\phi_{sd}}{dt} - \dot{\theta}_s \phi_{sq}\\ V_{sq} = R_s I_{sq} + \frac{d\phi_{sq}}{dt} - \dot{\theta}_s \phi_{sd}\\ V_{rd} = R_r I_{rd} + \frac{d\phi_{rd}}{dt} - \dot{\theta}_r \phi_{rq}\\ V_{rq} = R_r I_{rq} + \frac{d\phi_{rq}}{dt} - \dot{\theta}_r \phi_{rd}\end{cases} \quad (10)$$

$$\begin{cases}\phi_{sd} = L_s I_{sd} + M\, I_{rq}\\ \phi_{sq} = L_s I_{sq} + M\, I_{rq}\\ \phi_{rd} = L_r I_{rd} + M\, I_{sd}\\ \phi_{rq} = L_r I_{rq} + M\, I_{sq}\end{cases} \quad (11)$$

Power expression can be rewritten as follows:

$$\begin{cases}P = -V_s \frac{M}{L_s} I_{rq}\\ Q = -V_s \frac{M}{L_s} I_{rd} + \frac{{V_s}^2}{L_s \omega_s}\end{cases} \quad (12)$$

Figure 4, presents the block diagram of DFIG used in simulation. The input are rotor voltages ($V_{rd}$and V_{rq}) however, the outputs are the stator active and reactive power ($P_s$and Q_s).

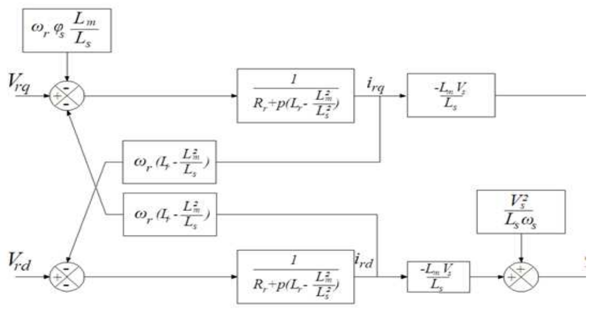


Fig. 4. *DFIG bock diagram*

Table 2, shows the main parameters of the induction generator which is used in this study.

Table 2. *DFIG parameters*

Components	Rating Values
R_s	*0.455 Ω*
Ls	*0.07H*
Rr	*0.19Ω*
Lr	*0.0213H*
M	*0.034H*
P	*2Polepair*

3. Methods Presentation

In this section, first, we describe two existed types for separate control of both active and reactive power: Direct/Indirect control methods using PI controllers, then in the end we present our proposed combined method by using FL-controller with a proper Fuzzy rules Inputs and outputs. In real installation, these methods are implemented to control the rotor/generator side converter as described in figure.1.

3.1. Direct Control with PI

Considering the block diagram of the system to be controlled "Fig. 5 ". Taking into account the relation between the rotor currents and stator powers, we see the appearance of the $\frac{MV_s}{L_s}$ term. Since the wind turbine is considered connected to a high power and stable network, this term is constant and therefore there is no necessary regulator between the rotor currents and powers is needed. But we provide a control loop for each power with an independent regulator by compensating the perturbation terms shown in the block diagram "Fig. 5, [21] [22] [23]. As shown it is clear that this method simple to implement

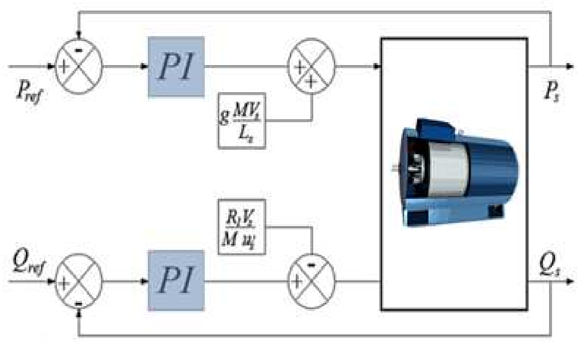


Fig. 5. *Directcontrol block diagram*

3.2. Indirect Control with Power-Loop

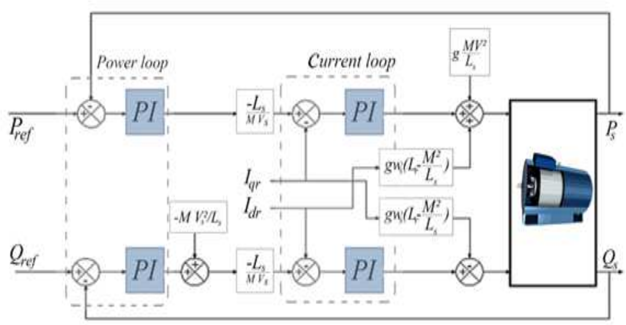


Fig. 6. *Indirect control with the power-loop*

The basic principle of the indirect method is to replicate the block diagram of the control system in the opposite direction [25] [26]. We reach a block diagram to express voltages according powers. Indirect control will therefore contain all the elements in the DFIG block diagram. To enhance indirect control, we insert an additional power loop to eliminate the static error while preserving the system dynamics. Thus, we obtain the block diagram shown in "Fig. 6 ", we distinguish the two control loops for each axis, one to control the current and another one for the power.

3.3. Direct Control with Fuzzy Logic Controller

The concept fuzzy set theory was developed by Lotfi Zadeh in 1965; this concept was developed in USA. But the rapid development of this technology has been in Japan. But after a few years in 1991 this technology came in to scientific laboratories and it became a most efficient tool in the industries. After this USA has been implemented this sophisticated controller to aerospace, motor control, process control, intelligence control, and electric power systems operation. Fuzzy logic has a lot of applications in present industry.

The fuzzy logic has three important stages, The Fuzzy logic control consists of three main stages, namely the fuzzification interface, the inference rules engine and the defuzzification interface. Implementation of a Fuzzy logic controller by the block diagram representation. And its analysis is shown in the form of a figure

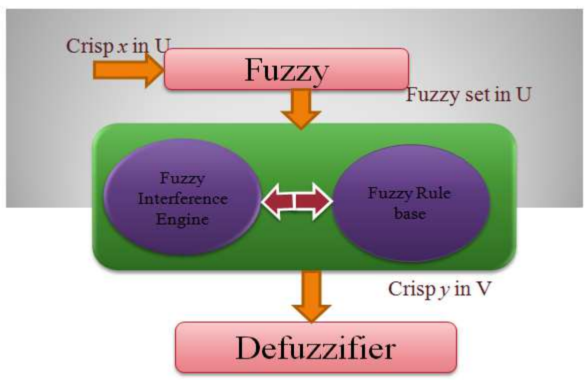


Fig. 7. *Implementation of Fuzzy logic controller*

As explained in the fuzzy control block diagram "Fig. 8 ", have two inputs (the error (e), and its derivatives (de)) and an output (of the order (cde)).

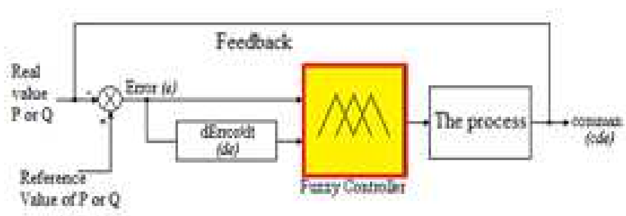


Fig. 8. *Fuzzy Control Synoptic Schema*

The fuzzy controller inputs are the active and reactive power errors, the error rate of change in a time interval. Linguistic variables and terms are shown in Table 3.

As described in Figure 6, this paper focuses on fuzzy logic control based on mamdani's system [24]. This system has four main parts. First, using input membership functions, inputs are fuzzified then based on rule bases and inference system, outputs are produced and finally the fuzzy outputs are defuzzified and applied to the main control system.

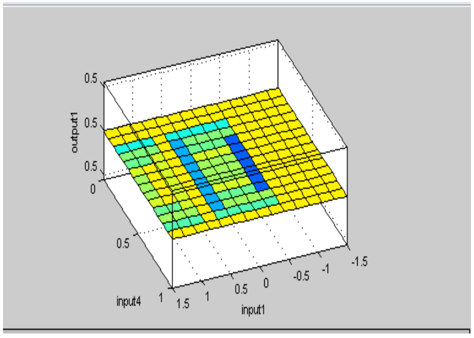


Fig. 9. *Surface view of the rules related to input and output conditions*

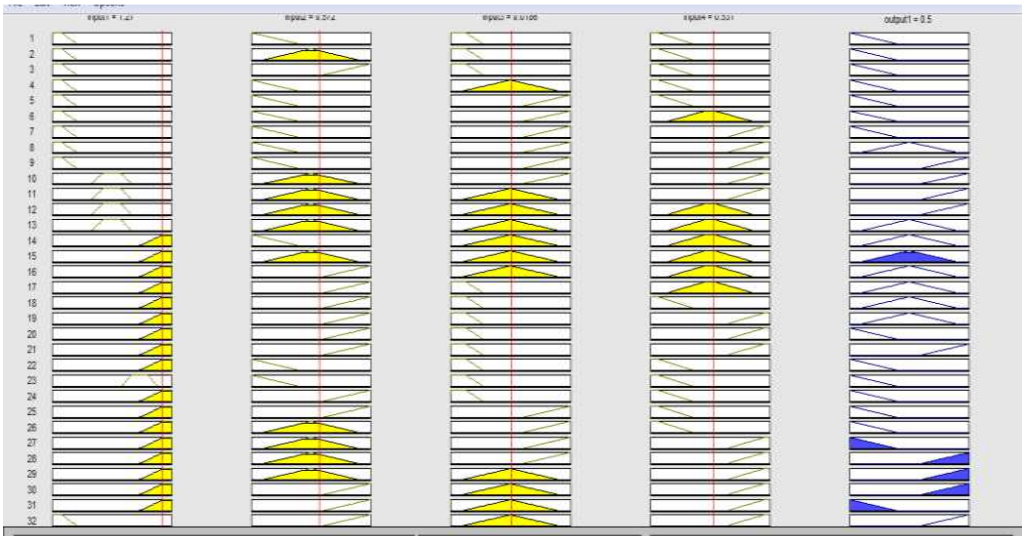
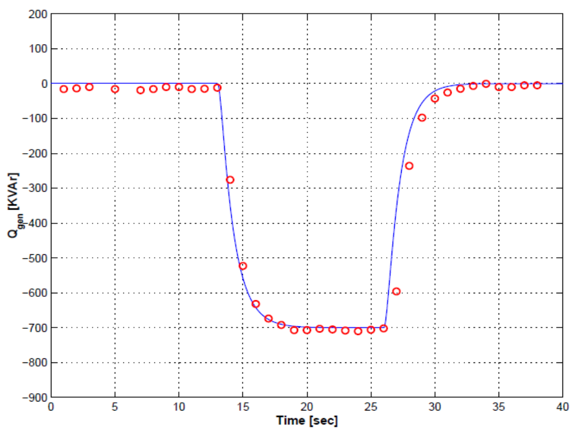


Fig. 10. *The rule viewer of the fuzzy logic The Fuzzy Rule base for controlling the PI controller to maintain active/ reactive and voltage profiles etc*

Table 3. *Rule base for Fuzzy Logic controller for three area system*

		ė				
		NB	**NS**	**ZZ**	**PS**	**PB**
	NB	S	S	M	M	B
e	NS	S	M	M	M	VB
	ZZ	M	M	B	VB	VB
	PS	M	B	VB	VB	VVB
	PB	B	VB	VB	VVB	VVB

We applied to the system levels of active and reactive power in order to observe the control behavior."Graph.01 and 02 ", presents the results of simulations with the direct control of PI. There is a reactive power error when active power is low. By cons, it shows a static error at the active and reactive power mainly due to the methodology of this regulation. When we are controlling the terms by using PI controller the K_p is considered [0 to 0.12]



Graph. 01. *Reactive power improvement by using PI and Fuzzy logic controller (PI- red and fuzzy- Blue)*

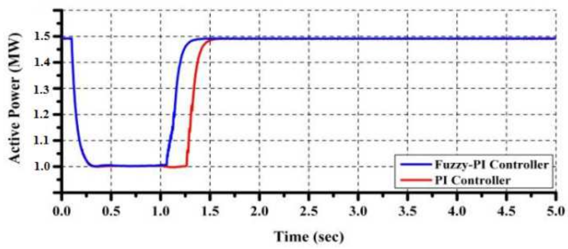
4. Simulation and Discussion

To simulate the results we considered the parameters for 1.5MWatt rated wind mill as mentioned in the below table4.

Table 4. *Ratings of the wind turbine considered for modeling*

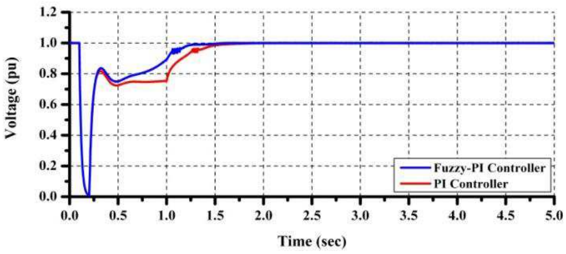
Wind turbine	Ratings
Cut-in speed	4.0m/s
Cut-out speed	25m/s
Rated wind speed	13m/s
Number of blades	3
Diameter	65m
Maximum tip speed	68m/s
Blade length	31.2 m

Direct control with PI and fuzzy correctors were implemented in MATLAB / SIMULINK software for testing.



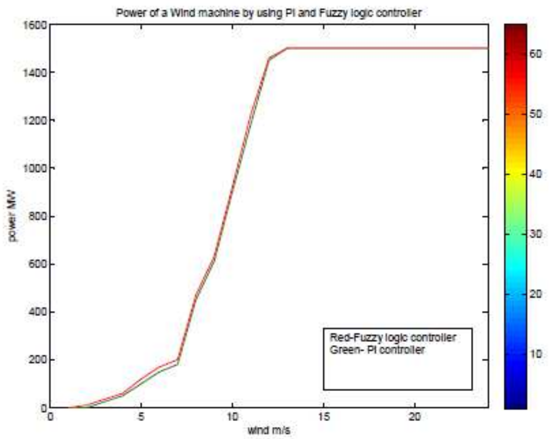
Graph. 02. *Active power improvement by using PI and Fuzzy logic controller (PI- red and fuzzy- Blue)*

We notice that the system has a satisfactory dynamic and null static error. For both active and reactive powers, there is a dynamic that reacts quickly and without overshoot. Levels are properly monitored and there are no more power errors. The coupling between the two powers is very small and hardly noticeable. It should not be a problem for the future machine model operation.



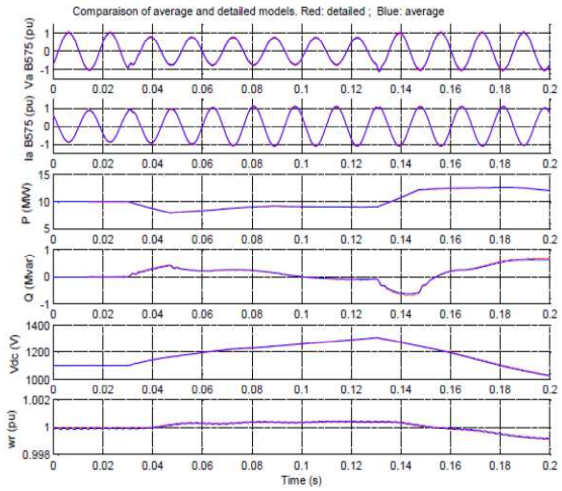
Graph. 03. *Voltage profile of the wind plant in per units*

The graph.01 describes the reactive power at the wind machine when it is running at the rated wind speed 13m/s. when the rotor is running at the 18rpm. Similarly the graph.02 shows the Active power component and graph.03 shows the voltage profile of the wind plant. All the graphical representations shows the controlling of the reactive, active and voltage profile by using the fuzzy and PI controller. When the machine is running at the rated speed.



Graph. 04. *Power of the wind machine when it is operated by PI and Fuzzy controller*

The above mentioned results are for a single wind turbine which is having rating of 1.5 MW. All the mentioned results are for a single wind machine.



Graph. 05. *Detail graphical representation of power profiles and voltage profiles.*

The same wind power plant is taken by increasing the machine rating to 10MW. These are the graphical results of the machine. In the future if the rating of the machine is increased or two or mo more machines are interconnected. The controller ratings and for the fuzzy rules will change in the future same fuzzy logic controller is applied for the interconnected machine to improve the performance of the machine.

5. Conclusion

In this paper the Fuzzy –PI controller is proposed to control the active and reactive powers of a Wind turbine. These controllers are connected Double Fed induction generator. To control the reactive power compensation in generally we have to use the compensation devices or to make more efficient we have to use the controllers. In this paper the PI and Fuzzy logic controllers are used at the Induction motor to control the power profiles like reactive power and active power profiles. So while doing the analysis as per the results obtained by the Simulink analysis the Fuzzy logic controller is the best controller to control the power profiles.

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Mr. Sunil kumar. J was born in Tirupathi, India. He received his M.Tech from Sri Venkateswar University, Tirupathi, in 2011. Present he is pursuing his PhD. currently working as a Assistant Professor in Adama science and technology university, Adama. His research interests include Power Systems, Renewable Energy, Fuzzy Logic, Neural Networks, Flexible AC Transmission System (FACTS). He is working as a reviewer for many journals like International Journal of Electrical Power & Energy Systems (Elesvier), Global Journal of Researches in Engineering, United States, International Journals of Engineering & Sciences. He is Program committee member for WSEAS, PESTSE 2014, and IEPS2014 (Ukraine).

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Dr. Ashok Kumar born in India, He is having 12+ years of teaching experience he completed his PhD from srikrishnaDevaraya university, India. Currently he is working as a Associate professor in Adama Science and Technology university. He guided many Masters and PhD Students under his guidance. He is a reviewer for many international journals. He published many journals in national and international conferences and journals. His research interests are Renewable energy, Power systems, Instrumentation and control systems.