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Maximum Power Extraction from Permanent Magnet Synchronous Generator in Wind Power Energy Systems Using Type-2 Fuzzy Logic

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***Abstract*— In this paper, the control scheme of wind variable speed in wind energy systems for permanent-magnet synchronous generators is presented. The algorithm of this scheme allows the system to track the maximum power in wind speeds lower than turbine nominal speed, and assures that, when the wind speed is higher than the nominal speed, power will not exceed its nominal value. The control system is constituted by two parts: one for the generator side, and the other for the grid side. The basis of the controller in generator side is to track the maximum power through controlling the wind turbine rotation speed (w) using fuzzy logic. Type-2 Fuzzy Logic has been employed in order to have a better and more efficient control, as well as to resist against the uncertainties in system parameters. In grid-side converter, the active and reactive power controls have progressed to be able to be controlled by d- and q-axis components. The d-axis current is set at zero for unity power factor and the q-axis current is controlled to deliver the power flowing from the dc-link to the electric utility grid. The simulation of this scheme has been conducted in Simulink/Matlab Software and fuzzy toolbox.**

***Index Terms*— Permanent-Magnet Synchronous Generator, Type-2 Fuzzy Controller, Wind-Energy Conversion System.**

I. INTRODUCTION

During the last two decades, major progresses have been made in wind-energy conversion capacity. Exploiting the variable speed and direct drive from wind turbines has been one of the modern and technological aspects of wind-energy systems [1,2]. Variable speed provides many advantages over constant speed; including increased output power, exploiting in the maximum point power of wind speed ranges, increased output power quality, decreased aerodynamic pressures, decreased noise, increased system reliability, a 10-15% increase in output power and decreased mechanical pressures in comparison to constant speed. Because of its low price, wind energy is among the most promising renewable resources in comparison to other conventional energy resources. However, only some special geographical zones can be considered as appropriate for wind energy production. Wind power does not harm the environment, but is an abundant natural resource. So, wind turbine can be used to convert mechanical power to electricity.

Wind turbines are categorized into two classes according to their drive method: direct drive (DD) and Geared Drive(GD). In GD, a gear box and squirrel cage inductive generator (SCIG) is used. The Gear box drive wind turbines are divided into three classes based on their configuration in constant speed conditions: stall, active stall, and pitch control systems[1]. Doubly-Fed Induction Generators(DFIG) are employed in variable speed applications, especially in high Power wind turbines. In small and medium size Direct Drive Wind Turbines a permanent-magnet synchronous generator (PMSG) with more poles is used to compensate the lack of gear box. PMSGs present numerous advantages including higher Energy per weight ratio, and no additional power supply for stimulation, high reliability because of the removal of mechanical parts such as slip rings.

In addition to the abovementioned points, the PM material performance is improving and its cost has been reducing during the past years. Therefore, having an eye on these advantages in permanent magnet wind turbine, direct drive in small and medium wind turbines sounds more attracting [3-6].

Using robust controllers to track maximum wind power has been developed in several literatures [7-11]. These controllers include some techniques called tip speed ratio (TSP), power signal feedback (PSF), and hill-climb searching (HCS). TSR controlling technique regulates the generator rotational speed in order to keep TSR in the maximum power point tracking. TSR is calculated by measuring both wind speed and turbine speed, and then the optimal TSR must be given to the controller. The first barrier to implement TSR control technique is the wind speed measurement which adds to system cost and presents difficulties in practical implementations. The second barrier is to provide an optimal amount of TSR, which varies in different systems. This variation is because of the turbine

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generator characteristics, which requires the designation of a special control software for each wind turbine [1]. PSF controlling technique[1] requires the maximum power curve of the wind turbines to track the maximum power point. The power curve for each wind turbine can be obtained by simulation or examining the turbine when it is off-line, or it can be obtained from the datasheet of wind turbines. This need to power curve can be counted as one of the problems in this method [1,12]. The HCS Technique does not need the information about wind speed, generator rotational speed or turbine characteristics. However, it works better when the wind turbine inertia is very small. For large inertia wind turbines, the system output power is interlaced with the turbine mechanical power and variations in the mechanically stored energy, which can be considered as a deficit for HCS technique. On the other hand, various algorithms have been used for maximum power extraction in wind turbines that are not mentioned here. For example, in [5] introduces an algorithm for producing a maximum power and controlling the reactive power of an inverter through power angle (δ) and inverter terminal voltage and modulation index (m_a), based on a variable wind speed turbine without speed sensor. In [13] an algorithm is presented to track the maximum power point by controlling the generator torque through d-axis current component, thus the generator speed control will work with variation in wind speed. This technique has been used to control active and reactive power produced in wind turbine through q- and d-axis current components. As such, [14] shows that it is possible to control active and reactive powers produced in wind turbine separately and thorough d- and q-axis current components, and to exploit the maximum power point in wind energy systems through DC current regulation in DC/DC boost converter entry. In [15] an algorithm has been provided to track the maximum power point through direct regulation of duty cycle in a DC/DC converter through modulation index of the PWM-VSC. Finally, MPPT control based on Fuzzy Logic Control (FLC) was shown in [14, 16-20]. The fuzzy logic control function is as follows: the generator rotational speed is compared to the reference speed in order to reach a maximum produced power given the variations in wind speed. In this paper, the WECS has been connected back to back to the grid, using PMSG and PWM-VSC control, as it has been shown in figure1. A modified MPPT control algorithm, using Type-2 Fuzzy Logic to regulate the rotational speed and to require the PMSG to work around the maximum power point when the speeds are lower than nominal speed and when the speeds are higher than the wind turbine nominal speed, has been employed to obtain a nominal power. The fuzzy inputs (ΔPm , Δwm) and are calculated at the output of rotational speed variations (Δ*m).

The fuzzy method details are discussed in the next sections. An indirect vector-controlled PMSG system has been used in the proposed system. The MPPT control system shown in this paper is able to track maximum output power via controlling the electromagnetic torque using two generator current components, iα and iß. The active and reactive power controls are obtained for the grid-side converter with quadrature and direct axis current, respectively. The MATLAB/Simulink and Fuzzy Logic Toolbox Software have been used to implement this project.

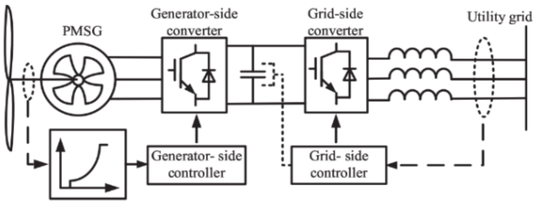


Figure 1. A general block diagram of the system

II. SYSTEM DESCRIPTION

The main structure of the connection between PMSG and wind turbine connected to the grid as *ac-dc-ac* has been shown in figure1. The generator has been connected to the grid through a back to back PMW-VSC connection. The grid-side converter is connected to the grid-side AC through a DC voltage. The control system is produced though the grid-side and generator-side converters. MPPT algorithm is obtained through the generator part and using FLC control. The grid-side converter control, which maintains the DC voltage within a desirable range, has been conducted by active power injection into the grid and reactive power control.

A. PMSG Model

The generator has been modeled according to the following voltage equations in rotor d- and q-axis [4].

$$v_{sd} = R_s i_{sd} + \frac{d\lambda_{sd}}{dt} - \omega_r \lambda_{sd} \qquad (1)$$

$$v_{sq} = R_s i_{sq} + \frac{d\lambda_{sq}}{dt} - \omega_r \lambda_{sd}$$

where λ_{sd} and λ_{sq} are stator flux linkages in the direct and quadrature axis, respectively. The equations for these values in absence of damper circuits in terms of stator currents and magnetic flux are revised as:

$$\lambda_{sd} = L_s i_{sd} + \psi_F\, i_{sq} \qquad (2)$$

where Ψ_f is the permanent magnet flux and L_s is PMSG stator inductance. The electromagnetic torque T_e is obtained from the following relation:

$$T_e = \frac{3}{2} P \left[\lambda_{sd} i_{sq} - \lambda_{sq} i_{sd} \right] \qquad (3)$$

where *p* denotes the number of pole pairs. For machines without salient pole, the stator inductance L_{sd} and L_{sq} are approximately equal to [21]. This means that the direct axis current i_{sd} does not contribute to the electrical torque. Our goal is to keep i_{sd} constant in zero in order to obtain a maximum torque with minimum current. The electromagnetic torque is obtained from the following relation:

$$T_e = \frac{3}{2} P \psi_F i_{sq} = K_c i_{sq} \qquad (4)$$

i_{sq} denotes the stator current in quadrature axis in rotor reference and K_c is the torque constant.

B. Wind Turbine Model

Wind turbine has the duty of converting wind energy to electric energy. This mechanical power is produced through a wind turbine connected to a generator shaft, as it has been stated in the following equation:

$$P_m = \frac{1}{2} C_p(\lambda, \beta) \rho A u^3 \tag{5}$$

where ρ is the air density (generally equal to 1.225 kg/m^3), β is the pitch angle (in degree), A is the area swept by the rotor blades (in m^2), u is the wind speed (in m/s) and Cp(λ,β) is the wind-turbine power coefficient. The power coefficient Cp(λ,β) is considered as the wind turbine power coefficient. It is the ratio of mechanical power available in turbine shaft to the power available in wind. A general equation for Cp(λ,β) according to turbine characteristics is stated as[1]:

$$C_p(\lambda, \beta) = 0.5176 \left(116 * \frac{1}{\lambda_i} - 0.4\beta - 5\right) e^{-21/\lambda_i} + 0.0068\lambda \tag{6}$$

C_P is a nonlinear function dependent upon λ (tip speed ratio) and blade pitch angle, β. Theoretically, the maximum value for C_P is 0.593, but practically it varies between 0.4 and 0.45. This is known as Betz constraint [3, 4]. λ is a ratio of turbine speed (Wm*R) to wind speed (u):

$$\lambda = \frac{\omega_m^* R}{u} \tag{7}$$

where w_m is the rotational speed and R is the maximum rotor radius. for a fixed β, C_P can only exist in the form of a nonlinear function of λ. According to Eq.7 , it can be said that there is a relationship between λ and w_m. Thus, in a certain *u*, power is maximum in a certain w_m, called optimal rotational speed,W_{opt}. This speed is consistent with the optimal tip speed ratio (λ_{opt}) [12]. The value of the tip speed ratio is constant for all conditions of maximum power points (MPPT). Therefore, to extract maximum power in variable wind speed, it is better for WT to operate in λ_{opt} conditions, in speeds lower than nominal speed. This is done by controlling the rotational speed WT, which is equal to the optimal rotational speed.

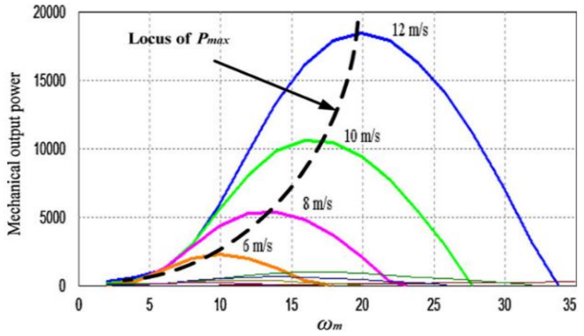


Figure 2. Output power characteristic

Fig. 2 shows the mechanical power produced by WT in generator shaft as a function of w_m. This curve is adopted from [1].

III. GENERATOR-SIDE CONVERTER CONTROL

The generator-side converter controllers are searching for the maximum output power which is possible through electromagnetic torque control, as it was seen in Eq.(4). The proposed control is shown in figure3. The speed control loop produces the q-axis current. In order to control torque in different wind speeds, the reference values of iα and iβ are calculated. The torque control can be obtained by controlling i_{sq} axis current, as shown in Eq.(4). Figure 4 shows the stator and rotor current space phasor and the excitation flux of the PMSG. As it can be seen, the quadrature stator current i_{sq} is controlled through rotor reference frame (β and α axis). Therefore, the reference values for iα and iβ can be estimated easily from i^*_{sq} amplitude and rotor angle, θr. So, first the rotor angle θr and the relationship between angular speed w_r and mechanical speed w_m should be found through the following equation:

$$\omega_r = \frac{P}{2} \omega_m \tag{8}$$

Therefore the rotor angle θr can be estimated from the electrical angular speed, w_r. the speed controller input, reference and actual rotor mechanical speed (rad/s) and the output is the (α and β) reference current components. The actual value for α and β axis is calculated from the three phases of PMSG current. The fuzzy logic is used to find the reference speed for maximum MPPT.

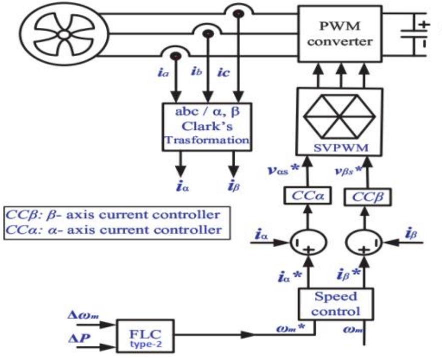


Figure 3. Generator-side control block diagram

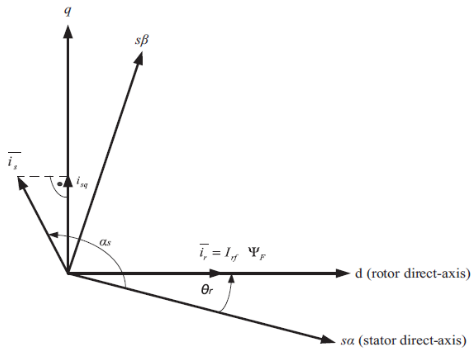


Figure 4. The stator and rotor current space phasors and the excitation flux of the PMSG.

IV. THE TYPE-2 FUZZY LOGIC CONTROLLER FOR MPPT

Regardless of its belonging function form and working algorithm, the biggest problem with Type-1 fuzzy logic is that the appointment of a membership degree for pixel is not certain. Therefore, in order to obtain a more efficient solution, the Type-2 fuzzy logic is used where the fuzzy function membership degree is fuzzy (figure 5).

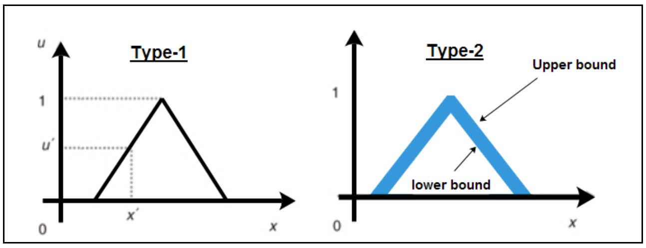


Figure 5. The difference between Type-1 fuzzy and Type-2, where in Type-2 fuzzy an upper and lower bound belonging is defined

In this method, the upper bound and lower bound of membership are calculated by:

$$\mu_U(x) = [\mu(x)]^{\frac{1}{\alpha}} \qquad (9)$$
$$\mu_L(x) = [\mu(x)]^{\alpha}$$

where α∈(1,2], and it can be easily considered equal to 2.

Figure 6 shows the general structure of a Type-2 fuzzy system. A Type-2 fuzzy system is constituted from four parts: fuzzification, rules, inference, and output process. In a Type-2 fuzzy system the output process in consisted of two stages: first, a Type-2 fuzzy set is drawn to a Type-1 fuzzy set, which is called type reduction or order reduction. Then the type-reduced set is defuzzified. The order reduction methods in Type-2 fuzzy systems are in fact the developed defuzzification methods in Type-1 fuzzy systems. order reduction includes three methods: centroid, center of sets and height [1]. The reader is referred to [22, 23] in order to read more about the concepts of set and Type-2 fuzzy systems.

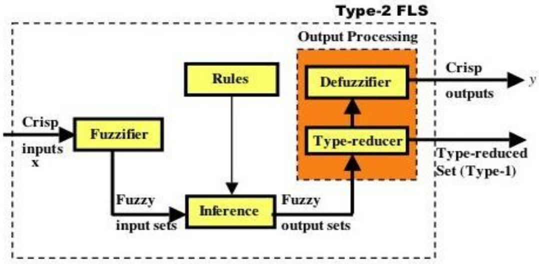


Figure 6. The structure of a Type-2 fuzzy system

In order to extract the maximum power in a variable wind speed, the turbine should always operate in λopt. This state can occur by controlling the turbine rotational speed. The tubine can work in optimal conditions using Type-2 Fuzzy controller. Each wind turbine has a different λopt value in a variable speed, but wopt varies from one wind speed to another one. According to Eq. (7), the relationship between w_{opt} and λopt for a constant R is calculated as:

$$\omega_{opt} = \frac{\lambda_{opt}}{R} u \qquad (10)$$

It can be seen from Eq.(10) that the relationship between the optimal rotational speed and wind speed is linear. The fuzzy controller (FLC) is used to find the reference rotational speed which can lead to the maximum power in variable wind speeds. FLC block diagram is shown in figure7. The main goal of using FLC instead of PI controller is to continuously adapt the rotational speed of the generator to the wind speed in a way that the turbine operates at its optimum level of aerodynamic efficiency. The advantages of using fuzzy over PI controller are: universal control algorithm, very simple, adaptive, fast response, extension of the operating range, parameter insensitivity and it can work properly even with an inaccurate input signals. The proposed Type-2 fuzzy logic does not need any information about wind speed or w_T parameters. Fuzzy logic provides a better and efficient response in tracking the maximum power point, especially when wind varies frequently. Both variables are used as FLC input (ΔWm,ΔPm) and ΔW*m is the output. The membership functions in are presented figure 8. The triangular membership functions are appropriate for those inputs and outputs that are more sensitive to zero value. FLC does not need a system mathematical model and its performance follows a series of simple rules. The basis of FLC is the reference speed ΔW*m, and it can be seen that it changes according to variations in ΔPm; that is, each change in speed lead to a change in power. FLC is effective in tracking the maximum power point, especially if the conditions change frequently.

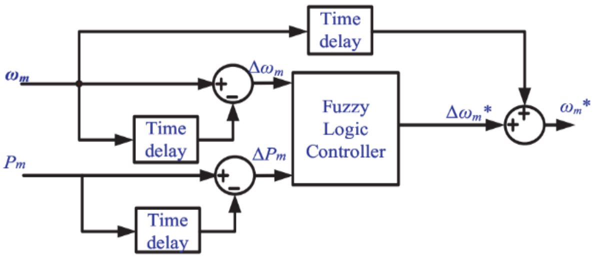
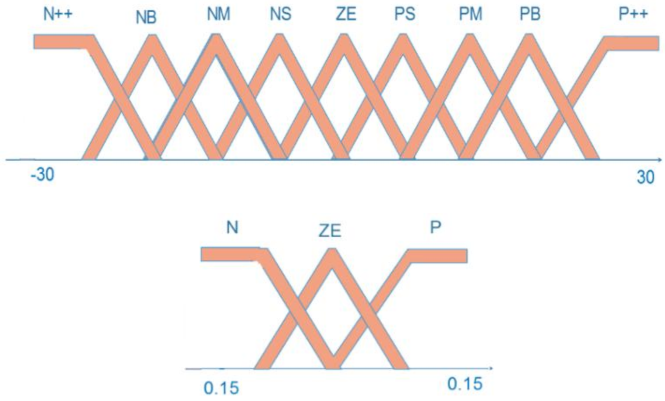


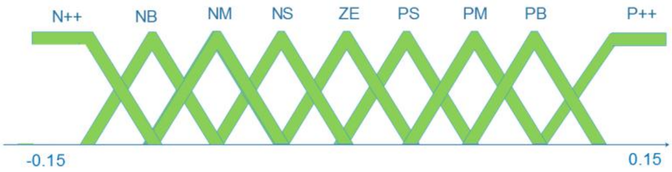
Figure 7. Fuzzy controller inputs and output

TABLE I. RULES OF FUZZY LOGICS CONTROLLER

$\Delta\omega_m$	ΔP_m								
	N++	NB	NM	NS	ZE	PS	PM	PB	P++
N	P++	PB	PM	PS	ZE	NS	NM	NB	N++
ZE	NB	NM	NS	NS	ZE	PS	PM	PM	PB
P	N++	NB	NM	NS	ZE	PM	PM	PB	PB



A- Input membership functions including ΔP and Δw



B- Output membership functions

Figure 8. Membership functions of Fuzzy logic controller

Table I lists the fuzzy rules for input and output variables. The next step in fuzzy is to choose the input and output control of the FLC. The Variations in power and reference speed are dependent upon the system. In figure.8 the speed reference variation is between -0.15 and 0.15 rad/s and the power varies between -30 and 30 watt. The membership functions are described as follows: N negative, N++ very big negative, NB negative big, NM negative medium, NS negative small, ZE zero, P positive, PS positive small, PM positive medium, PB positive big, and P++ very big positive.

V. GRID-SIDE CONVERTER CONTROL

Grid-side converter is used to keep the DC-link voltage at the reference value of 600 V. When the output power increases in relation to the input power, a capacitor is used to stabilize the DC voltage. The output power is stabilized by setting the capacitor at a constant value. By regulating the DC-link voltage, the reactive power flowing into the grid is controlled at zero value. This is done through the grid-side converter and controlling d- and q-axis currents. Active and reactive powers are calculated by the following equations:

$$P_s = \frac{3}{2}(v_d i_d + v_q i_q) \tag{11}$$

$$Q_s = \frac{3}{2}(v_q i_d - v_d i_q) \tag{12}$$

By conforming the q-axis reference to vd = 0, and using Eq (11) and Eq(12), the active and reactive powers are obtained from the following equations:

$$P_s = \frac{3}{2} v_q i_q \tag{13}$$

$$Q_s = \frac{3}{2} v_q i_d \tag{14}$$

Active and reactive power controls are obtained by controlling q- and d-axis grid elements, respectively. Two control loops are used for active and reactive powers. One external Dc-Link voltage control circuit for q-axis current (active power control) and one internal control circuit for reactive power control by regulating d-axis current in zero in order to obtain the regulated power coefficient, pf = 1. Eq(14) states this theorem. The grid-side converter block diagram is shown in figure 9.

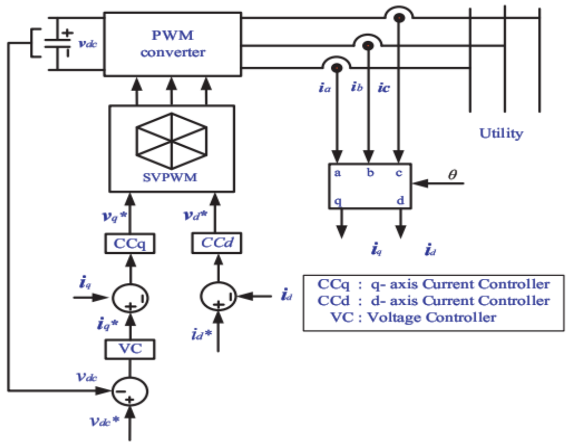


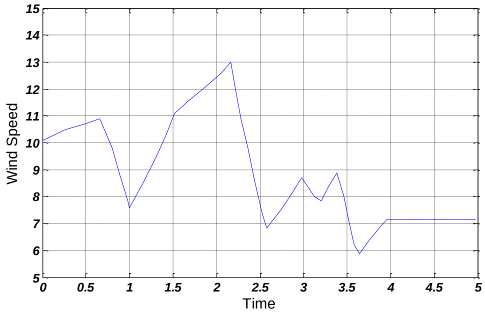
Figure 9. Grid-side converter block diagram

VI. THE SIMULATION RESULTS

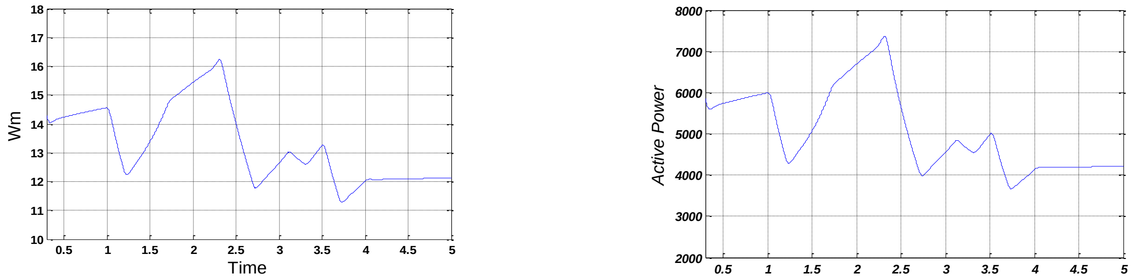
MATLAB/Simulink was employed to design this process. The characteristics of wind turbine and PMSG parameters are provided in the Appendix. PMSG can obtain the maximum obtainable power by directly controlling the generator-side converter.

Wind speed has been obtained from the actual wind speed in reference [1], where these wind speeds, vary between 6 m/s to 13 m/s as input to WT as shown in Figure10(a). Figure 10(b-e) shows the results obtained from Type-2 fuzzy logic in tracking the maximum wind power. In order to extract maximum power at variable wind speed, it is better for the wind turbine to operate in λopt. This occurs by controlling the rotational speed of the w_T. Therefore, it always operates at w_{opt}, where w_{opt} changes from one certain wind speed to another. Type-2 fuzzy logic controller is used to search the optimal rotational speed where maximum power at variable wind speed can be obtained. On the other hand, figure 10(b) shows the variations in actual rotational speed for rotor. As such, the actual rotational speed has also been estimated in a certain speed (Fig. 12), and these values are corresponding to the wind turbine power characteristics, shown in figure 2. Thus, the w_T always operates at optimal rotational speed and fuzzy investigation confirms the accuracy of the proposed FLC.

It can be seen in figure 10(b) that the control system follows the reference speed, which obtained from Type-2 fuzzy logic. Grid-side controller maintains the DC terminal voltage as 600 V, which shown in figure 10(c). DC voltage is regulated by sending the active power to the grid, as it is shown in figure 10(d). According to figure 10(e), the reactive power transmitted to the grid has been controlled in zero. The results from figure 10 show that the control system has been effective in tracking the maximum power and the control system has been able to control the reactive power in the grid. Figure 11 compares the Type-1 fuzzy logic and Type-2 fuzzy logic results. As such, in figures 12 and 13, the wind speed in a certain value is considered to be equal to 12 m/s. In this state, the proposed system could extract the maximum power in optimal conditions including active and reactive power ripple minimization as well as generator mechanical speed.

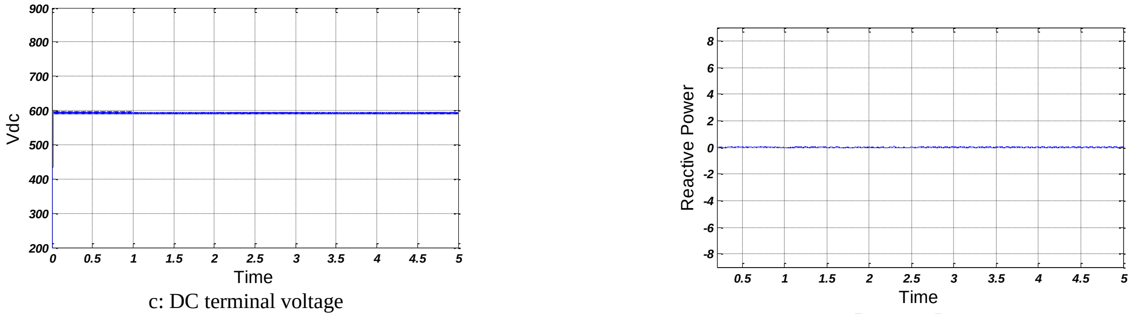


a: Wind speed



b: Rotor mechanical speed

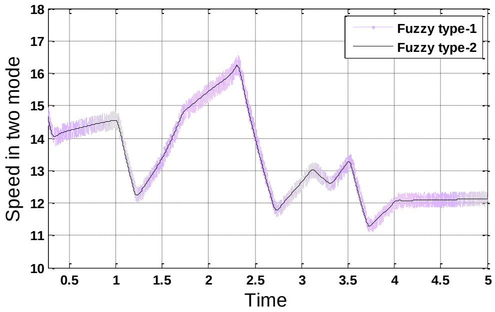
d: Active power



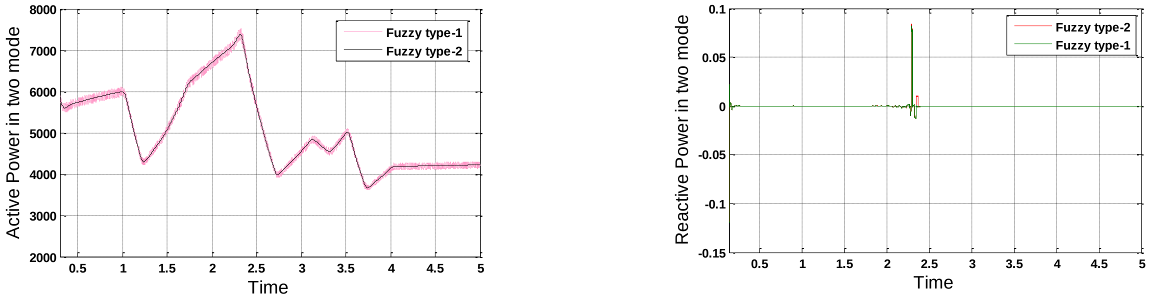
c: DC terminal voltage

e: Reactive Power

Figure 10. The obtained results from Type-2 fuzzy logic



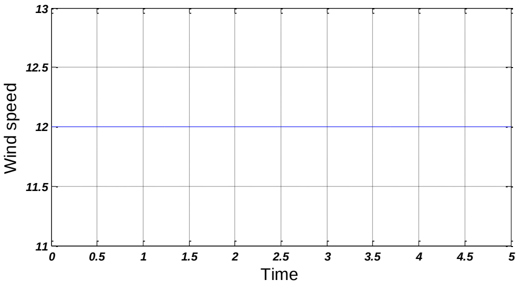
a: Rotational Speed



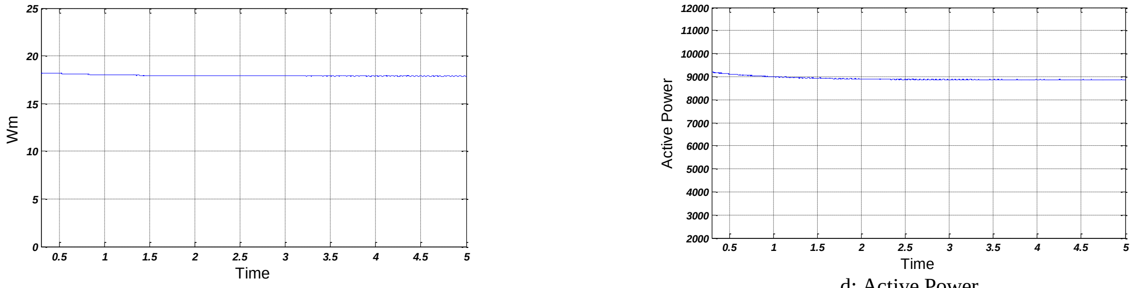
b: Active Power

c: Reactive power

Figure 11. Type-1 vs. Type-2 Fuzzy results

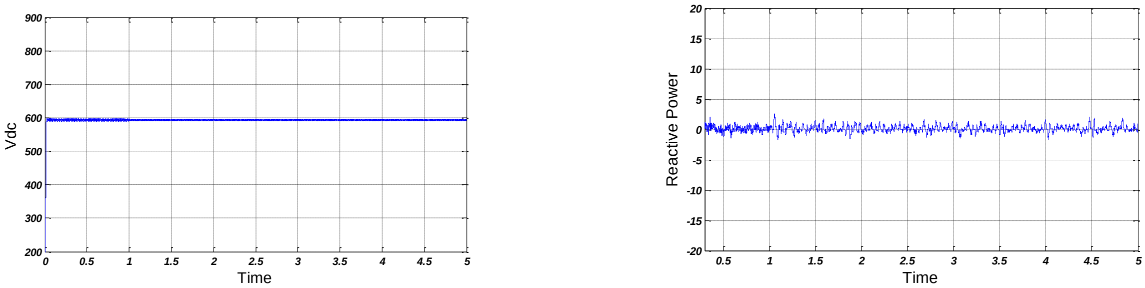


a: Wind speed



b: Rotor mechanical speed

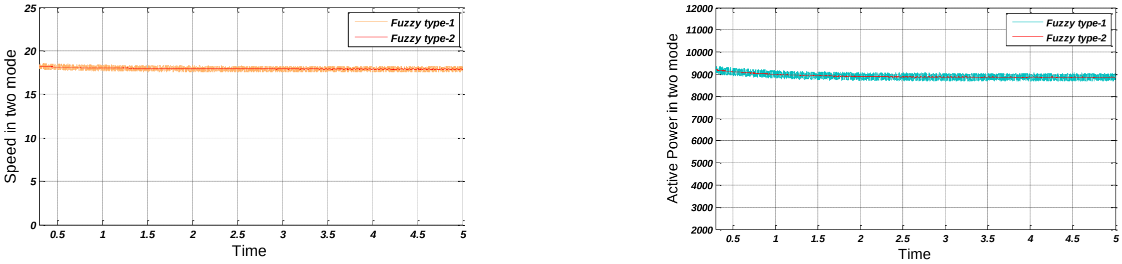
d: Active Power



c: DC terminal voltage

e: Reactive power

Figure 12. The results from Type-2 fuzzy logic according to a reference speed of 12 m/s



a: Active Power

b: Reactive Power

Figure 13. Type-1 vs. Type-2 Fuzzy in the speed reference of 12 m/s

VII. CONCLUSION

This Article studied the application of a Type-2 fuzzy logic controller to extract the maximum power from wind turbines using PMSG. The wind turbine system was connected using a back to back PWM converter. The control approach was grid-side and generator-side converters, modeled in MATLAB software. The generator-side converter was used to track the maximum produced power by turbine using a fuzzy control. Type-2 fuzzy logic was employed to eliminate the uncertainties and to choose an appropriate reference speed in the output. In grid-side converter the active and reactive controls made possible by controlling q- and d- axis currents. In order to have PF = 1, d-axis current was set equal to zero and to transfer DC voltage to the grid, q-axis current was controlled. The simulation results confirm the proposed approach.

APPENDIX : THE WIND TURBINE AND PMSG PARAMETERS

Wind turbine		PMSG	
Nominal output power	19 kw	R_s (stator resistance)	1m
Wind speed input	7- 13 m/s	L_d (d-axis inductance)	1m
Base wind speed	12m/s	L_q (q-axis inductance)	1m
Base rotational speed	190 rpm	No. of poles, P	30
Moment of inertia	1 m	Moment of inertia	100m
Blade pitch angle input	0	Mech. Time constant	1

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