

Power Output Maximization of A PMSG Based Standalone Wind Energy Conversion System Using Fuzzy Logic

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Abstract: *This paper proposes a Fuzzy Logic Controller for Maximum Power Point Tracking of a case study wind energy conversion system (WECS). The system consists of a standalone fixed pitch, variable speed wind turbine directly coupled to a permanent magnet synchronous generator (PMSG), an uncontrolled diode rectifier, a dc-dc boost converter, a fuzzy logic based controller and a load. For a given wind speed, there is an optimum speed of rotation that gives maximum power. The aim of the maximum power point tracking controller is to drive the WECS at the optimum speed that corresponds to maximum power at any wind speed. The designed Fuzzy Logic Controller determines the duty cycle D that yields optimum speed for maximum power extraction from the WECS for various wind speeds. It then applies this D to the DC-DC boost converter to control the speed of rotation of the PMSG to track maximum power point curve. Simulation results show that the designed system is able to extract maximum power for varying wind speeds.*

Keywords -Fuzzy Logic Controller, MPPT, PMSG, WECS

I. Introduction

Wind capacity is growing very quickly due to its increasingly competitive prices. During 2012, almost 45 GW began operation, and from the end of 2007 through 2012, annual growth rates of cumulative wind power capacity averaged 25% [1]. In recent years, the production of electricity from renewable energy sources like wind energy increases due to environmental problems and the shortage of traditional energy sources in the near future [2]. Wind power depends mainly on geographical conditions and weather conditions. Therefore, it is necessary to design a system capable of generating maximum power under these constraints [3]. Up to now, most of the wind energy generation systems have been implemented in large-scale WECS in the Megawatt level. However, small-scale WECS can provide a good alternative in urban areas and residential applications in remote places where connection to grid is almost impossible. For small wind generation (typically less than 100 kW), a permanent-magnet synchronous generator (PMSG) connected to a diode bridge is preferred because of its reliability, simple control, high efficiency, and low cost [4]. MPPT algorithms for WECS researched so far are mainly classified into three categories namely Tip Speed Ratio (TSR) control, Power Signal Feedback (PSF) control and Hill-Climb Search (HCS) Control. The TSR control method controls the rotational speed of the generator in order to maintain TSR (the ratio between blade tip speed to the wind speed) at the optimum value in order to extract maximum power out of the turbine. This method requires knowledge of the optimum TSR, wind speed, and turbine speed in order to extract maximum power point [5].

In PSF control, it is required to have the knowledge of the wind turbine's maximum power curve, and track this curve through its control mechanisms. Using wind speed or rotor speed as an input, the reference power is generated either using the recorded maximum power curve or using the mechanical power equation [5]. A slight variant of PSF is the optimal torque (OT) technique published in [6] which makes use of the quadratic optimal torque curve. The HCS control (or Perturb & Observe) algorithm continuously searches for the peak power of the wind turbine. Depending upon location of an operating point and the relation between changes in power and speed, the tracking algorithm computes the optimum control signal in order to drive the system to the point of maximum power [5]. According to [7], there is no difference between the PSF and the OT method in terms of the performance and the complexity of implementation.

The main advantage of HCS control over TSR and PSF control is that it neither requires knowledge of the maximum power nor the wind velocity to determine MPP. It is independent, simple, and flexible. However, it fails to reach the maximum power points under rapid wind variations if it is used for large and medium inertia wind turbines. Moreover, the problem of choosing an appropriate step-size is not an easy task; where larger step-size means faster response and less efficiency while, on the other hand, smaller step-size improves the efficiency but slower the convergence speed [8]. Hence, for conventional HCS control, there is always a tradeoff between the tracking speed and control efficiency. Another challenge is that in the normal HCS, the direction i.e. the sign of the next perturbation is decided by the increase or decrease in power due to the previous perturbation. Being blind to the wind change, this rule can be misleading as the sign might get dictated by the

change in wind rather than the applied perturbation. This wrong decision leads to the failure in keeping track of maximum power point [7].

In this paper, a Fuzzy Logic Controller (FLC) is used for maximum power point tracking. Fuzzy control works as well for complex nonlinear multi-dimensional systems, systems with parameter variation problem or where the sensor signals are not precise. It is basically nonlinear and adaptive in nature, giving robust performance under parameter variation and load disturbance effect.[9] It has been shown that a properly designed direct fuzzy controller can outperform conventional proportional integral derivative (PID) controllers,[10] offering the following advantages: It can work with less precise inputs, does not need fast processors, more robust than other non-linear controllers and has better stability, small overshoot, and fast response.

II. System Description

The WECS proposed in this paper consists of a wind turbine coupled to a PMSG to power a stand-alone system. A three-phase diode bridge rectifier is used for the AC/DC conversion. A boost converter (DC/DC) is used to vary the rotor speed. The proposed MPPT strategy uses a fuzzy logic controller to track the maximum power point curve of the WECS by varying the duty cycle of the DC-DC boost converter. The proposed control algorithm is able to achieve fast dynamic responses. The block diagram of the proposed system is shown in fig 1.

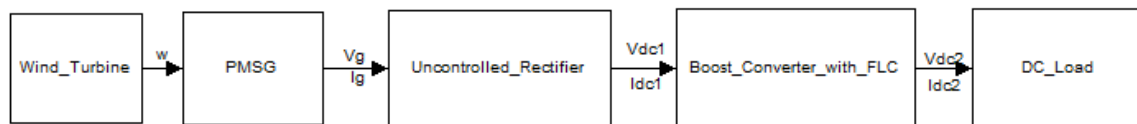


Figure1: Block diagram of the proposed system.

III. System Submodels

A. Wind Turbine Model

The mechanical power extracted by the turbine is given by: [11]

$$P_m = \frac{1}{2} \rho \pi R^2 v^3 C_p \quad (1)$$

Where: P_m = Mechanical Power(W), ρ = Air density in kg/m^3 , R = Radius of the turbine blade in m, v = wind speed in m/s and C_p = power coefficient. C_p is a function of the tip speed ratio (TSR) λ as well as the blade pitch angle β for pitch controlled wind turbine. In this work, the case study wind turbine has a fixed pitch hence β is set to zero. Hence $C_p = C_p(\lambda)$ and $\lambda = \frac{R\omega}{v}$ where ω = rotation speed of the rotor. C_p has a maximum value of 0.593 known as Beltz limit. From equation (1), when controlling the wind turbine, C_p is useful as it is the only variable and controllable parameter. Wind speed v is a variable but not controllable. There is a value of $\lambda = \lambda_{opt}$ for which C_p is maximum. If λ is maintained at its optimal value λ_{opt} the power coefficient is at its maximum value $C_{pmax} = C_p(\lambda_{opt})$ thus delivering maximum power for a given wind speed v . Maximum power is given by:

$$P_{max} = \frac{1}{2} \rho \pi R^2 v^3 C_p(\lambda_{opt}) \quad (2)$$

Where

$$\lambda_{opt} = \frac{\omega R}{v} \rightarrow \omega_{opt} = \frac{\lambda_{opt} v}{R}$$

Substituting ω_{opt} and rearranging gives:

$$P_{max} = \frac{1}{2} \rho \pi R^5 \frac{C_{pmax}}{\lambda_{opt}^3} \cdot \frac{\lambda_{opt}^3 v^3}{R^3} \quad (3)$$

This equation can be expressed as:

$$P_{max} = K_{opt} \omega_{opt}^3 \quad (4)$$

$$\text{Where } K_{opt} = \frac{0.5 \rho \pi C_{pmax} R^5}{\lambda_{opt}^3} \text{ and } \omega_{opt} = \frac{\lambda_{opt} v}{R}$$

The aerodynamic torque is given by the ratio between the power extracted from the wind P_m and the turbine rotor speed.

$$T_m = \frac{P_m}{\omega_m} \quad (5)$$

The optimum torque for a given wind speed is thus given by:

$$T_{opt} = \frac{P_{max}}{\omega_{opt}} = K_{opt} \omega_{opt}^2 \tag{6}$$

By analyzing the power produced by the wind turbine at various wind and rotor speeds, it can be seen that an optimum power coefficient constant K_{opt} exists. This coefficient shows the generated power associated with the corresponding optimum rotor speed. It is calculated from individual wind turbine characteristics.

The power coefficient C_p can be utilized in the form of look-up tables or in form of a function. The second approach is used in this paper where the power coefficient is defined as a function of the tip-speed ratio λ and the blade pitch angle β as [12]:

$$C_p(\lambda, \beta) = 0.5 \left(\frac{116}{Q} - 0.4\beta - 5 \right) e^{-\frac{21}{Q}} \tag{7}$$

Where

$$Q = \frac{1}{\frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1 + \beta^3}}$$

B. Permanent Magnet Synchronous Generator(PMSG) Model

The dynamic model of PMSG can be represented in the synchronous reference (d-q) system using the following equations[13]:

$$\frac{di_d}{dt} = \frac{1}{L_d} (-R_s i_d + \omega_e L_q i_q + u_d) \tag{9}$$

$$\frac{di_q}{dt} = \frac{1}{L_q} (-R_s i_q + \omega_e [L_d i_d + \psi_f] + u_q) \tag{10}$$

where subscripts d and q refer to the physical quantities that have been transformed into the d - q synchronous rotating reference frame, R_s is the stator resistance [Ω], L_d and L_q are the inductances [H] of the generator on the d and q axis respectively, ψ_f is the permanent magnetic flux [Wb] and ω_e is the electrical rotating speed [rad/s] of the generator, defined by:

$$\omega_e = P \omega_m \tag{11}$$

Where P is the number of pole pairs of the generator. The electromagnetic torque equation is given by:

$$T_e = 1.5P((L_d - L_q)i_d i_q + i_q \psi_f) \tag{12}$$

The active power P_{gen} (W) and reactive power Q_{gen} (VAr) of the PMSG are given respectively by:

$$P_{gen} = 1.5(u_d i_d + u_q i_q) \tag{13}$$

$$Q_{gen} = 1.5(u_q i_d - u_d i_q) \tag{14}$$

Rectifier Model

The output from the PMSG is rectified using a three-phase uncontrolled diode rectifier. The schematic of the 3phase diode rectifier is shown in fig.2

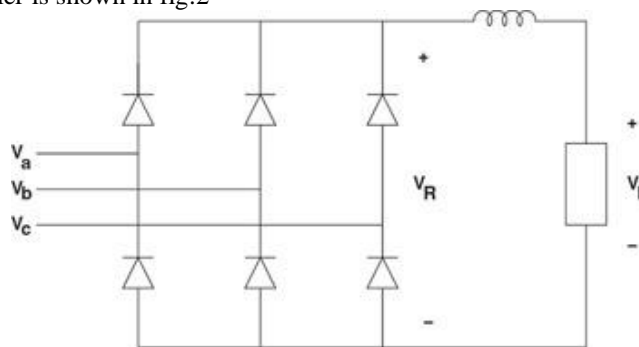


Figure2: Schematic 3Phase Diode Rectifier

The output DC voltage V_{dc1} of the rectifier depends on the line voltage as below:[14]

$$V_{dc1} = \frac{3}{\pi} \int_{-\pi/6}^{\pi/6} V_{LL} = \frac{3\sqrt{2}}{\pi} V_{LL} \tag{15}$$

where V_{dc1} is the rectifier output voltage and V_{LL} is the generator line to line output voltage.

$$V_{LL} = \sqrt{3} x V_g \tag{16}$$

From this, the relationship between V_{dc1} and phase voltage V_g is derived as:

$$V_{dc1} = \frac{3\sqrt{6}}{\pi} V_g \tag{17}$$

Similarly, the relationship between I_{dc1} and phase current I_g

$$I_{dc1} = \frac{\pi}{\sqrt{6}} I_g \tag{18}$$

The generator power output is then calculated as:

$$P_g = 3V_g I_g = V_{dc1} I_{dc1} \tag{19}$$

The resistance value per phase of the rectifier circuit from the viewpoint of ac side is R_g while the load resistance seen by the rectifier is R_{dc1} . These are given by:

$$R_g = \frac{V_g}{I_g} \tag{20}$$

$$R_{dc1} = \frac{V_{dc1}}{I_{dc1}} \tag{21}$$

DC-DC Boost Converter Model

As the PMSG voltage is variable with the wind speed, the DC output power of the rectifier is also variable. A boost DC-DC converter is used for maintaining the DC output voltage at a constant value V_{dc2} . [15].

The relation between the output and input voltages and currents of the DC-DC boost converter depends on the duty ratio D defined as a ratio of the switch on time to the sum of the on and off times

For a constant frequency operation [14]:

$$D = \frac{t_{on}}{t_{on} + t_{off}} = \frac{t_{on}}{T} \tag{22}$$

The output voltage and current of the boost converter are then defined as:

$$V_{dc2} = \frac{1}{(1-D)} V_{dc1} \tag{23}$$

$$I_{dc2} = (1 - D) I_{dc1} \tag{24}$$

where V_{dc2} and I_{dc2} are the output voltage and current of the DC-DC boost converter respectively while V_{dc1} and I_{dc1} are the input voltage and current.

If a load resistance R_L is connected at the output of the DC-DC boost converter, I_{dc2} can be expressed as:

$$I_{dc2} = \frac{V_{dc2}}{R_L} \tag{25}$$

Substituting V_{dc1} and I_{dc1} in (21) we get

$$R_{dc1} = (1 - D)^2 \frac{V_{dc2}}{I_{dc2}} \tag{26}$$

Using (25) we get

$$R_{dc1} = (1 - D)^2 R_L \tag{27}$$

where R_L is the load resistance in Ohms.

Thus from the viewpoint of the rectifier, the boost converter and the load resistance R_L can be considered a variable resistance R_{dc1} varied by changing the duty ratio D.

The expression for the resistance R_g seen by the generator can be obtained by substituting V_{dc1} and I_{dc1} in terms of V_g and I_g giving

$$R_g = \frac{\pi^2}{18} R_{dc1} \tag{28}$$

And finally, substituting R_{dc1} we get

$$R_g = \frac{\pi^2}{18} (1 - D)^2 R_L \tag{29}$$

From the foregoing analysis, it can be appreciated that the PMSG sees the rectifier and boost converter as a variable load resistance R_g which is a function of the duty ratio D. By varying the load resistance the generator output voltage V_g can be controlled [15].

Since V_g is proportional to speed of rotation ω , [16][17] then by controlling the duty ratio D we can be able to control the speed of rotation ω .

Fuzzy Logic Controller (FLC) Model

The inputs to the FLC are: Error $E(k) = I_{ref} - I_{dc}$ and change in this error $\Delta E(k) = E(k) - E(k - 1)$. Output is the duty cycle D that is fed to the switch of the DC-DC boost converter.

The block of the fuzzy logic controller is shown in fig3.

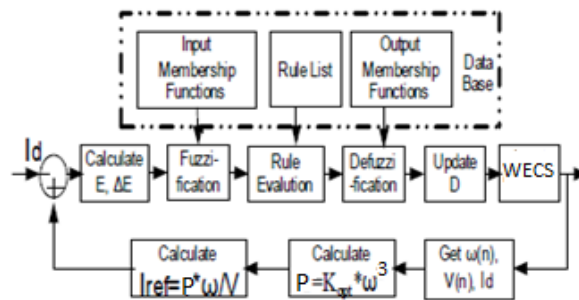


Figure3: Block diagram of the Fuzzy Logic Controller.

The model of the proposed of the fuzzy logic controller is shown in fig4.

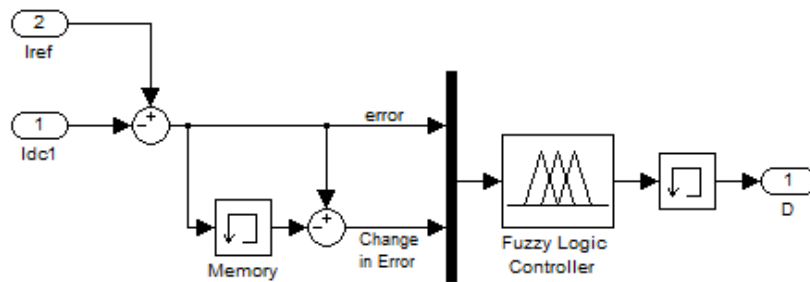


Figure4: Model of the Proposed Fuzzy Logic Controller.

The fuzzification module converts the crisp values of the control inputs i.e. error and change in error into fuzzy values or fuzzy membership functions. The data base and the rules form the knowledge base which is used to obtain the inference relation. The data base contains a description of input and output variables using fuzzy sets. The rule base is essentially the control strategy of the system. It contains a collection of fuzzy conditional statements expressed as a set of IF-THEN rules such as:

R(1) : **If** Error is Negative Large and Change in Error is Negative Large **THEN** D is Negative Large

For the given rule base, the fuzzy controller determines the rule base to be fired for the specific input signal condition and then computes the effective control action (Duty Ratio D). The mathematical procedure of converting fuzzy values into crisp values is known as defuzzification. Centre of Gravity (COG) defuzzification method is used in this paper.

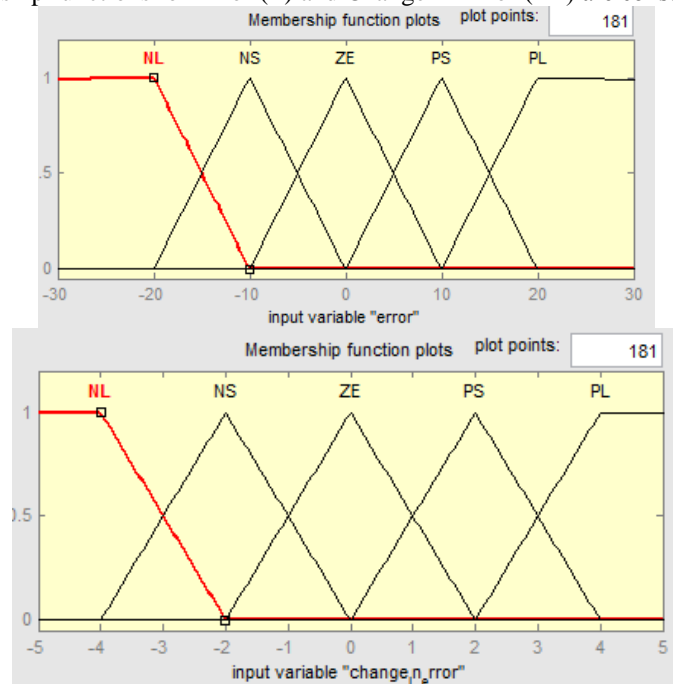
The designed control algorithm is as follows:

1. Measure generator speed, ω .
2. Determine the reference power using (4)
3. This power reference is then used to calculate the DC current reference by measuring the rectifier output voltage, V_{dc1} as given by:

$$I_{ref} = \frac{P_{ref}}{V_{dc1}}$$

4. The error between the reference dc current and measured dc current and the change in this error are the inputs to the Fuzzy Logic Controller. The output of the FLC is the duty cycle of the switch controlling the DC-DC boost converter.

The membership functions for Error (E) and Change in Error (ΔE) are constructed as fig.5



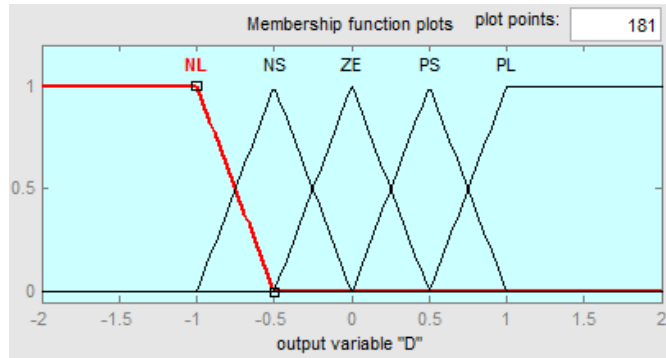


Figure5: Membership functions for Error(E), Change in Error (ΔE)and Duty Ratio(D)

The rule base for the Fuzzy Logic Controller is designed as in Table 1.

Table1: Rule base for the Fuzzy Logic Controller

Error/ Δ Error	NL	NS	ZE	PS	PL
NL	NL	NL	NS	NS	ZE
NS	NL	NS	NS	ZE	PS
ZE	NS	NS	ZE	PS	PS
PS	NS	ZE	PS	PS	PL
PL	ZE	PS	PS	PL	PL

The parameters of the case study wind energy conversion system are in Table2.

Table2: Parameters of case study wind energy conversion system

Wind Turbine		
Parameter	Units	Value
Rated Power	Watts	6000
Base Wind Speed	m/s	12
Air density	kg/m ³	1.225
Number of blades		3
Rotor Radius	m	2.1
Optimum coefficient K_{opt}	Nm/(rad/s ²)	1.67E-03
PMSG		
Parameter	Units	Value
Rated Power	Watts	6000
Armature resistance R_s	Ohms	0.425
Stator Inductance L_s	mH	8.4
Flux linkage	Wb	0.433
Rated speed, ω	rad/s	153
Rated Current I_a	A	12
Rated Torque	Nm	40
Load Resistance R_L	Ohms	1000
Inertia J		0.0008
Viscous Damping B		0.002
Pole Pairs		5
Static friction		0.001

IV. Simulation Results

Wind turbine power was plotted against speed of rotation for various wind speeds according to(1). The plot is shown in figure 5.

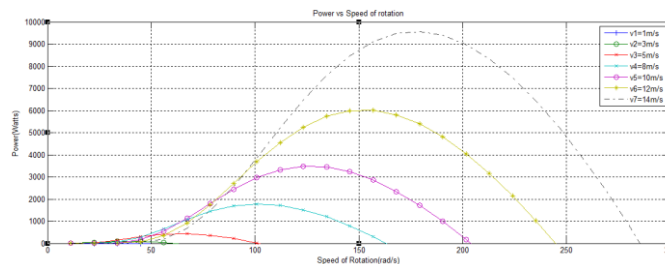


Figure6: Turbine power vs speed of rotation for various wind speeds

The designed fuzzy Logic controlled system was simulated using MATLAB/Simulink. Wind speed was varied from 12 to 4 to 8 to 14m/s. The results are as shown in figure 7(a) to (f)

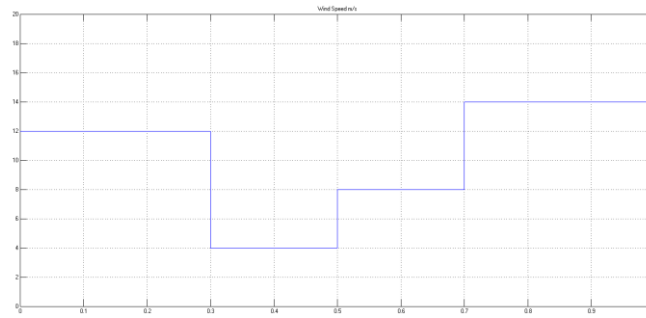


Figure7(a):Wind speed(m/s)

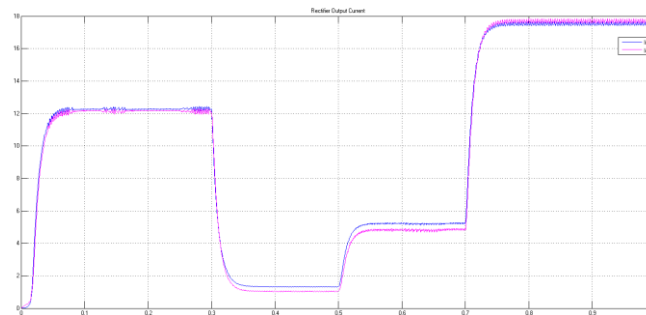


Figure7(b):Rectifier Output Current(A)

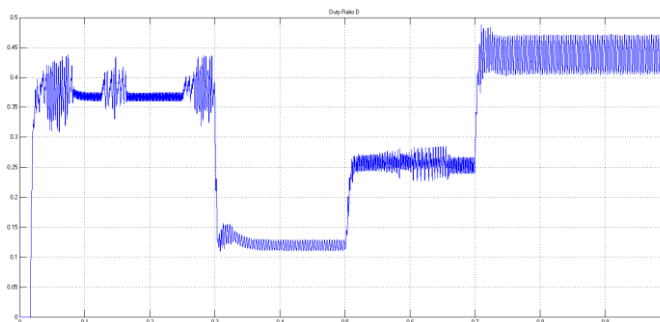


Figure7(c):Duty Ratio

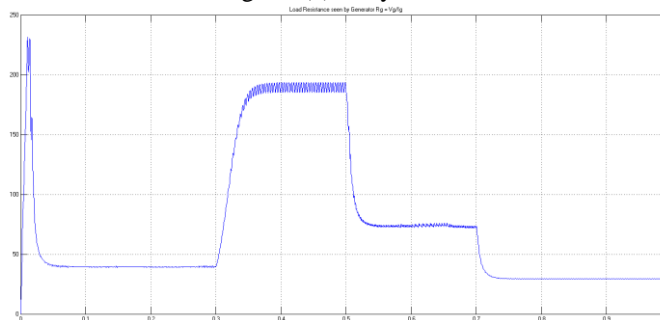


Figure7(d): Load Resistance $R_{dc1} = V_{dc1}/I_{dc1}$

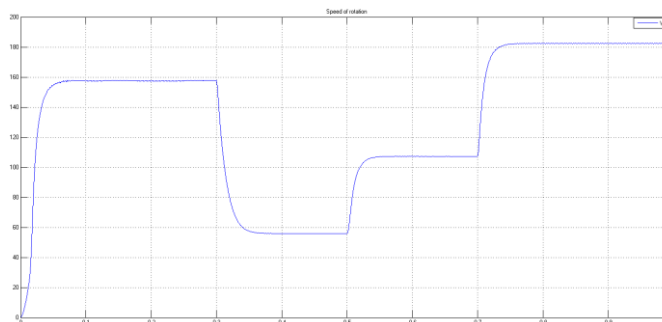


Figure7(e):Speed of rotation (rad/s)

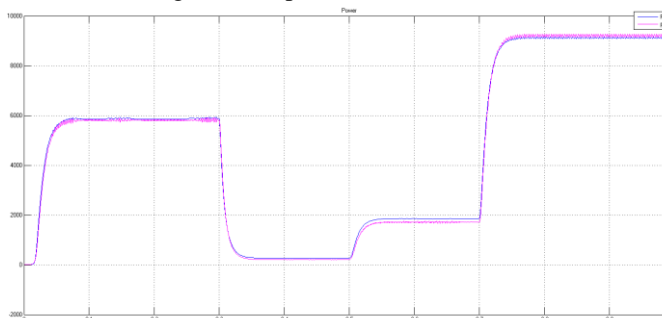


Figure 7(f): Power Output(Watts).

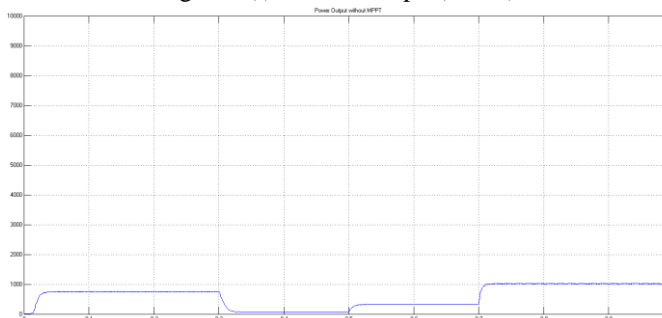


Figure 8: Power Output without MPPT(Watts).

From figure 7, for wind speeds of 8, 12 and 14m/s, the maximum power is 1785,6000 and 9550W respectively. This is achieved at speeds of rotation of 100,153 and 180rads/s respectively. This has been achieved as shown in Figures 8(e) and 8(f).

As the wind speed changed, the fuzzy logic controller changed the duty cycle of the DC-DC boost converter (Figure7(c)) according to the error between the reference current and the rectifier output current (Fig.7 (b)), resulting in a variation of the load seen by the PMSG (Fig.7 (d)). As a result, the voltage at the terminals of the PMSG changed. Since the speed of rotation is proportional to the terminal voltage, it varied accordingly (Fig.7 (e)). Electromagnetic torque is proportional to current and thus follows current variation to track its reference value. Consequently, the controller was able to track the reference maximum power for various wind speeds (Fig.7 (f)).

Figure 8 shows the Power output variation without MPPT.It can be seen that the introduction of the MPPT controller significantly increases the Power Output.

V. Conclusion

A Fuzzy Logic Controller for MPPT was designed and developed. It was shown that the designed controller is able to track reference maximum power for the WECS with good accuracy for fluctuating wind speeds. In this way the power output of the wind energy conversion system is maximized for varying wind speeds.

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