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FUZZY LOGIC BASED MPPT FOR PERMANENT MAGNET SYNCHRONOUS GENERATOR IN WIND ENERGY CONVERSION SYSTEM

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Abstract: In this paper, a comparative analysis of different control methods to extract the maximum power from Permanent Magnet Synchronous Generator (PMSG) based Wind Energy Conversion System (WECS) under different wind speed condition is presented. The WECS consists of a wind turbine, a PMSG and a DC/DC converter which is connected to a DC load. The Maximum Power Point Tracking (MPPT) control technique compared here are Proportional Integral (PI) control, Perturb and Observe (P&O) method and Fuzzy Logic Controller (FLC). The parameters considered for analysing the efficiency of the MPPT controller is the output DC voltage and power across the load. The steady state voltage and the dynamic response of the system under different wind speed is considered to justify the overall efficiency of the controllers. The system is designed and configured in MATLAB/SIMULINK software and the results are validated.

Keywords: Wind turbine, Permanent Magnet Synchronous Generator, Fuzzy Logic Controller, MPPT.

1. INTRODUCTION

In recent years, the use of renewable energy resource is increased due to increasing demand of power and depletion of fossil fuel such as coal for electricity generation. Moreover, the issue of climate change are causing concern and hence many regulations are proposed to reduce the Carbon dioxide (CO_2) emission (Krishna et al., 2015). Among the renewable energy, solar energy and wind energy is more utilised because of its abundant availability everywhere. The Wind Energy is gaining interest because of technology enhancement and significant power cost reduction. More effective control strategies are under research in order to obtain reliable, cost effective and quality power from the wind. As stated in (Errami et al., 2015) Permanent Magnet Synchronous Generator (PMSG) is most preferred wind generator due to its reliability and size for stand alone wind energy conversion system.

MPPT control algorithms can be employed in order to capture the maximum power from available wind by maintaining the optimum steady voltage across the load. A variety of MPPT techniques have been employed for Wind Energy Conversion System (WECS) in previous literature such as Hill Climbing Search (HCS) algorithm, Incremental and Conductance method (INC), Perturb and Observe (P&O) method, Fuzzy Logic Controller (FLC) and many Evolutionary Algorithms.

P&O method is well known MPPT technique due to its simplicity and effectiveness. But due to high non linearity in wind speed, P&O technique fails to track the maximum power point and hence introduces high fluctuations resulting in low power output (Dailii et al., 2015). Another control technique which is used frequently is PI control method. PI control is very simple to implement. PI control lacks in efficiency of the overall system due to its arbitrary selection of parameters. In order to overcome this problem FLC is employed to extract the maximum power from wind. FLC can track the non linearity of the system and gives the maximum output for the available wind. The input for the FLC is the DC voltage and current across the load, whereas the output is the duty cycle for the DC/DC Converter.

The buck converter is employed here to interface the wind generator to the DC Load. The output of the PMSG is AC which is converted in to DC using diode controlled rectifier in order to eliminate the ripple present in the AC component and smoothing capacitor is placed across the rectifier to minimise the ripple due to non linearity. When the wind power varies the FLC tracks the output voltage and current to generate an efficient duty cycle for the converter operation. Thus the maximum power is produced based on available wind speed.

This paper analyses the maximum power point tracking control approach for stand alone WECS. The performance of the conventional PI controller, P&O controller and FLC under variable wind speed is evaluated. The proposed control strategy posses the improved capability of capturing the maximum power from wind. Comparative efficiency of the controllers is analysed from the output power of the converter.

2. MODELLING OF WIND ENERGY CONVERSION SYSTEM

The simulation models of wind turbine, PMSG and power electronics converters which comprises the whole WECS system are explained in this section.

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Fig. 1 shows the overall view of WECS. A PMSG generator is mostly preferred for standalone WECS. The PMSG is direct driven thus there is no need of gear box to drive the generator thus reducing the complexity and size of entire system (Dehghan et al., 2009). They require low maintenance when compared to other generators. The diode controlled rectifier is used to convert AC voltage obtained from generator to DC voltage in order to eliminate the harmonics present in it due to linearity. A smoothing capacitor C_{DC} is used to remove ripple present in DC voltage. A DC/DC converter is designed to obtain the desired output.

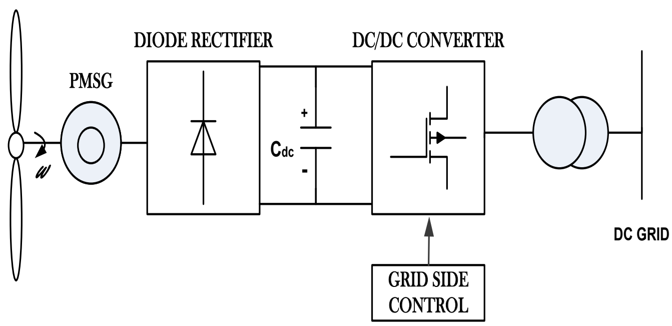

Fig. 1. Overall schematic of PMSG based WECS

2.1 Turbine Modelling

The mechanical power, P_m captured by the turbine is given by the equation

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

Where C_p is a rotor power coefficient, β is blade pitch angle, λ is a Tip Speed Ratio (TSR), ρ is air density, R is radius of wind turbine blade and V_{wind} is the wind speed. The rotor power coefficient is defined by the fraction of available wind power that can be transformed to mechanical power. C_p depends on the blade aerodynamics, which is the function of β and λ. The power coefficient of turbine is determined by TSR. C_p and TSR is determined by the shape of the blade. However, C_p in general blade design is assumed for simplicity (Babu et al., 2013).

$$C_p = (0.44 - 0.0167\beta)\sin\frac{\pi(\lambda - 2)}{13 - 0.3\beta} - 0.0018(\lambda - 2)\beta \tag{2}$$

The TSR (λ) can be defined as the function of a wind speeds.

$$\lambda = \frac{\omega_m R}{V_{wind}} \tag{3}$$

where, ω_m is the rotor speed of a wind turbine. The input torque for the generator is obtained from the formula:

$$T_m = \frac{P_m}{\omega_m} \tag{4}$$

From the above equation (4) it can be determined that the performance of the wind turbine is highly dependent on the wind speed (Galdi et al., 2008)

Table 1 summarizes the parameters of the wind turbine which is used for the simulation analysis.

Table 1. Parameter of Wind Turbine

Nominal Mechanical Output Power	8.5kW
Base Wind Speed	12m/s
Radius of wind Turbine	1.001m
Air Density, ρ	1.225kg/m^3
Pitch Angle, β	0^o

2.2 Modelling of PMSG generator

PMSG is widely used for stand alone small wind turbines because they have high efficiency and less maintenance (Baroudi et al., 2007). The PMSG is modelled in *dq* reference frame. Both *d* and *q* axis contains a voltage induced by the armature. The generator is implemented with DC Voltage and current. The current of *d* axis and *q* axis is determined by the equation 5 and 6 respectively (Alizadeh et al., 2015)

$$\frac{di_{sd}}{dt} = -\frac{R_{sa}}{L_{sd}} i_{sd} + \omega_s \frac{L_{sq}}{L_{sd}} i_{sq} + \frac{1}{L_{sd}} u_{sd} \tag{5}$$

$$\frac{di_{sq}}{dt} = -\frac{R_{sa}}{L_{sq}} i_{sq} - \omega_s \left(\frac{L_{sd}}{L_{sq}} i_{sd} + \frac{1}{L_{sq}} \psi_p \right) + \frac{1}{L_{sq}} u_{sq} \tag{6}$$

The electromagnetic torque obtained from the rotor of PMSG is given by the equation 7 (Phankong et al., 2013)

$$T_e = 1.5 \frac{P}{2} \left[\psi_p i_{sq} + i_{sd} i_{sq} (L_{sd} - L_{sq}) \right] \tag{7}$$

Where, i_{sd}, i_{sq}, u_{sd} and u_{sq} are the currents and voltages of *d* and *q* axis respectively. ω_s is the angular frequency of the generator. L_{sd} and L_{sq} are the inductance of the generator. ψ_p is the permanent flux, R_{sa} is the resistance of the stator and P is the number of poles.

Table 2. Parameters of PMSG

Rated Power	8.5kW
Stator Phase Resistance	0.425 Ω
Armature Inductance	0.000835 H
Friction Factor	0.001189 Nms
Pole Pairs	5
inertia	0.01197 kg.m^2

The Parameter of PMSG which is used for the study purpose in this work is presented in Table 2. According to author (Chen et al., 2015) the diode controlled rectifier are widely used for voltage conversion in small scale stand alone WECS due to its simplicity and low cost. However, Rectifier draws non sinusoidal current from PMSG. To overcome the problem a DC link capacitor is used, which can mitigate partial current harmonic elimination, thus achieving near sinusoidal current.

2.4 Modelling of DC/DC Converter

The DC/DC converter employed here is buck converter. Buck converter is used to step down the input DC voltage. By varying the duty cycle the output voltage can be controlled. This converter regulates the input voltage through the switch to reach the reference voltage which consists of maximum power. Fig. 2. shows the basic circuit of the buck converter. Buck converter operates in mainly two different modes namely continuous conduction mode and discontinuous conduction mode. (Bendib et al., 2014). The switch operates at high frequency to deliver chopped DC voltage output. The buck converter controls the power flow using the ON/OFF condition of switch which is controlled by the duty cycle switching. The average output voltage is given by the equation (8).

$$V_{out} = V_{in} * D \quad (8)$$

where V_{out} is the output Voltage V_{in} is the input voltage and D represents the duty cycle of the converter switch.

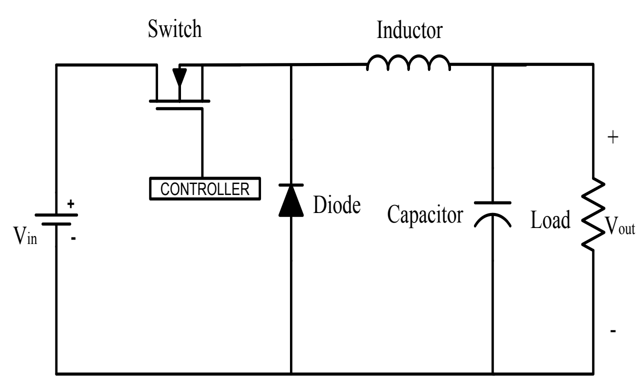

Fig. 2. Basic design of buck converter

Table 3. Parameters of buck converter

Inductor (L)	3.65 mH
Capacitor (C)	3 mF
Load(R)	150 Ω

In Table 3. the inductor and capacitor values which is used for simulation study is determined.

3. CONTROL STRATEGIES OF WECS

The MPPT based control strategy is used here to obtain the maximum power. Wind energy even though available in abundant, the wind speed varies rapidly. The efficiency of the WECS depends upon the accuracy in which the maximum power is extracted by the MPPT controller. The PMSG based MPPT control mainly focus on converting variable voltage and frequency to fixed voltage and frequency. The most commonly used power electronics converter configuration is analysed in this paper and the block diagram of the model used is shown in Fig. 3.

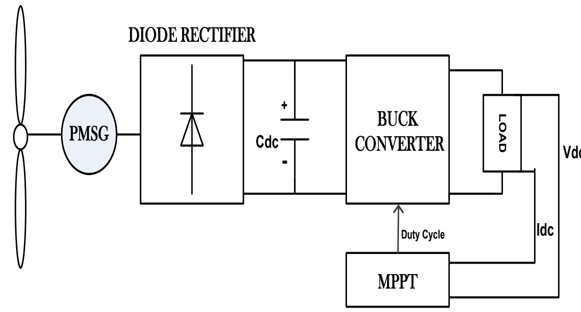

Fig. 3. Converter configuration of PMSG based WECS

In this paper three MPPT techniques such as conventional PI controller, P&O method and FLC MPPT method are utilized and comparative study is done to choose the efficient and appropriate MPPT technique so that the maximum power is extracted from the available wind.

3.1 PI Control

In PI based MPPT technique, an error signal is generated using the actual DC voltage and the reference DC voltage. The error signal is fed into the PI Controller from where an output signal is obtained. The output signal is then compared with the frequency repetitive triangular waveform to deliver a duty cycle which operates the DC/DC Converter switch thus obtaining the maximum power based on the variance in the wind speed. The equation used for PI controller is

$$D(s) = \left(K_p + K_i/s\right) * E(s) \quad (9)$$

Where, K_p is proportional parameter and K_i is integral parameter. $E(s)$, represents the error between reference voltage and output voltage and $D(s)$ is the duty cycle generated by the PI controller (Martin et al., 2015). Fig. 4. represents basic structure of PI controller.

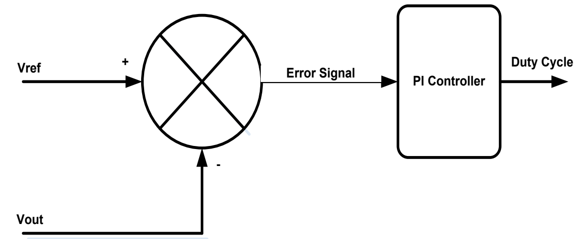

Fig. 4. PI controller

3.2 Perturb and Observe Control

The P&O method is used to search for the maximum optimal point for the given wind speed. The P&O method does not require any prior wind turbine knowledge. It is independent, flexible and simple technique. Here the P&O method uses the perturbed output voltage across the load to determine the optimal operating point that will extract the maximum power. If the power of the current cycle is greater than the previous one then the voltage is modified in same technique as the previous one. Whereas, if the power is lesser than the previous technique the voltage must be varied in the opposite direction. The only disadvantage of P&O technique in wind energy conversion is that they cannot track the rapid variation of the wind speed thus affecting the efficiency of the overall system and the speed of convergence (Dalala et al., 2013). The flow chart of P&O method is described in Fig. 5.

3.3 Fuzzy Logic Controller

To overcome the drawbacks of P&O method FLC algorithm is proposed. FLC has an advantage of fast convergence, imprecise input and handling non linearity. FLC generally consist of three stages Fuzzification, Rule base lookup table and Defuzzification as shown in Fig.6. The rules are designed on the basis of previous knowledge of the system (Simoes et al., 1997). An FLC is the artificial decision making controller that operates in closed loop. The inputs for fuzzy controllers are error signal and change in error signal. Once the signals are calculated and linguistic variables are obtained, the output of FLC is the duty cycle for buck converter is which is generated using the rules. FLC is termed to be the most efficient MPPT controller when compared with the PI and P&O controller (Tripathi et al., 2015). The efficiency of FLC is purely depend upon the previous knowledge of the system and right error computation and framing of rule based table.

Table. 4, represents the set of rules used for modelling FLC. Where, E represents the error signal and CE represents the Change in error. The rules are framed in five level namely Negative Big(NB), Negative Small(NS), Zero(ZE), Positive Small(PS) and Positive Big(PB).

Table 4. FLC Set of rules

E/CE	NB	NS	ZE	PS	PB
NB	ZE	PB	ZE	NB	NS
NS	PS	ZE	ZE	NB	NS
ZE	ZE	ZE	ZE	ZE	ZE
PS	PS	PB	ZE	ZE	NS
PB	PS	PB	ZE	NB	ZE

Inference mechanism is basically defined by membership functions of FLC which determines the relevance of rules from Table 4. Fig. 7, 8 and 9 represents the input and output membership function of FLC controller. Methods for implication and aggregation are defined as Minimum (min) and Maximum (max) respectively. The Defuzzification method uses centroid for processing.

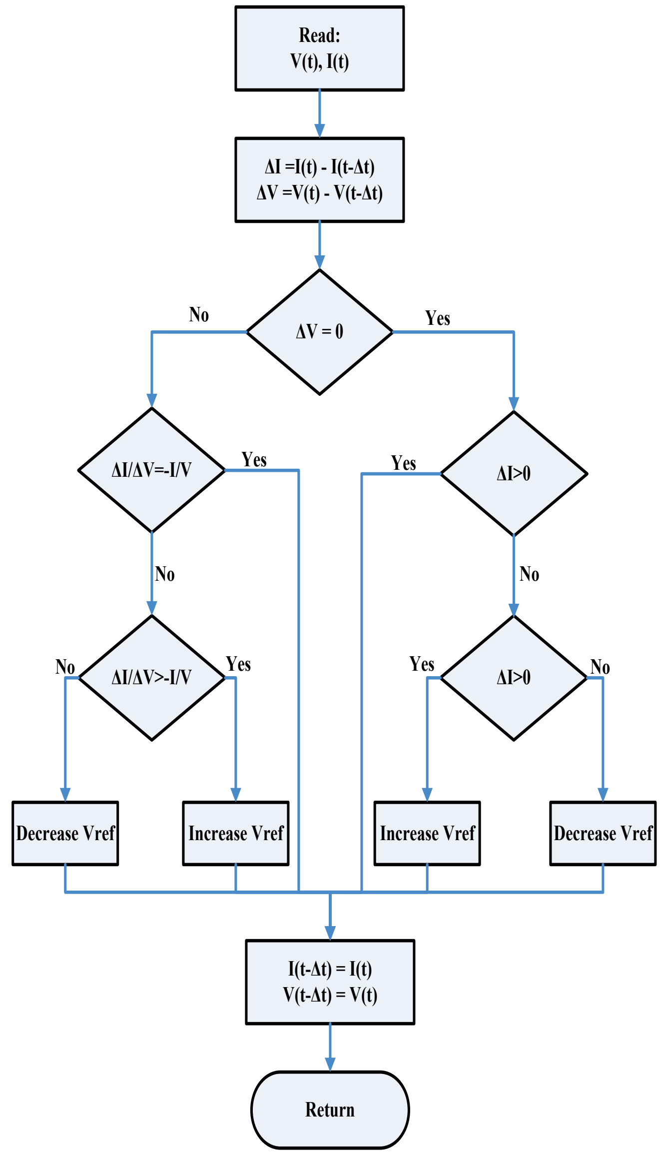

Fig. 5. Flowchart of P&O based control technique

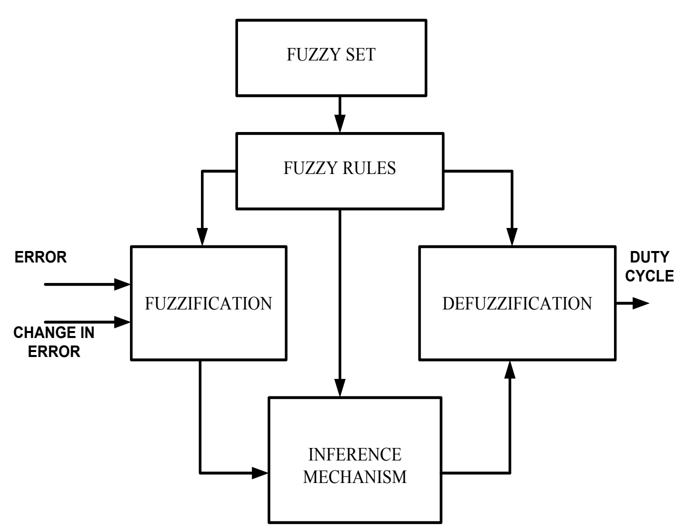

Fig. 6. Basic structure of FLC

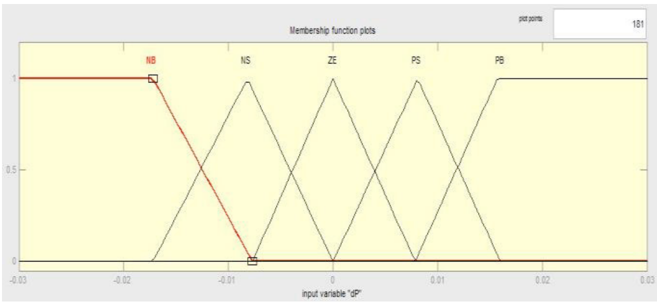

Fig. 7. Input membership function of error signal

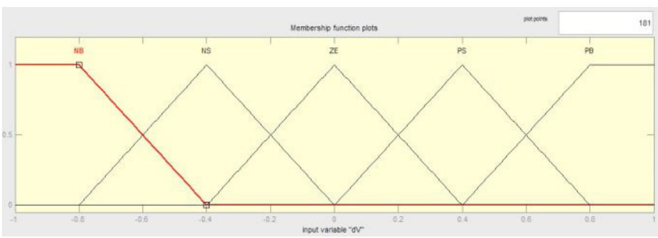

Fig. 8. Input membership function of change in error signal

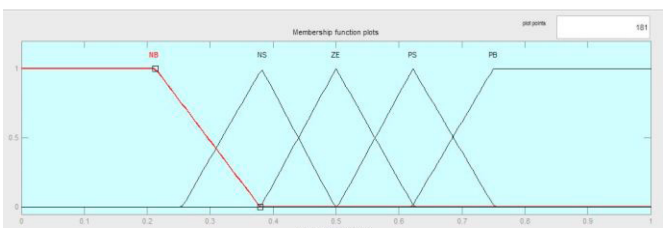

Fig. 9. Output membership function of duty cycle

FLC tracks the sudden change in wind speed more swiftly and precisely. The maximum power point is traced by the controller from the inference system which is mapped by the human knowledge earlier in form of rules. The controller tracks the change in output voltage, current and generates an error signal which is given as an input for fuzzification process, here the input data is converted into a suitable fuzzy linguistic sets using Mamdani method. Then the fuzzy set is processed in inference system where an appropriate fuzzy output is obtained using fuzzy rules. Then the fuzzy output is converted in to the systematic crisp value as a form of duty cycle in defuzzification. Thus the duty cycle is used to control the switching pattern of the converter switch.

4. RESULTS AND DISCUSSION

The detailed implementation of PMSG based WECS using buck converter incorporated with fuzzy logic controller in MATLAB/ Simulink is shown in Fig. 10. To check the tracking ability of MPPT techniques, the wind speed is varied from 3m/s to 12m/s as shown in Fig. 11. Three MPPT approaches in simulated in same varying wind speed conditions. From the analysis it can be stated that the FLC based MPPT technique is most efficient maximum power tracking power when compared with PI and P&O based technique.

Fig. 12 shows the output voltage comparison of MPPT controllers. The FLC based MPPT controller gives the maximum and constant voltage during the steady state characteristic of wind turbine. To analyse the performance of each MPPT controller power output is compared as shown in Fig. 13.

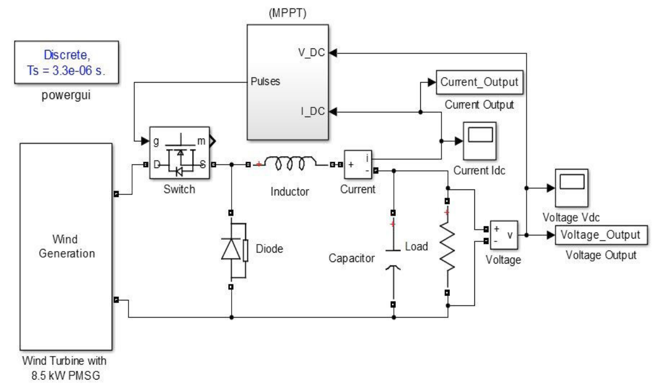

Fig. 10. MPPT controller model for WECS in Simulink

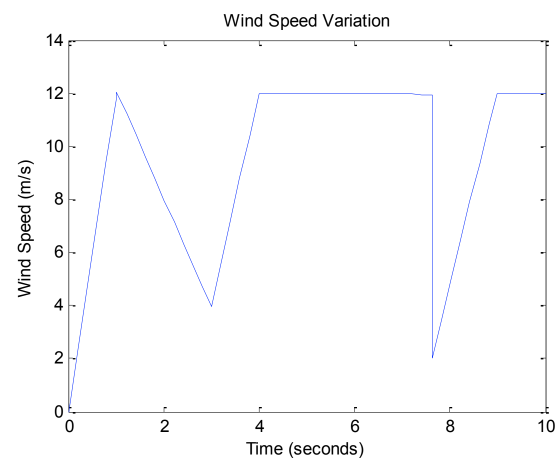

Fig. 11. Wind speed variation

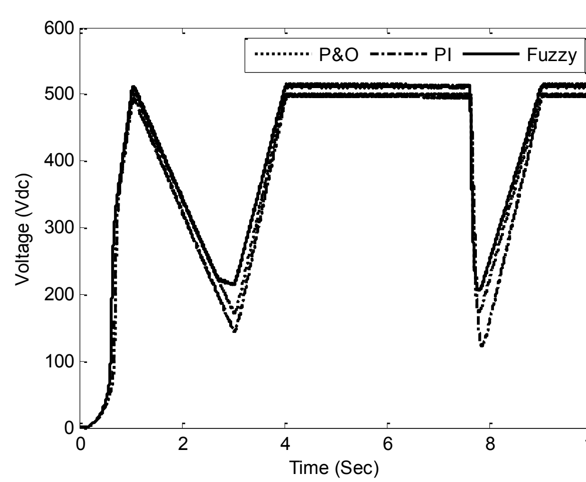

Fig. 12. Output voltage for different MPPT techniques

Table 5. shows the performance comparison of PI, P&O and FLC based MPPT controllers. The FLC has the high power out when compared with the other two controllers. The output voltage of FLC is equal to the reference DC voltage estimated to be the DC bus voltage of 500V. Whereas, the PI

and P&O controllers have an output voltage of 491V and 494V. Though there is only little difference in the power and voltage but when large wind turbines are connected then the difference will become huge.

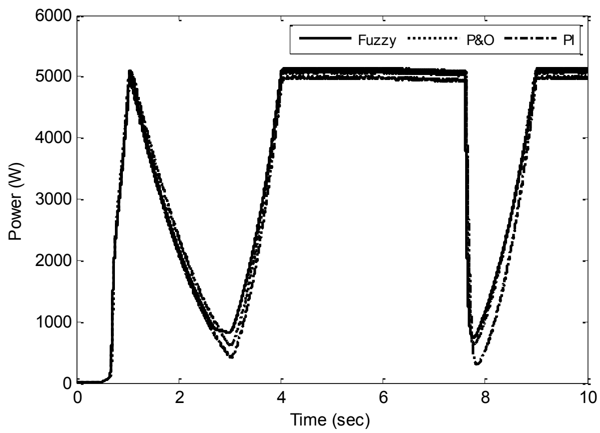

Fig. 13. Power obtained by different MPPT techniques

Table 5. Output of various MPPT techniques

MPPT Technique/Parameters	*PI Controller*	*P&O Controller*	*FLC*
Power	4992 W	5093 W	5112 W
Voltage	491 V	494 V	500 V

5. CONCLUSIONS

In this paper, three MPPT controllers like PI, P&O and FLC controller is modelled and the output is compared for wind energy under varying wind speed condition. The performance of each controller is analysed and it is verified that FLC based controller is more efficient and reliable than PI and P&O based controller. The PI controller fails to track the non linearity of the wind speed thus providing poor output power. The P&O based technique is suitable for the condition where the system is stable of with minimum variance. Wind Speed being high non linear the P&O algorithm oscillates around optimal point thus making it difficult to track the next point. The FLC method has a rapid tracking ability. The FLC control method requires previous knowledge of the system so that it can provide an efficient and steady state output. FLC is fast and efficient technique to track the maximum power point in WECS. The results obtained from FLC are superior and efficient than that of PI and P&O technique in terms of stability, faster tracking ability and fluctuations. Hence, it is concluded that the FLC based MPPT method is the best option for stand alone WECS.

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