# Fuzzy Control Based Adaptive Maximum Power Point Tracking Control Algorithm for Wind Energy Conversion Systems

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**Abstract:** ***This paper presents an Fuzzy control based adaptive maximum power point tracking (MPPT) algorithm for small scale wind energy conversion systems (WECSs) to harvest more energy from unstable wind. The proposed algorithm combines the computational behavior of hill climb search, tip speed ratio, and power signal feedback fuzzy control for its adaptability over wide range of WECSs and fast tracking of maximum power point. In this paper, the proposed MPPT algorithm is implemented by using buck– boost featured single ended primary inductor converter to extract maximum power from full range of wind velocity profile. Evaluation of the Fuzzy based MPPT controller is done on MATLAB/SIMULINK Environment. MATLAB Simulation results show that tracking capability of the proposed System under sudden and gradual fluctuating wind conditions is efficient and effective.***

**Index Terms—Maximum power point tracking, Fuzzy Logic Control (FLC), tip speed ratio algorithm, power signal feedback algorithm, single-ended primary inductor converter (SEPIC) dc-dc converter.**

## I INTRODUCTION

Interest in renewable energy is increasing as alternative energy source to conventional fossil fuel, because of latter's soaring prices, limited reserve capacity, and environmental concerns. Across the globe, research community is exploring all possibilities for the efficient energy conversion from freely available abundant renewable energy sources. Among the popular renewable energy sources, wind energy is gaining more support due to its less space occupancy and zero-carbon emission during operation. Variable speed wind energy conversion systems (WECSs) can harness more electrical energy than fixed speed WECSs by controlling their speed according to the variations in wind velocity [1], [2]. Optimal speed for the turbine $\omega_m$ (rad/s) is calculated by using wind velocity $V_\omega$ (m/s), turbine rotating speed $\omega_m$ (rad/s), and optimal TSR $\lambda_{opt}$ of the system as follows [4]–[6],

$$\omega_m^* = \frac{\lambda_{opt} V_\omega}{R} \tag{1}$$

where *R* is rotor radius in meter. Implementation of TSR algorithm requires the knowledge of $\lambda$ opt of the turbine and is system dependent.

In PSF control method, wind turbine operates at optimal operating point by using the prior knowledge of turbine's maximum power curve [7]–[10]. Implementation of this method requires the prior knowledge of maximum power curves which can be obtained through off-line experiments or system simulations. In HCS control method, an arbitrary small perturbation is given to one of the independent variables of the system and next perturbation is decided based on the changes in output power due to preceding perturbation [11], [12]. Drawbacks of this algorithm are, slow tracking response, especially for high inertia systems. Advanced HCS based on-line training algorithms are reported in [13] and [14] to improve the system tracking response of its maximum power point (MPP). In the present work, a simplified algorithm than [14] has been implemented to improve the system tracking response under rapid fluctuating wind velocity conditions.

Micro-grid is essentially a collection of distributed energy resources (DERs), potential energy storage devices, and loads connected together to form a relatively small-size distribution network [15]. Small-scale WECSs are main resources for DERs in microgrid systems and are usually installed at congested places with turbulent wind conditions where wind speed and direction vary frequently. Extraction of maximum power with fast tracking control strategy under fluctuating wind conditions is a challenging issue. In small-scale WECSs, power conditioning converter's control is most frequently adapting strategy to extract maximum power since pitch angle control is impractical due to their mechanical structure. In this work buck–boost featured single-ended primary inductor converter (SEPIC) dc–dc converter has been used to extract maximum power from total range of wind velocity profile.

This work assumes that the WECS has effective yaw mechanism to turn the turbine nacelle in the direction of the wind immediately against to the variations in wind flow direction. In this paper, a hybrid nature of MPPT control algorithm which combines the computational behavior of HCS-TSR-PSF Fuzzy based Control for system independent adaptivity and fast tracking capability of MPP is presented. The proposed MPPT- Fuzzy based Control has been evaluated by using a Matlab/Simulink. Simulation results show that the proposed Fuzzy based Control enables the WECS to harvest more energy by tracking the MPP under turbulent wind conditions.

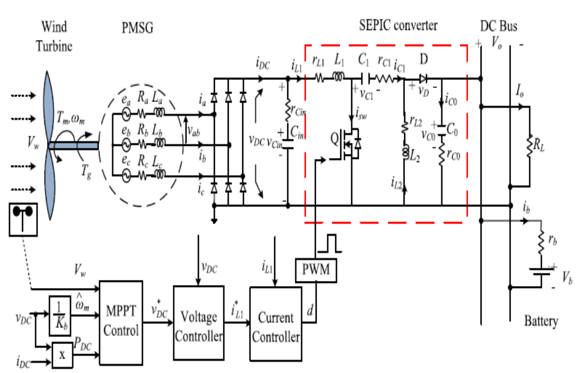



Fig. 1. WECS configuration.

## II SYSTEM CONFIGURATION AND MODELING

In the process of developing a laboratory-scaled dc micro-grid platform, WECS related system configuration is shown in Fig. 1. In small scale variable speed WECS, direct driven permanent magnet synchronous generator (PMSG) with diode rectifier is the most preferred configuration due to PMSG's high air-gap flux density, and high torque-to-inertia ratio. Its decoupling control performance is much less sensitive to the parameter variations of the generator [16]–[19].

**A. Wind Turbine Aerodynamic Model**

Mechanical output power *Pm* extracted from wind by the wind turbine and corresponding torque *Tm* imparted onto WG can be modeled as [20],

$$P_m = \frac{1}{2}\rho\pi R^2 V_\omega^3 C_P(\lambda, \beta) \quad (2)$$

$$T_m = \frac{P_m}{\omega_m} \quad (3)$$

where $\rho$ is air density (kg/m3 ), *Cp* is power coefficient which is function of TSR $\lambda$ and pitch angle $\beta$. The coefficient, $C_P$ can be modeled by using rotor blade's aerodynamic design principles [21],

$$C_P(\lambda, \beta) = C_1\left[\frac{C_2}{\lambda_i} - C_3\beta - C_4\right]e^{-C_5/\lambda_i} + C_6\lambda \quad (4)$$

Where

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.008\beta} - \frac{0.035}{\beta^2+1}$$

and empirical constants, $C_1$= 0.5176; $C_2$ = 116; $C_3$ = 0.4; $C_4$ = 5; $C_5$ = 21; *C6* = 0.0068.

In this work, DC motor based hardware wind turbine emulator is developed in the laboratory by using (2) and (3).

**B. PMSG-Diode Rectifier Model**

Induced e.m.f, $e_s$ (V), in stator winding of PMSG, when it is subjected to a constant flux, $\varphi$ ($W_b$), while rotating with a speed, $\omega_m$(rad/s), is given by

$$e_s = k\omega_m = k\,\frac{\omega_e}{P} \quad (5)$$

where *k* (V·s/rad) is machine induced voltage constant, *P* is total number of rotor pole pairs and $\omega_e$ is electrical angular frequency of PMSG stator induced voltage. In steady state, PMSG's terminal phase voltage, and output power, $P_g$ are given by

$$V_s^2 = E_S^2 - (\omega_e L_S I_s)^2 \quad (6)$$

$$P_g = 3V_s I_s = 3\sqrt{E_S^2 I_S^2 - (\omega_e L_S)^2 I_S^4} \quad (7)$$

where *Es* , *Is* and *Ls* are induced voltage in PMSG's stator winding, stator current and inductance respectively. To derive the basic relations, assuming that both the commutating angle and commutating inductance are negligible, the relation between diode rectifier output voltage, $V_{DC}$ and line voltage at terminals of PMSG, $V_t$ , can be related as [22],

$$V_{DC} = \frac{3\sqrt{2}}{\pi} V_t = \frac{3\sqrt{6}}{\pi} V_s \quad (8)$$

where $V_t$ is RMS value of line-to-line voltage of PMSG. By ignoring the power loss during diode circuit rectification, output power of WECS $P_g$ can be equated to

$$P_g = P_{DC} = 3V_s I_s = V_{DC} I_{DC} \quad (9)$$

PMSG output power $P_g$ and electromagnetic torque $T_g$ can be expressed as function of diode rectifier output current $I_{DC}$ by using (4)–(7), and are given as

$$P_g = \frac{3\sqrt{6}}{\pi} \omega_g I_{DC} \sqrt{k^2 - \frac{6}{\pi^2} (P L_S)^2 I_{DC}^2} \quad (10)$$

$$T_g = \frac{3\sqrt{6}}{\pi} I_{DC} \sqrt{k^2 - \frac{6}{\pi^2} (P L_S)^2 I_{DC}^2} \quad (11)$$

Wind turbine rotor speed can be controlled by controlling the generator torque as follows

$$\omega_m = \frac{T_m - T_g}{B_t} \quad (12)$$

where $B_t$ (Nm.s/rad) is turbine rotor friction coefficient. Based on (8) and (9), it can be concluded that by controlling diode rectifier output current, load torque on wind turbine and finally turbine speed can be controlled. This principle is employed to extract maximum power by a given WECS under different wind velocities.

### C. Small-Signal Modeling of SEPIC DC–DC Converter

Through off-line experiments on the developed laboratory scaled wind turbine emulator, it is noticed that operating range of the dc–dc converter's input voltage is 21–135 V. Among the conventional dc–dc converters, boost converter is one of the frequently used dc–dc converters in distributed generation systems, because of its higher efficiency in energy transfer. However, it can able to transfer energy only when its output stage voltage is higher than the input stage voltage.

Equivalent circuit of the SEPIC dc–dc converter is shown in Fig. 2. Output stage of the SEPIC converter is modeled as a combination of constant voltage source with series internal resistance of the battery. Further, for a given wind velocity and load, the WG and rectifier can be replaced by Thevenin's equivalent voltage, $V_{eq}$ and a series resistor, $R_{eq}$ at input stage of the SEPIC converter [24]. In this work to develop a suitable controller, state-space averaging method [25] is used for small-signal modeling of the SEPIC converter. A small-signal ac model (10) which describes the linear operation of SEPIC based plant, is derived and is given in (11).

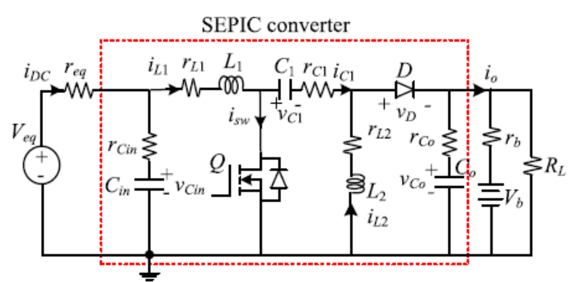



Fig. 2. Equivalent circuit of plant.

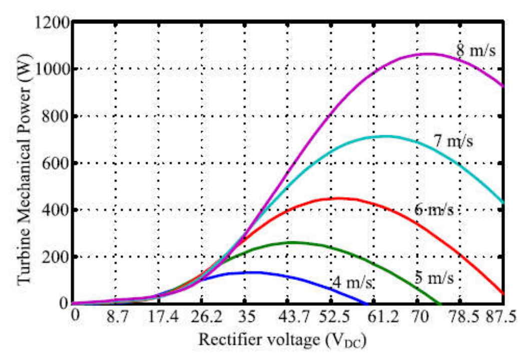



Fig. 3. MPPT converter input voltage and turbine power characteristics.

## III ADAPTIVE MPPT - FUZZY BASED CONTROL

At constant wind velocity, wind turbine output power becomes function of power coefficient (2), and at constant pitch angle, power coefficient becomes function of rotor speed as given in (1) and (3). From this discussion, condition for MPP can be obtained as,

$$\frac{dP_m}{d\omega_m} = 0 \tag{13}$$

Applying the chain rule [11],[12] can be written as follows

$$\frac{dP_m}{d\omega_m} = \frac{dP_m}{dV_{DC}} \cdot \frac{dV_{DC}}{d\omega_c} \cdot \frac{d\omega_C}{d\omega_m} = 0 \tag{14}$$

It can be concluded by using (4)-(6)

$$\frac{dP_m}{d\omega_m} = 0 \Leftrightarrow \frac{dP_m}{dV_{DC}} = 0 \tag{15}$$

Relation between turbine output power and rectifier output voltage is shown in Fig. 3. It is observed that this relation has a corresponding single optimal $V_{DC}$ value for every wind velocity and objective of the proposed Fuzzy based Control is to search for this optimal operating point $V_{DC}$ opted .

This sampling During steady wind, as described in flowchart, based on the changes in output power with respect to the changes in control variable, Fuzzy based Control provides reference signal$V_{DC}$ ref($k$ + 1) by implementing HCS control Fuzzy based Control. Meanwhile, Fuzzy based Control performs memory updating computations to optimize the existing data of the lookup table and optimal TSR vector.

### A. Fuzzy logic controller (FLC)

Fuzzy logic expressed operational laws in linguistics terms instead of mathematical equations. Many systems are too complex to model accurately, even with complex mathematical equations; therefore traditional methods become infeasible in these systems .However fuzzy logics linguistic terms provide a feasible method for defining the operational characteristics of such system. Fuzzy logic controller can be considered as a special class of symbolic controller. The configuration of fuzzy logic controller block diagram is shown in Fig.4.

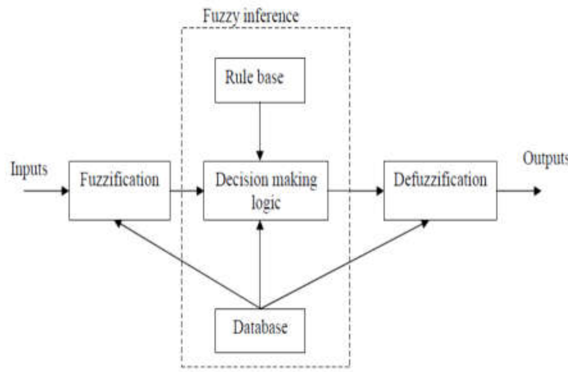



Fig4. Structure of Fuzzy logic controller

The fuzzy logic controller has three main components

1. Fuzzification
2. Fuzzy inference
3. Defuzzification

The following functions:

1. Multiple measured crisp inputs first must be mapped into fuzzy membership function this process is called fuzzification.
2. Performs a scale mapping that transfers the range of values of input variables into corresponding universes of discourse.
3. Performs the function of fuzzification that converts input data into suitable linguistic values which may be viewed as labels of fuzzy sets.

Fuzzy logic linguistic terms are often expressed in the form of logical implication, such as if then

rules. These rules define a range of values known as fuzzy member ship functions .Fuzzy membership function may be in the form of a triangular, a trapezoidal, a bell (as shown in Fig.4.2) or another appropriate from. The triangle membership function is defined in (4.1).Triangle membership functions limits defined by all $V_{a1}$ , $V_{a2}$ and$V_{a3}$.

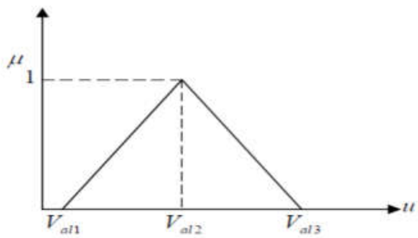
$$\mu(u_i) = \begin{cases} \frac{u_f - V_{al1}}{V_{al2} - V_{al1}}, V_{al1} \le u_f \le V_{al2} \\ \frac{V_{al3} - u_i}{V_{al3} - V_{al2}}, V_{al2} \le u_i \le V_{al3} \\ 0, \quad otherwise \end{cases} \tag{16}$$

$$\mu_t(u_i) = \begin{cases} \frac{u_f - V_{al1}}{V_{al2} - V_{al1}}, V_{al1} \le u_f \le V_{al2} \\ 1, \quad V_{al2} \le u_f \le V_{al3} \\ \frac{V_{al4} - u_i}{V_{al4} - V_{al3}}, V_{al3} \le u_i \le V_{al4} \\ 0, \quad otherwise \end{cases} \tag{17}$$

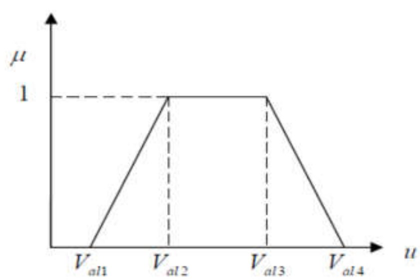
The bell membership functions are defined by parameters $X_P$, w and m as follows

$$\mu(u_i) = \frac{1}{1 + \left(\frac{|u_i - x_P|}{w}\right)^{2m}} \tag{18}$$

Where $X_P$ the midpoint and w is the width of bell function .m ≥ 1, and describe the convexity of the bell function.




(a)

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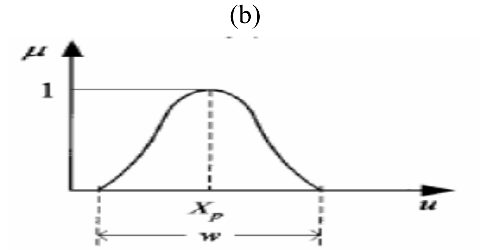



(c)

Fig.5: (a) Triangle, (b) Trapezoid, and (c) Bell membership functions.

The inputs of the fuzzy controller are expressed in several linguist levels. As shown inFig.4.3 these levels can be described as Positive big (PB), Positive medium (PM), Positive small (PS) Negative small (NS), Negative medium (NM), Negative big (NB) or in other levels. Each level is described by fuzzy set.

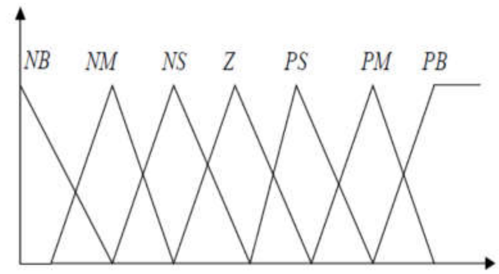



Fig.6: Seven levels of fuzzy membership function

**Fuzzy inference**

Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made, or patterns discerned. There are two types of fuzzy inference systems that can be implemented in the Fuzzy Logic Toolbox: Mamdani-type and Sugeno-type. These two types of inference systems vary somewhat in the way outputs are determined. Fuzzy inference systems have been successfully applied in fields such as automatic control, data classification, decision analysis, expert systems, and computer vision. flowchart. frequency of the Fuzzy based Control is adequately chosen based on the dynamics of the wind turbine. If the difference between two consequent samples of wind velocity is within ± 0.25 m/s, the Fuzzy based Control treats that the wind is steady wind otherwise turbulent wind.

If the turbine extracts more power compared to previous iteration $P_{DC}$ $(k)$ > $P_{DC}$ $(k-1)$, Fuzzy based Control checks the stored value of $P_{DC}$ max at the index of the present wind velocity $V_{wind}$ in lookup table and updates the memory if $P_{DC}$ $(k)$ > $P_{DC}$ max at $V_{wind}$ ex as depicted in flowchart. After updating the lookup table, updated value for TSR is calculated and is filled at the next entry location of the optimal TSR vector as follows,

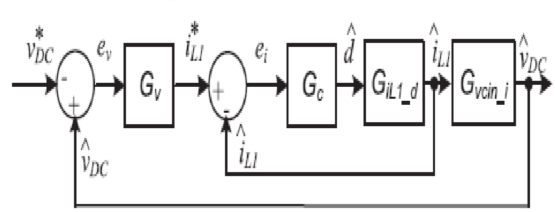



Fig.7: Double loop current-mode control structure

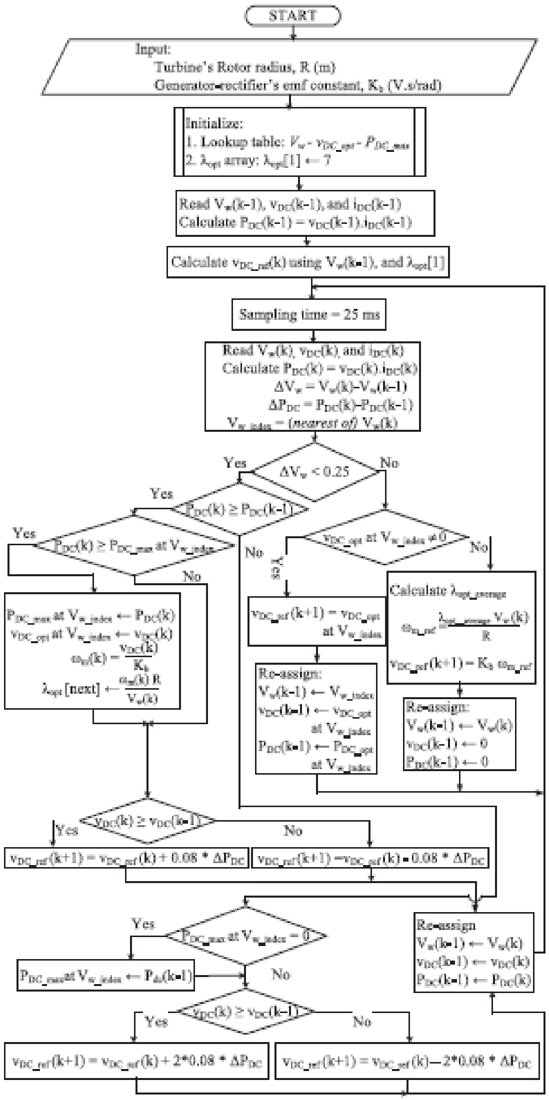



Fig.8: Adaptive MPPT- Fuzzy based Control

Table. I: SEPIC converter parameters

| Parameter | Value |
|---|---|
| Thevenin eq. resistance, $r_{eq}$ (m$\Omega$) | 2.2 |
| Input capacitance, $C_{in}$ ($\mu$F) | 30 |
| ESR of input capacitor $r_{C\,in}$ (m$\Omega$) | 1.0 |
| Input inductor, $L_1$ (mH) | 8.7 |
| ESR of input inductor, $r_{L\,1}$ (m$\Omega$) | 1.0 |
| Coupling capacitor, $C_1$ ($\mu$F) | 90 |
| ESR of coupling capacitor, $r_{C\,1}$ (m$\Omega$) | 3.0 |
| Output inductor, $L_2$ (mH) | 8.7 |
| ESR of output inductor, $r_{L\,2}$ (m$\Omega$) | 1.0 |
| Output capacitor, $C_o$ ($\mu$F) | 500 |
| ESR of output capacitor, $r_{C\,o}$ (m$\Omega$) | 3.0 |
| Battery internal resistor, $r_b$ (m$\Omega$) | 34.2 |

$$\lambda_{\text{opt}}[\text{next}] \leftarrow \frac{\omega_m(k)R}{V_\omega(k)} \tag{19}$$

Whenever wind turbine operates with better optimal performance than the stored operating point at a given wind velocity, Fuzzy based Control modifies the programmable memory. These continuous modifications of the memory towards the optimal operating points enable the Fuzzy based Control to acquire optimal characteristics of the given WECS. This adaptivity feature of the Fuzzy based Control makes it suitable to apply on wide range of WECSs. During turbulent wind conditions, Fuzzy based Control provides reference signal by implementing either PSF or TSR Fuzzy based Controlic computations. Fuzzy based Control searches the lookup table for $V_{DC}$ output at $V_w$ $(k)$ index. If the entry of $V_{DC}$ o p t at $V_{wind}$ ex is nonzero, PSF control Fuzzy based Control will be implemented by giving this entry as reference value $V_{DC}$ r e f $(k + 1)$ for the next iteration. If the value of $V_{DC}$ output at $V_{wind}$ ex is zero, Fuzzy based Control implements TSR control. The adaptability of the Fuzzy based Control allows the system to extract as much available wind

## V MATLAB SIMULINK RESULTS

An Matlab Simulink Model shown in Fig. 9, has been developed for the performance evaluation of the proposed MPPT control Fuzzy based Control in extracting maximum power by a given WECS. Schematic of this test rig is shown in Fig. 9. SEPIC dc–dc converter's response in reference signal tracking with double loop current mode controller has been verified and is shown in Fig. 8. The observed performance ensures that the tracking behavior of the converter is satisfactory even at wide variations in reference signal.

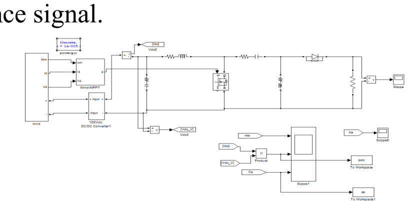


Fig. 9: MATLAB SIMULINK Model of the Proposed Fuzzy based PMSG.

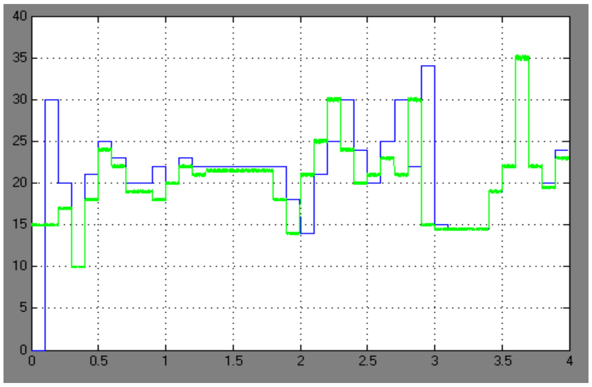



Fig.10: SEPIC's reference signal tracking response.

This controller can be used for understanding the behavioral characteristics of WECS and to evaluate the performance of newly proposed MPPT control Fuzzy based Controls. In host system, a MATLAB graphical user interface environment.

After running the system with proposed MPPT- Fuzzy based Control for the duration of 5000 s, it is observed that average value of the optimal TSR vector $\lambda_{opt}$ -average is 7.91 and data stored in lookup table is presented in Table II. In this section, behavior of the WECS with proposed MPPT- Fuzzy based Control is analyzed by using two stages of evaluations. In first stage, effectiveness of the proposed MPPT- Fuzzy based Control is evaluated by observing the system performance in extracting maximum power under sudden and gradually varying wind conditions. In second stage of evaluation, a comparative study has been done between system performance with conventional HCS Control and proposed MPPT- Fuzzy based Control against turbulent wind conditions.

Fig. 10 shows performance of the WECS with proposed MPPT- Fuzzy based Control under sudden and gradual varying wind conditions. In Fig. 10(a), at time $t_1$, when system experiences a sudden variation in wind velocity from 4.5 to 6.5 m/s, Fuzzy based Control executes turbulent wind condition related computations and searches the lookup table for $V_{DC}$ output at the index wind velocity of 6.5 m/s.

These results confirm the optimal performance of the WECS throughout the fast as well as gradually varying wind velocity conditions. Moreover, proposed Fuzzy based Control's continuous modifications in programmable memory during its implementation make the optimal tracking performance of the system more effective and efficient. System performance with HCS Fuzzy based Control and proposed MPPT- Fuzzy based Control under fluctuating wind conditions are compared in this section. HCS

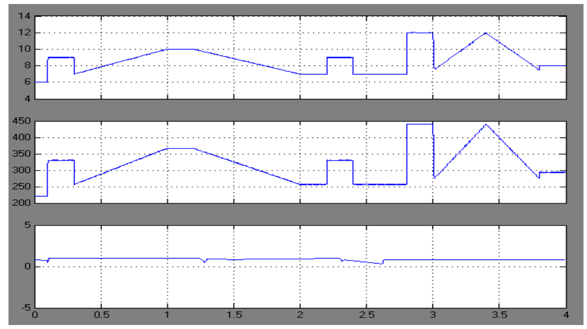
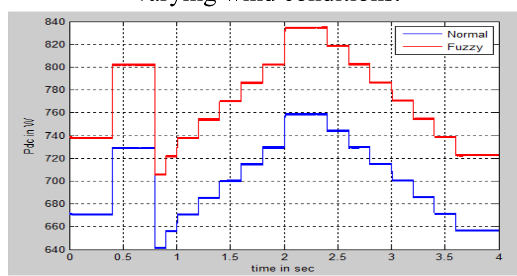
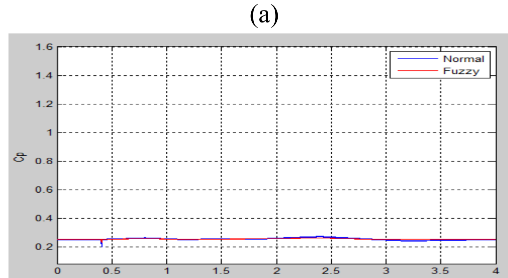


Fig.11: Performance of WECS with proposed MPPT- Fuzzy based Control. (a) Dynamic 2response under varying wind conditions.




(a)

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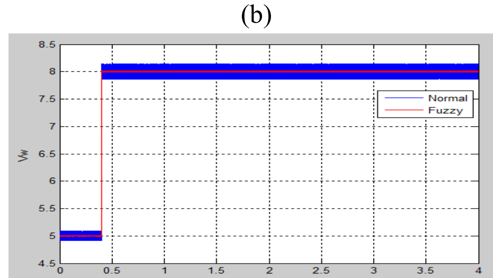


(c)

Fig.12: Performance evaluation of proposed MPPT- Fuzzy based Control. (a)Output Power in W (b) Turbine Power Coefficient (c) Wind Velocity

Whereas proposed Fuzzy based Control makes the system to track MPP immediately without any intermediate random search operations as shown in Fig. 11. By observing the variations in $C_P$ , it can be concluded that WECS with proposed Fuzzy based Control harvests more energy than with HCS Control.

# VI CONCLUSION

In this paper, an adaptive MPPT - Fuzzy based Control has been proposed for the fast tracking of MPP under tumultuous wind conditions for small scale WECSs. System behavior with proposed Fuzzy based Control under fast changing wind conditions has been observed and it is evident that the proposed MPPT - Fuzzy based Control can put the system at optimal operating point promptly against random variations in the wind velocity. System performance with proposed MPPT - Fuzzy based Control is compared with the HCS Control and MATLAB Simulation results proved that WECS with proposed MPPT - Fuzzy based Control harvests more energy than with HCS Control. The proposed MPPT - Fuzzy based Control provides the following advantages: 1) improved dynamic response of the system; 2) prerequisite of system's optimal characteristics data is not required and hence the Fuzzy based Control is adaptive; To extract maximum power from the wide range of wind conditions. Since small scale WECSs are main resources for DERs in microgrid systems, the proposed Fuzzy based Control is very much applicable for microgrid systems.

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