# A Novel Maximum Power Point Tracking Method Based on Extension Theory for Wind Energy Conversion System

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*Abstract*— **This paper proposed an intelligent maximum-power-point tracking algorithm to fully utilize wind energy conversation system (WECS) output power that depends on wind speed. The proposed method has been applied to a wind turbine based on a permanent magnet synchronous generator operating at variable speed. The proposed intelligent MPPT algorithm based on extension theory can automatically adjust the step size to track the WECS maximum power point (MPP).Compared with the conventional fixed step size and variable step size perturbation and observation (P&O),the proposed approach is able to effectively improve the dynamic response and power efficiency of the WECS simultaneously. This approach is simulated using MATLAB-SIMULINK software.**
**Keywords- wind turbine, PMSG, MPPT algorithm, extension theory**

## I. Introduction

In the last decade, great increase is seeing in use of renewable energy, due to the high cost of fossil fuels and the different policy of industrial countries with the aim of reducing air pollution. Specify, wind-energy-conversion-systems (WECS) are considered as the most cost effective of all the renewable sources. [1] Some countries like Germany, USA and Denmark use great amount of wind energy in comparison of conventional generation sources.

Wind turbines can, operate at two operation mode: fixed speed and variable speed. The generator is directly connected to the grid or load for a fixed speed wind turbine while it is controlled by power electronic devices to convert variable-frequency, variable-voltage power into constant-frequency constant-voltage, for a variable speed wind turbine.

The reduction of both the mechanical Structure stresses and the vocal noise and the possibility to control active and reactive power, are the main reasons to choice variable speed operation of wind turbines. In fact, variable speed operation increases the system efficiency and reduces generated power fluctuations [2]. Therefore, the use of a maximum-power-point tracking (MPPT) algorithm is necessary to extract as much power as possible from the wind when it's speed changes.

A large number of MPPT techniques have been proposed for wind generators [3, 4]. Some of them need mechanical sensors to measurement of the wind speed to calculate the value of the generator speed that forces it to operate at the maximum power point (MPP) [5]. Therefore, they are sensitive to modeling uncertainties and may become ineffective in some cases. Most common methods to achieve MPPT in wind turbines are tip-speed ratio (TSR) algorithm, hill-climb searching (HCS) algorithm and the Perturb & Observe algorithm (P&O). TSR control is based on regulate rotor speed to fix an optimal TSR. HCS control extracts MPP by search for the peak output power of the wind turbine. [6-8]

In considering the aforementioned drawbacks and then to fulfill the requirements of dynamic response and steady-state performance of an MPPT control for WECS, an intelligent control algorithm based on the P&O method with extension theory [9]is proposed in this paper. The proposed MPPT method can adjust the step size adaptively in response to varying wind speed. Less constructed data utilized means no learning procedures and a high convergence rate are needed. These are the good features of the proposed algorithm for improving the dynamic response and power efficiency of an MPPT control method.

The WECS used will be described firstly. It is followed by the presentation of the MPPT algorithm and the used dc-dc converters controllers. Finally the MATLAB-SIMULINK models used as well as the simulation results will be given.

## II. WIND ENERGY CONVERSION SYSTEM(WECS)

The wind generator system is formed by a fixed pitch wind turbine, a permanent magnet synchronous generator, a dc-to-dc boost converter and a resistance load. It is shown in Fig. 1.

The blades of a wind turbine extract the energy flow from moving and deliver it via a gear box unit to the rotor of an electric generator. The wind power is estimated by [10]:

$$P_{wind} = \frac{1}{2}\rho A v^3 \tag{1}$$

Where, is the air density which varies with air pressure and temperature, The power coefficient $C_p$ is usually given as a function of the tip speed ratio $\lambda$ and the blade pitch angle. The pitch angle is the angle between the plane of rotation and the blade cross section chord. The tip speed ratio of a wind turbine is defined as:

$$\lambda = \frac{u}{v} = \frac{r\omega}{v} \quad . \tag{2}$$

Where u is the tangential velocity of the blade pitch,ω is the angular velocity of the rotor, r is the rotor radius in meters, and v the wind speed. For the wind turbine used in this paper, $C_p$ is a function of $\lambda$ as is given by the following equation:

$$C_p(\lambda,\beta) = C_1\left(\frac{C_2}{\lambda_i} - C_3\beta - C_4\right)e^{\frac{-C_5}{\lambda_i}} + C_6\lambda \tag{3}$$

Where:

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + .08\beta} - \frac{.035}{\beta^3 + 1} \tag{4}$$

The output power of the wind turbine $P_t$ is calculated as:

$$P_t = \frac{1}{2}C_p(\lambda)\rho A v^3 \tag{5}$$

The coefficients $c_1$ to $c_6$ are: $c_1 = 0.5176, c_2 = 116, c_3 = 0.4, c_4 = 5 \text{ and } c_6 = 0.0068$ . The $C_p - \lambda$ characteristics, for different values of the pitch angle β, are illustrated in Fig.2. The maximum value of ($C_{pmax}$=0.48) is achieved for β = 0 degree and for λ= 8.1.

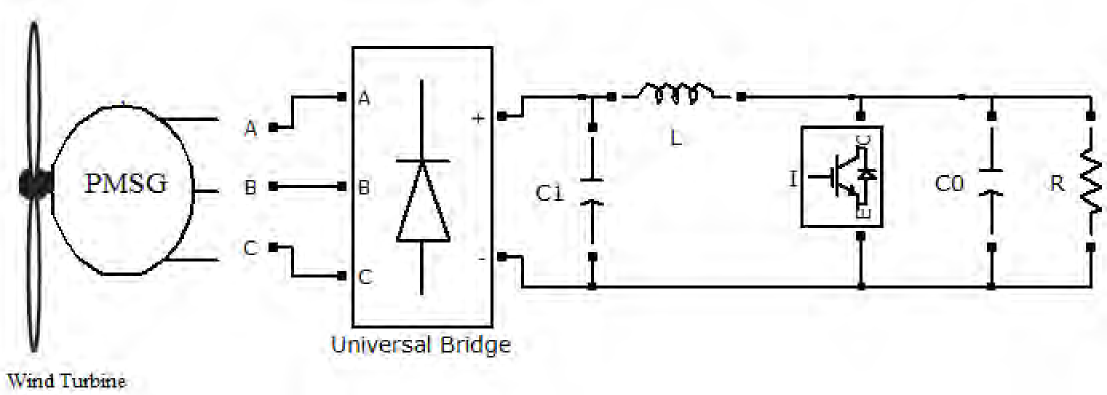


Figure 1. Wind generator system.

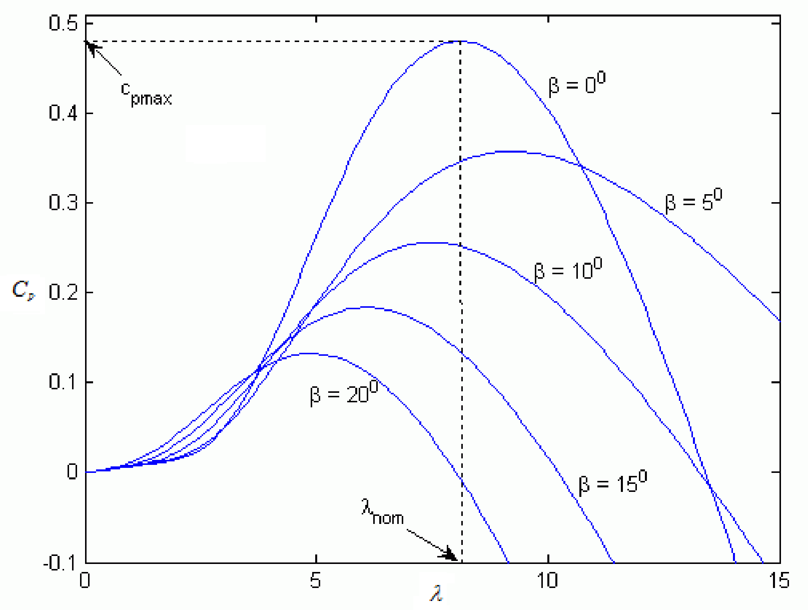


Figure 2. Typical $C_p$ versus λ curve.

## III. Extension theory

This theory is similar to fuzzy set, with this difference that the range of a fuzzy set is [0, 1]. But, the range of a extension set is $(-\infty,+\infty)$ .it allows us to define a set including any data in the domain. Transformation of the matter-element solves incompatibility problems. [9]

The matter-element theory includes extension theory of the matter-element and the transformation theory of the matter-element. we can use Extension equations, as the quantitative tool for solving problems.

### *A. The Matter-ElementTheory*

In extension theory, a matter-element (R) contains three fundamental elements: $R=(N\ \ C\ \ V)$ where C is a matter characteristic or a characteristic vector, ex: $C=[c_1,c_2,...,c_n]$ ,and V the same as C is a value or a vector, ex: $V=[v_1,v_2,...,v_n]$

### *B. Definition of Classical and Neighborhood Domains*

If we set $F_0=\left[a_p,b_p\right]$, $F=\left[a_q,b_q\right]$, f is a point in F, then a matter element $R_0$ of $F_0$ can be described as follows :

$$R_0=(F_0\ C\ V_p)=\begin{bmatrix} F_0 & C_1 & V_{p1} \\ \multicolumn{3}{c}{\dots\dots\dots} \\ & C_n & V_{pn} \end{bmatrix}=\begin{bmatrix} F_0 & C_1 & \left[a_{p1},b_{p1}\right] \\ \multicolumn{3}{c}{\dots\dots\dots} \\ & C_n & \left[a_{pn},b_{pn}\right] \end{bmatrix} \tag{6}$$

where are the characteristics of , and are the ranges of called the classical domains. Similarly, matter-element of can be also described as follows:

$$R_F=(F\ \ C\ V_q)=\begin{bmatrix} F & C_1 & V_{q1} \\ \multicolumn{3}{c}{\dots\dots\dots} \\ & C_n & V_{qn} \end{bmatrix}=\begin{bmatrix} F & C_1 & \left[a_{q1},b_{q1}\right] \\ \multicolumn{3}{c}{\dots\dots\dots} \\ & C_n & \left[a_{qn},b_{qn}\right] \end{bmatrix} \tag{7}$$

Also, are the ranges of called the neighborhood domains.

*C. Definition of Correlation Function*

If $F_0 \in F$ then the extended correlation function K (f) can be defined as follows:

$$K(f) = \frac{\rho(f, F_0)}{D(f, F_0, F)} \tag{8}$$

Where

$$\rho(f, F_0) = \left| f - \frac{a_p + b_p}{2} \right| - \left| \frac{b_p - a_p}{2} \right| \tag{9}$$

$$D(f, F_0, F) = \begin{cases} \rho(f, F) - \rho(f, F_0) & f \notin F_0 \\ -\left| \frac{b_p - a_p}{2} \right| & f \in F_0 \end{cases} \tag{10}$$

$$\rho(f, F) = \left| f - \frac{a_q + b_q}{2} \right| - \left| \frac{b_q - a_q}{2} \right| \tag{11}$$

The correlation function can be used to calculate the membership degree between f and $F_0$. The extended correlation function is shown in Fig. 3. When $K(f) > 0$, this indicates that $f$ belongs to $F_0$. When $K(f) < 0$ it describes the degree to which f does not belong to $F_0$. When $-1 < K(f) < 0$, it is called the extension domain, which means the element f still has a probability of becoming part of the set if the conditions change.

## IV. THE EXTENSION MPPT CONTROLLER

*A. The Proposed MPPT Scheme*

If we assume generator generated power converts to DC power with unit power factor, then we have:

$$P_g = 3V_{ph} I_{ph} = V_{dc} I_{dc} \tag{12}$$

Where, $P_g$ is generator generated power, $V_{dc}$ and $I_{dc}$ are rectified voltage and current, respectively, $V_{ph}$ and $I_{ph}$ are phase voltage and current of generator[11].

The value of average power is equal to:

$$V_{dc} = \frac{3}{\pi} \int_{-\frac{\pi}{6}}^{\frac{\pi}{6}} V_{LLmax} \cos\theta d\theta = \frac{3}{\pi} V_{LLmax} \tag{13}$$

Where, $V_{LLmax}$ is peak value of line to line input voltage of rectifier. Furthermore, the relation of rectified voltage and RMS phase voltage is:

$$V_{dc} = \frac{3}{\pi} \sqrt{6} V \tag{14}$$

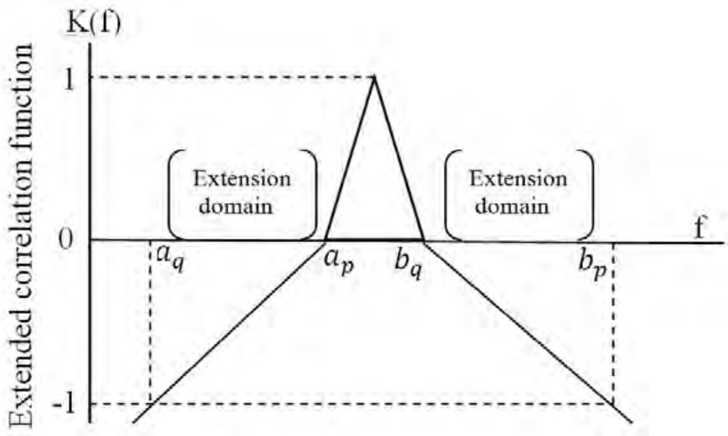


Figure 3. The extension correlation function.

Considering above equations, $P_{dc}$ as a function of $V_{dc}$ and $\omega$ is given by the following equation:

$$P_{dc} = \frac{\pi V_{dc}}{\sqrt{6}L\omega}\sqrt{(K\omega)^2 - (\frac{\pi}{3\sqrt{6}}V_{dc})^2} \tag{15}$$

Where, $\omega$ rotor speed, K ratio of armature voltage to rotor speed and L armature inductance.
It is noticed from (14) that the power extracted from the rectifier can be controlled by varying the dc bus voltage, which is a function of $\omega$. Considering $P_{dc}$-$V_{dc}$ characteristics given in Fig. 4.

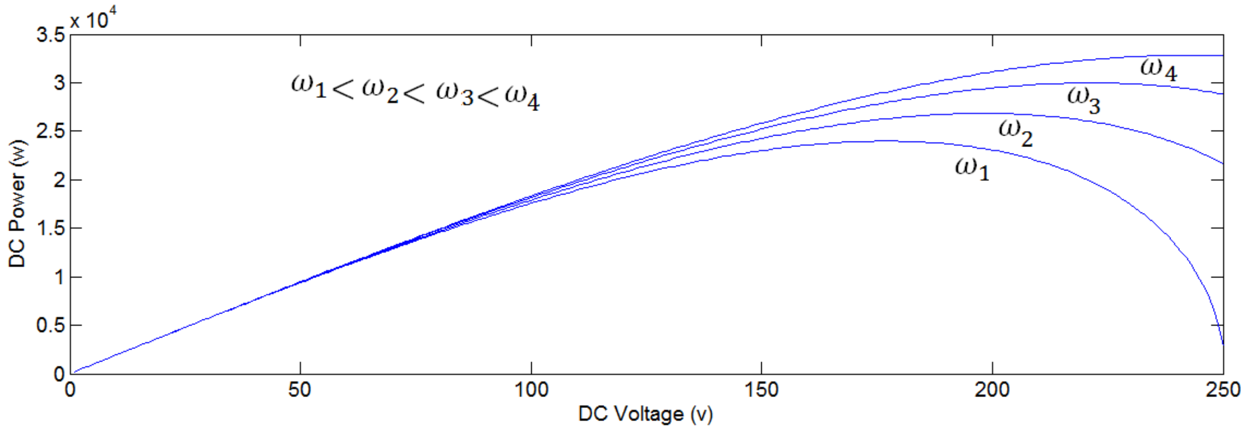


Figure 4. Typical rectified power versus rectified voltage.

It is known that the maximum power point is obtained when:

$$\frac{dP_{dc}}{dV_{dc}} = 0 \tag{16}$$

The function $P_{dc}(V_{dc})$ has a single point where maximum power extraction is achieved. It also means that the maximum power can be tracked by searching the rectified dc power, rather than environmental conditions, such as wind speed.
A simple wind system with MPPT subsystem shown in Fig. 5 is developed to test the effectiveness of the proposed method. A boost converter is used as the power interface between the WECS and the load to achieve maximum power. The output voltage $V_{dc}$ of the boost converter can be expressed as:

$$V_o = \frac{1}{1-D}V_s \tag{17}$$

Where $D$ is the duty cycle of the converter. It can be seen the input DC voltage $V_s$ can be shifted to a high level. This power converter is suitable for a lower WECS output voltage and higher desirable DC link voltage case.

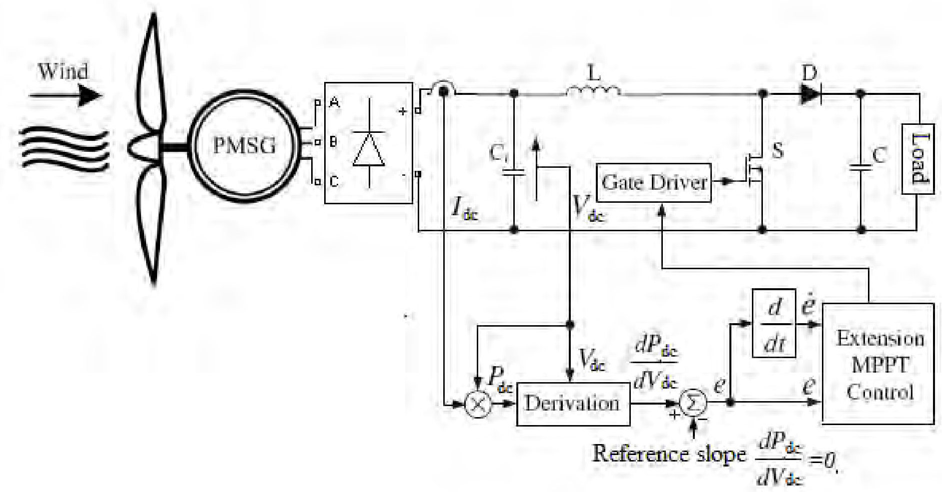


Figure 5. The Proposed Extension MPPT Scheme.

*B. The Extension MPPT Method*

To let the MPPT method possess adaptive capability, it is proposed the step size of the P&O MPPT method of the WECS is adaptively tuned by the extension error tuning scheme, which is driven by a slope error of the power $P_{dc}$ versus voltage $V_{dc}$ and its error change which are defined as $e(k)=\frac{p_{dc}(k)-p_{dc}(k-1)}{V_{dc}(k)-V_{dc}(k-1)}$ and $e^{\cdot}(k)=e(k)-e(k-1)$ with $P_{dc}(k)$ and $V_{dc}(k)$ being the output rectified power and voltage of the WECS at $k_{th}$ sampling interval, respectively. The major purpose of this MPPT controller is to let the resulting $\frac{dp_{dc}}{dv_{dc}}$ tracking response closely follow $\frac{dp_{dc}}{dv_{dc}}=0$, as shown in Fig.6.

Based on the experience of the P-V characteristic curve shown in Fig.6 and the experience of the MPP to be controlled, the numbers of quantization levels of the input variables $e(k)$ and $e^{\cdot}(k)$ are chosen to be 9 categories and The linguistic rules of the extension error tuning scheme are decided and listed in Table1.

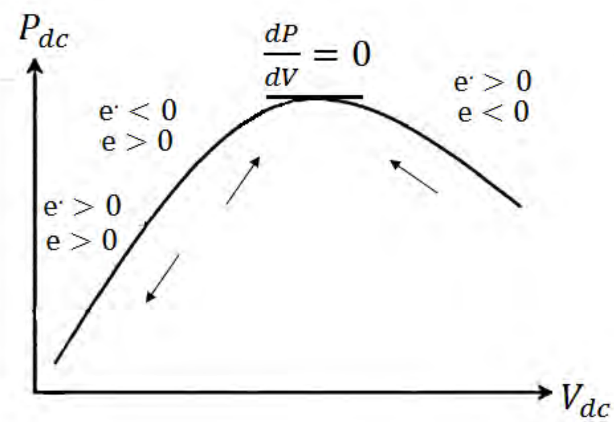


Figure 6. The P-V Curve Slope of Error and Change of Error.

TABLE I. QUANTIZED SLOPE E ERROR AND ERROR CHANGE AND DECISION DUTY CYCLE.

| Category Number | Slope Error Category e | Slope e Error Change Category $e^{\cdot}$ | Duty Cycle Step Size $\Delta D$ | Error Change Polarity |
|---|---|---|---|---|
| 1 | $0 < e < 15$ | $-100 < e^{\cdot} < 0$ | –0.01 | +1 |
| 2 | $15 < e < 20$ | $-100 < e^{\cdot} < 0$ | –0.03 | +1 |
| 3 | $20 < e < 50$ | $-100 < e^{\cdot} < 0$ | –0.05 | +1 |
| 4 | $0 < e < 15$ | $0 < e^{\cdot} < 100$ | –0.01 | –1 |
| 5 | $15 < e < 20$ | $0 < e^{\cdot} < 100$ | –0.03 | –1 |
| 6 | $20 < e < 50$ | $0 < e^{\cdot} < 100$ | –0.05 | –1 |
| 7 | $-15 < e < 0$ | $0 < e^{\cdot} < 100$ | 0.03 | +1 |
| 8 | $-25 < e < -15$ | $0 < e^{\cdot} < 100$ | 0.04 | +1 |
| 9 | $-35 < e < -25$ | $0 < e^{\cdot} < 100$ | 0.05 | +1 |

The slope error e is equal to zero at MPP of the WECS. When the operation point closes to MPP, slope error e decreases; on the contrary, the value of e will increase. And, the polarity of error change depends on the voltage changing direction, as shown in Fig. 6. According to the range of $e$ and $e^{\cdot}$ ,the extension MPPT algorithm can discriminate the category and then determine the duty cycle of the boost converter.

According to the P-V curve statistical records of WECS at 8 m/s – 12m/s, we can suppose the lower and upper boundary of each characteristic as the value ranges $< a_p, b_p >$ of classical regions for it. In addition, we can determine The value range $< a_q, b_q >$ of the neighborhood domain from the maximum and minimum values of every characteristic in the statistical records. For the selected Wind speed range 8 m/s – 12m/s, it can be represented as:

$$R_F = (F \ \ C \ \ V_q) = \begin{bmatrix} F & C_1 & \langle -35,50 \rangle \\ & C_2 & \langle -100,100 \rangle \end{bmatrix} \tag{18}$$

The flow chart of the proposed extension MPPT method is shown in Fig. 7, and its process is summarized as below:

Step 1. Establish the matter-element model of slope error and error changes category, which is performed as follows:

$$R_k = \begin{bmatrix} F_0 & C_1 & V_{p1k} \\ & C_2 & V_{p2k} \end{bmatrix} \qquad k = 1,2,...,9 \tag{19}$$

where $V_{pjk} = \langle a_{pjk}, b_{pjk} \rangle, j = 1,2$ is the classical domain of every characteristic set.

Step 2. Set the matter-element of the input slope error and error change as (14):

$$R_{new} = \begin{bmatrix} F_{new} & C_1 & V_{new1} \\ & C_2 & V_{new2} \end{bmatrix} \tag{20}$$

Step 3. Calculate the correlation degrees of the slope errors and error changes with the characteristic of each matter-element by the proposed extended correlation function shown in (7).

Step 4. Assign weights to the matter characteristic such as $W_1, W_2$ denoting the significance of every characteristic. In this paper, $W_1, W_2$ are set as $W_1 = 0.85$, $W_2 = 0.15$.

Step 5. Calculate the correlation degrees of every category:

$$K(f)_k = \sum_{j=1}^{2} W_j K_{kj} \quad k = (1,2,...,9) \tag{21}$$

Step 6. Select the maximum value from the normal correlation degrees to recognize the category of the input slope error and error change information and determine the duty cycle step size $\Delta D$ of the boost converter and the polarity P of error change $e^{\cdot}$. To increase the sensitivity and adaptive capability, the new duty cycle $D_{new}$ in the next time period is determined as follows:

$$D_{new} = D_{old} + \Delta D + (\Delta D \times P \times (K(f) - 1)) \tag{22}$$

where $D_{old}$ is the duty cycle of the boost converter in the previous sample period, $K(f)$ is the maximum correlation degrees of the category.

Step 7. Input a new slope error and error change, then return to Step 2, or else end the process.

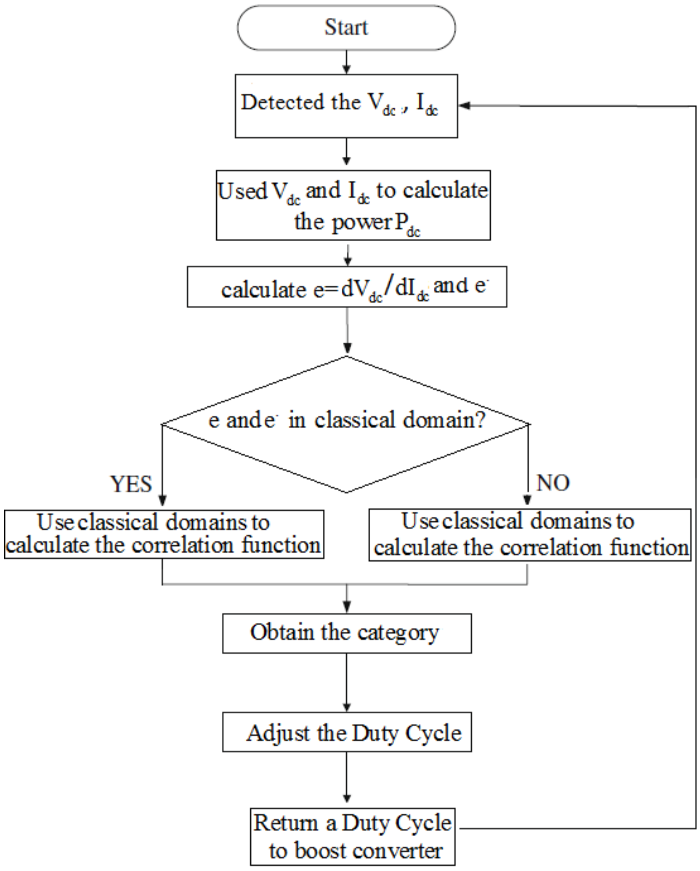

Figure 7. The Flowchart of the Extension MPPT Algorithm.

## V. SIMULATION RESULTS

The proposed control strategy has been numerically tested. in simulation by MATLAB/SIMULINK. we compare the dynamic response and efficiency of WECS using the following two different control approaches:

(1)P&O Algorithm (fixed step size).

(2) P&O Algorithm (variable step size).

(3) proposed Algorithm.

The wind turbine generator system used for the simulation has the following parameters:

1) Wind turbine parameters: $P_m$ = 30 kW; 140 r/min; $\rho$ = 1.25 kg/m$^3$; r = 5.7 m, Gear ratio = 7.5

2) Generator parameters: $R_s$ = 0.425 $\Omega$ ; $L_d$ = $L_q$ = 8.4 mH, Flux Linkage = 0.98 v.s.

The boost converter specifications are chosen as follows:

(1) DC capacitance:

(2) Filter inductance:

(3) Switching frequency:

To compare the performance of the proposed extension MPPT algorithm with other algorithms, the simulations are configured under the same conditions. The output power performance of three MPPT algorithms, under an wind speed step change from 9 m/s to 12 m/s at t=1.5s and from 12 m/s to 10 m/s at t=3s are shown in Fig.8.

*A. Fixed Step Size P&O Algorithm*

The sampling period used for the fixed step size P&O MPPT algorithm is chosen as 0.01 s. Therefore, the duty cycle of the power converter is updated every 0.01 s. also, the step size of duty cycle at this method is 0.05. The average power is 29.7kW for the defined period and response time of it, is 0.23s.

*B. Variable Step Size P&O Algorithm*

For reducing of oscillation at around the MPP in fixed step size P&O algorithm, we can change the value of $\Delta D$ at each sample. So, the new method is derived from the conventional P&O algorithm one by multiplying the steps in a ramp signal. This algorithm reduces the size of the duty cycle steps when the WECS is close to an MPP. [11]. the simulation result of it illustrates that The average power is 31.5kW (an increase of 6.06% compared with that of fixed step P&O) and It can be found that response time of it, is 0.18s.

*C. Extension Algorithm*

In proposed algorithm, the allowable maximum duty size is assumed 0.05. The efficiency of the maximum power extraction can be clearly observed as The average power of it, is 32.4kW. Compared with that from the variable step P&O method, it increases by 2.85%. On the other hand, The results point out the oscillations at wind step change instants are greatly reduced by utilizing the proposed extension MPPT algorithm. Also, the dynamic performance of the proposed method is obviously faster in comparison with other methods.

From the performance comparison for three methods above simulation results, we can see that MPPT is important for either high or low wind speeds, as shown in Table 2. Table 2 shows the average power, response time from each algorithm.

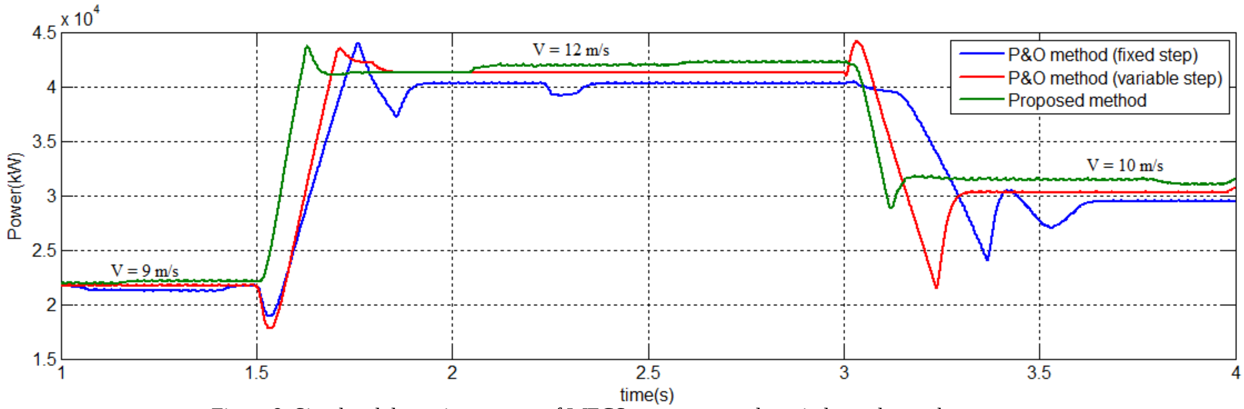


Figure 9. Simulated dynamic response of WECS output power due wind speed step change.

TABLE II. PERFORMANCE FOR VARIOUS ALGORITHMS.

TABLE III.

| | Average Power(kW) | Response Time (s) (Increasing instant) | Response Time (s) (Decreasing instant) |
|---|---|---|---|
| fixed step size P&O algorithm | 29.7 | 0.4 | 0.6 |
| variable step size P&O algorithm | 31.05 | 0.34 | 0.28 |
| Extension algorithm | 32.04 | 0.12 | 0.12 |

## VI. CONCLUSIONS

An extension maximum power point tracking method was proposed in this paper. This method use extension theory with for reaching the accurate MPP of WECS under Wind speed changes. The benefits of this method is speed up responses and improving energy conversion efficiency. Three MPPT control methods, fixed step size MPPT method (P&O), variable step size MPPT method (P&O), and the proposed variable step size extension MPPT method are established with the MATLAB based model for simulation. The simulation results illustrate the effectiveness and robustness of the proposed method. Further, the proposed intelligent MPPT algorithm needs less constructed data, and no learning procedure so it can be easily implemented using a microcontroller in the future.

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