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MAXIMUM POWER POINT TRACKING ALGORITHMS FOR WIND ENERGY SYSTEM: A REVIEW

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ABSTRACT
This paper reviews and studies the state of the art available maximum power point tracking (MPPT) algorithms. Due to the nature of wind which is instantaneously changing, there is only one optimal generator speed desirable at any one time that ensures maximum energy is harvested from the available wind. Therefore, including a controller that is able to track the maximum peak regardless of any wind speed is essential. The available maximum power point tracking (MPPT) algorithms can be classified according to the control variable, namely with and without sensor, and also the technique used to locate the maximum peak. A comparison has been made on the performance of the selected MPPT algorithms based on various speed responses and the ability to achieve the maximum energy yield. The tracking performance is performed by simulating wind energy system using the MATLAB/Simulink simulation package. Besides that, a brief and critical discussion is made on the differences of available MPPT algorithms for wind energy system, followed by a conclusion.

Keywords: MPPT; Wind energy system; PMSG; Boost converter

1. INTRODUCTION

Wind energy systems as one of the renewable energy sources have gained popular demand over the past decade due to many factors such as the possibility of depletion of conventional energy sources, its high costs, as well as having negative effects on the environment. Wind energy is preferred because it is clean, pollution-free, inexhaustible and secure. Therefore, a wind energy generation system could be one of the significant candidates as an alternative energy source for the future. The amount of mechanical energy that can be extracted from the wind is not solely dependent on the wind speed, but also governed by the ratio of the rotational speed to wind speed. There is a specific optimal ratio for each wind turbine, which is called the optimal tip speed ratio (TSR) or λ_{opt}, at which the extracted power is maximum. As the wind speed is instantaneously varying, it is essential for the rotational speed to be variable to maintain the equality of the TSR to the optimal one at all times. In the operation of variable speed condition, a power electronic converter is essential to convert the variable-voltage-variable-frequency of the voltage-fixed-frequency that is suitable for the grid. References (Baroudi et al., 2007; Zhe et al., 2009) have discussed the different possible configurations of power electronic converters and electrical generators for variable speed wind turbine systems.

Among the electric generators, permanent magnet synchronous generator (PMSG) is preferred due to its high efficiency, reliability, power density; gearless construction, light weight, and self-excitation features (Li et al., 2010; Molina et al., 2010; Muyeen et al., 2010; Mena 2007). Controlling the PMSG to achieve the maximum power point (MPP) can be done by varying its load. In this regard, a boost converter is one of the possible solutions, where, by controlling the duty cycle of the converter the apparent load seen by the generator will be adjusted and thus, its output voltage and shaft speed. In addition to that, operating the boost converter in discontinuous conduction mode (DCM) and applying a power factor correction (PFC) technique contributes in total harmonic distortion (THD) reduction and increases the power factor (PF) of the wind power generator (Kawale and Dutt 2009; Carranza et al., 2010).

In order to determine the optimal operating point of the wind turbine, a maximum power point tracking (MPPT) algorithm is essential to be included in the system. Several MPPT algorithms have been proposed in the literature. Reference (Raza et al., 2010) has reviewed and criticized many published MPPT algorithms and concluded that the two methods described in (Hui and Bakhshai 2008) and (Kazmi et al., 2011) are the best solutions due to their adaptive tracking and self-tuning capability. References (Mirecki et al., 2004; Brahmi et al., 2009; AJ Mahdi et al., 2010) have compared some of the available MPPT for PMSG-based wind energy conversion system. This paper reviews the fundamentals of the available MPPT algorithms for wind energy system. In addition, a comparison of simulation results is made on the three selected MPPT techniques. Finally, a critical discussion is made, and a conclusion is drawn.

2. SYSTEM OVERVIEW

Figure 1 illustrates the schematic diagram of the proposed wind turbine system. The system supplies a resistive load and consists of wind turbine rotor, PMSG, rectifier and a boost converter.

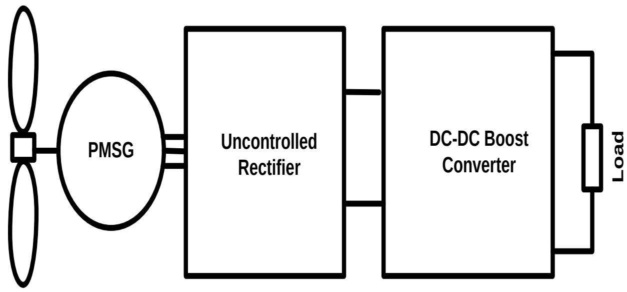


Figure 1 A brief block diagram of the proposed PMSG wind energy system

Wind turbine converts the wind energy at its input to a mechanical energy at the output, which in turn, runs a generator to generate electrical energy. The mechanical power generated by wind turbine can be expressed as (Freris 1990):

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

where ρ is the air density (kg/m^3), R is the turbine rotor (m), V_w is the wind speed (m/s), and C_p is the coefficient of performance. The turbine power coefficient, C_p describes the power extraction efficiency of the wind turbine (Grimble and Johnson 2008). It is a nonlinear function of both tip speed ratio, λ and the blade pitch angle, β. While its maximum theoretical value is approximately 0.59, it is practically between 0.4 and 0.45 (Zhe et al., 2009). The tip speed ratio is a variable expressing the ratio of the linear speed of the tip of blades to the rotational speed of wind turbine (Freris 1990).

$$\lambda = \frac{\omega_m R}{V_w} \tag{2}$$

Where ω_m is the mechanical angular velocity of the rotor measured in rad/s. There are many different versions of fitted equations for C_p made in the previous studies. This paper defines C_p as (Mena 2007):

$$C_p(\lambda,\beta) = 0.5\left(116\frac{1}{\lambda_i} - 0.4\beta - 5\right)e^{-\frac{21}{\lambda_i}} \tag{3}$$

$$\frac{1}{\lambda_i} = \frac{1}{\lambda + 0.08\beta} - \frac{0.035}{1+\beta^3} \tag{4}$$

In this paper, due to the assumption of a fixed pitch rotor, the β is set constant. Hence, the characteristics of the C_p mainly depend on the λ only. Fig. 2 presents the C_p as a function of the λ. Based on the figure, there is only one maximum point, denoted by the λ_{opt}, where the C_p is maximum. Continuous operation of wind turbine at this point guarantees the maximum available power can be harvested from the available wind at any speed, as shown in Fig. 3.

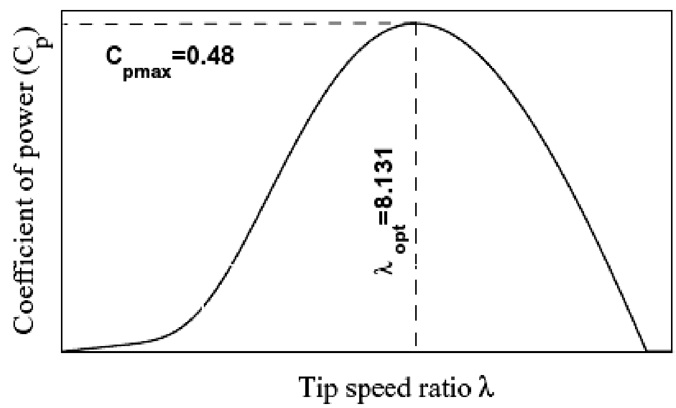


Figure 2 The characteristic of the power coefficient as a function of the tip speed ratio

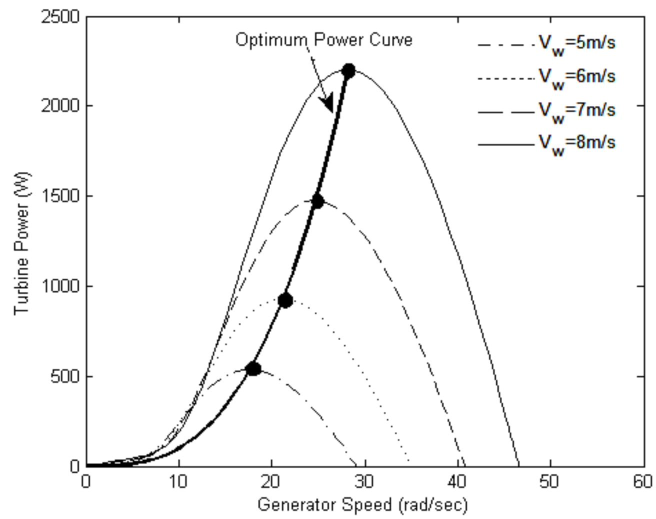


Figure 3 Characteristics of turbine power as a function of the rotor speed for a series of wind speeds

3. MPPT TECHNIQUES

A. Tip Speed Ratio Control

The optimal TSR for a given wind turbine is constant regardless of the wind speed. If the TSR is maintained constantly at its optimal value, this ensures that the energy extracted is in its maximum operating point too. Therefore, this method seeks to force the energy conversion system to work at this point continuously by comparing it with the actual value, represented in (2), and feeding this difference to the controller. That, in turn, changes the speed of the generator to reduce this error.

The optimal point of the TSR can be determined experimentally or theoretically and stored as a reference. This method is simple; however, it requires the measurement of wind speed consistently and accurately, which complicates its use in reality, as well as increases the system cost (Patel 1999; Barakati 2008; Wang, 2003).

B. Optimal Torque Control

As mentioned earlier, maintaining the operation of the wind turbine system at the λ_{opt} ensures that the maximum exploitation of the available wind energy be converted into mechanical energy. For the turbine power to be determined as a function of the λ and ω_m, equation (2) is re-written as the following equation in order to obtain the wind speed (Nakamura et al., 2002; Morimoto et al., 2005; Shirazi et al., 2009; Pucci and Cirrincione, 2011).

$$V_w = \frac{\omega_m R}{\lambda} \tag{5}$$

By substituting (5) into (1), the expression yields

$$\mathrm{P_m} = \frac{1}{2}\rho\pi R^5 \frac{\omega_m^3}{\lambda^3} C_p \tag{6}$$

If the rotor is running at the λ_{opt}, it will also run at the $C_{p\max}$. Thus, by replacing $\lambda = \lambda_{opt}$ and $C_p = C_{p\max}$ into (6), yields the following expression:

$$\mathrm{P_{m\text{-}opt}} = \frac{1}{2}\rho\pi R^5 \frac{C_{P\max}}{\lambda_{opt}^3}\omega_m^3 = K_{p-opt}\omega_m^3 \tag{7}$$

Considering that $P_m = \omega_m T_m$, the T_m can be plotted as in Fig. 4 and re-arranged as follows:

$$\mathrm{T_{m\text{-}opt}} = \frac{1}{2}\rho\pi R^5 \frac{C_{P\max}}{\lambda_{opt}^3}\omega_m^2 = K_{opt}\omega_m^2 \tag{8}$$

In general, this method is simple, very fast and efficient. However, the efficiency is lower as compared to the TSR control, since it does not measure the wind speed directly, which wind changes are not reflected instantaneously and significantly on the reference signal (Raza et al., 2010).

C. Power Signal Feedback Control

The block diagram of a wind energy system with power signal feedback (PSF) control is shown in Fig. 5. Unlike the OT control, in this method the reference maximum power curves of the wind turbine, Fig. 3, should be obtained first from the experimental results. Then, the data points for maximum output power and the corresponding wind turbine speed must be recorded in a lookup table (Tan and Islam 2004; Barakati 2008; Barakati et al., 2009). Instead of using the wind turbine maximum power versus shaft speed curve in obtaining the lookup table as (Barakati 2008), the maximum DC output power and the DC-link voltage were taken as input and output of the lookup table in (Quincy and Liuchen 2004). According to (Raza et al., 2010), there is no difference between the PSF and the OT method in terms of the performance and the complexity of implementation.

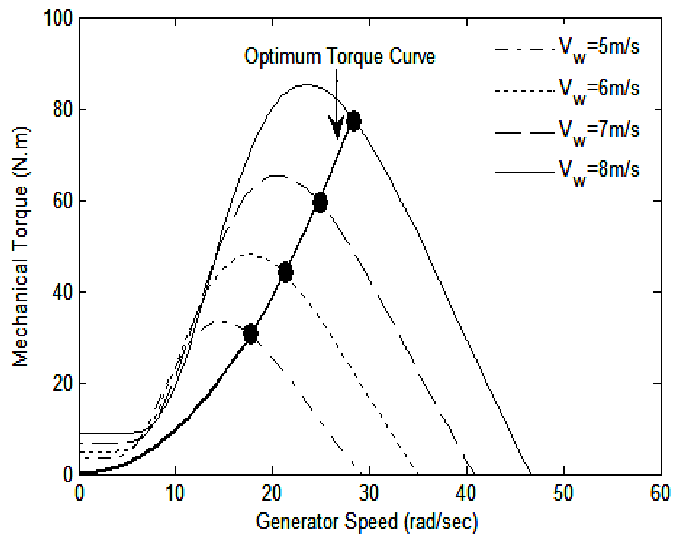


Figure 4 The torque-speed characteristic curve for a series of wind speeds

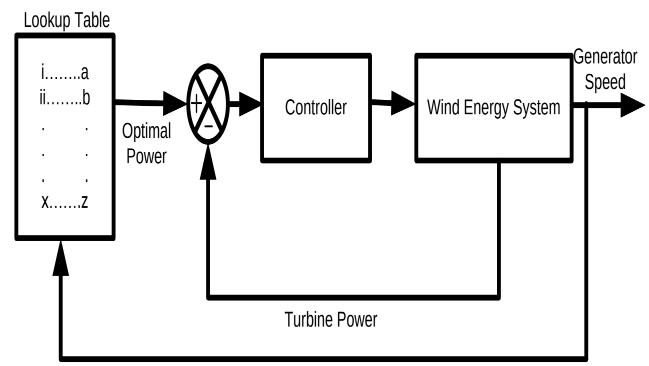


Figure 5 The block diagram of a wind energy with the power signal feedback control technique

D. Perturbation and Observation Control

The perturbation and observation (P&O) or hill-climb searching (HCS) method is a mathematical optimization technique used to search for the local maxima points of a given function. It is widely used in wind energy systems to get the optimal operating point that maximizes the extracted energy. This method is based on perturbing a control parameter in small step-size and observing the resulting changes in the target function, until the slope becomes zero. As shown in Fig. 6, if the operating point is to the left of the peak point, the controller must move the operating point to the right to be closer for the MPP, and vice versa if the operating point is on the other side. In literature, some authors perturb the rotational speed and observe the mechanical power. There are also others who monitor the electrical output power of the generator and perturb the inverter input voltage (Quincy and Liuchen 2004), or one of the variables of the converter; namely duty cycle, d (Koutroulis and Kalaitzakis 2006; Patsios et al., 2009; Hua and Cheng 2010), input current, I_{in} (Neammanee et al., 2006), or input voltage, V_{in} (Kesraoui et al., 2010). In methods that used electrical power measurement, the mechanical sensors are not required, and thus, they are more reliable and cost less.

Since the P&O method does not need a prior knowledge of the wind turbine characteristic curve, 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, on the other hand, smaller step-size improves the efficiency but slows the convergence speed (Ching-Tsai and Yu-Ling 2010; Hong and Lee 2010; Kazmi et al. 2011).

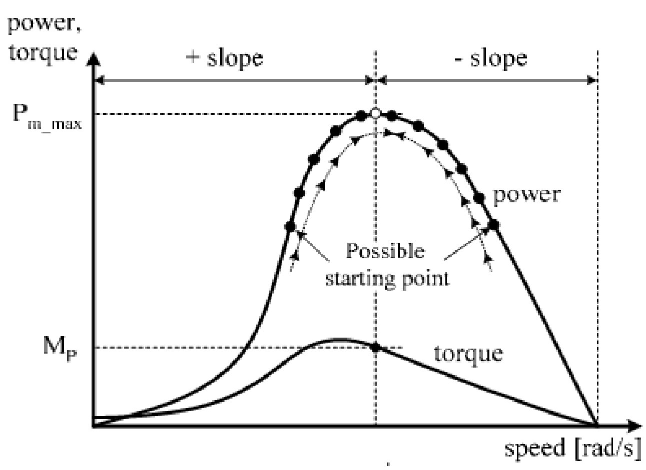


Figure 6 Wind turbine output power and torque characteristics with MPP tracking process (Neammanee et al., 2006)

E. Other methods

Many of the problems associated with the aforementioned methods have been solved by means of artificial intelligence control and hybrid methods. According to (Simoes et al., 1997), fuzzy logic control methods have the advantages of fast convergence, parameter insensitivity, and accepting noisy and inaccurate signals. They can also be used to obtain an optimal step size for conventional HCS method, as in (Trinh and Lee 2010). Wind speed measurement and its associated drawbacks have been solved by using neural network technique to estimate the wind speed depending on actual machine torque and speed (Lee et al. 2009; Pucci and Cirrincione 2011). The proposed control structure, Wilcoxon radial basis function network (WRBFN)-based with HCS MPPT strategy and modified particle swarm optimization (MPSO) algorithm, in (Lin and Hong 2010) diminish the effect of the wind turbine inertia on HCS method performance.

Hybrid method is the combination of two methods from the aforementioned ones; to exploit the advantages of one technique to overcome the disadvantage of the other. An example of this method is that in (Kazmi et al. 2011) where OTC method is merged with HCS to solve the two problems associated with the conventional HCS, the speed-efficiency trade-off and the wrong directionality under rapid wind change. Another example is combining PSF control and HCS in (Quincy and Liuchen 2004) to develop a sensor less and flexible method which is also applicable to all wind turbine levels.

4. SIMULATION RESULTS AND DISCUSSIONS

The performance of three MPPT control methods has been simulated and compared using the MATLAB/Simulink simulation package. The studied MPPT methods are: OTC, P&O of the duty cycle of the boost converter, and P&O of the input voltage of the boost converter. All the simulations were carried out with system parameters as (Mena, 2007). The load resistance, R is 20 Ω for all simulations. The step-sizes in P&O of the duty cycle and the input voltage were fixed at 0.5×10^{-3} and 0.001, respectively. The obtained performance with the different methods is shown in Fig. 8 and the results are also summarized in Table 1. According to the plot and result's analysis, the OTC controller is the fastest in achieving the steady-state and also in the recovery time upon wind speed change. In addition, the OTC method can reach the highest value of C_p and maintained the same value after the wind speed change. It is followed by the P&O in input voltage method, which took approximately double the time to reach the steady-state, with the C_p average of 0.4607. The slowest and less efficient one is the P&O in duty-cycle method, where the response time is eight times the first method, 0.02142. After being 0.46 before the wind speed step change, $C_{p\max}$ decreased to 0.42 when the step change occurred. Since the used perturbation and observation methods are the conventional ones, with a fixed step-size, the ripples of C_p changed under wind speed variations. In Fig. 9, the generator's output power for each method is depicted. While the generator's output power for the first two methods stabilized at the same time, 0.025 sec., it needed 0.175 sec more time for the third one. Taking the maximum mechanical input energy of the generator as a reference and measuring the electrical energy output of the generator under the selected methods, the efficiencies can be calculated, as listed in Table 1.

Table 1 Simulated Results: Power Coefficient Average Values, Response Times, Recovery Times; Energy and Efficiency

Method	Median	Response time (sec.)	Recovery time (sec.)	Energy (W)	Efficiency (%)
Max. theoretical value (reference)	0.48	--	--	734.5	--
OTC	0.4789	0.02488	0.0006	665.9	90.66
P&O of input voltage	0.4607	0.053	0.0014	645.9	87.94
P&O of duty-cycle	0.3956	0.2142	0.022	597.4	81.33

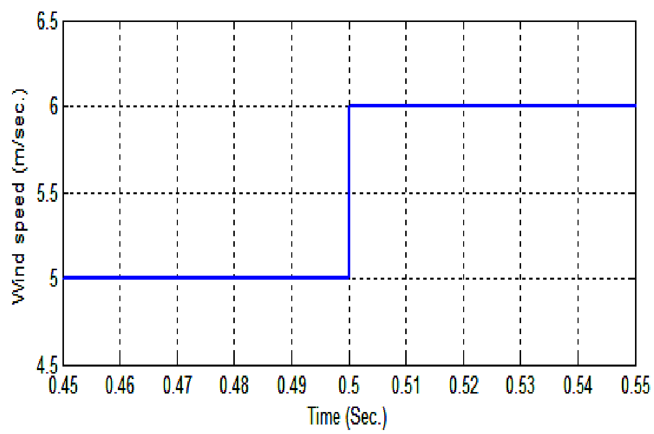
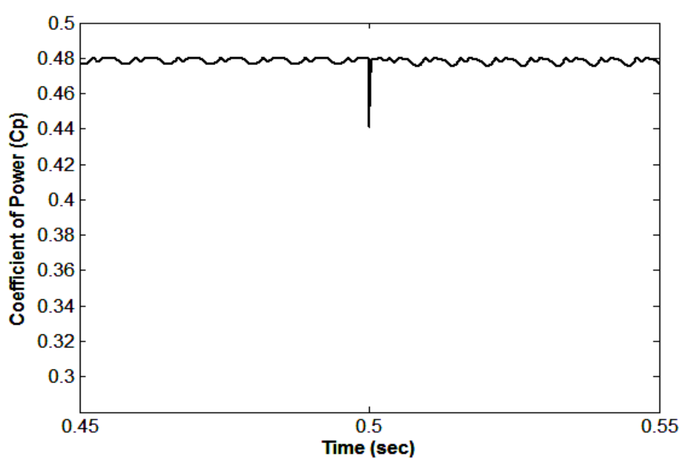
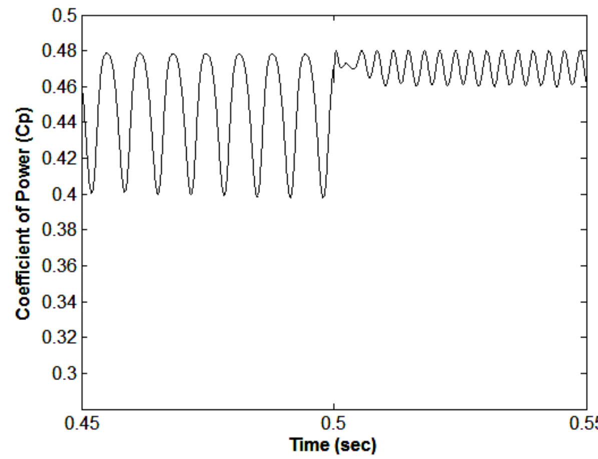


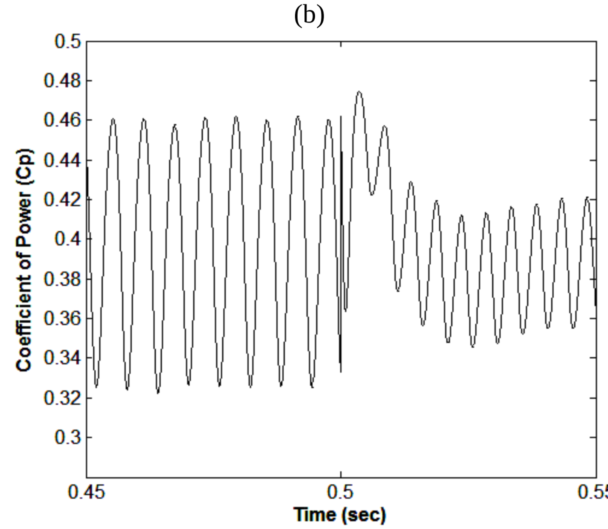
Figure 7 The wind speed



(a)

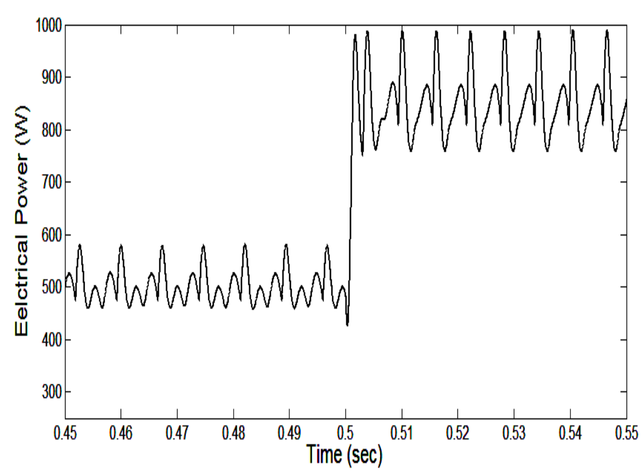


(b)

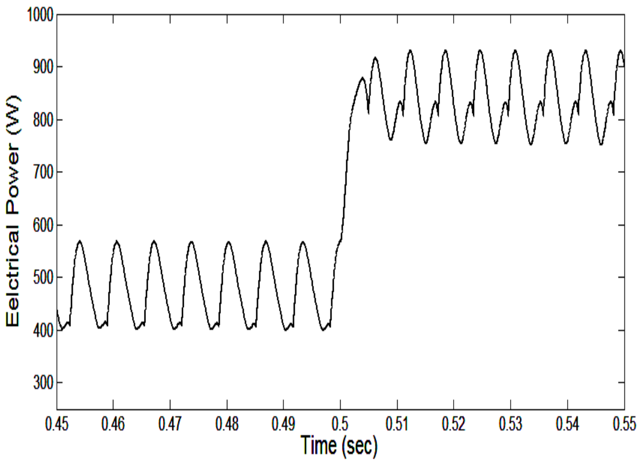


(c)

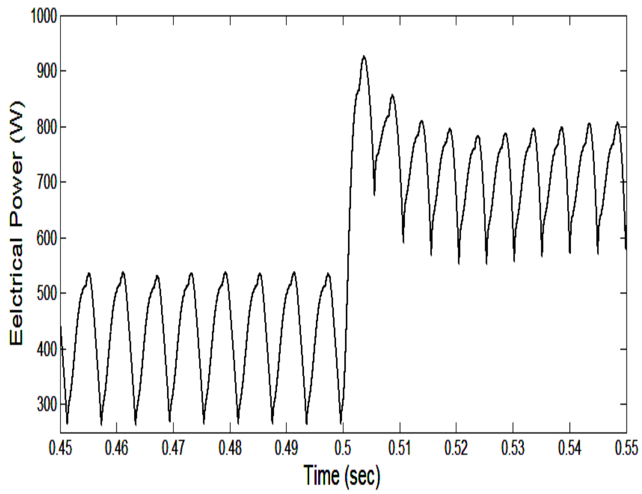
Figure 8 The power coefficient with: (a) OTC method (b) P&O of input voltage (c) P&O of duty cycle



(a)



(b)



(c)

Figure 9 The output power response produced by the PMSG generator with : (a) OTC method (b) P&O of input voltage (c) P&O of duty cycle

5. CONCLUSION

This paper discusses and reviews the available MPPT algorithms. In addition, simulation and comparison of selected three control methods in terms of the efficiency and speed of response were made. Simulation results demonstrate superiority of OTC method; where it obtained the maximum average value of C_p and held it at its maximum even with wind speed change. Nevertheless, its dependency on the wind turbine characteristics makes it inflexible. On the other hand, P&O method is flexible and simple in implementation, but it is less efficient and has a difficulty in determining the optimum step-size. Comparing the perturbation in duty cycle, perturbation of the input voltage to get a reference voltage is better, as there is a controller to force the input voltage to track the reference. Finding out an adaptive step-size algorithm and combining two or more of the available methods will improve the performance and overcome some of the obstacles of the current methods.

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