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A review of maximum power point tracking algorithms for wind energy systems

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ABSTRACT

This paper reviews state of the art maximum power point tracking (MPPT) algorithms for wind energy systems. Due to the instantaneous changing nature of the wind, it is desirable to determine the one optimal generator speed that ensures maximum energy yield. Therefore, it is essential to include a controller that can track the maximum peak regardless of wind speed. The available MPPT algorithms can be classified as either with or without sensors, as well as according to the techniques used to locate the maximum peak. A comparison has been made between the performance of different MPPT algorithms on the basis of various speed responses and ability to achieve the maximum energy yield. Based on simulation results available in the literature, the optimal torque control (OTC) has been found to be the best MPPT method for wind energy systems due to its simplicity. On the other hand, the perturbation and observation (P&O) method is flexible and simple in implementation, but is less efficient and has difficulties determining the optimum step-size.

Contents

1. Introduction

Wind energy systems have gained tremendous attention over the past decade as one of the most promising renewable energy sources due to the probable depletion, high costs, and negative environmental impacts of conventional energy sources. Wind energy is a pollution-free and inexhaustible source. Therefore, a wind energy generation system could be one of the potential sources of alternative energy for the future [1,2]. In Malaysia, numerous research studies have been conducted in the area of renewable energy, which include economic feasibility studies in renewable energy utilization, such as PV-diesel system [3] and PV-wind-diesel [4].

Wind turbines are controlled to operate only in a specified range of wind speeds bounded by cut-in ($V_{cut\text{-}in}$) and cut-out ($V_{cut\text{-}out}$) speeds. Beyond these limits, the turbine should be stopped to protect both the generator and turbine. Fig. 1 shows the typical power curve of a wind turbine [5,6]. From the figure, it can be observed that there are three different operational regions. The first is the low-speed region, where the turbine should be stopped and disconnected from the grid to prevent it from being driven by the generator [7]. The second is the moderate-speed region that is bounded by the cut-in speed at which the turbine starts working, and the rated speed (V_{rated}), at which the turbine produces its rated power. The turbine produces maximum power in this region, as

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Nomenclature

$V_{\text{cut-in}}$	cut in wind speed (m/s)
$V_{\text{cut-out}}$	cut out wind speed (m/s)
V_{rated}	rated wind speed (m/s)
λ, TSR	tip speed ratio
λ_{opt}	optimal tip speed ratio
PMSG	permanent magnet synchronous generator
MPP	maximum power point
DCM	discontinuous conduction mode
PFC	power factor correction
THD	total harmonic distortion
MPPT	maximum power point tracking
ρ	air density (kg/m^3)
V_w	wind speed (m/s)
C_p	power coefficient
β	blade pitch angle (degree)
ω_m	mechanical angular velocity of the rotor (rad/s)
R	turbine radius (m)
$C_{p\max}$	maximum coefficient of power
P_m	mechanical power of the turbine (kW)
T_m	mechanical torque of the turbine (N m)
PSF	power signal feedback
P&O	perturbation and observation
HCS	hill climb searching
d	duty cycle of the converter
I_{in}	input current of the converter (A)
V_{in}	input voltage of the converter (V)
ω	generator speed (rad/s)
ω^*	optimal generator speed (rad/s)
α	constant scaled factor
V_{ref}	input voltage reference of the converter (V)
V_{dc}	output voltage of the rectifier (V)
WRBFN	Wilcoxon radial basis function network
MPSO	modified particle swarm optimization
OTC	optimal torque characteristics

it is controlled to extract the available power from the wind. In the high speed region (i.e., between V_{rated} and $V_{\text{cut-out}}$), the turbine power is limited so that the turbine and generator are not overloaded and dynamic loads do not result in mechanical failure [7,8]. It is noteworthy that to protect the turbine from structural overload, it should be shut down above the cut-out speed. This paper focuses on the moderate-speed region, where the maximum power point tracking (MPPT) algorithm is needed.

Although the speed of the wind turbine could be fixed or variable, maximization of the extracted energy is achievable with variable speed wind turbines only. Since these turbines can change their rotational speed to follow instantaneous changes in wind speed, they are able to maintain a constant rotational speed to wind speed ratio [9]. It can be noted that there is a specific ratio called the optimum tip speed ratio (TSR) for each wind turbine for which the extracted power is maximized [1]. As the wind speed is instantaneously changing, it is necessary for the rotational speed to be variable to maintain the optimal TSR at all times. To operate in variable-speed conditions, a wind energy system needs a power electronic converter to convert the variable-voltage–variable-frequency of the generator into a fixed-voltage–fixed-frequency that is suitable for the grid [10–13]. In addition to increasing the energy capture, variable-speed turbines can be controlled to reduce the load on the drive-train and tower structure, leading to potentially longer installation life [8]. Researchers [10,14,15] have discussed the different possible configurations of power converters and electrical generators for variable-speed wind turbine systems.

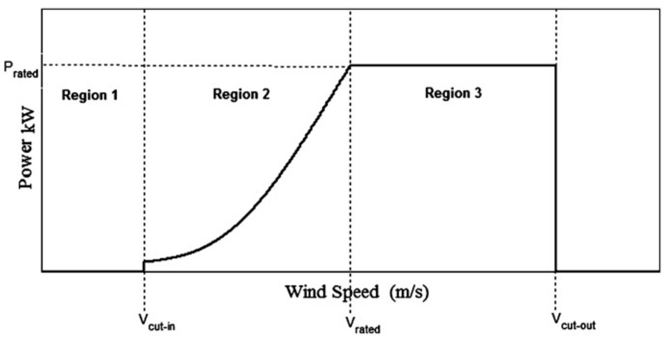

Fig. 1. Ideal power curve of a wind turbine.

Among electric generators, the permanent magnet synchronous generator (PMSG) is preferred due to its high efficiency, reliability, power density, gearless construction, light weight, and self-excitation features [16–20]. Controlling the PMSG to achieve the maximum power point (MPP) can be done by varying its load using a power electronic interface circuit. The interfacing can be done by a back-to-back converter or by a three-phase diode rectifier connected to a boost converter. According to Zhipeng et al. [20], using a rectifier and a boost converter is less expensive and more reliable. By controlling the duty cycle of the converter, the apparent load developed by the generator can be adjusted, and thus, its output voltage and shaft speed can also be adjusted. In addition, operating the boost converter in discontinuous conduction mode (DCM) and applying a power factor correction (PFC) technique contributes to a total harmonic distortion (THD) reduction and increases the power factor (PF) of the wind-power generator [21,22].

In order to determine the optimal operating point of the wind turbine, including a MPPT algorithm in the system is essential. Much has been written on the topic of MPPT algorithms, especially for wind energy systems. Raza Kazmi et al. [23] reviewed many published wind MPPT algorithms and concluded that the two methods described in Hui and Bakhshai [24] and Kazmi et al. [25] are the best solution due to their adaptive-tracking and self-tuning capabilities. Studies [1,26–28] have compared some of the wind MPPT algorithms particularly for PMSG driven wind turbines. Musunuri and Ginn Iii [29] categorized the available MPPT algorithms into nine groups based on the specified performance and measurement requirements. The authors also reported that there is an increasing trend of MPPT algorithm use among researchers over the past decade. Therefore, recent trends in the proposed wind MPPT technology should be reviewed and compiled. To the best of the current authors' knowledge, there is limited peer-reviewed literature on the MPPT algorithms for wind energy systems. This review complied and analyzed recently developed MPPT algorithms especially for wind energy systems, particularly the PMSG integrated with boost converter. The fundamentals of the available MPPT algorithms for wind energy systems are also reviewed and revised.

2. System overview

Fig. 2 illustrates the schematic diagram of the reviewed wind turbine system. The system supplies a resistive load and consists of a wind turbine rotor, PMSG, rectifier, and a boost converter.

Wind turbine converts the wind energy into mechanical energy, which then runs a generator to create electrical energy. The mechanical power generated by a wind turbine can be expressed as [30–32]:

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

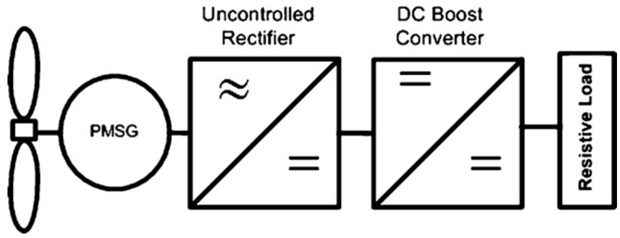

Fig. 2. A brief block diagram of the proposed PMSG wind-energy system [1].

The turbine power coefficient (C_p) describes the power extraction efficiency of the wind turbine [33]. It is a nonlinear function of both the tip speed ratio (λ) and the blade pitch angle (β). While its maximum theoretical value is approximately 0.59, in practicality it lies between 0.4 and 0.45 [15]. The tip speed ratio is a variable expressing the ratio of the linear speed of the blade tips to the rotational speed of the wind turbine [30–32], and can be expressed by Eq. (2):

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

Many different versions of fitted equations for C_p have been used in previous studies. This paper defined C_p based on the following [18]:

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

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

In the present work, due to the assumption of a fixed pitch rotor, the angle (β) is set to zero. Hence, the characteristics of C_p mainly depend on λ. Fig. 3 presents C_p as a function of λ. According to the figure, there is only one optimal point, denoted by λ_{opt}, where C_p is maximum. Continuous operation of the wind turbine at this point guarantees that it will obtain the maximum available power from the wind at any speed, as shown in Fig. 4.

3. MPPT techniques

3.1. Tip speed ratio (TSR) control

The optimal TSR for a given wind turbine is constant regardless of wind speed. If TSR remains constantly at the optimal value, it is guaranteed that the extracted energy will be maximized. Therefore, this method seeks to force the energy conversion system to remain at this point by comparing it with the actual value 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. Although this method seems simple as wind speed is directly and continuously measured, a precise measurement for wind speed is impossible in reality and increases the cost of the system [23,34–38]. The block diagram of the tip speed ratio control method is shown in Fig. 5.

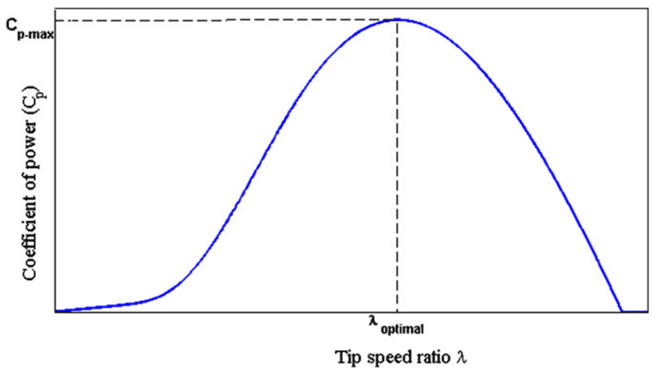

Fig. 3. The characteristic of the power coefficient as a function of tip speed ratio.

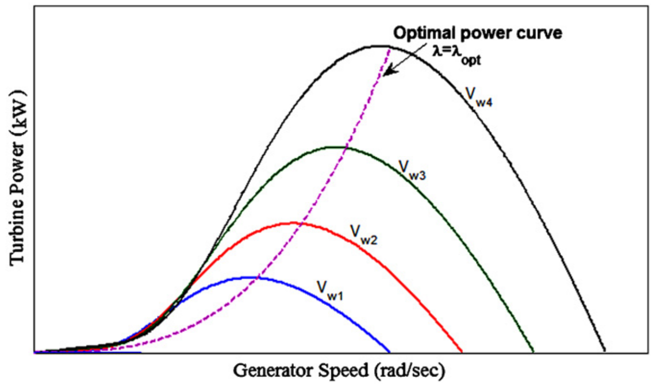

Fig. 4. Characteristics of turbine power as a function of the rotor speed for a series of wind speeds.

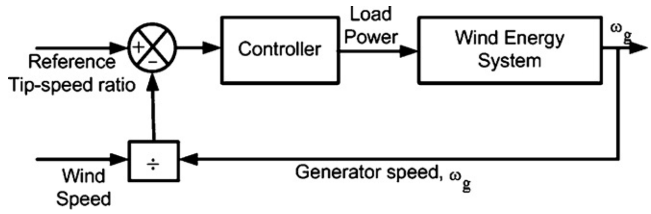

Fig. 5. The block diagram of the tip speed ratio control [1].

3.2. Optimal torque (OT) control

As mentioned previously, maintaining the operation of the system at λ_{opt} ensures the conversion of available wind energy into mechanical form. It can be observed from the block diagram, represented in Fig. 6, that the principle of this method is to adjust the PMSG torque according to a maximum power reference torque of the wind turbine at a given wind speed. For the turbine power to be determined as a function of λ and ω_m, Eq. (2) is rewritten in the following form in order to obtain the wind speed [39–42]:

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

By substituting Eq. (5) into Eq. (1), the expression yields:

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

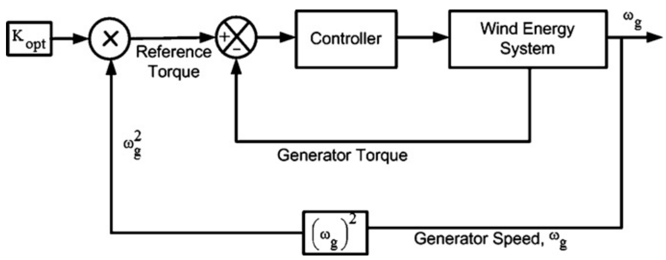

Fig. 6. The block diagram of optimal torque control MPPT method [1].

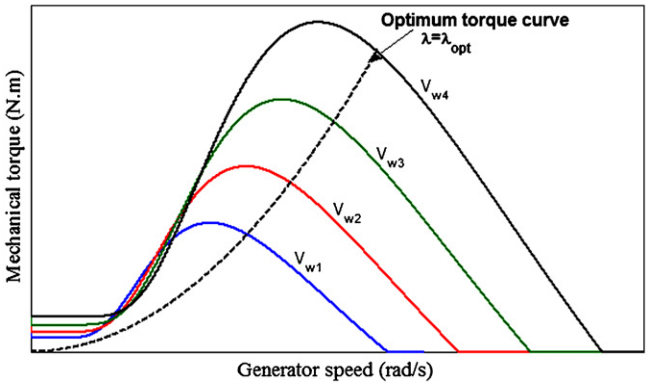

Fig. 7. The torque–speed characteristic curve for a series of wind speeds.

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

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

Considering that $P_m = \omega_m T_m$, T_m can be rearranged as follows:

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

It is a torque-control-based method, where the analytical expression of the optimum torque curve, represented by Eq. (8) and Fig. 7, is given as a reference torque for the controller that is connected to the wind turbine.

In general, this method is simple, fast, and efficient. However, efficiency is lower compared to that of TSR control method, because it does not measure the wind speed directly, meaning that wind changes are not reflected instantaneously and significantly on the reference signal [23].

3.3. Power signal feedback (PSF) control

The block diagram of a wind energy system with power signal feedback (PSF) control is shown in Fig. 8. Unlike the OT control, in this method the reference optimum power curve of the wind turbine (Fig. 4) 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 [43–45].

Rather than using the wind turbine's maximum power versus shaft speed curve to populate the lookup table as in Masoud [43], the maximum DC output power and the DC-link voltage were taken as input and output of the lookup table in Quincy and Liuchen [46]. According to Raza Kazmi et al. [23], there is no difference between the PSF and the OT methods in terms of performance and the complexity of implementation.

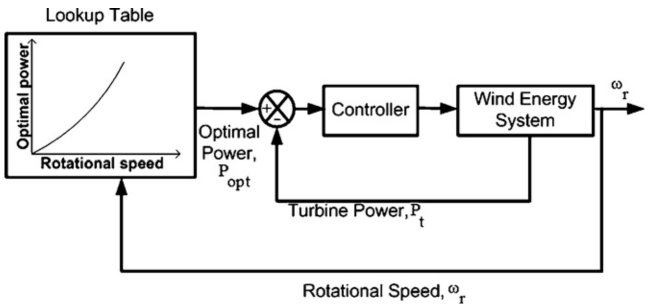

Fig. 8. The block diagram of a wind energy system with the power signal feedback control technique [1].

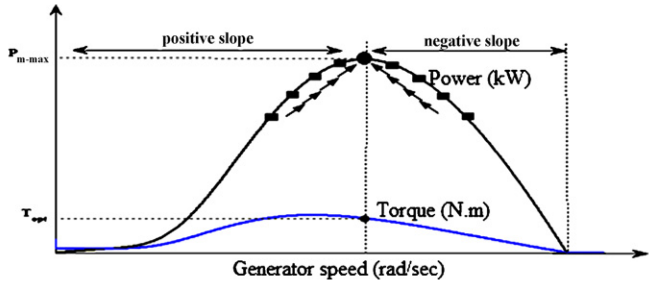

Fig. 9. Wind turbine output power and torque characteristics with MPP tracking process.

3.4. Perturbation and observation (P&O) control

The perturbation and observation (P&O), or hill-climb searching (HCS) method, is a mathematical optimization technique used to search for the local optimum point of a given function. It is widely used in wind energy systems to determine the optimal operating point that will maximize the extracted energy. This method is based on perturbing a control variable in small step-size and observing the resulting changes in the target function until the slope becomes zero. As shown in Fig. 9, if the operating point is to the left of the peak point, the controller must move it to the right to be closer to the MPP, and vice versa if it is on the other side. In the available literature, some authors perturbed the rotational speed and observed the mechanical power, while others monitored the output power of the generator and perturbed the inverter input voltage [46] or one of the converter variables, namely: duty cycle, d [47–51]; output current, I_{in} [52]; or input voltage, V_{in} [53]. In electrical power measurement, the mechanical sensors are not required, and thus they are more reliable and low-cost.

Since the P&O method does not require prior knowledge of the wind turbine's characteristic curve, it is independent, simple, and flexible. However, it fails to reach the maximum power points under rapid wind variations if used for large and medium inertia wind turbines. Additionally, choosing an appropriate step-size is not an easy task: though larger step-size means a faster response and more oscillations around the peak point, and hence, less efficiency, a smaller step-size improves efficiency but reduces the convergence speed [25,54,55], as shown in Fig. 10. In addition, initialization of the parameters significantly affects the system's performance [56]. The HCS method is also influenced by the value of the capacitance of the converter output capacitor, where a larger capacitance reduces the system's speed of response [57].

One major drawback that can lead to the failure of the tracking process is the lack of distinction between the power differences resulting from the change in the wind with those resulting from the change in the previous perturbation [25]. Fig. 11 demonstrates how indistinct differences in power can result in a wrong decision in determining the direction of the next step. Despite the presence of the peak on the left, the actual decision made was to move toward the right side of the curve, which meant moving further away from the peak and consequently decreasing the efficiency.

To improve the efficiency and the accuracy of the conventional P&O method, modified variable step-size algorithms have been proposed [25,48,49,52,53,56,58,59]. In adaptive step-size methods, the step-size is automatically updated according to the operating point. If the system is working on a certain point that is far from the peak, the step-size should be increased to speed up the tracking process. Conversely, the action is reversed to decrease the step-size when the operating point nears the MPP. The step-size is continually

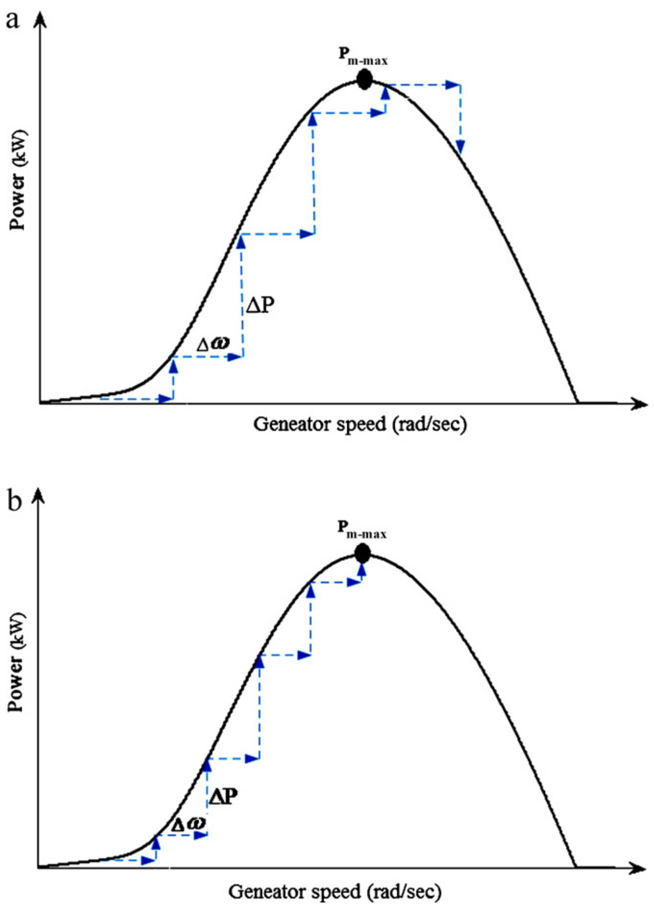

Fig. 10. HCS control (a) larger perturbation and (b) smaller perturbation.

decreased until it approaches zero in order to drive the operating point to settle down exactly at the peak point. This working principle reduces the oscillations that occur in the conventional P&O method, accelerates the speed to reach the maximum, and lowers the time needed for tracking.

In the literature, the controlling rule for adjusting the step-size varies from one group of studies to another, depending on the perturbed variable. Some studies [25,48,49,56,58,59] used the duty cycle of the converter as an input control to the system. In others, the load current [52] or the input voltage [53] were used as control inputs. In the studies [25,56], the distance from the current

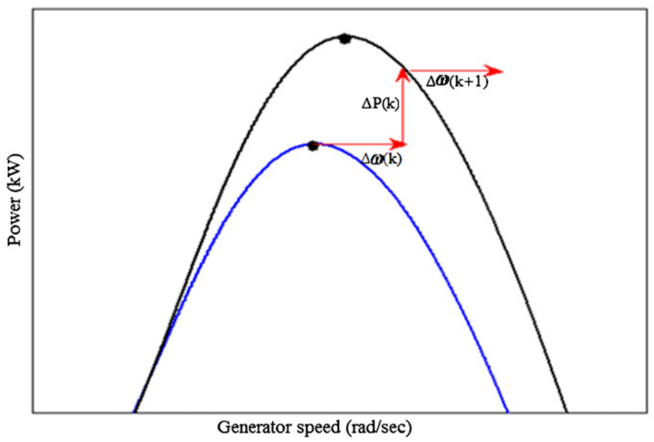

Fig. 11. The HCS control losing its trackability under changing wind conditions and traveling downhill instead of the uphill climb [23].

generator speed (ω) to the optimal speed (ω^*), which is determined from the optimal power curve, was used to adjust the perturbation size periodically at the end of each cycle as follows:

$$d(k+1) = d(k) + \alpha(\omega - \omega^*) \tag{9}$$

However, the perturbation size can be selected based on the scaled measure of the slope of power with respect to the converter's duty ratio [48,49]:

$$d(k+1) = d(k) + \alpha\frac{\Delta P(k)}{\Delta D(k)} \tag{10}$$

Syed et al. [58] used a dual step-size (d_{step}); one was a small perturbation (d_{min}) to be used when the operating point is close to the peak, while the other (d_{max}) was larger and used when the operating point is far from the peak:

$$d(k+1) = d(k) + d_{step}\cdot sign\{\Delta d(k)\}\cdot sign\{\Delta P(k)\} \tag{11}$$

In one study [52], the duty cycle was updated indirectly by changing the load current, and thus, the generator speed. The controlling rule is:

$$i_{ref}(k+1) = \Delta i_{ref}(k) + \alpha\frac{\Delta P(k)}{\Delta\omega(k)} \tag{12}$$

Similarly, in another study [53], the duty ratio was indirectly modified by changing the input voltage of the converter depending on the slope of the power with respect to the input voltage:

$$\begin{cases} V_{ref}(k+1) = V_{ref}(k) + \dfrac{\Delta P(k)}{\Delta Slope(k)} \\ Slope(k) = \dfrac{\Delta P(k)}{\Delta V_{dc}(k)} \end{cases} \tag{13}$$

3.5. Other methods

Many of the problems associated with the aforementioned methods have been solved by artificial intelligence control and hybrid methods. According to one study [60], the fuzzy logic control method has the advantages of fast convergence, parameter insensitivity, and acceptance of noisy and inaccurate signals. This method can also be utilized to obtain an optimal step-size for the conventional HCS method [9,61]. Wind speed measurement and its associated drawbacks have been resolved using neural network techniques to estimate the wind speed depending on actual machine torque and speed [41,62]. The control structure, Wilcoxon radial basis function network (WRBFN)-based with HCS MPPT strategy and modified particle swarm optimization (MPSO) algorithm presented in Lin et al. [63], diminishes the effect of the wind turbine inertia on HCS method performance.

A hybrid method is the combination of two methods that exploits the advantages of one technique to overcome the disadvantages of the other. An example of these methods was proposed by Kazmi [25], where the OTC method was merged with HCS to solve the two problems associated with conventional HCS: speed-efficiency trade-off and wrong directionality under rapid wind change. Another example was the combining of PSF control and HCS by Quincy and Liuchen [46] to develop a sensorless and flexible method that is applicable to all wind turbine levels.

4. Review results and discussion

The performance of three MPPT control methods is presented in Table 1 as carried out by Abdullah et al. [1]. The simulated system diagram is shown in Fig. 12. The studied MPPT methods were OTC, P&O of the duty cycle of the boost converter, and P&O of the input voltage of the boost converter. Simulations were carried out with system parameters as in Mena Lopez [18]. The load resistance was considered to be 20 Ω for all simulations. The step-sizes in P&O of

Table 1
Summary of performance of three algorithms [1].

Method	Median	Response time (s)	Recovery time (s)	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

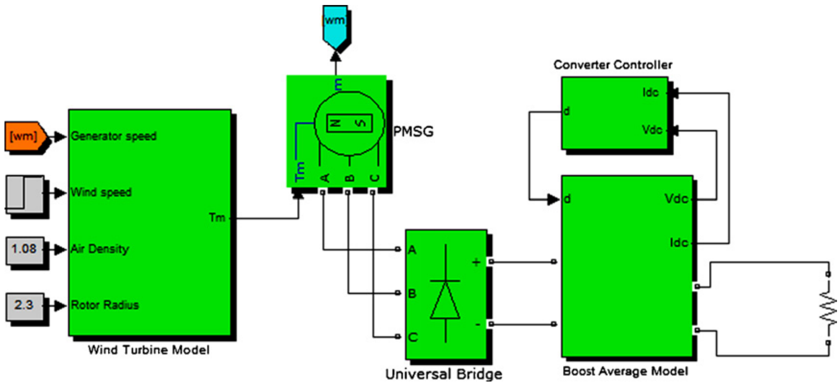

Fig. 12. The simulated system diagram [1].

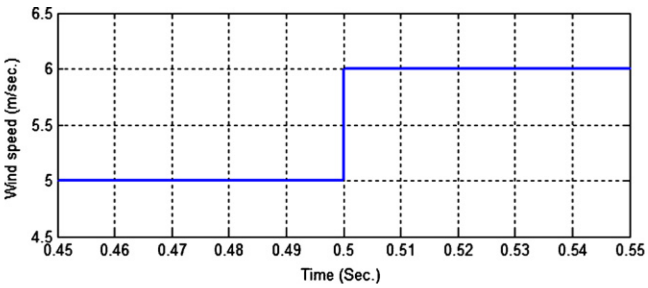

Fig. 13. A step change in wind speed [1].

the duty cycle and the input voltage were fixed at 0.5×10^{-3} and 0.001 V, respectively.

For the wind changes depicted in Fig. 13, the obtained performance from the different methods is shown in Fig. 14, and the results are summarized in Table 1 as well. Based on results and analysis, the OTC controller was found to be the fastest in achieving the steady-state. The recovery time upon wind speed change was also faster for this algorithm. In addition, the OTC method reached the highest value of C_p and maintained that value even after the change in wind speed. It was followed by the P&O in input voltage method, which took almost twice the time needed to reach the steady-state, with the average value of C_p being 0.4607. The P&O duty-cycle method was found to be the slowest and least efficient method, as the response time was eight times longer than the

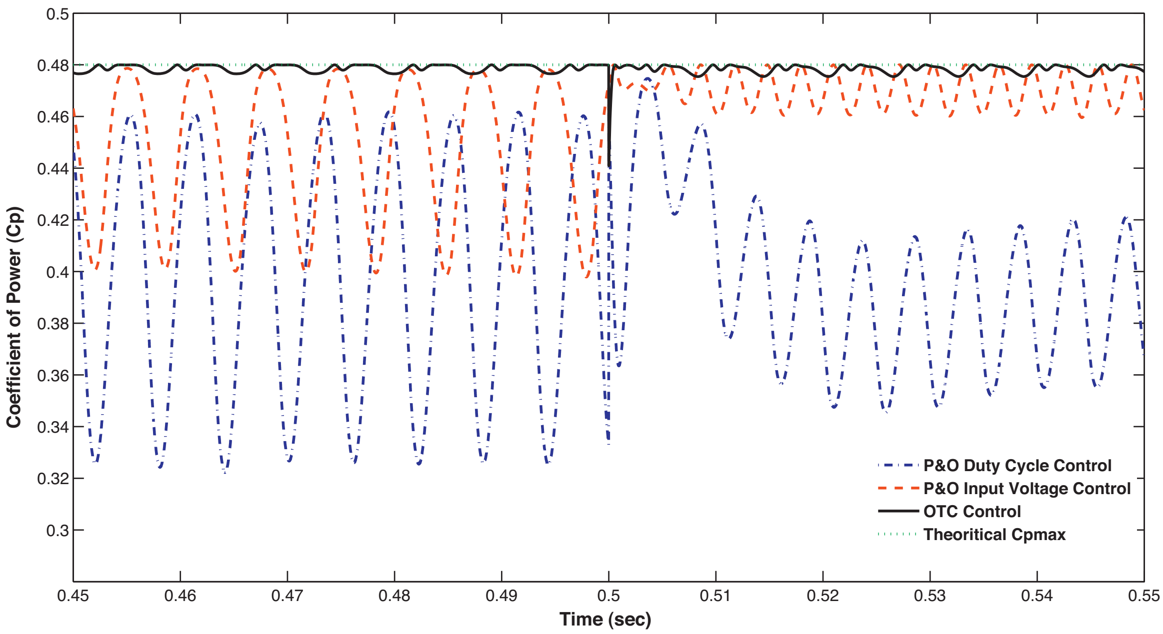

Fig. 14. The power coefficient [1].

Table 2
Comparison of characteristics of various MPPT methods [29].

Technique	Complexity	Convergence speed	Prior training/knowledge	Memory requirement	Wind speed measurement	Performance under varying wind conditions
Tip speed ratio control	Simple	Fast	No	No	Yes	Very good
Optimal torque control	Simple	Fast	Yes	No	No	Very Good
Power signal feedback control	Simple	Fast	Yes	Yes	Yes	Good
Perturbation and observation control	Simple	Depends	No	No	No	Good
Adaptive P&O control	High	Medium	No	No	No	Good
Other methods	High	Medium	Yes	Yes	No	Good

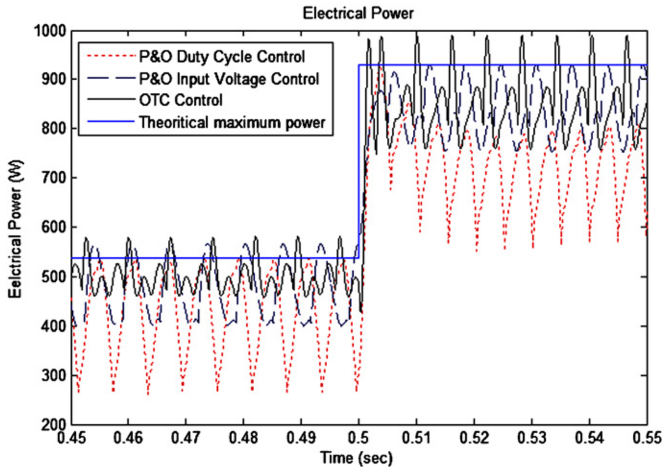

Fig. 15. The output power response produced by the PMSG generator [1].

first method. It was also found that P&O duty cycle method did not maintain the same value of $C_{p\,\max}$ all the time, as it decreased from 0.46 to 0.42 when a step change in the wind speed occurred. Since the conventional perturbation and observation methods were used with a fixed step-size, the ripples of the C_p changed under wind speed variations. Fig. 15 depicts the generator's output power for each method. As shown in the figure, while the first two methods were stabilized similarly in 0.025 s, 0.175 s more is needed for the third one. By 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 could be calculated as listed in Table 1.

As stated in Musunuri and Ginn Iii [29], there is some difficulty with choosing the appropriate MPPT algorithm for a given wind system. However, the main considerable aspects in selecting a particular MPPT strategy are represented in Table 2.

5. Conclusion

This paper reviewed and discussed the available MPPT algorithms for wind energy systems. In addition, the authors analyzed a simulation and comparison of three selected control methods in terms of efficiency and speed of response. Simulation results demonstrated the superiority of the OTC method in terms of simplicity and accuracy. This method obtained the maximum average value of C_p and maintained it at its maximum even with changes in wind speed. Nevertheless, its dependency on wind turbine characteristics made it inflexible. On the other hand, the P&O method is flexible and simple in implementation, but is less efficient and can be problematic in determining the optimum step-size. Compared to perturbation of the duty cycle, perturbation of the input voltage was found to be better in terms of accuracy and response time. Determining the adaptive step-size algorithms and combining two or more of the available methods will improve the performance and overcome some of the obstacles found in the current methods.

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