The compression of MPPT methods in small sized wind power plants

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Abstract

In this paper the maximum power point tracking (MPPT) algorithms for wind energy systems are reviewed. As the amounts of power produced in wind power plants is changing due to the instantaneous changing nature of the wind, it is desirable to determine the one optimal generator speed that ensures maximum energy yield. Thus, it is important to include a controller that can track the maximum peak regardless of wind speed. Categorizing the MPPT algorithms can be done regarding whether it has used sensors or not, as well as according to the techniques used to locate the peak value. The performance of different MPPT algorithms is compared on the basis of ability to achieve the maximum energy yield and various speed responses. According to available simulation results in the literature, in cases through which the flexibility and simplicity in implementations is considered, the perturbation and observation (P&O) method is preferred, but difficulties in determining the optimum step-size are the restrictions of this method. Due to its simplicity, the best MPPT method for wind energy systems has found to be the optimal torque control (OTC).

Keywords: MPPT, Wind power, PMSG, Boost converter

1. Introduction

Wind energy farms penetration into the existing power systems is rapidly increasing. Compared to the other renewable energy resources such as solar, geothermal etc., wind energy has received more attention with higher growth [1]. The remarkable advancements which have been reached during the past decade in wind power generation technology, along with the environmental issues pertaining to the fuel consuming power plants, have made the wind power one of the most economical resources for replacing the conventional power plants.[2,3]. Recently, 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 systems [4] and wind-diesel –PV [5]. Wind turbines are controlled to operate only in a specified range of wind speeds bounded by cut-in (V_{cut-in}) and cut-out ($V_{cut-out}$) 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 [6, 7]. From the figure, it can be observed that there are three different operational regions. The first is the low-speed region, in this region the turbine is prevented from driving the generator and is disconnected from the grid [8].

In the second region known as the moderate-speed, it is bounded by the cut-in speed at which the turbine starts working, and the rated speedV_{rated}, at which the turbine produces its rated power. The turbine produces maximum power in this region, as it is controlled to extract the available power from the wind. In the high speed region (i.e., between V_{rated} and $V_{cut-out}$), the turbine power is limited so that the turbine and the generator are not overloaded and dynamic loads do not result in mechanical failure [8, 9]. 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 required. 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 [10]. 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 [2]. 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 [11–14]. 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 a potentially longer installation life [9]. In [11, 15, 16] the different possible configurations of power converters and electrical generators for variable-speed wind turbine systems are discussed.

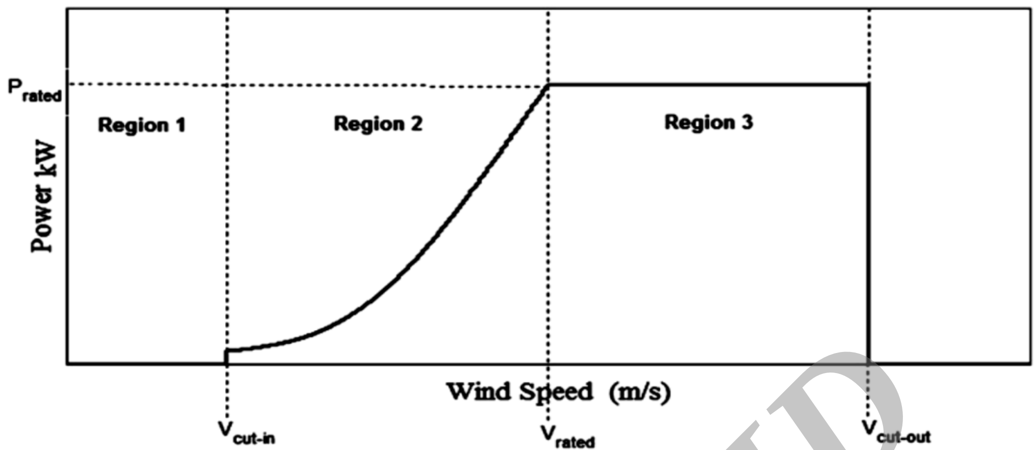

Fig.1. Ideal power curve of a wind turbine

From 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 [17–21]. 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. [21], 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. Also, by 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 it increases the power factor (PF) of the wind-power generator and contributes to a total harmonic distortion (THD) reduction [22,23].

It is crucial to include an MPPT algorithm in the system for determining the optimal operating point of the wind turbine. Much research has been done about MPPT algorithms, especially for wind energy systems. Raza Kazmi et al. [24] reviewed many published wind MPPT algorithms and concluded that the two methods described in Hui and Bakhshai [25] and Kazmi et al. [26] are the best solution due to their adaptive-tracking and self-tuning capabilities. Studies [2, 27–29] have compared some of the wind MPPT algorithms particularly for PMSG driven wind turbines. Musunuri and Ginn Iii [30] 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. The fundamentals of the available MPPT algorithms for wind energy systems are reviewed and revised and recently complied and analyzed developed MPPT algorithms especially for wind energy systems, particularly the PMSG integrated with boost converter are also discussed.

2. Topology of the system

The schematic diagram of the reviewed wind turbine system is illustrated in Fig. 2. 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. Wind turbine generates mechanical power that is obtained by [31–33]:

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

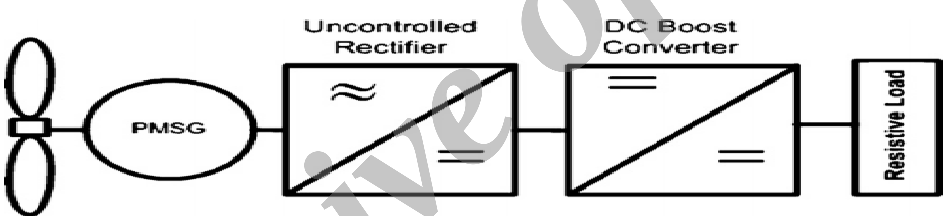

Fig. 2. A brief block diagram of the proposed PMSG wind-energy system [2]

To describe the power extraction efficiency of the wind turbine the turbine power coefficient (C_p) is used [34]. 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, practically it lies between 0.4 and 0.45 [16]. Eq. (2) is used for expressing the ratio of the linear speed of the blade tips to the rotational speed of the wind turbine [31–33], and is calculated as follows:

$$\lambda = \frac{\omega_m R}{V_w} \quad (2)$$

According to previous literatures various versions of fitted equations for $C_p$have been used. In this paper $C_p$based is calculated using following equation [19]:

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

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

As rotor pitch for this study assumed to be fixed, the angle (β) is considered to have zero amount. In this way, the characteristics of $C_p$mainly depend onλ. Fig. 3 presents C_p as a function ofλ. As shown in Fig. 4, there is only one optimal point, denoted byλ_{opt}, where $C_p$is maximum permanent operation of the wind turbine at this point guarantees that it will obtain the maximum available power from the wind at any speed.

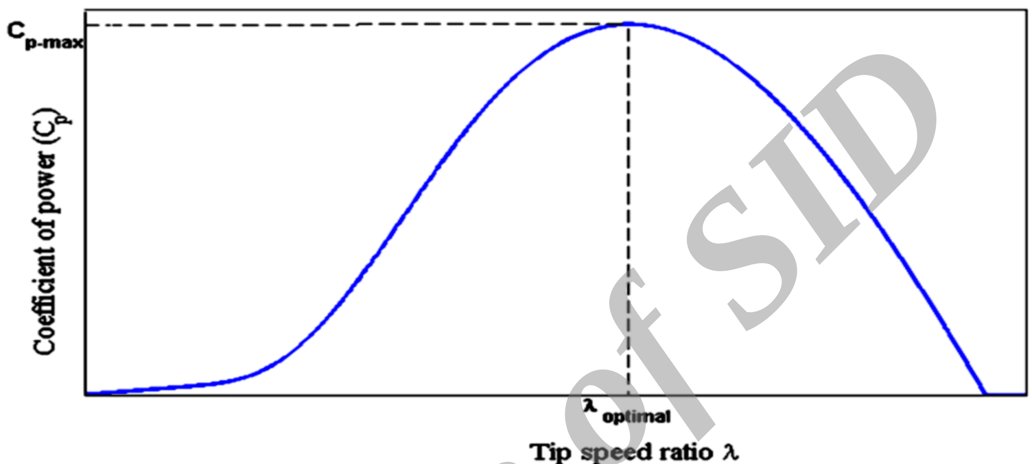

Fig. 3. The characteristic of the power coefficient as a function of tip speed ratio

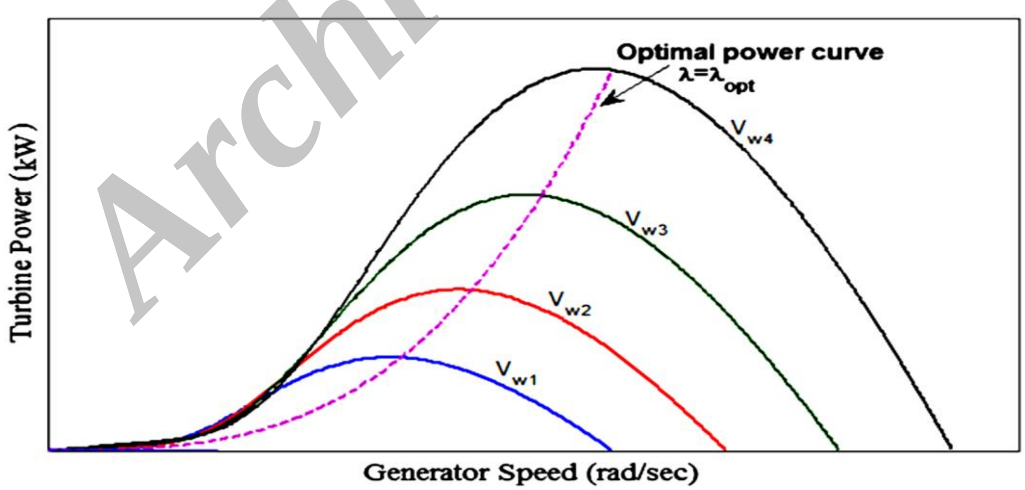

Fig. 4. Characteristic of turbine power as a function of the rotor speed for the series of wind speeds

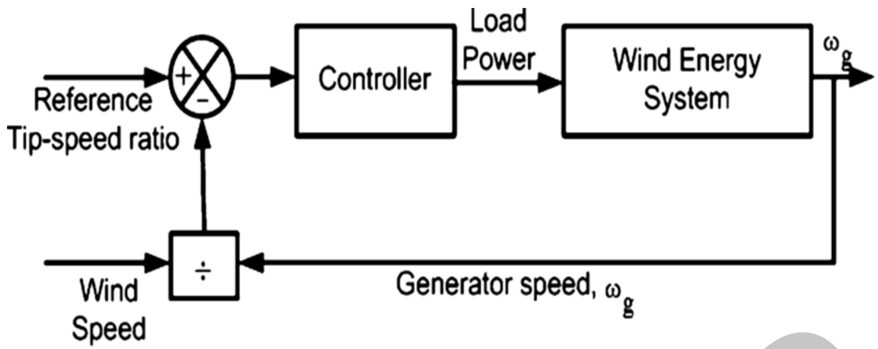

Fig. 5. The block diagram of the tip speed ratio control [2]

3. MPPT techniques for WT

Step 1: Tip speed ratio (TSR) control

In general, regardless of wind speed, the optimal TSR for a typical wind turbine is constant. Therefore, to guarantee maximized energy extraction, the TSR should remain constant at the optimal value. Hence, this method tries 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.Then the controller changes the speed of the generator to reduce the error and in this way this difference will decrease. 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 it increases the cost of the system [24, 35–38]. Fig. 5 shows the block diagram of the tip speed ratio control method.

Step 2: Optimal torque (OT) control

In order to get the optimest conversion of available wind energy into mechanical form, the operation of the system should be kept at λ_{opt}constantly. 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. Eq. (2) is rewritten in the following form in order to obtain the wind speed [40–43] so the turbine power can be determined as a function of λandω_m.

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

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

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

If the rotor is running atλ_{opt}, it will also run at$C_{p\ max}$.

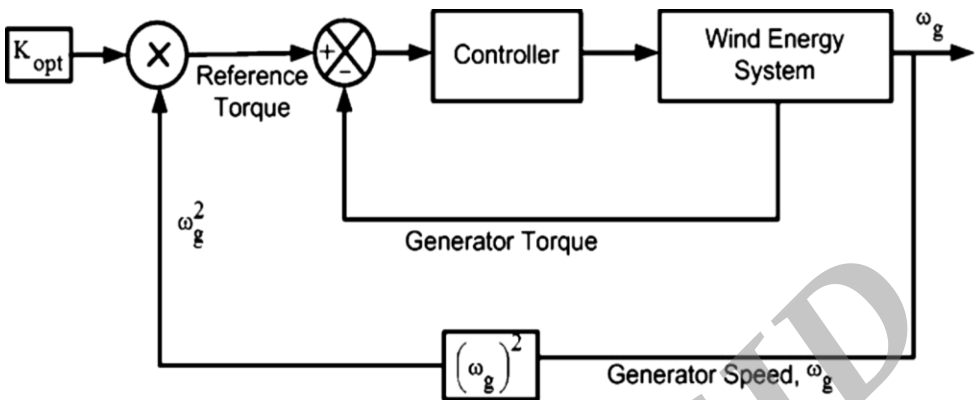

Fig.6. The block diagram of optimal torque control MPPT method [2]

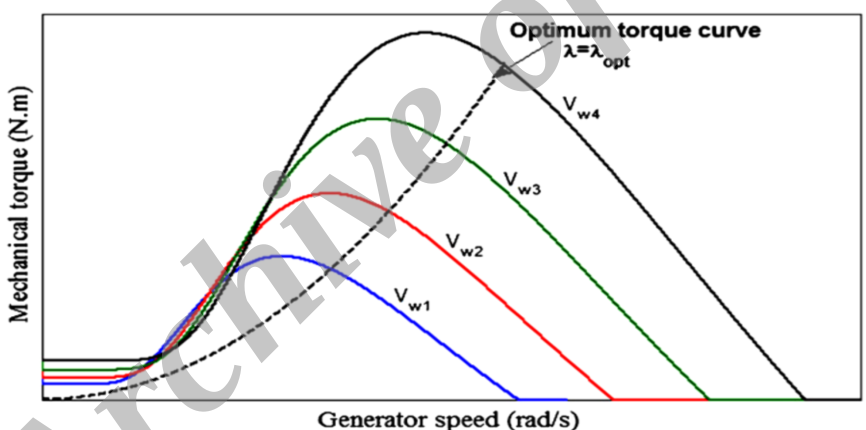

Fig.7. The torque-speed characteristic curve for a series of wind speeds

Thus, by replacing $\lambda = \lambda_{opt}$ and $C_p = C_{p\,max}$ into eq. (7), the following expression is obtained:

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

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

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. As this method does not measure the wind speed directly, meaning that wind changes are not reflected instantaneously and significantly on the reference signal, its efficiency is lower compared to that of TSR control method [24].

Step 3: Power signal feedback (PSF) control

Fig.8 shows the block diagram of a wind energy system with power signal feedback (PSF) control. This point should be taken into account that in this method unlike the OT control, 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 look up table [44–46]. Rather than using the wind turbine's maximum power versus shaft speed curve to populate the look up table as in Masoud [44], the maximum DC output power and the DC-link voltage were taken as input and output of the look up table in Quincy and Liuchen [47].

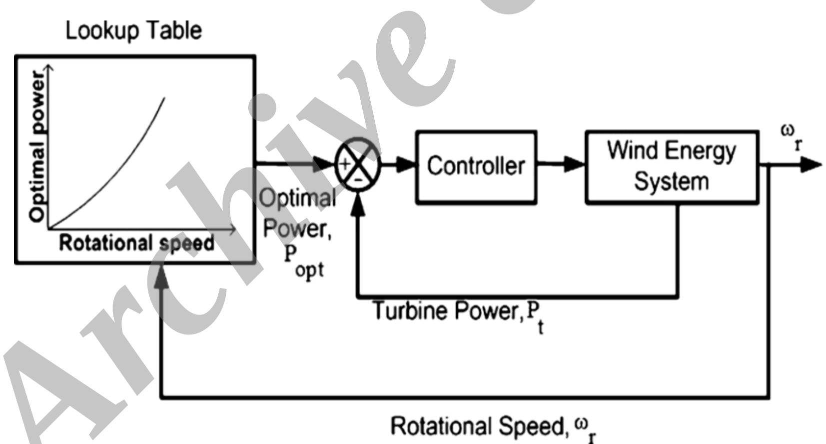

Fig.8. The block diagram of a wind energy system With the power signal feedback control technique [2]

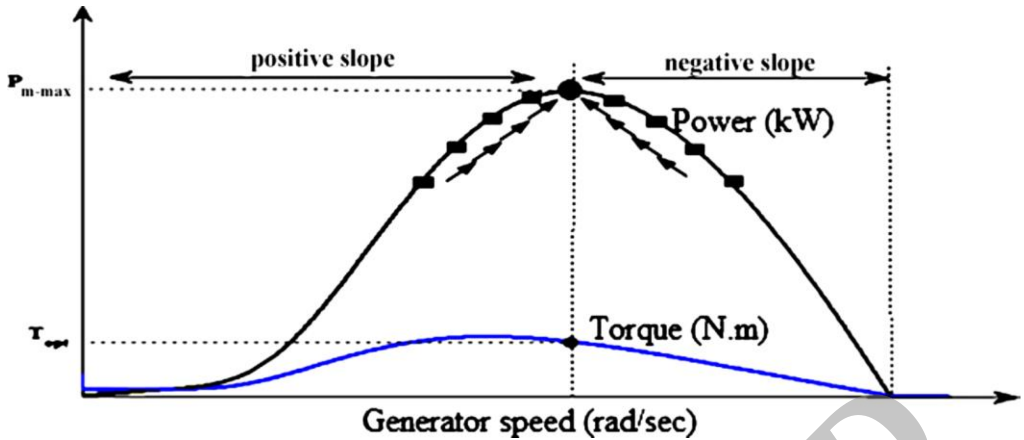

Fig.9. Wind turbine output power and torque characteristics with MPP tracking process

In [24] Raza Kazmi and et al conclude that there is no difference between the PSF and the OT methods regarding performance and the complexity of implementation.

Step 4: Perturbation and observation (P&O) control

The hill-climb searching (HCS) method or the perturbation and observation (P&O) method, is widely used in wind energy systems to determine the optimal operating point that will maximize the extracted energy and is a mathematical optimization technique used to search for the local optimum point of a given function. 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. Since in electrical power measurement, the mechanical sensors are not required, and electric parameter sensors are more reliable and low-cost, some others monitored the output power of the generator and perturbed the inverter input voltage [47] or one of the converter variables, namely: duty cycle, d [48–52]; output current, I_{in} [53]; or input voltage,V_{in} [54].

Although the P&O method fails to reach the maximum power points under rapid wind variations when it is used for large and medium inertia wind turbines, it does not require prior knowledge of the wind turbine's characteristic curve, and is independent, simple, and flexible. 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 [26, 55, 56], as shown in Fig. 10. Additionally, initialization of the parameters affects the system's performance significantly [57]. The value of the converter output capacitor in HCS method can also influence the system response, where a larger capacitance reduces the speed of system response [58].

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 can be one major drawback that leads to the failure of the tracking process [26]. Fig. 11 demonstrates that 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 decreases the efficiency by moving further away from the peak.

Modified variable step-size algorithms have been proposed to improve the efficiency and the accuracy of the conventional P&O method, [26, 49, 50, 53, 54, 57, 59, 60]. 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, when the operating point comes closer to MPP, the action is reversed to decrease the step-size.

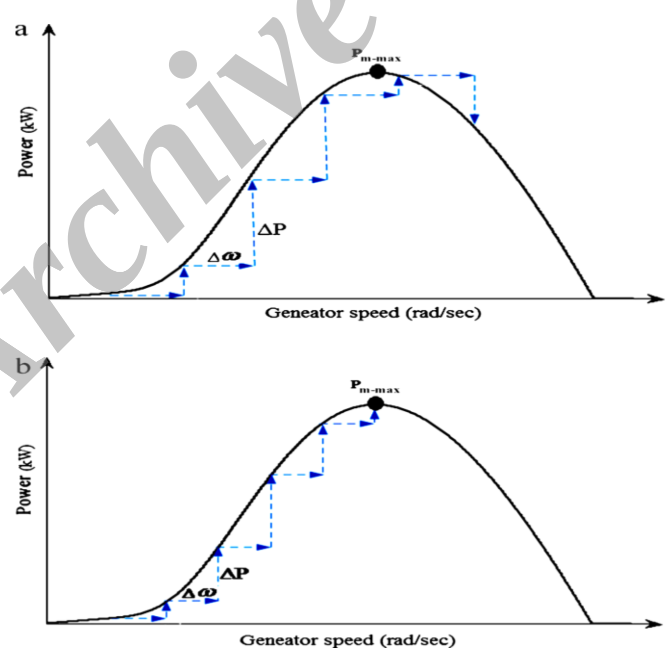

Fig.10.HCS control (a) larger perturbation and (b) smaller perturbation

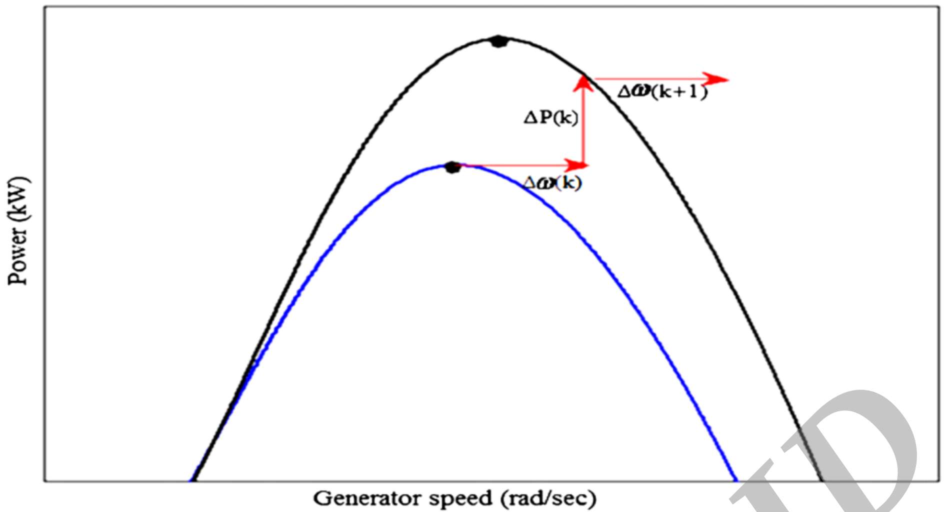

Fig.11.The HCS control losing its track ability under changing wind conditions and traveling downhill instead of the uphill climb [24]

Continually, the step-size is 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 occurs in the conventional P&O method, lowers the time needed for tracking, and accelerates the speed to reach the maximum. In previous studies, the controlling rule for adjusting the step-size varies from one group of studies to another, depending on the perturbed variable. Some studies [26-60] used the duty cycle of the converter as an input control to the system. In others, the load current [53] or the input voltages [54] were used as control inputs. In studies [26, 57], the distance from the current 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 by the following equation:

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

Based on the scaled measure of the slope of power with respect to the converter's duty ratio, the perturbation size can be selected [49, 50]:

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

Syed et al. [59] 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:

$$\mathrm{d}(\mathrm{k}+1) = \mathrm{d}(\mathrm{k}) + \mathrm{d}_{step} \,.\, \mathrm{sign}\{\Delta \mathrm{P}(\mathrm{k})\} \tag{11}$$

In [53], the duty cycle and generator speed was updated indirectly by changing the load current. The controlling rule for this method is:

$$\mathrm{i}_{ref}(\mathrm{k}+1) = \Delta \mathrm{i}_{ref}(\mathrm{k}) + \alpha \frac{\Delta \mathrm{P}(\mathrm{K})}{\Delta \omega(\mathrm{k})} \tag{12}$$

The duty ratio can indirectly be modified by changing the input voltage of the converter depending on the slope of the power with respect to the input voltage [54]:

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

Step 5: Other methods

According to [61], the fuzzy logic control (FLC) method has the advantages of fast convergence, parameter insensitivity, and acceptance of noisy and inaccurate signals. Thus, many of the problems associated with the aforementioned methods have been solved by artificial intelligence control and hybrid methods. The conventional HCS method can also utilize this method to obtain an optimal step-size [10, 62]. 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 [42, 63]. To diminish the effect of the wind turbine inertia on HCS method performance the control structure, Wilcoxon radial basis function network (WRBFN)-based with HCS MPPT strategy and modified particle swarm optimization (MPSO) algorithm have been presented in Lin et al. [64].

Kazmi at [26], exploited a hybrid method.

The key characteristic of this method is to combine two methods and uses the advantages of one technique to overcome the disadvantages of the other. An example of these methods was proposed by 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.

4. Review results and discussion

For the simulation system shown in Fig .12 the performance of three MPPT control methods is presented in Table 1 These simulations were carried out by Abdullah et al. [2].

Table1: Summary of performance of three algorithms [2].

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

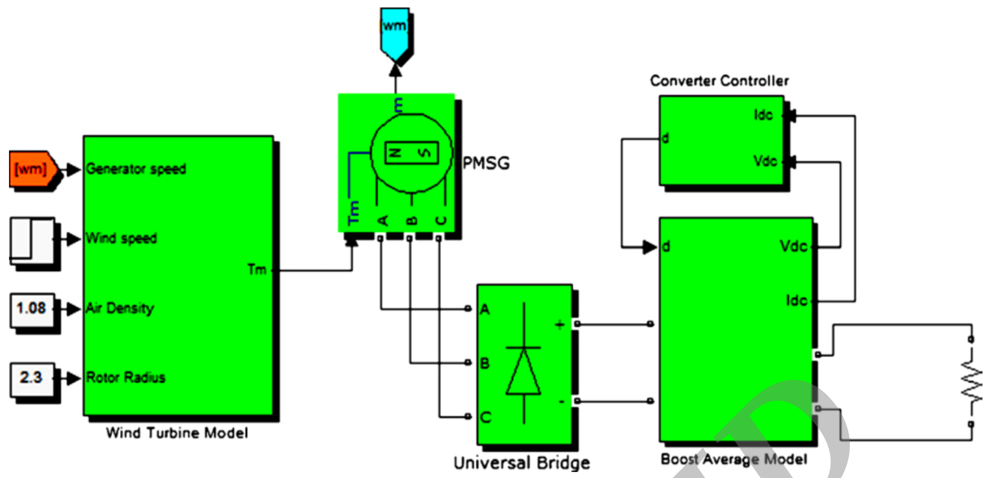

Fig.12. The simulated system diagram

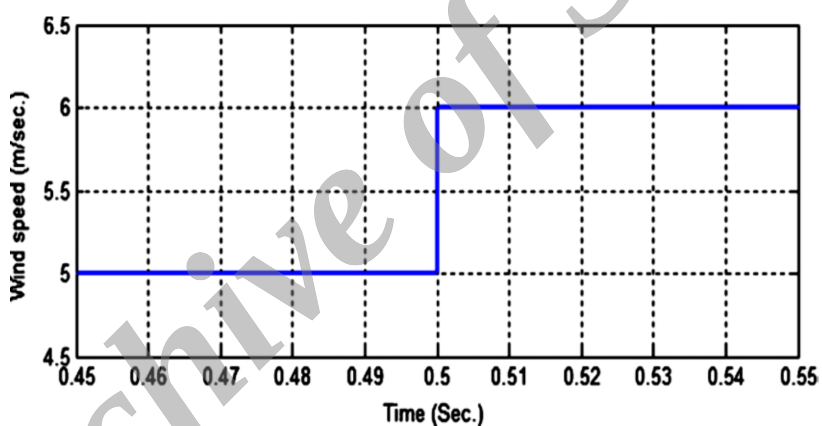

Fig.13. A step change in wind speed [1]

The OTC, P&O and P&O were the studied MPPT methods, in which the duty cycle of the boost converter in OTC, P&O, and input voltage of the boost converter in P&O method has been considered. Simulations were carried out with system parameters as in Mena Lopez [19]. For all simulations the load resistance was considered to be 20Ω. 0.5×10^{-3} was taken as fixed amount for the step-sizes in P&O algorithm and 0.001V was chosen to be the input voltage for P&O algorithm.

Table 2: Comparison of characteristics of various MPPT methods [30]

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

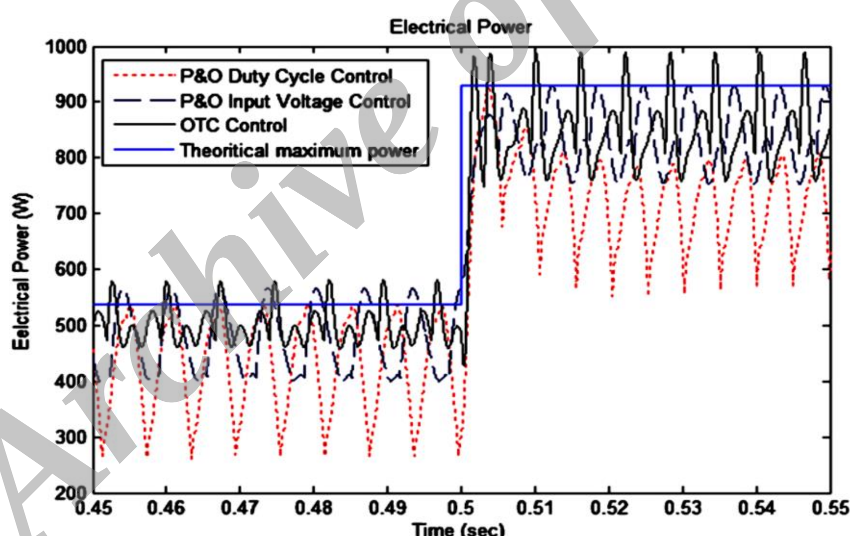

Fig.14. The output power response produced by the PMSG generator [2]

Fig 14 shows the obtained performance from the different methods for the wind changes depicted in Fig. 13, and the results are summarized in Table 1, as well the recovery time upon wind speed change was also faster for this algorithm. 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. . Based on results and analysis, the OTC controller was found to be the fastest in achieving the steady-state. As the response time was eight times longer than the first method, P&O duty-cycle method was found to be the slowest and least efficient 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.14 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. The main considerable aspects in selecting a particular MPPT strategy are represented in Table 2. However, as stated in Musunuri and Ginn Iii [30], there is some difficulty with choosing the appropriate MPPT algorithm for a given wind system.

5. Conclusion

The available MPPT algorithms for wind energy systems are discussed and reviewed in this paper. Additionally, a simulation and comparison of three selected control methods in terms of efficiency and speed of response were analyzed. The superiority of the OTC method in terms of simplicity and accuracy were demonstrated by simulation results. This method obtained the maximum average value of C_p and maintained it at its maximum value even with changes in wind speed. However, its inflexible behavior, due to dependency on wind turbine characteristics, was noticed as a weak point. On the other hand, less efficiency and difficulty in determining the optimum step-size was detected as a weak point for P&O method, but this is flexible and simple in implementation. Compared to perturbation of the duty cycle, perturbation of the input voltage was found to be better in terms of accuracy and response time. To overcome some of the obstacles found in current methods, determining the adaptive step-size algorithms and combining two or more of the available methods will improve the performance efficiency of the system.

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Appendix:

Nomenclature

V_{cut-in}	Cut in wind speed $\left(\frac{m}{s}\right)$	p_m	Mechanical power of the turbine (kw)
$V_{cut-out}$	Cut out wind speed $\left(\frac{m}{s}\right)$	T_m	Mechanical torque of the turbine (nm)
V_{rated}	Rated wind speed $\left(\frac{m}{s}\right)$	Psf	Power signal feedback
λ,TSR	Tip speed ratio	P&o	Perturbation and observation
λ_{opt}	Optimal tip speed ratio	Hcs	Hill climb searching
Pmsg	Permanent magnet synchronous generator	D	Duty cycle of the converter
Mpp	Maximum power point	I_{in}	Input current of the converter (a)
Dcm	Discontinuous conduction mode	V_{in}	Input voltage of the converter (a)
Pfc	Power factor correction	ω	Generator speed $\left({}^{rad}/_{s}\right)$
Thd	Total harmonic distortion	ω^*	Optimal generator speed $\left({}^{rad}/_{s}\right)$
Mppt	Maximum power point tracking	α	Constant scaled factor
ρ	Air density $\left({}^{kg}/_{m^3}\right)$	V_{ref}	Input voltage reference of the converter (v)
V_w	Wind speed $\left(\frac{m}{s}\right)$	V_{dc}	Output voltage of the rectifier (v)
C_p	power coefficient	Otc	Optimal torque characteristics
β	Blade pitch angle (degree)	R	Turbine radius (m)
ω_m	Mechanical angular velocity of the rotor $\left({}^{rad}/_{s}\right)$	$C_{p\,max}$	Maximum coefficient of power