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Review Article

Review on control techniques and methodologies for maximum power extraction from wind energy systems

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Abstract: This review study focuses on various methods and technologies used in past and present for obtaining maximum output power from a wind energy conversion system. There are plenty of solution for maximum power point (MPP), but the problem lies in the effective choice made among them and it needs the expert knowledge on every technique for picking up the best MPP method as every method on its own has some advantages and disadvantages. A comparison has been made among various MPP methods in terms of convergence time, efficiency, training, complexity and wind measurement. Here, different MPP tracking (MPPT) algorithms are classified based on wind speed measurement (WSR) and without WSR models. In this study, from the literature, a novel maximum electrical power tracking (MEPT) and maximum mechanical power tracking (MMPT) methods are compared with state-of-the-art MPPT algorithms. On basis of the results obtained from the literature available, the MEPT algorithm has fast convergence rate of 15 ms; on the other hand, optimal relation-based method is having large convergence rate of 364 ms and less efficient. A case study has been considered for performance validation, and MEPT and MMPT are having a good response for dynamic variation in wind speed.

Nomenclature

T_{opt}	optimum torque
β	pitch angle
np	number of pole pairs
ρ	air density
V_w	wind velocity
P_m	mechanical power
C_{pmax}	maximum coefficient of power
W_m*	maximum power at respective rotational speed
λ	tip speed ratio
R	turbine blade radius
Q	reactive power
P_{opt}	optimum power
W_r	rotational speed
P_t	turbine power
P	active power
ϕ	flux

1 Introduction

The development of any country depends on the amount of electrical energy consumption. Moreover, this consumption will increase when it is having sufficient amount of energy resources to generate the power. The man has been in a tradition to generate the power from the conventional energy, but later understood that intense usage of conventional resources has resulted in creating environmental problems such as global warming [1] due to increasing carbon dioxide emission from the fossil fuels and many other causes. As per the global wind statistics released by (global wind energy council), a total of 52,573 MW was installed in the year 2017 and the cumulative installed capacity reached to 539,581 MW. Among the major shares of wind potential, China is placed on the top list with 188,232 MW, about 35% of the total share. Later with the involvement of wind turbines and the evolution of new technologies [2], the wind energy has been a great advancement over the past few decades.

One more problem that arises in the conventional energy is that they are limited. Moreover, a continuous increment in the fossil fuel cost which will affect the common people to utilise the generated power with more freedom [3]. To overcome these problems, we need to effectively utilise the wind energy, as it can satisfy the growing energy demand with less impact on the environment and it is clean and renewable.

There comes the challenge that how we can effectively utilise the wind [4, 5]; in such a way that maximum power can be generated from the available wind [6]. There has been a continuous research for several decades, and still some improvements must be made in order to overcome a few disadvantages present in those models.

The output power of wind energy conversion system (WECS) depends on the accuracy by which the peak power is tracked with the help of maximum power point tracking (MPPT) controller for any kind of generator being used. For improving the energy produced by a wind turbine, when there are wide fluctuations in the wind speed, a controller is required that will track the MPP around the operating region. As the wind speed is dynamic in nature [7, 8], it is necessary to find the optimal generator speed; at that instant it will generate maximum energy. To achieve this objective, a controller is needed for tracking the maximum peak power irrespective of the wind speed. Most often this MPPT algorithm is operated when the wind speed is in the range of V_{cut_in} and V_{rated} [9, 10].

A novel maximum electrical and mechanical power tracking is proposed in [11]. Here, both maximum electrical power tracking (MEPT) and maximum mechanical power tracking (MMPT) are having greater MPPT efficiency and fast convergence rate compared with existing methodologies. This novel controller is simple in structure, low cost and has a good response to sudden wind speed variations. In [12], a single sensor is used for MPPT and is presented for generating the reference and a discrete time controller is proposed to bring the system to that reference point by implementing the MPPT algorithm.

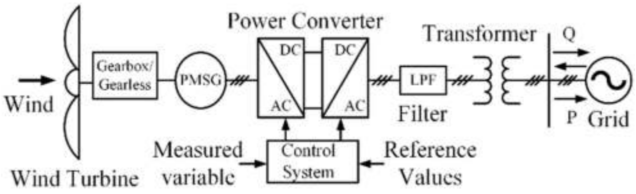

Fig. 1 *Block diagram of WECS connected to the grid through the converter*

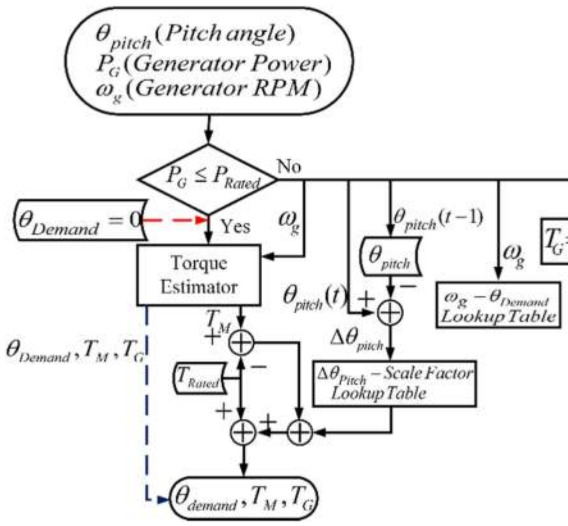

Fig. 2 *CPC system*

The controller in [12] shows better performance in terms of settling time and voltage ripples at the output. However, this algorithm does not operate under sudden changes in the wind speed. In [13], an improved optimal torque control (OTC) is developed since the conventional OT response has a slow response due to high inertia. Here, an effective tracking range is proposed for obtaining stable MPP efficiency.

Many MPPT techniques have been studied in the literatures [14, 15] and classified based on whether they use a sensor or without sensors [16] and some of them are based on directly controlled and indirectly controlled [17] methods for tuning the turbine speed to achieve maximum power. Some methods used wind speed [18] measuring instrument and few of them not used the measurement of wind speed [19].

On the basis of wind speed measurement (WSR), the MPPT methods used are the tip speed ratio (TSR)/WSR [20], power signal feedback (PSF) [21]. Few MPPT methods does not require the WSR such as hill-climbing search (HCS) [22], OTC [23], multivariable perturbation and observation (MVPO), optimal relation-based (ORB) method. There are few more methods that depend on this, but not completely, i.e. they require the historical data pertaining to the wind speed of performing that method and they are fuzzy logic control (FLC), neural network (NN) base [24] and direct adaptive fuzzy proportional–integral (PI) controller methods [25].

An experimental analysis of energy efficiency due to the impact of MPPT is studied in [26] for a small-scale WECS. It shows that the indirect method is operating at the best MPP compared with direct methods. A dual MPPT control strategy with a novel contra-rotating power split transmission presented in [27, 28]. It is a brushless contra-rotating power split transmission system for studying steady and dynamic performance.

Among these many algorithms, HCS is implemented frequently, because it is simple and flexible [29–32]. Although this method is simple, it is difficult to adjust the step size for tracking the maximum power and the speed is also low. Not only the step size, but also the perturbation direction and the ability to track changes [33]. This traditional HCS problem is overcome by implementing modified HCS and adaptive step HCS algorithms for tracking the MPP [34–37].

The incremental conductance-type (INC) algorithm overcomes the problems of HCS with better power extraction [26, 27]. To improve the system precision, performance and convergence speed, a modified INC algorithm is introduced in [38, 39].

In [40–43], explained the ORB algorithm, it requires the system parameter knowledge and also the optimum curve which is complex to obtain in the real-time applications [16, 33]. It is clear that individual algorithms are having a few drawbacks and it can be overcome by combining the advantages of two models to form a new hybrid model for performance enhancement. Some of the hybrid algorithms are proposed in [43–45].

In addition to above-mentioned models or algorithms, an adaptive MPPT based presented in [46–48] has all the advantages and in particular the ability to track MPP during dynamic wind speed changes. If we need to maximise the power generation in a wind farm, the MVPO algorithm can be implemented as described in [48] that does not require any sensors and control circuits. Recently, the applications of soft computing techniques such as NNs and fuzzy logic for MPP have been implemented successfully in [49–52]. These methods are not limited, but also there are many more MPPT algorithm control strategies [52–54] being proposed to overcome their drawbacks.

When dealing with the sensorless fuzzy logic-based MPP with a switched mode rectifier in [55] overcomes the conventional boost converter, which suffers from power losses, increases in cost and size.

Here in this paper, the author aims to review the principles and operation of different MPPT algorithms and discusses their advantages and disadvantages. A case study is taken for validating the convergence and dynamic response for MPPT algorithms. This makes a better choice on which algorithm can be selected for a particular system for obtaining maximum power extracted from WECS.

1.1 Types of generators used for wind energy systems

For WECSs, doubly fed induction generator (DFIG) [52, 53] and permanent magnet synchronous generators (PMSGs) [18, 56] are used. The DFIG is a popular type of generator used in wind energy systems [57, 58]. The rotor-side voltage is controlled by the rotor-side converter. Another advantage of using DFIG [59] is that we can individually control active and reactive powers to some extent.

The block diagram of WECS connected to the grid is shown in Fig. 1, where the turbine blades are moved by the wind velocity and the turbine shaft is connected to the generator through a proper gearbox. The output of the generator is connected to the grid via power electronic circuit. It consists of machine-side converter and the grid-side converter with a control system assembly for meeting the grid standards.

2 Control techniques in WECS

In a variable speed wind turbine, the wind speed is used for regulating the torque and the output power. It is difficult to control the torque of the wind turbine at rated wind speed, so generally torque control is implemented for low wind speed regime. The output power is regulated through pitch control of the wind turbine blade. The pitch angle is used to turn in or turn out the blades according to the control system of the wind turbine. The pitch control by which all the blades are turned in or out at the same instant is termed as collective pitch control (CPC) [60] as shown in Fig. 2, else it is known as individual pitch control (IPC) [61].

For CPC pitch angle (θ_{pitch}), generated power (P_{G}) and generator speed (ω_{g}) are taken as input and desired pitch angle is obtained through this controller. It checks the generated power with the rated power and acts according to it. In this way, it is possible to achieve generated power close to rated power without any effect of aerodynamic loading in the case of high wind speed regime, by turning the blades outwards. If the controller is not used, then the wind turbine will stall under high wind speed. Various controllers are used such as PI and derivative (PID), fuzzy, neural, sliding mode [62], adaptive, integrated and individual controller.

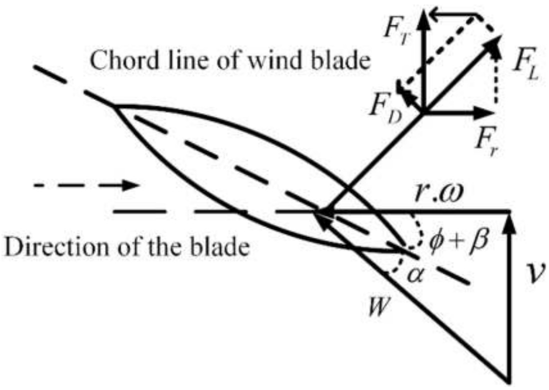

Fig. 3 *Dynamics of rotor blade model*

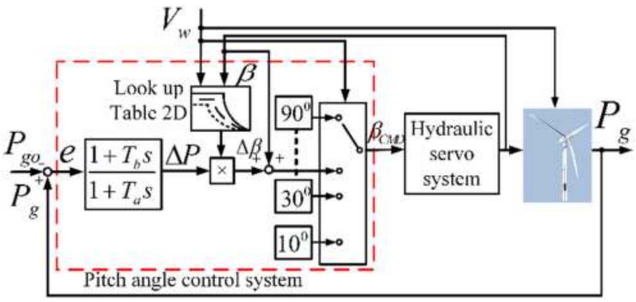

Fig. 4 *Pitch angle controller model*

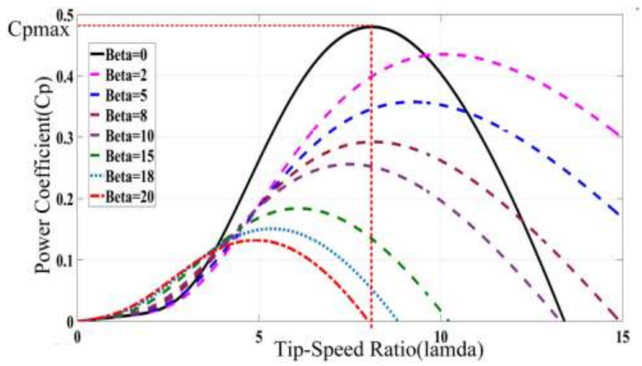

Fig. 5 *Power coefficient variation with TSR*

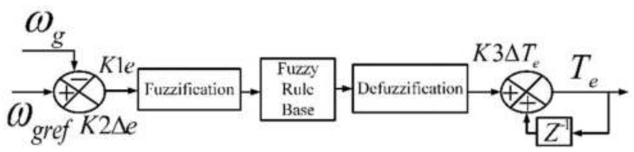

Fig. 6 *Fuzzy control MPPT block*

2.1 Blade aerodynamics

The characteristics of a turbine blade are decided by the geometric parameters, and the wind flow perpendicular to the blade plane (ϑ), blade angular speed (ζ), blade pitch (β) and twist angle ($\varnothing$) [63].

Rotation of blade produces a tangential velocity component at a distance of r. Owing to this, the resultant velocity of the blade will be W and α will become the angle between blade chord line and the wind. The rotor blade dynamics for a wind turbine is shown in Fig. 3.

The equations for the lift force (F_L) and the drag force (F_D) are calculated as

$$F_L = \left(\frac{1}{2}\rho A W^2\right) C_L \tag{1}$$

$$F_D = \left(\frac{1}{2}\rho A W^2\right) C_D \tag{2}$$

Here, C_L and C_D shown represents the lift and drag coefficients for the selected aerofoil. The lift and drag forces can be resolved into axial and tangential forces and given by F_T and F_R. When there is a net tangential force, it will tend to produce a torque on the turbine.

2.2 Pitch angle control

This pitch angle control has good performance for a variable speed horizontal axis wind turbine due to dynamics in the wind speed [63]. Owing to an increase in the wind speed, the pitch angle (β) will increase as shown in Fig. 3, thereby reducing the angle of attack (α) at the leading edge. When (α) decreases, the lift force also decreases leading to a reduction in the power produced by the wind turbine.

The pitch angle control for the wind turbine is shown in Fig. 4. The error is generated from actual power generated P_g and optimal power reference P_{go} value, this error e is given to controller. After referring the values from look-up table for respective wind velocity and pitch angle, the angle by which the blade has to be rotated is decided. This is given to hydraulic servo system and by this maximum power is generated through this pitch angle control.

Another advantage of varying pitch angle is to avoid mechanical overload and damage to the structure for variable wind speed conditions.

The efficiency of any wind turbine is decided on the basis of its power coefficient, the power coefficient variation with TSR is shown in Fig. 5. This TSR is a function of rotor speed and wind velocity [64].

2.3 Proportional integral and differential control

This is a robust control strategy and implemented in most of the applications, and here we apply for a wind turbine. Some of the PI controllers are presented in [65] and it can be used for variable speed wind and variable pitch under all operating wind speed regimes. A non-linear PID controller is used for uncertain blade pitch which is better suitable for large wind speed conditions.

The choice of gain for the PID is a major challenge and it must be taken into considerations and some of the methods for determining are presented in [66].

2.4 Fuzzy control

It overcomes the requirement of a prerequisite mathematical description of the system. The fuzzy will understand the system behaviour in the form of rules, and by using these rules the system performance will remain in the desired operating range. Fig. 6 shows the fuzzy controller for MPPT consisting of fuzzification, rule base and defuzzification blocks.

The generator speed is given by ω_g and the optimal value is referred to as ω_{gref}. Here, $k1$, $k2$ and $k3$ are normalised gains. The error present in the torque is given by T_e and the change in the error is given by ΔT_e. As the wind energy is highly uncertain, the fuzzy pitch angle controller will solve such issues and has been studied in [67].

When two fuzzy logic controllers are used in conjunction, maintain a flat power profile, when it is below rated [68]. In this manner, the power is optimised for low speed and restricting when it is at high wind speed conditions [69, 70]. If the fuzzy is allowed to work for only lower wind speed region, then a better mechanical power output has been achieved through this controller [71]. An improved power capture has been reported in [72] for a variable speed wind turbine.

2.5 Sliding mode control

When there is any time-varying parameter for a non-linear system, then the sliding mode control (SMC) can be used. Here, the dynamics of the system can be modified through a discrete control signal which makes the non-linearity to slide along the normal trajectory of the system [73]. In most of the scenario, this SMC is used for variable speed wind turbine [74, 75]. If there is any

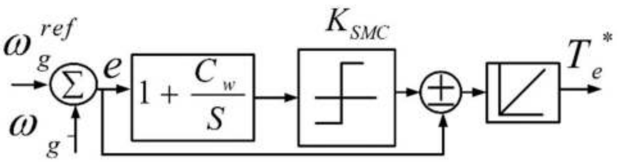

Fig. 7 *Sliding mode controller*

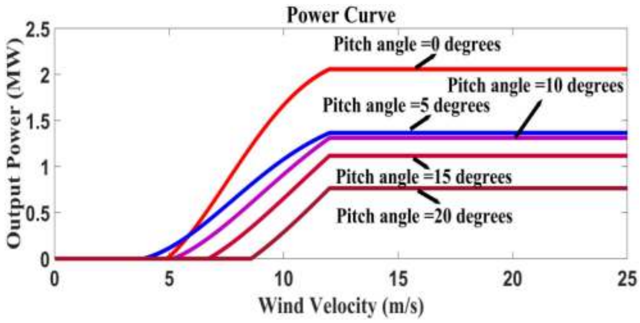

Fig. 8 *Individual pitch angle control*

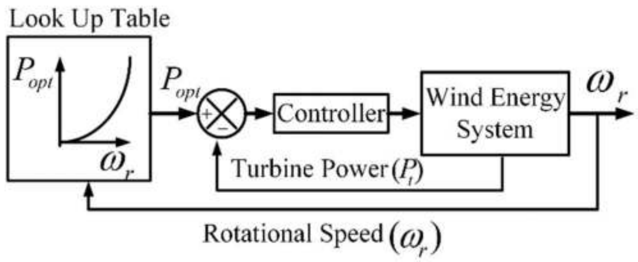

Fig. 9 *Block diagram for PSF*

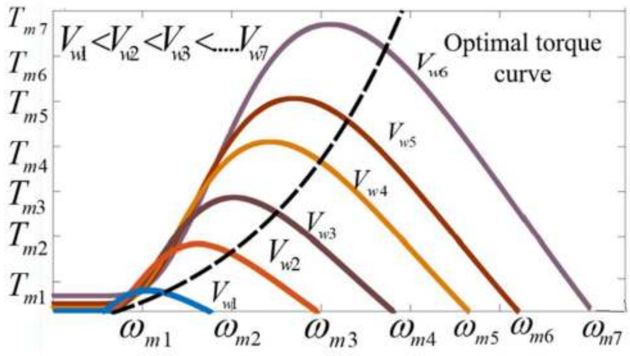

Fig. 10 *Turbine speed versus mechanical torque curve*

turbulence and any uncertainties in the system, the sliding model will provide regulated output power as shown in Fig. 7, while overcoming the mechanical stresses in the drive train transmission system. The error generated due to reference speed and actual speed is sent through PI controller. Another solution for the pitch angle control is to combine SMC and other methods for obtaining better performance.

2.6 Integrated control system

When the wind speed is exceeding above rated or falls below the rated wind speed, the system falls into a non-linear model with some random disturbances. The PID controller and other controllers are not suitable for stability improvement. To overcome these problems, researchers have integrated multiple controllers for replacing a suitable controller and such control is known as an integrated control system [76]. In [77], adaptive control (ADPC) is combined with neuro-fuzzy and the obtained controller is tested for fixed load, but not implemented for variable load condition and this performance is compared with the PID controller technique.

In some other studies [76], PID is integrated with an NN. In these two-hybrid methods, the main theme of using the NN is to obtain the gain of the controller. In [78], RBF and particle swarm optimisation is combined together for determining the gains of the PI-based pitch angle control.

Another controller named generalised predictive control (GPC) combined with the fuzzy NN is used for operating the wind turbine in all operating regions. By using fuzzy neural network (FNN), the instability can be reduced for GPC controller.

When RBF–PID NN is modelled based on ADPC [79], this RBF-NN is used to find the speed, PID parameters and varying the system constraints online so that it can able to work at dynamic wind speed conditions.

If there is any wind turbulence, then linear matrix inequality and linear parameter varying control methods are used for wind turbine pitch control [80]. For smoothening the output power and fluctuating torques, a novel pitch control is proposed in [81]. For increasing the output power from WECS in all operating wind speed regimes, RBF combined with ADPC in [82] is proposed and it provides torque reduction when the system changes its operation from above rated and below rated wind speed regimes.

2.7 Individual pitch control

With the continuous increase in the size and capacity of wind turbines, the rotor size, blade size, hub, tower etc. are consequently increasing. When the rotor size is changed, then it brings change in the load across the rotor. This problem is overcome by pitching each rotor blade individually by a certain amount. The variation in the pitch angle with wind speed is shown in Fig. 8. The IPC is proposed in [83] and recently this method has been investigated for the asymmetrical load present in the wind turbine.

3 MPPT algorithms

3.1 WSR-based MPPT algorithms

3.1.1 Power signal feedback: This method uses the reference power, i.e. the maximum power obtained at a particular wind speed. The block diagram is shown in Fig. 9; this method requires prior knowledge about characteristics of the wind turbine and the WSR. After getting this data, the maximum power [14] is obtained by performing the simulation for the wind turbine [17].

Fig. 10 shows the characteristic curve between turbine output torque and the turbine speed for different wind speeds. After obtaining the reference power from the power curve, a comparison is made with the present power. This error is sent to the controller consisting of the proportional integral controller which brings the system to operate at its MPP. The only disadvantage of using this PSF is that it requires a number of sensors for getting the prior knowledge of reference power.

Here, we use a look-up table for recording the maximum power that can be produced at corresponding wind turbine speed. From Fig. 10, the mechanical torque (T_m) of the wind turbine is controlled by varying the rotor speed (ω_m) with optimum C_p^{max}. The curve shows the magnitudes of torque for different wind speeds (V_w) and maximum power is achieved if the rotor is rotated at ω_m^*.

3.1.2 Tip speed ratio: The aim of this method is to maintain the TSR at a fixed optimum value, so that maximum power can be extracted [84]. Regardless of the wind speed, the optimal TSR [85] for a given turbine remains constant. So, it is guaranteed to extract maximum energy, if we maintain constant TSR for that particular turbine.

At the beginning itself, we need to determine either experimentally or by theoretically the value of optimum TSR λ_{opt} [17]. By comparing the actual value λ and the reference value λ_{opt}, the error is sent to the controller which brings the system to operate at its optimal location by changing the generator speed and reduces the error.

The reference TSR is obtained from the turbine power and speed characteristics and the controller will regulate the generator speed for maintaining the TSR at its optimum [17] value at which maximum power will be extracted. The only disadvantage of this method is that wind speed and turbine speed (ω) information must

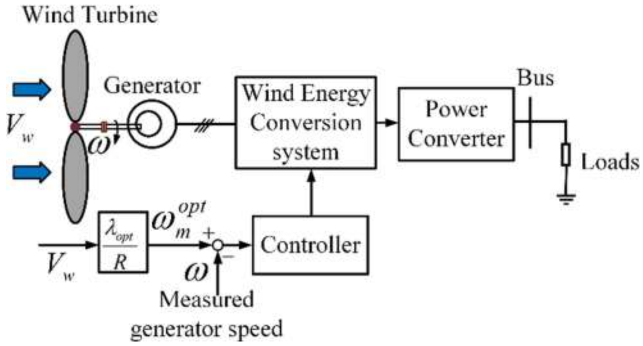

Fig. 11 *Block diagram of the TSR control*

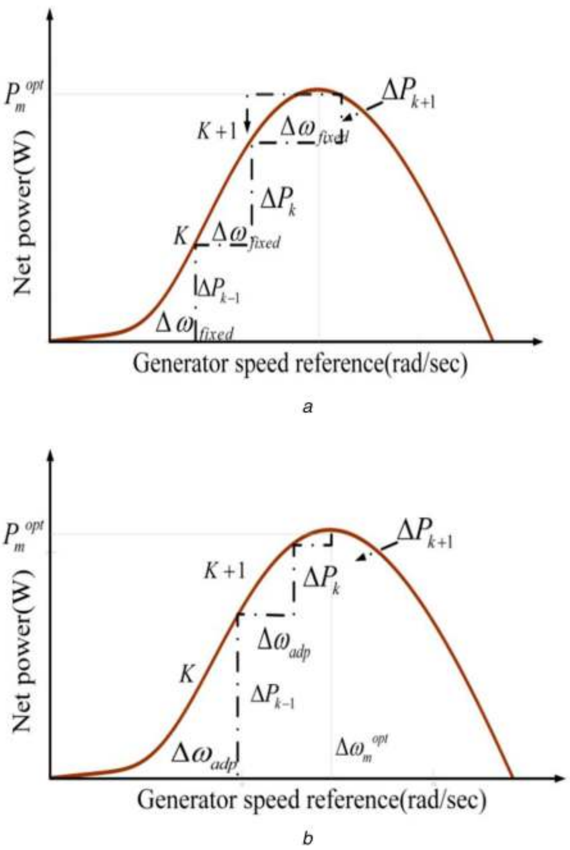

Fig. 12 *HCS with*
(a) Fixed step, ***(b)*** Adaptive step

be known prior to fixing the reference value of TSR. This also increases the cost including the complexity of the system for continuously varying wind speed.

For measuring the wind speed, the additional sensors will increase the cost of the system, and due to the presence of anemometer there exists some amount of frictional errors which introduces inaccurate results. Fig. 11 shows the block diagram representation of the TSR [86] for obtaining the optimum generator speed to achieve maximum output power.

3.2 Without WSR-based MPPT algorithms

3.2.1 Hill-climbing search: This HCS algorithm is also known as perturbation and observation (P&O) algorithm [87]. It has perturbing nature while tracking the wind speed, and observing the outcome of its variation in the wind speed, i.e. the turbine power. This HCS is an old method for tracking the MPPT due to its simplicity, adaptability and very flexible [88] in varying its output due to a change in wind velocity [87]. There are few problems with this HCS algorithm and they are overcome by implementing the adaptive step and the modified HCS algorithms.

In most of the cases, we need to consider the dc-link voltage or the dc current as the perturbing variable. In few cases, the voltage can also be utilised to prevent the generator from stalling, when the wind speed is very low. The acceleration or the deceleration can be performed based on the direct current (dc)-link voltage which is measured across the capacitor. On the basis of this voltage, it can be decided what will be the next step size for determining the optimal point for achieving the maximum energy extraction [19].

The utilisation factor is defined as how much amount of energy is being properly utilised for producing maximum output. This HCS or P&O is traditionally implemented [89] for a small rating of generators, and it is not giving better utilisation factor for a large rating of generators.

So, in order to overcome some of these problems, we are introducing a control algorithm [90] which can effectively alter the characteristics for getting MPP. This algorithm will utilise the already mentioned dc voltage and regulate this magnitude to MPP by adjusting the turbine speed.

This variation will continue until the changes in the desired quantity and the obtained quantity become zero. Suppose the operating point is existing in the left position, then the controller must operate in such a way as to move this operating point to the right for bringing it near to the MPP. In a similar manner, if it is in the right position the controller must operate to bring into the left nearer to the MPP.

In some research, few people considered the step changes [91] in the turbine speed, later observed the change in the mechanical power. Moreover, few others took the generated power as the observable quantity [92] and changed the voltage at the input terminals of the inverter in a stepped manner. The system response is affected by the magnitude of capacitance of the converter. If a large value of the capacitor is used, then it will affect the system response. A modified method in which the step size [21, 89, 93] is being varied is proposed in order to improve the system efficiency and accuracy. Still few modifications are made and brought the adaptive method in which the step size will update by itself automatically for meeting the required operating point.

When the operating point at which the system is working is very far [17] from the optimum value then the step size must be increased by improving the tracking process. If the operating point crosses the MPP, then the step size is reduced and further progressed till it reaches zero for achieving the desired MPP.

The step size or the distance to which the turbine speed (ω) must be adjusted for getting the desired speed (ω^*) is determined from the power curve for every cycle periodically. Consider the characteristic curve as shown in Fig. 12

$$X(k+1) = X(k) + \alpha(\omega - \omega^*) \tag{3}$$

but this incremental step size can be calculated based on the ratio of power to the duty ratio and scale by a factor of α which is represented as

$$X(k+1) = X(k) + \alpha \frac{\Delta P(k)}{\Delta D(k)} \tag{4}$$

in some papers, few authors used dual step (d_{step}) and a minimum step size as ($d_{\min}$), when the measured operating point is near to the peak value, whereas selecting a large increment value in the step size of ($d_{\max}$) in the case, when the operating point is lying far. It is expressed as

$$X(k+1) = X(k) + \ \alpha\,\text{step}\,\text{sign}\{\Delta X(k)\}\,\text{sign}\{\Delta P(k)\} \tag{5}$$

The change in the step size from the load current is given by

$$i_{\text{ref}}(k+1) = \Delta i_{\text{ref}}(X) + \alpha \frac{\Delta P(k)}{\Delta \text{slope}(k)} \tag{6}$$

$$\text{where } (k) = \frac{\Delta P(k)}{\Delta V_{\text{dc}}(k)} \tag{7}$$

A modified hill-climbing algorithm [89] as shown in Fig. 13 manages to achieve the control efficiency through proper balance

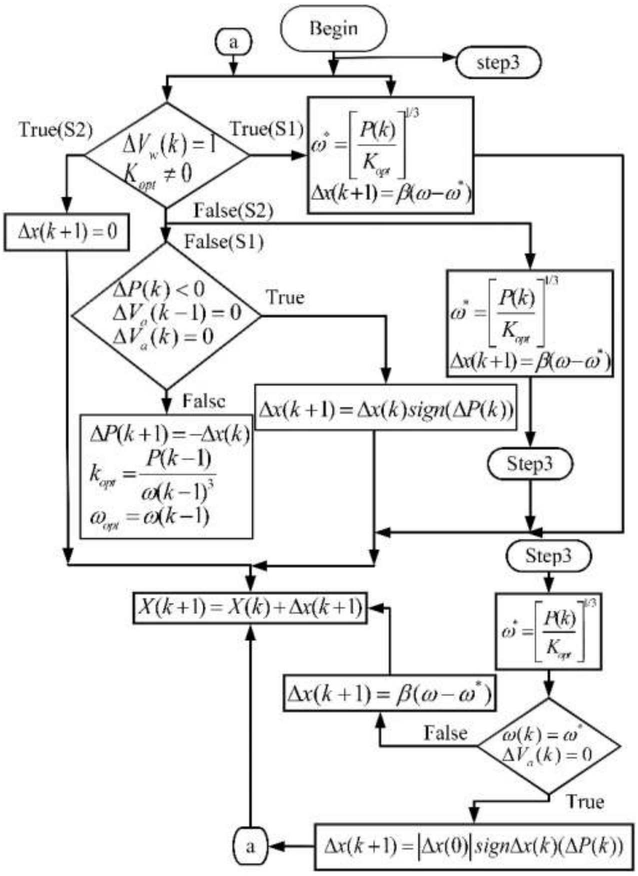

Fig. 13 *Modified HCS algorithm flowchart*

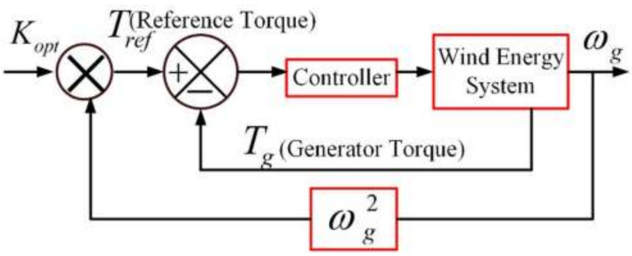

Fig. 14 *Block diagram of OTC method*

and it overcomes the problem of directionality, i.e. in which direction the step size is to be increased, whenever it comes across variation in the wind speed. In this algorithm, there are two states, in this first state the MPP is achieved based on the optimum value of K. Next, this value will be updated online and it undergoes a sequence of steps as shown in Fig. 13 below. In the first step, it tries to search for the optimum value of K by utilising the intelligent approach.

After this, in the second step, after obtaining the MPP at constant V_w. Suppose the wind speed is varying, then the online updated value will be used in the third step. The fixed step hill climbing is brought into the picture when the generator power change is in negative. At this movement, $\Delta\omega$ fixed is used and later after few perturbations [89], when the generators Δp is positive, then the adaptive approach is followed. The fixed step is comparatively large with an adaptive step which makes the starting time to low range value in Fig. 12*a*. The adaptive method is also helpful in avoiding the oscillation when the generator power is very close to MPP in Fig. 12*b*.

3.2.2 Optimal torque control: To obtain the maximum extracted power from the WECS, we need to operate the system near to λ_{opt}, which makes the system to achieve maximum output power.

The main objective of this method is to bring the generator torque close enough to maximum reference torque [17] at particular wind speed.

The turbine power in terms of λ and ω_m for obtaining the wind speed is given below:

$$\lambda = \frac{\omega_m R}{V_w} \tag{8}$$

$$V_w = \frac{\omega_m R}{\lambda} \tag{9}$$

The mechanical power developed by the turbine is given by

$$P_m = \frac{1}{2}\rho A V^3 C_p \tag{10}$$

By substituting (9) into (10) the expression results as follows:

$$P_m = \frac{1}{2}\rho\pi R^5 \frac{\omega_m^3}{\lambda^3} C_p \tag{11}$$

Now, if the wind speed is such that the rotor is λ_{opt}, then the power coefficient will be C_{pmax}. Therefore, by interchanging $\lambda = \lambda_{opt}$ and also $C_p = C_{pmax}$ in the above equation of (8), we get

$$P_{m\_opt} = \frac{1}{2}\rho\pi R^5 \frac{\omega_m^3}{\lambda^3} C_{pmax} = K_{p\_opt}\omega_m^3 \tag{12}$$

Let us take into consideration that $P_m = \omega_m T_m$ and there by T_m can be rearranged as

$$T_{m\_opt} = \frac{1}{2}\rho\pi R^5 \frac{C_{pmax}}{\lambda_{opt}^3}\omega_m^2 = K_{opt}\omega_m^2 \tag{13}$$

Expressions (12) and (13) are given as the reference power and torques as shown in Fig. 14. This is further connected to the controller after making a difference of the generator torque. The controller will modify the error and adjust the wind turbine speed for obtaining optimum operating point when the wind changes. The advantages of this method are, simple, fast and efficient, but having a lower efficiency when compared with other methods such as TSR due to its indirect measurement of wind speed.

3.2.3 ORB method: When we require optimum generator speed at all conditions for extracting maximum power, then ORB will be implemented [43]. Since it is having the advantage of the fastest tracking speed when compared with other methods. This method requires the knowledge of characteristic curves between turbine power and dc current at various wind speeds. Fig. 15 shown below clearly gives information about the turbine power, dc current. From this, we can track the MPP on observing the optimum current curve. The current should also never exceed its limits in order to continue its generation.

This method has the advantage of not requiring any kind of speed sensors for speed measurement, and also the look-up table. It only depends on the characteristic curves that were already obtained. The only disadvantage of using this method is that it cannot respond to rapid wind changes. To overcome the drawback, we can include P&O method for this ORB so that self-tuning is achieved as it does not require any prior knowledge. Now under MPP condition, the relation between dc current and the dc voltage is given as

$$I_{dc\_opt} = K V_{dc\_opt}^2 \tag{14}$$

$$K = \frac{I_{dc\_peak}}{V_{dc\_peak}^2} \tag{15}$$

Here, $I_{\text{dc-peak}}$ and $V_{\text{dc-peak}}$ represent the dc-side current and voltage at a particular speed under MPP condition. Now, if we consider that by varying the value of K in the above expression, we can obtain the optimum curve.

The flowchart for the ORB and also the combination of P&O are shown in Fig. 15 below. In this, until the value of K is not made to zero it follows the ORB path; otherwise, it will follow P&O method.

3.3 Other methods

3.3.1 Fuzzy logic control: The fuzzy logic controller [43] as shown in Fig. 16 is independent of the turbine and the generator properties [43, 94]. A fuzzy logic controller [95] consists of three stages, they are: (i) fuzzification, (ii) rule-based look-up table and (iii) defuzzification [96]. In the first process, the parameter or the variables will be converted to linguistic terms and this is sent to the look-up table based on the prior knowledge for determining various errors. This is again sent to the defuzzification [93] block, where these linguistic terms are changed into basic system input variables.

The modified version of fuzzy is achieved by implementing an NN [97]. We get another model named as neuro-fuzzy MPPT model which are explained in [24]. The only information or the data it requires is the voltage and the current from the rectifier side.

There is another advantage of using this method [93], i.e. there is a moderate need of sensors for determining the wind speed, and this reduces the cost and increases the system reliability [98].

When compared to other methods, the control strategy is easy and possess high practical data. When the wind speed is varying continuously, it can track the MPP with high accuracy. To generate the reference signals, this controller uses if–then rules [99], and this will be subjected to fuzzification. Further studies are made, and an SMC strategy [100] is brought into this for more advantage compared with prior methods.

This hybrid model [101] has the advantage of extracting maximum power from the WECS and for reduction of current harmonics, which are present on the generator side. The fuzzy logic generates optimum dc current, and a filter is accompanied for eliminating the harmonics. This method does not require any sensors and gives better accuracy results.

The system also provides robust performance [102–104] for system parameter variation and any external disturbances and provides better stability [105].

This hybrid model is having the advantage of simplicity, robustness to parametric variations and also non-linearities.

Although fuzzy has many benefits compared with other methods, but the only disadvantage of this is, it cannot be applied to each and every problem. Moreover, it requires studying the parameter for assigning the linguistic variables.

The wind power which is extracted is given by

$$P = \frac{1}{2}\pi\rho R^2 v^3 C_p(\omega, v, \beta) \tag{16}$$

At a particular wind speed, there will be maximum power extraction and it is given by

$$P_{\max} \propto \omega_{\text{opt}}^3 \tag{17}$$

The back electromotive force from the PMSG is written as

$$E = \frac{\sqrt{2}}{2} n_p \omega \phi \tag{18}$$

The dc-side voltage from the rectifier is given by

$$V_{\text{dc}} = \frac{3\sqrt{6}}{\pi}\left(E - \frac{\sqrt{6}}{6} n_p \omega L_g I_{\text{dc}}\right) \tag{19}$$

Here, dc-side current and the phase inductances are represented by L_g and I_{dc}

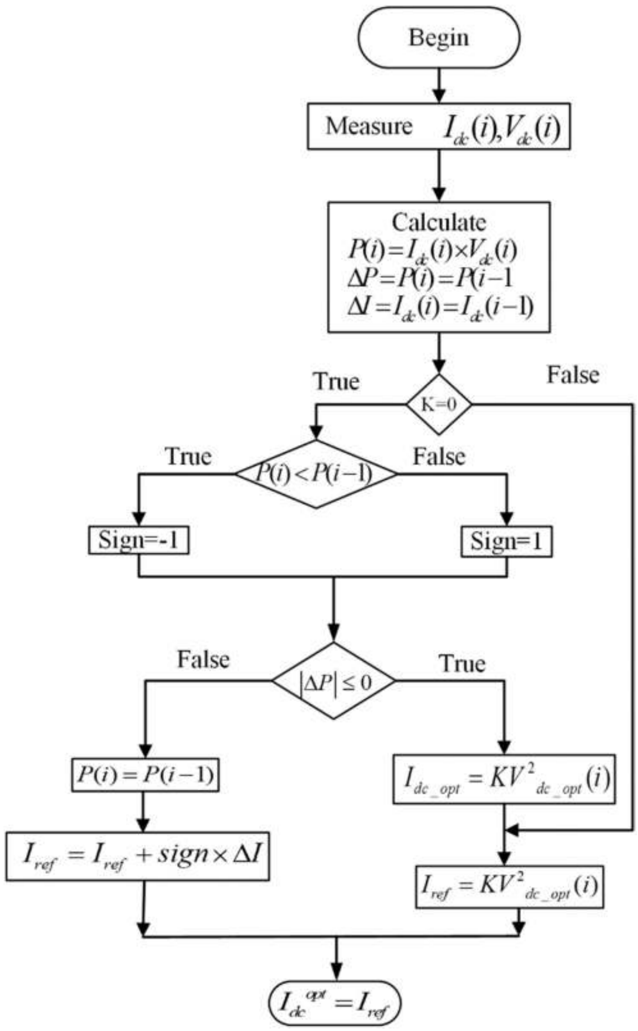

Fig. 15 *Flowchart of hybrid of the ORB and P&O MPPT algorithms*

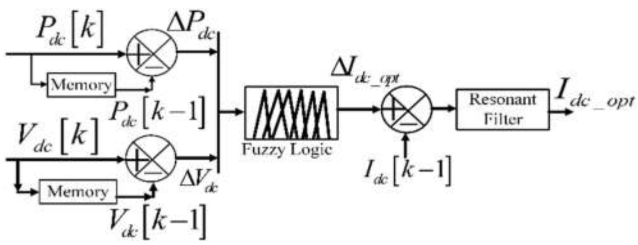

Fig. 16 *Fuzzy logic controller*

From the above expression, we can summarise as

$$V_{\text{dc}} \propto \omega \tag{20}$$

$$\therefore V_{\text{opt}} \propto \omega_{\text{opt}} \tag{21}$$

Now from the above, we can write the expression for P as

$$P_{\max} \propto \omega_{\text{opt}}^3 \propto V_{\text{dc}-\text{opt}}^3 \tag{22}$$

Now the optimum dc power is given by

$$P_{\text{dc}-\text{opt}} = P_{\max}\eta = V_{\text{dc}-\text{opt}} I_{\text{dc}-\text{opt}} \tag{23}$$

3.3.2 Neural network: The NN is another method to determine the MPP by taking various input variables and processing it in order to obtain the maximum power [106].

The NN [107] is based on the human biological neurone concept, where each neurone is assigned with some weights and according to the adjusted weights, they respond to the type of

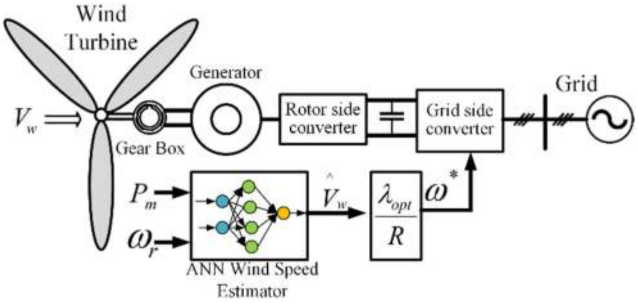

Fig. 17 *Artificial NN controller to estimate wind speed*

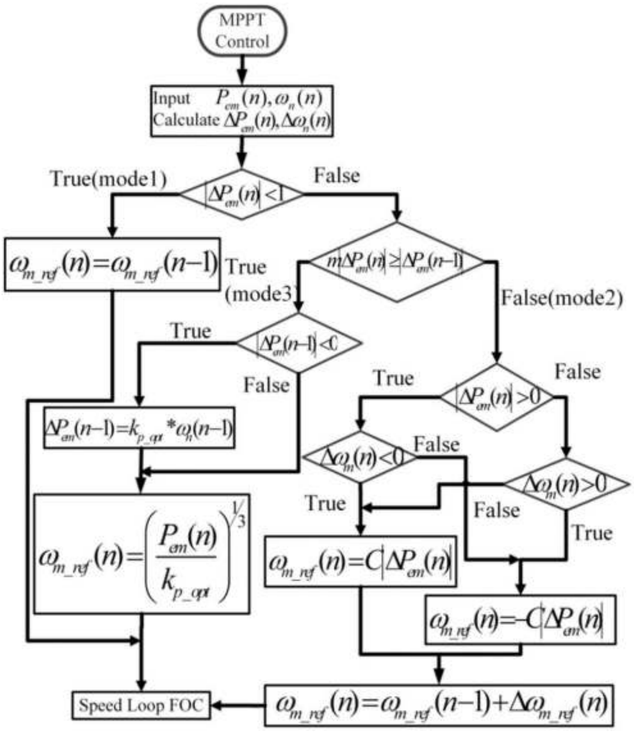

Fig. 18 *Flowchart for adaptive algorithm method for MPPT*

training we select. Whenever the output crosses the threshold, then only it is going to produce the response. Every NN has three layers they are classified as an input layer, hidden layer and output layer.

There is no restriction in assigning a fixed number of nodes and they can vary according to the requirement. In this scenario, we take the rotor speed and the mechanical power as the input parameters as shown in Fig. 17 for the input layer. On processing these inputs, the NN will produce the output in the form of the duty cycle, which will further control the power converter, in order to obtain the maximum power [108]. The drawback of the NN is, it is a 'black box' structure, more computational burden, overfitting problem and empirical nature in developing the model.

This method requires the look-up table which consists of predefined data of rotor speed ω_r, mechanical power P_m. By using the NN, we can generate various firing angles for the converter switches for getting the MPP. Fig. 17 shows the NN training for obtaining the wind speed V_w from the measured quantities.

3.3.3 Adaptive control: This is another approach for determining maximum power tracking for the WECS. This actually does not require any sensors, for calculating the wind speed and turbine parameters [109]. On analysing the system efficiency, we can come to a conclusion that at particular turbine output, we can observe the highest power. The same power is not supplied to the load due to the transmission losses.

The ADPC laws cannot be used in practical designs, as the unmodelled dynamics of the plant can be excited and results in an unstable system.

Now, this problem is considered as the highest priority [47] to supply maximum power to the load instead of implementing the methods for tracking maximum power, which can be obtained from the theoretical C_p. As we are not using any sensors [110], we are also reducing the cost. As the wind keeps on changing its speed, this MPPT [111] also shifts between many modes and it is explained below [56].

Mode 1: Change of wind speed in zero: Whenever the tacking point is having a large difference from the actual MPP and the calculated MPP. Then, the variable step of the hill climbing is being subjected to an increase in the tracking speed

$$|\Delta\omega_{\text{m - ref}(n)}| = C|\Delta P_{\text{em}}(n)| \quad (24)$$

Here, C is taken as constant.

Mode 2: From $\Delta\omega_{\text{m\_ref}}(n)$, it has been observed that the change is minimal, and also it is of the same magnitude as that of the deviations caused by the insulated gate bipolar transistor switching. So we need to maintain the tracking to be stable and unaltered.

Whenever the value of $\Delta\omega_{\text{m\_ref}}(n)$ is less than a relatively small, then

$$\Delta\omega_{\text{m\_ref}}(n) = \Delta\omega_{\text{m\_ref}}(n-1) \quad (25)$$

Mode 3: Change in the wind speed: When the wind speed change has been detected, we need to make sure that there will not be any sort of oscillations due to HCS step size. The approximate optimum power at this movement is given by

$$P_{\text{wind\_opt}} = K_{\text{p\_opt}}\,\omega_{\text{m\_opt}}^3 \quad (26)$$

The above expression has been used, till there will not be any wind change is been detected or been noted. Just like the PSF, the mode of operation will be swinging between modes 2 and 3. Hence, the value of $K_{\text{p\_opt}}$ is corrected by utilising the value obtained by using HCS in the previous mode 2 as shown in Fig. 18. So we can assure that the $K_{\text{p\_opt}}$ value never depends on the wind speed values. The mode 3 detection can be expressed when

$$(m\Delta P_{\text{em}}(n) \geq \Delta P_{\text{em}}(n-1)) \text{ and not } (\Delta P_{\text{em}}(n) < a) \quad (27)$$

Here

$$\omega_{\text{m}_{\text{ref}}}(n) = \sqrt[3]{\frac{P_{\text{em}}(n)}{K_{\text{p\_opt}}}} \quad (28)$$

3.3.4 Multivariable P&O: This is quite different because it uses multiple generators for getting maximum power extraction. Here, multiple generators are meant for a wind farm, where many generators are connected to a single point. It does not require any sensors, and such models provide a better economy in operation. While compared to conventional perturb and observe, this MVPO [112] reduces few components for getting MPP. In MVPO, the current from the generators is optimised using the basic principle of P&O.

Suppose there is any reduction in the power produced due to this generator current, then another generator current is used as perturbing variable which is to be taken in the opposite direction to the previous perturb.

In this way, we are utilising multiple currents which are available. The flowchart of the two generator model is shown in Fig. 19.

The above-mentioned techniques are intended for extracting maximum power from the WECS and the important parameter that estimates the efficiency is the power coefficient C_p.

The power coefficient of a wind turbine is defined as a non-linear relation between the TSR and pitch angle [113]. It is well known that whenever the wind speed varies, the power coefficient also changes according to the velocity.

The power coefficient analysis [113] expresses the power coefficient drop by taking the difference between the optimum values of k. Here, k can have any values and at a particular wind speed of $v1$ the k is given by

$$k = \frac{I_{\text{dc}-v1}}{V_{\text{dc}-v1}^2} \tag{29}$$

Here, $I_{\text{dc-}v1}$ and $V_{\text{dc-}v1}{}^2$ represent the optimum values of dc current and the voltages for MPPT when the wind is at $v1$ speed. The variation of power coefficient with wind speed is also presented in [113]. This explains that the power coefficient increases slowly as the wind speed increases and reaches a maximum value of 0.48 at 8 m/s and with further increase in wind velocity the power coefficient decreases. The values also vary with the wind turbine models and several power coefficient equations are given by

$$C_\text{p} = (1.12\lambda - 2.8)\text{e}^{-0.38\lambda} \tag{30}$$

$$C_\text{p} = 0.22\left(\frac{116}{\lambda_i} - 0.4\beta - 5\right)\text{e}^{-(12.5/\lambda_i)} \tag{31}$$

$$C_\text{p} = (0.44 - 0.0167\beta)\sin\frac{\pi(\lambda - 2)}{13 - 0.3\beta} - 0.00184(\lambda - 2)\beta \tag{32}$$

Now, for different turbine models, the power coefficient values vary as for expression (32) we get 0.419 and for expression (33) 0.438 and later expression (34) gives 0.44. By using the proposed model, the power coefficient is maintained constant at 0.48.

4 Deloading MPP control

From the economic point of wind turbine performance, wind turbines were designed to operate in the optimum power curve [114]. Owing to this, the frequency regulation is not possible for the WECS. To overcome this, a sufficient amount of reserve capacity should be made available for meeting frequency deviations [115]. Deloading is the process of reducing the power level in its optimal power curve by shifting wind turbines operation point to achieve sufficient reserve margin as shown in Fig. 20. From (10), it can be interpreted that the output power depends on the TSR and pitch angle, i.e. λ and β, respectively. The deloading has two types of controls: pitch control and speed control.

4.1 Deloading through speed control

On shifting the operating point on the left-hand side or right-hand side of MPP, the TSR value gets altered, thereby deloading is achieved through speed control [114]. When the frequency falls, then the wind turbine will deliver active power in proportion to frequency variation. Now the new operating point is located between A and B, i.e.

$$P_\text{ref} = P_\text{del} + (P_\text{max} - P_\text{del}) \times \left[\frac{\omega_\text{rdel} - \omega_\text{r}}{\omega_\text{rdel} - \omega_\text{rmax}}\right] \tag{33}$$

where P_max represents maximum power (pu), P_del shows the deloaded power (pu) and reference power is given by P_ref, respectively. ω_rmax, ω_del and ω_r are rotor speeds at maximum power, deloaded power and reference power, respectively.

4.2 Deloading through pitch angle control

This control is used for deloading the wind turbine in increasing the turbine blade angle. This plays a major role when the overspeed controller is unable to reduce the speed of the turbine when it reaches to rated speed. Fig. 5 shows the power variation for different pitch angles. There are several works in the literature dealing with the deloaded technique used for variable speed wind turbine [116].

Under normal operating conditions, the wind turbine will extract the operating point from look-up table data. When the deloaded mode is switched on, the pitch and speed control will operate simultaneously to reserve some power. The above (35) estimates the reference power for both pitch and speed control about 10% [116, 117]. Here, droop control also presented in order to deliver the active power from the rotating mass under deloading condition.

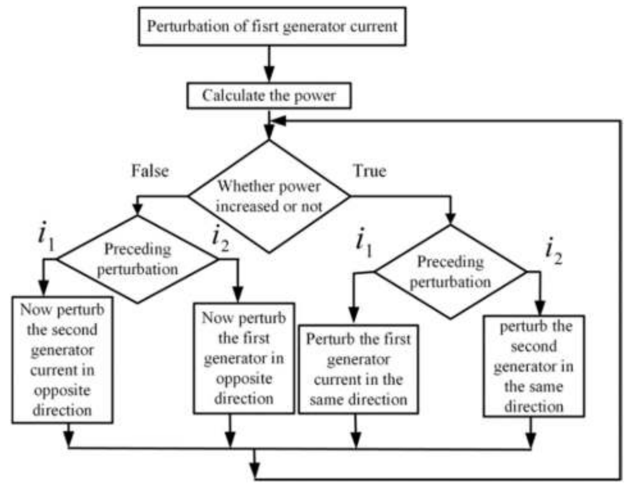

Fig. 19 *Flowchart for the MVPO algorithm on an feld oriented control (FOC) scheme*

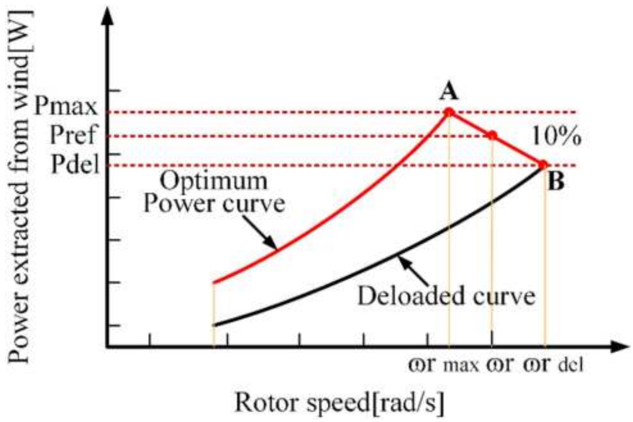

Fig. 20 *Calculation of power reference for 10% deloaded operation*

The delivered active power is proportional to frequency change and limited up to 10% of rated power. The overspeed control is operated to deload the turbine in the first mode [118]. In the second mode, both pitch angle and overspeed control are combined to achieve sub-optimal power. At a particular wind speed, overspeed control is unable to increase rotor speed and at this instant blade pitch angle is increased which changes the operating point. In the third mode, the pitch angle controller will operate independently for reaching the deloaded value [118].

A combination of pitch angle and speed control is presented in [119]. In this, the author proposed three major operating modes based on the wind speed. The author implemented a decision algorithm, for controlling pitch angle and overspeed controller. The algorithm determines the reference power for pitch angle control and power margin for overspeed control. In [120], the coordination between pitch angle and overspeed controller makes the wind turbine in frequency regulation. However, in [120] the decision is made based on reserve power.

In [121, 122], droop controller is used in combination with pitch and overspeed controller. The controllers are operated based on different wind speed range for frequency regulation. The overspeed control is used to measure the sub-optimal power from the deloading tracking curve and is stored in the look-up table.

5 Comparison of various MPPT algorithms

After reviewing various MPPT algorithms for maximum power extraction from WECS, a comparative Table 1 is presented. A comparison is made among different performance indexes such as convergence speed, memory requirement, training, WSR,

Table 1 Comparison of MPPT algorithms with a different performance index

Type of algorithm	WSR	Complexity	Memory	Convergence speed	Performance at varying wind speed	Dynamic response	Training knowledge	Efficiency, %
PSF [14, 21]	required	simple	necessary	fast	good	moderate	provided	91.50 [lit]
TSR [17, 20, 64, 84–86, 113]	required	simple	not necessary	fast	excellent	moderate	not required	92.32 [lit]
hill-climbing algorithm [17, 19, 22, 29–32, 34–37, 87–92, 123, 124]	not required	simple	not necessary	slow	average	slow	not required	81.33 [lit]
OTC [13, 23, 86]	not required	simple	no need	fast	excellent	fast	provided	90.66 [lit]
ORB [40–43]	not required	simple	not necessary	medium	medium	medium	not required	80.24 [lit]
FLC [24, 25, 43, 49–52, 67, 72, 95]	depends	more complex	necessary	fast	excellent	fast	must be provided	87.46 [lit]
NN [24, 49–52, 78, 79, 97, 106–108]	depends	more complex	necessary	fast	excellent	fast	must be provided	88.23 [lit]
ADPC [25, 46–48, 77, 79, 82]	depends	moderate	necessary	medium	excellent	medium	provided	90.35 [lit]
MVPO [112]	not required	moderate	no need	slow	good	slow	not required	86.34 [lit]
MMPT [11]	required	low	no need	very fast	excellent	fast	not required	98.04 [exp]
MEPT [11]	not required	low	not necessary	very fast	excellent	fast	not required	99.28 [exp]

complexity etc. The main objective of MPPT techniques is to track the optimum power during dynamic wind speed variations. Selecting the best MPPT is a difficult task.

While comparing, the techniques that require WSRs such as PSF, TSR and MMPT are fast and simple. Among these three techniques, PSF is having an efficiency of 91.50% and response time of 0.015 s with a recovery time of 0.22 s. The PSF has a convergence time of 31 ms, which reflects that the system dynamic response is slower compared with other techniques. The TSR method has an efficiency of about 92.32% better than PSF and here there is no need of training and memory. These methods maximise mechanical power capture from wind compared with electrical power output. Among these techniques, MMPT is having high efficiency of 98.04% and fast response. There are few limitations such as it requires accurate anemometer due to the presence of turbulence that adds cost. These techniques are difficult in applying in real time because wind velocity near the turbine is quite different compared with free stream velocity.

Another MPPT technique OTC is a fast, efficient that does not require WSR. This technique cannot measure wind speed directly, so the variation in the wind cannot be observed directly. Owing to this limitation, the efficiency of OTC is less compared with the TSR algorithm. The efficiency is found to be 90.66% and time of convergence is about 25 ms. The two algorithms PSF, OTC performance and complexity are similar in terms of training and it provides cost-effective control of WECS.

The MPPT techniques HCS and ORB are simple, the memory requirement is also very less. These techniques do not require any training in determining the optimal power and WSR. The only limitation of these techniques is these are not suitable for wind speed variations. These methods also do not require any sensors making them cheaper and reliable. The HCS is not affected by changing the generator parameters. The disadvantage of HCS is the time taken for reaching MPP is long and power loss occurs, it can also stall small wind turbines. If the step is small, then it results in slow MPP tracking and oscillates when step size is increased. This HCS algorithm has a slow dynamic response, so the efficiency is less compared with other methods about 81.33%.

The ORB is a simple MPPT method as it requires only dc voltage and dc current. It neither requires prior knowledge of the system or any mechanical sensors. It is independent and a flexible algorithm for MPP tracking and has efficient wind power tracking property. The major drawback of this method is it has poor efficiency compared with remaining methods and it accounts to 80.24% and convergence speed of 364 ms. By this, we can say how poor the system is responding to dynamic conditions. Till now individual algorithms have been compared and their merits and demerits have been focused. The individual algorithm demerits can be overcome by hybrid techniques.

There are few more MPPT algorithms such as adaptive, NN and fuzzy logics are more efficient as they can operate for non-linear systems. The only disadvantage of these models is they require prior training and knowledge for the system they are operating. From the above three model's fuzzy controller computation depends on the number of rules the controller is handling and also its complexity. Fuzzy control requires wind speed data as an input variable and it utilises to generate gate pulses through the fuzzification and defuzzification processes. It requires prior training and the performance is superior compared with other techniques. Its efficiency is better than ORB and its value is 87.46% with convergence speed of 175 ms. This fuzzy controller requires a memory block to store the data and recall whenever required. NN-based MPPT is having better system dynamics and power responses. The efficiency is better as the system performance changes according to the ageing of mechanical parts due to an environmental condition. The complexity is similar to fuzzy, but in the NN, it will have many hidden layers as per the system requirement. In the NN, there are two ways of learning: supervised learning and unsupervised learning. For supervised learning, the target should know, but in unsupervised learning, target is not necessary to train the network.

An adaptive algorithm is a robust approach for stochastic wind changes and power. MVPO requires total power generated from wind farm instead of individual generator power, thereby reducing current sensors compared with the classical solution. The advantage of this method is that it requires a single control as it optimises all generators at the same instant. Owing to this, the total installation cost gets reduced by implementing the MVPO approach.

In [9], a 600 W wind turbine connected to a 1 kW dc–dc boost converter in conjunction with microcontroller MC68HC11A8 is used for studying the performance of MEPT and MMPT is presented experimentally. In this experiment anemometer, MAX 40+ is used that requires 24 V and induces 4–20 mA proportional to the wind speed. The optimum TSR used for study is 4.92 ($\lambda_{opt} = 4.92$). For the experimental study, the microcontroller operates at a

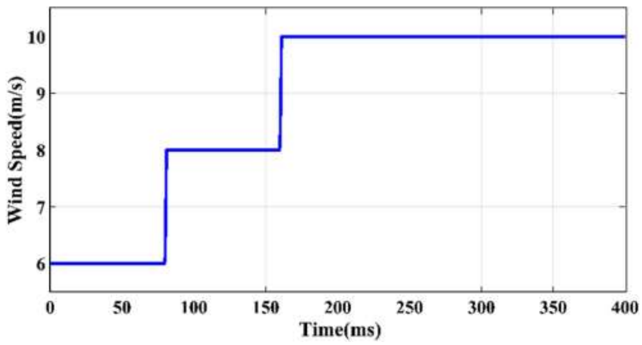

Fig. 21 *Wind speed variation for MPPT performance evaluation*

Table 2 Dynamic response for various MPPT algorithms [14]

MPPT method	Response time, s	Recovery time, s
TSR	0.015	0.2
PSF	0.015	0.22
OTC	0	0.11
P&O	0.025	0.275

Table 3 Efficiency comparison of MEPT and MMPT

Wind speed, m/s	Maximum available output electrical power of the WECS, W	Maximum output electrical power of the WECS extracted by		MPPT efficiency of the MMPT, %	MPPT efficiency of the MEPT, %
MMPT	MEPT				
4	27.1	25.2	26.7	96.88	98.52
6	88.4	85.4	87.7	97.3	98.98
8	221.6	216.6	219.7	97.62	99.14
10	431.4	424.2	428.3	98.04	99.28

Table 4 Components used for the experiment

Name	Range
vertical wind turbine	600 W
dc–dc boost converter	1 kW
op-amp	LTC 1047
microcontroller	MC68HC11A8
anemometer	MAX40+
software	LTSpice IV
switching frequency	100 kHz

sampling period of 100 µs and gives an appropriate duty ratio for tracking MPP of WECS. The measured voltage and current are fed to the converter and the power deviations are measured using MEPT control strategy.

When the slope between power and current is zero, then there is no change in angular speed and input current. The next values are read and proceed further until there is any change in slope.

If the slope is positive, i.e. ratio of power and current at present is greater than the previous value. Then, angular speed is decreased which is achieved by increasing the duty ratio.

The other possibility is that if the slope is negative, then angular speed will be increased by reducing the duty ratio. In the process of several iterations, it aims to choose the exact duty ratio so that maximum power can be obtained for the better efficiency with the least convergence time. For different power and current value, the changes in the duty ratios are as follows:

$$\Delta d = \begin{cases} 0.100 \text{ when slope} \geq 10\,\text{W/A} \\ 0.010 \text{ when } 1\,\text{W/A} \leq \text{slope} < 10\,\text{W/A} \\ 0.005 \text{ when } 0.5\,\text{W/A} \leq \text{slope} < 1\,\text{W/A} \\ 0.001 \text{ when } 0\,\text{W/A} \leq \text{slope} < 0.5\,\text{W/A} \end{cases} \quad (34)$$

Both MEPT and MPPT are implemented using the variable duty cycle and the condition for selecting appropriate duty cycle is presented in (36). The simulations are carried out by using LTspice IV software, and the wind speed for the case study is shown in Fig. 21.

To know the dynamic response, here we considered only TSR, PSF, OTC and P&O and its response time and recovery time [14] are presented in Table 2.

The efficiency is compared for two MPPT algorithms for different wind speeds and maximum efficiency is obtained at 10 m/s as shown in Table 3.

The specifications used for the experiment to determine the efficiency and convergence of MPPT techniques are given in Table 4.

Table 1 shows that, among various MPPT algorithms, MEPT and MMPT give high efficiency with a short convergence time of 15 and 18 ms. Results taken from the literature are shown as [Lit] and experimental results are shown as [Exp]. When compared with other MPPT techniques, MEPT costs only 44€, whereas for MMPT is 132€ for constructing the model, presented in [11].

Fig. 22 shows the comparison of various MPPT techniques with their efficiency and time of convergence [11]. Among all the MPPT algorithms, ORB gives the slowest convergence with 364 ms and the fast convergence is achieved by MEPT with 15 ms [11].

The efficiency is also very high for MEPT compared with remaining algorithms with 99.28%. While performing the experimental setup, we need to follow some standards that are

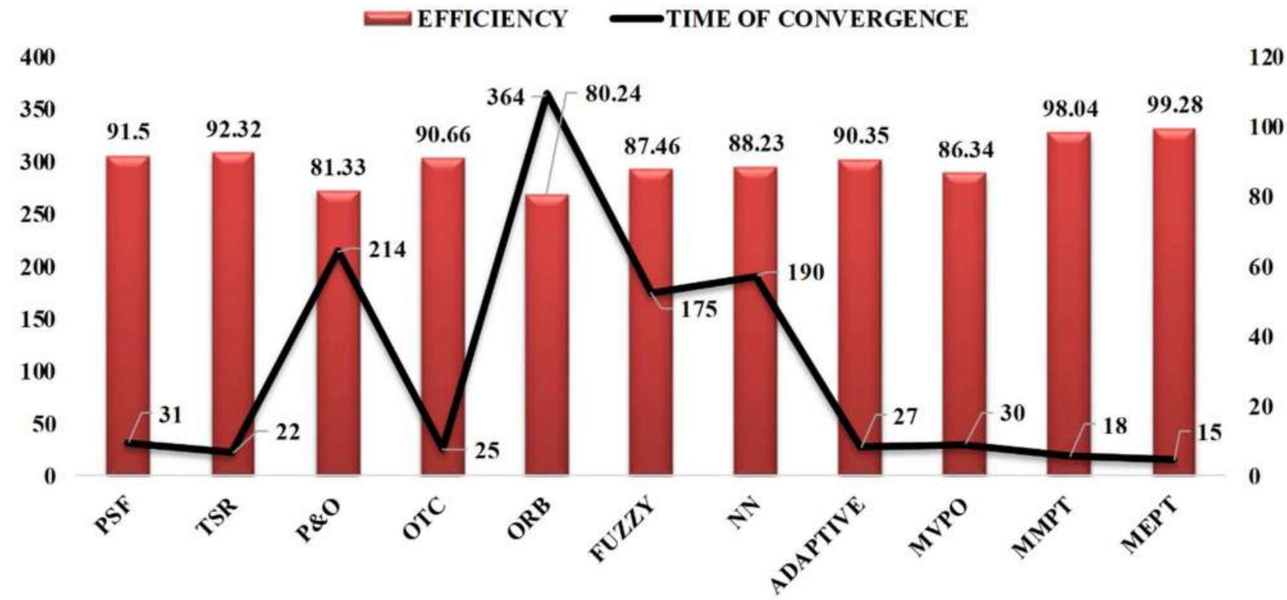

Fig. 22 *Comparison of time of convergence and efficiency for various MPPT algorithms [11]*

given framed in IEC-61400-1 design requirements. We know that wind is dynamic in nature and this is otherwise known as turbulence. When the wind turbines exist in a turbulence effect, the output power, durability and mechanical loading varies. In a long run, the turbine may damage if we did not test under different wind conditions. As per the IEC 60100-1 standards, there are majorly two types of wind conditions, i.e. normal and extreme wind speeds. Frequently, loading conditions are prevalent due to normal wind conditions, and extreme wind condition designs are rare. However, for designing and testing, we need to consider both the conditions for reliable operation of wind turbines. So during testing, the wind must be both normal and extreme conditions as per IEC-61400-1 standards. It is also given in IEC-61400-12 standard that the wind data must be recorded at a rate of 0.5 Hz and the duration of each processing data should be in the range of 30 s–10 min. The standard deviation of turbulence should be about 90% at any wind speed at specified hub height.

6 Conclusion

In this review, various methods and approaches for extracting maximum power from the WECS have been discussed. After comparing different methods for extracting maximum power from the WECS, it has been understood that MEPT with 99.28%, MMPT of 98.04%, TSR with 92.32%, OTC of 90.66% and the PSF with 91.5% algorithms have better efficiency and gives fast response. HCS and ORB have slow response with 214 and 364 ms, respectively. Some algorithms such as adaptive model (27 ms) and NN (190 ms) models showed betterment in terms of time response with higher efficiency. Now, from these many MPPT models, it has been confined that MEPT and MMPT give better efficiency and fast time of convergence including low cost of construction. All the methods have been summarised with their merits and demerits.

7 Acknowledgments

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8 References

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