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Different Methods on MPPT of Wind System: The Last Ten Years

Manan Parmar[1], Mihir Vasavada[2]
Student, Electrical engineering, L.D. College of Engineering, Ahmedabad, India[1]
Assistance Professor, Electrical Engineering, L.D. College of Engineering, Ahmedabad, India[2]

Abstract: This paper reviews and compares the last ten years of work concerning MPPT of Wind System with Different methods. These methods are: Hill Climbing Search (HCS), Optimal Torque Control (OTC), Perturbation and Observation (P&O), tip speed ratio (TSR), Power Signal Feedback (PSF) and Fuzzy Logic control (FLC). However, making a choice on an exact MPPT algorithm for a particular case require sufficient proficiency because each algorithm has its own merits and demerits. For this reason, an appropriate review of those algorithms is essential. Merits, demerits and comprehensive comparison of the different MPPT algorithms also highlighted in the terms of complexity, wind speed requirement, prior training, speed responses, etc. and also the ability to acquire the maximal energy output.

Index Terms: Wind System, Maximum Power Point Tracking (MPPT), MPPT Methods.

I. INTRODUCTION

Environmental concerns in energy generation from the conventional sources make fast development of renewable energy sources (RES), like wind, solar, fuel cell, etc. Rapidly increasing demand for electrical energy and the issues associated with limited reserves and the rising cost of fossil fuels such as oil, coal, and natural gas are also responsible for the growth and rise of renewable energy application [1-3]. In this frame of reference, among the various RES, wind energy is the most adorable and quickly developing source of electricity nowadays [4-6]. Here the crucial concern of the WECS is how to efficiently obtain the maximum output power from wind turbine at all instant in a wide range of wind speed [7]. To maximize the efficiency of the turbine, MPPT algorithm is used to bring the turbine to the MPP for all wind speed values.

II. THEORY

In WECS, electrical energy is generated from wind employing a wind turbine and an electric generator. The wind turbine is coupled to the prime mover either directly or by a gear box setup. The prime mover is coupled to the shaft of the generator's rotor, whereas the stator is linked either to standalone loads or the utility grid by an appropriate power electronic interface [8-12]. This setup converts mechanical energy to magnetic energy and later to electrical energy for the utility grid. The block diagram of a typical grid-connected WECS is shown in Fig. 1.

Output power from the wind turbine can be controlled to work more effectively within a specific range of the wind speeds bounded by cut-in ($V_{w\text{-}in}$) and cut-out ($V_{w\text{-}out}$) speeds. Out of this range, the turbine should not operate for safety of the turbine as well as generator. The rated power (P_{rated}) is obtained from the wind turbine at a specific wind speed (V_{rated}). Consequently, there are four main operating regions as demonstrated in Fig. 2 [13,14].

The first and fourth region is below $V_{w\text{-}in}$ and above $V_{w\text{-}out}$ respectively, where the turbine should be stopped and disconnected from the grid to prevent it from being driven by the generator. The second region is in between $V_{w\text{-}in}$ and V_{rated}, where a wind turbine controller starts to operate to extract energy as much as possible by MPPT algorithm. The third region is in between V_{rated} and $V_{w\text{-}out}$, where it is necessary to restrict the mechanical power generation to the rated power to avoid damage on the turbine. Thus, the MPPT algorithm is required to focus on the second region.

Although there are various types of wind turbines, relying upon fixed or variable wind speed, the maximum energy can be extracted only by variable speed wind turbines (VSWT). In contrast to fixed speed wind turbines (FSWT), VSWT needs a partial or full order power converter for power flow control, MPPT control and delivering a high quality of power [8-12]. Since these turbines can vary their rotational speed to follow the instantaneous variation in wind speed, they are able to preserve a constant rotational speed to wind speed ratio, called the optimum tip speed ratio (TSR) [15] for which the extracted power is maximized. In addition to this, VSWT can be controlled to minimize the stress on the tower structure, gears and wind generator (WG) shaft, since the blades absorb peaks of WT torque during the variation

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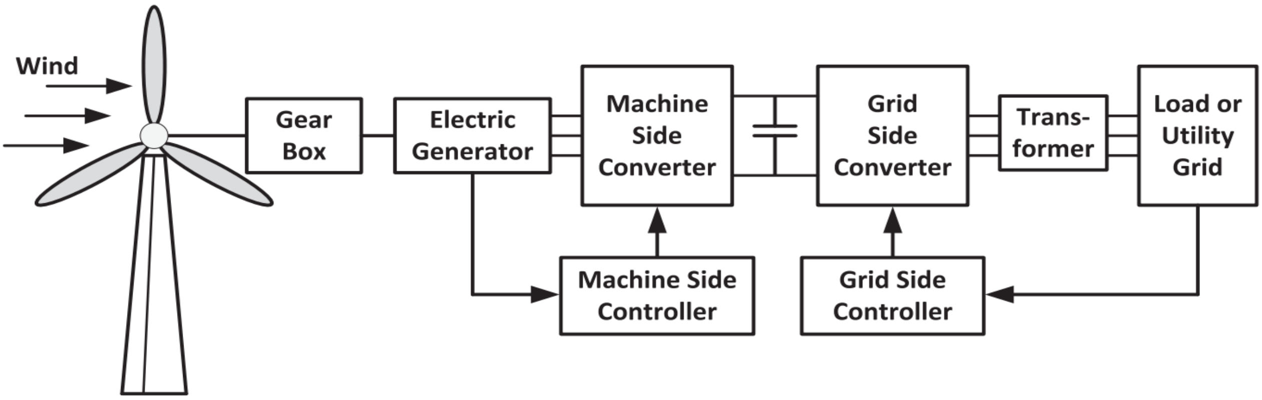

Fig. 1. Block diagram of a typical grid-connected WECS.

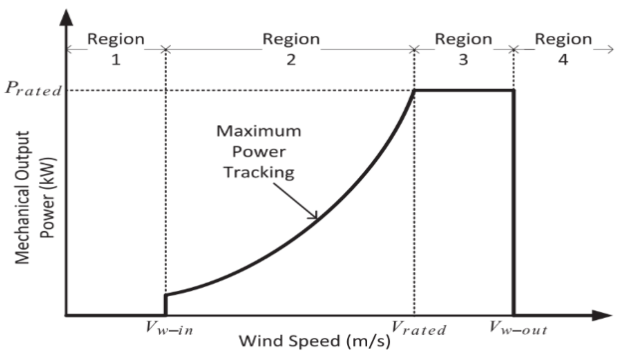

Fig. 2. Wind turbine control strategy based on four speed regions.

of the WG speed of rotation, leading to a longer installation life of WECS [12]. In VSWT system, the electric generators mostly fall into either synchronous generator or asynchronous generator [12,16], in which the prime mover and subsequently the rotor rotate at synchronous and super-synchronous speed respectively for generating mode. The Wound Rotor and Permanent Magnet type of generators are considered under synchronous generator and under asynchronous generator, the Squirrel Cage, Wound Rotor and Doubly Fed type of generators are considered.

III. MPPT ALGORITHM

A. *Tip speed ratio (TSR) MPPT algorithm*

In the TSR control algorithm, it is required to keep up the TSR to an optimum value at which extracted power is maximized by regulating the rotational speed of the generator [17,18]. This algorithm requires measured value of wind speed as well as generator speed to get the optimum TSR (λ_{opt}) of the turbine so as for the system to be in a position to extract maximum attainable power. The optimum rotational speed is determined as: $\omega_m^{opt} = \lambda_{opt} V_w / R$.

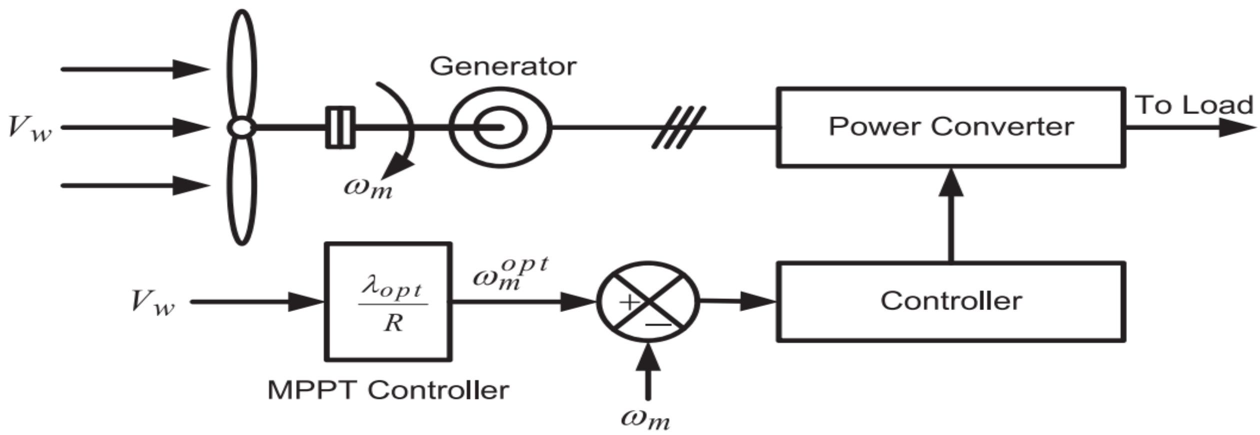

Fig.3 TSR MPPT algorithm of WECS.

The block diagram in Fig.3 shows a WECS with TSR control [19]. In this diagram the optimum rotational speed is compared with the actual value and the difference is then given into the controller, which changes the speed of the generator to reduce this error. It is concluded that this algorithm forces the mechanical power of the generator to track maximum mechanical power.

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The TSR algorithm is highly efficient and quick response [20]. But, the need of an accurate anemometer for measuring the wind speed causes the system more costly, particularly for small-scale WECS.

B. *Power signal feedback (PSF) MPPT algorithm*

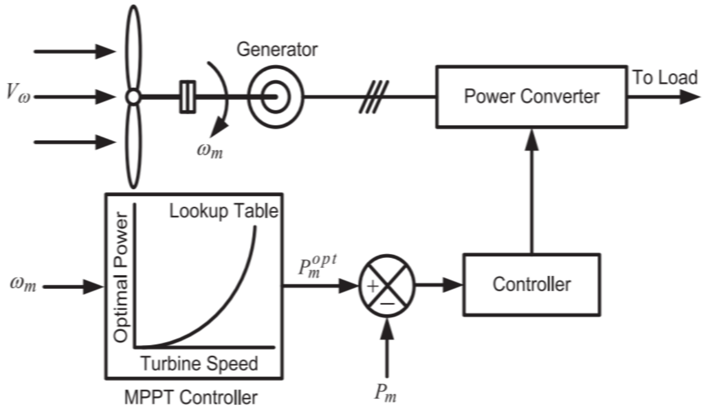

Fig.4 PSF MPPT algorithm of WECS.

This algorithm requires the knowledge of wind turbine's maximum power curve, which is tracked by its control mechanisms [17]. The maximum power curves can be obtained through simulations or experimental tests on individual wind turbines [21,22]. Fig.4 shows the block diagram of a WECS with PSF control [19,22]. In this method, optimum power P_m^{opt} is generated either using a pre obtained power–speed curve, or using the expression of turbine output power, where wind speed or the turbine speed is used as the input. The controller reduces the error between optimum power and actual power.

C. *Hill climb search (HCS) MPPT algorithm*

HCS is a mathematical optimization strategy, to locate the local maximum point of a given function [17,23]. In this strategy, if the operating point is on the left side of the peak point, the controller must move it to the right to be nearer to the peak point, and vice versa if it is on the other side. It is broadly used in WECS to extract maximum power by searching the optimal operating point. HCS MPPT algorithm is based on disturbing a control variable in some step-size and observing the resulting changes in the objective function until the slope becomes zero [24,25]. However, during rapid wind variation it is sluggish and detect the wrong direction to reach MPP. This problem is effectively solved by the modified HCS algorithm. The HCS algorithm also depends on the appropriate step size, lower step size causes sow response of the system and higher step size causes hunting close to the peak point. This demerit can be overcome by fixed and adaptive step HCS algorithm.

The modified HCS algorithm makes proper balance between tracking speed and control efficiency and solves the wrong directionality problem of HCS during changing wind conditions. The variable step size and the direction of the next perturbation are intelligently determined by observing the distance between the operating point and the operating point and the optimal curve [26]. Due to the changes in weather conditions, the air density also varies, which effect the k_{opt}

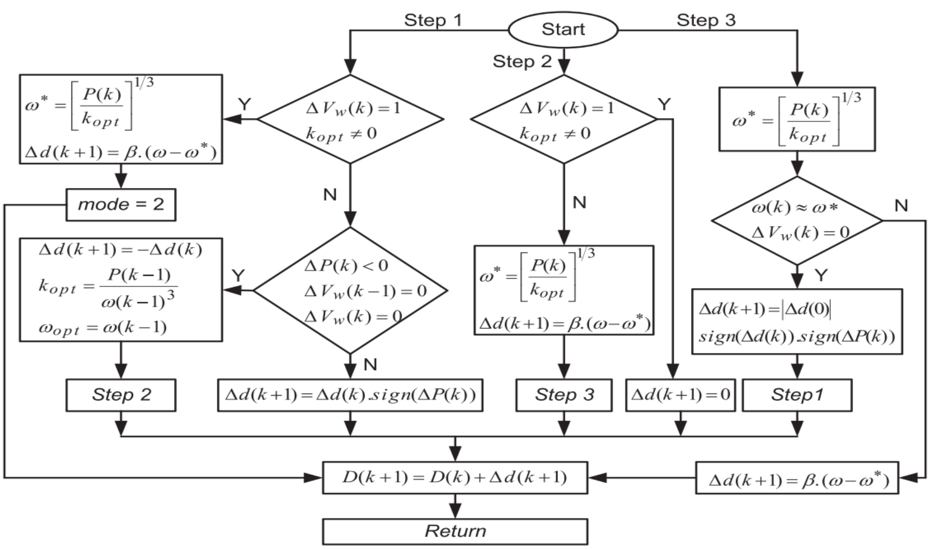

Fig.5 Flowchart of modified HCS MPPT algorithm.

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value as well as optimal power curve characterized by $P_{opt} = k_{opt}\omega_m^3$. The algorithm combines two parts. The first part uses HCS algorithm to track the MPP based on the precise value of k_{opt}. After attaining the peak point, the parameter k_{opt} is online updated in the second part of the algorithm.

The flowchart in Fig.5 shows the three steps of operation [27,28]. Step 1 searches for a k_{opt} value with the aim to track peak point through intelligent HCS method. Step 2 keeps the system at the detected MPP for the constant wind speed (V_w). Under variable wind speed, the online updated k_{opt} value is implemented in step 3. It is not possible to perfectly track the MPP, because the k_{opt} value is different for different wind speeds; however, it moves the operating point around very close to the peak power. Therefore, this strategy is quite useful for fast tracking.

D. *Incremental conductance (INC) MPPT algorithm*

This algorithm is independent of requirement of sensors and specifications of turbine and generator, which improves the reliability and reduces the cost of the system [29,30,31].

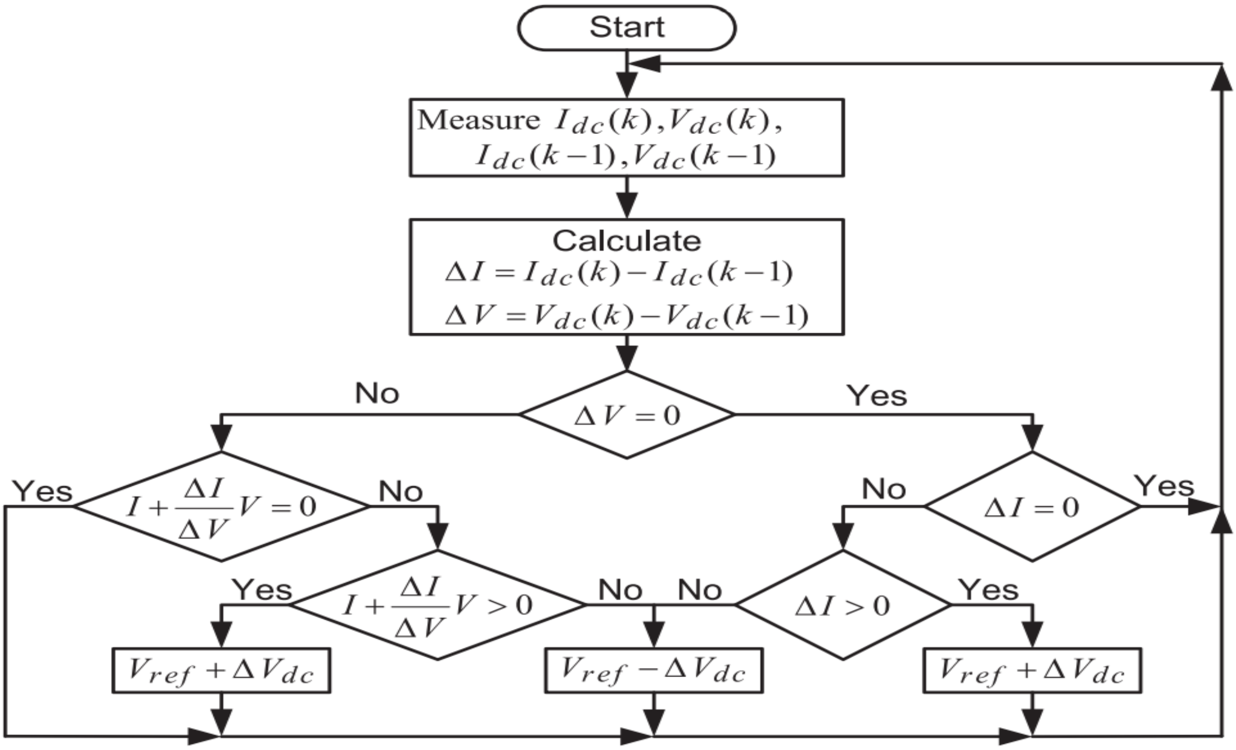

Fig.6 Flowchart of modified INC MPPT algorithm.

The basic principle is defined as the tangent slope (i/v + di/dv) of power–voltage characteristic should be zero at MPP, positive on the left side, and negative on the right side of MPP as described in Fig.5. The above equations signify that instead of observing for weather dependent parameters like speed and direction of wind, the MPP can be tracked by looking for output power of the rectifier.

The modified INC algorithm improves the performance of the INC algorithm by considering a variable step for Vdc variations as shown in Fig.6. It automatically adjusts the step size to track the MPP in WECS [32,33,34,35], which leads to enhancement of system accuracy and convergence speed. The implementation of Model Predictive control in wind turbine MPPT controller improves speed and reliability, and also mitigates the problem of oscillations around MPP [36]. The range of V_{dc} variations (ΔV_{dc}) has been limited, which changes depending on system design parameters and size of generator. Introducing variable steps in this algorithm causes the operating point to reach the peak power more rapidly and reduction of power fluctuation around MPP.

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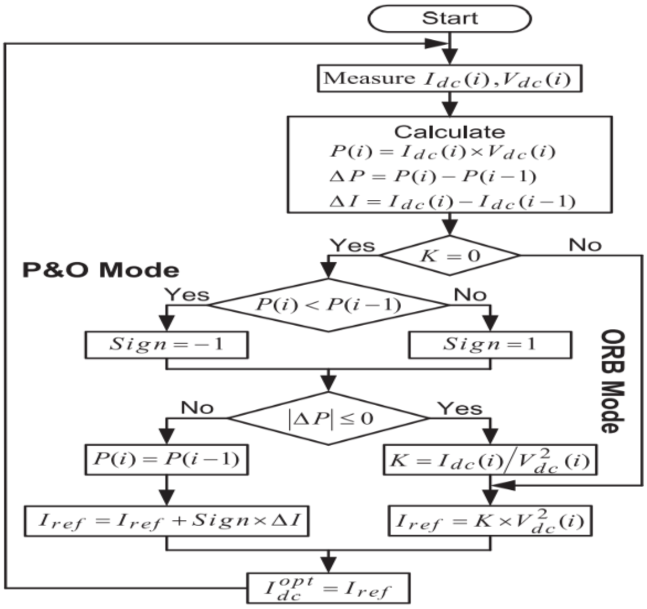

Fig.7 Flowchart of hybrid of the ORB and P&O MPPT Algorithm.

E. *Hybrid MPPT algorithm*One simple and effective solution to overcome the drawbacks of the conventional MPPT algorithm is by hybridization of two or more MPPT algorithm [37,38,39,40]. The ORB MPPT algorithm is combined with a self-tuning capability using the conventional P&O algorithm is demonstrated in Fig.7 [37,41]. In this algorithm, there are two modes of operation: the first one is a P&O mode, in which the conventional fixed step P&O MPPT algorithm is initially activated to search for an MPP at any local wind speed. Once the MPP is detected and the voltage and current are measured, the unknown parameter (k) in the ORB algorithm is easily calculated. Once the k is extracted, it will be used to calculate the optimal current curve, and at that time the hybrid MPPT algorithm switches to the second mode, which can track the MPP based on the equation of the ORB algorithm [42].

F. *Fuzzy-based MPPT algorithm*

Many control strategies have been proposed that use the Fuzzy Logic Control (FLC) for MPPT applications either independently or along with other methods. The main advantage of such controllers is that controller parameters can be changed very quickly in response to changes in the system dynamics without parameter estimation [45]. When the climatic condition changes, the performance of a fuzzy based MPPT algorithm is strong, however, their strength depends a lot on the knowledge of the user in choosing the appropriate error, levels of membership functions and selection of rule base [46]. The memory requirement also poses limitations in its implementation.

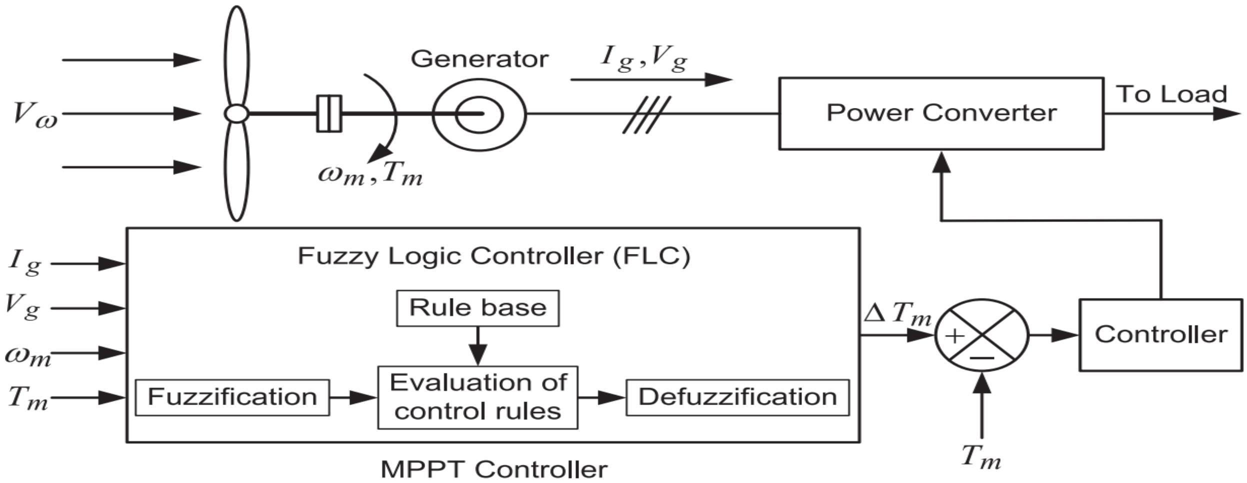

Fig.8 Fuzzy-based MPPT algorithm of WECS.

Literature use the difference between the P_{max}&P_{out} and the derivative of this signal as inputs with standard triangular membership functions for both input and output. Generator power and output torque variation are used as inputs in with triangular membership functions and seven rule base table. A rotational speed and an aerodynamic torque observer are taken as the input values of fuzzy-based MPPT as described in Fig.8. Another two input parameters, ΔT_a and $\Delta \omega_m$, are used to limit torque and speed variation. These input parameters are converted into predefined membership functions and sends them to an FLC. The FLC calculates output parameter, i.e. output torque by using the rule base and defuzzification method.

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G. *Neural network (NN)-based MPPT algorithm*

Similar to Fuzzy logic controller, the neural network (NN) have become popular and expanded with the development in soft computing technology [43,44]. The architecture of a Neural Network consists of three layers: input, hidden, and output layers and the number of nodes in each layer vary and are user dependent as shown in Fig.8 [47]. The input variables can be pitch angle, terminal voltage, output torque, wind speed, rotor speed, etc. or any combination of these variables. The output is generally a reference signal like reference power, rotor speed, reference torque, etc. that is used to drive the power electronic circuit of wind turbine close to the MPP. The convergence of operating point to the peak point depends on the weights assigned to the layers, the type of algorithm used by the hidden layer and the training given to the neural network for a particular system for different input–output patterns.

Fig.9 shows NN-based [44] wind speed sensorless MPPT algorithm for wind turbines, in which it uses the rotor speed (ω_m) and the output power (P_m) of the turbine as input variables. Due to the inertia of the system, rotor speed cannot change suddenly. Therefore, output of the NN is required to change gradually, from which the optimal rotor speed, ω_m^{opt} for the speed control mode is obtained and then it is set to control the generator to obtain the optimum power, P_m^{opt} for the power control mode. From the above process, ω_m and P_m can be used to directly obtain ω_m^{opt} and P_m^{opt}. Such relationships are learned by the NN using the training data. The above procedure decreases the speed response time, so the system settle down to the steady state faster than the power control mode and provide a smoother power transition in the speed control mode during wind speed variations. Therefore, this MPPT control represents a better trade off in terms of the system dynamic speed and power responses.

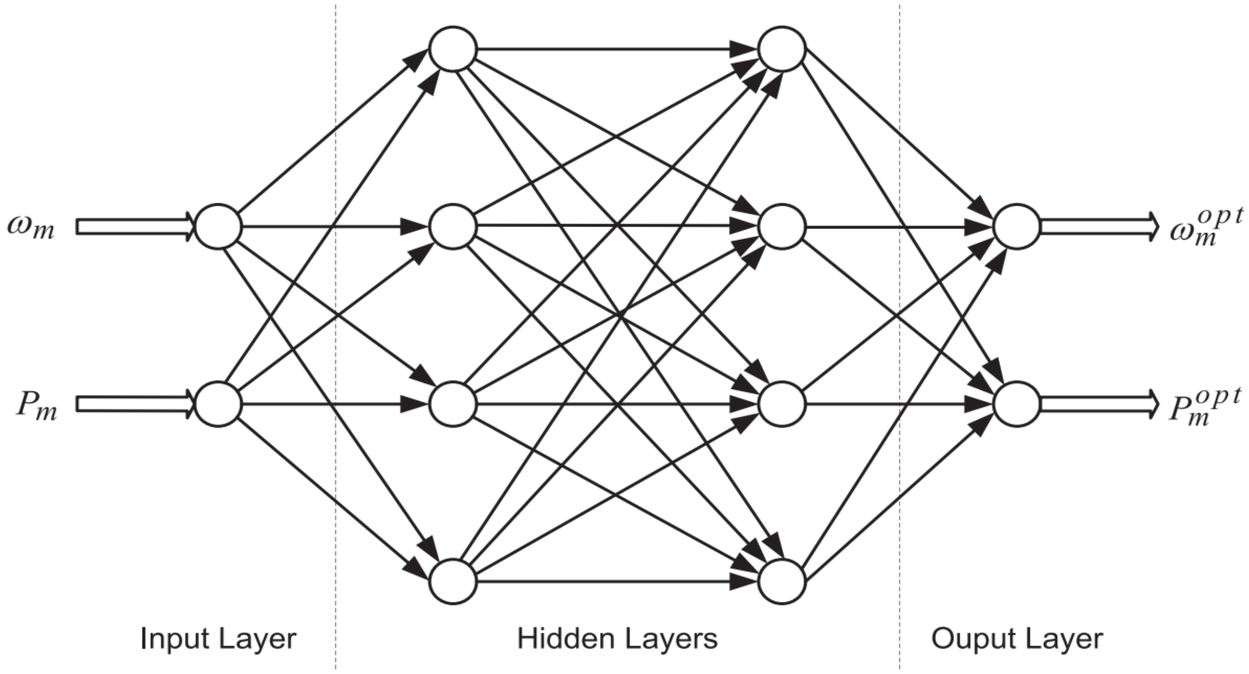

Fig.9 Structure of NN used for estimation of optimal turbine power and speed.

IV. COMPARATIVE ANALYSIS

From the above analysis of different MPPT techniques a comparative Table 1 was prepared in terms of complexity, convergence speed, wind speed measurement, performance, memory requirement and prior training. The main aim of the MPPT algorithm is to track the optimum power point of variable speed wind turbine. Choosing an appropriate MPPT technique is a tough task. In comparison, the indirect power control based algorithms such as TSR OT and PSF are simple and fast, but it maximizes the captured mechanical wind power instead of output electrical power. TSR control has good performance with fast response and high efficiency. An accurate anemometer is required, due to gust and turbulence, which is expensive and adds extra cost to the system, especially for small-scale WECSs. Practical implementation of this algorithm is difficult because the wind velocity close to the turbine is different from the free stream velocity. OT method is simple, fast, and efficient without wind speed sensor. However, it does not measure the wind speed directly, therefore, variation in wind speed is not reflected instantly and significantly on the reference torque, which makes the efficiency of this algorithm less as compared to TSR algorithm. The PSF and the OT algorithms are

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approximately similar in terms of complexity and performance. This algorithm provides robust and cost-effective MPPT control for WECSs.

Direct power based control techniques such as HCS, INC and ORB are simple and memory requirement is also less. These techniques calculate the optimal electrical power directly without prior training and measurement of wind speed. However, the performance of these algorithms is not satisfactory during wind variation and so their application is limited under varying wind conditions. These are also sensorless algorithm, which makes it cheaper and more reliable. HCS algorithm is common and simple to implement because it does not need any measurement of the mechanical quantities like rotor speed, turbine speed or wind speed. The algorithm is system independent and its tracking is not affected by the turbine or generator parameter shifts. By using the HCS algorithm, maximum power corresponding to any wind velocity can be captured. But the time taken to reach MPP is long and a considerable amount of power loss takes place during the tracking phase.

Algorithm	Complexity	Convergence speed	Memory requirement	Wind speed measurement	Performance under varying wind conditions	Prior training/ knowledge
TSR	Simple	Fast	No	Yes	Moderate	Not required
PSF	Simple	Fast	Yes	Yes	Moderate	Required
HCS	Simple	Low	No	No	Moderate	Not required
Modified HCS	High	Fast	No	No	Very good	Not required
INC	Simple	Low	No	No	Moderate	Not required
Modified INC	Medium	Medium	No	No	Good	Not required
Hybrid	Medium	Fast	No	No	Good	Not required
Fuzzy-based	High	Medium	Yes	Depends	Very good	Required
NN-based	High	Medium	Yes	Depends	Very good	Required

Table.1 Comparison of described MPPT algorithm based on different characteristics

The other MPPT algorithm like adaptive algorithm and soft computing based algorithm such as Neural Network and fuzzy logic very efficiently predict the optimal power and handle the nonlinearity of the system but previous knowledge about the system is required. Fuzzy control-based scheme is good; however, the computation time depends upon number of rules in controller which is based on system complexity. NN based MPPT control represents a better trade-off in terms of the system dynamic speed and power responses. The efficiency of the NN control strategies is generally good, since most mechanical parts have varying characteristics with aging and under different environmental conditions. The neural network has to be periodically trained to guarantee accurate MPPT.

V. CONCLUSION

Due to the increasing penetration of wind turbine in the power system grid it is necessary to extract maximum power from wind. For this purpose, a suitable MPPT algorithm is required. This paper presents a comprehensive review and discussion of the different MPPT algorithm used in the WECS. From the comparative study it has been observed that TSR, OT and PSF algorithms respond very fast respective to HCS, INC and ORB algorithm, but latter algorithms are extremely reliable and implementation cost is very low. From this study, it has been observed that the performance of adaptive and soft computing based MPPT algorithm is most promising due to higher efficiency and flexibility. Most of the important characteristics of MPPT are discussed and summarized in this paper. The last remarks put in evidence of the lack of a clear methodology to determine what is the best MPPT architecture and technique for a given installation.

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