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Maximum Power Point Tracking in Solar PV System – A Review

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Abstract

Photovoltaic (PV) technology is becoming increasingly prevalent. The popularity of solar PV technology stems from the fact that it has no negative environmental impact and generates energy from a renewable resource. i.e., sunlight. Although PV cells do not create any hazardous issue for the environment but due to various reasons, they are able to produce only a moderate amount of electrical output. Although researchers have developed PV cells with efficiencies up to 50 %, yet most of the commercially available Solar PV panels convert only 15-20 % of the insolation into electrical energy. Main problems faced might be due to poor weather conditions, partial shading, and many others. Maximum power point tracking (MPPT) is a methodology used in photovoltaic systems to extract most power out of the cells. The paper explores the implications of several investigations performed on the problem of attaining the maximum power point (MPP) in a photovoltaic system. The parameters observed are convergence speed, implementation complexity, parameters sensed, and True MPPT.

Keywords: Solar Photovoltaic, MPPT, Renewable Energy, Grid Connected PV, Full and Partial Shading

Introduction

Renewable energy is a source of green energy available in the nature like sunlight, wind, geothermal heat, rain, ocean tides and others. Unlike non-renewable resources like fossil fuels, the distributed resources of energy are non-exhaustible [1]. To generate electrical power from distributed generators, solar insolation and wind energy are the most common sources of energy. Although smooth integration of solar power with the grid also requires efficient control strategies [2], solar energy is still the most preferred resource, as power generated from wind turbines is highly unpredictable [3].

The electricity generation through PV cells is an environment friendly method [4]. A solar PV system is a system comprised of one or more solar cell panels which are combined with inverter and other electrical and mechanical hardware components [5]. Photo voltaic cells capture the sunlight and convert it into electrical energy exploiting the photo voltaic effect. A single PV cell panel produces a little amount of electrical energy. Several solar PV panels are joined to create a solar array. An array can produce higher amount of electrical power than a single solar PV panel [6].

The array's direct current (DC) output will be integrated into the electrical utility system. This needs DC to AC (alternating current) conversion. A complete solar PV unit contains photovoltaic panels, together with all the components of BOS (Balance of System) like inverters, battery, chargers, disconnects, circuit breakers, wiring, racking, etc. [5]. Fig.1 [7] shows a basic photo voltaic system. The inverter converts DC to AC and simultaneously, the inverter output can also be fed straight to the home appliances.

On the basis of functionality, component configuration, system operation, and connected equipment, the two broad classifications of PV systems are as under:

- Grid connected PV system
- Standalone PV system

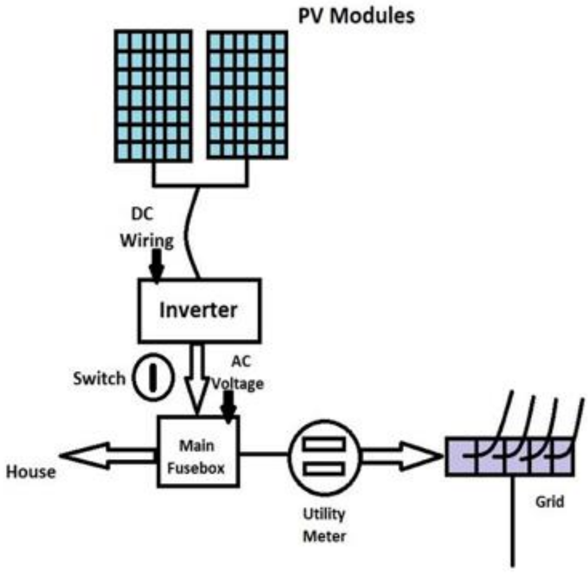

Fig.1 *Photo voltaic system*

The grid connected PV system is built to operate parallelly and is coupled to the utility grid. This type of system mainly consists of inverters for converting DC to AC. The inversion from DC to AC is always according to the power and voltage demand of the grid. In case the PV module output is greater than the demand of the load, the AC is fed back to the grid through a two-way interconnection between the utility network and the AC output circuits of the PV system. Fig.2 [8] shows the block diagram of the system.

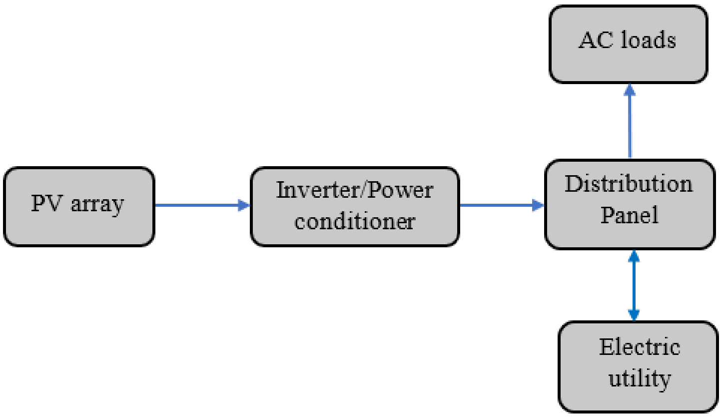

Fig.2 *Grid connected PV system*

Standalone PV systems operate independently, without any connection with the grid. The standalone PV systems supply either AC or DC loads. Simple standalone PV systems are direct coupled systems. As the battery module is absent in a direct coupled system, it operates only in the sunlight hours and do not store energy. Another category of standalone PV system powering DC and AC loads with battery storage is shown in Fig.3 [8]. In general, stand-alone PV systems are suitable for running small appliances, pumps, fans etc.

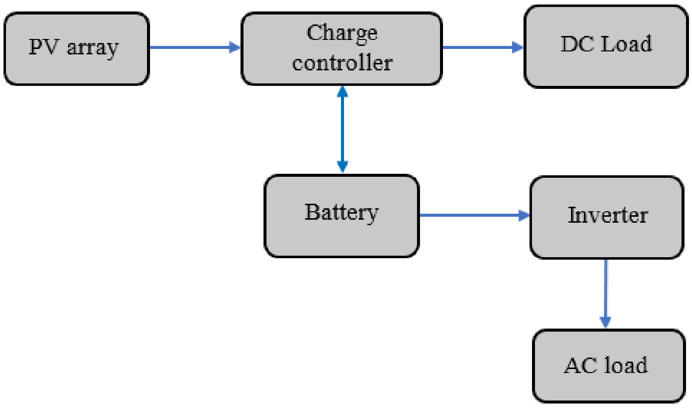

Fig.3 *Standalone PV system with battery storage*

PV systems are environmentally favorable, yet they are not very efficient. The main problems are low conversion efficiency and unreliable weather conditions. The operating point of a PV module is largely dictated by the connected load at its output. To get maximum power delivered by a PV module, it is therefore imperative to run the PV module at the operating point corresponding to the maximum power, called the MPP.

Tracking the array's MPP is an important element of a PV system. The output of a solar array varies depending on irradiation and the temperature. At the MPP on the solar array current-voltage (I-V) curve, the PV system operates on maximum efficiency and gives the highest output. The graph in Fig.4 [9] shows current vs voltage graph for MPPT. The MPP for a PV system needs to be calculated using some algorithms. Therefore, MPPT techniques are required [10].

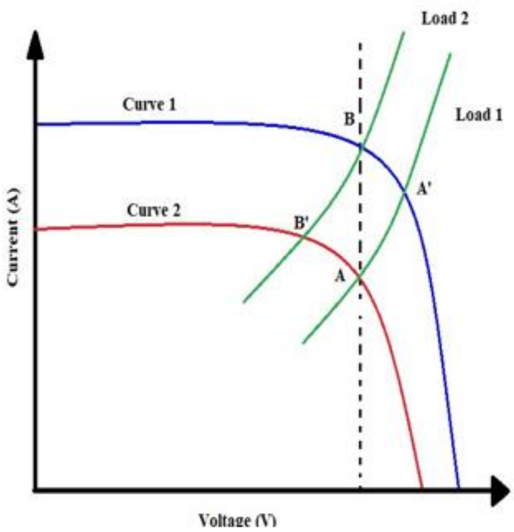

Fig.4 *I-V curve for MPPT*

The MPPT technique raises the efficiency of a solar panel. The maximum power transfer theorem asserts that the power at output terminals of a circuit is maximum when the impedance of the connected load is equal to the circuit's Thevenin impedance. The problem of MPP tracking is same as matching the impedance of a circuit [11]. Load impedance can be matched with that of source by changing the boost convertor duty cycle [4]. The boost convertor is connected at the source side of the circuit to raise the voltage at load terminals.

Though some accurate and efficient MPPT algorithms are available for extracting maximum power, yet environmental and PV panel conditions also affect the amount of power generated and hence the power extraction using MPPT. These problems can be

- Changes in irradiance and temperature causing output to fluctuate. [12].
- Poor weather, geographical location, shading, dust accumulation on panels causing appreciable reduction in the output [8].
- Hotspots in the panels giving rise to short-circuiting and leading to poor performance and decreased lifespan of the panels.
- Micro-cracks and internal corrosion in the panel, which eventually damage the panels and reduce their lifespan [13].
- Potential Induced Degradation (PID), which reduces the performance and accelerate the aging of the panels [14].

Literature Review

The intent of this review article is to explore the various techniques introduced in recent times to detect the MPP in PV systems. The MPPT is used to optimize the performance of the PV systems. With various weather conditions hindering the optimal performance of the PV systems like varying irradiance levels, varying temperatures, shading (full and partial), and so on, locating the MPP for optimal output is of utmost importance. The recent works considered in this literature survey provide their contribution to the field.

Gavali and Deshpande [15] presented a particle swarm based optimization (PSO) algorithm. The purpose of the paper is to devise a MPPT technique for PV systems to help deliver maximum power while under various environmental conditions using PSO algorithm. Usually, this algorithm is used to optimize non-linear functions and while a conventional PSO algorithm is used to solve problems having time invariant targets. The block diagram of Fig.5 [15] represents the Simulink implementation of the proposed model.

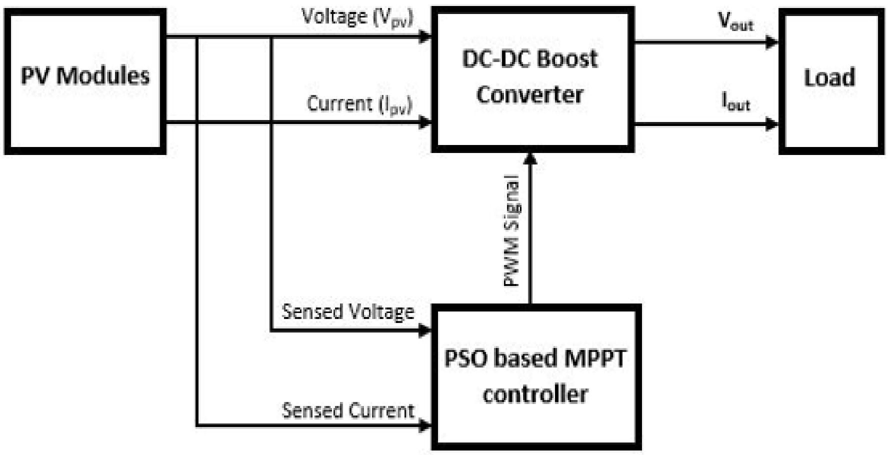

Fig.5 *Simulink implementation*

The paper modifies the PSO algorithm to suit the requirements of MPPT technique to give the equation,

$$P_{pv}\{d_i(K+1)\} > P_{pv}\{d_i(K)\} \quad \text{.....................(1)}$$

Where,
P_{pv}= PV module power output
d = duty cycle of PWM
i = particle number
K = Looping cycle number

The paper implements the module in Simulink. The paper connects two KYOCERA KC 120 modules in series to provide the total output of the panel as 240 W. The paper compares the results obtained after applying the PSO algorithm with that of perturb and observe (P&O) MPPT algorithm under the condition that G = 1000 W/m^2 and T_c = 25° C. The results infer that the PSO algorithm tracks the P_{pv} efficiently, with reduced oscillations, and instantly as compared to P&O algorithm. The PSO algorithm has an efficiency of 98.54 % with a power output average of 236.85 W, whereas P&O algorithm has an efficiency of 97.40 % with a power output average of 233.75 W. The demerit of applying PSO is that it has low convergence rate when it is iterative and falls into a local optimum.

Zandi and Mazinan [16] suggested artificial neural network (ANN) to provide high speed and convergence precision to obtain the MPP in PV system. The paper tracks the MPP in shadow mode by implementing ANN. Fig.6 [16] shows the schematic of the proposed system.

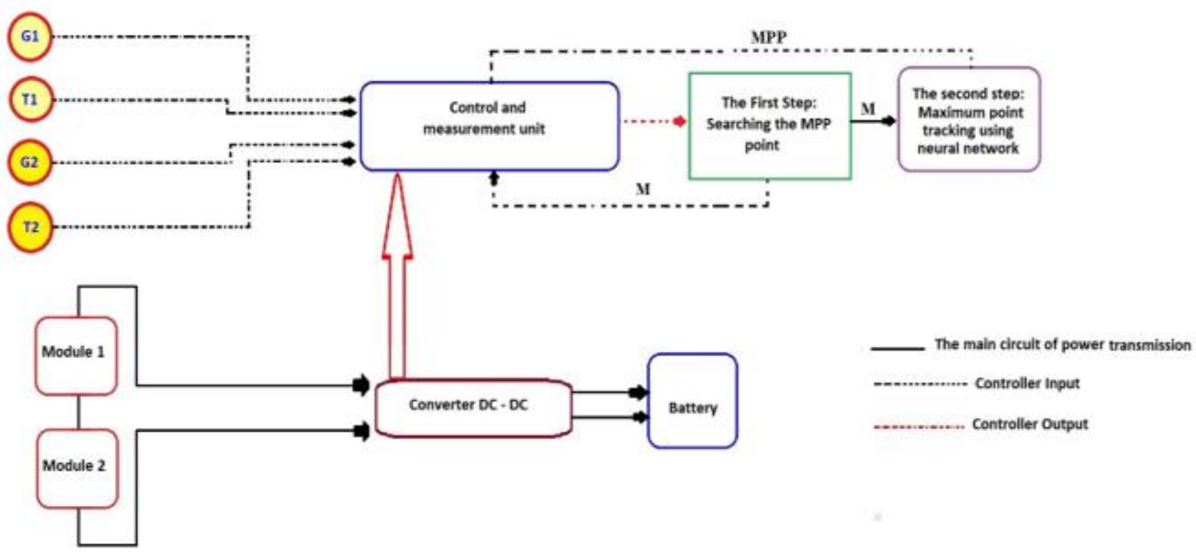

Fig.6 *Proposed system schematic*

To locate the MPP, the equations used are as follows:

$$D = \frac{V_O - v_i}{V_O} \quad \text{..........................(2)}$$

$$a_{m+1} = f_{m+1}(W_{m-1}a_m + b_{m+1}) \qquad \text{.......................(3)}$$

$$D_{opt} = \frac{V_O - v_{i-mpp}}{V_O} \qquad \text{.......................(4)}$$

Where,
$a_0 = \text{p}$
$m = 0, 1, \ldots\ldots, M - 1$
$a = a_m$

The paper implied that if the duty cycle (D_{opt}) corresponding to maximum power point is known at any given temperature and radiation condition, then the operating point of array can be directed to the point of maximum power output by comparing D_{opt} and D. The input to the ANN is the change of the power to the output voltage of the PV array and its output is the optimal duty cycle. The ANN's design is R-S1-S2, where R is the number of inputs in the network, S1 is the number of neurons in the hidden layer (100), and S2 is the number of neurons in the output layer (1). The back propagation rule is used, and the estimated error is less than 0.0002. Three simulations are carried out named 2 Stages Neural Network Simulations (2S-NNS) 1, 2, and 3. All the simulations correspond to various weather conditions. In 2S-NNS1, the system reaches MPP point precisely with tracking error < 1 % and converges to the real values in 0.005 s. In 2S-NNS2, the system reaches MPP with tracking error < 0.5 %. In 2S-NNS3, the system reaches MPP with a better accuracy compared to the previous two systems, with a tracking error of almost 0. According to the paper, the efficiency of the feed forward, two stage, and neural network for MPPT is greater than 98 % with a convergence time of 10 milliseconds. The use of ANN leads to some disadvantages such as network complexity, hardware dependence, and so on [17].

Gosumbonggot et al. [18] come up with a short ranged MPPT algorithm for a series connected PV system in partial shading scenario. The paper focuses on the issue of partial shading, which is a major factor affecting the optimal operation of PV systems. Shadows can hinder MPPT by shading the points of maximum power. Partial shading degrades the PV cells, thereby generating less energy. As indicated by the following equation, if the change in temperature is insignificant, then the photocurrent of PV is almost proportional to the irradiance.

$$I_{ph\_m} = \left(I_{sc\_n} + K_i \Delta T\right) G_i \qquad \text{.......................(5)}$$

MATLAB-Simulink functions are utilized to program the short-range tracking algorithm. The paper provides three cases to observe stable tracking of the MPP with results i.e., case1 with tracking power, voltage and error percentage of 109.3 W, 54.96 V and 0.09 respectively, case2 with tracking power, voltage and error percentage of 73.94 W, 56.20 V and 0.14 respectively, and case3 with tracking power, voltage and error percentage of 55.99 W, 56.16 V and 3.61 respectively.

The results conclude that the new method detects the MPPT without having to follow the entire range of PV curves. The Fig.7 [18] depicts the PV graph of the performance of the proposed model. Tracking begins with the scanning of ranges that reach the peak during the first 0.001 s, then the system recognises the MPPT and keeps tracking towards it. The third inspection has the damping up to 13.6 % but the power response was more stable after 0.009 s with less damping. Partial shading distributes power peaks in the PV curve and the short-range tracking tracks the Global MPP. The MPP is identified within 0.003 s. The paper also compares this method with P&O algorithm for MPPT tracking. The results of the paper are better in comparison to the P&O algorithm. The drawback of the suggested system is that as it progresses along the PV curve, the damping increases.

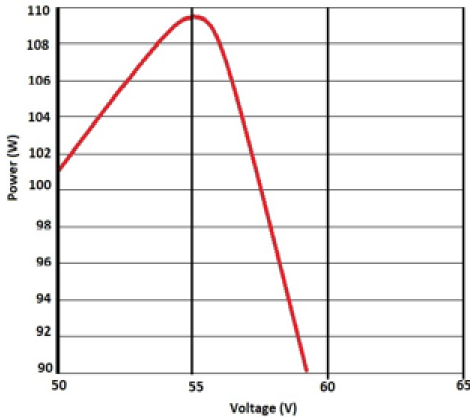

Fig.7 *PV graph of the proposed model's performance*

Gosumbonggot et al. [19] also proposed a method for attaining high efficiency and quicker tracking of operating power for the PV systems even under partial shading. The method proposed is called Partial Shading and Global Maximum Power Point Detections. The graph thus obtained after applying this method is depicted in Fig.8 [19]. The algorithm proposed can be divided into the main program and the global MPP tracking slope calculation program. The paper proposes two cases, one short term and one long term. The changes in weather are simulated by performing both short term and long-term testing. The formula for tracking global MPPT slope is given as,

$$Peak\ detection\ slope = \frac{P_{HIGH} - P_{LOW}}{V_{HIGH} - V_{LOW}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots(6)$$

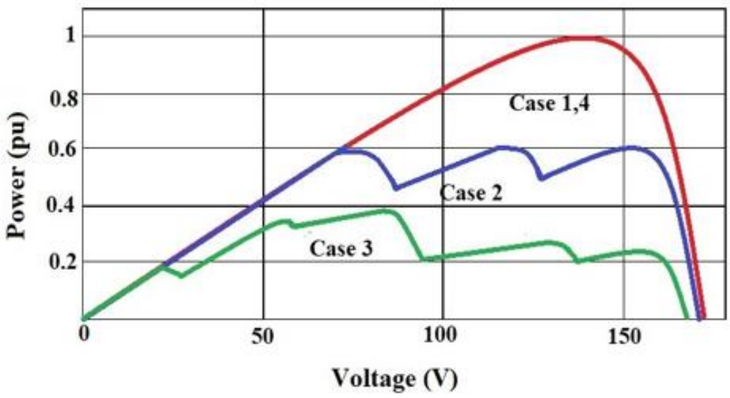

Fig.8 *PV graph of the proposed system*

The simulation of the proposed method is done in the MATLAB-Simulink environment. In the short-term condition, the algorithm shows successful tracking. When there is no shading, the PV curve stabilises at 1023.5 W and changes to 554.4 W under shading condition. In case of long-term testing, the results were tabulated to be 1.7766 kWh with an increase in power of 5.71 % for the rapid change, 3.6467 kWh with an increase in power of 9.09 % for the high level with a steady change, and 0.9886 kWh with an increase in power of

8.69 % for the low level with a steady change. The results are positive for the new proposed model. The power generated shows an increase of 9.09 % in shading conditions. This method has a disadvantage that when the slope of PV curve is positive, there exist a neglect of tracking.

Premkumar and Sowmya [20] devised an efficient tracker to find MPP in a partially shaded PV system. The emphasis is on the effect of partial shading impeding the maximum performance of PV systems. The method suggested is based on the whale optimization (WO) algorithm with a reinitialization process. The algorithm adapts to the shadow pattern and attempts to pin-point the global peak with high tracking efficiency as well as high rate of tracking. The proposed algorithm eliminates the calculation problem that is commonly encountered by hybrid MPPT techniques. Power oscillation during the fluctuating operating conditions is mitigated. The paper implements the WO algorithm for finding the MPPT as shown in Fig.9 [21]. The WO-MPPT finds the global point with less power oscillations and the tracking was highly efficient. The WO-MPPT controls the duty cycle assuming the position of the up-to-date search agent to reduce power oscillation. Power fluctuation is reduced, and efficiency is increased, thanks to the direct control method. If the search agents are in a close range, the position of the best agent is updated.

Fig.9 *The depiction of Whale Optimization Algorithm*

Based on the simulation results, the paper concludes that the WO algorithm is better than the results of other MPPT techniques like P&O and many others as it gives high gain and less loss of power. The WO-MPPT is capable of operating in different conditions like rapid and extreme isolation change and so on. The tracking efficiency of the proposed system is > 95 % and convergence time is < 0.15 s. The disadvantage in using the Whale Optimization algorithm is that the algorithm is less efficient in inspecting the search space.

Fatemi et al. [22] come up with a new form of P&O algorithm. The paper focuses on the problem of sudden climate parameters which influence the efficiency of the system. The P&O algorithm is an old tracking technique that the paper tries to enhance into a three-point P&O tracking technique.

The simulation is developed and executed in the MATLAB/Simulink environment. The paper compares the three-point P&O algorithm with the Hill Climbing algorithm based on variations in power, MPP and output voltage. Based on a model of a practical single diode, the two algorithms are implemented separately. Under ambient conditions simulated in the MATLAB, the three-point P&O is superior to the Hill algorithm in tracking MPPT as well as power fluctuations. Even under varying conditions, the three-point P&O excels Hill Climbing algorithm for the variables given above. The Fig.10 [22] depicts the graph obtained after simulation of the model.

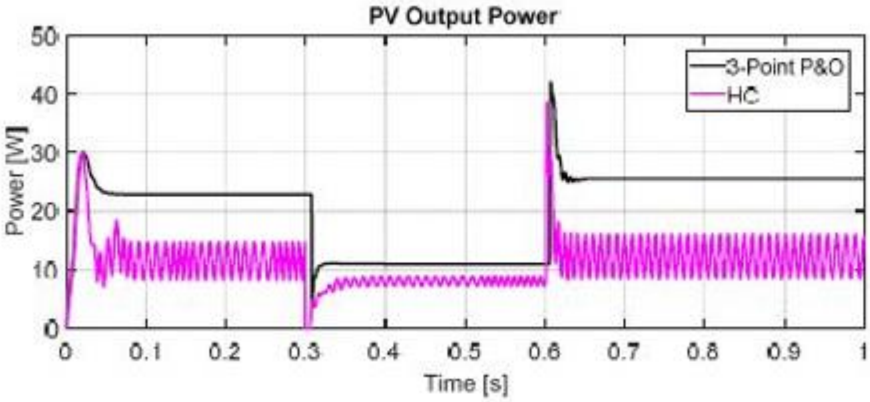

Fig.10 *PV power output under varying conditions*

By comparing the three-point P&O and the Hill Climbing algorithms, it is deduced that under both stable conditions as well as varying conditions, the three-point P&O algorithm shows better performance. The proposed algorithm produces higher power output while the duty cycle is not constant. The downside of using P&O algorithm is that oscillations are present around the MPP.

Azad et al. [23-24] compared the two algorithms, P&O and incremental conductance (INC) method in terms of speed, complexity, sensors used and efficiency and concluded that INC method performs better to extract maximum power. While the P&O algorithm can give global electrical efficiency of 97.58 %, the highest efficiency of 98.53 % can be achieved by integration of Incremental Conductance algorithms into the MPPT controller [24]. Azad et al. [25] also proposed P&O method for varying weather conditions to match the load on MPPT with maximum power offered by the PV generator with highest electrical efficiency.

Bataineh and Hamzeh [26] proposed an MPPT algorithm that implements the concept of search algorithms for PV power generation systems, with the goal of achieving efficient operation under both stable and varying weather conditions. The irradiation and temperatures are simulated to be stable and vary in the testing of the paper's proposed algorithm. The algorithm's performance is also investigated under full and partial shading conditions. The aim of the paper is to provide an optimal MPPT algorithm that allows both stand-alone and grid connected PV systems to function at the optimal conditions under stable and varying weather conditions. Fig.11 [26] shows the proposed model.

The search algorithm has the advantage of not requiring knowledge of PV cell characteristics, of being simple to execute, and of providing definite convergence. The proposed algorithm makes use of the Lipschitz search method, which has the ability to limit the function's change rate. It also makes use of the Shubert algorithm. The model of the suggested algorithm simulates the PV cell's performance based on changing and steady factors of irradiation and temperature. The proposed model is a PV panel attached to a DC-DC boost converter that has resistive loading. The model for the proposed algorithm is tested using a simulation in MATLAB/Simulink. The results show that the proposed system performs efficiently under various extreme weather conditions compared to P&O algorithm. The MPPT is found in 0.7 s, the model takes smaller response times, and steady state MPPT is reached by stabilising the oscillations. The proposed model finds the global MPPT under full and partial shading conditions. The disadvantage of using Lipschitz search method is that the algorithm has large no. of iterations towards finding the convergence point.

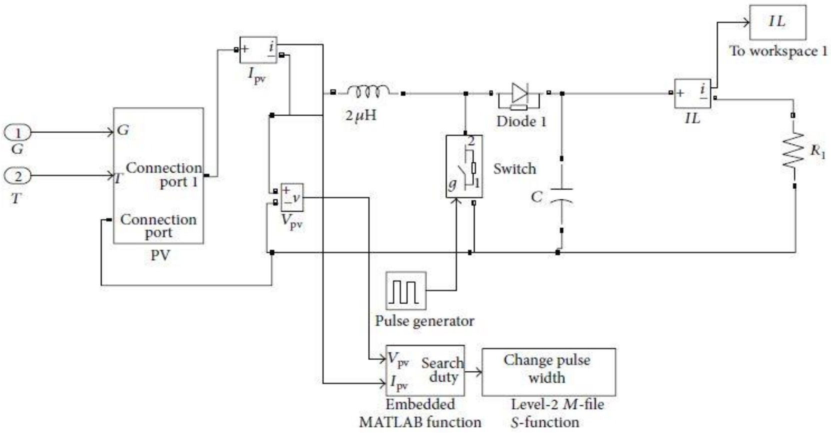

Fig.11 *Simulation model of the proposed system*

Thueanpangthaim et al. [27] devised a MPPT algorithm for stand-alone PV systems using a current based method. The proposed system tries to mitigate the disadvantages faced by the P&O technique in giving a transient and steady response. The algorithm provides MPPT for all the irradiance values. The authors preferred current based method for finding the MPPT. Using the current based approach, the method gives better transient as well as steady state responses. Figure 12 [27] shows a model of the system, while Figure 13 [27] reveals the graph obtained from simulation.

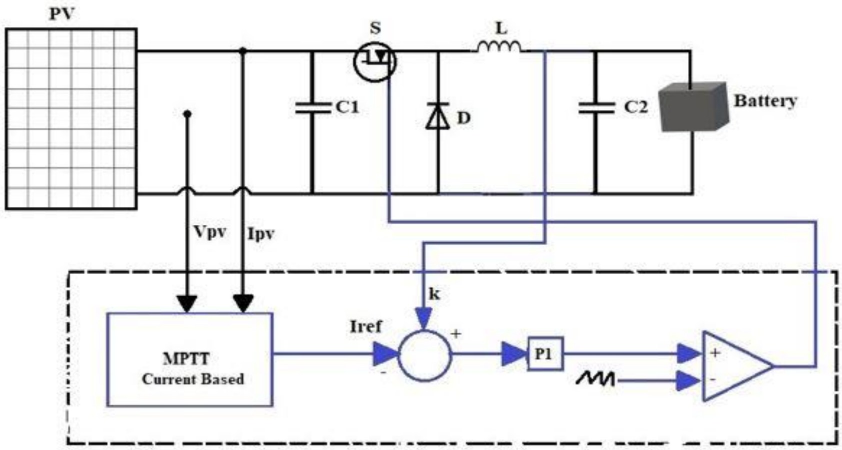

Fig.12 *The model of the proposed system*

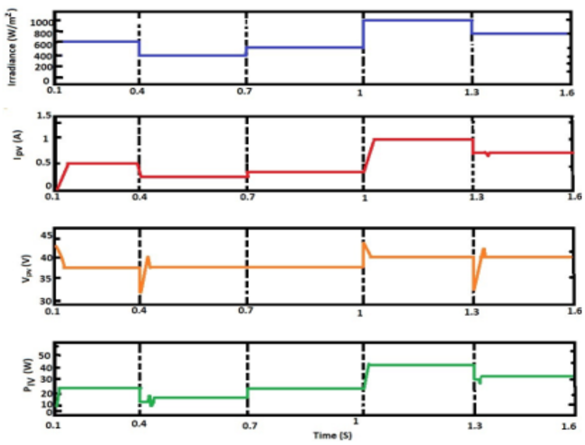

Fig.13 *Simulation results of the proposed model*

The gist of the comparison of the various MPPT techniques on basis of convergence speed, implementation complexity and sensed parameters is given in Table 1.

Table 1 *Comparison of various MPPT techniques*

MPPT technique	Convergence speed	Implementation complexity	Sensed parameters	True MPPT
Hill climbing	Varies	Low	Voltage and Current	Yes
P&O	Varies	Low	Voltage and Current	Yes
INC	Fast	Low	Voltage and Current	Yes
Neural network	Fast	High	Varied	Yes
Three-point P&O	Varies	Low	Varied	Yes
Current based	Fast	Low	Current	Yes
Whale optimization	Fast	High	Varied	Yes
Partial shading and global MPPT detection	Varies	High	Varied	Yes
Particle swarm based	Fast	High	Varied	Yes
Short ranged MPPT	Fast	High	Voltage	Yes

Conclusion

Solar energy can be tapped as an efficient, renewable, and eco-friendly source of energy. Solar PV panels produce a large amount of electricity. Because of the many hindrances like varying irradiation, temperature, shading etc., MPPT techniques are introduced. MPPT techniques analyse the surroundings and redirect the solar panels to perform at maximum power. This article is a modest effort made to highlight the pros and cons of various MPPT methods as it conducts a comparative analysis of various techniques introduced, that identify the MPPT for both grid and stand-alone PV systems. Among all the methods discussed in the paper including WO technique, PSO, ANN backed approach, three-point P&O and INC method to identify the MPP in a PV system, P&O and INC are found to be the most popular and efficient methods, but they also have some challenges to overcome. In future works, the emphasis should be on faster and more accurate identification of MPP, devising control strategies that manage power generation in PV systems more efficiently and discovering the possibilities for improving the efficiency of PV inverters.

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