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Simulation Analysis of Hill Climbing MPPT for Photovoltaic System under Partial Shading Condition

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ABSTRACT

Photovoltaic systems have become an energy generator for a wide range of applications. The applications could be standalone PV systems or grid connected PV systems. A standalone PV system is used in isolated applications where PV is connected directly to the load and storage system. With a standalone photovoltaic, when the PV source of energy is very large, having energy storage is beneficial. A major challenge in the use of PV is posed by its nonlinear current–voltage (I–V) characteristics, which result in a unique maximum power point (MPP) on its power–voltage (P–V) curve. The matter is further complicated due to the dependence of these characteristics on solar insolation and temperature.

In this thesis, the HC method is designed to track maximum power from the PV array. Power–voltage characteristic of photovoltaic (PV) arrays displays multiple local maximum power points when all the modules do not receive uniform solar irradiance, i.e., under partial shading conditions (PSCs). Conventional maximum power point tracking (MPPT) methods are shown to be effective under uniform solar irradiance conditions. However, they may fail to track the global peak under PSCs. This thesis proposes a new method for MPPT of PV arrays under both PSCs and uniform conditions. By analyzing the solar irradiance pattern and using the popular Hill Climbing method, the proposed method tracks all local maximum power points. The performance of the proposed method is evaluated through simulations in MATLAB/SIMULINK environment.

Keywords— Current–voltage (I–V) characteristic, maximum power point tracking (MPPT), partial shading condition (PSC), photovoltaic (PV) array, power–voltage (P–V) characteristic.

I. INTRODUCTION

Photovoltaic systems have become an energy generator for a wide range of applications. The applications could be standalone PV systems or grid connected PV systems. A standalone PV system is used in isolated applications where PV is connected directly to the load and storage system. With a standalone photovoltaic, when the PV source of energy is very large, having energy storage is beneficial. Whereas a PV system that is connected through a grid is used when a PV system injects the current directly into the grid itself. The advantage of the grid-connected system is the ability to sell excess of energy.

The ever-increasing demand for low-cost energy and growing concern about environmental issues has generated enormous interest in the utilization of nonconventional energy sources such as the solar energy. The freely and abundantly available solar energy can be easily converted into electrical energy using photovoltaic (PV) cells. A PV source has the advantage of low maintenance cost, absence of moving/rotating parts, and pollution-free energy conversion process. However, a major drawback of the PV source is its ineffectiveness during the nights or low insolation periods or during partially shaded conditions. High initial capital cost has been another deterrent in the popularity of PV systems [1].

A major challenge in the use of PV is posed by its nonlinear current–voltage (I–V) characteristics, which result in a unique maximum power point (MPP) on its power–voltage (P–V) curve. The matter is further complicated due to the dependence of these characteristics on solar insolation and temperature. As these parameters vary continuously, MPP also varies. Considering the high initial capital cost of a PV source and its low energy conversion efficiency, it is imperative to operate the PV source at MPP so that maximum power can be extracted. In general, a PV source is operated in conjunction with a dc–dc power converter, whose duty cycle is modulated in order to track the instantaneous MPP of the PV source.

Several tracking schemes have been proposed [2]–[12]. Among the popular tracking schemes are the perturb and observe (P&O) or hill climbing [4], [5], incremental conductance [8], short circuit current [2], open-circuit voltage [7], and ripple correlation approaches [6]. Some modified techniques have also been proposed, with the objective of minimizing the hardware or improving the performance [7], [9]–[12]. The tracking schemes mentioned above are effective and time tested under uniform solar insolation, where the P–V curve of a PV module exhibits only one MPP for a given temperature and insolation. Bruendlinger et al. have tested various commercially available inverters in partially shaded conditions and have found that the power loss due to shading can be as high as 70% [13]. Under partially shaded conditions, when the entire array does not receive uniform insolation, the P–V characteristics get more complex, displaying multiple peaks [only one of which is the global peak (GP); the rest are local peaks] [14]. An analytical model, based on Lambert function and its properties, has been presented [15]. It is capable of simulating the presence of multiple peaks under various conditions like different insolation and temperature levels, shading patterns, mismatch, etc. The computational time and the memory needed by this model is less.

The presence of multiple peaks reduces the effectiveness of the existing MPP tracking (MPPT) schemes, which assume a single peak power point on the P–V characteristic. The occurrence of partially shaded conditions being quite common (e.g., due to clouds, trees, etc.), there is a need to develop special MPPT schemes that can track the GP under these conditions. The other option is to use intelligent PV modules [16] or alternating current modules.

Some researchers [17]–[19] have worked on GP tracking schemes for PV arrays operating under non uniform insolation conditions. Miyatake et al. [17] have reported an MPPT scheme that uses Fibonacci sequence to track the GP under partially shaded conditions. However, the method does not guarantee GP tracking under all conditions. Kobayashi et al. [18] have proposed a two-stage method to track the GP.

A. Literature Survey

Solar energy is abundant, freely available and promising renewable energy source, and can be converted directly to electrical energy by PV modules. The PV system size ranges from single PV module to large power plant; however the building-integrated PV (BIPV) systems have widespread adoption worldwide [1]. In most cases, the BIPV system is connected to the utility grid through a PV inverter which may have mainly two different topologies such as central and string. Nowadays the string topology is the present technology for BIPV systems due to some limitations of the central inverter one such as power losses in centralized MPPT, non-flexibility, and losses in string diodes etc. [2].

All types of grid-connected PV inverters must have MPPT facility to extract maximum power from the PV modules, since its output characteristic is nonlinear and depends on the temperature and solar irradiance. Conventional MPPT methods, which are well summarized in [3], can accurately track the maximum power point under uniform irradiance condition [4]. Among them, the perturbation & observation (P&O) and incremental conductance methods are the most popular ones, especially for low-cost applications [5]. On the other hand, trees, clouds, near buildings, TV aerials, chimneys and other roof structures can create partial shading on the PV module surfaces, which affect the power-voltage characteristic drastically, and create multiple local peaks [6], [7]. In such a case, conventional MPPT schemes are not effective since they are designed for single peak, and may converge to any local peak instead of the global one causing significant reduction in system performance [8]. As an example, 41% of the installed PV systems in the German 1000 Roofs Programme were affected by shading causing 10% energy loss [9]. It is reported in [10] that the power loss due to the improper MPPT may be as high as 70% according to the real measurements. Thus, in recent years, numerous studies worldwide have been performed to mitigate the power loss due to partial shading [11].

Total cross tied connection of PV modules, increases the immunity against partial shading [12], [13], but it is not applicable for string topology. On the other hand, several MPPT methods for non-uniform irradiance operation have been proposed in literature. Some of them are hardware-based; such as dynamic reconfiguration of PV modules according to the shading pattern [14], [15], a DC/DC converter in series with each string [16], distributed MPPT concept [17], [18], module integrated DC/DC converter [19], [20], multilevel converter [21], parallel connected MPPT [22], and power electronics equalizers [23]. All of these methods require additional power circuitry which decreases the reliability and efficiency, and increases both hardware complexity and the system cost. However some other MPPT methods are based on a search algorithm, and can be realized by only modifying the control software in the present commercial power converters. These methods may be more preferable since they don't increase component count of the system. However, some of them are very complex to apply for commercial equipment; such as Fibonacci search algorithm [24], [25], artificial neural network and fuzzy logic with polar controller [26], particle swarm optimization [27], [28], Bayesian fusion technique [29], differential evolution [30], sequential extremum seeking control [31], ant colony optimization [32], modified fuzzy-logic controller [33] and parametric search algorithm in [34]. Alternatively, less complex schemes are two stages MPPT control algorithm [35], global peak search algorithm [36], dividing rectangle (DIRECT) [37] and predetermined linear function based [38] search algorithms. Additionally, [39] proposes a global MPPT search algorithm by employing constant power operation. However in order to detect small power differences between local peaks, the perturbed power levels should be very small which, in turn, makes the algorithm slower. Moreover it needs a constant input power DC/DC converter.

All the search algorithms use a wisely defined operating voltage range so as to ensure that none of the potentially global power peak is missed. However most of them scan almost 80% of entire P-V curve [11] that increases the scanning time significantly and therefore causes extra power loss. This drawback is particularly severe for PV systems having high open-circuit voltage. On the other hand, another important issue which is generally ignored is the power loss caused by the search algorithm under uniform irradiance condition. In this case the P-V curves should be periodically checked to detect changes in operating conditions, such as partial shading etc. Checking methods based on the scanning of the overall P-V curve take long time and significantly increase the energy loss. In this concern, only few algorithms [35], [37] have dedicated methods to rapidly detect uniform irradiation operation.

II. PROBLEM FORMULATION

Nowadays, solar energy as a clean and free available renewable energy resource is too important for reducing the dependency on conventional sources. Photovoltaic (PV) systems produce electric power by directly transforming the inexhaustible solar energy into electricity. However, the relatively high cost, low conversion efficiency of electric power generation, dependency on environmental conditions (e.g., solar irradiance and temperature), and nonlinearity of the power–voltage (P–V) and current-voltage (I–V) characteristic of PV arrays are the main challenges in utilization of PV arrays. Tracking the global peak (GP) of a PV array in all conditions is significantly important to guarantee the maximum achievable power. Many maximum power point tracking (MPPT) methods have been proposed in the literature [1]–[3]. Popular MPPT methods like perturbation and observation (P&O), hill climbing (HC), and incremental conductance (IC) methods are shown to be effective when the solar irradiance condition is uniform for all PV modules. Since, the tracking becomes more complicated under partial shading conditions (PSCs), i.e., when all the modules do not receive uniform solar irradiance, these basic methods fail to track the GP. Though in uniform solar irradiance conditions the P-V characteristic of PV array has just one peak, the P-V characteristic of PV array displays multiple peaks under PSCs. Hence, several MPPT methods are proposed which are applicable in PSCs. These methods can be categorized into two groups: hardware-based methods and software-based methods [4]. In [5] and [6], a controller is assigned for each module. These hardware-based methods can resolve the problem, since the P-V characteristic of a module (with just one bypass diode) always has a single peak. These methods, however, are not cost-effective and require much more devices in comparison to software-based algorithms.

Ishaque et al. [7] have proposed an effective MPPT method for PV systems based on particle swarm optimization (PSO) algorithm. This method is too complex to be applied to the commercial appliances, since some parameters have to be set by the user. In [8], artificial neural network (ANN) algorithm has been opted. The main problem of ANN-based methods is that the ANN's accuracy under different conditions is highly dependent to the amount of available training data. In addition, they need to be retrained when the PV array is changed. In [9]–[12] genetic algorithm, flashing fireflies, artificial bee colony, and simulated annealing are used in PV applications, respectively. These methods have good performances but similar to the aforementioned issues for the PSO and ANN methods, the implementation complexity of these methods is their major problem; since they involve complex calculations and several parameters have to be set by user.

In [4], the HC method has been improved. It can efficiently detect the shading condition. Then, by measuring power in suitable points, it chooses the highest one and performs the HC around this point. However, it does not have an acceptable accuracy for tracking the GP, since it compares the power of points near the LPs instead of the LPs themselves. In [13], a modified P&O method has been introduced which benefits from a unique characteristic that has been observed in the P-V curves. Although it has a great performance, since almost two measurements are done for each LP, the tracking speed is low. In [14], it is claimed that the GP is around the intersection of the I-V characteristic of PV arrays and a certain line. It depends on short circuit current of array which is problematic [1]. This problem is almost resolved by updating this value based on the solar irradiance. However, it is uncommon to find sensors that measure solar irradiance levels [1]. In [15], a relationship is defined between the PV power and a control signal to track the P-V curve and find the GP. Although its accuracy is high, it is slow because it searches almost all the range of the P-V curve. The proposed method in [16] uses the critical observations reported in [13] in a different way, but it does not have any procedure for detecting whether there is an LP near the target point or not. As a result, it may fail in some PSCs. Moreover, the approach in [16] involves complex calculations (e.g., calculation of square root) compared to similar methods; hence, it is not as simple as other similar methods for experimental implementation. By choosing lower and upper voltage limits, [17] narrows the searching window and tracks the GP very fast. On the other hand, authors admit that the method may fail when two LPs have nearly equal power values. The proposed method in [18] maps out the solar irradiance pattern based on the voltage of modules and chooses an appropriate voltage to track the GP around it. Obviously, employment of one voltage sensor for each module is not feasible and cost effective. In [19], two methods are proposed. The first one searches the P-V curve for MPPs by means of IC. However, it skips parts of the area based on short circuit current of the modules and the highest local power. This method would be very slow since it must scan almost all the P-V curve. Although the second method has improved the speed of tracking compared to the first one, it still uses one current sensor for each bypass diode, which is not cost effective.

The proposed method in [20] applies ramp voltage command to the converter. Therefore, it avoids the oscillation of voltage and current of the system in transient intervals. Hence, long delays in usual methods for correct sampling of voltage and current are not needed any more. However, it searches almost all the range of P-V curve and therefore, its tracking speed is not good. Proposing a method which meets accuracy, convergence speed, simplicity, minimum needed parameters, minimum cost, and other important factors [1] at the same time is still of a great importance. In this thesis, we propose a novel method for MPPT of PV arrays which works effectively in PSCs and at the same time, has great performance in diverse factors mentioned above. By measuring PV current in defined points, the method maps out the solar irradiance pattern. Based on the mapping, it chooses appropriate points for tracking the LPs. Then, it performs HC in these points and tracks all the LPs. Finally, by comparison of the acquired LPs, it chooses the GP.

In this thesis, the HC method is designed to track maximum power from the PV array. Power–voltage characteristic of photovoltaic (PV) arrays displays multiple local maximum power points when all the modules do not receive uniform solar irradiance, i.e., under partial shading conditions (PSCs). Conventional maximum power point tracking (MPPT) methods are shown to be effective under uniform solar irradiance conditions. However, they may fail to track the global peak under PSCs. This thesis proposes a new method for MPPT of PV arrays under both PSCs and uniform conditions. By analyzing the solar irradiance pattern and using the popular Hill Climbing method, the proposed method tracks all local maximum power points. The performance of the proposed method is evaluated through simulations in MATLAB/SIMULINK environment.

III. HILL CLIMBING ALGORITHM

An efficient Photovoltaic system is implemented in any place with minimum modifications. The PV energy conversion system using Hill Climbing MPPT method is explained in this Chapter. The hill climbing method of MPPT implemented by Maheshappa et al (1998), dealt with increasing or decreasing the array operating voltage and observing its impact on the array output power. This algorithm is independent of place of installation and prior study of the geographical data is not required. Any system implemented using the hill climbing algorithm is considered to be most efficient system.

Noguchi et al (2000) proposed a novel maximum-power-point tracking (MPPT) method with a simple algorithm by using a short-current pulse of the PV array to determine an optimum operating current for the maximum output power. Here, the optimum operating current was instantaneously determined by taking a product of the short-current pulse amplitude and a parameter k because the optimum operating current was exactly proportional to the short circuit current.

Nicola Femia et al (2005) proposed that optimization approach lies in customization of the perturb and observe MPPT parameters to the dynamic behavior of the PV system. Kasa et al (2000) presented a perturbation and observation method with a capacitor identifier for MPPT. The variation of duty ratio was determined by considering its circuit parameters. The actual capacitance of an electrolytic capacitor in parallel with the photovoltaic array has 50% tolerance of its nominal value. Teulings et al (1993) presented a digital hill-climbing control strategy combined with a bidirectional current mode power cell that makes to get a regulated bus voltage topology, suitable for space applications, by means of two converters. MOSFET-based power conditioning unit (PCU) along with a control algorithm to track the maximum power point was discussed. Maximum power from each PV array was extracted in spite of mismatch in the array characteristics. When the variation of duty ratio was determined based on its nominal value, the performance of the MPPT was degraded.

The hill climbing algorithm locates the maximum power point by relating changes in the power to changes in the control variable used to control the array. This system includes perturb and absorb algorithm which was proposed by Xiao et al (2004). Hill-climbing algorithm involves a perturbation in the duty ratio of the power inverter. In the case of a PV array connected to a system, perturbing the duty ratio of power inverter perturbs the PV array current and consequently perturbs the PV array voltage. Fig.3.1 shows the characteristic of PV array curve. In this method, by incrementing the voltage, the power increases when operating on the left of the MPP and decreases the power when on the right of the MPP. Therefore, if there is an increase in power, the subsequent perturbation is kept at same point to reach the MPP and if there is a decrease in power, the perturbation is reversed. This algorithm is summarized in Table 3.1. The process is repeated periodically until the MPP is reached. The system then oscillates about the MPP. The oscillation is minimized by reducing the perturbation step size.

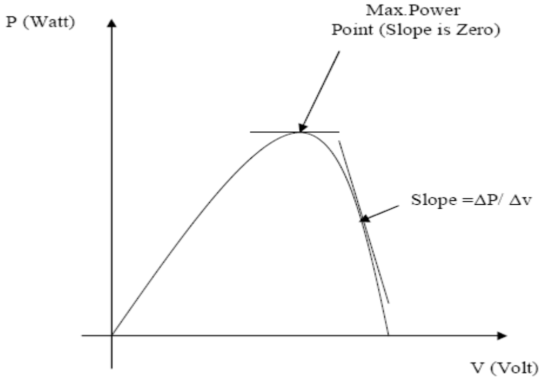


Fig.3.1: Characteristic PV Array Power Curve

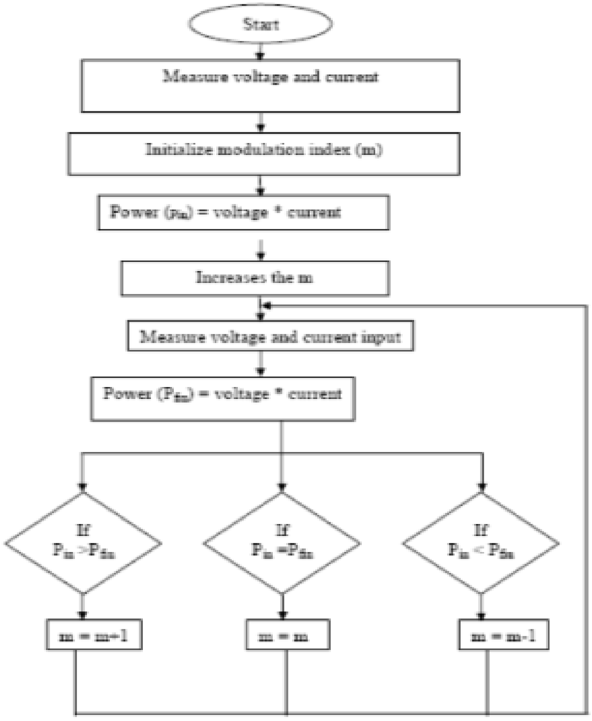


Fig.3.2: Flow Chart for Calculating Modulation Index Value

Table 3.1: Summary of Hill climbing algorithm

Perturbation	Change in Power	Next Perturbation
Positive	Positive	Positive
Positive	Negative	Negative
Negative	Positive	Negative
Negative	Negative	Positive

Fig.3.2 shows the flow chart of the implemented algorithm by measuring the array voltage and array current information. The PV array output is calculated and compared to the previous PV array output power. Initially the modulation index (m) value is set and if the final output power is equal to the initially measured output power, the control circuit maintains the same m value. If it is greater, then m value is increased and *vice versa*.

Eftichios Koutroulis et al (2001), proposed a simple method in which the PV array output power delivered to a load was maximized using MPPT control systems, in which the control unit drive the power conditioner such that it extracted the maximum power from a PV array. In this method, a Buck-type dc/dc converter was used where the duty cycle variation was not analyzed. To overcome this, PWM technique is implemented to switch on the inverter circuit.

The level of power flow depends on the desired array voltage value determined by the MPPT algorithm. There are two possible situations that need to be addressed. First, an increase in the array voltage is required, and secondly, a decrease is required. The voltage output of the voltage source inverter (VSI) is fixed; the power flow is varied by altering the VSI output current. If the MPPT algorithm requires a decrease in the array voltage, the output current is increased in phase with the grid voltage to a stable magnitude determined by modulation index using PWM generator. This causes an increase in the positive power flow towards the load. The extra power comes from the array, which causes the array voltage to fall to the desired value as suggested by Krein et al (2003). The desired voltage is reached, the output current goes down to a level that the power on the array and load are equal once again. If an increase in the array voltage is required, the opposite effect occurs by which a constant voltage is maintained.

Algorithm and flow chart:

The algorithm used for MPPT is discussed below:

Step 1: Sensing and measuring the voltage and current of PV array

Step 2: Initialize the modulation index to a particular value

Step 3: The initial power Pin is calculated

Step 4: Increase the value of m

Step 5: Sense the PV array voltage and current

Step 6: Calculate the modified power Pfin

Step 7: If the change in power is positive, increase m value; if it is negative, decrease m value' and if there is no change in power, m value is retained.

Step 8: Repeat step 5.

IV. SIMULATION RESULTS

This Chapter presents detailed simulation results of the proposed Hill climb method and will be compared with conventional MPPT. The simulated system is shown in Fig. 4.1. Simulation studies are carried out in the MATLAB/SIMULINK environment.

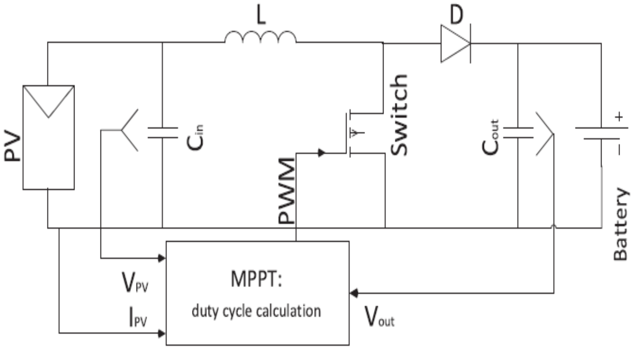
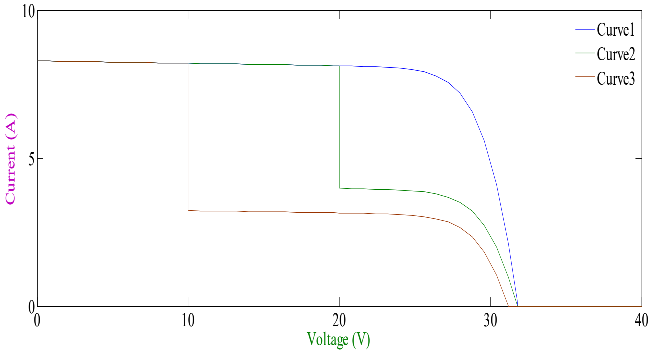


Fig.4.1: Block diagram for proposed methodology

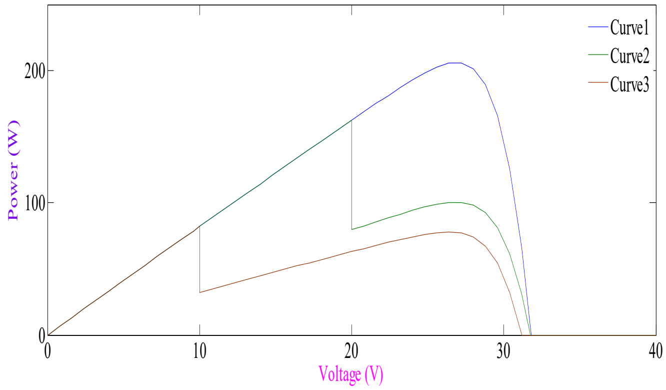
In this section several simulation results will be presented. The simulated PV system is a 3 × 2 PV array. The PV array is connected to a boost DC-DC converter which tracks the maximum power point. 12-V battery is connected in the output side. Also the schematic of the system is shown in Fig. 4.1.

The performance of the algorithm is tested under four consecutive solar irradiance conditions. From 0 to 0.3 s, the solar irradiance level is equal to 1000 W/m^2 for all the modules. Finally, from 0.9 to 1.2 s the solar irradiance is equal to 1000 W/m^2 for all the modules again. I-V and P-V curves of the PV array in these four states are shown in Fig. 4.2. Array's corresponding voltage, current, power and duty cycle waveforms are shown in Fig. 4.3 (a)–(d), respectively. Moreover, zoomed view of per unit array's voltage, current, power, and duty cycle waveforms in 0.3

to 0.5 s, 0.6 to 0.8 s, and 0.9 to 1.1 s intervals are depicted in Fig. 4.4(a)–(c), respectively.

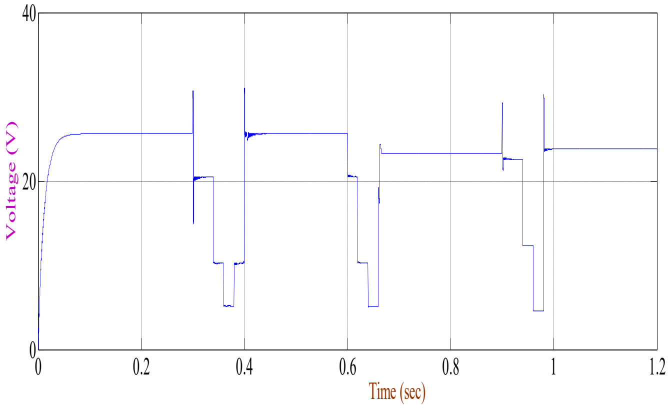


(a) I-V Characteristics

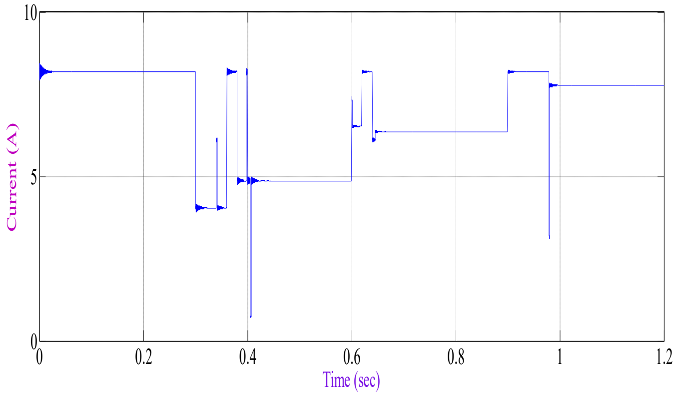


(b) PV Characteristics

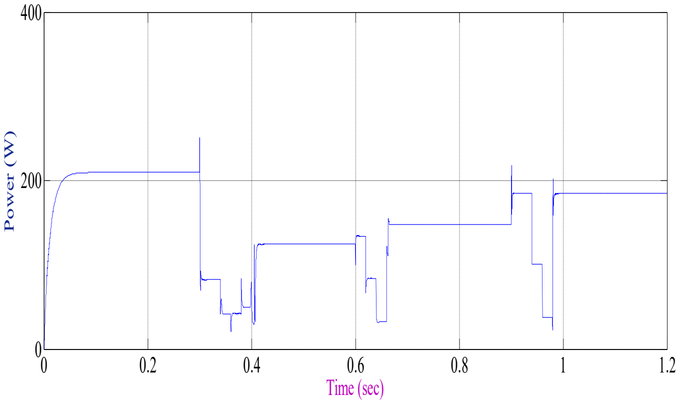
Fig.4.2: Curves under first simulation



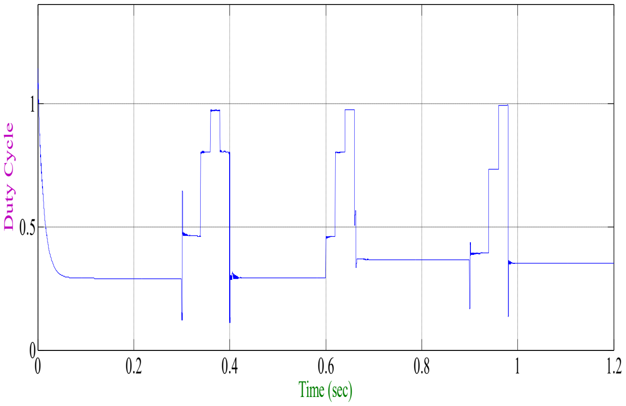
(a) Voltage



(b) Current

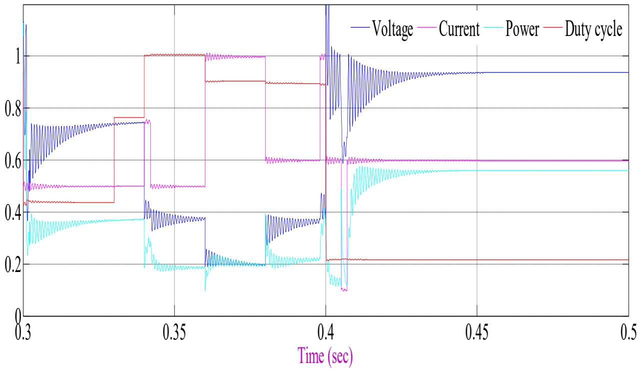


(c) Power

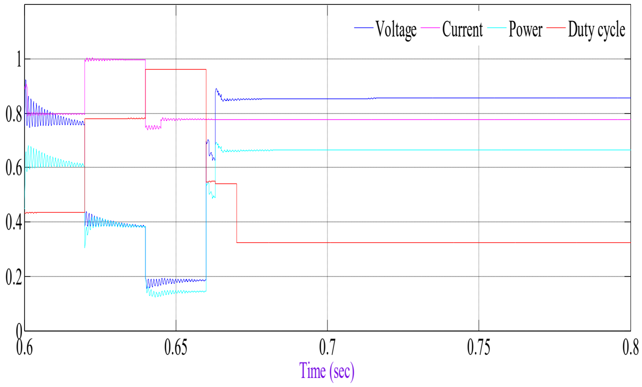


(d) Duty cycle

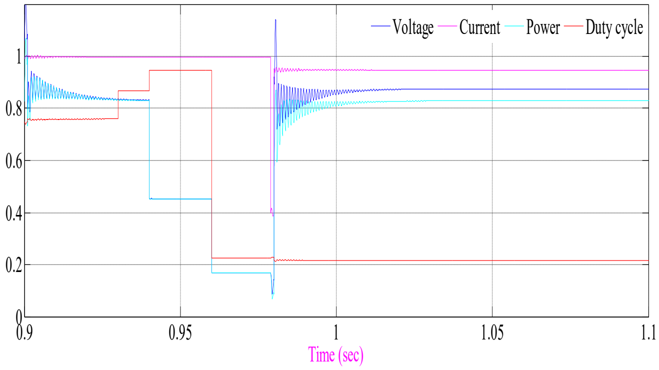
Fig.4.3: Corresponding array curves under first simulation



(a) 0.3-0.5 s



(b) 0.6-0.8 s



(c) 0.9-1.1 s

Fig.4.4: Zoomed view of per unit arrays voltage, current, power and duty cycle waveforms in the first simulation

Simulations are done to compare the new method against two highly cited methods to show its benefits over those. It should be considered that prior works, such as [23], has shown that some of main hypo in [13] are not correct, and it may fail to track the GP in some conditions. However, still [13] is now a classic and highly cited method, and most algorithms are compared to it. For comparing the proposed method against [13] and [17], a P-V curve is shown in Fig.4.5. Also, the corresponding power waveforms of the proposed method, [13] and [17] are illustrated in Fig.4.6 (a)–(c), respectively.

It is illustrated in Fig.4.6 (a) that the proposed method tracks the GP with corresponding 97 W powers within 0.093 s. The method proposed in [13] tracks the same peak.

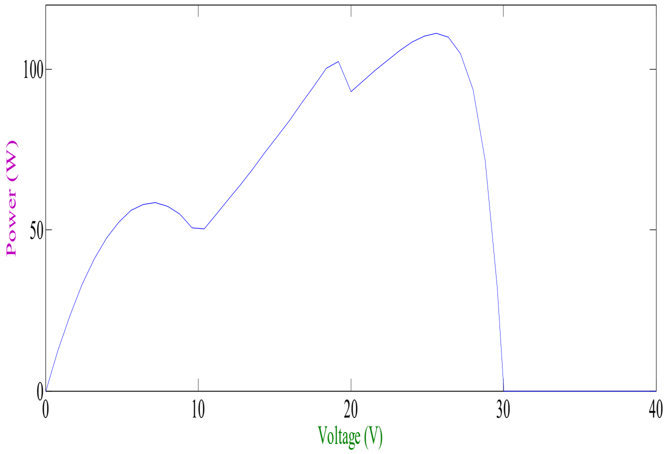
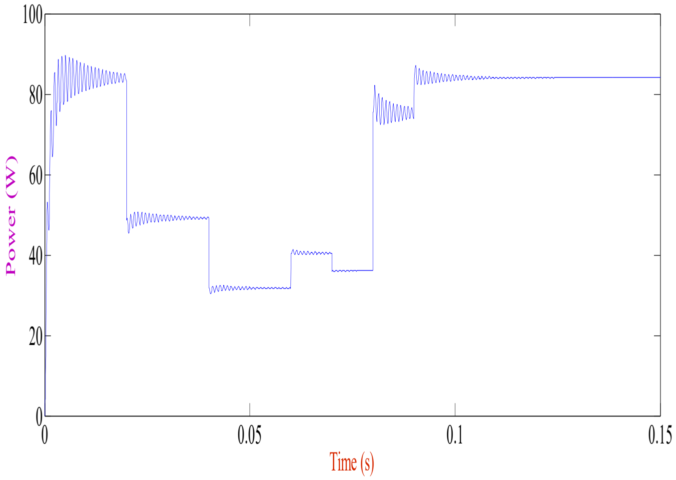
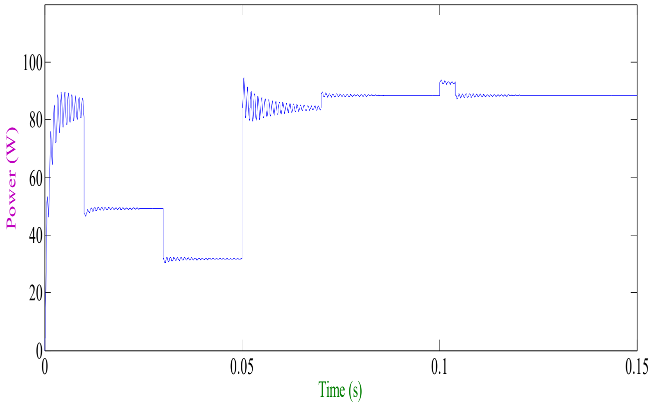


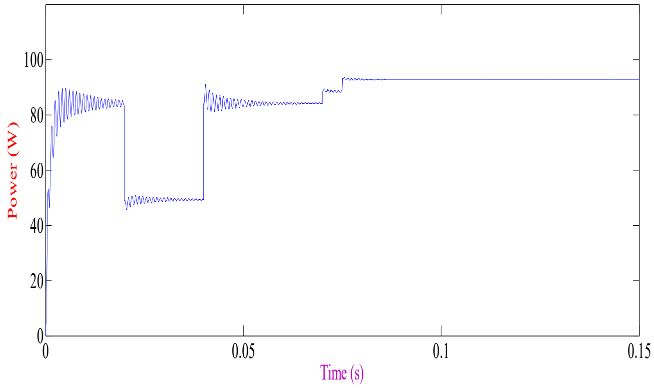
Fig.4.5: P-V characteristics under second simulation



(a) Proposed Method



(b) Proposed method in [13]



(c) Proposed method in [17]

Fig.5.6: Performance comparison with traditional methods

V. CONCLUSION

In this thesis, Hill Climbed MPPT method was proposed which has a great performance under PSC. Based on the simulation results, it was shown that the current in each step of the I-V characteristic is almost constant until the beginning point of the next step. In addition, it was proved that the starting points of each step in the I-V curve are in near left side neighborhood of the multiples of $V_{oc,m}$. The proposed method is in fact, a modified HC method which tracks the GP effectively under different conditions. Thus, the implementation of this method is simple. Once the PSCs appear, the number and length of I-V characteristic's steps are recognized by measuring the current value in multiples of Voc,m .Finally, the GP is detected by comparing the LPs. Simulation results have validated the advantages of this method in terms of accuracy and speed over two popular existing methods.

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