A Novel Curve Scanning Based Maximum Power Point Tracking Algorithm Under Partial Shading Conditions

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***Abstract*— Photovoltaic systems have become essentially needful among the renewable energy sources. Due to low conversion efficiency of the PV based generation system, one of the most crucial factors in the operation of the system is the extraction of the maximum power from the PV array which is indispensable especially under Partial shading condition. There are several conventional maximum power point tracking (MPPT) methods like P&O, INC etc. that work fine under uniform irradiance condition. But under partial shading conditions, the power-voltage curve exhibits multimodal nature with multiple peaks with local maximum power point (LMPPs) and global maximum power point (GMPP), where these methods fail to track the maximum power point. This paper proposes a novel and fast maximum power point tracking algorithm that scans the entire voltage range by shifting the operating point along the P-V curve by controlling the duty of the DC-DC converter interface. This method tracks the GMPP subsequently by changing the duty in steps thus varying the voltage over the entire operating range of the PV-converter interface. The proposed model exhibit improved tracking accuracy and enhanced tracking speed without additional circuit requirements with improved efficiency of 96.49% under PSC and 99.34% under UIC. The performance of the proposed algorithm has also been validated through MATLAB/Simulink simulation results.**

Keywords—Maximum Power Point (MPP), Global Maximum Power Point (GMPP), Local Maximum Power Point (LMPP), Partial Shading Condition (PSC), Uniform Irradiance Condition (UIC), Photovoltaic (PV).

I. INTRODUCTION

There is a serious concern regarding the plight of the environment due to the overutilization of fossil fuels and other non-renewable energy resources. With the growing energy demand of civilization, an urge has been generated for the integration of distributed energy resources to the power system. These resources are inexhaustible and ecofriendly in nature. Among these sources, photovoltaic based sources have emerged as the best alternative because of the absence of any rotating part, closeness to the load centers and ease of penetration directly into the distribution system. As a result, the present installed capacity of the PV system is estimated to be roughly around 512 GW cumulatively by the end of 2018 which has subsequently increased even more in many countries in subsequent years.

PV generation system finds a lot of applications in today's practical scenario like in industrial and power sectors. For the accomplishment of this goal, multiple PV modules are needed which are to be connected in series and parallel combination to form PV arrays to constitute a photovoltaic generation system. PV Panels being costly with low conversion efficiency, to achieve that maximum efficiency, maximum power needs to be extracted from the system. Now the power-voltage (P-V) curve is highly non-linear in nature, obtaining maximum power from the PV system requires a proper algorithm. Now to obtain maximum power, there are several conventional methods that are used to track maximum power point like P&O, INC etc. However, these methods work fine under uniform insolation, when each cell receives the same solar irradiance. As this generates a single peak in the power-voltage curve of the panel even though multiple cells are connected in series and parallel. During PSC, multiple peaks are generated in P-V curve. The maximum among all the PV peaks is called the GMPP and rest other peaks are LMPP. The drawback of the above all conventional methods used for MPP tracking is that it converges at one of the LMPP. This reduces the overall efficiency of the system.

Recently many techniques have been developed for tracking GMPP. Some are based on software and some on hardware. The software-based methods adopted includes optimization techniques like PSO [1]-[3], flashing fire flies [4], artificial bee colony [5], fuzzy logic [6] and ANN based algorithm and so on. In these methods, the GMPP can be determined by taking various samples of the entire range of operating voltage but the initial sampling need to cover of the entire range. But as the number of samples increase, the complexity of network increase and the computation time increases thereby decreasing the speed of operation. In [7]-[10], the PSO algorithm used which has low tracking speed. In [9], the PSO algorithm is modified to improve its speed and complexity. There are other methods like [11] which is basically a P&O algorithm where voltage step size is determined by diving rectangular methods but attaining GMPP is not assured. Under PSC, [12] needs to sense the solar insolation level and ambient temperature of surrounding. Several I-V curve tracing methods have been devised. In [13] proposed using artificial bee colony algorithm for MPPT tracking under PSC, but if the number of bees is low then it gets trapped at LMPP. In [14], improved Java MPPT method is proposed, but algorithm-specific parameters are absent.

This paper presents a novel MPPT algorithm that alters the operating point while scanning the entire range of operating voltage. This uses a converter interface whose duty is varied in a stepped manner according to change in PV power & voltage so as to extract maximum power. The LMPP values of power, duty, and voltage are stored at each interval and a maximum of the stored values are obtained to get the duty, voltage & power at operating point corresponding to GMPP. The algorithm-II is the novelty of the proposed methodology. This method is cheap in implementation and forms a simple closed-loop system by measuring current and voltage. Furthermore, high and adjustable speed, robust and guaranteed performance in all conditions are the main advantages that impose minimum disturbance to the power

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system. This new MPPT algorithm possess superiority in the performance over other recently developed methods. According to simulated results, the tracking efficiency improves and its advantages are emphasized.

II. System Configuration

Fig.1 shows the schematic view of a single staged DC-DC converter interface that extracts power from the PV module and delivers it to the load. A local passive resistive load is connected at the output of DC-DC converter. This PV array consists of two series connected PV modules. The DC-DC converter is of traditional non- isolated type boost converter that boosts the voltage to desired levels depending on the duty govern by MPPT algorithm which is given to the switch. In this paper, high frequency power mosfet is used as switch. The input filter capacitor filters out the ripple content in the input voltage. The output of the MPP tracking algorithm is used to generate duty which is then compared with high frequency carrier wave to generate switching signal for the mosfet. Each of the circuit elements inductor and input-output filter capacitors are designed at appropriate values considering the ripple content in voltage, current and power transaction.

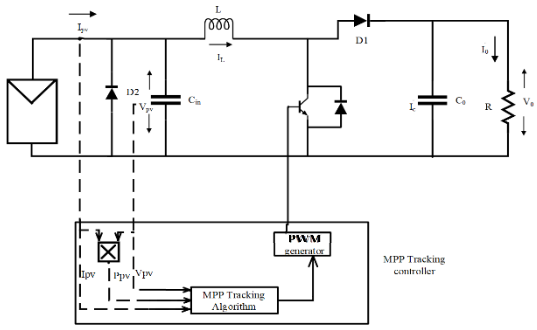

Fig.1 Schematic Diagram for Proposed MPPT Controller

III. CHARACTERISTICS OF PV GENERATION SYSTEM

A. Characteristics under Uniform Irradiance Condition

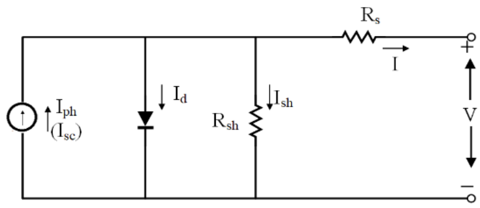

Fig.2 Equivalent Single-Diode Model of PV Cell

Under the literature study, only the single diode model of solar cell has been taken into consideration. This consists of PV modules which are the series-parallel combination of individual solar cells. Based on this model as in Fig.2, the parametric relationship between output cell voltage & current is as follows:

$$\mathrm{I} = \mathrm{Ipv} - \mathrm{Io}\left[e^{\left(\frac{\mathrm{V+IRs}}{\eta \mathrm{VT}}\right)} - 1\right] - \left(\frac{\mathrm{V+IRs}}{\mathrm{Rs}}\right) \quad (1)$$

where, I is Output current of the PV cell; I_{pv} is Equivalent Photocurrent of the cell; I_0 is Reverse Saturation current of the Equivalent diode; Ƞ is Ideality Factor; V_T is Thermal Voltage of the cell; R_s is Equivalent Series resistance between cells and within the cells; R_{sh} as Equivalent Shunt Leakage resistance of the cell.

Further, PV arrays are made of series-parallel combination of many PV modules. Let N_s = series connected cells to achieve desired voltage rating & N_p = Parallel strings to achieve desired current ratings. Thus, under UIC,

$$\mathrm{I} = \mathrm{Np} * \mathrm{Ipv} - \mathrm{Np} * \mathrm{Io}\left[e^{\left(\frac{\mathrm{V}+\frac{\mathrm{Ns}}{\mathrm{Np}}\mathrm{IRs}}{\eta \mathrm{NsVT}}\right)} - 1\right] - \left(\frac{\mathrm{V}+\frac{\mathrm{Ns}}{\mathrm{Np}}\mathrm{IRs}}{\frac{\mathrm{Ns}}{\mathrm{Np}}\mathrm{Rs}}\right) \quad (2)$$

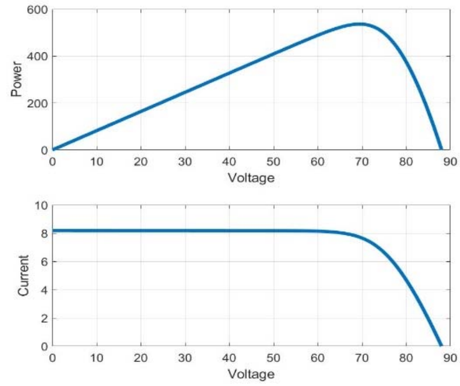

Fig.3 P-V & I-V Plots of PV Modules under UIC

Using the above equations, two number of panels (each of 270.66W) are connected in series and their I-V and P-V curves are both depicted in the Fig.3. The voltage & current relationship is highly non-linear.

B. Characteristics under Partial Shading Condition

A Photovoltaic array is made up of several PV modules connected in series to increase the voltage rating and in parallel to increase the current rating of the PV generation system. Under UIC, current in the PV module remains same cell but under PSC, some modules get bypassed due to partial shading effect. For the presented work, two modules connected in series are shown in Fig.4. In the series connected module, one PV module receives an insolation of 1000W/m^2 and other module receives the insolation of 800W/m^2.

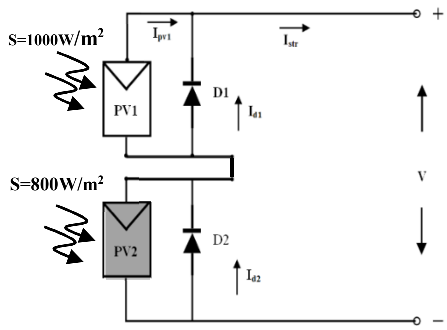

Fig.4 Series-connected PV Modules under PSC

The combination of PV modules shown in the Fig.4 is simulated. P-V characteristics is shown in Fig.5. This generates LMPP (represented by A) and GMPP (represented by B). The GMPP can occur either in the lower or higher voltage range depending on the type of shading pattern. So, this makes it very difficult to track the GMPP directly using

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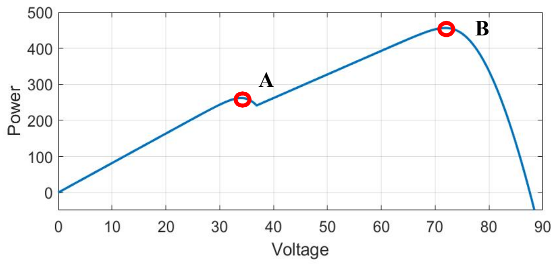

Fig.5 P-V Characteristics of PV Modules under PSC

conventional methods simply by hill climbing approach. This requires some advanced, well designed algorithm and methodology for MPP tracking.

IV. Proposed Algorithm Under PSC

In partial shading conditions, to reduce the power loss due to convergence of operating point by the conventional methods at local maxima, a new algorithm is needed to be devised to extract maximum power even under PSC. Furthermore, advanced techniques have also been discussed but those lag in their optimal performance in terms of tracking speed, tracking efficiency and other factors.

The proposed method describes an algorithm which is an efficient technique in tracking the GMPP with improved tracking ability and speed. The algorithm is further sub-divided into certain other blocks, sub-processes and algorithms that loops around continuously depending on the condition as shown in Fig.6. The blocks and processes are

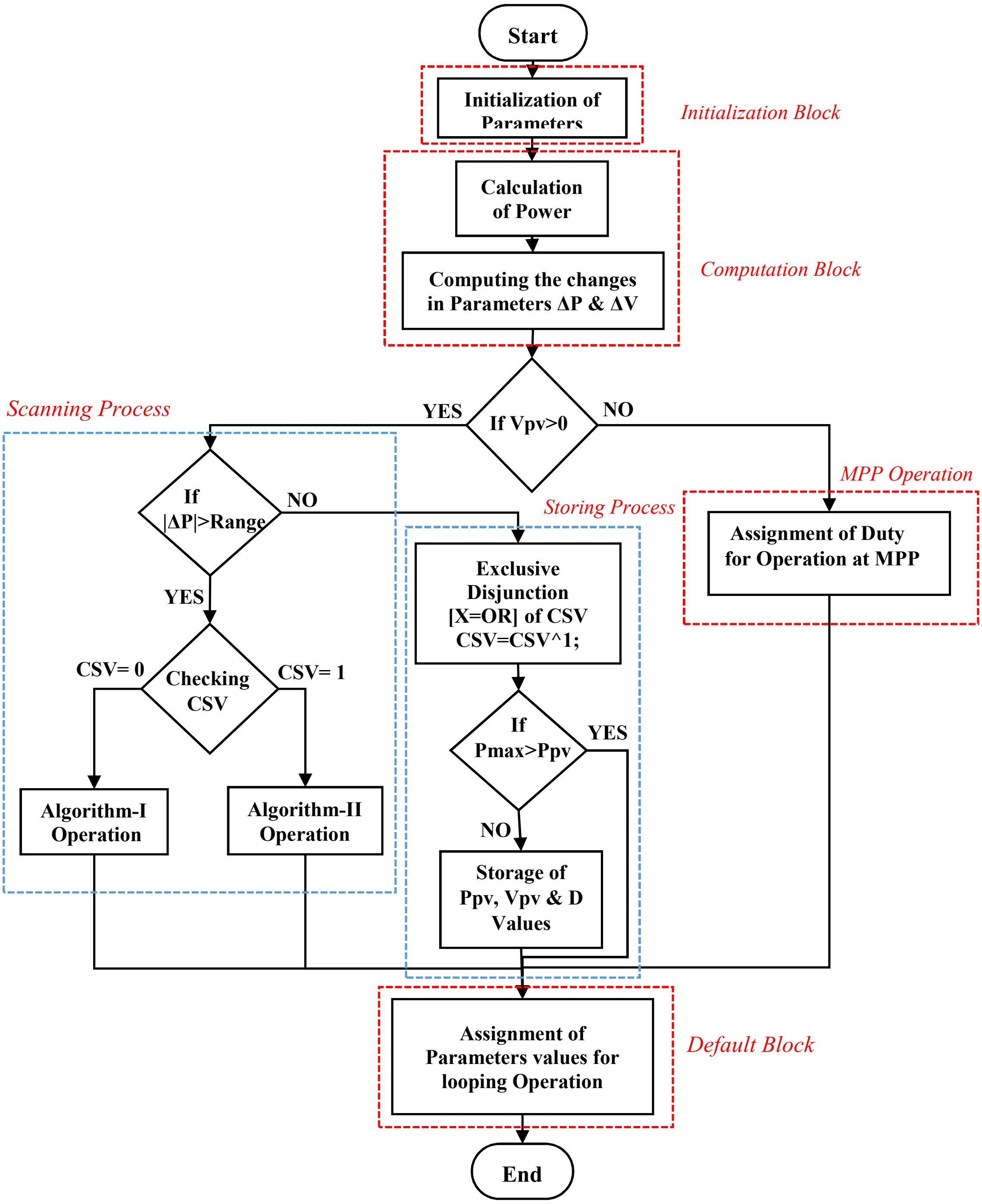

Fig.6 Flow chart diagram for Proposed Curve Scanning Algorithm

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classified as Initialization Block, Computation Block, Scanning Process, Storing Process & Default Assignment Block.

The proposed algorithm includes several parametric variables those are analyzed for the working of the various processes. The parametric variables with their notations are Ppv, Vpv, & Ipv as Sampled value of power, voltage & current of PV module respectively. CSV is Condition Specifying Variable that chooses the algorithms. DeltaP, DeltaV & DeltaD are step change in power, voltage & duty of PV module respectively. Dmax, Pmax & Vmax are variables that stores sampled LMPP values of duty, Vpv & Ppv respectively. Dprev & Pprev are variables that stores previous instantaneous sampled value of duty & Ppv respectively.

A. Initialisation Block

The initialization block starts with the examination of the value of prevailing duty, if its value is NULL, then the algorithm initializes it with a constant value. The other variables P_{prev}, P_{max}, D_{max} etc. are also initialized with zero. The initialization variables are as follows:

$$\mathrm{Dprev} = 0.3;\ \mathrm{Pmax} = 0;\ \mathrm{Dmax} = 0; \mathrm{Vmax} = 0 \tag{3}$$

This initial value results in some PV voltage & current which are sampled and compared with the subsequent resulted voltage values as the process continues in order to generate the duty.

B. Computaion Block

In this block, power is calculated by the present value of PV voltage & current. DeltaP & DeltaV are computed by comparing the present values with the previously stored values and corresponding duty is generated. The sensitivity, tracking speed and tracking efficiency is dependent on this step change, which is denoted by DeltaD.

$$\mathrm{Ppv} = \mathrm{Vpv} * \mathrm{Ipv};\ \mathrm{DeltaP} = \mathrm{Ppv} - \mathrm{Pprev} \tag{4}$$
$$\mathrm{DeltaV} = \mathrm{Vpv} - \mathrm{Vprev};\ \mathrm{DeltaD} = 0.001 \tag{5}$$

Before the scanning process begins, the voltage of the PV module is checked to determine whether the system is already in operation. If it is already in operation, then it will exhibit some initial non-zero voltage that will compel the process to move into the MPP tracking algorithm loop. But however, if the PV system initiates its operation for the very first time, then V_{pv} (voltage) equals zero, resulting in initialization of variables in the initialisation block which then subsequently bypasses the MPP tracking algorithm loop.

C. Scanning Process

The process is constituted by several other sub-processes and sectionalized into distinct novel algorithms. The scanning process institutes the MPP tracking algorithm and forms the most crucial element of the entire process. The scanning process begins with analyzing the value of DeltaP. If its value is in a specified range signifying the slope tending to zero, then the scanning process leads to storing process, otherwise the value of condition specifying variable (CSV) is checked to track the MPP choosing the appropriate algorithm.

When the step change DeltaD is applied to the duty, then this causes a subsequent step change in PV voltage as well as power. This change is however uniform in voltage domain but not in power domain. The value of DeltaP are more while climbing the hill due to greater magnitude of the slope and moving towards top, the value of DeltaP decreases as the magnitude of slope decreases.

The proposed model comprises of two algorithms in order to traverse the P-V curve under PSC. These algorithms switch alternatively depending on the value of CSV. When CSV=0, Algorithm-I is processed and when CSV=1, Algorithm-II is processed. Considering the above phenomenon, the range of DeltaP is set so that scanning and storing process are distinguished.

Algorithm-I

This is primitively a Hill-Climbing approach that traverses the P-V curve by analyzing the changes in the PV power and voltage when CSV=0. Based on the change in these variables, the duty is varied to change the operating point. This algorithm basically takes into account the P-V curve and then formulates the direction of traversal as

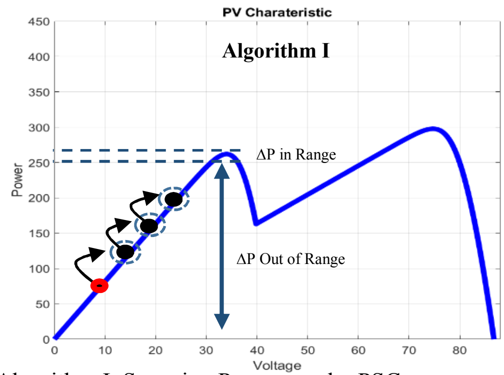

Fig.7 Algorithm-I, Scanning Process under PSC

depicted in the Fig.7. Thus, the illustrated process tracks MPP by moving towards the peak of every hill. This scanning process is unidirectional in nature.

Algorithm-II

This primarily is a Hill-Descending or Reverse Hill-climbing approach. The traversal process works identically to algorithm-I but in an inverse way. During the traversal the variation in the parametric variable is analyzed. This algorithm works only when CSV=1. As it is shown in Fig.8, in this algorithm, it tries to skip the lower tip portion by increasing the PV voltage with much higher rate to move

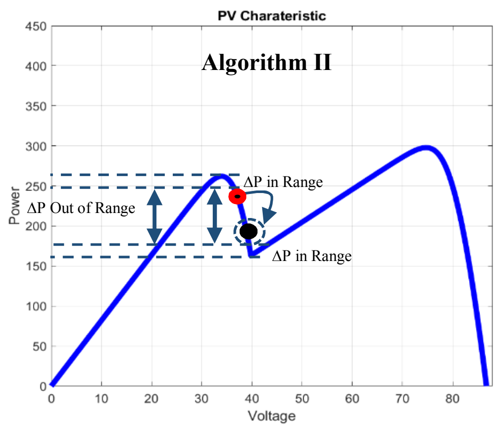

Fig.8 Algorithm-II, Scanning Process under PSC

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towards the GMPP without converging at LMPP. This algorithm-II is the novelty of the proposed methodology.

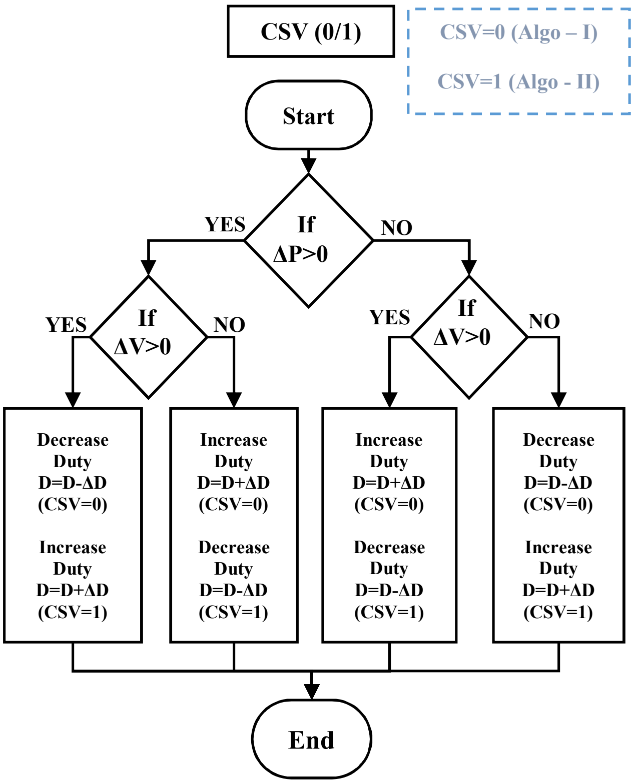

Fig.9 Flow chart diagram for Scanning Process

As per the flow diagram shown in Fig.9, now when these algorithms are adopted alternatively, the value of CSV changes due to its exclusive disjunction (X-OR) with '1' so that it takes values '0' & '1' alternatively. The entire

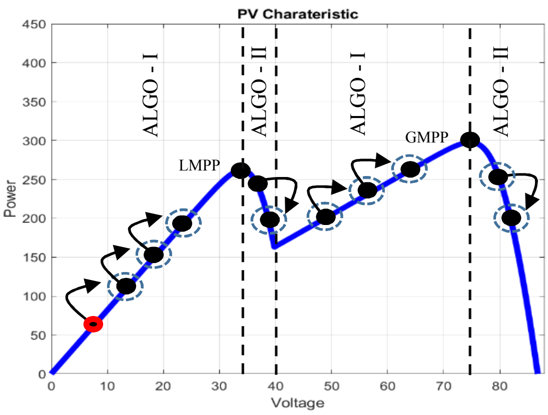

Fig.10 Overall Scanning Process (Algo-I + Algo-II)

methodology for the scanning process is depicted in the given Fig.10. By virtue of alternate functioning of the algorithms the entire voltage range is scanned unidirectionally.

D. *Storing Process*

The process deals with storing all the MPP values followed by comparison, to fix the GMPP as operating point. This process is initiated if DeltaP is in specified range. The storing process is followed by the comparison of the present MPP with the previously stored power value. This process goes on in a linear fashion to store the comparatively greater MPP value for future reference till V_{OC}, to finally converge at GMPP.

E. *Default Assignment Block*

This block is executed at the end of each iteration. The variables D_{prev}, P_{prev} & V_{prev}. are assigned the present values of duty, power & voltage at the end of each loop, for comparison with run-time value of PV power & voltage in the subsequent iteration.

$$\text{Dprev} = \text{D}; \text{Vprev} = \text{Vpv}; \text{Pprev} = \text{Ppv} \tag{6}$$

This assignment allows the continuous operation of the algorithm under PSC as well as under UIC.

V. Simulation Results

To validate the proposed MPPT algorithm, the simulations have been done in MATLAB\Simulink software. In the proposed system, DC-DC boost converter serves as the energy conversion unit. The values of the designed parameters are decided keeping in view the power transaction and voltage fluctuations. The minimum value of the inductor is set to ensure that its large enough to keep the boost converter operating in continuous conduction mode. Also, the input and the output filter capacitors are designed to keep the voltage variations within specified limits of the nominal boosted value of output voltage. Thus, appropriate pulse width modulated duty is devised by utilizing the proposed methodology, which extracts maximum power from the PV generation system.

Under PSC, the unshaded module (PV-1) is under an insolation level of $1000 W/m^2$ and the shaded module (PV-2) is under an insolation level of $800 W/m^2$ both at a temperature at 25□. For simulation, two series connected PV modules are used as shown in Fig.4. The parameters configuration are indicated in Table-I.

TABLE-I

PARMETERS OF SYSTEM CONFIGURATION

S.No	Parameter	Value
1.	Switching Frequency	10KHz
2.	Input Capacitor	100µF
3.	Inductor	200µH
4.	Output Filter Capacitor	500µF
5.	Open circuit Voltage of PV string V_{OC}	88V
6.	Short circuit Current PV string I_{SC}	8.1A
7.	Maximum Power at MPP P_{MAX}	536W
8.	Maximum Voltage at MPP $V_{PV(max)}$	69.43V
9.	Maximum Current at MPP $I_{PV(max)}$	7.8A

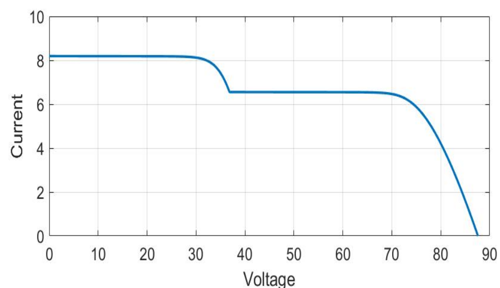

Fig.11 I-V Characteristics of PV Modules under PSC

Under PSC, GMPP & LMPP powers are 456W & 269.7W respectively and the algorithm tracks 440W with an efficiency 96.49%. Under UIC, MPP power are 536W and the algorithm is able to track 532.5W with a tracking efficiency of 99.34%. Fig-11 shows, under UIC at MPP, corresponding voltage is 69.43V and current is 7.723A.

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Under PSC, at GMPP, corresponding current and voltage are 6.4A and 71.3V respectively. As the scanning process continues there is a steep increase in power that overshoots the GMPP and goes till 540W at t=0.04s. From t=0.04s to t=0.08s, the oscillations gradually decrease and finally at t=0.1s, the power settles at 440W with minimum oscillations of 20W about the mean value. The voltage and current wave forms settle at about an average value of 66V & 6.65A respectively. Thus, the GMPP power is tracked and delivered to the load through the converter interface. These results were obtained based on the independently only for a given partial shading pattern with irradiation levels of 1000W/m^2 on PV-1 and 800W/m^2 on PV-2.

Here in this section, dynamics of the proposed algorithm is obtained with change in irradiance level with respect to

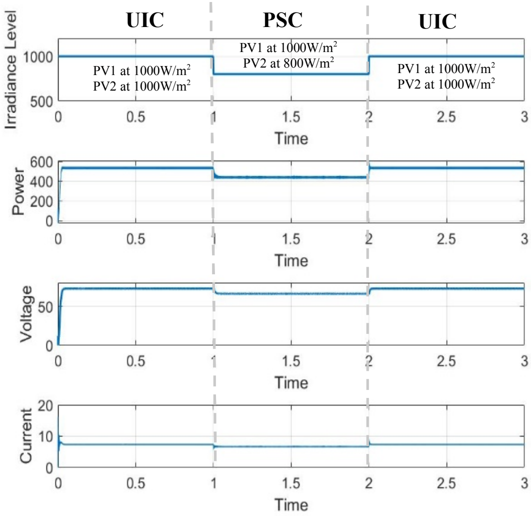

Fig.12 Measured Waveforms of Ppv,Vpv,Ipv PV Modules under PSC

time. For simulation, a sudden change in irradiance is set at t=1s & t=2s as seen from Fig.12. At t=1s, the insolation changes from UIC (1000W/m^2 on PV-1, 1000W/m^2 on PV-2) to PSC (1000W/m^2 on PV-1, 800W/m^2 on PV-2). At t=2s, change in irradiance level occurs from PSC (1000W/m^2 on PV-1, 800W/m^2 on PV-2) to UIC (1000W/m^2 on PV-1, 1000W/m^2 on PV-2). During the transition period, there is a little overshoot in power, voltage & current waveforms. The major oscillations get minimized within 0.08s after the insolation change. From t=0 to t=1s (UIC), tracked power, voltage & current are 532.5W, 72.6V & 7.32A respectively. From t=1s to t=2s (PSC), tracked power, voltage & current are 440W, 66V & 6.65A respectively. From t=2s onwards (UIC), tracked power, voltage & current are 532.5W, 72.6V & 7.32A respectively. Thus, Proposed methodology aims at stable MPP tracking operation both under uniform insolation and partial shading conditions.

VI. Conclusions And Discussion

The main purpose of this paper is to develop an efficient, agile and accurate methodology to extract maximum power from the photovoltaic generation system even under partial shading condition. The non-linear and multi-modal nature of the P-V curve of PV modules under partial shading condition makes it difficult to track the GMPP. Despite of the available advanced methods to track the GMPP, these methods lag in respect of tracking speed, complexity & accuracy. This paper aims at providing a highly simple circuit for MPPT operation with a tracking efficiency of 96.46% with enhanced accuracy as validated by simulation results.

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