A Novel Globalized MPPT Approach for Large Scale Solar PV System under Partial Shading Conditions

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Abstract-The conventional MPPT algorithm fails to track the maximum power from multiple peaks on P-V curve of multiple solar panels. Under this partial shading conditions, the tracking process becomes complex and it often loses certain portion of energy by traditional methods. This paper particular proposes a novel variable step size or variable duty cycle (VDC) based globalized MPPT (GMPPT) approach to achieve MPPT operation under sudden varying environmental condition with inclusion of partially shaded conditions. By considering the difference in the irradiation level for different solar PV panel at every instant, the proposed Globalized MPPT algorithm can identifies the status of partial shading conditions and ensures the MPPT operation. The main novelty of the work is to introduce variable duty cycle technique in GMPPT algorithm to trace the peak point of solar PV, which improves the dynamic response. The detailed explanations of Globalized MPPT operation has been reported in this paper. The mathematical modelling of solar PV and performance characteristics have been developed in PSCAD/EMDTC software and investigated in detail. Finally, to validate the proposed globalized MPPT approach, the simulation study was carried out and results have been discussed in this paper.

Keywords Globalized MPPT, solar PV, renewable energy, partial shading, PSCAD/EMDTC.

1. Introduction

Many countries are seeking alternate solutions to generate the electricity through renewable energy systems [1]. Among all renewable energy systems, the solar PV based power generation is growing sector due to free from pollution and avoid environmental hazards. In large scale solar PV system, multiple units of series and parallel combination of solar PV panel are connected to generate the energy. Due to non-linearity of the performance characteristics of solar PV, it is a complex task to perform the system under varying environmental conditions, especially under partial shading conditions. Especially, under partial shading conditions, the solar PV array operates as reverse PN junction diode and generates lesser energy. During these conditions, it behaves as a load and internal hotspots created, which drastically reduces the open circuit voltage. The traditional MPPT algorithm gets fail to extract the maximum power during partially shaded conditions [2].

The solar PV module characteristics are highly nonlinear in nature as discussed and the model gets further complicated when the PV array receives non-uniform solar irradiations. The maximum power can generate only at certain voltage and current points in the entire region [3]. Here, to operate under the maximum power throughout the day is conceptually tough. But, with the help of power converter and its technologies, it can generate maximum power over a time. To extract the maximum power from solar PV system, several MPPT algorithm techniques have been proposed by various authors [4-6]. Among this, the P&O algorithm is widely used by most of the researchers due to its less complexity and easier to control the system [7]. However, it has certain limitation that the operating of MPPT gets oscillates in around the peak point. It means the voltage is continuously adjusted and controller may need more effort [8]. To overcome this drawback, adaptive P&O and modified P&O algorithm has been proposed. The change in duty ratio of power converter is gets varied depends on the distance between current operating point and peak operating points [9]. But this can be performed well only under normal operating conditions and it often fails to trap the maximum power under partial shaded conditions. Thereby, a huge power can be lost due to mismatch in the MPPT operation [10].

Numerous papers have been reported this partial shading issues and power drop in the system [11-13]. A few authors have been investigated in detail about the variations in the solar performance characteristics under partial shaded conditions [14]. In [15], the detailed investigation against the internal hotspot of the solar panel and remedies are also discussed in this paper. In [16], the energy losses are determined due to partial shading effect using ray-tracing technique. As discussed previous literature to avoid the hotspot effect in the series connected PV modules, bypass diodes are connected across the modules [17]. I-V and P-V characteristics produce multiple peaks under partially shaded condition. Under this condition, it is hard to trace the peak points in the universal point of MPPT using traditional MPPT algorithm. The conventional MPPT algorithm might be trapped at one of the localized MPPT regions.

From this paper, it is clear that the 15 to 75 % of energy gets deviated from the original generation due to this effect [18]. Model free Reinforcement learning is one of the most attractive futuristic approaches to construct the optimal action for MPPT operation and a new transfer reinforcement learning (TRL) approach with space decomposition has been proposed and implemented to achieve MPPT under partial shading conditions [19]. The flower pollination (FP) algorithm is proposed in [20], to obtain MPPT operation to minimize this huge power loss. However, the convergence of the system is poorer and it is not an optimal method. Global MPPT algorithm is also used to identify the exact location of the system under any variations in the solar performance characteristics. But, there is a delay in the adjustment of duty ratios due to non-linearity behaviours, especially sudden varying environmental conditions. This proposed research gets motivated from these kinds of studies and improves the performance of tracking to achieve MPPT under partial shading conditions.

From all these research papers, it is concluded that there is certain research gap to address the issue of tracking under partial shading conditions. By keeping the improved performance of MPPT operation under partial shading conditions as a research objective, this paper proposes a novel globalized MPPT approach to extract the maximum power from solar PV system. This proposed Novel GMPPT algorithm can track the global peaks under all possible shading conditions for the PV arrays connected in series. The variable duty cycle (VDC) control mechanism of globalized MPPT approach is a key element of hypothesis of proposed work and it helps identify and the track the global peak points under dynamic conditions, therefore, the computational time can be reduced. The detailed investigation on the proposed algorithm and operation details are explained in this paper. And also, the variations on the duty ranges under steady state and dynamic conditions are explained in this paper.

2. Performance of Solar PV System under Partial Shading Conditions

The performance of a string of series connected PV arrays is loses it energy if its entire PV arrays do not get equal solar irradiation, i.e., under partially shaded condition. In a series connected PV string of modules, the current remains same under all the modules carry the same current.

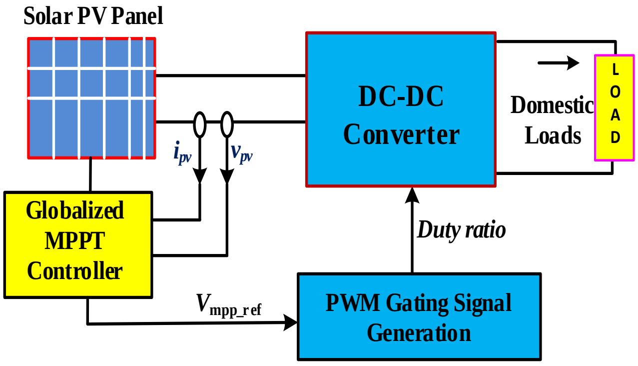


Fig. 1. Block diagram of proposed Globalized MPPT approach.

The block diagram the proposed globalized MPPT approach is clearly represented in Fig. 1. According to irradiations and temperature, the performance characteristics are gets changed and MPPT controllers become essential function to deliver maximum power. From the design perspective of MPPT, the designers have to consider the complexity and flexibility of the algorithm and limited sensors requirement, convergence speed and effectiveness of the system.

When single source of panel is connected, the oscillations around MPP point and convergence time are the serious issues and many algorithmic approaches are available to mitigate this problem. But when solar PV operates under partial shading conditions, it is hard to identify the peak point of power graph. Therefore, the converter fails to extract maximum power to load; it leads to considerable losses of power during steady state. And also, the voltage at load side gets oscillates due to imbalance of power under standalone condition. Moreover, it affects the performance of supplementary units connected along with this solar PV system. The instantaneous voltage and current of solar PV array is measured and applied to proposed globalized MPPT controller. Based on sensed feedback of voltage and current, MPPT controller identifies the operational point and corresponding voltage at solar PV. Based on the reference voltage set point, PI controller helps to produce tuned error signal to intersect with carrier pattern. Based on all these outputs, the respective PWM gating signals can be generated to extract the available maximum power from solar PV. It tracks the power under any situation and the procedure of this route has been explained in this paper.

3. Mathematical Modeling of Solar PV Array

The modelling of solar PV generater helps the designers to have better oreintation control mechnaisma nd asses the power generation cpapability before installing at any location. It is a single diode model and current sharing accurate mathematical model has been reported in this paper. The basic practical solar cell along with current source is considered in the equivalent circuit. When two cells are connecte din series, certain stages of array can be shaded from cloud and this particular case is also considered in this mathematical model. When the solar PV arrays are connected in series (shaded aad un-shaded cells), the equivalent circuit is shown in Fig. 2.

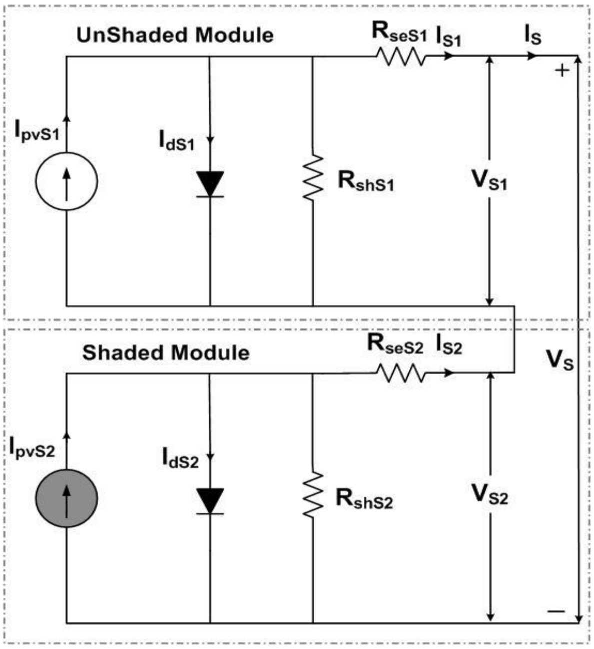


Fig. 2. Equivalent circuit of series connected solar PV array.

As shown in Fig. 2, when two modules are connected in series the mathematical relations under partial shading conditions can be expressed as,

$$I_{S1} = I_{pvS1} - I_o\psi_{S1} - \lambda_{S1} \tag{1}$$

$$I_{S2} = I_{pvS2} - I_o\psi_{S2} - \lambda_{S2} \tag{2}$$

Where $I_{pv1}$and V_{pv1} are the solar generated current and voltage of the series un-shaded module, I_{pvS1} is light generated current of series un-shaded module. Using (1), the total current generation gets reduced due to fewer parameters as mentioned below,

Where

$$\psi_{S1} = \left[exp\left(\frac{q(V_{S1}+I_{S1}R_{seS1})}{\alpha kT_{S1}}\right) - 1\right]$$

$$\lambda_{S1} = \frac{V_{S1} + I_{S1}R_{seS1}}{R_{shS1}}$$

$$\psi_{S2} = \left[exp\left(\frac{q(V_{S2}+I_{S2}R_{seS2})}{\alpha kT_{S2}}\right) - 1\right]$$

$$\lambda_{S2} = \frac{V_{S2} + I_{S2}R_{seS2}}{R_{shS2}}$$

$I_{S2}$and V_{S2} are the similar parameters for series connected solar PV array. Under shade condition, the I_{pvS2} is forced to flow through both the modules. R_{seS1} and R_{seS2} are the series internal resistanc eof solar PV. R_{shS1} and R_{shS2} are the shunt resitanc eof solar PV. The temperature play an important role affecting the solar PV characteritics. For better understanding, the equations (1) and (2), $I_{S1}$and I_{S2} can be rewritten as

$$I_S = I_{S1} = I_{S2} = I_{pvS2} - I_o\psi_S - \lambda_S \tag{3}$$

Where

$$\psi_S = \left[exp\left(\frac{q(V_{S2}+I_S R_{seS2})}{\alpha KT_{S2}}\right) - 1\right]$$

$$\lambda_S = \frac{V_{S2} + I_S R_{seS2}}{R_{shS2}}$$

The voltage of shaded cell gets affected and sometimes it acts a load. Thereby, the power primarily gets loses at generation side itself. Finally, the total solar PV panel voltage is,

$$V_S = V_{S1} + V_{S2} \tag{4}$$

$$V_S = V_{S1} + Sum\ of\ (V_{S2} voltage\ of\ shaded\ cell) + (V_{S2} voltage\ of\ unshaded\ cell) \tag{5}$$

When PV modules are connected in series without connecting bypass diode; they do not exhibit multiple MPP under partially shaded condition. The generated output power of solar PV can be written as

$$P_{MPPS} = V_{MPPS}\left[I_{pvS2} - I_o\psi_{MPPS} - \lambda_{MPPS}\right] \tag{6}$$

Where $\psi_{MPPS} = \left[exp\left(\frac{q(V_{MPPS}+I_{MPPS}R_{seS2})}{\alpha kT_{S2}}\right) - 1\right]$

$$\lambda_{MPPS} = \frac{V_{MPPS} + I_{MPPS}R_{seS2}}{R_{shS2}}$$

4. Global Maximum Power Point Tracking Algorithm

The globalized MPPT algorithm is proposed and the key factor behind this approach is stepped comparison. It helps to track the GMPP using variable step size when the multiple PV modules are under partial shading condition. Basically, the operation details of proposed GMPPT approach can be begin with traditional P&O, GMPPT and multiple step function. All these units are implemented in GMPPT algorithm to perform efficient and effective manner. In the event of partial shading (PS), the timer interrupt occurs (block 4), and the control will shift from the main control algorithm, to trace the updated global MPP V_{UMPP} (k). The shading condition is identified in the algorithm when the difference in radiation levels in different PV modules is more than a pre-specified value, and the interrupt is programmed to activate. The proposed scheme starts with total series and parallel connected panel.

The proposed globalized MPPT control algorithm operates as follows. Firstly, it collects the information from previous cycle of operation like P_{MPP} and V_{MMP} to identify the location of the votlage and maximum power point from the IV and PV characteritics. Then, the instant voltage generation V'_{PV} (k) and current I'_{PV} (k) (stage 7) can be determined. Using above these instants, using propsoed approach, the values of updated global MPP point V'_{UMPP} (k) (stage 8) can be obtianed.

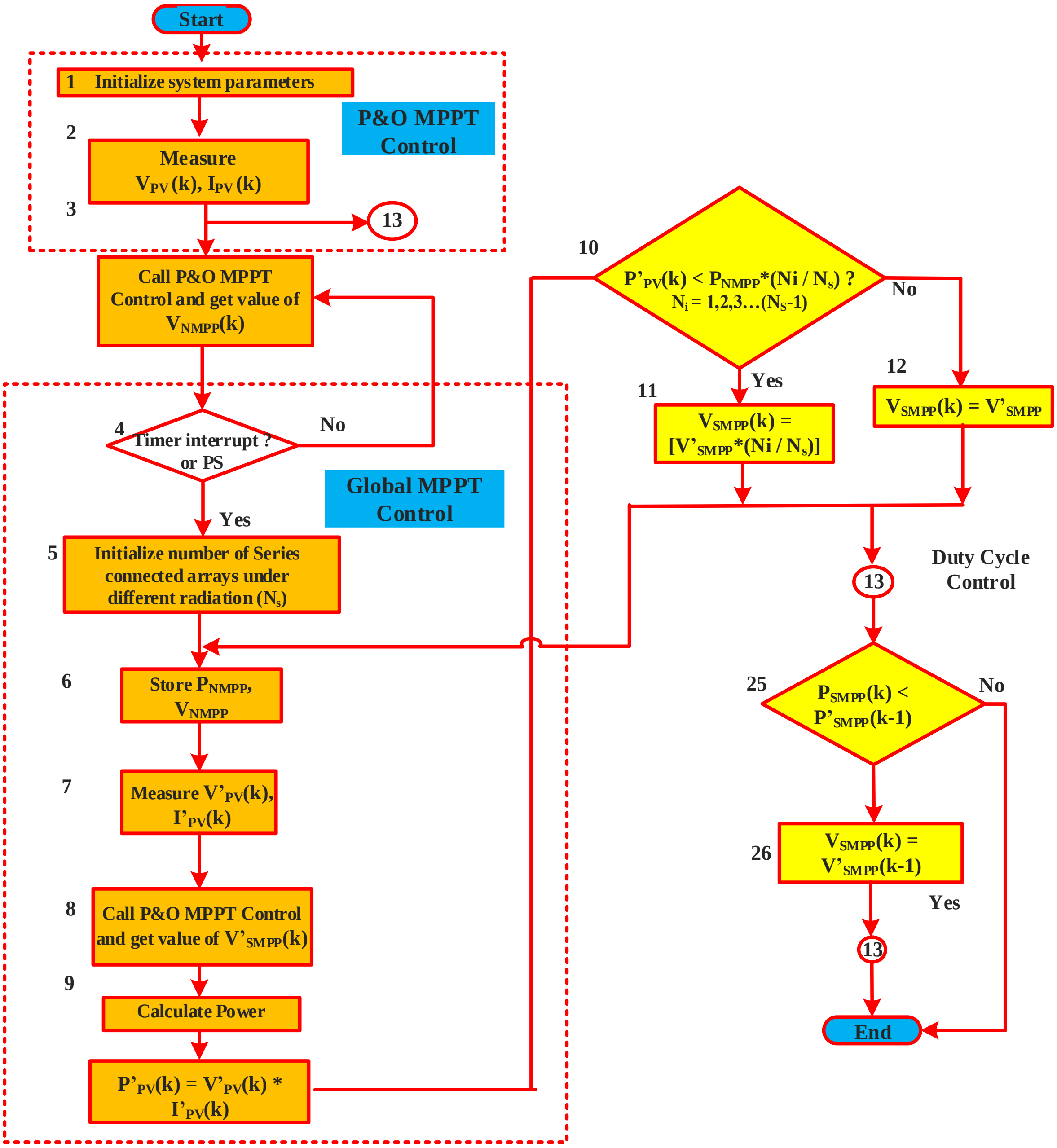


Fig. 3. Flowchart of Proposed Globalized MPPT algorithm

In order to verify the operation, the present power can be estimated using P'_{PV} (k) = V'_{PV} (k) × I'_{PV} (k) (state 9). And also,the present power deviations can be identified from the staircase power, i.e., *if* P' (k) < P_{GMPP}× (N_i/N_S) (state 10). It improves the relaibilty of the entire algorithm. After satisfies this above condition, the present MPP voltage becomes V_{SMPP} (k) = V'_{SMPP} (k) × (N_i/N_S) (state 11), otherwise, V_{SMPP} (k) becomes V'_{SMPP} (k) (state 12).

Based on the irradiation values, the same amount of power generated and it continuous and repeated till this statement becomes true. Thereafter to achieve practical power generation, the command shifted to duty ratio control unit. In duty ratio control unit, the GMPP controller helps to find the deviation from the present generated power. If it negative, then it originate with next perturbation otherwise it hold previous duty ratio ($P_{SMPP}(k)$<$P'_{SMPP}(k$-1), then $V_{SMPP}(k)$ = $V'_{SMPP}(k$-1)).

4.1 Duty Cycle Control

The duty cycle controller helps to identify the suitable duty ratio to extract the peak power from solar PV array. The flowchart of duty ratio control under globalized MPPT algorithm is illustrated in Fig. 4. It is also has to follow certain steps to ensure the MPPT operation under partial shading conditions. Initially, it collects V_{UMPP} from the state 11, 12 or 26 under partially shaded portion of solar PV array. And collect V_{NMPP} from state 3 at un-shaded portion (state 13).

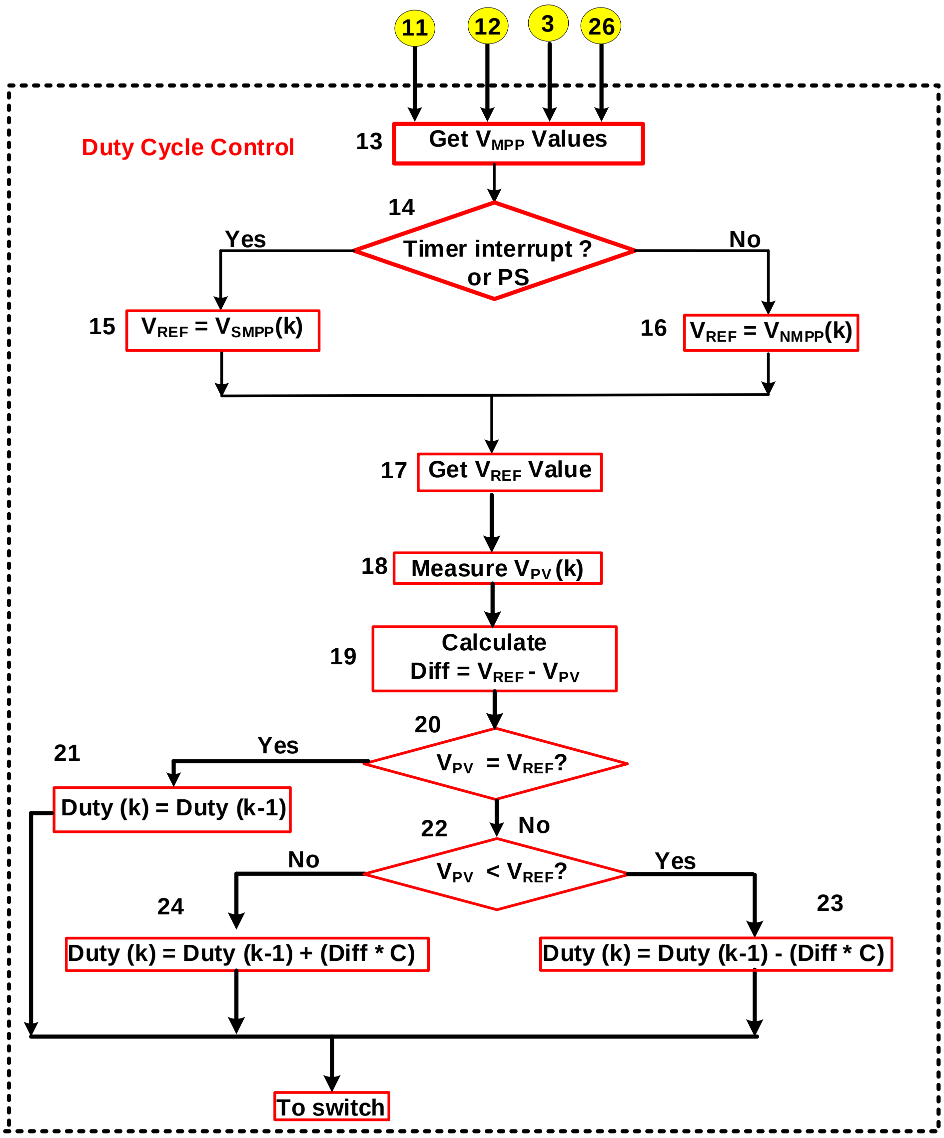


Fig. 4. Flow chart of duty ratio control under partial shaded conditions

The interrupted condition from state 14 can be identified, if yes, reference voltage becomes V_{UMPP} (k) (state 16), else it becomes V_{NMPP} (k) (state 15). It gets continued until this error becomes zero, the duty ratio is to be adjusted otherwise maintain the previous duty ratio. If reference voltage is equal to V_{PV} (state 20), $D_{new} = D_{k-1}$ (state 21), otherwise, D is to be adjusted between 0 to 1 (state 23 and 24). From all these states (5 to 26), the condition of duty ratio is repeated and MPPT operation is achieved with higher accuracy during partially shaded conditions.

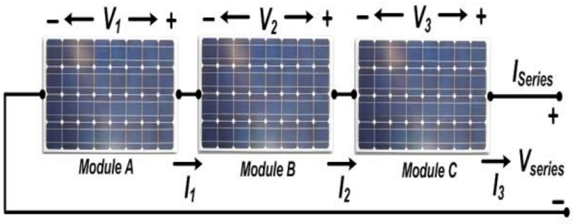
5. Simulation Result of Global Maximum Power Point Tracking

To perform simulation study, PV panels are connected in a series connection. Each of solar PV array is connected as parallel strings with 10 modules are connected in series. By considering all the modules are operated at same irradiation level. The proposed GMPPT algorithm is discussed in the previous section is applied with the assumption of two arrays at different irradiation levels. It is considered that one array is at an irradiation level of G1 = 1000 W/m2, and another at radiation level of G2 = 400 W/m^2, with Ns = 2, and Ni = 1. The detailed simualtion set up parameters are reported in Table 1.

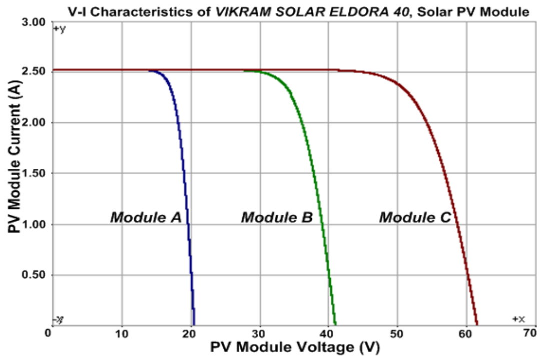
Table 1. Simualtion set up parameters

PV Module	Value
Maximum power (P_{MAX})	75 W
Voltage at MPP (V_{MPP})	17.3 V
Current at MPP (I_{MPP})	4.35 A
Open circuit voltage (V_{OC})	21.8 V
Short circuit current (I_{SC})	4.75 A
Input capacitor (C_1)	100 [µF]
Inductor (L)	1.2 [mH]
Output capacitor (C_2)	200 [µF]
Resistive load (R)	60 [Ω]
Switching frequency (F_s)	20 [kHz]

A 75 W of each solar pv panel has been considered and conncetd in series, which is shown in Fig. 5(a). The complate mathemtical modelling has been built in PSCAD/EMDTC software. The dc-dc boost converter is connected to load to drive the power. The passive elements and its ratings are displayed in Table 1. 17.3 V is maximum power point reference votlage and open circuit votlage is 17.3 V and 21.8 V, respectively. Ferrite core inductor is utilized to boosting up the soalr PV votlage based on MPPT operation. To reduce the filter at output side, 200 uF capactior is utlized.



(a)



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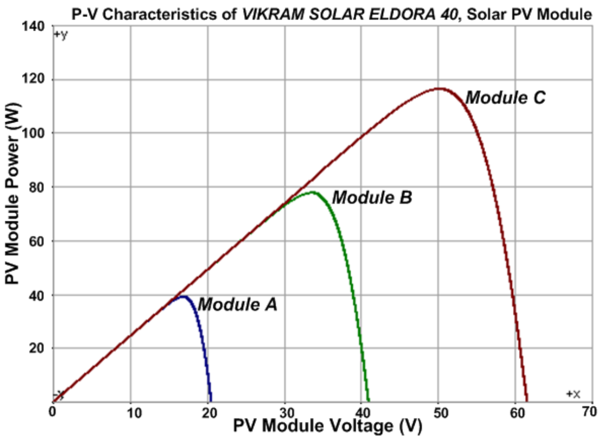
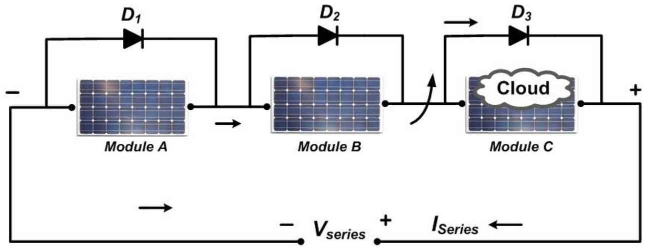


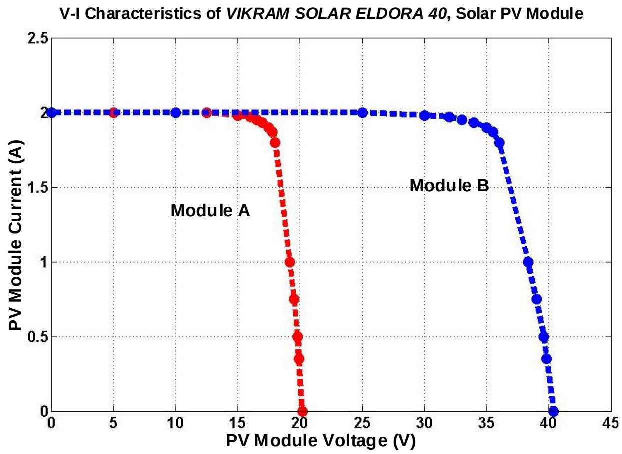
(c)

Fig. 5. Simulated results of three panels connected in series under normal irradiation conditions (a) Solar PV connected in Series (b) IV characteristics (c) PV characteristics

The IV characteristics of all three modules for solar PV system are clearly illustrated in Fig. 5(b). It is clearly understandable the current remains same with different voltage levels. Similarly, the PV characteristics are also plotted in Fig. 5(c). From 5(b) and (c), it is clear that the developed mathamtical model yield the output similar to the theoratical one under unshaded condition. Under partial shaded conditions, the solar panels are connected in series is shown in Fig. 6. When any one of the array or string or panel is facing issues of partial shading, the voltages are getting dropped to the desired level. It has been measured at each samples and plotted as shown in Fig. 6.



(a)



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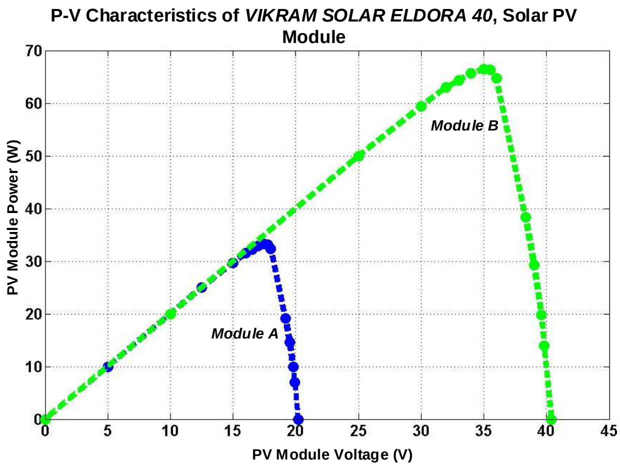
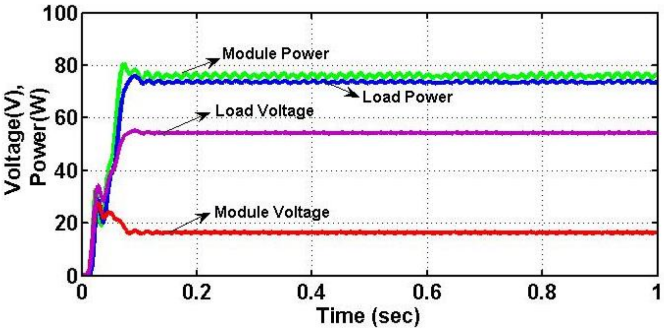


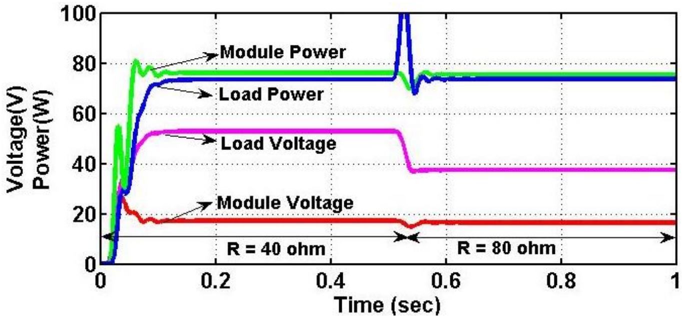
(c)

Fig. 6. Simulated results of three panels connected in series under partial shaded conditions (a) Solar PV connected in Series (b) IV characteristics (c) PV characteristics

The power generation of the particular panel is zero; it is validated through I-V characteristics as shown in Fig. 6 (b). And also, the PV characteristics under this condition is observed and shown in Fig. 6(c). For the practical case, there is slight deviations from the nominal value of IV and PV characterticis, however, the nature of the plot is following the idela one.



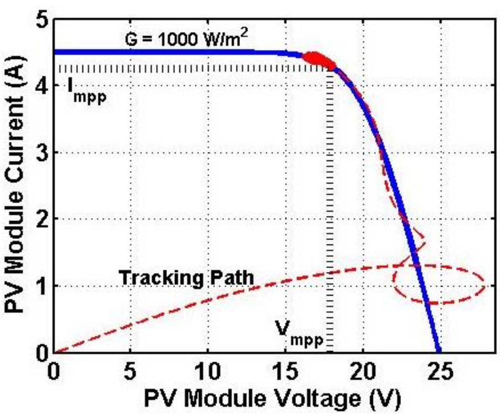
(a)



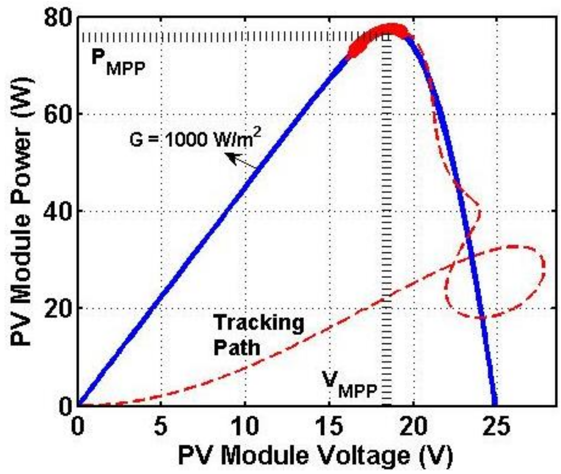
(b)

Fig. 7 Simulation results of solar PV (a) under steady state conditions (b) under dynamic conditions

To validate the power generation under partial shading conditions, the load has been connected at boosted output, the measured results have been observed. Under normal irradiation level, the power graphs are observed and captured in Fig. 7(a). The module voltage, current and power of the solar PV array is shown in Fig. 7(a).



(a)



(b)

Fig. 8. MPPT route of (a) IV characteristics and (b) PV characteristics of solar Panel

It is seen from Fig. 7 (a) that the load voltage is higher than module voltage due to boosted output and power remains approximately same for load side and generated side. Similar to this, under dynamic irradiation conditions, the simulation results of solar PV module voltage, current and power is observed and plotted in Fig. 7 (b). From Fig. 7, the losses of the system can be estimated from the difference of power generation and utilization at load. It is clearly indicated in the IV characteristics of solar PV, as shown in Fig. 8 (a). Similarly, the proposed GMPPT route is also traced in x-y plot of PV characteristics, as shown in Fig. 8 (b). The route of proposed globalized MPPT operation is observed through simulation studies and presented in Fig. 8 (a) and (b). To trace the maximum power, the algorithm takes fewer samples and during this convergence time, the route never gets oscillates under any point. It ensures, it has very lesser convergence time to attain maximum power point position.

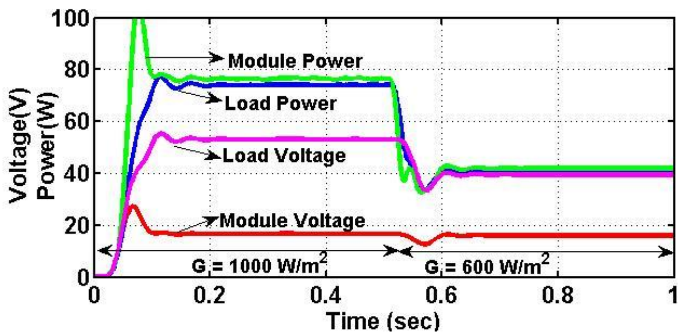
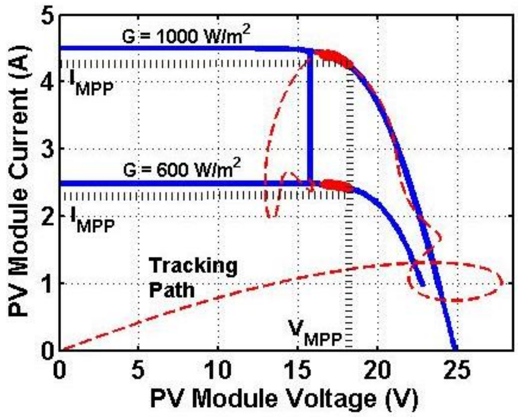
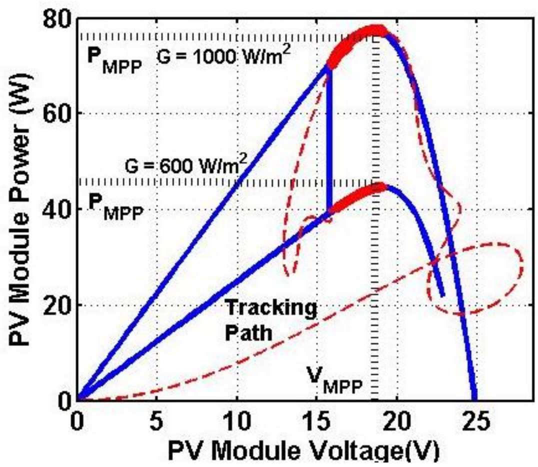


Fig. 9. Simulation results of solar PV in partial shaded condition

To verify the proposed algorithmic approach under partial shaded conditions, the simulation results of solar PV module voltage, current and power under sudden change in irradiation condition are observed and presented in Fig. 9. Under change in irradiations, the module power generation gets reduced and immediately, the proposed algorithm identifies the right operational point to deliver the maximum power. It can be clearly captured in Fig. 9. And also, the time taken to settle the power is very less, it is clearly seen from the dynamic condition occurred at 0.55 seconds of Fig. 9. To validate the route of MPPT operation, the IV and PV characteristics of solar panel is shown in Fig. 10. Under first case, the current at maximum power point is 2.5A. Due to change in irradiation, the new tracking power is shifted up as shown in Fig. 10 (a). For better view, the maximum power under different conditions is clearly captured in PV characteristics as shown in Fig. 10 (b). There is no oscillation in the route of MPPT during dynamic conditions and therefore it ensures that the proposed algorithm can take lesser convergence time to attain MPPT point.



(a)



(b)

Fig. 10. MPPT route of solar PV with proposed globalized MPPT approach (a) IV characteristics and (b) PV characteristics

To validate this convergence time, various MPPT approaches have been investigated in detail by implementing each algorithm for a fixed run time with same simulation set up parameters. Then, the convergence time has been estimated in the simulation study and summarized in Table 2 of the revised manuscript. From Table 2, it is clearly indicates that the proposed variable BAT or VDC fed GMPPT algorithm can improvise the dynamic performance than recently reported articles.

Table 2. Simulation results of convergence time with other published articles

MPPT Technique	Convergence time (t_c)
Original cuckoo search (OCS) [9]	3.51
Improved cuckoo search ICS [11]	1.52
Bat (duty ratio) Algorithm BA [4]	0.33
Ant Colony Optimization PSO [14]	0.51
Proposed VDC fed GMPPT Algorithm	0.22

6. Conclusion

The performance of the proposed novel globalized MPPT algorithm with staircase operation has been demonstrated under various irradiation conditions with partial shading effect. The proposed algorithm tracks the power by adjusting the duty ratios of dc-dc converter and the operational details of variations in the duty ratio are explained. The detailed operation of proposed GMPPT algorithm reported in this paper. Three major functions of proposed algorithm have been explained in a detailed way with flowchart. The results show that the proposed direct variable step size or variable duty cycle (VDC) based globalized MPPT (GMPPT) algorithm has good tracking approach with higher accuracy under steady state and dynamic conditions. It makes proposed system simpler, cost effective and increases overall efficiency of the photovoltaic systems. From the measured results, it is concluded that the proposed globalized MPPT algorithm is most suitable for solar PV systems operates under partial shading conditions with lesser convergence time compared to recently reported other algorithms.

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