Solar PV Characteristic Independent Fast Global Maximum Power Point Tracking Algorithm

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***Abstract*—This paper proposes a novel maximum power point tracking algorithm for solar PV system that can work even under partial shading conditions. The proposed algorithm is easy to implement, does not depend on any system parameters, and always takes same amount of time for tracking global maximum power point. The algorithm is based on duty ratio variation rather than solar PV characteristics for tracking the global maxima. The propositions are simulated using MATLAB/Simulink and typical results are presented. It is shown that tracking time and accuracy can be improved with the variation of switching frequency and the filter inductor (L) and capacitor (C) values used in the boost converter. It is further shown that using the proposed algorithm, global maximum power point with >99% accuracy can be reached within 1 ms.**

***Index Terms*—Global Maximum Power Point(GMPP), Maximum Power Point(MPP), solar PV, Partial shading, renewable power generation, boost converter.**

I. Introduction

Solar photovoltaic (PV) based power generation systems are one of the fastest growing due to the abundant availability of solar power, reducing cost and increasing efficiency of solar panels, noise free operation etc. However, for extracting maximum power output from a solar panel, it has to be operated only at the peak of its Power-Voltage(P-V) characteristic. Due to variation in temperature and irradiation or partial shading, P-V characteristic changes and hence the maximum power point (MPP) also changes correspondingly. The objective is to track the maximum power point accurately within short time and extract maximum output from the solar panels at all conditions.

For achieving this, many algorithms have been developed in literature and these can be broadly classified into two categories, one that consider P-V characteristic to be monotonically increasing until its peak and the other which consider practical P-V curves with shading effects.

Algorithms based on monotonic characteristic of P-V curve are perturb and observe [1], incremental conductance [2], hill climbing strategy [3], fractional open circuit voltage and short circuit current based methods [1], and hybrid methods combining any two or more of these algorithms [4]. While each one of them has their own advantages and limitations, these techniques broadly can be useful for small power installations where P-V curve is only increasing till maximum power. Therefore, these methods cannot track MPP in partial shading conditions. Partial shading may happen due to many reasons like passing of a small cloud or due to nearby building/wall or moist weather or dust accumulated on the panel etc. The impact is more predominant large installations where huge number of panels are connected in series/parallel to form an array. Due to partial shading on one or more panels, the P-V curve of the entire array can exhibit different shapes having multiple local maxima (but one global maxima). To extract maximum power in this case, the system must be made to operate at global MPP (GMPP). Few authors have proposed techniques that can also work under partial shading conditions and track the GMPP [5-17].

[5] samples the PV curve at 0.8 Voc (Voc=open-circuit voltage) interval and finally applies Peturb and Observe technique on those samples whose $\frac{dP}{dV} < 0$. In order to track GMPP quickly, [6] used a voltage step of 0.5 Voc and scan GMPP from minimum to maximum voltage but there may be a case that it may not find GMPP. Algorithm proposed in [7] divides the PV curve into sub region and the sub region with highest power value is evaluated which is called candid region. Applying the similar procedure, search region becomes smaller until the vicinity of GMPP is achieved. This method is complex to implement and also takes long time to reach GMPP.

Many new algorithms are being developed to track GMPP with optimization techniques like particle swarm optimization [8], fuzzy logic control [9], simulated annealing [10], artificial neural network[11] and fireflies [12] etc. Though these techniques are shown to track GMPP, they increased the complexity and computational burden of algorithm and consequently the speed of response decreases. [13],[14] varied duty ratio in large steps and in [13] the entire curve is fed to the controller memory which then picks the GMPP using perturb and observe with smaller step in the vicinity of the larger step. This not only require huge memory for remembering the entire curve but also involve large computational burden on the controller. The GMPP tracking time is also high (>2s) in these algorithms. [15] used PI controller to get the GMPP along with duty variation. This technique also involves huge memory, complex to implement, and also has variable tracking time depending on shading and other conditions.

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To overcome the drawbacks of existing algorithms, a novel algorithm is proposed in this paper that can track GMPP in 10 milliseconds or less. The algorithm is very simple and easy to implement and is not dependent on initial values which can affect the tracking accuracy. Also, the proposed algorithm is independent of the PV characteristics and can track GMPP within same amount of time in almost all partial shading conditions.

This paper is organized as follows. After the introduction in Section I, system configuration and proposed algorithm are presented in Section II. Simulation results and their discussions are provided in Section III and Section IV concludes the paper.

II. System Configuration and Proposed Algorithm

A. PV Cell Modelling

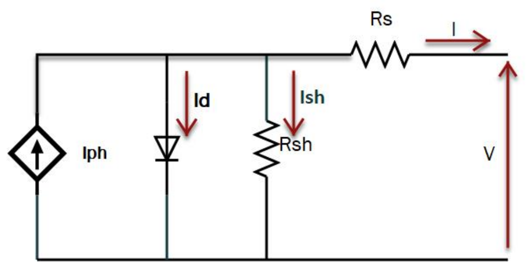

Fig. 1: PV cell equivalent circuit model

Among the various PV models available in literature, the single diode model is most popularly used mainly because it is easy in implementation. The purpose of this model is to emulate the PV behaviour in the form of an electrical circuit and use it in simulation for further analysis. The single diode model used in this paper is shown in Fig. 1. From Fig. 1, the I-V characteristics of a solar panel can be expressed as

$$I = I_{ph} - I_o(e^{\frac{q(V+IR_s)}{nKN_sT}} - 1) - I_{sh} \tag{1}$$

where I_{ph} is the photo current, R_s and R_{sh} are the series and shunt branch resistances, T is the temperature in Kelvin, N_s is the number of series connected cells, I_{sh} is the shunt branch current, I_o is the saturation current, K is Boltzmann's constant and n, q are constants for a given cell. The same circuit with equivalent parameters can be considered for a PV panel which has many cells connected in series-parallel combination and also for a PV array which is formed by connecting various panels in series/parallel.

B. Power vs. Voltage (P-V) Curve of a PV Array

When a large number of PV panels/modules are connected in series or parallel, there may be a case of PSC (Partial shading condition) on some of the modules. In PSC, some of the modules can start acting as sink which may result in hot-spots in the shaded module and cause damage to them. In order to overcome this problem, a bypass diode is connected in parallel with each PV module which free wheels in case of shading. In such a case, the P-V curve of the array consisting of many panels will not retain the monotonic shape and hence MPPT algorithms relying on shape of P-V curve under uniform irradiation may fail in PSC.

Suppose three panels are being connected in series with standard solar radiation and temperature on each panel as shown in Fig. 2, the P-V curve of the array will exhibit monotonic behavior as duplicated in Fig. 3. When the same three panels are given different irradiation and temperature, the P-V curve of the array can have many local maxima but with one global maxima as shown in Fig. 4.

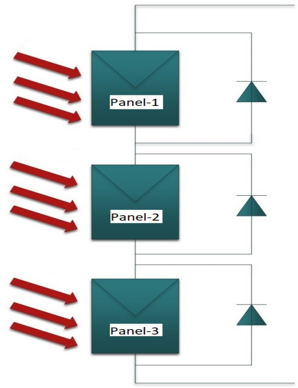

Fig. 2: Solar panels connection pattern

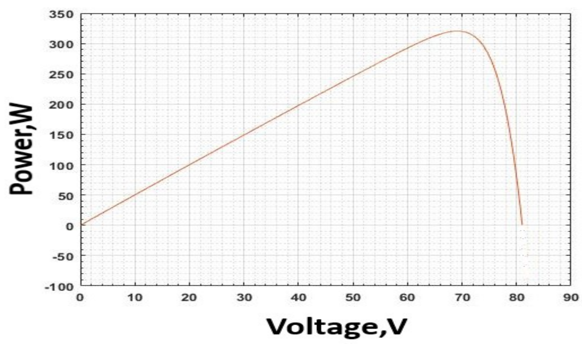

Fig. 3: Power curve with uniform irradiation

C. Boost Converter

Most solar PV installations use boost converter for MPPT tracking. Therefore, the proposed algorithm is also designed and implemented on boost converter to make it useful for existing installations with minimum modifications.

For an ideal boost converter, the relation between input and output voltage, current, and resistance is given by

$$I = \frac{I_{load}}{(1-d)} \tag{2}$$

$$V = V_{load}(1-d) \tag{3}$$

$$R_{in} = \frac{V}{I} = R_{load}(1-d)^2 \tag{4}$$

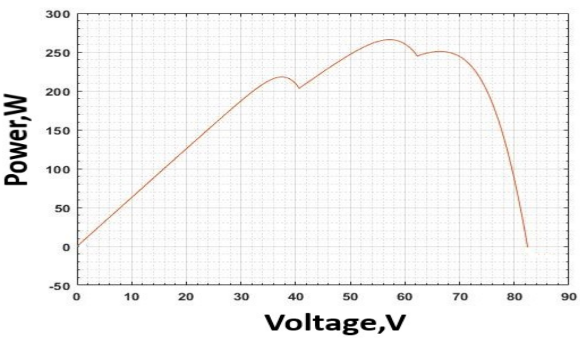

Fig. 4: Power curve with non-uniform irradiation

where I is the input current (from PV panel), I_{load} is the output current, V is the input voltage (across PV panel), V_{load} is the output voltage, R_{in} $(= \frac{V}{I})$ is the input resistance, R_{load} is the load resistance, and d is the duty ratio given to the converter.

For a given load resistance R_{load}, the input resistance of the boost converter can vary from $R_{in} = 0$ to $R_{in} = R_{load}$ for d=1 and d=0 respectively. Hence, the converter gets restricted to operate in the region of V-I for which $R_{in} = \frac{V}{I} \leq R_{load}$. The same has been depicted in Fig. 5 where I-V and P-V graph of a solar panel are plotted and d=0 and d=1 lines are indicated. As shown, using a boost converter having load R_{load}, it is not possible to operate for V greater than ob in the x-axis. Correspondingly, the PV curve lying in the region abd is inaccessible. Therefore, any MPPT algorithm can work if and only if the MPP lies in the region for which $R_{in} \leq R_{load}$.

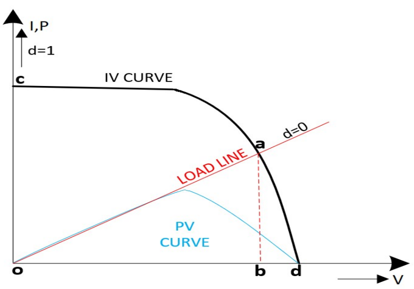

Fig. 5: I-V, P-V and load line characteristics for a given R_{load}

D. Proposed Algorithm

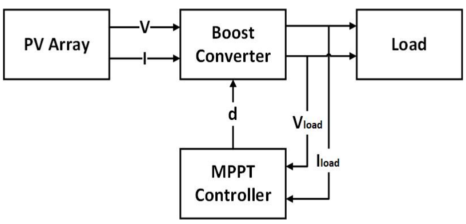

Fig. 6: System block diagram with GMPPT

The system block diagram is shown in Fig. 6. It consists of a PV array connected with a dc/dc boost converter supplying a load. The output voltage and current are sensed and fed back to the controller which based on the MPPT algorithm generates the control/duty signal and gives to the converter.

As mentioned in the introduction, the available Global MPPT algorithms for the partial shading case either took longer time ($>$ 2s) and/or were complex in implementation requiring huge number of calculations and memory.

From the P-V curve in uniform irradiation or partial shading case, it can be observed that for a particular V and I, global maximum power is drawn from the panel. This V and I for a given load can be achieved by the boost converter for a particular duty ratio, d_{max} obtained from (4). The proposed algorithm uses this principle and obtains the duty ratio for global MPP by

1) varying the duty ratio with smallest step possible so as to reach the exact D_{max}, the duty ratio required for maximum power.
2) checking power at every step and comparing with the previous one and updating D_{max} accordingly.
3) updating the d to D_{max} once $d = 1$ is reached.

The detailed flow-chart of the proposed algorithm is shown in Fig. 7. According to the flowchart, whenever GMPP tracking is required, the parameters, time (t), duty ratio (d), maximum power (P_{max}), and duty ratio corresponding to maximum power (D_{max}) are initialized to zero. As time increases to $(t + \Delta t)$, duty ratio is also incremented to $(d + \Delta d)$. Power is computed using output voltage and current feedback. If the present output power at $(t + \Delta t)$ is greater than that at t, P_{max} and D_{max} are updated with the present power and duty ratio. Otherwise, it holds the previous values. This is continued until d reaches 1 and then the current D_{max} value is given to the converter for tracking maximum power. This algorithm is repeated whenever there is a sudden change in power or after every preset time that is required for the location (say 3 sec).

E. Highlights of the Proposed Algorithm

As seen from the flow-chart given in Fig. 7, all possible operating points are being checked by varying the duty ratio. Hence, it is ensured that the maximum power will be tracked for every shape of P-V curve since the algorithm is independent of PV characteristics. The proposed algorithm also is easy to implement on any low cost controller since it involves minimum number of mathematical computations and requires less memory. Memory is required only for storing and updating P_{max} and D_{max} values at every step. The time required for finding GMPP (d_{max}) will remain always constant and is equal to the time taken for varying the duty ratio from 0 to 1. For achieving the GMPP faster, the duty ratio has to be varied from 0 to 1 in less time. Considering a switching frequency of 100 kHz (time period=10 μs), if d is varied for its entire range in 10 ms, the converter takes 1000 steps of d for tracing the GMPP. Therefore, the accuracy in the estimation of d_{max} corresponding to a step size of 1/1000 should be $>$99% (including sensor, switching, and filter delays if any)

for finding the GMPP in 10 ms. For implementation of this algorithm in hardware, the speed of the ADC used for sensing V and I has to be 100 ksps or more.
Similarly, the tracking time of GMPP can be further reduced by varying the d value from 0 to 1 in lesser time. Implementation with lesser time requires the converter to operate at higher switching frequency to have more number of steps in d and correspondingly smaller values of inductor and capacitor in the boost converter to enable the circuit to quickly adapt to the changes made in d. Please note that if the switching frequency is increased, the reduction in L and C values will not increase the ripples in voltage and current.

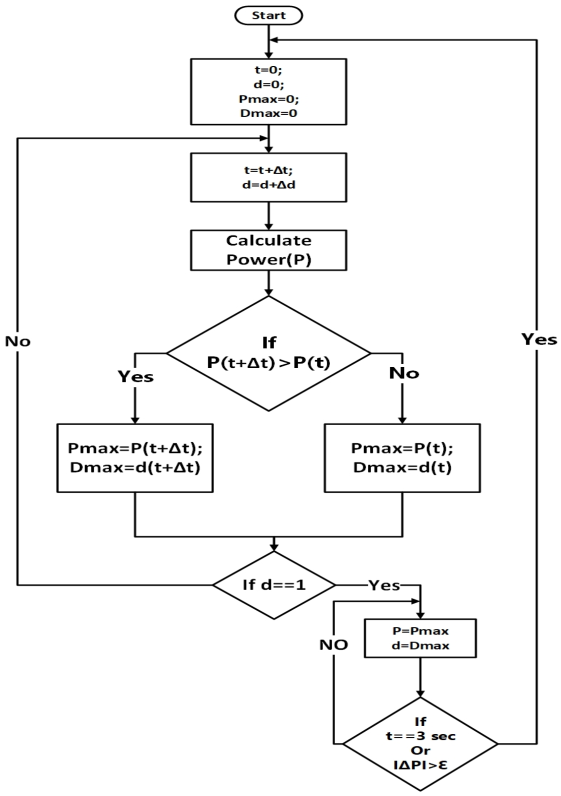

Fig. 7: Flowchart for proposed GMPP algorithm

III. Simulation Results

The PV array consisting of three solar panels connected in series (Fig. 2) along with boost converter and the proposed GMPPT algorithm has been modeled in MATLAB/Simulink and tested at different operating conditions. The specifications of the solar panels and boost converter used are given in Table I and Table II respectively. The voltage and current at the load are sensed and fed back to the controller for GMPPT tracking. The simulink model is tested at different operating conditions and this section provides some typical results.

A. GMPPT IN 10 ms

Consider a situation where a short moving cloud passes through the panels and creates different shading on the three panels (arranged as in Fig. 2). The PV panel and boost converter specifications used are as given in Table I and II respectively. Assume that the first, second, and the third panel received an irradiation of 1000 W/m^2, 800 W/m^2, 650 W/m^2 respectively at time, $t = 0$. Since the irradiation is different on the three panels, the P-V curve may have different peaks similar to Fig. 4. In such a case, the proposed GMPPT algorithm is implemented from $t = 0$ as given in the flowchart of Fig. 7. The duty ratio is varied from 0 to 1 in 10 ms as shown in Fig. 8. According to the algorithm, the power is calculated at every step and at the end of 10 ms, the maximum output power (P_{max}) and the duty ratio required for achieving it (d_{max}) are obtained. After 10 ms, d_{max} is fed to the converter for GMPP operation (Fig. 8). The power and the load voltage curves are shown in Figs. 9 and 10 respectively, where it can be seen that the converter extracts and operates at maximum power at the end of 10 ms where GMPP is obtained.

After sometime (say 0.02 sec) when cloud passed away, standard irradiance may be incident (1000 W/m^2) on all the panels. Since the irradiation changed, the maximum output power and hence GMPP would change and the algorithm has to be run again for tracking the new GMPP. As shown in Fig. 8 duty ratio is again varied from 0 to 1 (from 0.02s to 0.03s) to track the new GMPP. From the output power and voltage curves shown in Figs. 9 and 10, it can be confirmed that the algorithm is able to track and maintain maximum power output from the PV panels. As shown in the flow-chart, this algorithm will repeat after every preset time (say 3s) or when a sudden change is observed in the output power due to partial shading.

TABLE I: SUK 100 Wp Solar Panel Rating

Sr.No	**Panel Parameters**	
1	**Power(max)**	*100 W*
2	**Open Circuit Voltage**	*21.4 V*
3	**Short Circuit Current**	*6.3 A*
4	**Current(max power)**	*5.7 A*
5	**Voltage(max power)**	*17.7 V*
6	**Tolerance**	*3%*

TABLE II: Boost Converter Specifications

Sr.No	**Parameters**	
1	**Inductor**	*1 mH*
2	**Capacitor**	*10 μF*
3	**Load Resistance**	*20 Ω*
4	**Switching Frequency**	*100 kHz*

B. GMPPT IN 1 ms

TABLE III: Effect of L, C and switching frequency (f_{sw}) on GMPPT

d=0 to d=1 time	L (mH)	C (μF)	f_{sw}(kHz)	GMPPT (Yes/No)	Accuracy	Ripple (%)
10 ms	1	10	100	Yes	>99%	<2
10 ms	1	10	1000	Yes	>99.5%	<0.2
1 ms	1	10	1000	No	-	-
1 ms	0.1	1	1000	Yes	>98.8%	<2
1 ms	0.1	1	2000	Yes	>99%	<1

It has been observed that the filter inductor (L) and capacitor (C) values used in the boost converter has to be reduced in

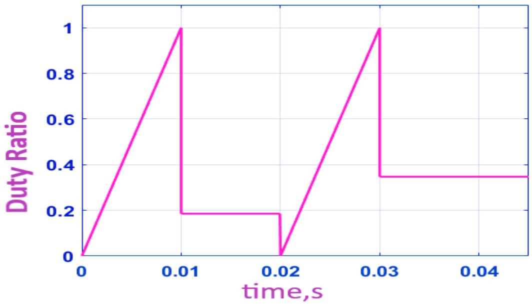

Fig. 8: Duty ratio for 10 ms tracking time

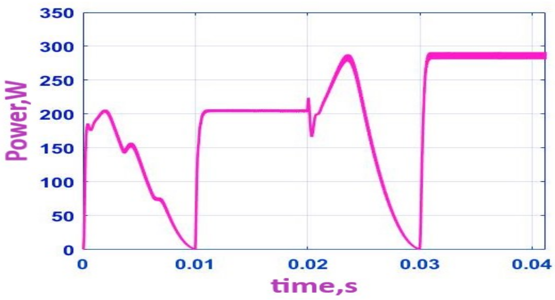

Fig. 9: Output power for 10 ms tracking time

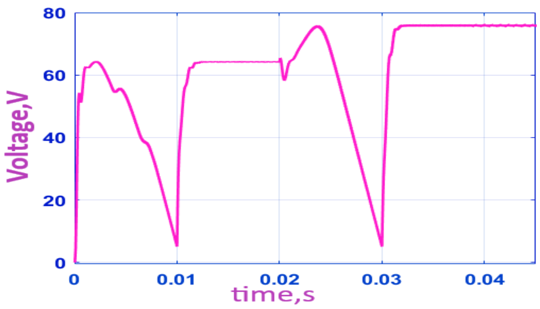

Fig. 10: Output voltage for 10 ms tracking time

order to operate the proposed algorithm satisfactorily in lesser time (<10 ms). This is because of the higher settling time required by both L and C for a change in the duty ratio. So, the L and C values have been reduced linearly with the required tracking time. For 1 ms operation, the L and C values are 1/10 of those used in 10 ms operation. It must be noted that with the same 100 kHz switching, 1 ms duty variation gives only 100 steps in d and this may reduce the accuracy in GMPP estimation. So, the switching frequency has been increased 10 times to 1 MHz to have more (1000) steps in d for reaching the GMPP accurately. With these specifications, similar shading conditions as given in Section III-A are applied on the PV system and the proposed algorithm is implemented with 1 ms tracking time. As shown in Fig. 11, the duty ratio is varied and the GMPP is obtained in 1 ms both for partial shading and healthy conditions of PV panels. The same can be observed from the output power curve as shown in Fig. 12 where maximum power is always extracted from the solar array. The corresponding output voltage curve is shown in Fig. 13 where it can be observed that the output voltage has small ripple even with smaller L and C values. This is due to the use of increased switching frequency which is helping not only in the reduction of voltage and current ripples but also in the accurate GMPP tracking by giving more steps in d.

The proposed algorithm has been extensively tested at different tracking times for different L, C, and switching frequencies. These results are not presented here due to space constraint. However, some typical case studies have been presented in Table III from where it can be observed that L,C has to be smaller for faster tracking and the accuracy in tracking will be higher for higher f_{sw}. This shows that with proper design in L, C, and switching frequency values (based on hardware limitations), the proposed algorithm is able to reach GMPP in smallest time possible.

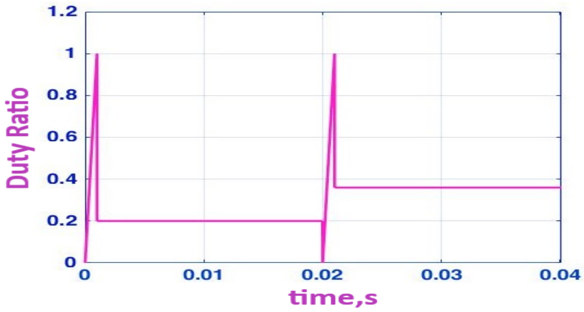

Fig. 11: Duty ratio for 1 ms tracking time

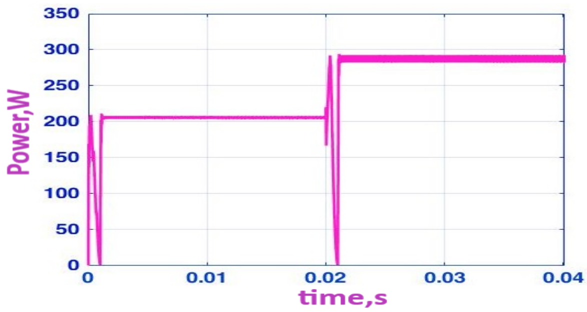

Fig. 12: Output power for 1 ms tracking time

C. Limitation of boost converter

As mentioned in Section II-C, the GMPP tracking fails if $R_{in} > R_{load}$. The same has been tested here. A partial shading condition (with the three panels receiving 1000 W/m^2, 800 W/m^2, and 650 W/m^2 irradiations respectively) is applied and the load resistance has been reduced to 10 Ω such that the GMPP lies in the $R_{in} > R_{load}$ region. As expected, even the proposed algorithm could not reach the GMPP as shown in Fig. 14 where the output power after 10 ms is only $\approx$150 W $<$ GMPP. This is the limitation offered by the boost converter.

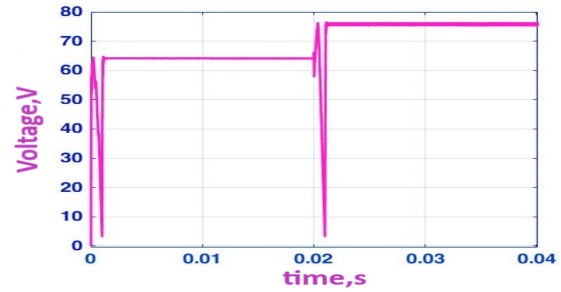

Fig. 13: Output voltage for 1 ms tracking time

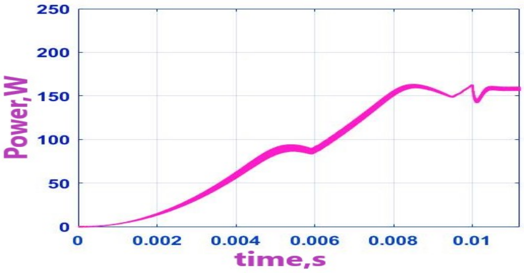

Fig. 14: Output power characteristic for $10ohm$ load

IV. Conclusion

This paper presented a new algorithm to extract global maximum power from solar PV array under partial shading conditions. The proposed algorithm achieved GMPP by varying the duty ratio quickly (in 10 ms or less) and checking the output power for every switching cycle. The present and past values of power are compared at every d and the maximum value of power and corresponding d_{max} are updated. Once, d reaches one, d_{max} is given to the converter for operating at GMPP. This algorithm is not only easy to implement but also require less memory as d_{max} and P_{max} values are not stored but updated at every switching cycle. Many GMPP algorithms existing with duty ratio variation are not using the precise step size and also propose to use Peturb and Observe or some other algorithm in addition to duty ratio variation whereas the proposed algorithm does not require any algorithm along with the proposed algorithm. Since every possible operating point is being checked, the algorithm is independent of solar panel/array characteristics and hence can track GMPP in all partial shading conditions in same amount of time at which the duty is varied. For satisfactory operation of the proposed algorithm in smaller tracking times, the L and C parameters of the converter need to be made smaller in values to enable the circuit to adapt to the fast variation in d. It is recommended to increase the switching frequency for tracking the GMPP with more accuracy. Higher switching frequency also decreases the ripples in output voltage and currents. MPP cannot be tracked if the GMPP lies beyond the range ($R_{in} \leq R_{load}$) of the boost converter. Further work in this area could be to design a converter that can operate in the entire P-V range at all loads. All the propositions have been verified using MATLAB/Simulink based simulations and the proposed algorithm is found to track GMPP in partial shading conditions satisfactorily.

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