

An Enhanced Incremental Conductance Algorithm for Photovoltaic System

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Abstract—The energy obtained from the photovoltaic array is dependent on the available solar insolation, the panel tilt angle and the power point tracking algorithm of the system. Some of the Conventional MPPT methods are developed by considering uniform solar irradiance. During partial shading conditions, solar panel may produce multiple Local Maximum Power Points (LMPPs) in its power voltage characteristic curve. A new algorithm has been developed in this paper by using sequential sampling embedded with existing incremental conductance procedure in order to predict the Global Maximum Power Point (GMPP). The tracking capability of proposed algorithm is verified with simulation works carried out in MATLAB/SIMULINK. The results of proposed algorithm are likened with the results classical Perturb and Observe (P&O) and Incremental Conductance algorithms.

Index Terms— Global Peak (GP), Photovoltaic (PV), Maximum Power Point Tracking (MPPT), Incremental Conductance, Single Ended Primary Inductor Converter (SEPIC).

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I. INTRODUCTION

Power demand is increasing nowadays because of increase in population and to satisfy their needs. Along with conventional energy sources, other energy sources such as the solar energy, bio-mass energy, wind energy etc. contribute to meet out the power demand conditions. These additional energy sources have gained huge interest due to environmental issues and looking for low-cost energy. [1-3] Solar energy is

the united with the power and heat of the sun's rays. Solar energy is clean and available in most of the places. Photovoltaic energy conversion is the simple process and a smart method of converting the incident sun irradiance into an electrical energy [23] with the help of solar cells. As like other energy generation units, it won't produce any noise, pollution and it is robust and reliable. These PV panels consist of semiconductor materials and it producing electrical energy when it is subjected to sunlight and its output depends on forbidden energy gap level of semiconductor material used in PV panel. PV cell's output efficiency characteristics depends on solar intensity, temperature and resistance [17]. To achieve the maximum output efficiency condition, a control strategy known as maximum power point tracking (MPPT) is needed to identify the PV operating point that allows extraction of maximum power from the array.

In literature, many MPPT methods have been reported, including current mode model, [5] voltage operating mode, [25] Peak converter with Predictive Digital Current Control, [27] Hill Climbing, [2], [7] Incremental Conductance, [4], [20], [23] Perturb and Observe, [3] Particle Swarm Optimization, [13] and Neural Network [11]. These algorithms give better result when the PV modules are subjected to uniform solar irradiation. This process gives only one MPP in its P-V characteristic curve with respect to given temperature and insolation. Because of the conflict in tracking the Global MPP (GMPP) under multiple local maxima with partial shading condition, the above mentioned conventional algorithms results in PV systems with lower conversion efficiency.

Several solutions have been proposed, to verify the effectiveness of MPPT algorithms even under partial shading condition, with some modifications made on conventional algorithms. A modified Perturb & Observe (P&O) algorithm reported by Abdelsalamet.al. [26] does not need any predefined system dependent constants and it confirms the adaptive tracking and zero steady state oscillations about the MPP. In this method, adaptive perturb is generated with the help of PI control action. In the modified incremental conductance algorithm [4], a simple linear equation that tracks the GMPP dictates the terminal voltage of the panel according to the MPP voltage obtained using incremental and instantaneous conductance of the PV module. This method requires additional circuits at the output of the converter.

Some methodologies [8]-[10], [14] have been presented to improve the efficiency of the solar PV modules even under partial shading condition and are results in significant reduction in overall cost. In the method proposed by Carlos Olalla [8], the converter is designed to process only mismatch fraction of power

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and is capable of effectively tracking the MPP. This method has a limitation is of producing maximum efficiency when the mismatch is lesser than 25% only. For rapidly fluctuating shading condition, Lijun Gao, [16] has proposed a system which consists of PV cells connected in parallel with simple wide bandwidth MPP tracker but it leads to system complexity.

In literature, [25] the fractional open circuit method dealing the effect of nonlinear relationship between maximum peak voltage (V_{mpp}) and open circuit voltage (V_{oc}) of the PV array under change in temperature and irradiance has been reported. But this increased the implementation complexity and experiences additional power loss. The fractional short-circuit current [20] is a result of the linear relation between I_{mpp} and I_{sc} . The power converter used in this method is employed with an additional switch and so that the cost and components involved in the operation are increases.

The partial shading problem [6], [18] in solar PV module results in hot spot and it sometimes leads to permanent damage of the module. In order to predict the hot spot issues and to provide the remedial action, panel temperature is measured with the help of infrared sensors [21], [24] with regular MPP tracking procedures. The differential power processing architecture [12] in the literature helps the solar PV module to overcome the unmatched MPPs due to partial shading and other conditions. Even above said methods are resulted in good conversion efficiency, these leads to critical analysis in finding GMPP.

In solar energy conversion process using DC-DC converters, sometimes the effects of parasitic elements [25] as well as energy conversion efficiency may be suppressed during the conversion process. To overcome these issues, the additional parasitic elements were added along with the DC-DC converter. It improves the PV generation by increasing the output voltage and is achieved by simple MPPT controller with two sensors in feedback.

A fuzzy logic based MPPT [19], [22] methods available in the literature are well suited for varying climatical conditions even system mathematical model is not accurate. It can handle imprecise inputs non-linearity operations but it needs best efforts in constructing the fuzzification, rule base table, look up and defuzzification processes. A Neural Network [11], [15] will be trained as unique for the PV array so that it can be utilized for PV arrays having different characteristics. Particle Swarm Optimization technique [13] which uses the velocity equation for the exploration process for accurate GMPP but it highly depends on few parameters in the governing equation.

TABLE I

VARIATION OF VOLTAGE AND CURRENT OF THE PV MODULE DURING THE VARIATION OF SOLAR IRRADIATION

Solar irradiation	Variation of voltage (dV)	Variation of current (dI)
Increase	Increase	
Decrease	Decrease	

All the methods which are mentioned above have difficulties in GMPP tracking and Have complex additional circuits. In this paper, a simple method for tracking GMPP even under the presence of partial shading conditions in the system is proposed.

This is done by the sequential sampling of duty cycle with a time scale of 0.1 followed by general Incremental Conductance algorithm applied to control a ZETA converter. This system is presented in Fig. 1 and Fig. 2.

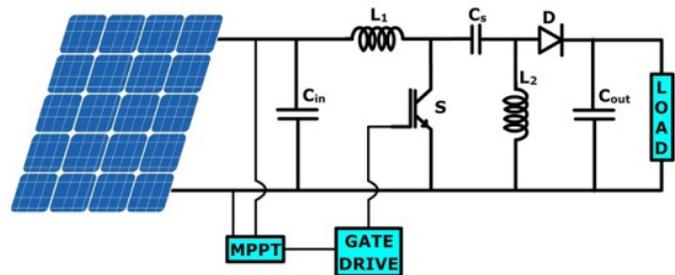


Fig. 1. Proposed PV System with MPPT Controller.

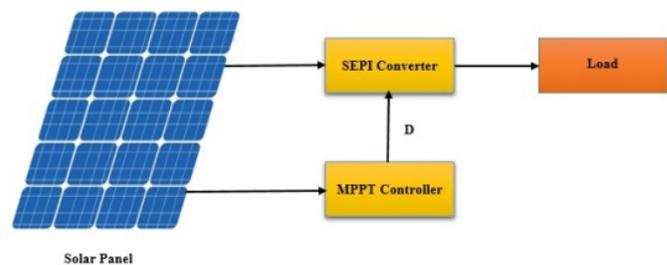


Fig. 2. General block diagram of an MPPT system.

MPPT algorithms achieve maximum power extraction from the panel by adjusting the impedance connected to the panel terminals. The DC-DC converter, which forms the connection between the panel and the load, varies its input impedance as duty cycle varies. In this paper, to track the maximum power from the panel, the duty cycle of the ZETA converter is adjusted. A PV cell is the fundamental building block of a PV panel; a PV panel is a combination of several PV cells in series and parallel connections. The electrical equivalent of solar PV cell is modeled as current source with an anti-parallel diode, a shunt resistance and a series resistance. The V-I characteristics of the solar panel are shown in Fig. 4. The maximum power point is the point where the VI product is maximum for the given V-I curve. In this method, the proposed MPPT algorithm adjusts the duty cycle of the ZETA converter to excerpt the maximum power from the PV panel.

II. SINGLE ENDED PRIMARY INDUCTOR CONVERTER (SEPIC / ZETA CONVERTER)

The ZETA converter is like a buck-boost converter, but it has non-inverted output voltage. It employs a series capacitor to pair the energy from the input to the output. The conventional ZETA converter is presented in Fig. 3. It is operated under fixed frequency and exhibits high transient performance.

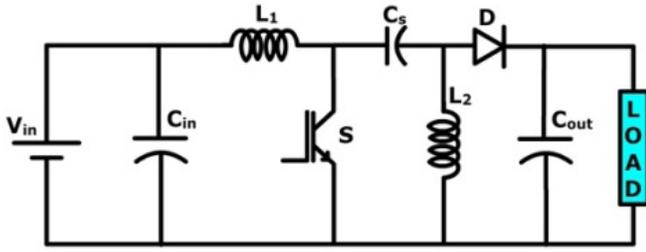


Fig. 3. Circuit diagram of SEPI converter.

A. Operation

The ZETA converter is intended to operate in continuous conduction mode. The converter topology consists of inductors L_1 and L_2 , capacitors C_s and C_{out} and diode D . An ideal case is assumed for diodes, switches and passive components. Since this topology has only one switch, there are two modes of operation.

Mode 1: Switch S is ON (as shown in Fig. 4)

Inductor L_1 charges to V_{in} through switch S . The voltage across capacitor C_s discharges through S into inductor L_2 . Diode D is OFF and capacitor C_{out} supplies the load current.

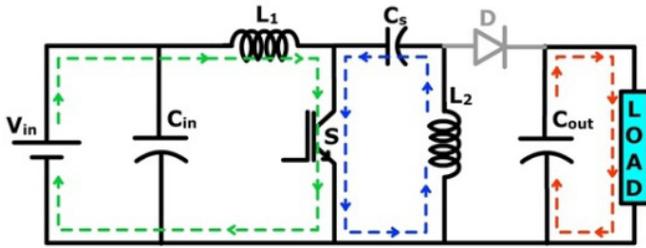


Fig. 4. With S_1 closed current increases through L_1 and C_1 discharges increasing current in L_2 .

Mode 2: Switch S is OFF (as shown in Fig. 5)

Inductors L_1 and L_2 reverse polarity. Diode D turns on. Both capacitors C_s and C_{out} are charging in this mode. The input voltage and the voltage across L_1 charges C_s and C_{out} and supplies load current. The voltage across L_2 charges C_{out} and supplies load current through D .

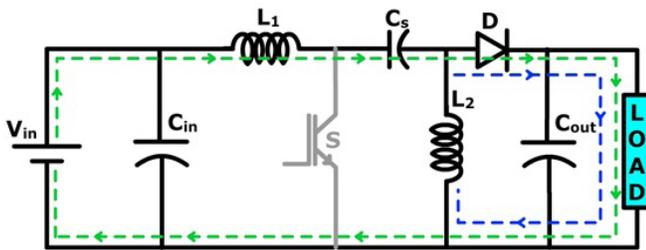


Fig. 5. With S_1 open current through L_1 and current through L_2 produce current through the load.

At Steady-state,

$$V_{in} = V_{L_1} + V_{C_s} + V_{L_2} \quad (1)$$

Because V_{in} and the average voltage of V_{C_s} are equal and $V_{L_1} = -V_{L_2}$

The average currents can be summed as follows:

$$I_D = I_{L_1} + I_{L_2} \quad (2)$$

The Zeta Converter is designed according to Equations (3)-(7) given below,

The Converter output voltage is obtained as,

$$V_{dc} = D \cdot \frac{V_{in}}{(1-D)} \quad (3)$$

Boost inductor L_1 value is,

$$L_1 = \frac{D \cdot V_{in}}{f_s \cdot (\Delta I_{L_1})} \quad (4)$$

Capacitor C_s value is determined by,

$$C_s = \frac{D}{R \cdot f_s \cdot \frac{\Delta V_{C_s}}{V_0}} \quad (5)$$

Inductor L_2 value is,

$$L_2 = \frac{(1-D)V_{dc}}{f_s (\Delta I_{L_2})} \quad (6)$$

Output filter capacitor C_{out} value is,

$$C_{out} = \frac{I_{av}}{2 \omega \Delta V_{r,r}} \quad (7)$$

III. CHARACTERISTICS OF PV MODULE UNDER PARTIAL SHADING CONDITION

PV modules can be connected in different sequences¹⁶ such as series, parallel or combination of both depends on the designer's need. Partial shading is an unavoidable in some plant condition and is location dependent. In construction, the PV module consists of strings in which number modules are connected in series. If any of these modules are subjected to partial shading condition, then reverse bias cell operation will be happened and it results in hot spot conditions. If it exceeds beyond some limit condition, then it leads to potential breakdown¹⁸ of the shaded cell as shown in Fig. 6(b). This problem can be avoided by connecting bypass diode along with module and this take over the string current in case of partial shading conditions as shown in Fig. 6(a). Solar electrical panel's power is dropped out around by 50% because of partial shading conditions. In order to avoid this, some changes are made in the proposed algorithm to track the accurate GMPP, i.e. in a given time interval, the duty cycle moves across the locus traced by the waveform without any climbing in order to take the samples of the entire waveform, to find the GMPP. While predicting the GMPP, the duty cycle is considered over the waveform to obtain the samples of entire waveform by avoiding the climbing.

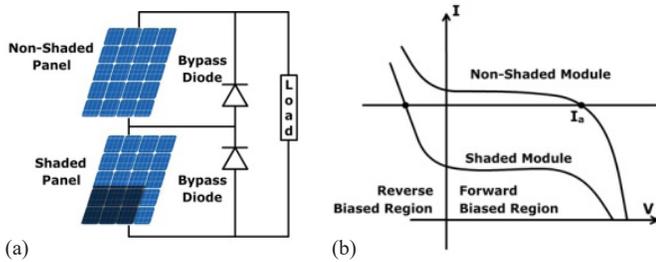


Fig. 6. (a) PV array under partial shading conditions (b) I-V curves of PV module.

IV. THE EXTENDED INCREMENTAL CONDUCTANCE ALGORITHM

In the literature cited, the P&O Algorithm and the Modified Incremental Conductance Algorithm utilize the hill-climbing concept, which tracks the operating point of the PV array. The P&O algorithm is a simple method in which, while considering perturbation in the same alignment, the power value has been increased. In case of decrement in power value, forthcoming perturbation will be considered in opposite direction. But this algorithm fails to track the accurate GMPP. The Modified Incremental Conductance is an intelligent algorithm. The shifting of Duty cycle 'D' in the Modified Incremental Conductance allows the system even works on partial shading conditions. But it is slow because it has to climb all the hills at once and hence lacks accuracy. Here, the proposed algorithm is needed not to climb all the hills; instead the sequential sampling of duty cycle has been applied to reduce the tracking time. Sampling will be taken at specified interval of the duty cycle such as at 10%, 20% ... 100%. This helps to understand the waveform within 10 samples. By this data, it can get the maximum power near the Global Maximum Power Point (GMPP) and for accuracy; an Incremental Conductance is applied from that point. The quick and accurate locking of GMPP is shown in Fig. 7.

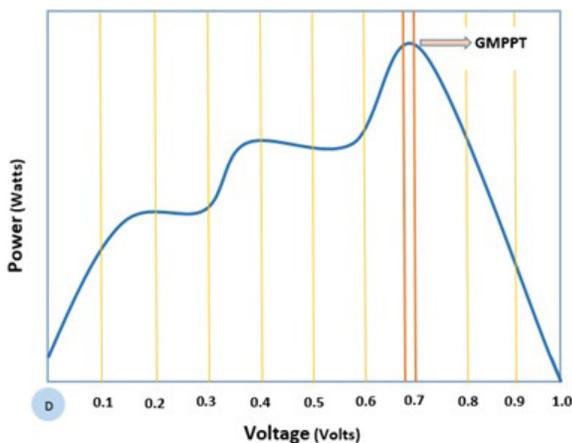


Fig. 7. Power curve by taking 10 rough samples.

A. Algorithm

The algorithm has two sections 1.Sequential sampling of the duty cycle for best D and 2.Incremental Conductance. In the flow chart shown in Fig. 8, the power values (P_{mpp1} , P_{mpp2}), the

temporary duty cycle value (Temp_D), voltage and current are set to zero, the extension variable (Extent) is set to 1.

The two variables required in this algorithm are Temp D and extension variable.

1. The Temp D is a type of variable which is supposed to hold the temporary duty cycle, until it is finalized where the power is maximized by the sequential sampling of the duty cycle.
2. The extension variable is a type of Boolean variable consists of either 0 or 1 and helps to execute the extension, i.e. if extent>0 it is true then it starts executing the Incremental Conductance algorithm.

The Duty cycle increases sequentially with a time delay of 0.1, then the power is read and stored in a temporary variable P_{mpp1} . This is compared with previous power P_{mpp2} . If P_{mpp1} is greater than the P_{mpp2} , then the value of P_{mpp1} is transferred to P_{mpp2} else the increment at Temp D happens again. After increment of Temp D, again, it read the power and stored it in a P_{mpp1} and the processes as same again, i.e. P_{mpp1} is compared with P_{mpp2} for the best power. This process continues so on until the P_{mpp2} holds the maximum power. When the P_{mpp2} holds the maximum power, then the Temp D variable holds the temporary duty cycle which delivers maximum power. This D will be the starting point of the Incremental conductance at the hill of Global maximum power point (GMPP) for tracking accurate GMPP. The algorithm is detailed below.

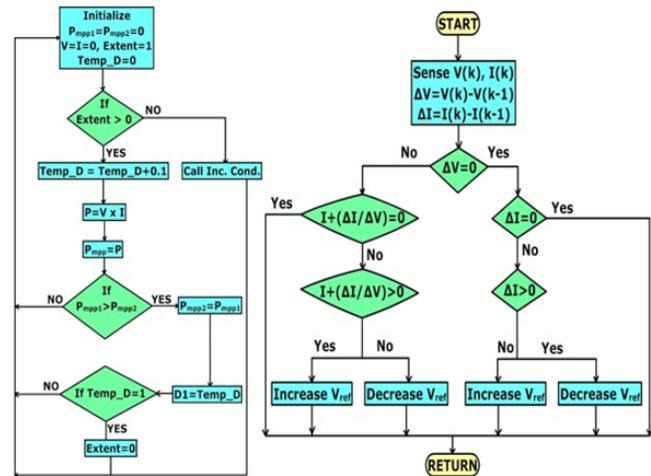


Fig. 8. Flow chart of the proposed algorithm.

ALGORITHM: AN ENHANCED INCREMENTAL CONDUCTANCE ALGORITHM

Label 1: Initialize $P_{mpp1} = P_{mpp2} = 0$, $V = I = 0$, $Extent = 1$,
 $Temp_D = 0$
 if $Extent > 0$
 $Temp_D = Temp_D + 0.1$;
 $P = V * I$;
 $P_{mmp1} = P$;
 If $P_{mmp1} > P_{mmp2}$
 $P_{mmp2} = P_{mmp1}$;
 $D_1 = Temp_D$;
 If $Temp_D1 = 1$
 $Extent = 0$

```

else
go to Label 1
else
go to Label 1
else
Call the Incremental Conductance algorithm*
go to Label 1

```

* - Conventional Incremental Conductance Algorithm 23

V. DUTY CYCLE COMPUTATION OF DC-DC CONVERTER

Varying the duty cycle will help the PV system to maintain the MPP which in turn varies the output voltage. The variation in duty cycle changes the input impedance of the converter which directly controls the amount of power drawn from the panel. This power drawn is maintained around MPP. In the proposed system, the duty cycle is controlled in two stages. Prediction of near maximum power point with the help of sequential sampling will be happened first followed by applying the incremental conductance algorithm to track the GMPP as a sequence process.

In the first part of the proposed technique, a sequential sampling of power by incrementing the duty cycle with the specific time delay is considered. In simulation side, the sampling process is considered with sampling interval with 0.1 -time delay. In sequence, the duty cycle varied from 0.1, 0.2, 0.3, ... 0.9 and 1. Within this variation of the duty cycle, the voltage reaches from zero to V_{max} . This executes the entire power wave form. The every sample that has taken at every duty cycle increment will help to determine the nearest point of MPP. By comparing the power with previous power when it is sampled will give maximum power in between 0 and the maximum duty cycle. The selection of duty cycle depends on the position where the maximum power is possible. To implement the next technique, the duty cycle at maximum MPP which is nearby is selected from the first technique. In next technique, the Incremental Conductance is going to be applied. In this, If $dv/di < 0$, then the operating point is after the MPP. If $dv/di > 0$, then the operating point is before the MPP. If $dv/di = 0$, then the GMPP is available.

$$\text{Duty Cycle (D)} = \frac{T}{P} \times 100\% \quad (8)$$

Where,

T= ON time of the switch

P= Total period of the signal

The voltage gain of the SEPIC is given by,

$$V_o = \frac{D}{(1-D)} \times V_{dc} \quad (9)$$

Where,

D = Converter duty cycle ratio

V_o = Output voltage of the converter

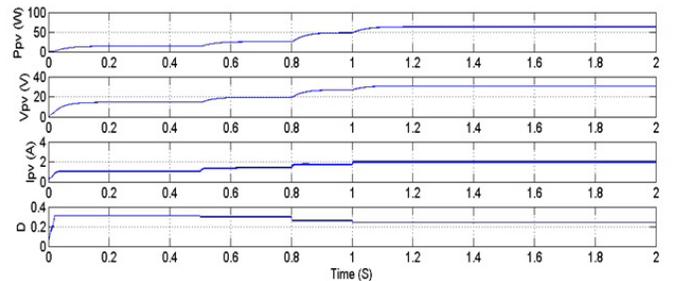
V_{dc} = PV panel output voltage

VI. SIMULATION RESULTS

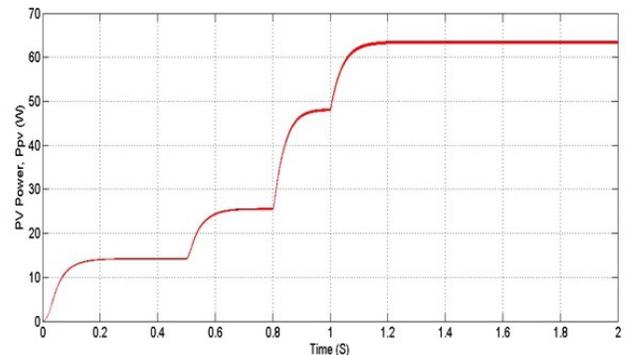
The proposed algorithm is simulated under the ambient temperature of 25°C with four different solar irradiation levels as input for partial shading conditions. The proposed system consists of a Model of PV array, Single Ended Primary Inductor Converter (SEPIC) and the MPPT controller are integrated in required sequence in MATLAB/Simulink model. PV module specifications considered in the simulation work is detailed in Table II. The solar panel supplies the load through an SEPI Converter whose values of the components as C_{in} and $C_{out} = 3900 \mu\text{F}$, L_1 and $L_2 = 125 \mu\text{H}$, $C_s = 1000 \mu\text{F}$ and the load resistance is of 10 -ohm value. For the semiconductor switch operation, the switching frequency is considered as 20 kHz. The sequential sampling of the duty cycle is carried out with a time delay of 0.1, 0.2, ..., 0.9 and 1 in the simulation work. Fig. 9 (a) shows the power voltage characteristic curve and Fig. 9 (b) shows the simulation results for PV array under different solar irradiation values such as 1.0 kW/m², 0.6 kW/m², 0.4 kW/m² and 0.3 kW/m².

TABLE II
PARAMETERS OF PV MODULES AT AMBIENT TEMPERATURE OF 25°C AND
INSOLATION=1000 W/M²

Maximum Power (Pmax)	≈ 64 W
Voltage at MPP (Vmpp)	31.8 V
Current at MPP (Impp)	2.0 A
Open Circuit Voltage (Voc)	39.75 V
Short Circuit current (Isc)	3.69 A



(a)



(b)

Fig. 9. (a) and (b) Simulation results for the PV system under partial shading conditions where the solar irradiation values are 1.0 kW/m², 0.6 kW/m², 0.4 kW/m² and 0.3 kW/m².

The SEPI Converter usually varies the output voltage to vary the power and to retain the operating point at Maximum Power Point as known as GMPPT. This converter is placed between the solar panel and the load and it is controlled by the MPPT controller, which is replicated in the coding of Extended Incremental Conductance algorithm. Here the duty cycle is sampled by taking roughly 10 samples and find the best D. This D is considered as concluding duty cycle value. The P_2 is the GMPP where is located nearly at value $0.8 \cdot V_{oc}$. The performance of the proposed method is confirmed by likening the results with Perturb and Observe and Modified Incremental Conductance algorithm to ensure its effectiveness and is shown in Fig. 10.

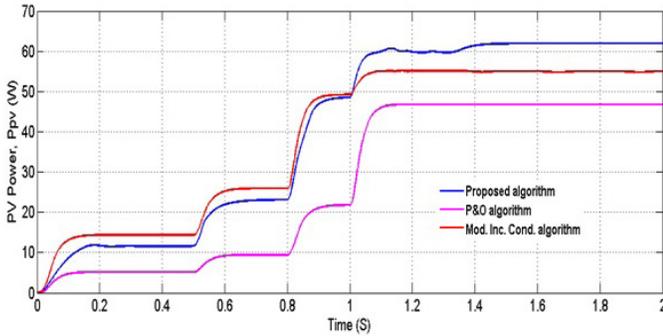


Fig. 10. Simulation results of a comparison of proposed algorithm with the modified Incremental Conductance algorithm and P&O algorithm.

The conventional algorithms show comparatively fewer results in the case of power when compared to proposed algorithm. The P&O algorithm fails to track the accurate GMPP under partial shading conditions. Even the modified Incremental Conductance algorithm is capable of tracking the maximum power point in presence of partial shading conditions, it may produces a delay which creates an inefficiency because of its large execution cycle. The voltage level in P&O, modified Incremental Conductance and proposed algorithms are detailed in Figs. (11)-(13).

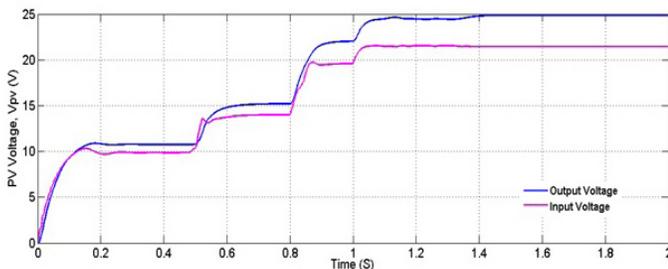


Fig. 11. Input and output voltage waveforms of P&O algorithm with SEPI Converter.

It is observed that the power efficiency has been improved by 2.63% and 28.77% as compared to the modified incremental conductance algorithm and P&O algorithm respectively. The comparison of proposed algorithm with modified incremental conductance and P&O algorithms is detailed in Table III. The proposed algorithm includes sequential sampling process in addition with the modified incremental conductance algorithm

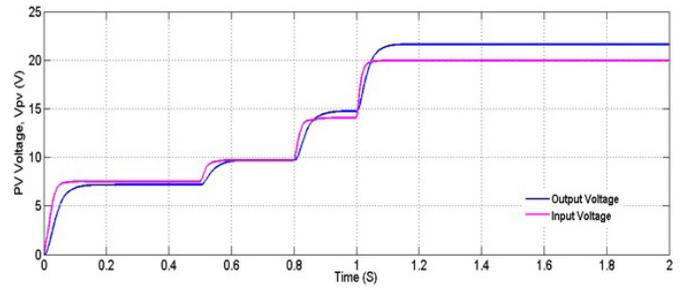


Fig. 12. Input and Output voltage waveforms of Modified Incremental Conductance algorithm with SEPI Converter.

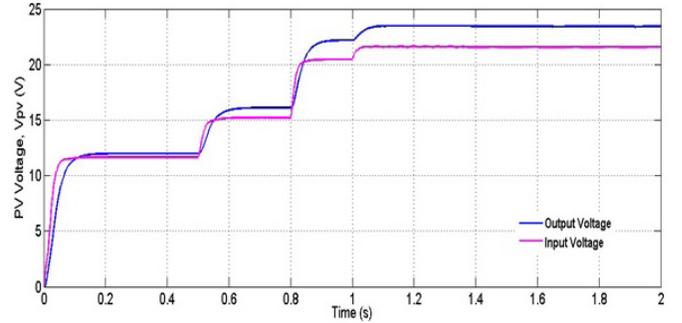


Fig. 13. Input and Output Voltage waveforms of proposed algorithm with SEPI Converter.

and hence the complexity is somewhat more but the tracking the tracking time of GMPP is reduced considerable amount and it results in faster response in tracking process. Also, it acts very fast towards the input changes and gives better performance.

TABLE III
COMPARISON OF PROPOSED ALGORITHM, MODIFIED INCREMENTAL CONDUCTANCE ALGORITHM AND PERTURB & OBSERVE (P&O) ALGORITHM

Evaluated parameters	Proposed Algorithm	Modified Incremental Conductance Algorithm	P&O Algorithm
PV Power	High (63.5W)	Comparatively less (58.5W)	Low (47.5W)
Tracking speed	Effective than Modified Incremental Conductance (based on no.of iterations)	Fast	Slow
Steady state oscillation	No	No	Yes
Ability to track accurate GMPP	Yes	Yes	No
Algorithm complexity	Complex	Complex	Simple

VII. CONCLUSION

In this paper, a new approach for GMPP tracking of a PV system has been proposed based on the sequential sampling of duty cycle and integrated with SEPI Converter. The proposed

method retains the Incremental Conductance algorithm as the second stage process after the sampling process. To prove the validity of the enhanced Incremental Conductance algorithm proposed in this paper, the results obtained with the help of MATLAB/Simulink model. Obtained results concludes that the proposed system can replace the conventional algorithm at all partial shading conditions irrespective of the shape of the power waveform and gives a better efficiency. From the results As compared to the Incremental Conductance and P&O algorithms, the power can be extracted from the PV panel by applying the proposed method is improved considerably. Even the complexity of the proposed model is somewhat more; it gives better accuracy in tracking the MPP and gives better power extraction from the PV panel. The proposed method is reliable in sense of reduced complexity in sampling process, easy to develop, apply and can get the accurate GMPP even under partial shading conditions. The proposed algorithm detailed in this paper can be extended to any converter topology with good energy conversion ratio and efficiency for the better power conversion process.

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