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Enhancement of Maximum Power with PV Arrays under Partial Shading Conditions Using Incremental Conductance

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ABSTRACT: An improved analysis of maximum power point tracking with incremental conductance of solar photovoltaic array under partial shaded condition is proposed in this paper. To improve the extracted maximum power from a PV array during partial shading conditions the switched photovoltaic (PV) approach is proposed in this paper. In this paper we use the IC technique, it is used to track the maximum power point of the PV source. MPPT can minimize the system cost and maximize the array efficiency. The proposed system is simple and cost effective. However, compared to other existing solutions it may provide lower power enhancement, which makes it more suitable for domestic applications. This research was aimed to explore the performance of a maximum power point tracking system which implements Incremental Conductance (IC) method. The IC algorithm was designed to control the duty cycle of Buck Boost converter and to ensure the MPPT work at its maximum efficiency. The comparison has been made for series and parallel connected solar photovoltaic modules under partial shading condition and it is inferred that parallel connections must be dominant under partial shading condition. I-V characteristics of Parallel array shows that I_{sc} of parallel array is sum of short circuit current of all modules connected in parallel. Simulation results show the possibility of enhancing the PV array's extracted output power during partial shading with the proposed system.

KEYWORDS: Maximum power point tracking (MPPT), partial-shading switched PV.

I. INTRODUCTION

The purpose of this paper is to study and compare three maximum power point tracking (MPPT) methods in a photovoltaic simulation system using IC method. With the increase in demand of energy it desired to switch to the renewable energy sources and solar photovoltaic is ideal green energy. Extracting maximum power from photovoltaic (PV) sources is an important criterion in PV-fed applications, especially in case of partial shading. Normally with no shading, the power-voltage characteristic of PV array has only a single power peak, which is simple to be tracked using any of the conventional maximum power point tracking (MPPT) techniques [1]. To extract maximum power from module recognition of optimal operating point is important as solar photovoltaic module is nonlinear power source and output power of modules varies with temperature and insolation. During partial shading, the characteristic has multiple peaks (global and local maxima) [1], [2]. PV power generation systems have one big problem that the amount of electric power generated by PV module is always changing with weather conditions, i.e., irradiation. Therefore, a maximum power point tracking (MPPT) control method to achieve maximum power (MP) output at real time becomes indispensable in PV generation systems. The conventional MPPT algorithms may fail to track the global maximum power point (MPP), as it will be trapped on the first peak point while searching [3]. To avoid that, the global MPPT [4]–[6] should be used to extract the global maximum power. Conventionally, global MPPT is mainly depending on scanning PV characteristics from open-circuit to short-circuit condition to identify the relevant voltage and current of the global MPP. In [4], a fast global MPPT algorithm is presented to identify the global MPP in a relatively short time.

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Partial shading may takes place due to clouds, trees, dirt and dust in solar power generation systems. In partial shading, multiple peaks are followed in the PV characteristic curve. MPPT is a technique used to track the maximum power point of the PV source. MPPT can minimize the system cost and maximize the array efficiency.

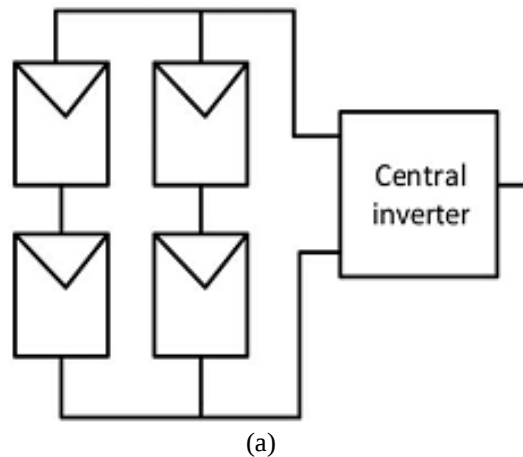


Fig. 1. Different PV converters arrangements: (a) Central inverter;

Generally, for conventional PV systems the configuration of the existing inverters can be classified into central inverters, string inverters, module-integrated inverters. The central inverter, shown in Fig. 1(a), offers high reliability and simplicity in installation.

Central inverter can extract the peak of the overall characteristic of PV array which may be less than the sum of the available maximum power of each module in the array (due to mismatch losses during shading). The string inverters, shown in Fig. 1(b), use multiple inverters for multiple strings in a PV array.

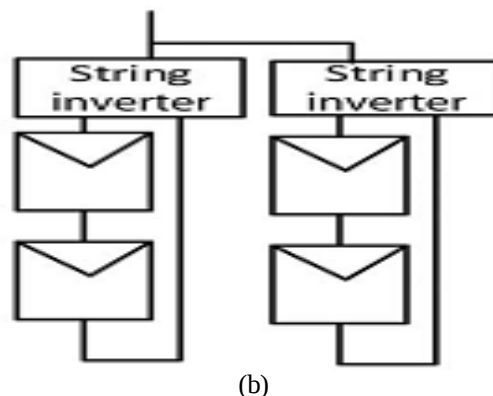


Fig. 1. Different PV converters arrangements(b) string inverters;

String inverters provide MPPT on a string level with all strings being independent of each other, which reduces the mismatch losses in case of shading. Distributed MPPT converters, shown in Fig. 1(c), use multiple converters for multiple modules in a PV array.

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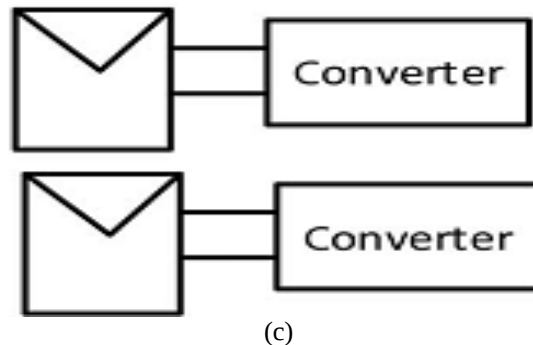


Fig. 1. Different PV converters arrangements c) module-integrated converters;

Distributed converters provide MPPT on a module level with all modules being independent of each other which results in extracting the exact maximum power.

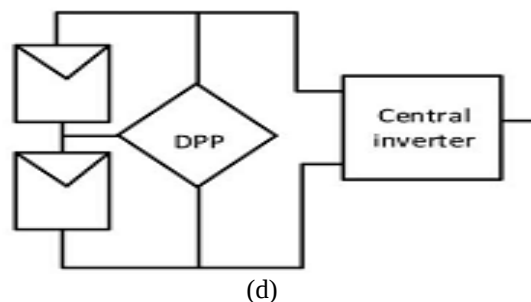


Fig. 1. Different PV converters arrangements (d) differential power processing (DPP).

However, the used converters should process the full power of the module. The DPP, shown in Fig. 1(d), was recently proposed [8], which is efficiently able to extract the exact maximum power with partially rated converters. Recently, maximum power extraction from a partially shaded PV array using shunt-series compensation has been presented in this paper. However, it uses a relatively large number of switches.

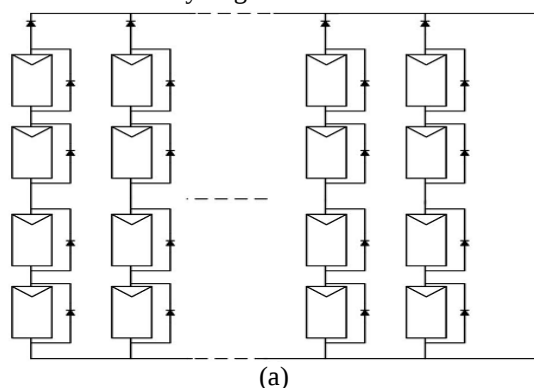


Fig. 2. Modifying existing PV system to the switched PV-based system: (a) Conventional PV array; (b) proposed Switched PV-based overall system;(c) state1: all controlled switches are closed; (d) state2: all controlled switches are opened.

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To enhance the extracted maximum power from PV array another approach has been presented in this paper during partial shading, namely, dynamic PV array reconfiguration approach, at which the electrical reconnection of the available PV modules can be done. To enhance the extracted maximum power from a PV array (switched PV approach) a new technique is proposed in this paper, which can be applied to existing PV systems.

Assume an existing PV system with n parallel-connected strings, and m series-connected modules per string, i.e., array with a dimension of $(m \times n)$. Selection of a suitable dimension during partial shading will be mainly based on which of these available dimensions will generate higher power. The performance of MPPT techniques is compared on the basis of desirable features like difficulty, speed, hardware accomplishment, sensors required, cost, range of value and efficiency of the system. The main advantages of the proposed system are simplicity and cost effectiveness, which makes it suitable for domestic applications. It may also be used with large PV arrays during cloudy days. Compare the proposed system with the aforementioned configurations is presented in this paper. The results show that although the proposed system may not be able to extract the exact maximum power, it can effectively enhance the extracted output power. Power generated by PV module depends upon the solar irradiation, cell temperature and load impedance. The demand of PV system installation has been increased over past few decades, technological improvement, lowered system costs, governmental initiatives, rising electricity bills.

II. PROPOSED CONCEPT(SWITCHED PV APPROACH)

When one or more PV cells are shaded, bypass diodes are added in parallel for protection, prevent from the damage due to overheating, when cells are connected in series. Partial shading may occur due to environmental conditions, such as clouds, dirt and dust, trees and buildings. However, in power voltage characteristics curve also changes rapidly, multiple peaks are obtained. When the PSC occurs, the shaded PV cell act as a load instead of power flow, generating multiple peaks in the I-V characteristic curve and multiple peak values in the P-V curve. To prevent this problem, PV module is comprised of parallel connected bypass diodes [13].

In the proposed system, each string in the PV array is divided into two equal sections, which are connected as shown in Fig. 2(b). Hence, one controlled switch (S_i) and two diodes are needed for each string. These extra diodes and switches are rated at half of the open circuit voltage of the string voltage and short circuit current of the module.

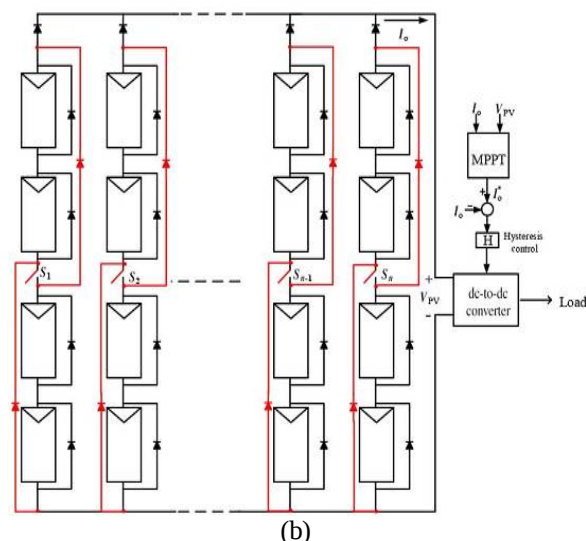


Fig. 2. Modifying existing PV system to the switched PV-based system: (b) proposed Switched PV-based overall system

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The proposed topology has two states of operation, namely, state1 and state2. The following sections illustrate the difference between these two states.

A. State1

State1 is activated when all of the controlled switches are closed as shown in Fig. 2(c), which represents the conventional connection of the PV array.

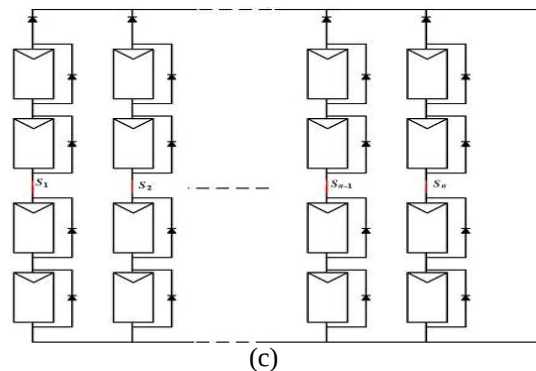


Fig. 2. Modifying existing PV system to the switched PV-based system (c) state1: all controlled switches are closed

In this state, the highest possible output voltage is the open circuit voltage of the whole string (i.e., V_{oc}), whereas the highest possible output current is the short circuit current of modules multiplied by the number of strings (i.e., nI_{sc}). The output converters should be able to withstand both values.

B. State2

State2 is activated when all of the controlled switches are opened as shown in Fig. 2(d).

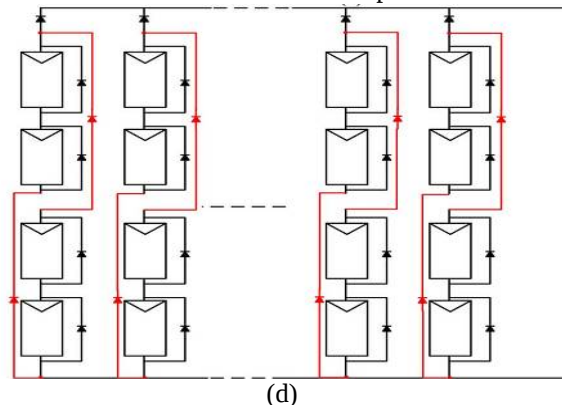


Fig. 2. Modifying existing PV system to the switched PV-based system (d) state2: all controlled switches are opened.

In this state, the highest output voltage is the half of the open circuit voltage of the whole string (i.e., $0.5V_{oc}$), whereas the highest output current is double the short circuit current of the module multiplied by the number of strings (i.e., $2nI_{sc}$). To avoid using an output converter with a high current rating (compared to state1), the MPPT will limit the output current reference to the current rating of semiconductor devices of output converter. Therefore, in case of resistive or battery load, the output converter should have buck and boost capability to successfully provide the power

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to the load irrespective of the value of the input voltage. Alternatively, a single-stage quasi Zsource inverter, which has bucking and boosting capabilities, can be used.

C. Selecting One of the States

During shading, the extracted power in state2 may be higher than the extracted power in state1 based on the value of k . In order to check which of the two states yields a higher power, the MPPT algorithm will activate state1 first, then it searches for the global MPP (P_{mpp1}) and saves it. Afterward, it activates state2 and searches for the corresponding global MPP (P_{mpp2}) in this state and saves it as well. Based on the saved global MPPs, the MPPT will decide to switch the system to the state which gives higher power. The MPPT routine should be repeated every predetermined period using timer interrupt flag to update the system state to minimize the possible power loss due to changing of shading condition.

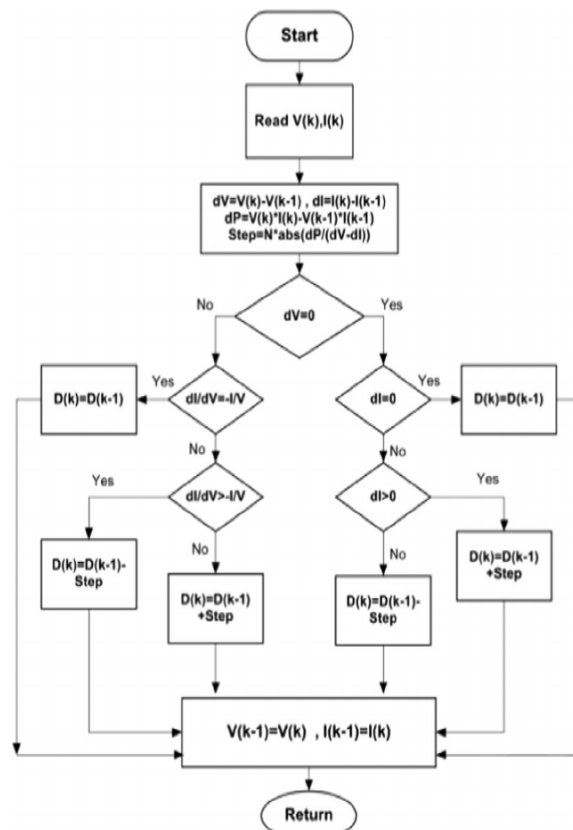


Fig. 3. Flowchart for IC MPPT of switched PV approach.

A flowchart of the relevant MPPT is shown in Fig. 3, where I_{oref} is the reference of PV output current, I_o is the PV output current, V_{pv} is the PV output voltage, P is the PV output power, P_{mpp1} is the maximum power at state1, P_{mpp2} is the maximum power at state2, ΔI is the current increment, n is the number of parallel strings in state1, I_{sc} is the short circuit current of the PV module, and k is a constant which ranged from 1 to k_{max} .

D. Effect of the Proposed Approach on the Converter Rating

When the proposed reconfigurable approach is employed, the current rating of semiconductor switches of the output converter should be higher than $nI_{sc} k_{max}$. Through limiting the value of k_{max} to 1.5, the switches' current ratings can be limited to 150% of their ratings in case of conventional PV array (i.e., $m \times n$ fixed PV array dimension).

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E. Illustrative Example

For a PV array shown in Fig. 4(a), the corresponding power– voltage characteristics of the array in both states are shown in Fig. 4(b).

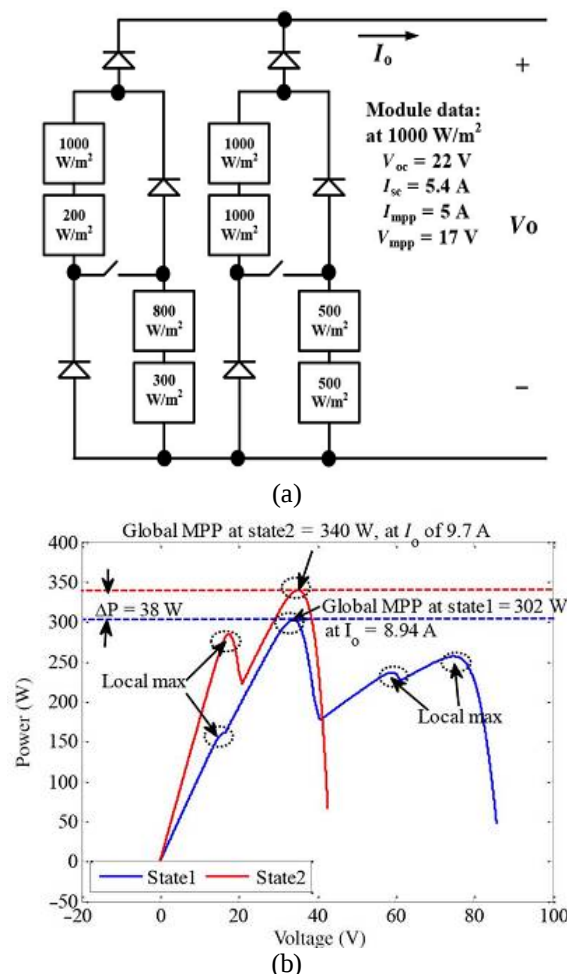


Fig. 4. Illustration of power enhancement using the switched PV-based system for a given case study (state1: switches are closed; state2: switches are opened).(a) Switched PV architecture. (b) Power-voltage characteristic in both states.

The simulation results also show that the extracted power from the proposed technique during partial shading is always higher than the central inverter scheme while lower than the DPP scheme. The extracted powers for all types of the aforementioned options are summarized in Table I.

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TABLE I
TOTAL EXTRACTED POWER FOR PROPOSED SCHEME AS WELL AS OTHER EXISTING OPTIONS

PV Extracted power (W)		Pattern (1) Fig. 5(a)	Pattern (2) Fig. 5(b)	Pattern (3) Fig. 5(c)	Pattern (4) Fig. 5(d)	Pattern (5) Fig. 5(e)
Central inverter		1020	883	781	776	563
String inverters		1020	932	844.5	787	611
DPP		1020	977	934	891	805
Proposed ($k=1.33$)	State1	1020	883	781	776	563
	State2	910	877	875	871	770

Based on the shape of shading pattern and the value of k , the extracted power from the proposed system may be lesser or higher than the power extracted from string inverters scheme.

In the presented case, it is clear that state2 is able to extract more power but at a higher output current it is worth mentioning that the current of maximum power at state2, in the presented case, is less than $2I_{sc}$, i.e., irrelevant to the value of k , the same amount of power will be extracted. It has to be noted that, for another shading pattern and another value of k , the extracted power from state2 may be less than or equal to the extracted power in state1. In the following simulation section, the extracted power from different states assuming different shading patterns is determined.

INCREMENTAL CONDUCTANCE MPPT

In incremental conductance method the array terminal voltage is always adjusted according to the MPP voltage it is based on the incremental and instantaneous conductance of the PV module.

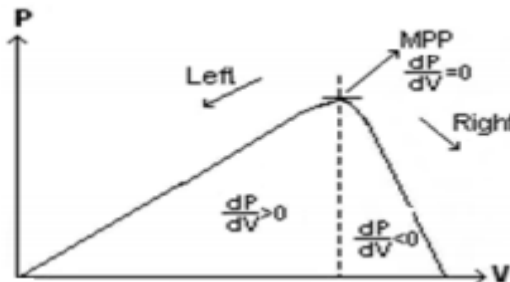


Fig-6: Basic idea of incremental conductance method on a P-V Curve of solar module

Fig-6 shows that the slope of the P-V array power curve is zero at The MPP, increasing on the left of the MPP and decreasing on the Right hand side of the MPP. The basic equations of this method are as follows.

$$\begin{aligned}
 \frac{dI}{dV} &= -\frac{1}{V} \quad \text{At MPP} \\
 \frac{dI}{dV} &> -\frac{1}{V} \quad \text{Left of MPP} \\
 \frac{dI}{dV} &< -\frac{1}{V} \quad \text{right of MPP}
 \end{aligned} \quad (1)$$

Where I and V are P-V array output current and voltage respectively. The left hand side of equations represents incremental conductance of P-V module and the right hand side represents the instantaneous conductance. When the ratio of change in output conductance is equal to the negative output conductance, the solar array will operate at the maximum power point.

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INCREMENTAL CONDUCTANCE MPPT ALGORITHM

This method exploits the assumption of the ratio of change in output conductance is equal to the negative output Conductance Instantaneous conductance. We have,

$$P = VI \quad (2)$$

Applying the chain rule for the derivative of

$$\frac{\partial P}{\partial V} = \frac{\partial(VI)}{\partial V} \quad (3)$$

The above equation could be written in terms of array voltage V and array current I as

$$\frac{\partial I}{\partial V} = -I/V \quad (4)$$

The MPPT regulates the PWM control signal of the dc – to – dc boost converter until the condition: $(\partial I/\partial V) + (I/V) = 0$ is satisfied.

In this method the peak power of the module lies at above 98% of its incremental conductance. The Flow chart of incremental conductance MPPT is shown below.

III. ASSESSMENT OF THE PROPOSED SYSTEM

Different simulation models with global MPPT (for the aforementioned PV technologies) and a model of the proposed system with its proposed MPPT have been built for assessment. When one or more PV cells are shaded, bypass diodes are added in parallel for protection, prevent from the damage due to overheating, when cells are connected in series. To prevent this problem, PV module is comprised of parallel connected bypass diodes [13]. In multiple peaks, one GMPP are obtained in the curve. A PV array of two strings is assumed, each string consists of six series modules. The parameters of each module are given in Table I.

TABLE I
DETAILS OF EMPLOYED PV MODULE AT INSOLATION LEVEL OF 1000W/m²

Open circuit voltage	22 V
Short circuit current	6 A
Voltage at maximum power	17 V
Current at maximum power	5 A

In the presented case, five different shading patterns are applied to the modules as shown in Fig. 5 (assuming that the written number inside each module represents the isolation level of this module).

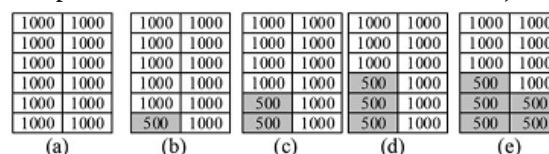


Fig. 5. Different shading patterns used for assessment. (a) No-shading condition. (b)-(e) Different partial-shading conditions.

The total extracted power is calculated for the proposed scheme as well as the other aforementioned options (assuming lossless systems).

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IV. SIMULATION RESULTS

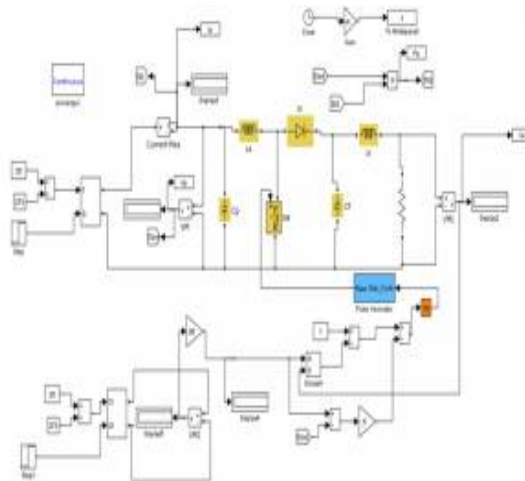


Fig:2 simulation model of MPPT for solar photovoltaic panel.

The results show that during normal operating condition with no shading, all techniques are extracting the same amount of power. Under shading condition, the DPP technique gives the highest extracted output power as it extracts the exact maximum power.

TABLE III
DETAILS OF PV MODULE AT 1000W/m²

Open circuit voltage		21.7 V
Short circuit current		3 A
SEPIC converter data	Inductors	$L_1 = 20 \text{ mH}$, $L_2 = 3.35 \text{ mH}$
	Capacitors	$C_1 = 100 \mu\text{F}$, $C_2 = 10 \text{ mF}$
	Load	100Ω

Although the proposed scheme provides lower power compared to DPP, it has several merits over the DPP approach such as 1) lower size, weight, cost, and complexity; and 2) more reliable, needs lower devices, and easier in maintenance as simple contactors may be used as controlled switches for the proposed scheme.

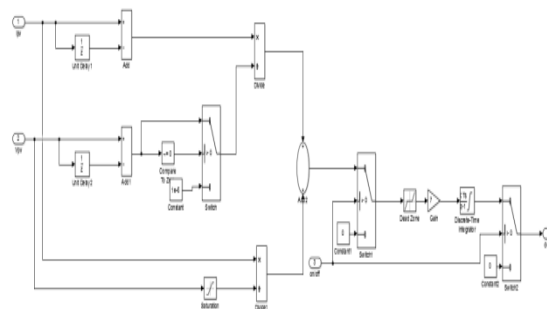


Fig.3 Simulation diagram of Incremental conductance method

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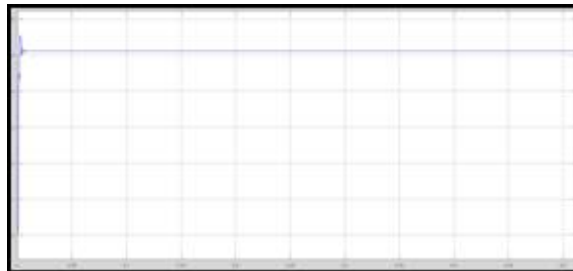


Fig.4 Simulation waveform of load current with IC

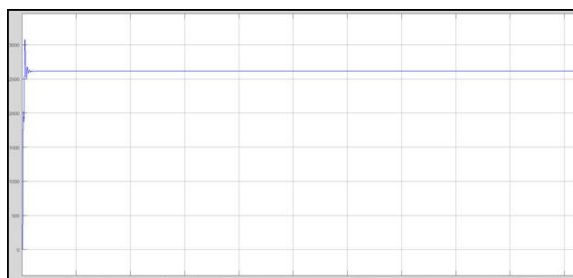


Fig.5 Simulation waveform of power with IC

V. CONCLUSION

A switched PV-based system is presented to enhance the total extracted power from PV array during shading conditions is proposed in this paper. Among various algorithm techniques, soft computing methods ensure better MPPT operation for any solar irradiation, cell temperature and different load conditions. Among all the MPPT strategies, the incremental conductance technique is widely used due to the high tracking accuracy at steady state and good adaptability to the rapidly changing atmospheric conditions. The proposed scheme is compared with other existing techniques for PV energy harvesting systems. In the incremental conductance method, the controller measures incremental changes in PV array current and voltage to predict the effect of a voltage change. To extract maximum power from module recognition of optimal operating point is important as solar photovoltaic module is nonlinear power source and output power of modules varies with temperature and insolation. This research was aimed to explore the performance of a maximum power point tracking system which implements Incremental Conductance (IC) method. The comparison shows a promising performance for the proposed reconfigurable PV array compared to the conventional PV array with central and strings inverters approaches. By using the simulation results we can analyze the proposed method.

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