Experimental investigations and comparison of various MPPT techniques for photovoltaic system

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Abstract. This paper deals with Matlab/Simulink and experimental investigations of various maximum power point tracking (MPPT) techniques namely incremental conductance (Inc), perturb and observation (P&O), constant voltage control (CVC) method, and introduction of a novel reference power (Pref) method for extracting the maximum power from the solar photovoltaic (PV) system. The complete system model along with these MPPT methods are developed in Matlab/Simulink and simulation results are obtained during sudden increase in irradiation of 1000 W/m^2 , and verified experimentally. These MPPT methods are also implemented on Inverse-Sepic converter, which claims to extract maximum power from the PV system. Various experimental observations are taken to access the performance of these MPPT techniques such as settling time of the full load current under sudden exposure of irradiation level of 1000 W/m^2 , performance during step increase in irradiation level (from 500 W/m^2 to 1000 W/m^2) and vice versa. Extensive results are taken to compare these methods. The proposed Pref method is found to have lowest settling time to stabilize the load current as 520 ms, whereas, Inc method takes 1.24 s. Further, the efficiency of Inverse-Sepic converter with Pref method achieves the highest efficiency of 95.26%, whereas, it extracts lowest efficiency on same input as 90.77% with P&O method. The overall performance of the proposed Pref method is found to be superior as compared to other discussed MPPT methods as verified by experimental results.

Keywords. DC-DC Converter; perturb & observation (P&O); incremental conductance (Inc); constant voltage control (CVC); photovoltaic (PV) cell; renewable energy resources (RERs).

1. Introduction

In the last two decades, the solar energy source played a vital role in the environment protection. Thus the renewable sources should be increased so that the generation of electricity will be provided without any adverse impact on environment. Renewable energy plays a vital role in the production of electricity. United States organized a firm called EIA (Energy Information Administration) to gather the hazards caused by the non-renewable sources. They proved that non-renewables sources can cause greenhouse effect [1]. Normally non-renewable sources include plastics, oil, coal and uranium. These resources are not easy to degrade. So, they causes more hazards to the environment. Fossil fuels are leading to global warming. Nitrous oxide is released during the burning of fossil fuels. That causes allergy to the people living nearby [2]. The pollution not only affects the people but also it causes acid rain, photochemical pollution and release greenhouse gases [3]. The

UCS (Union of Concerned Scientists) researched about the non-renewable sources and stated that it creates damage to the Ozone layer. In 2016, a report was prepared by mentioning that more than 90 million drums of oil per day were consumed globally. Year by year oil usage is increasing, that leads to increased utilization of non-renewable resources [4]. The production cost of solar photovoltaic has been decreasing considerably in the last couple of years. PV-module is nowadays available in a packaged structure that was connected with series and parallel combination of solar cells [5–7].

PV modules are commonly used in distributed power generation and also in centralized power generation. It is noise and pollution free power generation. On the other hand, there are various demerits of PV module such as more expensiveness and lack of full electricity generation during cloudy days. In order to overcome the limitations in PV module, the technique is developed namely MPPT [8], which is applied to control the DC to DC (direct current) converter [9]. The MPPT technique manages the electronic interface by matching the source resistance and the load

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resistance. The MPPT technique is followed by solar photovoltaic to gain the maximum power [10]. The P&O technique is executed by means of identifying the present solar power and adjust the duty cycle for trying to track the maximum power. PV systems are connected in different configurations, based on the required load current and voltage [11]. It is based on the relationship with the external grid, battery banks, inverter systems and electric load. The problem addressed by MPPT is based on the power transfer capability from different solar cells, which depends on sunlight which is falling on the solar panels and characteristics of the electric load. The efficiency of the power transfer will change according to sunlight and load characteristics. Complex relationship exists between the solar cells with total resistance and temperature [12]. It produces the non-linear output and hence non-linear I-V curve which is used to analyze the efficiency. There are many methods which are involved in tracking the maximum power point (MPP) and some of them are Perturb & Observe method (P&O), Incremental conductance method (Inc), Fractional Open Circuit voltage (FOCV) method, Fractional short circuit current (FSCC) method, CVC method, etc.

The objectives of this paper are as follows:

- Development of simulation model of system, which comprises of mainly solar PV, Inverse Sepic DC-DC converter along with P&O, Inc, CVC and novel Pref MPPT methods.
- Design and development of Inverse-Sepic DC-DC converter.
- Experimental implementation of these MPPT methods on Inverse-Sepic converter and validation of simulation results using hardware results.
- Comparison of novel Pref method with other implemented MPPT methods under different operating conditions.

2. System description

The system under consideration consists of various MPPT methods using the Inverse-Sepic Converter, is illustrated in figure 1. The load voltage and current are controlled by this converter. The four MPPT methods are used to drive this converter one by one. The voltage and current of the solar panel are sensed and duty cycle of inverse sepic converter is obtained by using different MPPT (P&O, Inc, CVC and Pref) methods. The feedback system of the converter is associated with the load.

The power achieved in tracking involves the load conditions and the atmospheric conditions. The oscillations are maintained low during the tracking operation [13]. There are three control variables that are involved in the tracking procedure which include: finding out the value of duty cycle, current and voltage. There are various types of converters that are practiced in the tracking methods and

Figure 1. Schematic arrangement of testing system.

they include buck converter, boost converter, buck-boost converter, and Inverse-Sepic converter which are used to increase or/and decrease of the voltage [14]. Here Inverse-Sepic Converter circuit is used in the power tracking operations. The 4TH order DC to DC converter which is made up of 2 inductors and 2 capacitors is modelled as Inverse-Sepic converter. This type of converter is flexible for both step-up and step-down mode of operation. The Inverse sepic converter is also known as zeta converter. The Inverse-Sepic converter consists of an electronic circuit that converts the level of voltage from one state to another state. For any kind of photovoltaic systems, the Inverse-Sepic converter is used to maximize the power [15–17].

3. Implementation of various MPPT techniques

A brief description about MPPT technique namely P&O, Inc, CVC and novel Pref method MPPT techniques are discussed in this section.

3.1 P&O MPPT technique

Generally, photovoltaic modules (PVM) are widely used in energy storage systems and water pumping [18]. The flowchart of P&O MPPT method is shown in figure 2. The steps are as follows.

- Measure the values of voltage and the current, respectively at k^{th} and $(k-1)^{\text{th}}$ instant as $V_{PV}(k), I_{PV}(k), V_{PV}(k-1), I_{PV}(k-1)$.
- Do the calculation of $P_{PV}(k)$ as $P_{PV}(k) = V_{PV}(k) \cdot I_{PV}(k)$ and $P_{PV}(k-1) = V_{PV}(k-1) \cdot I_{PV}(k-1)$.
- Check for the condition listed below

$$P_{PV}(k) > P_{PV}(k-1).$$

- If yes then increase the operating voltage, otherwise decrease the operating voltage.

According to this loop, the power will increase or decrease and move near the max power point [19]. The

Figure 2. Main steps in flow chart of P&O method.

operation consists of arrangement of feedback parameters. Normally this method perturbs the system's operating point that causes the fluctuations in the MPP voltage. The voltage and current fluctuate simultaneously. The step size must be maintained higher so that the noise factor can be minimized correspondingly.

3.1a Limitations undergone in P&O method: If the step size is not maintained high, then results in slowing down of the system response. The system response is affected with respect to the sudden change of irradiance and temperature. If there is any kind of fluctuations arise then the result obtained will have no stability in response.

3.2 Inc MPPT technique

Normally, Inc technique is used for the power tracking quickly in solar power system. The performance of Inc method is very precise in controlling the voltage in varying

atmospheric conditions [20]. There are two types of step size that are implemented in the Inc method, namely: Fixed step-size and Variable step-size. Compared to other tracking techniques, Inc is considered as the high accuracy tracking method. Good adaptability and maintenance of steady state are the two main features of Inc method [21]. The flowchart is shown as figure 3. The equations involved in the Inc method is shown below,

$$P = (V_{pv} \times I_{pv}) \quad (1)$$

$$\begin{aligned} \text{For MPP, } dP/dV_{pv} &= I_{pv} + V_{pv} (dI_{pv}/dV_{pv}) \\ &= I_{pv} + V_{pv} (\Delta I/\Delta V) \end{aligned} \quad (2)$$

$$\frac{\Delta P}{\Delta V} = I_{pv} + V_{pv} \left(\frac{\Delta I}{\Delta V} \right)$$

Where, $\Delta I/\Delta V = -I_{pv}/V_{pv}$ for MPP

$$\Delta I/\Delta V > -I_{pv}/V_{pv} \text{ for left of MPP} \quad (3)$$

$$\Delta I/\Delta V < -I_{pv}/V_{pv} \text{ for right of MPP} \quad (4)$$

In this method the value of $\Delta I/\Delta V$ is compared with I_{pv}/V_{pv} instantaneously, in this way the panel operating voltage is to increase or decrease until the maximum power point is attained. The behavior of Inc algorithm is not like as P&O algorithm, it stops adjusting when the maximum power point is reached.

3.3 CVC MPPT technique

The adjustment in the reference voltage V_{REF} is done by using the CVC method. The reference voltage is changed according to the climatic variations [22, 23]. If there are any changes found in environmental conditions, then it is detected in the CVC method and the alterations are done accordingly. Due to the variations caused in the environmental conditions, the tracking seems to be critically not possible. The DC-DC converter is designed in such a way that the open-circuit voltage is sampled with the interruption of the source in the circuit. In the experiment, the circuit takes the sample of V_{oc} in every 20 min. After 20 min. the load will be disconnected for 100 millisecond from the supply. In this time the circuit takes the new value of V_{oc} and set the V_{ref} accordingly (Appendix A). The main steps of flow chart for CVC method are shown in figure 4.

$$\frac{V_{ref}}{K} = V_{oc} \quad (5)$$

Using this equation, the value of $V_{oc} = 18.18$ volt which is predefined panel voltage, $K = 0.80$ and $V_{REF} = 18.18 \times 0.80$ is used in the hardware circuit.

The main steps of the CVC method are given below.

Brief steps of flowchart are given as:

First of all the value of V_{ref} will be calculated by using the value of V_{oc} and then

Figure 3. Main steps in flow chart of Inc method.

$$V_{pv} = \frac{nkT_c}{q} \ln \left(\frac{I_L + I_s - I_{pv}}{I_s} \right) - R_s I_{pv} \quad (7)$$

To calculate the total array voltage, it is multiplied with the total number of cells which are connected in series solar panel. The total current is equal to the sum of individual current flows in the cell which are connected across each other. The output voltage and current of PV system reliant on quantities that vary with the change in atmospheric conditions which affect the output power of solar panel.

Enrique [25] has described a simplified exponential relationship between output voltage and current of PV cell.

$$I_{pv} = n_p \left[I_L - I_s \left[e^{q \left(\frac{V_{pv}}{n_s} + \frac{I_{pv} R_s}{n_p} \right) / nkT_c} - 1 \right] - \frac{V_{pv} + \frac{I_{pv} R_s}{n_p}}{R_{sh}} \right] \quad (8)$$

$$P = I_{pv} \cdot V_{pv} \quad (9)$$

$$P = n_p \cdot V_{pv} \cdot \left[I_L - I_s \left[e^{q \left(\frac{V_{pv}}{n_s} + \frac{P R_s}{V_{pv} n_p} \right) / nkT_c} - 1 \right] - \frac{V_{pv} + \frac{P R_s}{V_{pv} n_p}}{R_{sh}} \right] \quad (10)$$

$$\left(\frac{dP}{dV_{pv}} \right)_{MPP} = 0 \quad (11)$$

Equation (8) is used to obtain the power generated by solar panel and shown in Equations (9) and (10). The I-V curve of photo-voltaic solar cell depends on incident irradiance and cell temperature. The maximum power point provides the optimal operation point for an efficient use of the panel.

3.6 Hardware circuit description of Inverse-Sepic converter

The circuit diagram is shown in figure 6. As it is a DC-DC converter, which produce regulated and stepped up or down output voltage is produced. The Inverse-Sepic converters are used for maximizing the harvest energy from photo-voltaic systems. So the Inverse-Sepic converters are called as power optimizers [26–28]. In this paper, the INVERSE-SEPIC converter is designed and controlled using a PIC microcontroller. These types of converters are used in certain type of loads like light emitting diode. The Inverse-

Figure 6. Circuit diagram of Inverse-Sepic converter.

In sepic converter, Q_1 (MOSFET 1) and Q_2 (MOSFET 2) are two switches which operate in opposite phase. When Q_1 is on as a switch then current starts to flow through the primary inductor L_1 , load, C_1 (coupling capacitor) and inductor L_2 . When Q_2 is turned on, the energy stored in the L_2 inductor is delivered to the load. The energy stored in inductor L_1 will be zero through the capacitor C_1 . The current flow continuously through the load is supplied by the inductor L_2 .

On state equations are given as,

$$V_{L1} = V_{in} \quad (12)$$

$$V_{L2} = V_{in} + V_{c1} - V_{out} \quad (13)$$

$$\text{Off state } V_{L1} = -V_{c1}$$

$$V_{L2} = -V_{out} \quad (14)$$

4. Simulation model and result

The Matlab simulation model of MPPT using all four methods are shown in figure 7. Matlab 14b, 64 bit version is used to solve the system model. The Ode23s (stiff/Mod. Rosen Brock) solver is used for this purpose.

This circuit topology uses a sepic converter with buck-boost operation, but it delivers the continuous output current which is clean and low -ripple output current.

The output of load current (Matlab Model) for Inc method, P&O method, constant voltage control method, Pref method are shown in figure 8(a), figure 8(b), figure 8(c), figure 8(d), respectively. The irradiance is kept constant at 1000 W/m^2 . The load current in Pref method is settled at 1.069 amp in 543 msec which is shown in figure 8(d). The load current in CVC method is settled at 1.025 amp in 75.4 msec which is shown in figure 8(c). The load current in Inc method is settled at 1.049 amp in 1.253 sec which is shown in figure 8(a) and in case of P&O method the load current is settled at 1.014 Amp at 1.14 sec as shown in figure 8(b).

4.1 Schematic of Inverse-Sepic converter

The schematic of Inverse-Sepic is shown in figure 9. It has two low voltage surface mount device (SMD) and metal oxide field effect transistor (MOSFET), one of which is connected in parallel and other is connected in series with load. The circuit consists of two inductors, one inductor is used for boost operation and other inductor performs buck operation in the circuit. The circuit works in continuous conduction mode (CCM) mode. Q_1 is on during first cycle due to which current flows in the inductor L_1 and by the load through the inductor L_2 and coupling capacitor C_1 . When Q_2 is on in the second cycle then energy stored in the

Figure 7. Simulation model of complete system.

Figure 8. Load current of different MPPT methods.

inductor L_2 is delivered to the load. A coupling capacitor C_1 is used to set the inductor L_1 to its primary value.

The inductor L_2 gives nonstop current to the load. On account of the SEPIC converter the summation of input and output voltages appear across Q_1 . Q_1 offers the higher switching loss because of higher voltage strain over the switch. Since the inductors use common magnetic core, their magnetic coupling is evident in terms of mutual induction. It will make the total inductance increased by twice the value resulting in reduced ripple current. In order

to decide the DC transfer function (transformation ratio), the volt-second adjust technique is exploited. Here the converter work in Continuous Conduction Mode (CCM) and achieves the stable state [29]. The circuit operates in buck mode when the duty cycle is under 50% and as a boost converter when it works for above 50% duty cycle.

As it is needed to charge the bootstrap capacitor, in a synchronous rectifier MOSFET the drain connection is used for phase pin. The gate of the main MOSFET Q_1 is driven by isolation capacitor. The gate and source of main

Figure 9. Schematic of Inverse-Sepic converter.

MOSFET is fully separated from the MOSFET Q_2 driver. The PIC microcontroller is used to control the operation of MOSFETs. The dumbbell inductors are used for making both inductors. The polarized and non-polarized capacitors are used for storage and tuning purpose. The two connectors are separately provided for input and output purpose, one extra connector for 5V dc output (optional). The over voltage and under voltage lockout conditions are provided for circuit protection. The circuit will check the maximum power in every 25 ms.

```
// Every 25ms track Mppt point
if (MpptVar.MpptCycCnt == CLEAR)
```

The soft-start is also provided for proper turn on of the circuit

```
Delay_ms(300);
// Give 300ms power on delay for stabilization
```

4.2 PCB design with legend

This printed circuit board (PCB) layout is designed in OrCAD tool. The double side PCB who's Die positive and Die negative are shown in figures 10(a) and (b), respectively. The PCB circuit design with legend is shown in figure 10(c). Most of the components are SMD, in which all the resistors are 1% tolerance.

4.3 Hardware and components

The real hardware circuit of Inverse-Sepic converter is shown in figure 11, which consists of capacitors and inductors at input-output stages along with power (surface mount device) SMD MOSFETs Q_1 and Q_2 whose $V_{DS} = 40V$, $R_{DS(ON)} = 0.0040 \Omega$ at $V_{GS} = 4.5V$ and $I_D = 34$ Amp. The switching frequency is 10 KHz. The package of MOSFET is SO-8. A fourteen pin PIC

Figure 10. PCB patterns.

microcontroller is used for controlling of MOSFETs. The coupling capacitor (C_1), connected in parallel with C_2 , and is charged to the output voltage level. The inductors $L_1 = 30.4$ mH and $L_2 = 80.2$ mH are used as energy storage elements.

The value of MPPT interval is 25 msec and oscillator frequency is 16 MHz and the value of NCO clock is 500 KHz means 2 μ sec On Time. The value of output voltage of converter is 14.4 volts. The specifications of hardware are given in table 1. In this method, the Power ($V \cdot I$), So that the algorithm will track MPPT even if $\Delta V = 0$, because ΔI will effect ΔP . Pref has a constant value. It is defined by the user, which depends on panel specifications. Here, the value of Pref has been calculated which is equal to the value at MPP. The voltage at MPP is specified at 80% of VOC for the solar panel under consideration, it means voltage at MPP is 0.80×18.18 V panel = 14.55 V. The panel maximum current is 1.1 A (90% of short circuit current). So Pref (Ref power) = 16 w (Appendix B). When the value of real power is equal to Pref, then the circuit will be stabilized. Otherwise, it will adjust near MPP. The value of Pref is independent from ambient condition. In equation (6), term N ($(Pref - Pr)/Pref$) has the maximum value as 2

Figure 11. PCB circuit of Zeta converter.

when Pr is 0 and the minimum value is 0 when Pref is equal to Pr . The value of $N = 2$ provides the stable value with lower oscillations so the circuit has been operated on this value (for calculation of scaling factor see Appendix C). For current and voltage sensing in real time, SMD resistors are provided (Appendix D). The circuit will take the samples of input current and voltage in every 8 milliseconds and track the maximum power point accordingly (Appendix E).

Table 1. Hardware system specification.

Sl. No	Circuit Item	Specification
1	DC-DC Inverse-Sepic converter	V_L (output voltage) = 14.4 Volt V_{input} range = 9–20 Volt I_L = 1.11 Ampere (max) P_L = 16 Watt (max) $V_{input} < 14.4$, boost operation $V_{input} > 14.4$, buck operation P_{ref} = 16 Watt, N (scaling factor) = 2
2	Solar PV Panel	Open Circuit voltage V_{oc} = 18.18 Volt I_{sc} = 1.23 Amp V_{mpp} = 14.55 Volt I_{mpp} = 1.1 Amp

4.4 Testing set-up

The experimental results are captured using DSO model RIGOL DS11048 and performed with solar irradiance controller. In this experimental set-up the Panel rating is 18.18 Volt, which is connected to the input of Inverse-Sepic converter. The pictorial view of set-up under investigation is shown in figure 12. The output voltage of Inverse-Sepic converter is 14.4 volt. The radiation is kept at 1000 W/m² and 500 W/m² at the time of testing using the irradiation

Figure 12. Testing set-up (a) and (b).

control unit. For current measurement, the resistor of 1 ohm is connected in series with the output positive terminal of Inverse-Sepic converter. The voltage drop across these resistors is taken which comes out to be proportional to the load current (Ohm's law). The resistive load is used for the experiment purpose.

4.5 Duty cycle

The output voltage of converter is 14.4 V, if the output voltage of panel is less than 14.4 volts then circuit works in boost mode and if the panel output is greater than 14.4 volts then the circuit works in buck mode. The duty cycle of Inverse-Sepic converter is adjusted in continuous current mode (Appendix F) as,

$$V_{out} = V_{in} \times (D / (1 - D)) \quad (15)$$

Where, V_{out} is the output voltage which is set on (14.4 Volt) and V_{in} is the input voltage range (8 to 20 Volt) of Inverse-Sepic converter. By using these values the Duty cycle will be adjusted as,

At Duty $D < 0.5$ = Buck operation

Duty $D = 0.5$ = V_{out} is same as V_{in}

Duty $D > 0.5$ = Boost Operation

5. Hardware results and discussion

The results of different MPPT methods are shown in figure 13. The results for Inc, P&O, CVC and P_{ref} method are shown in figures 13(a), 13(b), 13(c) and 13(d), respectively. The results are captured on different irradiation conditions (500 W/m² to 1000 W/m², 1000 W/m² to 500 W/m², 0 to 1000 W/m²) created by solar irradiance control unit. The MPLAB software is used to programing and load the coding in the PIC microcontroller. The pickit-3 Burner is use for loading the program.

The cursor of D.S.O is set on auto tracking mode. In figure 13 (d) (i) and figure 13 (d) (ii) the output current of P_{ref} , is stabilized at 367 mAmp in minimum time. Load side characteristics with respect to time are captured in DSO and the corresponding results are obtained for the comparison purpose and shown in table 2.

As shown in table 2, for the sudden irradiance of 1000 W/m², the load current in P_{ref} method takes 520 msec to stabilize at rated load current at 1.06 Amp while Inc, P&O, CVC methods take 1.24 sec to achieve 1.04 Amp, 1.19 sec to achieve 1.01 Amp, 75.2 msec to achieve 1.02 Amp, respectively. The P_{ref} method shows the higher efficiency which is 95.26% while other methods are settled down on lower efficiency in comparison with P_{ref} method. The efficiency is calculated by using the formula $\eta = \frac{P_{out}}{P_{in}}$.

The results of simulation are as shown in table 3, for sudden irradiance of 1000 W/m², the load current in P_{ref}

(i) Load current when irradiance raise 500W/m^2 to 1000W/m^2 (i) Load current when irradiance raise 500W/m^2 to 1000W/m^2 (ii) Load current when irradiance decreases 1000W/m^2 to 500W/m^2 (ii) Load current when irradiance decreases 1000W/m^2 to 500W/m^2 (iii) Load current when irradiance raise 0W/m^2 to 1000W/m^2 (iii) Load current when irradiance raise 0W/m^2 to 1000W/m^2

(a) Performance of Inc MPPT method

(b) Performance of P&O MPPT method

Figure 13. Hardware results of different MPPT methods.

(i) Load current when irradiance raise 500W/m² to 1000W/m² (i) Load current when irradiance raise 500W/m² to 1000W/m² (ii) Load current when irradiance decreases 1000W/m² to 500W/m² (ii) Load current when irradiance decreases 1000W/m² to 500W/m² (iii) Load current when irradiance raise 0W/m² to 1000W/m² (iii) Load current when irradiance raise 0W/m² to 1000W/m²

(c) Performance of CVC MPPT method

(d) Performance of Pref MPPT method

Figure 13. continued

Table 2. Comparisons of experimental results for considered MPPT methods.

MPPT Method	Settling time of output current (msec), When sudden irradiance changes from 0 to 1000W/m ² is applied		Output Voltage of Inverse- Sepic converter (Volts)	Input Power (watt)	Efficiency
	Time (sec)	Output Load current(Amp)/O/P Watt			
Inc	1.24	1.04/14.95	14.384	16	93.43%
P&O	1.19	1.01/14.52	14.385	16	90.77%
CVC	0.752	1.02/14.66	14.383	16	91.67%
Pref	0.520	1.06/15.24	14.385	16	95.26%

Table 3. Comparisons of Simulink results for considered MPPT methods.

MPPT Method	Settling time of output current (msec), When sudden irradiance changes from 0 to 1000W/m ² is applied		Output Voltage of Inverse-Sepic converter (Volts)	Efficiency
	Time (sec)	Output Load current(Amp)/O/P Watt		
Inc	1.253	1.049/15.08	14.386	94.27%
P&O	1.14	1.014/14.58	14.385	91.13%
CVC	0.0754	1.025/14.73	14.385	92.12%
Pref	0.543	1.069/15.37	14.386	96.06%

Table 4. Hardware result when irradiance changes from 500 W/m² to 1000 W/m².

MPPT METHOD	Load current shifting (output current in Amp) when irradiance changes from 500W/m ² to 1000W/m ²	Settling time of output current (msec) When irradiance changes from 500 to 1000 W/m ² .	Input power of converter (watt)	Output voltage of converter (Volt)	Output power (watt)	Efficiency of converter
Inc	688 mAmp to 1.04 Amp	13.6	16	14.383	14.95	93.43%
P&O	680 mAmp to 1.01 Amp	12.4	16	14.384	14.52	90.77%
CVC	672 mAmp to 1.02 Amp	38.4	16	14.383	14.66	91.67%
Pref	693 mAmp to 1.06 Amp	7.60	16	14.382	15.24	95.26%

method takes 543 msec to stabilize at rated load current at 1.069 Amp while Inc, P&O, CVC methods take 1.253 sec to achieve 1.049 Amp, 1.14 sec to achieve 1.014 Amp, 75.4 msec to achieve 1.025 Amp, respectively. This shows that Pref is having the ability to settle down quickly with changing irradiance. The Pref method shows the higher efficiency which is 96.06% while other methods are settled down on lower efficiency in comparison with Pref method.

Table 4 shows the output comparison of different algorithms when irradiance rise suddenly from 500 W/m² to 1000 W/m² on solar panel. Table 4 shows the Input voltage and input power and corresponding outputs of converter when drives with different algorithms under same irradiance conditions. Under these test, the Pref algorithm is stabilized at higher value of current which is 1.06 Amp with the efficiency of 95.26% while the other algorithms is stable at lower efficiency. When the irradiance changes from 500 W/m² to 1000 W/m², the Pref method takes only 7.60 msec while Inc, P&O and CVC takes 13.6 msec, 12.4 msec, 38.4 msec, respectively. This shows and validate that

Pref is having the ability to settle down quickly with changing irradiance.

Table 5 shows the output results of different algorithm when the irradiance suddenly falls from 1000 W/m² to 500 W/m². In this condition, Pref algorithm is stable at 0.693 Amp with 94.90% efficiency which is again higher when compared with other algorithms. When irradiance changes from 1000 W/m² to 500 W/m², Pref, Inc, P&O and CVC methods take 7.20 msec, 10.4 msec, 11.2 msec and 30 msec, respectively. It further shows from the results that Pref has the ability to settle down quickly under changing weather condition.

6. Conclusions

In this paper, the hardware and Matlab/Simulink performance of various MPPT methods implemented on Inverse-Sepic converter was reported. Further, a MPPT tracking system based on variable step size by Pref methods was

Table 5. Output result when irradiance changes from 1000 W/m² to 500 W/m².

MPPT METHOD	Load current (output current Amp) when irradiance changes from 1000 W/m ² to 500 W/m ²	Settling time of output current (msec) When irradiance changes from 1000 to 500 W/m ²	Input power of converter (Watt)	Output voltage of converter (Volt)	Output power (watt)	Efficiency of converter
Inc	1.04 Amp to 688 mAmp	10.4	10.5	14.378	9.89	94.19%
P&O	1.01 Amp to 680 mAmp	11.2	10.5	14.372	9.77	93.04%
CVC	1.02 Amp to 672 mAmp	30	10.5	14.370	9.67	92.09%
Pref	1.06 Amp to 693 mAmp	7.20	10.5	14.379	9.96	94.90%

also proposed in this paper. The obtained results of Inc, P&O, CVC and Pref are compared with each other and significant benefits are observed for Pref method. The rate of power delivered is maximum in case of Pref method as compared to the other methods. It is quite suitable to withstand with sudden changes in irradiation level due to its low rising time and stability of load power.

The main concluding points are as follows.

- The Simulink results of various MPPT methods implemented on Inverse-Sepic converter have been verified by experimental results.
- Load current in Pref method has been stabilized in 0.520 sec with 1.06 Amp current which is near to maximum current value with the highest efficiency of 95.26% for sudden exposure of 1000 W/m² irradiation level, whereas P&O method extracts minimum efficiency of 90.77%.
- Load current in Pref method takes 7.20 sec and 7.60 sec to stabilize for both cases, when step change in irradiance from 1000 W/m² to 500 W/m² has been applied or vice versa.

List of symbols

q	Electron charge [1.602×10^{-19} C]
k	Boltzmann constant [1.38×10^{-23} J/°K]
n_p	Number of cells connected in parallel
n_s	Number of cells connected in series
n	Deviation factor of the characteristics of an ideal p–n junction/Ideality constant
T_c	Cell operating temperature [°K]
R_S	Series resistance of cell (0.001 Ω)
R_{sh}	Intrinsic parallel resistances associated to the panel [Ω]
I_{pv}	Panel output current [A]
I_s	Reverse saturation current [A]
I_L	Photo-current generated by solar radiation [A]
V_{pv}	Panel output voltage [V]

P_r Real power of solar PV [W]

D Duty Cycle

P_{ref} Reference power of solar PV [W]

Appendix A: Voc measurement for CVC method

```
// VOC Periodic scanning for updating MPPT reference
if(WAITING == MpptVar.VocScanState)
{
    // Decrement MPPT scan counter(Till 1200sec timeout)
    if(CLEAR < SysVar.SacnCtrMs)
    {
        SysVar.SacnCtrMs--;
    }
    else
    {
        MpptVar.VocScanState = SACN_TRIG;
        // Turn off Load for 100ms for Voc Stabilization
        SysVar.SacnCtrMs = 100; //100ms
        DISABLE_LOAD
    }
}
else if(SACN_TRIG == MpptVar.VocScanState)
{
    // Consider Panel voltage after 100ms from Load cutoff
    if(CLEAR < SysVar.SacnCtrMs)
    {
        SysVar.SacnCtrMs--;
    }
    else
    {
        //update Mppt Ref
        MpptVar.VinRef = ADC_V_Panel_Avg * MPPT_FACTOR;
        // update Voc Scan state
        MpptVar.VocScanState = WAITING;
        // Turn on Load And wait for next cycle for VOC scan.
        SysVar.SacnCtrMs = 1200000; // 20min
        ENABLE_LOAD
    }
}
```

Appendix B: Calculation of Reference Power Pref

As in Code:


```
#define MPPT_REF_POWER (2949×450) //14.55V×1.1A
Typically MPPT achieves at 80 % of VOC of panel. 0.80×18.18
v panel = 14.55V and panel current is 1.1Amp. So MPPT power (Ref power) = 16w.
```

Appendix C: Calculation of scaling factor N

```
temp = ((temp / MPPT_REF_POWER)*5) / 10;
and
#define MPPT_SCALE_FACTOR 640//4.0v. (640/4096*25v)
Vout (k) = Vout (k-1) +/- N (Pref-Pr)/Pref. Here Max N = 4 and it
should be in Volt scale (25v = 4096count, 4V = 640count).
N is MPPT_SCALE_FACTOR.
Again to tune N from 0 to 4 we provided scaling X/10. X configured as 5.
So Effective N = 4*(5/10) = 2.
```

Appendix D: Input, output resistor for current and voltage measurement

The sensing resistors are as follows

S.NO	SENSE	LEGEND	CONNECTED TO PIN NO's OF MICROCONTROLLER	VALUE
1	INPUT CURRENT	R3	8	100Ω ±1% tolerance
2	OUTPUT CURRENT	R15	12	100Ω ±1% tolerance
3	INPUT VOLTAGE	R14	11	3KΩ ±1% tolerance
4	OUTPUT VOLTAGE	R13	7	1KΩ ±1% tolerance

In real time the circuit read the input current by series resistor R3. The value of R3 is 100Ω ±1% tolerance for scaling purpose. The R3 resistor is connected to pin no 8 of the microcontroller. The output current is sensed by series resistor R15 of 100Ω ±1% tolerance which is connected on pin 12 of microcontroller. The Input voltage is carried out across the potential divider resistor R14 of 3KΩ ±1% tolerance and the output voltage is carried out across the potential divider resistor R13 of 1KΩ ±1% tolerance (Ref figure no. 8).

The value of sensing voltage resistor R_{14} is decided by the voltage division method. The value of sensing voltage $V_{R_{14}}$ is given in data sheet.

$$V_{R_{14}} = \frac{R_{14}}{R_{12} + R_{14}} \times V_{in} \quad (\text{Ref Fig no. 8})$$

Similarly the value of sensing voltage resistor R_{13} is decided by the voltage division method. The value of sensing voltage $V_{R_{13}}$ is given in data sheet.

$$V_{R_{13}} = \frac{R_{13}}{R_{11} + R_{13}} \times V_{out} \quad (\text{Ref Fig no. 8})$$

Appendix E: MPPT point tracking program

```
void MpptTrack(void)
{
    // get averaged (8ms) Vin, Iin samples.
    MpptVar.VinAvg = MpptVar.VinAvg >> 3;
    MpptVar.VinAvg = MpptVar.VinAvg >> 3;
    MpptVar.Power = (long) MpptVar.VinAvg * MpptVar.IinAvg;

    //Compute dp, dv, di.
    delta_p = MpptVar.Power - MpptVar.Prev_Power;
    delta_i = (long) MpptVar.IinAvg - MpptVar.Prev_IinAvg;
    delta_v = (long) MpptVar.VinAvg - MpptVar.Prev_VinAvg;
    TrackDir = 0;

    // Check for change in voltage
    if ((delta_v > V_TH_POS) || (delta_v < V_TH_NEG))
    {
        slope = delta_p / delta_v;
        if (slope > 0)
        {
            TrackDir = 1;
        }
        else if (slope < 0)
        {
            TrackDir = 2;
            slope = slope*-1;
        }
    }
    else // No change in voltage
    {
        if (delta_i > I_TH_POS) TrackDir = 1;
        else if (delta_i < I_TH_NEG) TrackDir = 2;
    }
    if (TrackDir > 0)
    {

```

Appendix F: Calculation of duty cycle

The duty cycle is adjusted by the equation

$$V_{out} = V_{in} \times (D / (1 - D))$$

Where V_{out} is the voltage across the load and V_{in} is the input voltage of inverse sepic converter.

Where, V_{in} is $V_{in} (k) = V_{in} (k-1) \pm N (Pref-Pr)/Pref$. By using these values the Duty cycle will adjust.

At Duty $D < 0.5$ = Buck operation
 Duty $D = 0.5$ = V_{out} is same as V_{in}
 Duty $D > 0.5$ = Boost Operation

Step based on Pref

```
if (MpptVar.Power > MPPT_REF_POWER) (MpptVar.Power = Pr)
    temp = MpptVar.Power - MPPT_REF_POWER;
else
    temp = MPPT_REF_POWER - MpptVar.Power;

temp = ((temp / MPPT_REF_POWER)*5) / 10;

MpptVar.StepValue = MpptVar.StepValue + MPPT_SCALE_FACTOR*temp;
```

So, as per the step size, V_{out} will be calculated like,
 $V_{out} (k) = V_{out} (k - 1) \pm N (Pref - Pr)/Pref$.

Here Max N = 2.

The increment and decrement of voltage is as follows

As per Code:

```
// Increase Vin reference
if ((TrackDir == 1) && (MpptVar.VinRef < MAX_MPPT_VOLT)) //19.5 Volt
{
    MpptVar.VinRef += MpptVar.StepValue;
}
// decrease Vin reference
if ((TrackDir == 2) && (MpptVar.VinRef > MIN_MPPT_VOLT)) //8 Volt
{
    MpptVar.VinRef -= MpptVar.StepValue;
}
```

References

- [1] Azevedo G, Cavalcanti M, Oliveira K, Neves F and Lins Z 2009 Comparative evaluation of maximum power point tracking methods for photovoltaic systems. *J. Solar Energy Eng.* 13(3): 031006
- [2] Calavia M, Perie J, Sanz J and Sallan J 2010 Comparison of MPPT strategies for solar modules. In: *International Conference on Renewable Energies and Power Quality* 1(8):1440–1445
- [3] Dahbi S, Aziz A, Benazzi N, Elhafyani M, and Benahmed N 2016. Advanced MPPT controller based on P&O algorithm with variable step size and acceleration mechanism for solar photovoltaic system. In: *Proceedings of the Mediterranean Conference on Information & Communication Technologies 2015*, pp. 57–67
- [4] Dahech K, Allouche M, Damak T and Tadeo F 2017 Backstepping sliding mode control for maximum power point tracking of a photovoltaic system. *Electric Power Syst. Res.* 143: 182–188
- [5] De Melo Bento A, Acevedo-Bueno D and Cabral da Silva E 2016 Dual input dual output single switch DC-DC converter for renewable energy applications. In: *IEEE Energy Conversion Congress and Exposition (ECCE)*
- [6] De Brito M, Galotto L, Sampaio L, e Melo G and Canesin C 2013 Evaluation of the Main MPPT Techniques for Photovoltaic Applications. *IEEE Trans. Ind. Electr.* 60(3): 1156–1167
- [7] Dileep G and Singh S 2017 Application of soft computing techniques for maximum power point tracking of SPV system. *Solar Energy* 141: 182–202
- [8] Dolara A, Faranda R and Leva S 2009 Energy Comparison of Seven MPPT Techniques for PV Systems. *J. Electromagn. Anal. Appl.* 01: 152–162
- [9] Fathabadi H 2016 Novel fast dynamic MPPT (maximum power point tracking) technique with the capability of very high accurate power tracking. *Energy* 94: 466–475
- [10] Fathabadi H 2017 Novel fast and high accuracy maximum power point tracking method for hybrid photovoltaic/fuel cell energy conversion systems. *Renew. Energy* 106: 232–242
- [11] Harrag A and Messalti S 2015 Variable step size modified P&O MPPT algorithm using GA-based hybrid offline/online PID controller. *Renew. Sustain. Energy Rev.* 49: 1247–1260
- [12] Ishaque K and Salam Z 2013 A review of maximum power point tracking techniques of PV system for uniform insolation and partial shading condition. *Renew. Sustain. Energy Rev.* 19: 475–488
- [13] Taghvaei M, Radzi M, Moosavain S, Hizam H and Hamiruce Marhaban M 2013 A current and future study on non-isolated DC–DC converters for photovoltaic applications. *Renew. Sustain. Energy Rev.* 17: 216–227
- [14] Tey K and Mekhilef S 2014 Modified incremental conductance MPPT algorithm to mitigate inaccurate responses under fast-changing solar irradiation level. *Solar Energy* 101: 333–342
- [15] Tomar R 2016 Comparison between Perturb & Observe Method and Incremental Conductance Method for Maximum Power Point Tracking of PV Module. [online] Available at: http://dspace.thapar.edu:8080/jspui/bitstream/10266/4344/1/Rahul_801441021.pdf
- [16] Verma D, Nema S, Shandilya A and Dash S 2016 Maximum power point tracking (MPPT) techniques: Recapitulation in solar photovoltaic systems. *Renew. Sustain. Energy Rev.* 54: 1018–1034
- [17] Priyadarshi N et al 2017 *An Experimental Study on Inverse-Sepic Buck–Boost Converter for Application in PV System*. Handbook of Distributed Generation Springer International Publishing: Cham, Switzerland, 393–406
- [18] Liu L, Meng X and Liu C 2016 A review of maximum power point tracking methods of PV power system at uniform and partial shading. *Renew. Sustain. Energy Rev.* 53: 1500–1507
- [19] Ram J, Babu T and Rajasekar N 2017 A comprehensive review on solar PV maximum power point tracking techniques. *Renew. Sustain. Energy Rev.* 67: 826–847
- [20] Ramli M, Twaha S, Ishaque K and Al-Turki Y 2017 A review on maximum power point tracking for photovoltaic systems with and without shading conditions. *Renew. Sustain. Energy Rev.* 67: 144–159
- [21] Rezk H and Eltamaly A M 2015 A comprehensive comparison of different MPPT techniques for photovoltaic systems. *Solar Energy* 112: 1–11
- [22] Saravanan S and Babu N R 2016 Maximum power point tracking algorithms for photovoltaic system—A review. *Renew. Sustain. Energy Rev.* 57: 192–204
- [23] Gupta CL 1993 Solar passive buildings for developing countries. *Sadhana* 18(1): 77–104
- [24] Altas A and Sharaf A M 1991 A solar powered permanent magnet DC motor drive schem. In: *Proc., Annu. Conf. Solar Energy Soc. Canada*, Toronto, pp. 65–70
- [25] Enrique J M, Duran E Sidrach-de-Cardona M and Andujar J M 2007 Theoretical assessment of the maximum power point tracking efficiency of photovoltaic facilities with different converter topologies. *Solar Energy* 81(1): 31–38
- [26] Kundu U and Sensarma P 2017 Discontinuous conduction mode analysis of phase-modulated series resonant converter. *Sadhana* 42(8): 1299–1307
- [27] Rajani SV and Pandya V 2015. Simulation and comparison of perturb and observe and incremental conductance MPPT algorithms for solar energy system connected to grid. *Sadhana* 40(1): 139–153
- [28] Panda A, Pathak MK and Srivastava SP 2016 A single phase photovoltaic inverter control for grid connected system. *Sadhana* 41(1): 15–30
- [29] Bharadwaj P and John V 2014 Direct duty ratio controlled MPPT algorithm for boost converter in continuous and discontinuous modes of operation. In: *Power Electronics (IICPE), 2014 IEEE 6th India International Conference* (pp. 1–6)