A current sensor based adaptive step-size MPPT with SEPIC converter for photovoltaic systems

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Abstract
Efficient maximum power point tracking (MPPT) is an important problem for renewable power generation from photovoltaic systems. In this work, a current sensor based MPPT algorithm using an adaptive step-size for a single ended primary inductance converter (SEPIC) based solar photovoltaic system is proposed. Due to lower sensitivity of power to current perturbation as compared to the voltage one, such a scheme is shown to yield better efficiency at steady-state. A new adaptation scheme is also proposed for faster convergence of the MPPT technique. Hence, the proposed scheme yields better transient as well as steady-state performance. A prototype converter is used along with digital implementation of the proposed MPPT technique to demonstrate the superiority of the proposed algorithm over the fixed step-size and voltage based ones. Simulation and experimental results corroborates the same.

1 | INTRODUCTION

Photovoltaic (PV) power generation is commonly used as renewable energy source because of the advantages, e.g. pollution free, noiseless, lesser maintenance and easy to install in distributed fashion and in varied sizes [1, 2]. The output of PV module depends on operating conditions, such as PV-cell temperature and insolation-level [3, 4]. Researchers developed various techniques to extract maximum power from the PV sources. Some of the MPPT techniques are perturb and observe (P&O) [5–7], hill climbing (HC) [8], incremental conductance (IncCond) [9, 10], fractional voltage/current MPPT control [11], fuzzy-logic (FL) [12, 13], neural network (NN) [14, 15], optimization techniques [16], and sliding mode (SM) control [17–19].

Among the conventional MPPT techniques, P&O and the IncCond techniques are widely used due to their simplicity yet being efficient [20]. A demerit of P&O like algorithms is that it drifts away from MPP [5] for sudden changes in insolation leading to lesser efficiency. In [21], the drift problem is presented and resolved by modified P&O algorithm. Other machine learning MPPT techniques, e.g. NN [14], FL [12], SM [17], and optimization techniques, show improved performance. But these are not commonly used due to need of expensive controllers and complexity for implementation and big data processing for the training of the system to enhance the tracking accuracy [22].

In conventional MPPT techniques, the perturbation step-size is selected by considering convergence speed and steady-state performance. For faster convergence and to enhance the steady-state response, an adaptive step-size MPPT technique is proposed in [21]. In such adaptive methods, the step-size is a linear function of either the derivative of power to duty-cycle ($dP_{pv}/dD$) [23] or the derivative of power to voltage ($dP_{pv}/dV_{pv}$) [24]. This leads to transient performance is improvement by reducing the tracking time. However, most of these methods are applied to voltage sensor based MPPT techniques.

Both the current and the voltage sensors are used for implementing some of the MPPT algorithms, e.g. P&O that leads to increased cost [5–16]. Only a handful of techniques use either a voltage [21, 25] or a current sensor [26]. Only voltage based methods are considerably cheaper as compared to the current based methods due to larger cost involved in current sensing.
On the other hand, it is well known that the PV voltage varies logarithmically with solar insolation [27]. It makes all the voltage sensor based MPPTs to be less sensitive for large change in irradiation and hence yields slower convergence (due to large insolation change) when initial point is far away from the MPP. It is otherwise for the current sensing since the PV current varies linearly with insolation level. This property is very useful for a fast current sensor based MPPTs than voltage sensor based one for frequent change in insolation [27, 28].

In the context of choice of converters, several different converters are used for impedance matching to obtain maximum power from the PV systems, e.g. buck [26], boost [2], buck-boost [29], SEPIC [5, 27] converters. The selection of converter topology depends on the PV module voltage and the load voltage [30]. For example, the buck topology is used only for the cases where the PV module voltage is always higher than the load voltage. Similarly, the boost topology is applicable if the PV module voltage is always lower than the load voltage. Clearly, both are extreme ended considering the fact that insolation variation in a day is over a wide range. On the other hand, the drawback of buck-boost converter is that the output is inverted which results in complex sensing and feedback circuit. It also has discontinuous input current that limits the ability of the converter. A comparison of several buck-boost converters from different point of view is given in [31]. Among these, although the SEPIC converter has poor efficiency and higher cost, it still has the merits of non-inverting polarity, continuous input current, works as buck-boost converter over wide range and low input current-ripple [5]. It is suitable for either voltage or current applications [32, 33]. The main losses in the DC–DC converters are switching losses in the MOSFET and the diode, copper losses in the inductor windings and inductor core losses. A comparison of losses in converters is given in [34], it can be seen that all the converters have same number of switches (MOSFET and diode), hence the switching losses will be the same. The losses in the inductors are lower for the SEPIC converter due to the reduced input current ripple that decreases the peak inductor current though it has two inductors. These properties make SEPIC converter a suitable candidate for PV applications.

In this paper, SEPIC converter is used for development of a new MPPT technique, which is realized using a single current sensor. A Hall-effect current sensor is used for current sensing, which has many advantages like excellent accuracy and linearity, wide frequency bandwidth, optimized response time, lower temperature drift, high resistance to external noise and current overload capacity. A new variable step-size algorithm is developed that yields a large step-size when the operating point is away from MPP. This results in faster convergence for change in MPP. An experimental setup is developed for the implementation of the Proposed MPPT technique and an ARDUINO UNO microcontroller is used for the programming of algorithm.

A 40 W PV panel is considered for simulation and experiment. It has uses in standalone applications, such as solar lantern, solar mobile charger, small solar battery banks, solar garden lights, solar street light etc. It can also be used as portable power supply. It is shown through simulation and experimental results that the proposed algorithm yields improved convergence time and thereby improves the efficiency of the system.

This paper is organized as follows Section 2 presents the importance of current sensor in PV system. Section 3 presents development of the switching function for the current sensor based MPPT algorithm. A novel adaptive technique is proposed in Section 4. The design parameters of SEPIC converter is explained in section 5. Simulations as well as experimental results are shown in Section 6 and 7, respectively. This paper ends with conclusion in Section 8.

2  |  THE LINEARITY OF PV CURRENT WITH INSOLATION

A single-diode electrical equivalent circuit [35] is well known for modelling of PV modules. The $V-I$ relationship of a PV-module is given by Equation (1).

$$I_{pv} = I_p - I_{ns} \left[ \exp \left( \frac{V_{pv}}{n_b R_p} \right) - 1 \right] - \frac{V_{pv} + I_{pv} R_{se}}{R_p} \tag{1}$$

where $V_{pv}$ and $I_{pv}$ are the output voltage and current of the PV-module, respectively. $I_{ns}$ is the reverse saturation current, $R_{se}$ and $R_p$ are the series and parallel resistances, respectively, $n_s$ is the number of series connected PV cells in a module, $b$ is the ideality factor of the diode, $v_1 = kT/e$ is thermal voltage, $T$ is module temperature in Kelvin, $e$ is charge on electron, and $k$ is the Boltzmann’s constant.

For an ideal PV module, the series and parallel resistances in Equation (1) are zero and infinite, respectively. Then the voltage–current relationship can be written as:

$$I_{pv} = I_p - I_{ns} \left[ \exp \left( \frac{V_{pv}}{n_b i_1} \right) - 1 \right] \tag{2}$$

where $I_p$ is the photo–current and it is expressed in terms of the insolation $G$ and the PV cell temperature $T$ as follows.

$$I_p = \left[ i_{STC} + k_{sc} (T - T_{STC}) \right] \frac{G}{G_{STC}} \tag{3}$$

where $k_{sc}$ is the short circuit current temperature coefficient, $i_{STC}$ is the short circuit current at $G_{STC} = 1000$ W/m$^2$, $T_{STC} = 298$ K.

From Equations (2) and (3), it is clear that the $V_{pv}$ is non-linear with $G$, whereas the PV current $I_{pv}$ depends linearly. Because of nonlinear relation between voltage and solar insolation, the convergence to maximum power point (MPP) is non-linear for a voltage sensing based algorithm. However, the linear relationship between PV current with $G$ would be beneficial for detecting solar insolation changes irrespective of the insolation level. Due to this, a current based MPPT algorithm can be adopted for uniform convergence over wide range of insolation and the same is studied in this work. It may be noted that linear characteristic is beneficial since uniform convergence can be
achieved using simpler logic, whereas intrinsically complex logic is required to tackle non-uniform behaviour.

3 DEVELOPMENT OF SWITCHING FUNCTION FOR CURRENT SENSOR BASED MPPT

In this section, switching functions for current sensor based MPPTs are derived. It is shown that the switching function $S$ will depend on the converter chosen. Based on the appropriate selection of switching function, the MPPT algorithm is developed. Since the SEPIC converter is only used in this work, we start with this as described in the following.

3.1 Switching function for SEPIC converter

The PV system considered is given in Figure 1. A SEPIC converter is used to supply the load form the PV panel. The duty-cycle of the converter is adapted by the MPPT controller for operation at the MPP. The proposed MPPT controller uses only one current sensor for determining the MPP. The corresponding switching function is derived below.

The output voltage of SEPIC converter can be written as

$$V_o = \frac{D}{(1-D)}V_{pv}$$  \(\text{(4)}\)

where $V_o$ is the output voltage and $D$ is the duty-ratio of SEPIC converter. The efficiency $\eta$ of the SEPIC converter can be expressed for a load $R$ as

$$\eta = \frac{V_o I_o}{V_{pv} I_{pv}}$$  \(\text{(5)}\)

$$\eta = \frac{V_o^2}{V_{pv}^2 \frac{R}{R_{eq}}} = \left(\frac{V_o}{V_{pv}}\right)^2 \frac{R_{eq}}{R} = \left(\frac{D}{1-D}\right)^2 \frac{R_{eq}}{R}$$  \(\text{(6)}\)

where $R_{eq}$ is the equivalent resistance of the converter. Then, $R_{eq}$ can be obtained from Equation (6) as

$$R_{eq} = \eta \left(\frac{D}{1-D}\right)^2 R$$  \(\text{(7)}\)

The PV module power $P_{pv}$ can be expressed by using Equation (7) as:

$$P_{pv} = I_{pv}^2 R_{eq} = \eta I_{pv}^2 \left(\frac{1-D}{D}\right)^2 R$$  \(\text{(8)}\)

We can also write

$$P_{pv} = \left(\sqrt{P_{pv}}\right)^2$$  \(\text{(9)}\)

From Equation (9), the variation of $P_{pv}$ with respect to the duty ratio $D$ can be written as:

$$\frac{dP_{pv}}{dD} = 2\sqrt{P_{pv}} \left[\frac{d\sqrt{P_{pv}}}{dD}\right]$$  \(\text{(10)}\)

By putting the value of $P_{pv}$ from Equation (8) into Equation 10, we get

$$\frac{dP_{pv}}{dD} = \left[I_{pv} \left(\frac{1-D}{D}\right) + \left(\frac{1-D}{D}\right) \frac{dI_{pv}}{dD}\right] 2\sqrt{\eta R P_{pv}}$$  \(\text{(11)}\)

$$\frac{dP_{pv}}{dD} = \left[-I_{pv} dD + D(1-D) \frac{dI_{pv}}{dD}\right] 2\sqrt{\eta R P_{pv}}$$  \(\text{(12)}\)

The $P_{pv} - D$ characteristic waveform of a PV module is shown in Figure 2. One can observe that $dP_{pv}/dD$ is equal to zero at the MPP. Furthermore, $dP_{pv}/dD$ is greater than zero to the left of the MPP and $dP_{pv}/dD$ is less than zero to the right of the MPP.
Hence, for maximum power, $\frac{dP_{pv}}{dD} = 0$ and it can be calculated from Equation (12) as:

$$D(1 - D)dI_{pv} - I_{pv}dD = 0 \tag{13}$$

Thereby, the switching function $S$ can be written as the following:

$$S = [D(1 - D)dI_{pv} - I_{pv}dD]$$

$>$0, to the right of MPP

= 0, at MPP

$<$0, to the left of MPP

(14)

Note that the right of MPP indicates increased duty-ratio and the left of MPP indicates decreased duty-ratio. Hence, a MPPT controller can be developed based on the sign of switching function $S$. The corresponding $S = D$ characteristic waveform is also shown in Figure 2. It is clear that $S$ passes through zero at MPP.

### 3.2 Switching function for buck converter

The switching function $S$ for tracking the MPP in case of buck converter can be obtained by evaluating $R_{eq}$ and $\frac{dP_{pv}}{dD}$ as follows

$$R_{eq} = \frac{\eta R}{E^2} \tag{15}$$

$$P_{pv} = \eta R(I_{pv}/D)^2 \tag{16}$$

$$\frac{dP_{pv}}{dD} = 2\sqrt{\eta R P_{pv}} \left[ \frac{DdI_{pv} - I_{pv}dD}{D^2dD} \right] \tag{17}$$

$$S = [DdI_{pv} - I_{pv}dD]$$

$>$0, to the right of MPP

= 0, at MPP

$<$0, to the left of MPP

(18)

### 3.3 Switching function for boost converter

Similarly, the switching function $S$ for tracking the MPP in case of boost converter can be obtained as follows

$$R_{eq} = \eta R(1 - D)^2 \tag{19}$$

$$P_{pv} = \eta R[I_{pv}(1 - D)]^2 \tag{20}$$

$$\frac{dP_{pv}}{dD} = 2\sqrt{\eta R P_{pv}} [(D - 1)dI_{pv} - I_{pv}dD] \tag{21}$$

The position of operating point is decided by calculating sign of $S$. If $S > 0$ then the next duty-cycle $D(m + 1)$ is decreased by $\Delta D(m)$, and if $S < 0$ then the next duty-cycle $D(m + 1)$ is increased by $\Delta D(m)$ as mentioned in Equation (25).

The variation in $S$ is large during transient-state for a change in insolutions say from 0 to 800 W/m² and from 800 to 500 W/m² as shown in Figure 3. Whereas the variation in $S$ is small at steady-state as given in Figure 4. Thus, a FSS scheme is not suitable for MPPT controllers for varying insolation.
condition. An adaptive perturbation step-size is considered to change the $\Delta D$, which is written in terms of $S$ as

$$\Delta D(m) = \alpha S(m) \left| \frac{S(m)}{S(m)} \right|$$  \hspace{1cm} (26)$$

$$\Delta D_{\text{min}} \leq \alpha \leq \Delta D_{\text{max}} \left| \frac{S(m)}{S(m)} \right|$$  \hspace{1cm} (28)

where $\alpha$ is a constant to be chosen and $\text{Sign}$ is the signum function. The value of $\alpha$ should be calculated based on Equation (28). The PV power for different values of $\alpha$ are shown in Figure 5. It can be observed that for $\alpha$ less than 1, the convergence time deteriorates rapidly. For $\alpha \geq 1$, there are little variation in the convergence time. In this work, we have taken $\alpha = 1$. In the right hand side of Equation (27), the component $\text{Sign}(S(m))$ facilitates the necessary switching towards and around the MPP, whereas $S^2(m)$ generates the adaptive feature in $\Delta D$ so that $\Delta D$ is large when $S$ is large and otherwise. Hence, it ensures faster convergence to MPP when $S$ is large. Thus, the proposed MPPT improves the transient response of the PV system due to its ASS nature.

### TABLE 1  SEPIC converter design consideration

| Parameters       | Variable | Value |
|------------------|----------|-------|
| PV voltage       | $V_{p}^{(\text{min})}$ and $V_{p}^{(\text{max})}$ | 10 V and 17.4 V |
| Load voltage     | $V_o$    | 17.4 V |
| Load current     | $I_L$    | 2.3 A  |
| Voltage drop across diode | $V_D$ | 0.5 V |
| Switching frequency | $f_s$ | 50 kHz |
| Load resistance  | $R$      | 5 Ω    |

The upper limit of the perturbation step-size $\Delta D_{\text{max}}$ is chosen as 0.5 (thumb rule) and lower limit $\Delta D_{\text{min}}$ can be selected based on the steady-state performance and the resolution of the ADC (analogue to digital converter) used in the microcontroller for realizing the algorithm [26]. The lower value of perturbation step-size $\Delta D_{\text{min}} = 0.005$ is considered in this work. The value of $\Delta D$ will remain between $\Delta D_{\text{min}}$ and $\Delta D_{\text{max}}$. The limiting values of $\Delta D$ can be taken care of by the following condition.

$$\Delta D = \begin{cases} 
\Delta D_{\text{max}}, & \text{if } \Delta D > \Delta D_{\text{max}} \\
\Delta D, & \text{if } \Delta D_{\text{max}} \leq \Delta D \leq \Delta D_{\text{min}} \\
\Delta D_{\text{min}}, & \text{if } \Delta D < \Delta D_{\text{min}} 
\end{cases}$$  \hspace{1cm} (29)

The flow-chart of the proposed current sensor based algorithm is given in Figure 6. It can be seen that only the PV current $I_{pv}$ is sensed through the current sensor and thereby switching function is calculated.

### 5 | DESIGN OF THE SEPIC CONVERTER

In this paper, a SEPIC converter is used as an interface between the PV module and the resistive load as shown in Figure 7. One advantage of this converter is that, it isolates the input and the output by using coupling capacitor $C$ [36]. The capacitor $C$ protects against overload and short circuit condition. In this paper the SEPIC converter is designed [37] for a 40 W PV module. The design consideration for the converter is given in Table 1.

#### 5.1 | Duty-cycle consideration

For continuous conduction mode (CCM) operation of the SEPIC converter, the maximum duty-cycle is calculated by

$$D_{\text{max}} = \frac{V_o + V_D}{V_{pv}^{(\text{min})} + V_o + V_D}$$  \hspace{1cm} (30)$$

By putting all the values in Equation (30), one gets

$$D_{\text{max}} = 0.641 \approx 0.64$$  \hspace{1cm} (31)$$
5.2 Inductor selection

Conventionally, the peak to peak ripple current is considered to be 20% to 40% of the maximum input current \( I_{pv} \) at the minimum input voltage \( V_{pv(min)} \). Here, the peak to peak ripple current is considered to be 20%. The ripple current flowing in \( L_{in} \) and \( L_o \) can be calculated as:

\[
\Delta I_L = I_{pv} \times 20\% = I_o \times \frac{V_o}{V_{pv(min)}} \times 20\% \quad (32)
\]

By putting all the values in Equation (32), one gets

\[
\Delta I_L = 0.8004 \, \text{A} \approx 0.8 \, \text{A} \quad (33)
\]

Thereby, the value of inductor is chosen for CCM operation as:

\[
L_{in} = L_o \geq \frac{V_{pv(min)} \times D_{max}}{\Delta I_L \times f_s} \quad (34)
\]

By putting the value of \( \Delta I_L \) from Equation (33) into Equation (34), we get the values of inductors as:

\[
L_{in} = L_o \geq 160 \, \mu\text{H} \quad (35)
\]

In this paper the value of inductor \( L_{in} = L_o = 180 \, \mu\text{H} \) is chosen for simulation and experimental validation.

5.3 Output capacitor selection

The value of output capacitor is calculated by considering the output voltage ripple \( V_{ro} = 0.3 \, \text{V} \)

\[
C_o \geq \frac{I_o \times D_{max}}{V_{ro} \times 0.5 \times f_s} \quad (36)
\]

\[
C_o \geq 196 \, \mu\text{F} \quad (37)
\]

The value of \( C_o = 220 \, \mu\text{F} \) is selected for proposed SEPIC converter.

5.4 Coupling capacitor selection

The value of coupling capacitor \( C \) is calculated by considering the ripple voltage on \( C \) as \( V_r = 1.3 \, \text{V} \). Then

\[
C = \frac{I_o \times D_{max}}{V_r \times 0.5 \times f_s} \quad (38)
\]

\[
C = 45.29 \, \mu\text{F} \quad (39)
\]
The coupling capacitor $C = 47 \mu F$ is selected which meets the RMS current requirement that produce the small ripple voltage on $C$.

### 5.5 Input capacitor selection

The inductor $L_{in}$ is connected at the input side of the SEPIC converter. Due to this inductor the input current waveform is triangular and continuous. The inductor makes sure that the current passes through the input capacitor $C_{in}$ must have low ripples. The RMS current in the input capacitor is given by

$$I_{in(rms)} = \frac{\Delta I}{\sqrt{12}}$$

The input capacitor $C_{in}$ is selected based on the RMS current handling capability. Although in SEPI converter $C_{in}$ is not so critical, a considerable capacitor value $C_{in} = 440 \mu F$ or higher would prevent impedance interactions with input supply.

### 6 SIMULATION RESULTS

The PV module model number ELDROA 40P in MATLAB Simulink [5] is used for simulation of the PV system as given in Figure 7 and MATLAB function block is used for programming of proposed algorithm. The electrical parameters of this module are $V_{oc} = 21.9 \text{ V}$, $I_{sc} = 2.45 \text{ A}$, $V_{mpp} = 17.4 \text{ V}$ and $I_{mpp} = 2.3 \text{ A}$. The SEPI converter used in the simulation has the components as follows: $L_{in} = 180 \mu H$, $L_o = 180 \mu H$, $C_{in} = 440 \mu F$, $C = 47 \mu F$, $C_o = 220 \mu F$, load $R = 5 \Omega$, and switching frequency $f_s = 50 \text{ kHz}$.

#### 6.1 Comparison between fixed and adaptive step-size

The proposed MPPT technique is first verified by considering FSS ($\Delta D = 0.005$ and sampling time ($T_s$) = 20 ms, whereas $\Delta D_{min} = 0.005$ is chosen for adaptive step-size (ASS) technique [21]. The tracking performance for a decrease in insolation from 800 to 500 W/m$^2$ at 1 s with the FSS and ASS techniques are shown in Figure 8. The variation in PV current with respect to the change in insolation is shown in Figure 8(a). It is clear that both the techniques are effectively converges to the MPP, but the convergence time is quite large with the FSS ($\Delta D = 0.005$) technique. It can also be seen that the convergence time with the FSS technique during transient period for $G = 800 \text{ W/m}^2$ is $T_1 = 720 \text{ ms}$, and the convergence time is reduced to $T_1 = 60 \text{ ms}$ for the adaptive technique. Similarly, the convergence time $T_2$ is reduced to 112 from 278 ms with the ASS technique as compared to the FSS technique for a decrease in insolation from $G = 800$ to 500 W/m$^2$ at 1 s. The corresponding PV voltage

**FIGURE 8** Convergence response of CSB MPPT technique using fixed and adaptive step-size with resistive load. (a) PV Current $I_{pv}$ (b) PV Voltage $V_{pv}$ (c) PV Power $P_{pv}$ (d) Duty-cycle $D$
and PV power are shown in Figure 8(b,c), respectively. From PV power waveform, it can be observed that the steady-state oscillation is less, hence the steady-state power loss is reduced. From Figure 8(d), it can be seen that \( D \) is oscillating between two-levels at steady-state, and due to this the power loss is less compared to the three level method such as P&O as it is shown in ref. [21]. From the tracking performance given in Figure 8, it can be noticed that both the transient and the steady-state responses are improved for the proposed ASS technique.

### 6.2 Comparison between current and voltage sensor based MPPT techniques

In [21], a voltage sensor based (VSB) MPPT technique is proposed for the SEPIC converter. In this method, only PV module voltage \( V_{pv} \) is sensed for MPP tracking and the switching function \( (Q) \) has been derived in Equation (41) to implement this algorithm, where

\[
Q = \begin{cases} 
  D(1 - D)dV_{pv} + V_{pv}dD & \text{if } >0, \text{ on left of MPP} \\
  0, & \text{at MPP} \\
  <0, \text{ on right of MPP} 
\end{cases}
\]

(41)

For both the voltage and the current sensor based MPPT, the following operating conditions are considered: FSS \( \Delta D = 0.005 \), insolation \( G = 800 \text{ W/m}^2 \). From Figure 9(a,b), it can be observed that the oscillations around MPP at steady-state is much smaller for current sensor based MPPT compared to the VSB one. For the current sensor based one, the power level is always above 30.1 W, whereas for the voltage based one, the power level goes much below to 30.1 W. The comparison of dynamic performance of both the MPPT techniques for the same operating condition is shown in Figure 10. The MPP convergence time of current sensor based technique is \( T_i = 720 \text{ ms} \) which is smaller than the convergence time of VSB technique \( T_v = 780 \text{ ms} \). It is observed that the current sensor based technique is faster than the VSB technique.

Figure 11 shows a comparison of \( S \) and \( Q \) variation with respect to \( D \). From Figure 11, it can be observed that the switching function \( S \) (for the current sensor) is more regular around the MPP with a saturation characteristic visible. Moreover, it is considerably uniform (large constant value) on the right side of the MPP in comparison to the irregular variation in \( Q \) (for voltage based). Hence, it is expected that the switching function \( S \) will work better than \( Q \) for large change in insolation.

### 6.3 Simulation results with different operating conditions

The simulation results with different loads are shown in Figures 12 and 13 for uniform insolation level \( G = 800 \text{ W/m}^2 \) and temperature \( T_{emp} = 43^\circ \text{C} \). The generated PV power shown in Figure 12 is same for all the loads. It is also clear that the
The proposed CSB technique is able to track the MPP for different load conditions and the MPP convergence time is same irrespective of the loads. From Figure 13, it is clear that the load power $P_o$ is different for all the loads. The load power increases with increase in the load resistance due to the varying efficiency of the converter. For series RL and parallel RC loads, the PV power variations are shown in Figure 14. It is clear that, for both the RL and RC loads, responses are same as the resistive one in Figure 12. However there are small changes in the transient response, though the settling times are almost similar.

The simulation result with variable temperature is given in Figure 15 for uniform insolation level $G = 800 \text{ W/m}^2$. Any PV module generates maximum power at standard test condition ($G = 1000 \text{ W/m}^2$ and temperature $T_{\text{emp}} = 25 \degree\text{C}$). It can be observed that the PV power $P_{pv}$ increases with decrease in temperature.

The proposed CSB MPPT technique is also studied for different switching frequencies and the resulted PV power is shown in Figure 16. It can be observed that the PV power is almost same for these frequencies. The average PV power is different due to oscillations around the MPP at the steady-state.

### 6.4 Performance comparison

A performance comparison with a recent technique [36] that uses SEPIC converter and adaptive technique step-size is made in this section. Note that results in ref. [36] considered SEPIC converter for impedance matching, adaptive nature of step-size and tested for change in insolation-levels, that are similar to the method adopted in this paper. The only difference between the work in this paper and ref. [36] is the MPPT algorithm. This technique in ref. [36] based on two fixed step-size, one is large step-size $\Delta D_{LS}$ and other is small step-size $\Delta D_{SS}$. Two step-sizes are considered for the adaptation purpose. A large step-size is chosen when the operating point is far from the MPP, say area $A$, to improve the MPP tracking time, and small step-size is considered when the operating point nearing the MPP, say area $B$, to reduce the oscillation at steady-state. Hence, this is not a true adaptive MPPT technique. The operating area $B$ is detected by the following condition [36]:

$$\frac{|\Delta P_{pv}|}{|\Delta T_{pv}|} \leq Z \quad (42)$$
Another important condition is defined to detect large variation in either load or insolation as [36]:

$$\frac{\Delta I_{pv}}{\Delta V_{pv}} + \frac{I_{pv}}{V_{pv}} < E$$  \hspace{1cm} (43)

In this paper, for the sake of comparison, the result of [36] is also simulated with $Z = 1.64$ and $E = 0.1092$ calculated from Equations (42) and (43), respectively, for change in insolation level from $G = 0$ to 800 W/m$^2$. The large step-size $\Delta D_L = 0.03$ and small step-size $\Delta D_{SS} = 0.005$ are considered. The PV power convergence responses for enhanced auto-scaling incremental conductance (EAS IncCond) MPPT [36] and CSB MPPT with ASS are shown in Figure 17, it can be seen that the MPP convergence time for EAS IncCond technique $T_2 = 140$ ms, which is larger than the convergence time for CSB (ASS) technique $T_1 = 60$ ms. This is due to the fixed step-size (though overall adaptive) used for the transient period, hence the convergence depends on how large step-size is chosen. From Figure 18, it can be seen that the EAS IncCond MPPT technique has three-level operation around MPP, whereas the CSB MPPT technique have two-level operation. It is shown in ref. [21] that two-level operation is beneficial. Due to this, the oscillation around MPP in PV power is less with the proposed technique as compared to the EAS IncCond technique and this can be seen in Figure 17.

Next, a comparison of efficiencies is made. The average MPP tracking efficiency $\eta_{mpp(\text{avg})}$ is calculated as [36]:

$$\eta_{mpp(\text{avg})} = \frac{P_{\text{mpp(\text{avg})}}}{P^{*}_{\text{mpp(\text{avg})}}} \times 100 \; \text{ (44)}$$

where $P_{\text{mpp(\text{avg})}}$ is the extracted average maximum power from the PV module. $P^{*}_{\text{mpp(\text{avg})}}$ is the available average maximum PV power. For insolation level $G = 800$ W/m$^2$, it is 30.28 W. The PV power reaches at steady-state after time $t = 0.14$ s for both the techniques as shown in Figure 17. Hence, the values of $P_{\text{mpp(\text{avg})}}$ and the corresponding average efficiencies $\eta_{mpp(\text{avg})}$ are calculated for the time ranges $t = 0$ to 0.2 s and $t = 0.2$ to 1.0 s to differentiate between the transient and steady-state efficiencies as shown in Table 2. It can be observed that the average efficiency is improved with the proposed adaptive step-size CSB MPPT technique considerably during transient-state, whereas the average efficiency is almost similar at steady-state since the small step-size $\Delta D_{SS}$ and minimum step-size $\Delta D_{\text{min}}$ are same for the two techniques.

A comparison of PV power for CSB (ASS) MPPT technique and EAS IncCond MPPT technique with battery load (12 V, 7 Ah) is shown in Figure 19. It can be observed that the MPP convergence times $T_1 = 40$ ms and $T_2 = 100$ ms with battery load are reduced as compared to the convergence time with resistive load shown in Figure 17. This is because the SEPIC converter works in buck-mode as the battery voltage is less than the $V_{mpp}$. Hence the average tracking efficiencies are improved at transient-state due to the reduced tracking time and almost similar at steady-state as compared to resistive load. This shows that the proposed MPPT technique performs well for battery load as well.

### Table 2: Comparison of CSB (ASS) MPPT with enhanced auto scaling IncCond MPPT technique

| Parameters          | EAS IncCond [36] | CSB (ASS) |
|---------------------|-----------------|-----------|
| Sensors             | Voltage ($V$) & Current ($I$) | Current ($I$) |
| Steady state operation | 3-level          | 2-level   |
| Complexity          | Medium           | Low       |
| Adaptive step-size $\Delta D$ | $\Delta D_L = 0.03$ & $\Delta D_{SS} = 0.005$ | $\alpha = 0.5$ [S] |
| Convergence time    | $T_2 = 140$ ms  | $T_1 = 60$ ms |
| $P_{\text{mpp(\text{avg})}}$ (0–0.2 s) | 23.4054 W | 26.8450 W |
| $\eta_{mpp(\text{avg})}$ (0–0.2 s) | 77.30% | 88.65% |
| $P_{\text{mpp(\text{avg})}}$ (0.2–1 s) | 30.1174 W | 30.1968 W |
| $\eta_{mpp(\text{avg})}$ (0.2–1 s) | 99.46% | 99.73% |

![Figure 17](image17.png) Comparison of adaptive current sensor based MPPT technique and enhanced auto scaling IncCond MPPT technique with resistive load

![Figure 18](image18.png) Comparison of duty-cycle at steady state for CSB (ASS) MPPT and EAS IncCond MPPT techniques
EXPERIMENTAL SETUP AND VALIDATION

To verify the tracking performance and functionality of the current sensor based technique, an experimental model of the SEPIC converter with controller circuit is designed in laboratory. The converter have the same parameters as given in Section 6. An ARDUINO UNO controller has been considered for implementation of the proposed technique and to provide the desired switching signal to the converter. The experimental setup of the PV system is shown in Figure 20.

To implement the current sensor based technique, current measurement is required. The current is measured using LEM LTS6-NP hall effect current transducer. An IRFIZ44N power MOSFET, STPS2045CT power Schottky diode and HCPL3120 gate driver ICs are used for SEPIC converter design. An ELDORA 40P PV model having the same parameters as given in Section 6 is used to perform the experiment and halogen lamps are used for artificial insolation. The insolation of light is controlled by manual switches and the insolation is measured by using the solar power meter WACO 206.

The current sensor based MPPT technique with the fixed and ASS techniques are compared for a change in insolation. The start-up tracking performance with the FSS technique for a change in solar insolation level approximately from $G = 500$ to $800$ W/m$^2$ and from $G = 800$ to $500$ W/m$^2$ are given in Figure 21(b,c), respectively. It can be observed that the convergence time to reach at MPP are $T_2 = 2000$ ms and $T_3 = 1300$ ms, respectively. Similarly, the tracking performance with ASS technique corresponding to start-up and change in solar insolation levels approximately from $G = 500$ to $800$ W/m$^2$ and from $G = 800$ to $500$ W/m$^2$ are shown in Figure 22(a–c), respectively. From Figure 22, it can be observed that the convergence time $T_1$ is reduced to 1000 from 2500 ms, $T_2$ is reduced to 600 from 2000 ms and $T_3$ is reduced to 550 from 1300 ms with the ASS technique compared to the FSS technique. Thus, the ASS technique is effective in terms of reduced convergence time.

For evaluation of the steady-state performance of the proposed technique, experiments are performed with sampling time $T_s = 1$ s, and the corresponding waveforms are shown in Figure 23. It can be observed that the proposed MPPT technique is giving two-level operation during steady-state, which effectively reduces the steady-state power loss as compared to EAS IncCond technique [21].

The average efficiencies of the experimental results are calculated based on Equation (44) and shown in Table 3, where the value of $P_{	ext{mpp}}^{\text{avg}}$ is 30.28 W for the insolation-level 800 W/m$^2$. From Figures 21(a) and 22(a), it is clear that the PV voltage and the current reach steady-state after time $T_1 = 2.5$ s. Hence the average extracted maximum powers $P_{	ext{mpp}}(\text{avg})$ and the corresponding average efficiencies $\eta_{\text{mpp}}(\text{avg})$ is calculated for the two time ranges, one for 0 to 2.6 s and the other for 2.6 to 9 s to differentiate the transient and steady-state efficiencies as shown in Table 3. It can be observed that the efficiency $\eta_{\text{mpp}}(\text{avg})$ is considerably improved with the proposed adaptive step-size.

![Figure 19](image1.png) Comparison of adaptive current sensor based MPPT technique and enhanced auto scaling IncCond MPPT technique with battery load

![Figure 20](image2.png) Experimental model of the PV system

| Parameters | CSB (FSS) | CSB (ASS) |
|------------|-----------|-----------|
| Convergence time $T_1$ | 2500 ms | 1000 ms |
| $P_{\text{mpp}}(\text{avg})$ (0–2.6 s) | 21.8357 W | 24.9187 W |
| $\eta_{\text{mpp}}(\text{avg})$ (0–2.6 s) | 72.11% | 82.29% |
| $P_{\text{mpp}}(\text{avg})$ (2.6–9 s) | 27.9017 W | 27.9185 W |
| $\eta_{\text{mpp}}(\text{avg})$ (2.6–9 s) | 92.14% | 92.20% |
FIGURE 21 Convergence response of CSB MPPT technique using FSS with resistive load. (a) start-up at $G = 800 \, \text{W/m}^2$ (b) for increase in insolation level (c) for decrease in insolation level

FIGURE 22 Convergence response of CSB MPPT technique using ASS with resistive load. (a) start-up at $G = 800 \, \text{W/m}^2$ (b) for increase in insolation level (c) for decrease in insolation level
algorithm during both the transient and steady-state as compared to the fixed step-size one. However, it may be noted that the efficiency calculated here is based on true insolation-level of 800 W/m² though actual insolation-level may vary since the environmental condition is not ideal in the experimental setup. The efficiencies tabulated are just indicative for comparison of the two methods and does not indicate absolute efficiency of the system.

Experiments are also performed for lead-acid battery load (12 V, 7 Ah) using CSB technique with ASS and EAS IncCond [36] technique, and the corresponding convergence responses for change in insolation-level from 0 to 800 W/m² are shown in Figures 24 and 25, respectively. It is clear that both the techniques are effectively tracking the MPP point with the battery load. The SEPIC converter always operates in buck mode, because the rated battery voltage is less than the maximum power point voltage ($V_{mpp}$). Hence, the variation in the duty-cycle is less for change in insolation level, due to which the MPP convergence time (600 ms) is reduced with the battery load as compared to the resistive load (1000 ms). The average tracking efficiencies are also calculated for the results shown in Figures 24 and 25 for the two time ranges as shown in Table 4. It can be observed that the efficiencies for resistive load and battery load are almost similar for both the time ranges. Hence, the proposed technique improves the performance for battery load as well. The comparison of simulation and experimental results using CSB (ASS) MPPT technique are shown in Table 5.

8 | CONCLUSION

This paper considers the MPPT problem for PV system. A current sensor based MPPT algorithm using a novel ASS method to control the duty-cycle of SEPIC converter is proposed. Due to the linear property of current with insolation change, the proposed MPPT ensures uniform convergence compared to the voltage sensor based one. The same is validated by simulation and experimental results. The presented results show the steady-state power deviation is lesser in the current sensor based algorithm as compared to the voltage sensor based one due to the low sensitivity of the current sensor. Also, the proposed
**TABLE 5** Comparison of simulation and experimental results of CSB MPPT technique using adaptive step-size with resistive load

| Parameters                     | Simulation | Experimental |
|-------------------------------|------------|--------------|
| Convergence time              | 60 ms      | 1000 ms      |
| (0–800 W/m²)                  |            |              |
| Convergence time              | 112 ms     | 550 ms       |
| (800–500 W/m²)                |            |              |
| **P**<sub>mppt(avg)</sub> (Steady-state) | 30.1968 W  | 27.9185 W    |
| **η**<sub>mppt(avg)</sub> (Steady-state) | 99.7%      | 92.20%       |

MPPT algorithm has faster tracking time due to a new adaptive step-size scheme proposed. Hence, the proposed technique improves both the transient as well as steady-state responses. The scheme may be extended to a combined voltage and current sensor based scheme where switching function of the voltage and current sensor based algorithms can be combinedly used and benefit of both the schemes can be explored. Also, it is proposed to use this technique along with soft computing techniques for enhancing the transient response of PV systems under partial-shading conditions similar to the works in refs. [38, 39].

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