Abstract—Although solar energy is available throughout the day its insolation varies from morning to evening and with changing climatic conditions. As the efficiency of solar PV panel is low it becomes mandatory to extract maximum power from the PV panel at any given period of time. Several maximum power point tracking (MPPT) techniques are proposed for the purpose. Incremental conductance MPPT technique has higher steady-state accuracy and environmental adaptability. This paper investigates implementation issues of Incremental conductance MPPT algorithm. High frequency DC-DC Buck converter is used to interface PV panel with load. The Matlab Simulink model of the system is developed and results are validated with experimental results obtained using laboratory prototype of the system.

Keywords— Continuous Conduction Mode (CCM), DC-DC Buck Converter, Incremental Conductance (IC), Maximum Power Point Tracking (MPPT), Photovoltaic (PV)

I. INTRODUCTION

The depletion of fossil fuel resources on a worldwide basis has necessitated an urgent search for alternative energy sources to meet up the present day demands. Among all the renewable energy option solar energy is clean inexhaustible and environment friendly potential source. The harnessing of solar energy using PV modules comes with its own problems that arise from the change in insolation conditions. These changes in insolation condition severely affect the efficiency and output power of the PV modules [1].

A lot of research has been done to improve the efficiency of the PV modules. A number of methods to track the maximum power point of a PV module have been proposed to overcome the limitation of efficiency [2]. A MPPT is used for extracting the maximum power from the solar PV module and transferring that power to the load. And a dc-dc converter (step up / step down) act as an interface between the load and the PV module as it serves the purpose of transferring maximum power from the solar PV module to the load. By changing the duty cycle the load impedance is matched with source impedance to attain the maximum power from the PV panel [3]. Fig. 1 shows the basic block diagram of DC-DC Converter operating at MPP. Different maximum power point tracking algorithms have been proposed including fractional open circuit voltage, fractional short circuit current, perturb and observe (P&O), incremental conductance, and artificial-intelligence-based algorithms [4]-[5]. These algorithms may vary in there complexity, efficiency, cost, and there potential application.

In high power applications, the cost of MPPT control is low as against the cost of the photovoltaic (PV) array and power converters. However, for low power applications, the implementation cost of an MPPT algorithm is a concern [6]-[7]. The most commonly used hill-climbing MPPT technique is the P&O algorithm. The P&O algorithm perturbs the operating point of the PV generator by increasing or decreasing a control parameter by a small amount and measuring the PV array output before and after the perturbation. If the power increases, the algorithm continues to perturb the system in the same direction; otherwise the system is perturbed in the opposite direction [8].

Another very popular hill-climbing MPPT algorithm is the incremental conductance. This MPPT algorithm is based on the fact that the power-voltage curve of a PV generator at constant solar insolation and cell temperature levels has normally only one MPP [9]-[10]. At this point the derivative of the power with respect to the voltage equals zero which means that the sum of instantaneous conductance (\(I_{pv}/V_{pv}\)) and the incremental conductance (\(dI_{pv}/dV_{pv}\)) equals zero. On the right-hand side of the MPP, the sum of the instantaneous conductance is negative while on the left-hand side of the MPP, the sum is positive. The incremental conductance algorithm compares the instantaneous conductance of a PV generator with its incremental conductance and decides whether to increase or decrease a control parameter accordingly [11]. An improved MPPT algorithm for PV sources was proposed to reduce the tracking time where a dc-dc boost converter was used to track the MPP and was brought out that tracking performance depends upon the tracking algorithm used [12]. In this paper, the tracking capability of incremental with buck converter conductance at different insolation level is presented and the simulation results are verified with the experimental results.
II. MODELING AND CHARACTERISTICS OF PV MODULE

The phenomenon named ‘photovoltaic effect’ consists mainly transforming the solar light in electric energy by means of the semiconductor devices named photovoltaic cells. Fig. 2 shows the equivalent circuit diagram of a single solar cell. Here, $I_{ph}$ is the photo current source with a reverse connected diode. $R_s$ and $R_{sh}$ are series and shunt resistance respectively. As the value of $R_{sh}$ is very large it is neglected in the analysis [13].

$$I = I_{ph} - I_d$$

$$I_d = I_0(e^{Vd/RT} - 1)$$

Where $I_o$ is the reverse saturation current of the diode, q is the electron charge, $V_d$ is the voltage across the diode, K is Boltzmann constant $1.38 \times 10^{-19} J/K$ and T is the junction temperature in Kelvin (K).

Substituting eq. (2) in (1) gives

$$I = I_{ph} - I_o(e^{Vd/RT} - 1)$$

Substituting voltage across diode $V_d = \left(\frac{V + IR_s}{N}\right)$ in eq. (3) gives

$$I = I_{ph} - I_o(e^{(V + IR_s)/NRT} - 1)$$

Where, V is the PV cell voltage, T is the temperature (in Kelvin) and N is the diode ideality factor [1]. The typical I-V and P-V characteristics of the PV module are shown in Fig. 3 & 4.
Here, Short-circuit current \((I_{sc})\) is the maximum output current, open-circuit voltage \((V_{oc})\) is the maximum output voltage, MPP current \((I_{m})\) is the maximum power point current, MPP voltage \((V_{m})\) is the maximum power point voltage and MPP Power \((P_{m})\) is the power at maximum power point these all values are at certain sunlight and temperature of the PV module.

III. DC-DC BUCK CONVERTER

The dc-dc buck converter converts a higher dc input voltage to lower dc output voltage. The basic dc-dc buck converter topology is shown in Fig. 5. It consists of a controlled switch \(S_w\), an uncontrolled switch diode \((D)\), an inductor \((L)\), an capacitance \((C)\) and a load resistance \((R)\) \([14]\).

In the description of converter operation it is assumed that all the components are ideal and also the converter operates in Continuous conduction mode (CCM). In CCM operation the inductor current flows continuously over one switching period. The switch is either ON or OFF according to the switching position this results in two circuit states. The first sub-circuit state is when the switch is turned ON, the diode is reverse biased and inductor current flows through the switch, which can be shown in Fig. 6(a). The second sub-circuit state is when the switch is turned OFF and current freewheels through the diode \([15-16]\) which is shown in Fig. 6(b).

When switch \(S_w\) is ON and D is reverse biased, then inductor current \(i_L\) and capacitor voltage \(V_C\) are given by eq. (5) and (6).

\[
\frac{di_L}{dt} = \frac{1}{L} V_g - V_o \tag{5}
\]

\[
\frac{dv_o}{dt} = \frac{dv_c}{dt} = \frac{1}{C} i_c \tag{6}
\]

When the switch is OFF and D is forward biased, \(i_L\) and capacitor voltage \(V_C\) are given by eq. (7) and (8).

\[
\frac{di_c}{dt} = -\frac{1}{L} V_0 \tag{7}
\]

\[
\frac{dv_o}{dt} = \frac{dv_c}{dt} = \frac{1}{C} i_c \tag{8}
\]

The state space representation for converter circuit configuration can be expressed as given in eq. (9)
\[ \frac{dx}{dt} = \begin{cases} A_1 x + B_1 U & \text{when Sw is closed} \\ A_2 x + B_2 U & \text{when Sw is opened} \end{cases} \]

Where \( x = [x_1 \ x_2]^T = [V_c \ i_L]^T \) (9)

The state transition matrix \( A \) and \( B \) input matrix are system matrices as shown in eq. (10)

\[
A_1 = A_2 = \begin{bmatrix}
-\frac{1}{L} \left( \frac{r_c + a \alpha_c}{R} \right) & -\frac{a}{RL} \\
\frac{1}{C} \left( \frac{1 - a \alpha_c}{R} \right) & -\frac{a}{RC}
\end{bmatrix},
B_1 = \begin{bmatrix}
\frac{1}{L} \\
0
\end{bmatrix},
B_2 = \begin{bmatrix}
0 \\
0
\end{bmatrix}
\]

Where \( a = \frac{R}{R + r_c} \)

IV. INCREMENTAL CONDUCTANCE MPPT ALGORITHM

A typical solar panel converts about 30-40\% of the incident solar insolation in to electrical energy [17]. Maximum power point tracking technique is used to improve the efficiency of the solar panel. According to maximum power transfer theorem, the power output of a circuit is maximum when the Thevenin impedance of the circuit (source impedance) matches with the load impedance. Hence the problem of tracking the maximum power point reduces to an impedance matching problem. There are several techniques to track the MPPT but this paper deal with Incremental conductance.

A. Incremental Conductance Algorithm

Incremental Conductance method uses the information of source voltage and current to find the desired operating point. From the P-V curve of a PV module shown in Fig. 4 it is clear that slope is zero at maximum point [17], so the formulas are as follows

\[
\left( \frac{dP}{dV} \right)_{\text{mpp}} = \left( \frac{d(VI)}{dV} \right)_{\text{m}}
\] (11)

\[
0 = I + V \left( \frac{dI}{dV} \right)_{\text{MPP}}
\] (12)

\[
\left( \frac{dI}{dV} \right)_{\text{MPP}} = -\frac{I}{V}
\] (13)

Equation (13) is the condition to achieve the maximum power point, when the variance of the output conductance is equal to the negative of the output conductance, the module will work at the maximum power point. The flow chart of the incremental conductance is shown in Fig. 7 [12].

![Flow chart of the Incremental Conductance method](Image)

In this flow chart, \( V(k) \) is the new detection voltage and \( I(k) \) is the new detection current, \( V(k-1) \) and \( I(k-1) \) is previous detection values. When the new value is read in to the program, it calculates the previous value compare with the new one, and then determine the voltage differentials is zero or not, according the voltage differentials is zero, the current differentials can be determined zero or not. If both of them are zero, it shows that they have the same value of impedance and the value of duty ratio will remain the same as before. If the voltage differential is zero, but the current differential is not zero, it shows that the insolation has changed. When the difference of the current values is greater than zero, duty ratio will increase, when the difference of the current value is less than zero the duty ratio will decrease. If the voltage differential is not zero
determine it whether satisfy the eq. 13 or not, when eq. 13 is satisfied the slope of the power curve will be zero that means the system is operating at MPP, if the variance of conductance is greater than the negative conductance values, it means the slope of the power curve is positive and the duty ratio is to be increased, otherwise it should be decreased [18].

The motive is to automatically find the voltage $V_{MPP}$ or current $I_{MPP}$ at which a PV module should operate to obtain the maximum power output $P_{MPP}$ under a given temperature and irradiance. As switch-mode dc-dc converter is used as intermediate power processor, it changes the values of current and voltage levels such that maximum power can be extracted from a PV module. A buck converter can be used to maximize the power transfer through the use of impedance matching. An application of this is in a maximum power point tracking commonly used in photovoltaic system.

For electric power eq. (14) is as follow

$$V_0I_0 = \eta V_g I_g$$  \hspace{1cm} (14)

Where:-

- $V_0$ is the output voltage, $I_0$ is the output current,
- $\eta$ is the power efficiency (ranging from 0 to 1), $V_g$ is the input voltage, $I_g$ is the input current

By ohm’s law

$$I_0 = \frac{V_0}{Z_0}$$

$$I_g = \frac{V_g}{Z_i}$$  \hspace{1cm} (15)

Where $Z_0$ is the output impedance, $Z_i$ is the input impedance.

Substituting these expressions for $I_0$ and $I_g$ in to the power equation (14) yields:

$$\frac{V_0^2}{Z_0} = \frac{\eta V_g^2}{Z_i}$$  \hspace{1cm} (16)

As we know that for the continuous mode, (where $I_L > 0$)

$$V_0 = DV_g$$  \hspace{1cm} (17)

Where, $D$ is the duty cycle

Substituting the value of $V_0$ in eq. (16) we get:

$$\left(\frac{DV_g}{Z_0}\right)^2 = \frac{\eta V_g^2}{Z_i}$$

This reduces eq. (18) to

$$\frac{D^2}{Z_0} = \frac{\eta}{Z_i}$$  \hspace{1cm} (19)

And finally

$$D = \sqrt{\frac{\eta Z_0}{Z_i}}$$  \hspace{1cm} (20)

The eq. (20) shows that it is possible to adjust the impedance ratio by adjusting the duty cycle. This is very useful in calculating the MPPT because insolation changes very dynamically.

<table>
<thead>
<tr>
<th>PV panel parameters</th>
<th>Values</th>
</tr>
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<tbody>
<tr>
<td>Voc</td>
<td>22.04V</td>
</tr>
<tr>
<td>Isc</td>
<td>1.13A</td>
</tr>
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<td>Pmax.</td>
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<td>Impp</td>
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<td>Tolerance</td>
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V. RESULTS & DISCUSSION

The Matlab Simulink model of the complete system is shown in Fig. 8. The complete model is divided in to three parts for easy understanding i.e. PV model, IC MPPT method & DC-DC Buck converter, in PV panel total of 36 individual cells are connected in series to yield a voltage $V_{PV} = 18V$. The I-V and P-V characteristics of the model under varying solar insolation condition with fixed ambient temperature are shown in Fig. (9) & (10) respectively. It is observed that both open circuit voltage
and short-circuit current gets reduced at lower solar insolation levels.

The power system block set model of DC-DC buck converter supplied with PV panel is shown in Fig. 11. The duty ratio for the converter is decided by the MPPT algorithm based on the solar insolation and prevailing ambient condition. The dc-dc buck converter is designed to operate at 25 kHz.

Fig. 12 shows the change in solar insolation from 500 w/m² to 1000 w/m² at 25°C. The variation in input power and voltage is shown in Fig. 13&14 respectively. The variation in output power, voltage and current is shown in Fig. 15, 16 & 17 respectively.

Fig. 8 Simulink block diagram of complete PV system

Fig. 9 Characteristic curve of (Ipv-Vpv) at different solar insolation

Fig. 10 Characteristics curve of (Ppv-Vpv) at different solar insolation

Fig. 11 INC MPPT simulation setup

Fig. 12 Change is solar insolation
A fixed resistance of $R_L = 4.5$ ohm is connected across the load side of the buck converter to match the input resistance $R_{in}$ because for the buck converter input resistance is always greater than the load resistance and the relation of input resistance with load resistance and duty ratio is given by eq. (21).

$$R_{in} = \frac{R_L}{D^2} \quad (21)$$

At simulation time 0.06 there is an increase in solar insolation from 500 w/m$^2$ to 1000 w/m$^2$ and it is clear from the above Fig. (13-16) that output voltage is decreasing and output current is increasing and from Fig. 17 it is also clear that at simulation time 0.06 when insolation are changing the duty ratio is adjusting itself to produce maximum power at different insolation.
To verify proposed theory a laboratory prototype PV system is constructed as shown in fig. 18. The artificial sun is realized by the incandescent lamp set and the solar insolation on the PV panel is changed by changing the magnitude of AC supply voltage. The prototype converter circuit parameter values are: $L=150\mu H$, $C=50\mu F$. The semiconductor devices used for making DC-DC buck converter are an International rectifier IRF 540 Power mosfet, a Motorola MUR 840 fast recovery diode. An international rectifier IR2110 gate driver drives the switching device Mosfet. IC 6N136 is used for isolation purpose.

In Fig. 15 and fig. 17 shows the output voltage and duty ratio values for MPPT. Experimental results shown in Fig. 18 also verify the IC algorithm, as it is clear from the Fig. 19 for the duty ratio 58% and input voltage of 18 volt the achieved output voltage is 8.10 Volt. This verifies the laboratory prototype model results with the Simulation results.

VI. CONCLUSION

A standalone PV system connected with buck converter and IC algorithm for extracting maximum power at different environmental condition is proposed. We realize that the basic function of DC-DC converter in PV system is like intermediate power processor which changes the current and voltage levels such that maximum power can be extracted from the PV array. Changing voltage and current level is nothing but converting a given fixed load to a variable load. Hence the results obtained at different environmental condition are found to be satisfactory as they validate the experimental results too. MPPT algorithm responds in very fast manner and its accuracy is higher that it reaches to steady state very quickly.

ACKNOWLEDGMENT

The authors sincerely thank Director MITS, Gwalior, India for his support during this research work.

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