Implementation of Incremental Conductance based Maximum Power Point Tracking for Standalone Photovoltaic System

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***Abstract*—This paper presents design of the PV (Photovoltaic) array and implementation of the IC (Incremental Conductance) based MPPT (Maximum Power Point Tracking) for the stand alone system. The effect on the I-V and P-V curves of the PV array is investigated for different atmospheric conditions i.e. different insolation and temperature values. The performance of IC based MPPT is also analyzed for different atmospheric and for different load conditions. The system is simulated in the simulink/matlab and results are presented.**

***Keywords*— Incremental conductance; MPPT; Insolation.**

I. INTRODUCTION

Solar cell is a semiconductor device which converts sunlight into electricity by using photovoltaic effect. So it can also be called as photovoltaic (PV) cell. The cost of the PV array is high and the conversion efficiency of light to electricity is very less [1]. So it is necessary to extract as much energy as possible from the system to make a PV module is more useful. A PV module is used efficiently only when it is made to operate at its optimal operating point. The amount of power that can be extracted from the array is depending on the operating voltage of that array. At any moment the operating point of a PV array depends on insolation levels, temperature [2] and the load of the system. The atmospheric conditions and load variables are changing constantly making it very difficult to extract all of the solar energy available from panels without a controlled system. With the use of maximum power point tracking algorithms along with power electronic converters maximum power is extracted from the array. There are different techniques present in the literature for tracking MPP [3]. In this paper IC based MPPT is presented. It gives a true MPPT and the operating point does not oscillates around the MPP [4], as in case of P&O based MPPT operating point oscillates around the MPP. IC based MPPT gives better tracking performance for fast changing atmospheric conditions.

II. MATHEMATICAL MODELING OF PV ARRAY

For modeling the PV array first it is necessary to model the PV cell [5]. The following terminology is used for modeling the PV array.

- ***PV Module*** is a collection of PV cells, mainly connected in series.
- ***PV Module String*** is a series connected PV Modules.
- ***PV Array*** is a parallel connected PV Module Strings.
- ***Insolation (G)*** is the rate at which solar energy received by the earth on a unit surface expressed in W/m^2.
- ***Short circuit current (I_{sc}):*** It is the maximum current the solar cell can produce. It mainly depends up on insolation and area of the solar cell. The short circuit current density of a solar cell is around $35mA/cm^2$.
- ***Open circuit voltage (V_{oc}):*** It is the maximum voltage that a solar cell can produce. Its value depends up on the operating temperature of the cell. The open circuit voltage of solar cell is around 0.5-0.7 V
- ***Maximum power point (P_{mp}):*** It is the maximum power that a solar cell produces under **S**tandard **T**est **C**onditions (STC) i.e. $G=1000W/m^2$ and $T=25^0C$.
- The voltage and currents corresponding to maximum power is expressed as V_{mp} and I_{mp} respectively.

Based up on the voltage requirements PV modules are connected in series and can be called as PV module string. Based up on the current requirements the group of PV module strings are connected in parallel and it can be called as PV array. Ideal electrical equivalent circuit PV cell consists of a current source in parallel with anti-parallel diode. But in practical some losses are present in the PV cell [1]. To represent those losses series and shunt resistances (R_s& R_{sh}) are included in the circuit. Fig. 1 represents electrical the equivalent circuit of a practical PV cell.

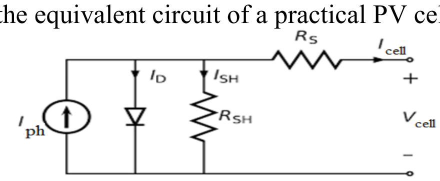

Fig.1. Electrical equivalent circuit of PV cell

From the above circuit output current (I_{cell}) of the cell is given by

$$I_{cell} = I_{Ph} - I_D - I_{Sh} \quad (1)$$

Where, I_{ph} is the photon current whose magnitude depends upon solar insolation (G) and Temperature (T). I_D and I_{sh} are the diode and shunt branch currents respectively.

Where,

$$I_{ph} = \frac{G}{G_{ref}}\left[I_{sc,ref} + C_{I_{sc}}\left(T - T_{ref}\right)\right] \quad (2)$$

$$I_D = I_O\left(e^{\frac{q(V_{cell}+I_{cell}R_S)}{\eta KT}} - 1\right) \quad (3)$$

$$I_{Sh} = \frac{V_{cell}+I_{cell}R_S}{R_{Sh}} \quad (4)$$

G =Solar insolation (W/m^2)
T =Operating temperature (°C)
G_{ref} =Reference value of solar insolation (G_{ref}=1000W/m^2)
T_{ref} =Reference value of temperature (T_{ref}=25°C)
$I_{sc,ref}$ =Short circuit current of a cell referred to T_{ref} and G_{ref}
C_{Isc} =Solar cell short circuit temperature coefficient
I_o =Reverse saturation current of diode (A)
V_{cell} =Output voltage of a cell
I_{cell} =Output current of a cell
η =Diode ideality factor (1-3)
K =Boltzmann constant, $1.38\text{x}10^{-23} J/K$
R_s =Series resistance
R_{sh} =Shunt resistance

Let us assume that if the operating temperature is equal to the reference temperature the term $C_{I_{sc}}(T - T_{ref})$ is equal to zero and the remaining equation can be written as I_{ph} α G. So the photon current of the cell is directly proportional to the solar insolation G. Under short circuited condition the current through the short circuited path is I_{sc}=I_{ph}-I_D. And it can be written as I_{sc} α I_{ph} α G, so short circuited current of the solar cell is directly proportional to the photon current, which in turn depends up on the insolation value G. Substituting equations 2,3 and 4 in 1 and rearranging the terms results the following equation.

$$I_{cell} = I_{ph} - I_O\left(e^{\frac{q(V_{cell}+I_{cell}R_S)}{\eta KT}} - 1\right) - \frac{V_{cell}+I_{cell}.R_S}{R_{Sh}} \quad (5)$$

Under open circuit condition I_{cell}=0 and V_{cell} =V_{oc}. The term V_{oc}/R_{sh} is negligibly small because the value of $R_{sh}$is very high. The generated photon current is flown through the diode. That is given by

$$I_{ph}=I_O\left(e^{\frac{qV_{OC}}{\eta KT}} - 1\right) \quad (6)$$

(Or) $$V_{oc}=\frac{\eta KT}{q}\ln\left(\frac{I_{ph}}{I_O} + 1\right) \quad (7)$$

(Or) $$V_{oc} \,\alpha\, \ln(I_{ph}) \quad (8)$$

(Or) $$V_{oc} \,\alpha\, \ln(G) \quad (9)$$

From the equations (8) and (9) open circuit voltage lowery depends up on photon current I_{ph} or the insolation value G. So the open circuit voltage V_{oc} will not change much even the change in insolation.

The output current of an PV array I for connecting N_s number of modules in series and N_p number modules strings in parallel can be expressed as (In the equation current through R_{sh} is neglected for the sake of simplicity)

$$I = N_P\left\{I_{Ph} - I_O\left(e^{\frac{q(V_{cell}+I_{cell}R_S)}{\eta KTN_S}} - 1\right)\right\} \quad (10)$$

III. INCREMENTAL CONDUCTANCE (IC) METHOD MPPT

The object of maximum power point tracking is to adjust the actual operating voltage of array according to the voltage corresponding to maximum power [3]. The basic idea of IC based MPPT is, at the maximum power operating point the derivative of the power with respect to the voltage is equal to zero. From Fig.5 note that to the left of the MPP the power is increasing with the voltage, i.e. dP/dV > *0,* and it is decreasing to the right of the MPP, i.e. dP/dV< 0. This can be rewritten in the following equations

$$\frac{dP}{dV} = 0 \text{ at the MPP} \quad (11)$$

$$\frac{dP}{dV} > 0 \text{ to the left of the MPP} \quad (12)$$

$$\frac{dP}{dV} < 0 \text{ to the right of the MPP} \quad (13)$$

These equations can be written in terms of the array current and voltage using

$$\frac{dP}{dV} = \frac{d}{dV}(IV) = I + V\frac{dI}{dV} \quad (14)$$

$$\frac{dI}{dV} = -\frac{I}{V}\left(\frac{dP}{dV} = 0\right) \text{ at MPP} \quad (15)$$

$$\frac{dI}{dV} > -\frac{I}{V}\left(\frac{dP}{dV} > 0\right) \text{ left of MPP} \quad (16)$$

$$\frac{dI}{dV} < -\frac{I}{V}\left(\frac{dP}{dV} < 0\right) \text{ right of MPP} \quad (17)$$

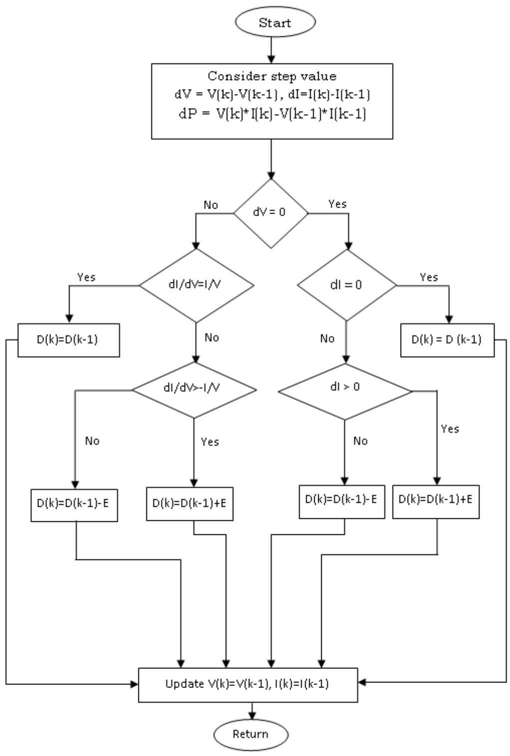

Fig.2. Flow chart for IC based MPPT

Hence, the PV array terminal voltage can be adjusted relative to the MPP voltage by measuring the incremental and instantaneous array conductance's *(dI/dV* and *I/V,* respectively) and making use of equations (15-17). Fig.2 represents the complete operation of the incremental Conductance algorithm. In this algorithm the incremental changes are represented as the difference between present values I(k),V(k) and the corresponding values stored at the end of the preceding cycle, *I(k-1)* and *V(k-1)* i.e. *dI=I(k)-I(k-1)* and *dV = V(k) – V(k-1)*. In the algorithm, mainly the *search* is carried out by comparing *dI/dV* against - *I / V*. The array terminal voltage will be shifted towards MPP voltage by adjusting the control reference signal D based on this search. At the MPP, *dI/dV = - I/V,* no control action is needed, therefore the adjustment stage will be by passed and the algorithm will update the stored parameters at the end of the cycle as usual. Two other checks are included in the algorithm to detect whether a control action is required when the array was operating at the MPP in the preceding cycle (dV=*0);* in this *case* the *change* in the atmospheric conditions is detected using *(dI ≠0).* Now the control signal *D,* adjustment will depend on whether *dI* is positive or negative, as shown in the flow chart. When the above incremental Conductance algorithm was tested and it is observed that the condition *dP/dV* = 0 (or *dI/dV= -I/V)* seldom occurred because of the approximation made in the calculation *of dI* and *dV*. However, this condition *can* be detected by allowing a small marginal error (E) in the above comparisons, i.e. *dP/dV* = ±*E* and the value of E depends on the required sensitivity of Maximum power point tracking.

IV. SIMULINK MODEL FOR PLOTTING I-V AND P-V CURVES

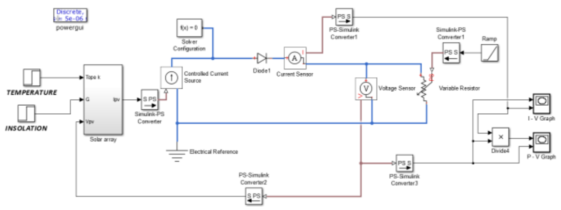

Fig.3. Simulink model for a PV array

Figure 3 shows the simulink model of the PV array for plotting the I-V and P-V curves. The array specifications are given in the Table.1. For plotting the curves variable resistor is used, whose value is changed from 0ohm to 1Mega-ohm with respect to simulation time. Fig.4& Fig.5 represents the I-V and P-V curves of PV array for different values of insolation. From the curves it is evident that with increase in solar insolation there is a significant increment in the short circuit current and the small decrement in the open circuit voltage, as a result maximum power is increased.

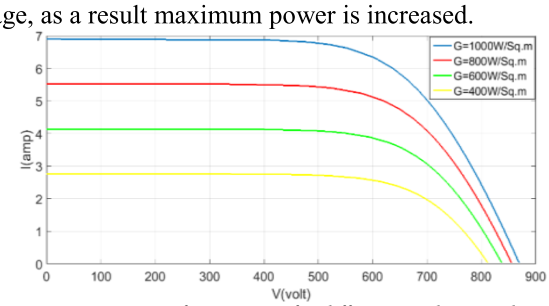

Fig.4. I-V curves of a PV array for different insolation values

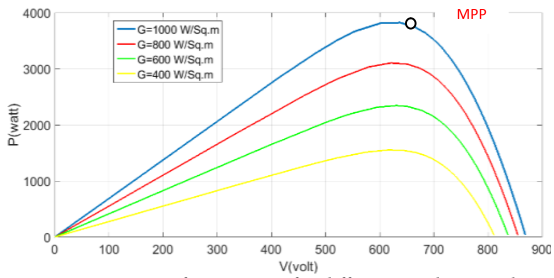

Fig.5. P-V curves of a PV array for different insolation values

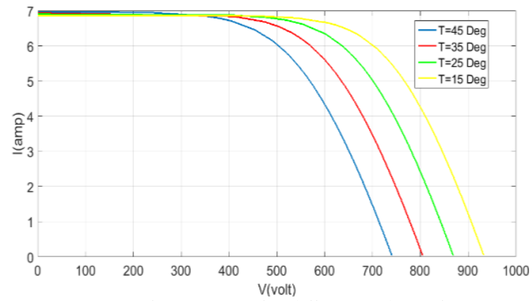

Fig.6. I-V curves of a PV array for different values of temperature

From the figures 6 & 7, it is evident that with increase in temperature significant decrement in open circuit voltage and the minute increment in short circuit current; as a result maximum power is decreased.

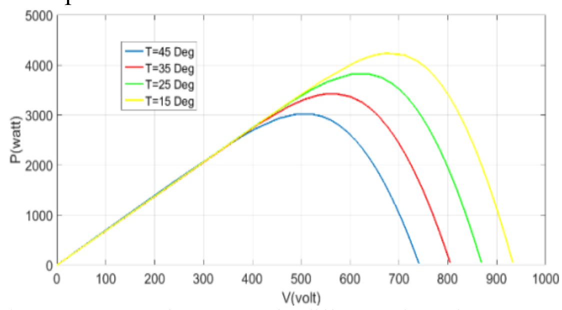

Fig.7. P-V curves of a PV array for different values of temperature

TABLE I. Specifications for PV array

Description	Parameter
No. of modules per string	22
No. of module strings connected in parallel	2
Number of cells per module	36
Open circuit voltage of an array at STC	865V
Short circuit current of an array at STC	6.9A
Maximum power output at STC	3830W

V. RESULTS AND ANALYSIS

Simulation results for implementation of MPPT by using buck converter:

MATLAB/Simulink representation of the PV panel connected to the load through a boost converter controlled by the MPPT controller is given below in the Fig. 8. In this work simulation was carried for a 3.82kW PV panel. Simulation is carried out for different cases and results are presented. In all the cases temperature is assumed as a constant value which is 25°C.

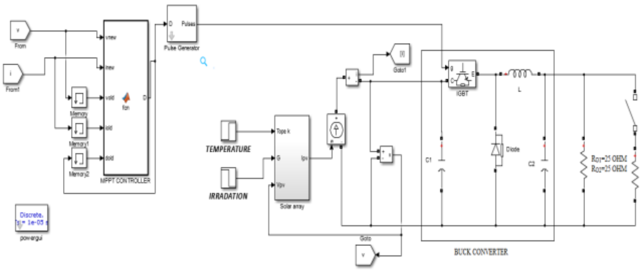

Fig.8. Simulink model of MPPT using Buck converter

Case-1: Without MPPT

a) Constant solar insolation and change in load

In this case solar insolation is considered as 1000W/Sq.m which is shown in Fig.9 and the load resistance is variable one whose value is 25Ω up to 1sec and it is reduced to 12.5Ω as shown in the Fig.10.

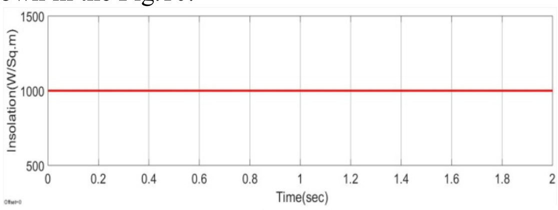

Fig.9.Solar insolation

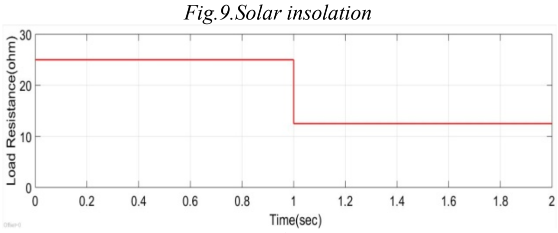

Fig.10.Load resistance

PV panel Power output is different for different load resistance values. Panel delivers 1190W of power for a load resistance of 25Ω up to 1sec, later due to change in the load resistance to 12.5 Ω the power delivered by the panel reduced to 380W as shown in the Fig.11. The corresponding load voltage values are shown in Fig.12.

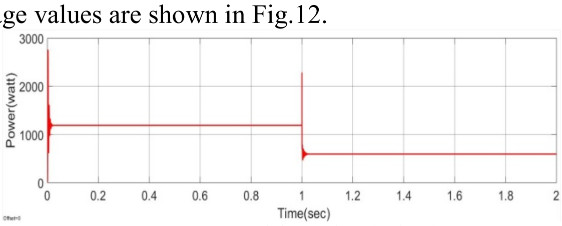

Fig.11. Power delivered to the load

Fig.12. Voltage across the load terminals

b) Fixed load and variable insolation

In this case the insolation is taken 1000W/m^2 up to 1sec after that it reduced to 800W/m^2 as shown in Fig.13 Throughout the simulation load resistance is taken as 25Ω as shown in Fig.14 Corresponding power and voltage values of the load is as in Fig.15 and Fig.16 respectively.

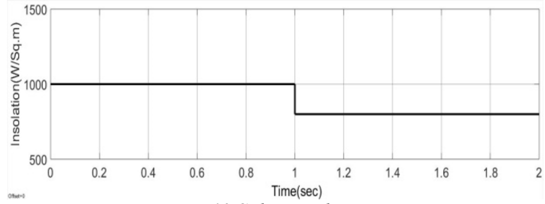

Fig.13.Solar insolation

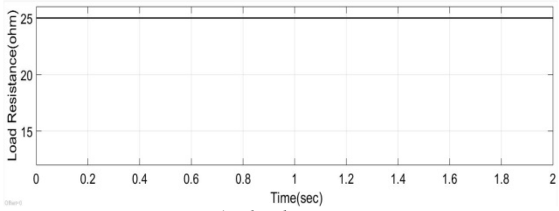

Fig.14. load resistance

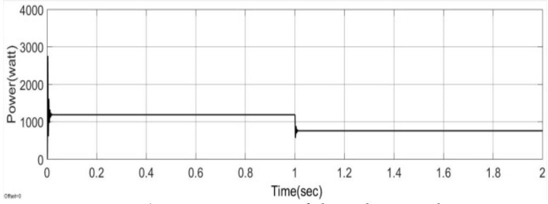

Fig.15.Power output of the solar panel

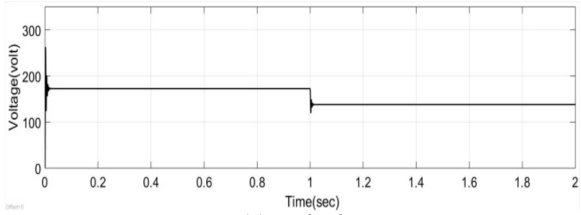

Fig.16.Load voltage

Case-2: With MPPT

a) Constant solar insolation and change in load

The panel gives maximum power output at a load resistance of 105Ω under STC which is found from I-V and P-V curves of an array (V_{mp}/I_{mp}=105Ω). The MPPT controller adjusts the duty ratio of the converter such that load resistance seen from the input terminals is always equal to the 105 Ω as shown in Fig.17.Hence the panel delivers maximum power to the load i.e. 3.8Kw as shown in Fig. 19 and the corresponding load voltage is as shown in Fig.20. The duty ratio values corresponding to the load resistance has been adjusted by MPPT controller as shown in the Fig.17 and the load resistance seen from the input terminals of the controller is as shown in Fig.18.

Theoretically it is being verifying by using Buck converter input resistance formula $R_{in}=R_0/D^2$[3]. By rearranging the terms Duty Ratio can be written as $D = \sqrt{(R_o/R_{in})}$.

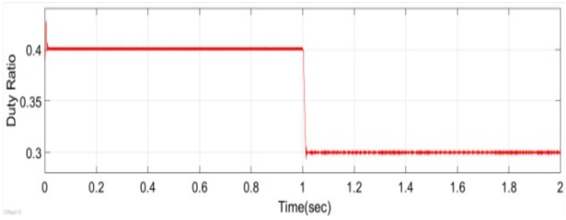

Fig.17. Duty ratio of the converter

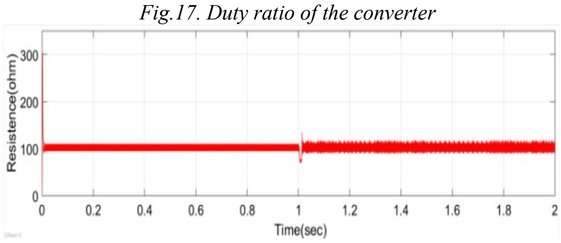

Fig.18. Load resistance seen from the input terminals of converter

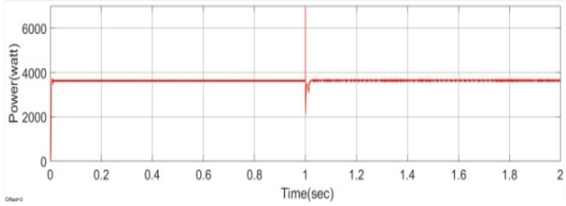

Fig.19. Power delivered to the load

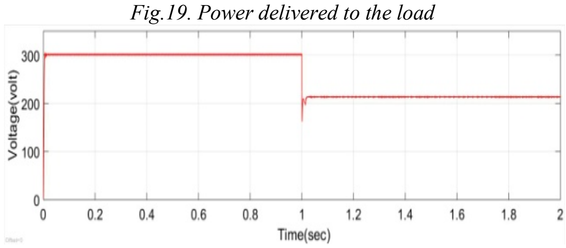

Fig.20. Voltage across the load

b) Fixed load and variable insolation

In this case insolation is considered as a variable one whose value is 1000W/m^2 up to 1sec, later it changes to 800W/m^2 as shown in Fig.21 and the load resistance is taken as a fixed one whose value is 25Ω as shown in Fig.22 The optimal resistance of the load corresponding to maximum power is different for different insolation values. From the I-V and P-V curves whose values are 105Ω (V_{mp}/I_{mp}) and 125Ω (V_{mp}/I_{mp}) for 1000W/m^2 and 800W/m^2 insolation values respectively. Here the MPPT controller adjusts the duty ratio of the converter such that the resistance seen from the input terminals of the converter is equal to 105 Ω for an insolation of 1000W/m^2 and 125 Ω for an insolation of 800W/m^2 respectively as shown in Fig.24. The duty ratio of the converter for different insolation values as shown in the Fig.23 and the corresponding resistance seen from the input terminals of the converter is given in Fig. 24 Fig.25& Fig.26 represents the power delivered by the PV panel and the load voltages respectively for the corresponding insolation values.

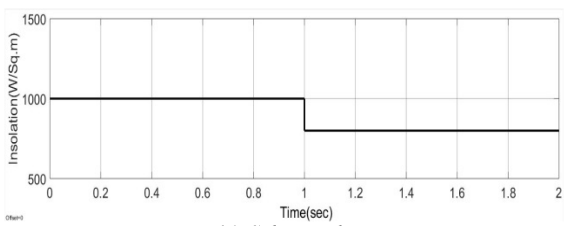

Fig.21. Solar insolation

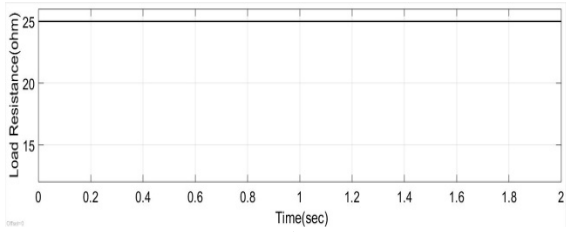

Fig.22. Load resistance

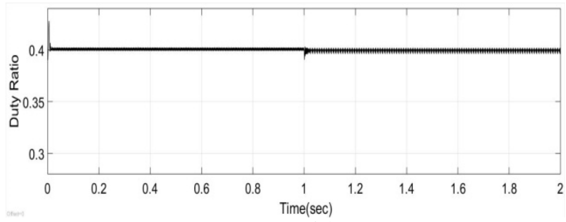

Fig.23. Duty ratio of the converter

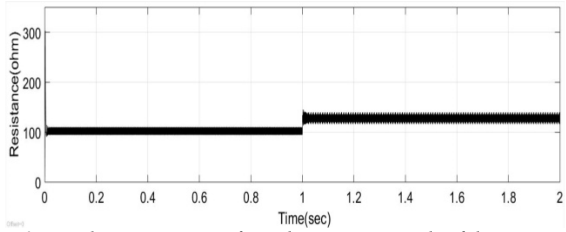

Fig.24.Load resistance seen from the input terminals of the converter

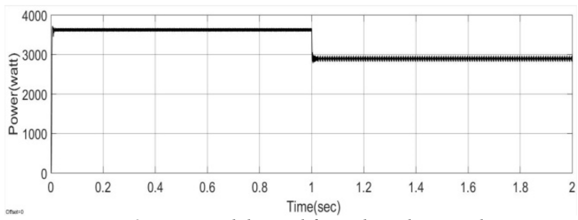

Fig.25. Power delivered from the solar panel

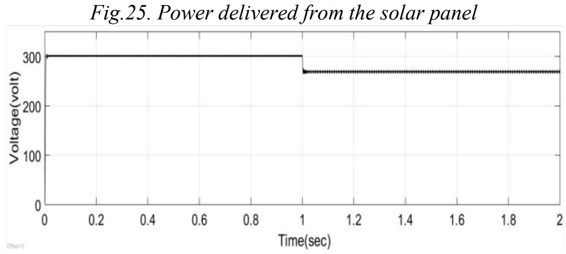

Fig.26. Load voltage

c) Change in insolation and change in load

In this case insolation is 1000W/m^2 up to 1sec later it changes to 800W/m^2 and load resistance is 25Ω up to 2sce then changes to 12.5Ω. The MPPT controller adjusts the duty ratio of the converter such that the panel delivers maximum power to the load. The corresponding results are presented in the following figures

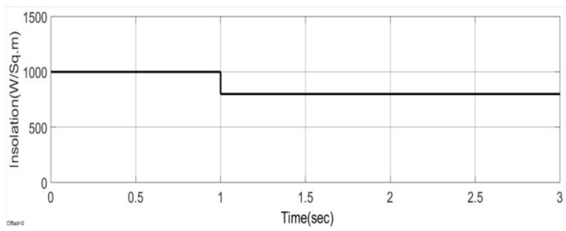

Fig.27. Solar Insolation

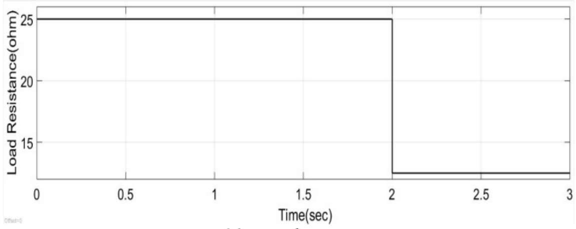

Fig.28. Load resistance

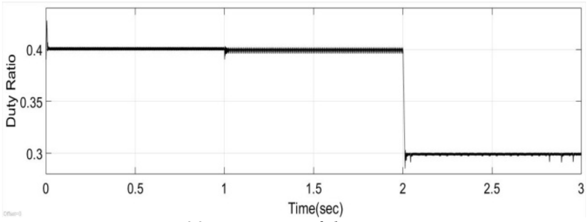

Fig.29.Duty ratio of the converter

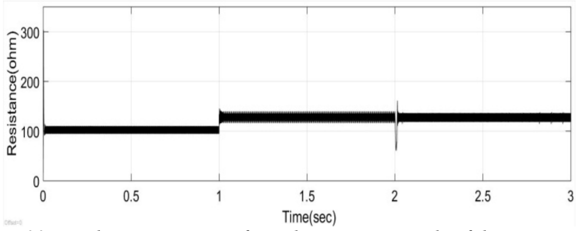

Fig.30. Load resistance seen from the input terminals of the converter

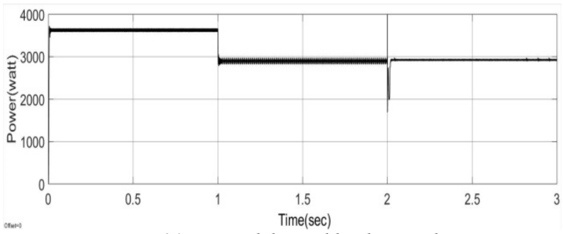

Fig.31.Power delivered by the panel

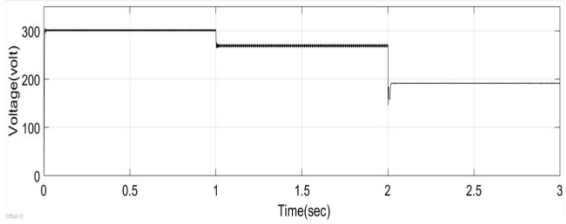

Fig.32. Load voltage

CONCLUSION

In this paper mathematical modelling of a PV cell, variation in I-V and P-V characteristics of a PV array for different atmospheric conditions are presented. Application of DC-DC converter (buck converter) along with IC based MPPT is used for tracking maximum power from the solar panel. IC algorithm is tested for different cases i.e. fixed insolation and variable load, variable insolation and fixed load and variable insolation and variable load. From the results it is observed that IC algorithm gives good performance for all cases, even under rapid atmospheric or load variations.

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