Implementation of Simple Low Cost PV Panel Characterization Kit using Arduino

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Abstract: Temperature, solar irradiation, direction and spectrum of sunlight always has influence on the generation of power in photovoltaic (PV) system. Temperature and irradiation are erratic in nature. It affects the efficiency of PV module. In view of module's low efficiency, it is prudent to work the module at peak power point. By that maximum power can be delivered to the load under waffling temperatures and solar radiations. The PV panel characteristics are known under the standard test conditions (STC). In practical situations, the PV characteristics are undisclosed out of STC. Therefore, the measurement of PV peculiarities such as voltage, current and power are required in real-time. This paper adducing a low cost PV characterization kit which is based on Arduino UNO and Excel. It is used to monitor the characteristics on PV side as well as load which is connected to source through maximum power point tracker. A simulation study of the MPPT with perturb and observe algorithm is carried out in MatLab/Simulink. Hardware is built to validate the simulation results

Keywords: PV panel, Arduino, Excel, MPPT.

1. Nomenclature

V_{pv}	-	Output voltage of a PV module (V)
I_{pv}	-	Output current of the PV module (A)
I_{ph}	-	Photocurrent in the PV module (A)
I_o	-	Saturation current of PV module (A)
V_{oc}	-	Open circuit voltage across the PV module at 25⁰C and 1000W/m^2
I_{sc}	-	Short circuit current flow through the PV module at 25⁰C and 1000W/m^2
T_r	-	Reference temperature = 298 K
T	-	Module operating temperature (K)
Q	-	Electron charge = 1.6×10^{-19} C
K	-	Boltzman constant = 1.3805×10^{-23} J/K
N_s	-	Number of cells connected in series
N_p	-	Number of cells connected in parallel

2. Introduction

Now-a-days inexhaustible energies are growing faster than the fossil fuels. Sunlight, wind, tides, waves and geothermal heat are the renewable energies which are used for energy conversion. In India the conceivable of renewable energy source for producing electrical energy is around 81, 200 MW out of that only 5594 MW i.e. 6.9% has been used so far. Energy produced by photovoltaic (PV) effect is considered as most essential due to abundant availability of solar energy.

Under standard test condition the performance and characteristics of PV module is afforded by manufacturers. In real time the characteristics of module is unknown due to variations in temperature and insolation on the panel [1]. In Section III, precise circuit modeling of PV module is carried out using MatLab for different irradiation and temperature. Since module efficiency is low under varying temperature and irradiation, it is prudent to operate the module at peak power point. The amount of radiation that reaches the earth surface varies time to time. So, the characterization kit is developed to measure the characteristics of PV module by using Arduino Uno and excel software is briefly described in Section VI.

By that the maximum power can be provide to the load beneath waffling temperatures and solar radiations. In Section V, design of boost converter and modelling of MPPT is discussed. MPPT is done by applying perturb and observe algorithm in Simulink.

3. Modeling of PV Panel

Each solar cell is made by p-n junction diode. When the sunlight falls on the panel, that light energy is directly converted into electrical energy without any mechanical operation. Electrons are excited from lower energy level to higher energy state. When the p-n junction is electrically shorted the current starts flow through p-n junction.

For this work, single diode model (Fig. 1) is considered. This structure consists of current source parallel with the diode [2]. In practical condition it has intrinsic series and shunt resistance which is R_s and R_{sh} respectively.
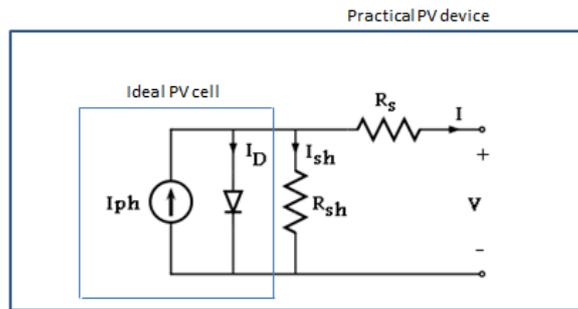

Fig. 1. Equivalent circuit

The basic mathematical equations from theory of semiconductors and photovoltaic for trace the I-V characteristics [3] of the photovoltaic cell and module are liable in the following Table 1.

Table 1

Mathematical Equations of PV Module

Photocurrent	$I_{ph}=[I_{SCr}+ K_i(T_k- T_{ref})]\times \dfrac{\lambda}{1000}$
Module reverse saturation current	$I_{rs}= \dfrac{I_{SCr}}{[\exp\left(q\dfrac{V_{oc}}{N_S kAT}\right)-1]}$
Module saturation current	$I_o=I_{rs}\left(\dfrac{T}{T_r}\right)^3 \exp\left[\dfrac{q\times E_{go}}{Ak}\left(\dfrac{1}{T_r} -\dfrac{1}{T}\right)\right]$
Module output current	$I_{PV}=N_p\times I_{ph}-N_P\times I_O\left[\exp\left(\dfrac{q\times(V_{PV}+I_{PV}R_S)}{N_S AkT}\right)-1\right]$

PV characteristic curves are basically a graphical representation of operation of solar module under varying temperature and irradiation. The main electrical attribute of a PV module are the correlation between the current and voltage produced on typical module. The potency of the solar radiation (insolation) that strikes the module controls the current (I), increase in the temperature of solar cell shifts its voltage (V).
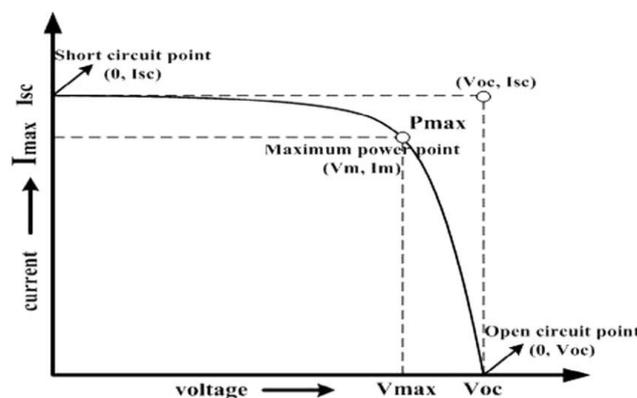

Fig 2: Charactersitics of PV Module

Fig. 2 describes the I-V characteristics of typical module. When the module is fully loaded i.e. positive and negative are shorted, than the current reaches maximum. This is so called short circuit current (I_{sc}). P_{MAX} represents the max power point [4].

- **MatLab Modelling**

The source current I_{ph} is represents the cell photocurrent. It is light generated current at STC (usually at 25⁰C and 1000W/m²). The detailed Simulink model of photocurrent I_{ph} is displayed in Fig. 3. The I_{sc} short circuit current value is noted from datasheet.
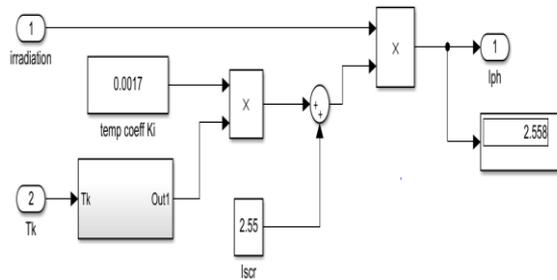
Fig 3 Simulation of photocurrent

Detailed Simulink model of module saturation current is shown in Fig. 4. Module saturation current depends on the atmospheric temperature.
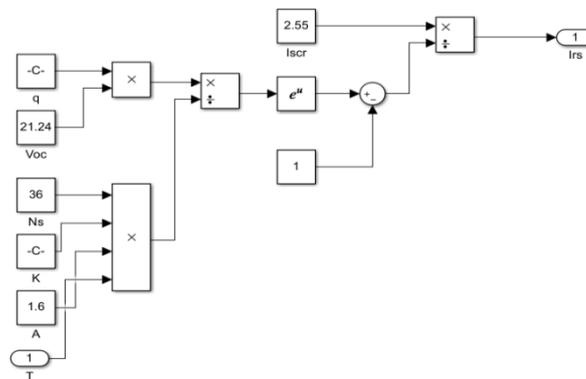
Fig 4 Simulation of reverse saturation current

Detailed model of module saturation current I_o is demonstrated in Fig. 5. The module operating temperature, reference temperature and reverse saturation current are consider as input.
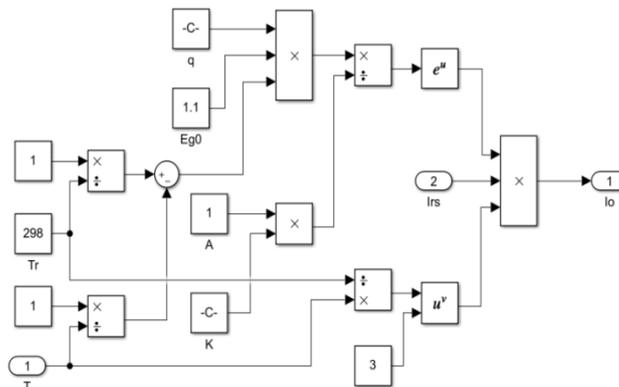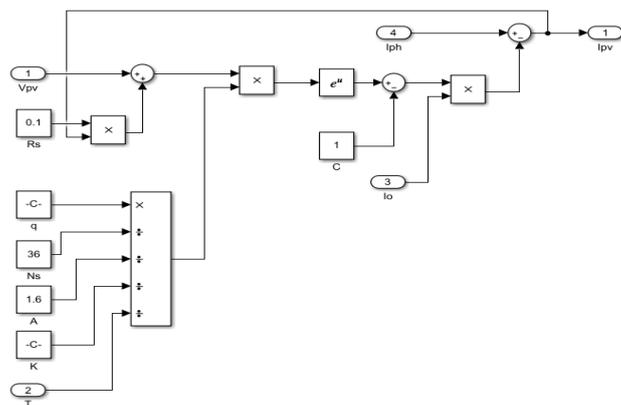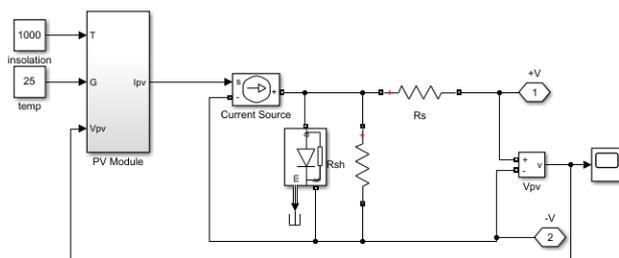
Fig 5 Simulation of saturation current

Detailed model of module output current I_{pv} from the basic equation for single diode model representation is shown in Fig. 6. PV module simulation is demonstrated in Fig. 7.
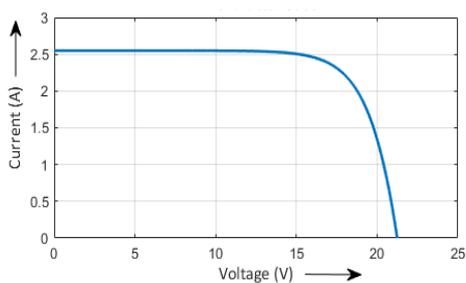
**Fig 6** Simulation of module output current

Fig 7 Complete Simulation of PV module

In I-V characteristics the current drops rapidly with small rise in voltage. This characteristic is shown in the Fig. 8.
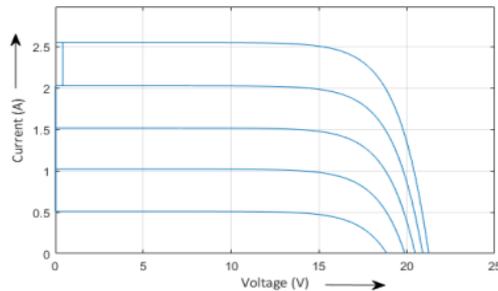

Fig 8 Simulated I-V Charactersitics

In P-V characteristics, it is clear that the cell does not produce any power at zero current or at zero voltage. It produces the maximum power at voltage corresponding to knee point, which is called as MPP. P-V characteristic is demonstrated in Fig. 9.
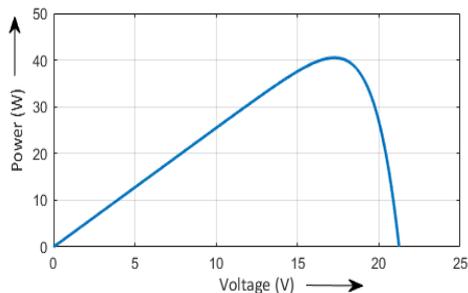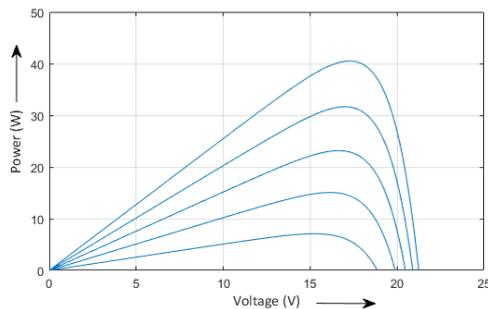

Fig 9 Simulated P-V Charactersitics

The amount of the solar radiation (insolation) that strikes the module alter the current (I), when insolation decreases large change can be viewed in current i.e., short circuit current and it provides small change in open circuit voltage [4]. I-V and P-V characteristics are demonstrated in Figs. 10 and 11 respectively.
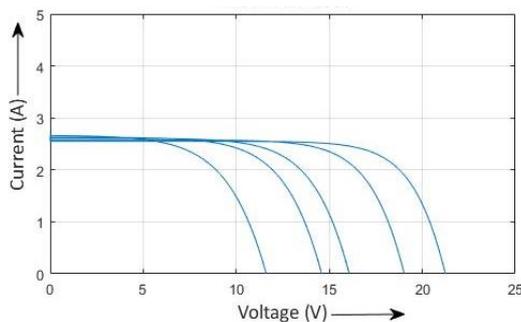
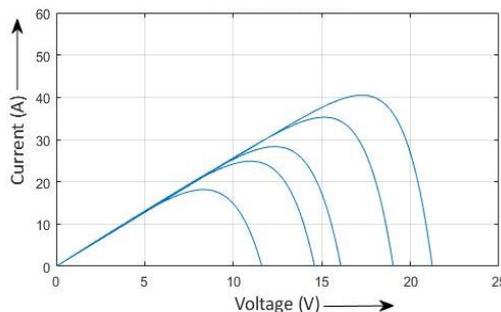**Fig 10** Simulated I-V Charactersitics for different insolation levels

Fig 11 Simulated P-V Charactersitics for different insolation levels

The atmospheric temperature and cell temperature disturb the voltage of the PV module. Increase in the temperature of the solar cell reduces its voltage (V) and slightly disturb the module's short circuit current. The current verses voltage and power verses voltage characteristics of PV module under varying temperature are given in the Figs. 12 and 13 respectively.

Fig 12 Simulated I-V Charactersitics for different temperatures

**Fig 13** Simulated P-V Charactersitics for different temperatures

Table 2 shows the PV module power under different insolation and temperature. Variation in power and temperature indirectly affect the output power and efficiency.

Table 2 Comparison of PV Module Power

Insolation (W/m²)	Temperature (°C)	V_{PV} (V)	I_{PV} (A)	P_{PV} (W)
1000	25	21.2	2.55	40.5
1000	30	20.1	2.54	37.5
800	25	19.2	2.04	32
600	32	18.5	1.53	21
400	35	17.5	1.1	12.7

4. Characterization Kit

Development of PV characterization kit is used to measure the voltage, current and power in real-time. The output parameters of PV panel are acquired by sensors. This PLX-DAQ is used to directly send the data to excel when it is connected to any microcontroller. UART bus allows the communication between the ATMega 328 controller in the Arduino Uno and the computer [5]. Acquired data is plotted as graph in excel spreadsheet. Block diagram is shown in the Fig. 14.
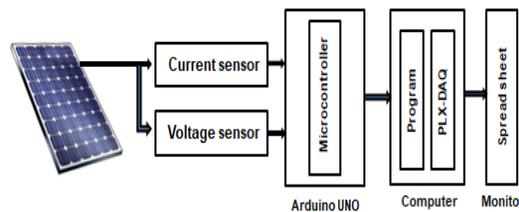

Fig 14 Block diagram of characterization kit

A.   Real time Characterization System

The microcontroller is integrated in the Arduino UNO board and it consumes DC power of 5V. The sensed current and voltage is given to the analog input pin of the Arduino board which is act as data acquisition board. Voltage sensor compute the output voltage of PV panel which is between 0 and 25 V. Arduino board analog input voltage is restricted to 5 V. So the voltage sensor can curtail the measured voltage up to 5 times i.e. between 0 and 5. The current is converted to voltage V_o thus the measured current is obtained by (1). The schematic is described in Fig. 15.

$$I_S = \frac{V_O * 1000}{R_S * R_L} \tag{1}$$
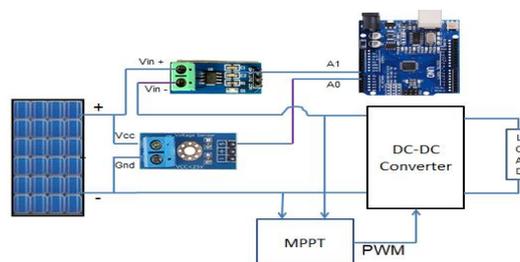
Fig 15 Schematic view of hardware

The PLX-DAQ Excel Macro data recording is restricted up to 26 channels of data from microcontroller. Data is reaping from the processor, and then it is saved and plotted as graph in real time monitoring. Assessing of Arduino IDE and PLX-DAQ Excel Macro are open. Arduino programming code must have same baud rate which is mentioned in PLX-DAQ window. PLX-DAQ spread sheet window is shown in the Fig 16 and sample measured is shown in Fig 17.
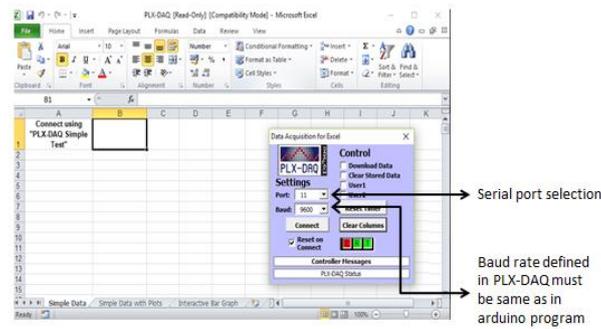
Fig 16 PLX-DAQ spreadsheet window

Fig 17 Sample of experimentally measured data

- **Fault classification**

Failure diagnosis is done by classifying the fault by viewing the I-V characteristics. By monitoring the graph that displayed in the PLX-DAQ Excel Macro, type of fault be can identified. This method mainly covers uniform dust fault, partial shading fault and short circuit fault [6]. Fig 18 shows the structure of PV string. Simulink model is shown in Fig 19.
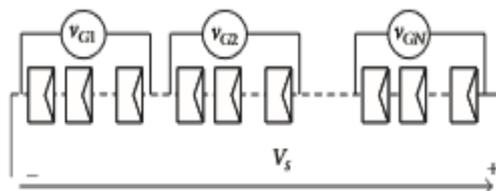
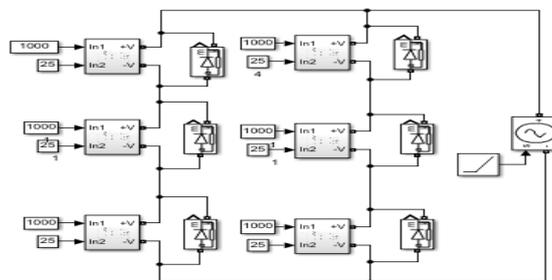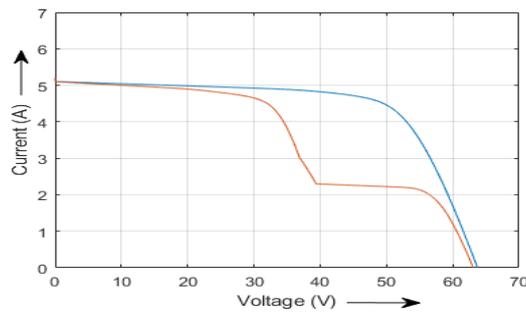

Fig 18 Structure of PV sting

**Fig 19** Simulation of PV module for fault classification

- **Partial shadow**


Fig 20 I-V curve comparison during partial shading

Some cells of PV panel is under shading and rest of cells are illuminated it is called partial shading. The number of steps shows the percentage of cell shading. Red curve shown in Fig 20 defines the partial shading.

- **Short and open circuit fault**
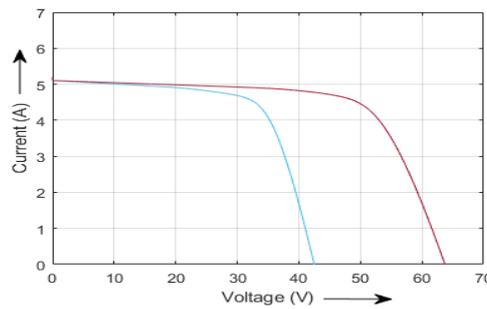
Fig 21 I-V curve comparison during short circuit fault

Considerable open circuit voltage drop is noticeable when short circuit faults occur. Blue curve shown in the Fig 21 defines the short circuit fault. The open circuit fault gives drop in short circuit current that shows in the Fig 22. Fig 23 shows the both shirt circuit and partial shading fault.
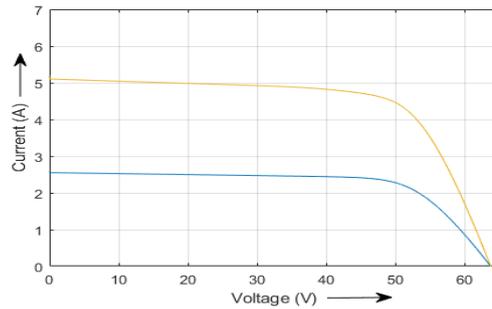
Fig 2I-V curve comparison during open circuit fault
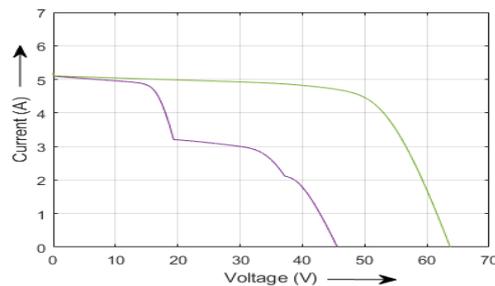
Fig 22 I-V curve with two faults

5. Design of Converter and MPPT

The fluctuating or variable input from PV or any other source is boosted to constant output voltage. To produce constant output voltage feedback loop is necessary. Normally boost converter boost (Fig 24) the output voltage 3 to 4 times the input voltage.

Here the boost converter is designed for photovoltaic (PV) system, which always provides the varying voltage depending upon temperature an insolation. Boost converter is designed to directly couple with PV system without any battery supply. The output of the PV module is tracked and depending upon that PWM pulse is generated by controlling the turn on period of the boost converter [7]. In order to control the input resistance to match with the load resistance DC to DC converter is required.
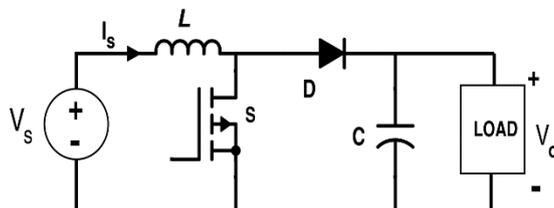

Fig 23 Boost Converter

The design equations for boost converter are discussed below.

- The conversion gain of boost converter is given by

$$V_O = \frac{V_{in}}{1-D}$$

(2) where, V_O = Output voltage ; V_{in}= Input voltage; D = Duty cycle.

- To operate the boost converter in continuous conduction mode, inductance must be greater than L_{min} value i.e., $L \geq L_{min}$. The minimum value of inductance for CCM is given by

$$L_{min} \geq \frac{V_s \times D}{f_s \times \Delta I_o}$$

(3)

where, V_S = Supply voltage; f_S = Switching frequency; ΔI_O = Current ripple.

- Output voltage ripple is minimised only by large filter capacitance. When the load is disconnected from the source, then supply to load is given by C min. The minimum value of the filter capacitance, that results in the reduced ripple voltage V_c, is given by

$$C_{min} \geq \frac{V_o \times D}{f_s \times \Delta V_o \times R}$$

(4)

where, Io = Output current; ΔV_O = Voltage ripple; ΔI = 30% to 50% of I_O; ΔV = 3% to 5% of Vo.

Based on the design equations the simulation parameters are computed and given in Table 3.

Table 3 Simulation Parameters of Boost converter

| Parameters	Values
Input voltage	18 V
Duty cycle	0.5
Inductor	10 mH
Input capacitor	220 μF
Output capacitor	220 μF
Switching frequency	5 kHz
Load resistance	30 Ω

The DC-DC converter for given component values in Table 3 is simulated with developed PV circuit model as shown in Fig. 25.
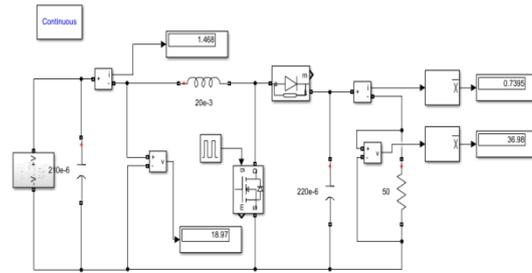
**Fig 24** Simulation of Boost Converter with PV source

MPPT is not a mechanical tracking system and it does not a physically move the module to point them on sun's direction. MPPT is not a mechanical system that achieves the PV modules to produce all the power that PV panel capable of [8]. The efficiency of panel is low; there is need to operating the PV module at MPP.

The max power from the solar array is extracted by the MPP tracker and transfers it to the load. Simplest Control algorithm that used in this paper is Perturb & Observe [9] and the flow chart is given below.
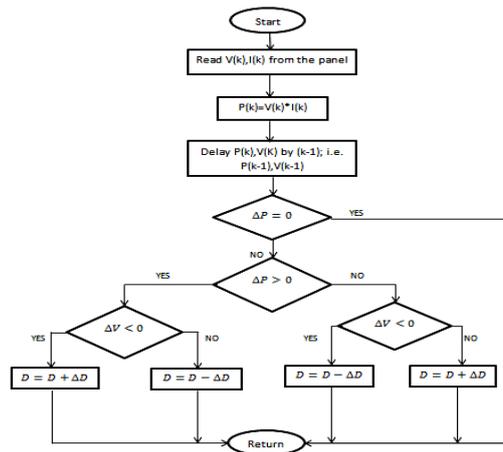
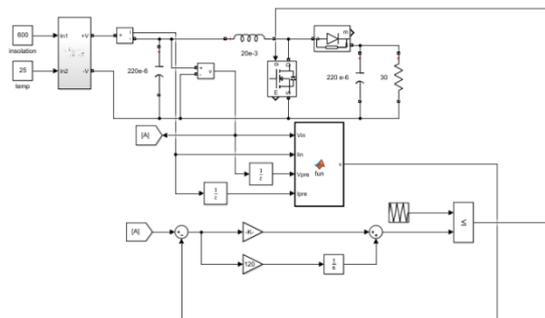**Fig 25** Flow chart of duty basd P&O algorithm

MatLab / Simulink model of P&O algorithm [4] is given in the Fig. 27. V_{in} and I_{in} is taken as input to the MPPT unit and on time of converter is achieved as the output.
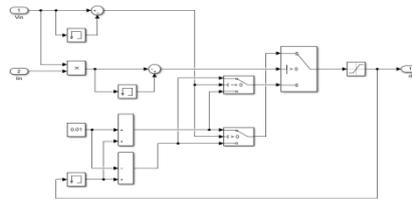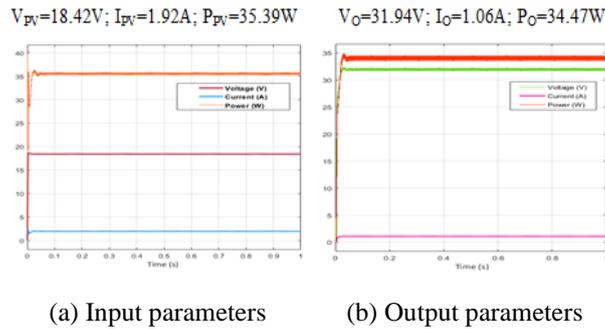

Fig 26 Simulink model of P&O algorithm based MPPT

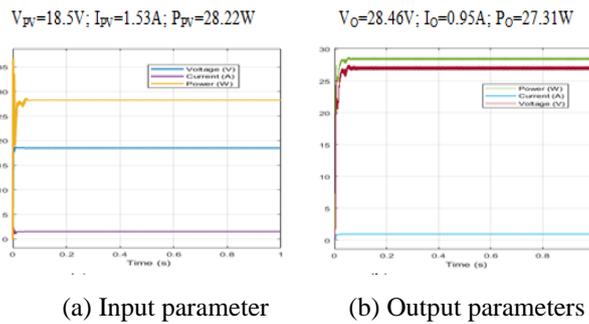**Fig 27** Simulink model of MPPT conrolled boost converter

The Simulink model for closed-loop control is shown in Fig. 28.

The results of the input side and output side parameters of the MPPT for insolation of 1000 W/m^2 and temperature 25°C are shown in the Fig 29(a) and 29(b).
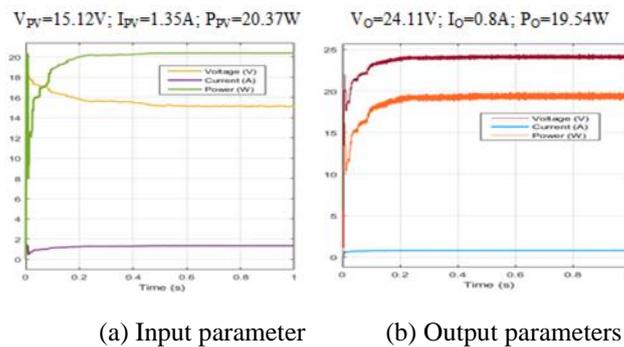

V$_{PV}$=18.42V; I$_{PV}$=1.92A; P$_{PV}$=35.39W   V$_O$=31.94V; I$_O$=1.06A; P$_O$=34.47W

(a) Input parameters   (b) Output parameters

Fig 28 Parameters at input and outside of MPPT controller at 1000 W/m2 and 25°C

Results of the input side and output side parameters of the MPPT for insolation of 1000 W/m^2 and temperature 30°C are shown in the Fig. 30(a) and 30(b).

V$_{PV}$=18.5V; I$_{PV}$=1.53A; P$_{PV}$=28.22W   V$_O$=28.46V; I$_O$=0.95A; P$_O$=27.31W
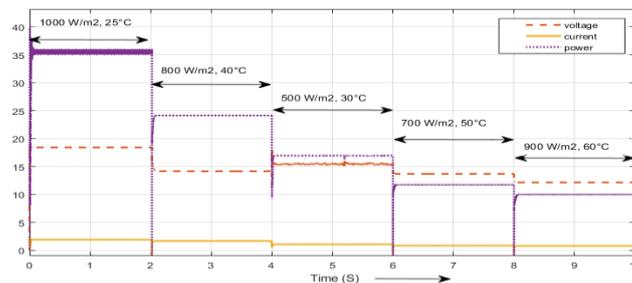
(a) Input parameter   (b) Output parameters

Fig 29 Parameters at input and outside of MPPT controller at 1000 W/m2 and 30°C

Results of the input side and output side parameters of the MPPT for insolation of 600 W/m^2 and temperature 32°C are shown in the Fig. 31(a) and 31(b) respectively.

V$_{PV}$=15.12V; I$_{PV}$=1.35A; P$_{PV}$=20.37W   V$_O$=24.11V; I$_O$=0.8A; P$_O$=19.54W

(a) Input parameter   (b) Output parameters

Fig 30 Parameters at input and outside of MPPT controller at 1000 W/m2 and 30°C

Results of input side parameters of MPPT Simulation for various temperature and irradiation is shown in Fig. 32 and output parameter for various irradiation and temperature is shown in Fig. 33.

Fig 31 Parameters at input side of MPPT controller at various temperature and irradiation
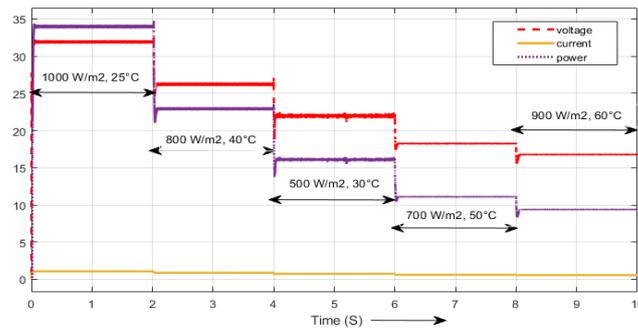
Fig 32 Parameters at output side of MPPT controller at various temperature and irradiation

6. Hardware implementation of MPPT

Based on simulation, the hardware implementation for MPPT is done. The PV panel is interface with this MPPT to get maximum PV efficiency. The specifications for proposed system are given in the Table. 4.

Table 4 Hardware specifications

Components	Specification	Quantity
MOSFET	IRFP460	1
Arduino	UNO	1
Inductor	10 mH	1
Input Capacitor	220 μF	1
Output Capacitor	220 μF	1
Diode	IN5408	1
Current sensor	ACS712	1
Voltage sensor	0.00489V(resolution)	1
PV panel	36 W	1

Pulse generated by using Arduino for conventional boost converter with switching frequency of 5 kHz is shown in the Fig. 34.
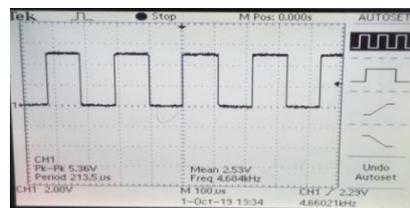

Fig 33 Arduino pulse for boost converter

The hardware setup of conventional boost converter for the input voltage 16V is shown in the Fig. 35 and it produces the DC output voltage of 30V. Relative duty cycle is 0.5. The simulation results are experimentally validated.

Fig 34 Hardware setup for convention boost converter

7. Conclusion

The single diode model of photovoltaic module provides easier and efficient modelling of the photovoltaic (PV) module. The PV Array has been analysed and designed with the help of formulas and Simulations. The models showcase that the PV current I_{PV} is a function of the solar illustration and temperature. Since the efficiency of the PV Array is low and varying in nature, a method to track the max power at all conditions is required.

A convenient MPPT algorithm is considered in this project. Perturb & observe (P&O) algorithm uses the PV voltage and current to track the max power produced. The PV module with the MPPT is implemented in a DC-DC converter to check its efficiency. In this phase, the PV module has been modelled and the efficiency of the PV module is improved by using the P&O MPPT technique. The MPPT through DC-DC converter, of the PV module is simulated by using MatLab/Simulink. The power changes obtained for various irradiation is compared

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