

Low Cost PV Emulator Design for Assessment of Maximum Power Point Tracking Schemes

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Abstract—Power electronics engineers frequently use PV emulators to examine various maximum power point technique (MPPT) schemes, dc/dc converters or inverters etc. The emulators existing in the marketplace are often costly, so a low cost PV emulator will of great help for the researchers to perform basic study on PV systems. This paper presents a novel low cost PV module emulator that will be very helpful to work in the labs using predefined PV conditions, thus evading the shortcomings (i.e. fluctuations due to changing atmospheric conditions) of real PV sources modules. The proposed emulator consists of DC source as input, a current source in parallel with a diode to realise a simplest equivalent circuit of a PV module. This emulator can have settings to vary the insolation as well as temperature i.e. short circuit current and open circuit voltage respectively. As a test event, a 30W PV emulator is designed and presented. Its current source consists of 01 diode, 03 transistors, 08 different resistors and a potentiometer connected in a particular fashion with the DC source. 20 diodes have been used in parallel to this current source to make a simplest equivalent PV module circuit. The analysis of the proposed design has been done using PROTEUS. Also its performance comparison is done using MATLAB-SIMULINK. The results demonstrate that the emulator can satisfactorily replicate the PV module's I-V, P-V characteristics and thus can be used to assess various maximum power point tracking schemes.

1. INTRODUCTION

The remarkable progress in installed photovoltaic (PV) systems in the past few decades has compelled the researchers to enhance the performance of PV systems so as to optimally utilize it. Also the advancement and exploitation of solar PV energy is becoming an important way to increase energy security along with the decrease in environment pollution [1-3].

The electrical power produced by a PV array varies incessant with change in weather conditions mainly irradiance and temperature. This continuous fluctuation makes it problematic to segregate the variables affecting the PV hardware. Some concerns that are met with the enlarged PV penetration are inadvertent islanding, extraction on maximum power from these sources using MPPT (maximum power point trackers),

the effect of PV sources on voltage regulation of power system and synchronization with prevailing protection schemes [4, 7]. All these above concerns have to be researched thoroughly and for that we need a more sophisticated way of testing the PV based equipment. Thus a PV emulator is a good means to do the practical experiments in the labs in a controlled environment. PV emulators put on the characteristics and dynamics of a PV module more correctly than the programmable power supply. These PV emulators offer a more controlled environment to test the PV hardware as compared to a real PV module.

Due to changing environmental conditions, actual PV module will have a changing characteristic and thus will be not suitable to do research experiments. A PV emulator offers more control to permit improved testing of PV equipment. The researcher can on his own alter either the irradiance or temperature or both and decide how these factors affect the PV hardware that is being tested. Having consistent electrical characteristics will allow the analysis and optimization of PV systems. The better control that a PV emulator provides allows for more urbane measurements of maximum power point tracking (MPPT) procedures under various conditions [5-6].

The low efficiency of current solar power supply technologies, without MPPT systems, can require a nominal capacity for an installation which renders solar PV prohibitively expensive. To test and evaluate such MPPT systems, a device which can replicate the voltage-current characteristic of a real solar array is required, in effect, a solar array emulator.

A large number of PV emulators have been commercialized over the years but most of them are very costly and out of reach of the student research community. So a low cost PV emulator will of great help for the researchers to perform basic study on PV systems [8].

This paper presents a novel low cost PV module emulator that will be very helpful to work in the labs using predefined PV conditions, thus evading the shortcomings (i.e. fluctuations due to changing atmospheric conditions) of real

PV sources modules. The proposed emulator is based on single diode model of PV cell and consists of DC source as input, a current source in parallel with a diode to realise a simplest equivalent circuit of a PV module. This emulator can have settings to vary the insolation as well as temperature i.e. short circuit current and open circuit voltage respectively. As a test event, a 30W PV emulator is designed and presented. Its current source consists of 01 diode, 03 transistors, 08 different resistors and a potentiometer connected in a particular fashion with the DC source. 20 diodes have been used in parallel to this current source to make a simplest equivalent PV module circuit i.e a single diode model (a current source in parallel with single diode). Also, to validate the proposed emulator, the results obtained using PROTEUS are compared with a PV module modelled (basic single diode model) in MATLAB/SIMULINK.

2. BASICS OF PV CELL AND SINGLE DIODE MODEL

Photovoltaic cell transforms the radiant energy of the sun straight into electricity. A Representation of a PV cell with a load is presented in figure1. The single diode model of a PV cell is given by Fig. 2, this also represents the simple equivalent circuit of a PV cell with load. A representative *i-v* curve of the solar cell for a definite ambient irradiation (S or G) and a definite cell temperature (T) is shown in Fig. 3. For a resistive load, the load line is straight having a slope $I/V=1/R$. It has to be pointed out that the power supplied to the load is determined by the value of linked resistance. If the load R is small, the cell functions in the region M-N of the curve (Fig. 3) where the cell acts as a fixed current source, practically equal to the short circuit current. And if the load R is large, the cell works in the section P-S of the curve, the cell performs as a fixed voltage source, nearly equal to the open-circuit voltage [1].

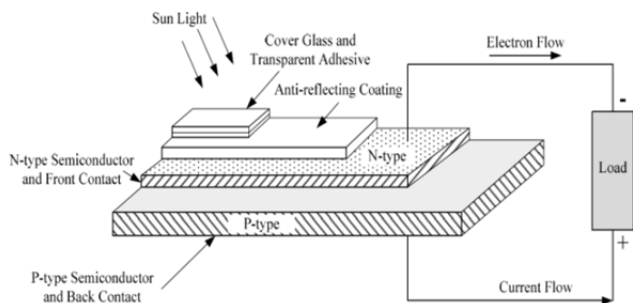


Fig. 1: Diagram of a PV cell with a load.

The fundamental equation describing the I-V characteristic of the ideal PV cell is given by Eq. 1

$$I_C = I_{PH} - I_0 \left(e^{\frac{qV_d}{kT_C}} - 1 \right) \tag{1}$$

$I_{PH} = I_{SC}$ is the short circuit current whose magnitude depends on the area of the cell and is directly proportional to the solar insolation. V_d is the voltage across the diode, k is Boltzmann constant ($1.38 \times 10^{-23} \text{ J}^\circ\text{K}$), q is electron charge ($1.602 \times 10^{-19} \text{ C}$), I_0 is reverse saturation current of diode (0.000025A) and is calculated using Eq. 2, T_c is reference cell operating temperature (25°C) [1].

$$I_o = \frac{I_{sc,n} + K_I \Delta T}{\exp\left(\frac{V_{oc,n} + K_V \Delta T}{aVt}\right) - 1} \tag{2}$$

K_I is the current coefficient, K_V is the voltage coefficient, $V_{oc,n}$ is the open circuit voltage at the nominal condition (usually 25°C and 1000 W/m^2), $\Delta T = T - T_n$ (being T and T_n the actual and nominal temperatures) [1-3].

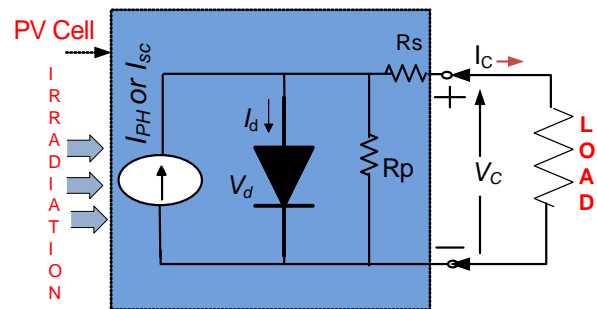


Fig. 2: Simple equivalent circuit of a PV cell.

In a real-world PV cell, there are series of resistances in the current track through the semiconductor material, the metal grid, contacts, and current gathering bus.

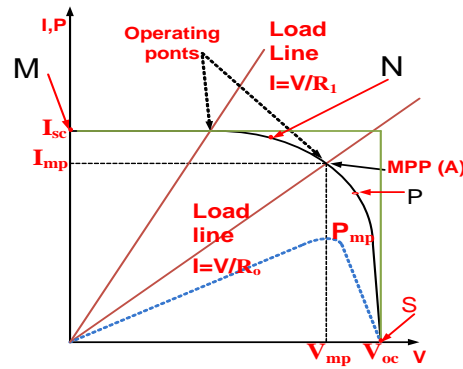


Fig. 3: I-V and P-V characteristics of PV cell

The losses in these resistances are consolidated collectively as a series resistor (R_s). R_p justifies the loss associated with a small leakage of current through a resistive path in parallel with the intrinsic device. I-V and P-V characteristic of a PV cell is shown in Fig. 3. The intersection of load line (i.e. $I=V/R$) and I-V plot of PV cell gives the operating point. R_l

and R_o are dissimilar load resistance. R_o resembles to the load at which MPP overlaps with the operating point [9].

3. EMULATION - DESIGN APPROACH

Power electronics engineers frequently use PV emulators to examine various MPPT schemes, dc/dc converters or inverters etc. The emulators existing in the marketplace (Fig. 4) are often costly, so a low cost PV emulator will of great help for the researchers to perform basic study on PV systems. The proposed emulator design (Fig. 5) offers a modest circuit that performs as a PV-module simulator at a very low cost. It has a DC voltage source as its input and its circuit is based on the simplest equivalent circuit i.e. single diode model of a PV cell [10-13]. In Fig. 5, the number of diodes connected in series acts as a single diode and the circuit before these diodes acts as a variable current source.

In a real PV cell, its output short circuit current (I_{sc}) depends on the falling irradiance and thus in the proposed circuit the current source output is made proportional to the irradiation. The irradiation or output current is varied by controlling the potentiometer of the Fig. 5.

Also the open circuit voltage (V_{oc}) of a real PV cell varies with the temperature and to incorporate this feature instead of one diode a large number of diodes connected in series are used. By changing the number of series connected diodes, the open circuit voltage changes and thus the variation due to change in temperature is observed. Easy way to vary the open circuit voltage is to short circuit the desired number of series connected diodes. In Fig. 5 only 20 series connected diodes have been used, this number can be increased 30, 40 or 50 according to the voltage requirement. By decreasing the number of diodes the open circuit voltage increases and thus can be varied accordingly.

The maximum value of short circuit current that can be obtained using the proposed circuit is 2A. The value of RV1 is 10K Ω . The value of resistors R1 and R2 is 1K Ω . R3, R5, R6, R7 and R8 resistors has a value of 220 Ω . R4 resistor has a value of 150 Ω . The transistor Q1 is BD139. The power BJTs Q2 and Q3 are BC160 (MJ15023 can also be used). The series connected diodes are MUR1520. RV2 acts a variable resistive load. These circuit elements have been taken from the PROTEUS library to simulate the proposed emulator.

To obtain the effect of change in irradiation, the potentiometer is varied which controls the base current of transistor Q1 i.e. BD139 and ultimately controls the Collector current of Q1.

The variation in collector current of Q1, controls the base current of power BJT Q2 as well as Q3. This final varies the collector currents of Q2 and Q3. Thus a variation in output current of the emulator is obtained by varying the potentiometer. The calibration of potentiometer to relate it with the short circuit current for change in irradiation and also the number of series connected diodes to relate it with the open circuit voltage for temperature variation has to be done before actually performing the experiments.



Fig. 4: Emulators commercially present in the market

4. SIMULATION OF SINGLE DIODE MODEL

The purpose of simulating the single diode model is to have a comparison between the curves obtained from the proposed emulator and the standard PV curves obtained from the simulated model. The simulation has been done in MATLAB/SIMULINK. Equations 1 to 4 are the basic

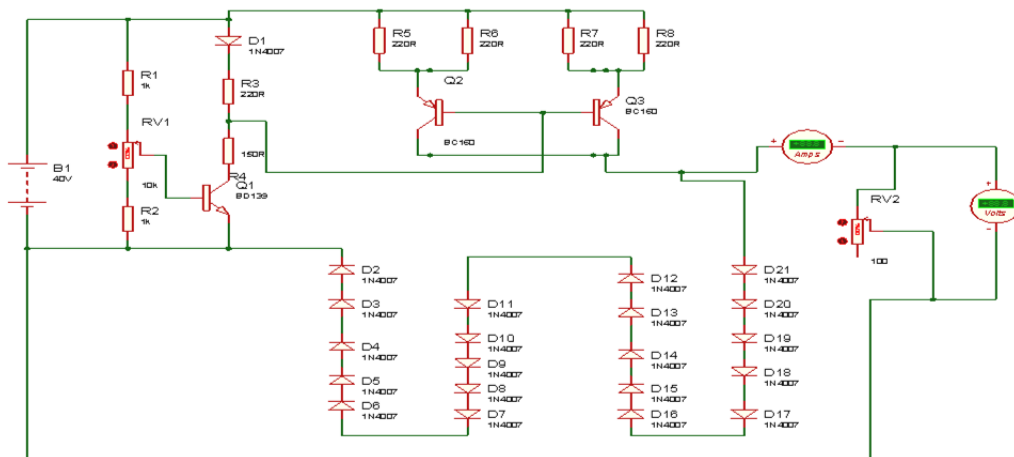


Figure 5: Proposed Emulator Designed in PROTEUS

governing equations used to model a simple single diode model of a PV module and finally an array. The implementation of these equations in SIMULINK is shown in figures 6 to 9. Fig. 10 gives the overall circuit of PV Module. Symbols have their usual meaning.

$$I_o = \frac{I_{sc,n} + K_1 \Delta T}{\exp\left(\frac{V_{oc,n} + K_2 \Delta T}{aV_t}\right) - 1} \quad (1)$$

$$I_{pv} = [I_{sc,n} * (\frac{R_p + R_s}{R_p}) + K_i \Delta T] \frac{G}{G_n} \quad (2)$$

$$I_m = I_{pv} - I_o \left[e^{\left(\frac{V + R_s I}{aV_t}\right)} - 1 \right] \quad (3)$$

$$I_m = (N_{pp} * I_{pv}) - (N_{pp} * I_o) \left[\exp\left(\frac{V}{aV_t} + \frac{R_s I}{N_{ss} + N_{pp}}\right) - 1 \right] \quad (4)$$

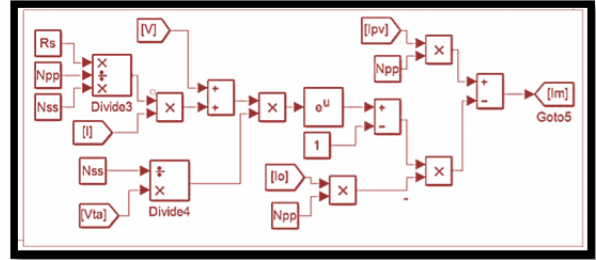


Fig. 9: PV array Modelling

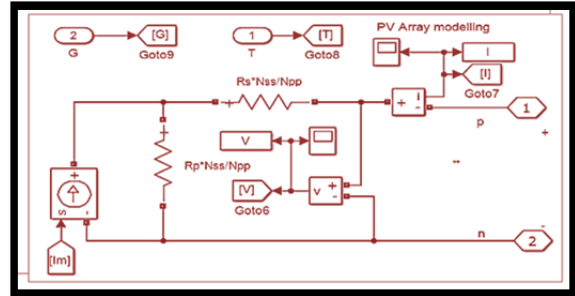


Fig. 10: Circuitry Design for PV Module

Table 1: Designed parameters used for the modelling purpose

S. No	Parameters	Value
1.	K_i	0.0032A/K
2.	K_v	-0.1230V/K
3.	N_s	54
4.	N_{ss}	1
5.	N_{pp}	1
6.	R_s	0.2651Ω
7.	R_p	415.405

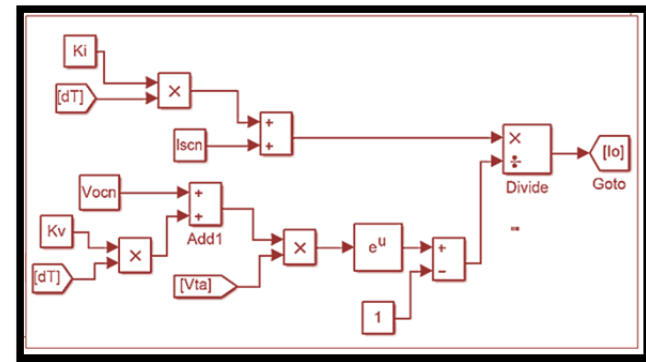


Fig. 6: Mathematical Modelling Implementation for I_o

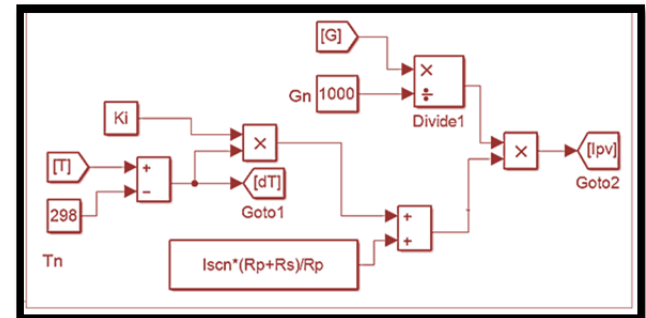


Fig. 7: Mathematical Modelling Implementation for I_{pv}

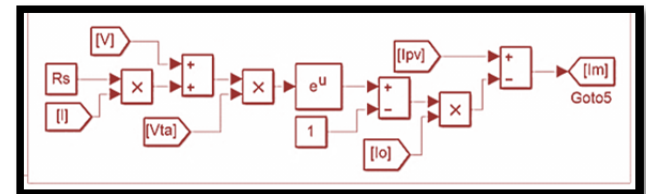


Fig. 8: Mathematical Modelling Implementation for model current I_m

Table 2: Parameters of PV module used for analysis

S. No	Parameters	Value at 1000W/m ² & 25°C
1.	V_{oc}	25V
2.	I_{sc}	1.5A
3.	P_{max}	26W +/- 2%
4.	I_{mp}	1.37A
5.	V_{mp}	20.15V

5. RESULTS AND COMPARISON

The results obtained from the simulated model in MATLAB are shown in Fig. 11 and 12. From these figures, the variation in P-V and I-V curves with the variation in irradiation and temperature can be observed by analyzing the results.

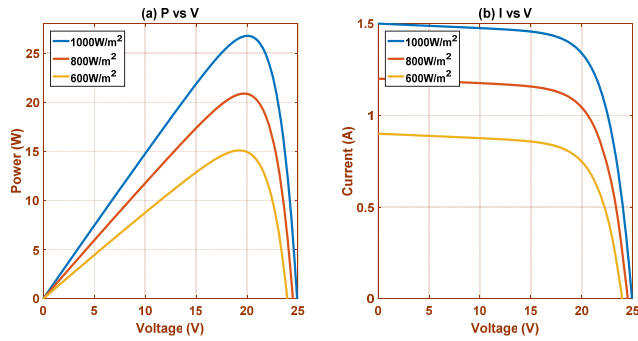


Fig. 11: (a) P vs V and (b) I vs V curves for different values of irradiation at 25°C (results obtained using SIMULINK)

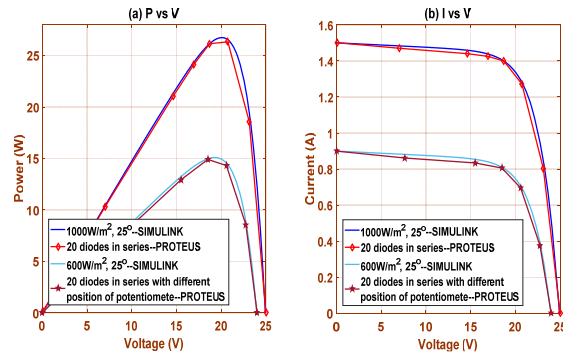


Fig. 14: Comparison between obtained using SIMULINK and PROTEUS results (with different position of potentiometer knob)

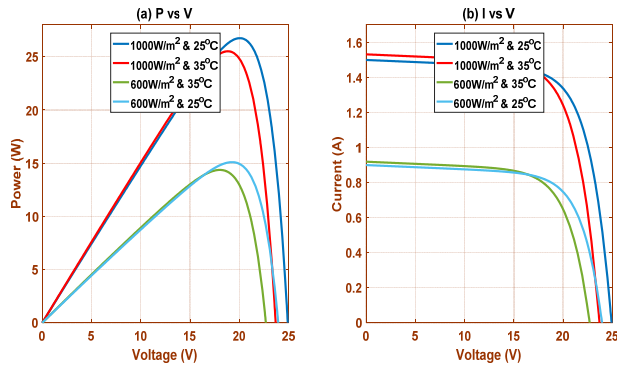


Fig. 12: (a) P vs V and (b) I vs V curves for different values of temperature and irradiation (results obtained using SIMULINK)

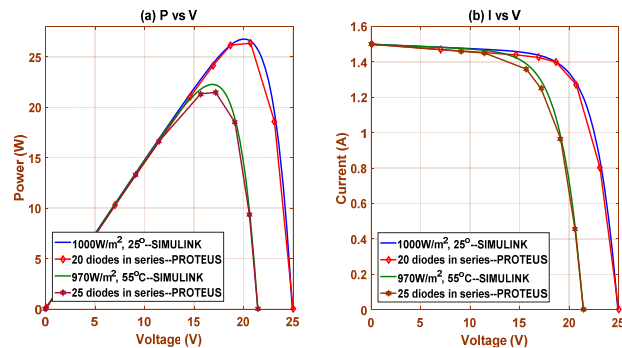


Fig. 13: Comparison between obtained using SIMULINK and PROTEUS results (with different number of series connected diodes)

Fig. 13 shows the comparison between (a) P vs V and (b) I vs V curves for different values of temperature obtained using SIMULINK and PROTEUS (for different number of series connected diodes). Fig. 14 shows the comparison between (a) P vs V and (b) I vs V curves for different values of irradiation obtained using SIMULINK and PROTEUS (for different position of potentiometer knob).

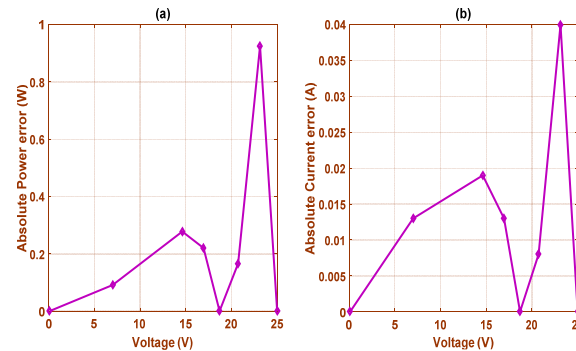


Fig. 15: Absolute error in power and current as obtained from PROTEUS for 20 series connected diodes and 1000W/m² potentiometer setting.

The absolute error in power and current as compared to SIMULINK results are shown in Fig. 15. The maximum error in power is less than 1W and in current it is around 0.04A.

6. CONCLUSION

This article presents a unique PV emulator that is very useful for conducting research experiments for validating new features in a PV based systems especially to verify a new MPPT technique. The results obtained using the proposed circuit in PROTEUS is compared with the results of simulated model in MATLAB. The results are up to the mark and shows that the emulator performs well. The low cost along with good performance is an attractive feature of this emulator. Further a number of this emulator can be connected in series and parallel combinations, using bypass and blocking diodes respectively, for partial shading studies.

Overall this emulator is a low cost replacement to the commercially viable PV emulators.

7. ACKNOWLEDGEMENTS

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