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Photovoltaic Emulator

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In order to facilitate the testing of PV systems, PV panels are required and it is necessary to connect them in different configurations to get the required output voltage and power. The output of PV panels depends on environmental factors like insolation, temperature, inclination of the panel, partial shading, etc. hence it is difficult to maintain and reproduce the same characteristics of PV panel. Therefore PV emulator is required to maintain and reproduce the same characteristics irrespective of weather conditions to facilitate the testing of PV systems. The aim of this paper is to design a controlled DC-DC converter which acts as PV emulator.

Keywords: *Controller, converter, emulator, insolation, photovoltaic.*

1.0 INTRODUCTION

Now-a-days the entire world is concentrating on clean energy and drawing the attention of researchers towards renewable energy sources (res). many aspects like pollution,global warming, government policies, subsidies, etc have increased concern on clean energy. wind energy has highest share in non-convention power generation but solar power has high growth rate. Global annual installation of wind energy and solar energy in the year 2014 is 36.95 gw and 49 gw respectively [1]. this shows the high growth rate of solar energy. Out of all renewable energy sources solar energy is one among the most prominent and fast growing because of its benefits like no moving parts, less running cost, limitation on site location etc. in contrary, solar energy has disadvantages like high initial cost, low efficiency of PV panel, dependency on weather conditions and large installation area. In addition to this there are problems like partial shading, accuracy of maximum power point tracking, high thd, voltage instability etc. therefore research in this area is required, to eliminate such problems, and it is crucial to test PV systems before installation.

However there are some drawbacks to use real PV panels to test these systems. The drawbacks are high cost of PV panels, large size, time consuming to connect the modules differently, and dependency on weather conditions. Therefore, there is a need of proper test equipment, which is PV emulator.

This paper presents PV emulator where closed loop buck converter is used to extract the characteristics of PV panel at desirable insolation and temperature i.e. at controlled weather conditions.

1.1 Literature survey

PV Emulator is very useful to researchers working in the area of solar energy because PV Emulator is seen as group of panels thereby reducing their work. Different types of PV Emulator using different controllers have been proposed by

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several researchers. The common approach to realize PV Emulator is to use DC-DC converters as power circuit with different controllers.

D-SPACE controller is used to realize a DC-DC converter based PV Emulator [2]. In this paper authors used mathematical model of PV array which is developed using MATLAB/ SIMULINK™ to generate reference signal. Piecewise linear approach using micro-controller has been proposed to implement low cost PV Emulator [3]. Here, authors used two-switch Buck-Boost Converter as power circuit and 8 bit micro- controller to achieve desired characteristics. Some authors used controlled rectifier along with DC/DC converter as power circuit [4-5]. In [4] authors have simulated PV Model in Lab-View and interfaced to real world through data acquisition system. In [5] author have proposed 3-ph rectifier and high frequency transformer to test PV inverters upto 4 kW, 650 V, 7 A. A PV Emulator was made using programmable DC Power supply [6]. This PV Emulator gives voltage and current as desired thus implementing PV characteristics. Neural network based PV Emulator has been proposed by some of the authors [7-8]. These authors used "Growing Neutral Gas" network to control DC-DC converter to obtain desired characteristics.

1.2 Importance of PV Emulator

PV Emulator is required due to following reasons:

1. Large area is required for the commissioning of an actual PV array and also one has to reconnect for studying the characteristics for different array configurations.
2. The emulation of a PV array by simply having either a Current Source or Voltage Source is difficult.
3. It is difficult to reproduce and maintain the similar characteristics with the PV array when the isolation is low and the other environmental conditions change.
4. By making some minor changes in the programming of the controller, such an emulator can reproduce different desired characteristics within no time and no extra cost.

2.0 CHARACTERISTICS AND MODELING OF PV PANEL

The I-V (current vs. voltage) and P-V (power vs. voltage) characteristics of solar PV module is shown in Figure 1. These I-V and P-V characteristics mainly depend on temperature, insolation, inclination of panel and partial shading. Temperature and insolation will vary throughout the day, therefore I-V and P-V curve varies accordingly. The I-V and P-V curve for different panels and for the panels connected in different configurations (series, parallel or both) remains same, only I_{sc}, V_{oc}, V_{mpp}, I_{mpp} values change.

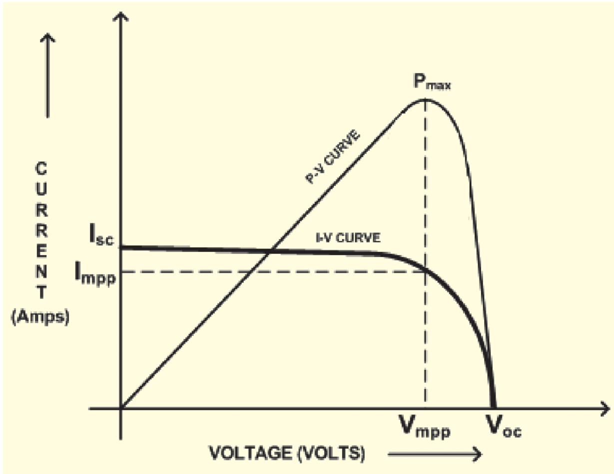

FIG. 1 PV & IV CURVES

These curves also depends on albedo factor, altitude, latitude, inclination of panel, partial shading etc where tracking maximum power point (MPP) accurately in short time interval is a challenging task.

2.1 Modeling of PV Module

Mathematical model of photovoltaic cell is represented in this paper. This mathematical model is a single diode model which is obtained from approximation of two diode model. Single diode model (Shown in Figure 2) [9] is most popular than two diode model [10] because of its simplicity and easy implementation. PV cell can be represented with a ideal current source in parallel with a diode, shunt resistance. A series resistance is also included to consider contact resistance.

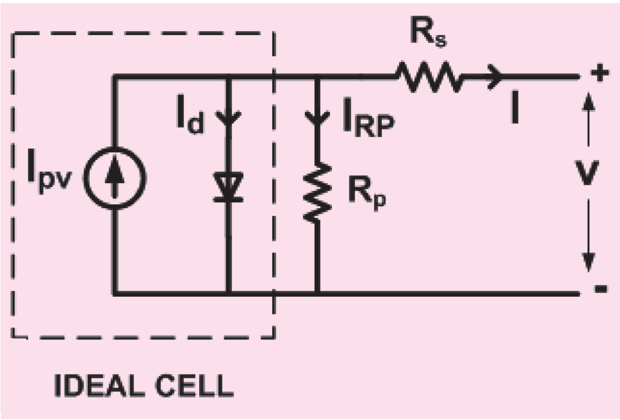

FIG. 2 SINGLE DIODE MODEL OF SOLAR CELL

$$I = I_{PV} - I_d - I_{RP} \quad \text{....(1)}$$

$$\Delta T = T - T_n \quad \text{....(2)}$$

$$I = I_{PV} - I_o \times e^{\left(\frac{V+R_S \times I}{V_t \times a}\right)} - \frac{V + R_s \times I}{R_p} \quad \text{....(3)}$$

$$I_{PV} = \left(I_{PV,n} + (K_I \times \Delta T)\right) \times \frac{G}{G_n} \quad \text{....(4)}$$

$$I_o = \frac{I_{sc,n} + (K_I \times \Delta T)}{e^{\left(\frac{V_{oc,n}+K_V \times \Delta T}{a \times V_t}\right)} - 1} \quad \text{....(5)}$$

$$V_t = \frac{N_s \times K \times T}{q} \quad \text{....(6)}$$

And I_{PV} α insolation

Where

V : Panel output Voltage in volts

I : Panel Output Current in Amps.

I_{PV} : Current Generated by incident light at nominal condition (25°C, 1000W/m_2) in Amps.

I_d : Current through the diode in Amps.

R_P : Parallel resistance (to consider leakage current) in ohms.

I_{RP} : Current through parallel resistance in Amps.

R_s : Series Resistance (to consider contact resistance) in ohms.

I_o : Reverse saturation or leakage current in Amps.

a : diode ideality constant.

I_{sc} : Short-circuit current of PV panel in Amps.

V_{oc} : Open circuit voltage of PV Panel in Volts.

K_I : Short-Circuit current temperature coefficient

T_n : Nominal temperature in Kelvin.

T : Cell temperature in Kelvin.

K_v : Open circuit voltage temperature coefficient.

G : Irradiation on the surface of PV panel in watts/m^2.

G_n : Nominal irradiationin watts/m^2.

N_s : No. of cells connected in series.

K : Boltzmann constant (1.3806503 x 10^{-23} J/K).

q : Electron charge (1.60217646x10^{-19}C).

In this paper, 50 W PV Panel (WS-50) is modeled without considering the effect of partial shading of PV panel.

3.0 DESCRIPTION OF PV EMULATOR

3.1 Power circuit

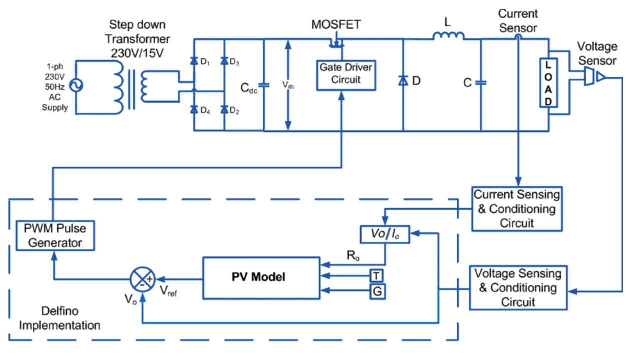

FIG. 3 SCHEMATIC REPRESENTATION OF PHOTOVOLTAIC EMULATOR

The power circuit of PV Emulator consists of rectifier and DC-DC buck converter to obtain I-V characteristics of PV panels. Power circuit along with controller is shown in Figure 3.

The input to the rectifier is fed from single phase 50Hz step down transformer which also provides isolation from mains. Here KBPC 2510 full bridge rectifier module is used for rectification and capacitor filter is used for smoothing the output voltage, i.e., to get DC from pulsating DC.

3.2 Output capacitor filter design for rectifier

The size of capacitor depends on ripple voltage, load resistance and is given by

$$C_{dc} = \frac{V_p}{V_{ripple} \quad R_L} \text{ x } \Delta t \qquad ....(7)$$

Where Vp is the peak voltage in volts

Vripple is ripple in output Voltage in volts

R_L is the load resistance in ohms

Δt (in sec) is time between successive peaks of the output waveform of rectifier.

The value of capacitance used in the circuit is 0.05F for a peak voltage of 15√2, output voltage ripple of 2%, load resistance of 10 Ω and Δt is 10 ms (for a frequency of 50 Hz and full-wave bridge rectifier circuit is used)

3.3 Design of L & C filter for buck converter

Buck converter operates with one switch, hence switching losses, conduction losses are less and the converter efficiency is generally greater than 90% under wide variations in load. The output voltage of the converter is unipolar and supplies unidirectional current.

The value of inductor depends on peak to peak ripple current and given by

$$\Delta I = \frac{V_a(V_s - V_a)}{fLV_s} \qquad ....(8)$$

$$\Delta I = \frac{V_s k(1-k)}{fL} \qquad ....(9)$$

$$L = \frac{V_s k(1-k)}{f x \Delta I} \qquad ....(10)$$

Where Vs is the supply voltage in volts

K is the duty ratio.

F is the frequency in hertz.

ΔI is peak to peak ripple current.

For a supply voltage of 21 V, duty ratio of 0.5, frequency of 25 kHz, load current of 8 A, and ripple current not exceeding 1% the value of inductance is 2.625 mH. The practical value chosen is 2.3mH.

The critical value of inductance to operate the converter in continuous conduction mode is given by

$$L_c = \frac{(1-k)R}{2f} \qquad ....(11)$$

The critical value of inductance is so chosen that it must supply continuous current at low duty ratio and light load.

For a duty ratio of 0.1 and load resistance of 10 Ω and 25 kHz frequency the value of critical inductance is 0.18 mH. Inductance value choosen is greater than critical value to ensure continuous conduction mode.

The size of capacitance depends on peak to peak ripple voltage and given by

$$\Delta V_c = \frac{V_a(V_s - V_a)}{8LCf^2V_s} \qquad ....(12)$$

$$\Delta V_c = \frac{V_s k(1-k)}{8LCf^2} \qquad ....(13)$$

$$C = \frac{V_s k(1-k)}{8Lf^2 \Delta V_c} \qquad ....(14)$$

For supply voltage of 21 V, duty ratio of 0.5, inductance of 2.3 mH, frequency of 25 kHz and peak to peak ripple voltage not exceeding 1.5 % the value of C is 1.26 mF. The practical value chosen is 1000 μF.

4.0 CONTROL LOGIC

The controller used here is Delfino (TMS320F28335). As the voltage across the load and current through the load can't be directly sensed by controller, voltage sensor (LV20P) and current sensor (LA25np) are used along with signal conditioning circuit.

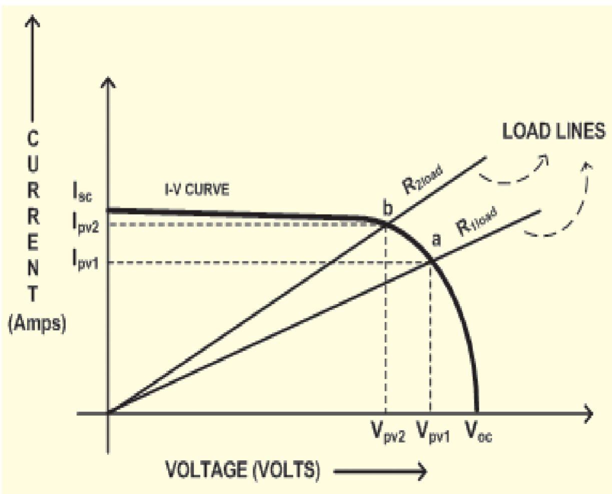

FIG. 4 OPERATING POINT OF PV EMULATOR

Figure 4 shows I-V curve of PV module to be emulated and load line corresponding to load resistance. Load line varies with load. As the load resistance is decreased from R_1load to R2load slope of load line increases. Converter should operate at the operating point which is the intersection of load line and I-V curve of module, to operate as a PV Emulator. The operating I-V characteristics generated by PV emulator incorporating PV array specifications provided by manufacturer.

Figure 5 shows the Flow Chart to explain how the controller controls the converter to act as PV Emulator.

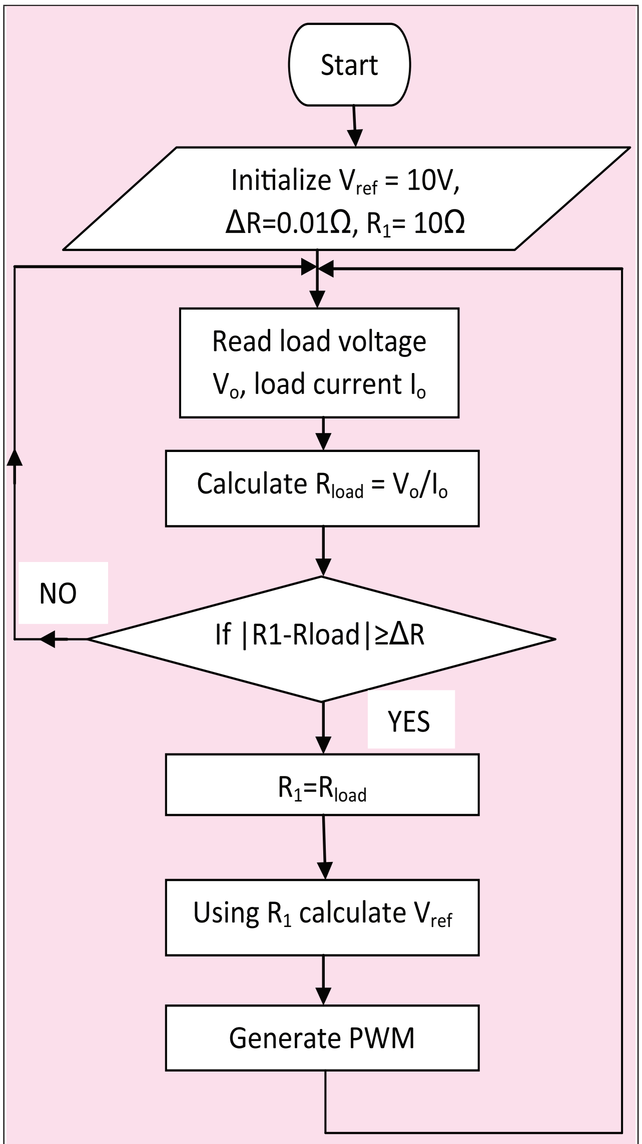

FIG. 5 FLOW CHART OF CONTROL

Initialize V_{ref} and R_1 to some random values, to get random output voltage and output current through the load. Then the controller reads output voltage (V_o) across the load and current through the load (I_o) and calculates load resistance $R_{load}=V_o/I_o$. Now it calculates change in load. These steps are followed for continuous monitoring of load. Whenever controller detects the change in load it generates $V_{ref.}$ V_{ref} is calculated by solving the non linear equation with Newton-Raphson method. Using this V_{ref} PWM pulses are generated accordingly to operate the switch thus controlling the converter to act as a PV Emulator.

5.0 SIMULATION RESULTS

In this paper I-V characteristic of 50 W Waree panel with insolation of 750 W/m^2 and cell temperature of 25^{o}C is generated as shown in Figure 6.

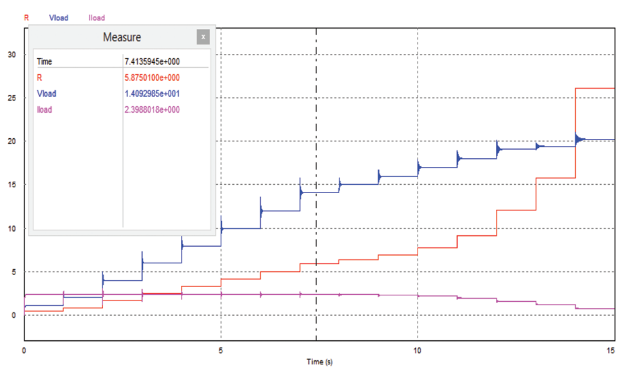

FIG. 6 SIMULATION RESULTS WITH VARIABLE LOAD

In this section the performance of PV Emulator with variable linear load is analyzed. The operating point of PV Emulator depends on load. If load=2.5 Ω, the operation will be at a point where the ratio of voltage and current of PV module is equal to 2.5 Ω.

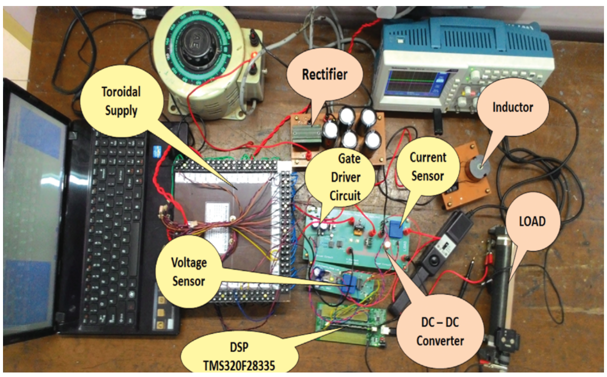

FIG. 7 HARDWARE PROTOTYPE

This is achieved at point 'D' where the voltage and current are 6 V & 2.4 A respectively as shown in Figure 8. When the load is increased from 0.45 Ω to 26 Ω operating point moves from 'A' to 'O'. Thus depending on load, there exists a unique point on I-V characteristics where PV Emulator should operate. Table 1 shows the operating points of PV Emulator when load is varied.

The steady state operating points are highlighted in Figure 8. Thus DC-DC converter is controlled as a PV Emulator to behave that of PV module.

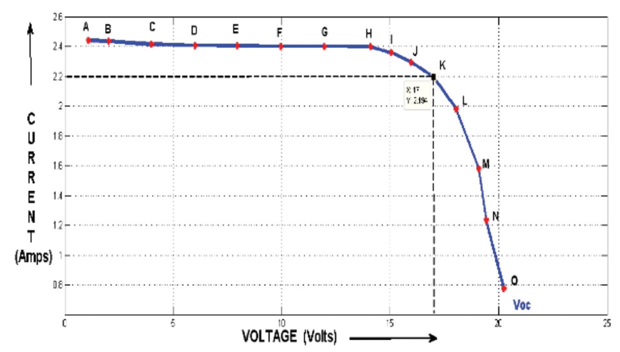

FIG. 8 SIMULATION RESULT FOR I-V CURVE

TABLE 1

OPERATING POINTS OF CONVERTER

T (s)	$R_{load}(\Omega)$	V_{load}(V)	I_{load} (A)	Oper. pt	P_{max}
1	0.45	1.1	2.44	A	2.68
2	0.83	2.03	2.43	B	4.95
3	1.66	4.00	2.41	C	9.67
4	2.50	6.02	2.41	D	14.7
5	3.31	7.96	2.40	E	19.12
6	4.15	9.97	2.40	F	23.93
7	4.99	11.98	2.40	G	28.74
8	5.87	14.09	2.40	H	33.81
9	6.37	15.04	2.36	I	35.47
10	6.95	15.95	2.29	J	36.60
11	7.75	17.00	2.20	K	37.30
12	9.10	18.03	1.98	L	35.74
13	12.07	19.08	1.58	M	30.16
14	15.75	19.42	1.23	N	23.95
15	26.09	20.23	0.77	O	15.67

6.0 DESCRIPTION OF PROTOTYPE EQUIPMENT

The components used to implement DC-DC converter are IRFP250 MOSFET (200V, 30A) and its corresponding driver circuit which consists of Opto-coupler (6N137) for isolation and driver (4425) for bipolar gate pulses.Fast recovery diode RHR15120 has been used. Taking high frequency and core losses into consideration, ferrite core has been selected for inductor. The supply to the converter is given from a single phase rectifier. KBPC2510 rectifier module is used in this prototype. The capacitors used are five 10 mf in parallel for DC-Bus and 1000 µF in the

DC-DC converter to achieve ripple less than 2% of output voltage ripple. The microprocessor used in this prototype to control DC-DC converter is TMS320F28335 which is digital signal processor (DSP) as it integrates the peripherals needed, has flexibility in programming, its speed and its robustness against perturbations. The physical implementation of the prototype is shown in Figure 7.

6.1 Experimental results

Once the Emulator has been designed and constructed, its performance is tested. In this paper 50 W Waree panel is emulated at insolation of 750 W/m^2 and cell temperature of 25^{o}C. Figure 9. shows the theoretical and experimental I-V curves.

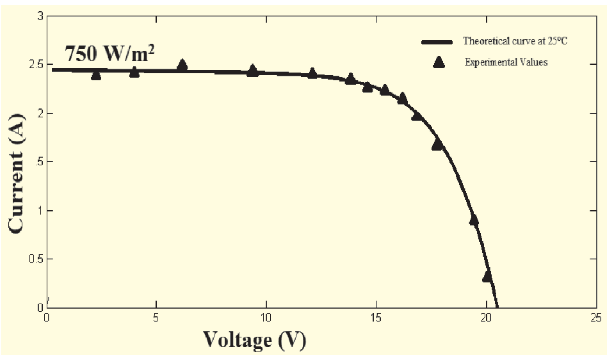

FIG. 9 COMPARISON OF THE THEORITICAL CURVE & EXPERIMENTAL VALUES

7.0 CONCLUSIONS

The DC-DC converter based PV Emulator has been proposed and emulated. The PV Emulator designed can realize PV panel with different specifications and different configurations. The simulation is done in P-SIM^{TM} version 9.0.3. The performance of the PV emulator has been tested by connecting variable linear load and this system is able to behave electrically similar to PV array.

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