

Development of a Microcontroller Based PV Emulator with Current Controlled DC-DC Buck Converter

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Abstract- Testing and validation of Photovoltaic based energy conversion systems requires Photovoltaic (PV) panels in laboratory environment. A flexible testing system, which eliminates these panels and emulating the dynamic characteristics of PV sources in real time are gaining importance. This paper presents a new algorithm for emulation of PV characteristics using a DC-DC buck converter in current control mode. The algorithm tracks the point on the V-I characteristics of the PV under varying loads by generating the corresponding current reference. This reference current is used for the generation of gate pulses for the DC-DC converter, which acts like a constant current source to emulate the PV panel. In the proposed system, real time variation of irradiance and temperature are incorporated as a time varying input parameters to the PV emulator. The proposed algorithm has been simulated numerically using MATLAB/SIMULINK platform and is experimentally verified on a laboratory test bench consisting of a DC-DC buck converter of 50 W rating with ATmega328 as a core controller. Both simulation and hardware results are presented showing the effectiveness of the proposed system under dynamic loading and environmental conditions.

Keywords—DC/DC Buck converter, PV Emulator, Maximum Power Point (MPP).

1. Introduction

A controlled environment to test PV equipment is difficult since consistent repeatable conditions are impossible to reproduce. A PV panel electrical characteristics is based on a variety of factors including the amount of irradiance received, temperature of the panel, and the material used to make the PV panel. Recently, the more and more growing interest in applications of Renewable Energy Sources (RES), with all the related problems of their optimal exploitation, has increased the need of experimental equipment to carry out measurements and tests, without the direct use of the renewable source (PV panels). To test the large power rating PV based systems, large power rating panels are required which are more costly and requires more space.

A PV emulator will simulate the current and voltage characteristics of a photovoltaic panel under these varying conditions. Having consistent electrical characteristics reproduced, which allows easier analysis and system optimization with this PV emulators. Any type of PV panel characteristics with its scaled model can emulate with

dependent parameters will eliminates the need of costly PV panels.

Nowadays, PV emulators are commercially available and so many universities proposed PV emulators with different algorithms [1]-[8], The PV emulator with analog circuits using photo sensor which magnifies the output voltage is developed[1]-[2]. In this paper, the power output of the simulator circuit can be controlled by a light intensity supplied from LED. The real time emulator using Lab VIEW and NI-ELVIS platform for emulating the PV cell characteristics with fair accuracy is tested [3]. Some emulators are built by sensing the current through load and finding the voltage at that point by using V-I characteristics [4].

Some PV emulators are based on the load resistance with the PV cell resistance comparison [5]-[6]. The lookup table is used in PV emulators to store the resistance, voltage, current data at each point of V-I characteristics and search algorithm is developed to find the reference voltage at a given load resistance [7]. Some PV emulators are also developed using

programmed power supplies with computer interface [9]-[11].

In this paper, emulation of PV characteristics is proposed using real time load resistance measurement. This proposed PV emulator is shown in Fig.1. It is built using DC-DC buck converter for obtaining the desired PV cell characteristics at different irradiance and temperature conditions. The necessary current at a given load is supplied at a given voltage by the DC-DC converter. This is tracking the load resistance and current reference is generated which is better than the voltage reference control techniques [5]-[7]. This emulator incorporates the PV characteristic using mathematical model incorporating the realistic PV array details available on the PV panels. The real time realization of the PV model incorporating the non-linear behaviour and dependence of temperature and irradiation is implemented using Arduino micro controller. The emulator dynamics is modelled using MATLAB/SIMULINK and then tested with 50W DC/DC converter with the sensors and microcontroller. The performance of the emulator under dynamic load variation is matches with the real time emulator of the PV panels.

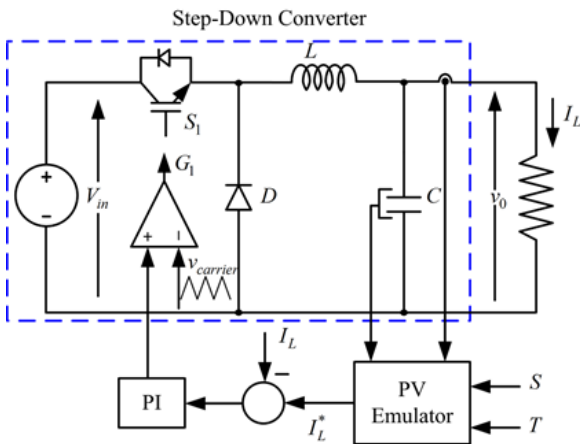


Fig. 1. Proposed PV Emulator with Buck converter.

2. PV Modeling

The single diode model as shown in Fig. 2 is used as a PV equivalent. This model offers a good compromise between simplicity and accuracy.

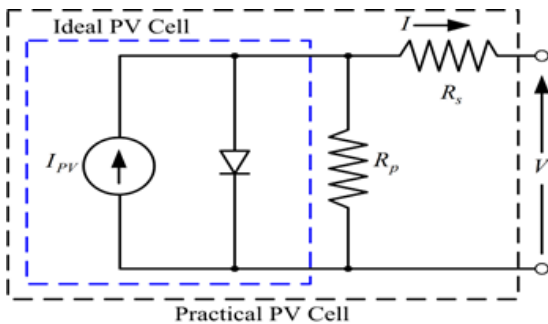


Fig. 2. Single-diode model of a PV cell.

Practical arrays are composed of several connected PV cells and hence the inclusion of additional parameters to the basic

equation is needed for representation of a practical PV array. The PV array output current is given by equation (1).

$$I = I_{PV} - I_0 \left[\exp\left(\frac{V + R_s I}{V_t} * a\right) - 1 \right] - \left(\frac{V + R_s I}{R_p}\right) \tag{1}$$

Where I_{PV} and I_0 are cell photovoltaic and diode leakage currents respectively, V is the output voltage across module, V_t is the thermal voltage of the module with N_s cells connected in series, K is Boltzmann constant (1.38×10^{-23} J/K), q is charge of electron (1.6×10^{-19} C) and T (in Kelvin) is the temperature of the module. The cell photovoltaic current is calculated from

$$I_{PV} = (I_{PV,n} + K_I \Delta T) \frac{G}{G_n} \tag{2}$$

and the diode leakage current is computed from

$$I_0 = \frac{I_{SC,n} + K_I \Delta T}{\exp\left(\frac{(V_{oc,n} + K_V \Delta T)}{aV_t}\right) - 1} \tag{3}$$

Where, I_{PVn} is light generated current at nominal condition (usually 25°C and 1000 W/m^2), T_n is nominal temperature, G is irradiance on device surface (W/m^2), G_n is nominal irradiance (W/m^2), K_I is temperature coefficient of short circuit current.

3. Proposed Emulator Algorithm

In this PV emulator algorithm, the point on the PV cell I-V characteristics for a load without comparing the actual resistance with the estimated PV resistance given in [5]-[6]. The set point obtained with this algorithm is fast as shown in Fig. 3 (a) and (b)

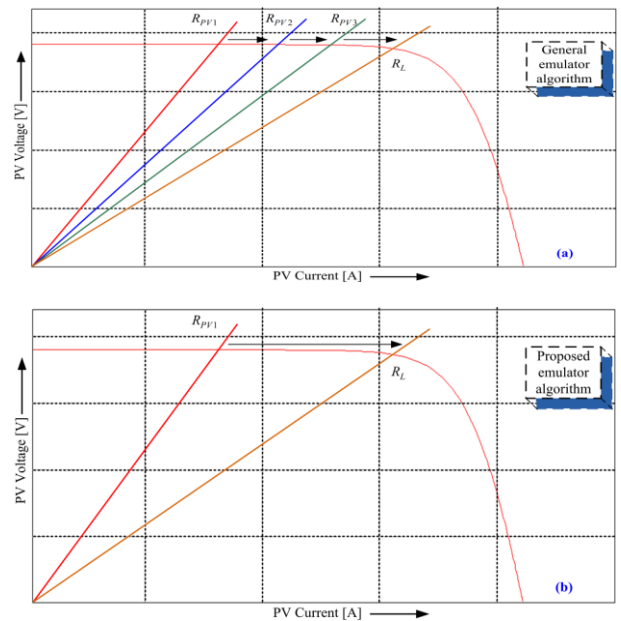


Fig. 3. (a) General existing emulator tracking principle (b) Proposed emulator tracking principle.

In Fig. 4, a flow chart statement showing the operating principle is presented. As shown in flowchart, using mathematical modelling equations of PV cell, resistance at each PV cell voltage in the steps of 0.1V up to open circuit voltage for a given irradiance and temperature is obtained. This open circuit voltage depends on the temperature and irradiance. It is obtained by comparing power at each voltage with zero, whenever it is negative that voltage is the open circuit voltage. The load resistance $R_o(=V_o/ I_o)$ is calculated by sensing the buck converter output voltage (V_o) and current (I_o). Now PV cell current corresponding to R_o is calculated in iteration, this value of current act as reference value for the output current, which is controlled using a proportional integral controller.

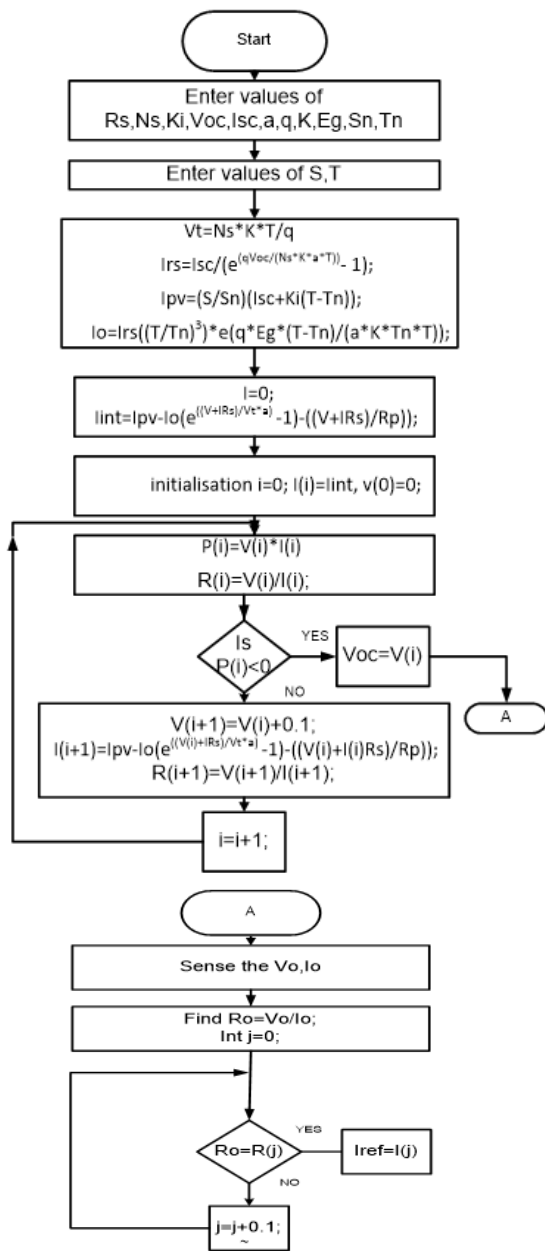


Fig. 4. Proposed emulator algorithm.

The major components are PV emulator algorithm which comprises a real time execution of the PV model under study, DC-DC buck converter, DC source and sensors for irradiation and temperature.

The output voltage (V_o) and current (I_o) are sensed through voltage divider and current sensors respectively. This is then conditioned for interfacing to the controller. The temperature and irradiance are used as the input parameters for the controller to simulate the PV characteristics.

4. Small Signal Modeling of Converter and Control Design

The DC-DC converter is modelled using small signal analysis in order to derive the transfer function relation between input current and duty cycle. For the sake of simplicity, all elements are considered ideal. The power to the converter is supplied from the source at voltage V_{in} . The switch operates at high switching frequency with a switching period T_s . The inductor L and capacitor C are the dynamic elements of the circuit and the current through inductor i_L and voltage across capacitor v_C are the dynamic variables. There are two linear circuits obtained in the converter, one corresponding to each of the switch (ON & OFF) position. Fig. 5(a) shows the equivalent circuit when the switch is ON and the governing equations for the circuit are

$$V_{in} = L \frac{di_L}{dt} + v_C \quad ; \quad \frac{di_L}{dt} = \frac{V_{in}}{L} - \frac{v_C}{L} \tag{4}$$

$$i_L = C \frac{dv_C}{dt} + \frac{v_C}{R} \quad ; \quad \frac{dv_C}{dt} = \frac{i_L}{C} - \frac{v_C}{RC} \tag{5}$$

Fig. 5 (b) shows the equivalent circuit when the switch is OFF and the governing equations for the circuit are

$$\frac{di_L}{dt} = -\frac{v_C}{L} \tag{6}$$

$$\frac{dv_C}{dt} = \frac{i_L}{C} - \frac{v_C}{RC} \tag{7}$$

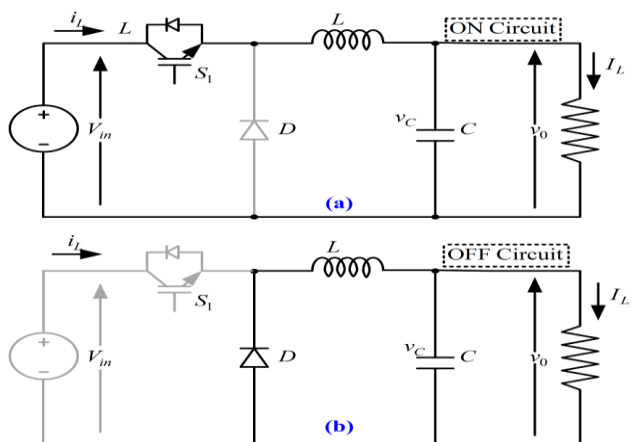


Fig. 5. Modes of operation of the converter.

It is convenient to express these equations in the form of state space model

During ON time,
 $\dot{x} = A_1x + b_1v_{in}$ (8)

$v_0 = q_1x$

During OFF time,
 $\dot{x} = A_2x + b_2v_{in}$ (9)

$v_0 = q_2x$

where

$$\dot{x} = \begin{bmatrix} \frac{di_L}{dt} \\ \frac{dv_C}{dt} \end{bmatrix}; A_1 = A_2 = \begin{bmatrix} 0 & -\frac{1}{L} \\ \frac{1}{C} & -\frac{1}{RC} \end{bmatrix}$$

$$b_1 = \begin{bmatrix} \frac{1}{L} \\ 0 \end{bmatrix}; b_2 = \begin{bmatrix} 0 \\ 0 \end{bmatrix}; q_1 = q_2 = [0 \quad 1]x$$

The averaged model of the converter is obtained by averaging the two state models over the switching cycle

$\dot{x} = Ax + bv_{in}; v_0 = qx$

$A = A_1d + A_2(1-d)$

$b = b_1d + b_2(1-d)$

$q = q_1d + q_2(1-d)$

As the output current is the parameter to be regulated, the output current to control transfer function is derived as follows.

$$\frac{\hat{i}_L(s)}{\hat{d}(s)} = \frac{v_{in}}{R} \frac{1}{1 + s\frac{L}{R} + s^2LC}$$
 (10)

The gain and time constant of the PI controller is tuned according to the requirement of gain cross over frequency of 8000 rad/s and a steady state error requirement of <1%. The bode plot of uncompensated and compensated system is shown in Fig. 6.

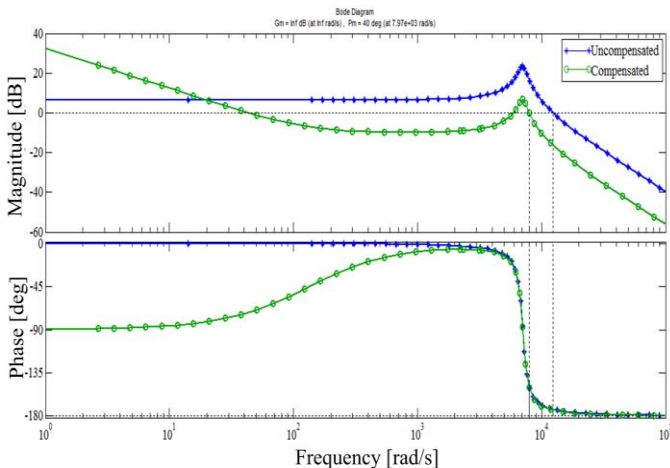


Fig. 6. Bode plot of output to control transfer function.

5. Simulated Steady State and Dynamic Performance of the Emulator

In this section, simulation of PV model with mathematical equations and proposed PV Emulator is presented. The proposed new algorithm performance of the PV emulator under steady state and dynamic behaviour is tested with varying load. The equations described in section 2 for PV is modelled and simulated in MATLAB. It consists of controlled current source with anti-parallel diode and the equivalent resistances of a PV model with the parameter given in Table 1 is shown in Fig. 7.

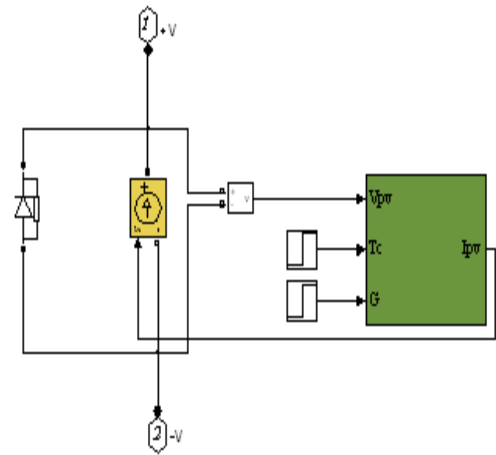


Fig. 7. PV model simulation diagram in MATLAB.

Table 1. Electrical Specification of PV array.

Maximum power	50 W
Voltage at power (V_{mp})	17 V
Current at maximum power (I_{mpp})	2.94 A
Open-circuit voltage (V_{oc})	21 V
Short-circuit current (I_{sc})	3.17 A

Table 2. Specification of DC-DC converter

Inductor L	0.2 mH
Capacitor C_1 & C_2	100 μ F
Switching frequency	20 kHz
Switches MOSFET - IRFP 250	200 V, 30 A
Diodes - RHRP8120	1200 V, 8 A

The PV emulator is tested for MPP condition by connecting the load resistance of value equal to the internal impedance at MPP of the PV panel. At this value of load resistance, PV model is delivering the 50W power which is maximum of the panel at standard test condition (STC). For the same load, PV emulator set the reference current I_{ref} value is 2.94 A, which is regulated through the load and thus the PV emulator is delivering the power of 50W corresponding to MPP at STC as shown in Fig. 8.

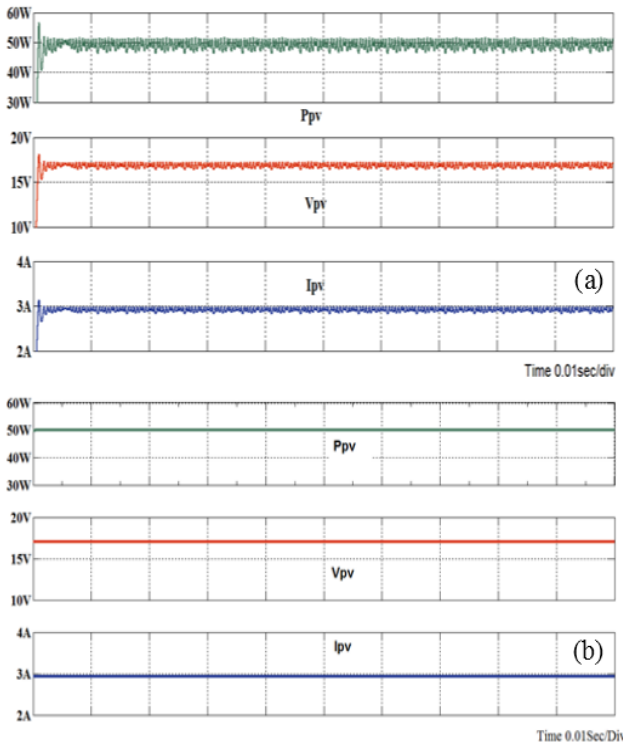


Fig. 8. Performance at MPP condition (a) PV Emulator (b) PV model

In the proposed PV emulator, algorithm is simulated with buck converter and is also tested for different loading conditions with different irradiance and temperatures. As shown in Fig. 9, initial load is $10\ \Omega$ and changed to $6.16\ \Omega$ at 0.01 sec. This decrease in load resistance across PV model increases the power, similarly in the proposed emulator also power is increased for decreasing the load resistance

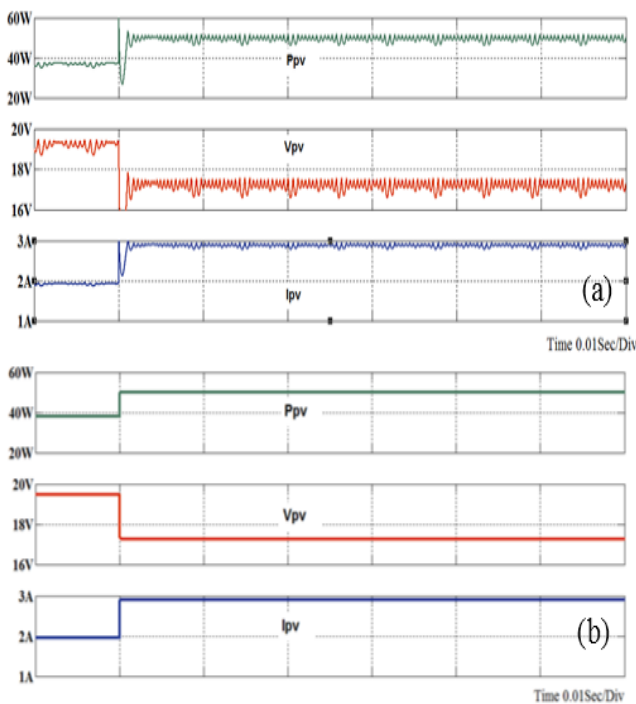


Fig. 9. Performance For load change from $10\ \Omega$ to $6.16\ \Omega$ (a) PV Emulator (b) PV model.

At fixed load of $7.21\ \Omega$, PV emulator and PV mathematical model are tested by changing the irradiance $500\ \text{W/m}^2$ to $1000\ \text{W/m}^2$ and temperature from $323\ \text{K}$ to $298\ \text{K}$ as shown in Fig.10, Fig.11 respectively. The performance indicated in this figures concludes that the emulator characteristics are matching with the mathematical modelling of PV cell characteristics. This confirms that the proposed algorithm is working effectively.

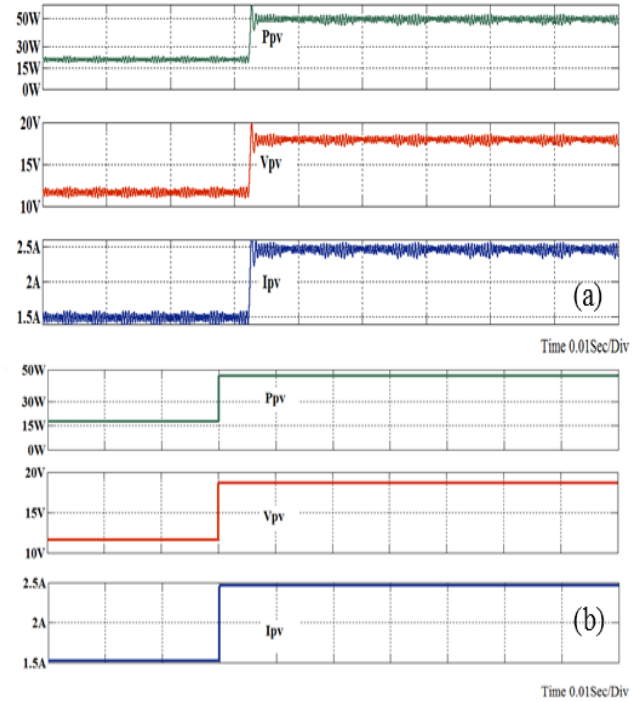


Fig. 10. Irradiance changed from $500\ \text{W/m}^2$ to $1000\ \text{W/m}^2$ at $7.21\ \Omega$ load (a) PV Emulator (b) PV model

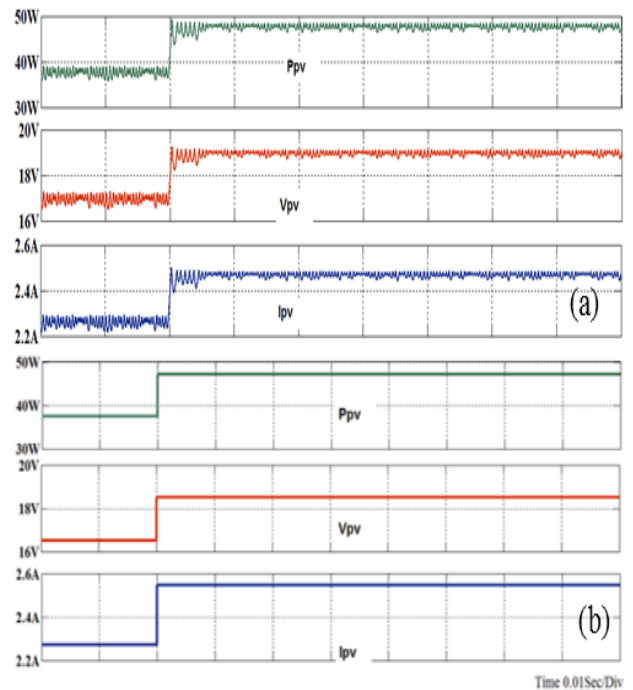


Fig. 11. Temperature changed from $323\ \text{K}$ to $298\ \text{K}$ for $7.21\ \Omega$ load (a) PV Emulator (b) PV model

6. Experimental Steady State and Dynamic Performance Results

This proposed PV emulator algorithm is realized in hardware using arduino microcontroller (Atmega328). The parameters of the converter are same as the simulation parameters in Table 2. The PI controller and PWM generator is realized using the same controller working as core controller for all control action. The I/O pins are interfaced with the driving circuit to activate the switching devices. The DC-DC buck converter topology is built with the MOSFET (IRFP250). The interfacing drivers with isolation circuit using TLP350 IC is built. The output voltage measurement is done by using potential divider and the current measurement was done by using current sensor (WCS 2705). Signal conditioning circuit was employed to condition the sensed signals before inputting to the controller.

Experimental results are shown in Fig.12 (a) for steady state performance. It is tested for maximum power output by adjusting the load resistance value corresponding to the resistance at maximum power point. A power of 50Wp drawn for the given loading condition, which corresponds to the power at MPP is delivered by the emulator. The V_o and I_o are equal to 17V, 2.94A respectively, which are the desired values of V_{mpp} and I_{mpp} .

Experimental results presented in Fig 11(b), (c) and (d) for the change in load, temperature and irradiance respectively. This shows PV emulator behaviour under varying dynamic conditions.

The step change in load from 10Ω to 6.16Ω causes the variation in power. This variation of power is shown in Fig.12 (b). From these results it is observed that the power obtain is equal to the simulated performance value given in Fig.8. Similarly a change in irradiation from $500W/m^2$ to $1000W/m^2$ with a fixed load of 7.21Ω is given in Fig.12 (c). The variation in the power from 20W to 48W is observed. It is also tested for variation in temperature from 323K to 298K and presented in Fig.12 (d). These results are in good agreement with the simulated results as indicated in previous section. This confirms the modified algorithm for PV emulator algorithm is satisfactorily working under various loading condition. This simulator now can be integrated for PV performance studies with front end DC-AC converters, MPPT algorithms and energy storage devices

7. Conclusion

The operating principle of proposed PV emulator based on load resistance tracking is presented. The basic design control algorithm is tested with simulation in MATLAB and its performance under steady state and dynamic conditions are evaluated. The hardware prototype is built using ATmega328 controller with all interfacing electronic circuitry for the control of 50 W DC/DC converter power circuit. This laboratory emulator is tested for its steady state and dynamic operation under varying operating parameters. The maximum power transfer at critical loading condition is confirmed and verified for a given PV specifications. Under varying parameters like temperature and irradiation, the behaviour of PV emulator is as desired.

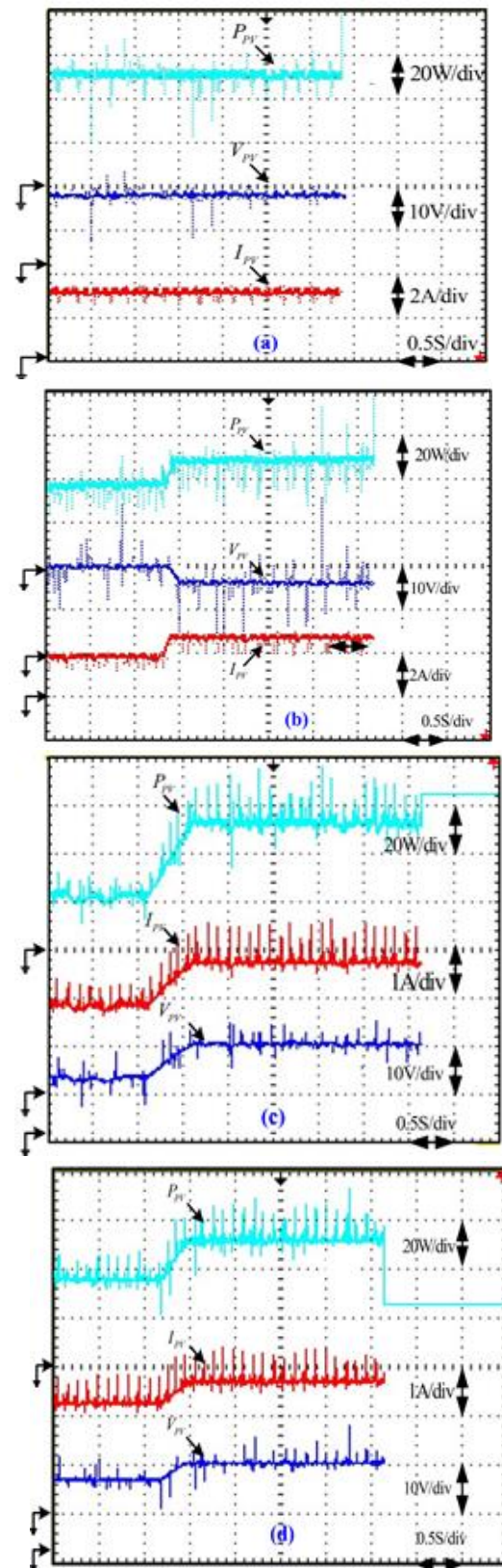


Fig. 12. PV Emulator output waveforms (a) at MPP condition (b) Loading from 10Ω to 6.16Ω (c) Irradiance changed from $500W/m^2$ to $1000W/m^2$ and (d) Temperature changed from 323K to 298K.

The hardware results obtained validates and closely resembles the simulation results. Thus the proposed system serves as a replacement to PV array and it is possible to extend the power rating as desired for the analysis in laboratories.

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