

A dynamic photo voltaic emulator using dSPACE controller with high accuracy solar photo voltaic characteristics

T. Sudhakar Babu, S. Mohammed Azharuddin, B. Nishant, and N. Rajasekar

Citation: *J. Renewable Sustainable Energy* **8**, 015503 (2016); doi: 10.1063/1.4940414

View online: <http://dx.doi.org/10.1063/1.4940414>

View Table of Contents: <http://aip.scitation.org/toc/rse/8/1>

Published by the [American Institute of Physics](#)

A dynamic photo voltaic emulator using dSPACE controller with high accuracy solar photo voltaic characteristics

T. Sudhakar Babu, S. Mohammed Azharuddin, B. Nishant, and N. Rajasekar
*Solar Energy Research Center, School of Electrical Engineering, VIT University,
Vellore 632014, India*

(Received 21 May 2015; accepted 8 January 2016; published online 22 February 2016)

An alternative method of testing maximum power point tracking and solar Photo Voltaic (PV) system performance with a solar PV emulator is presented in this paper. Solar PV emulators are Hardware-in-Loop setup, which mimics the characteristics of a PV panel. Further, these emulators are supplementary to strenuous field testing and commercial solar PV training systems available for research prototyping. In this paper, a solar PV emulator built using a DC-DC Buck Converter and dSPACE ds1104 controller is proposed. In addition, MATLAB/SIMULINK Environment is used to construct the Mathematical Model of Solar PV Module. The proposed Solar PV Emulator has the following features: (1) ease in interfacing with faster dynamic response, (2) ability to monitor and control in real-time using a control desk, (3) higher bandwidth DC-DC buck converter, (4) stable output with lower response time, (5) lower output voltage and current ripple, and (6) capability to reproduce near accurate static and dynamic characteristics of any solar PV module. To illustrate the performance of the proposed emulator, the I-V characteristics of a shell SP70 PV panel are obtained. To further understand the dynamic and steady state behaviour of the system, experimentations are done at different operating conditions. Finally, to know the suitability of the proposed emulator for maximum power point tracking, the Perturb & Observe algorithm is tested for uniform and partial shading conditions. © 2016 AIP Publishing LLC. [<http://dx.doi.org/10.1063/1.4940414>]

I. INTRODUCTION

The rise in energy demands and rapid changes in the technological and industrial sectors have alarmed the power generation industry. Further, concerns about the haphazard environmental and climatic changes and restrictions on emissions from fossil fuels have motivated researchers to find alternate energy resources that have the least carbon footprint and are perpetual in nature. In recent years, research on renewable energy, in particular solar energy, has caught worldwide attention as it is abundant and practically inexhaustible. Moreover, it is pollution free and provides noiseless operation. In the last couple of decades, Solar Photo Voltaic (PV) technology has been gaining significant interest since considerable incentives have been given to promote its large scale development.¹

A solar PV cell is a device which converts the incident sunlight into electricity; cells of solar PV are grouped to form a module and are further grouped to create a PV array. Limited by its non-linear characteristics and environmental dependency, solar PV arrays are connected to Power Electronic Converters (PEC), wherein different Maximum Power Point Tracking (MPPT) methods are employed to extract maximum power output from the PV array.²⁻⁴ MPPT methods are an integral part of the solar PV system since they maximize the output of PV, and therefore help to improve the PV system efficiency.^{5,6}

Since MPPT methods are implemented in solar PV system via PEC, these converters are needed to be tested for all possible kinds of faults like grid disturbances and reliability before practical implementation. Therefore, its repeated field testing under different environmental conditions becomes very critical as these converters form the backbone of the entire Solar PV

system.⁷ Moreover real time continuous field testing with all types of environmental conditions becomes practically impossible, since PV array characteristics cannot be controlled and it varies with respect to environmental conditions. A cost effective solution to the above problem may be employing a solar PV emulator instead of an actual solar PV Panel. Solar PV emulator is a hardware prototype capable of mimicking the electrical characteristics of a solar PV Panel in a controlled environment.⁸ Generally, solar PV emulators are built using power electronics circuits to reproduce the static and the dynamic behaviour of real solar cells or arrays over a wide range of environmental and load conditions.⁹ In fact, these emulators are compact, cost-effective, and can be an appropriate substitute to actual solar PV module in places where real time testing is limited by time consuming field tests, high initial cost, and space constraints.

Many researchers and industries have developed solar PV emulators for mimicking the solar PV characteristics.^{10–21} In Refs. 10–12, by amplifying the photo-current and voltage of a photodiode, a solar PV simulator is proposed. An equivalent circuit of the PV using a current source and a diode for emulating solar PV characteristics was proposed in Ref. 13. With the help of digital controller and by controlling the switching states of the converter I-V characteristics of PV panel is simulated in Refs. 14 and 15. A lookup table approach is used in Ref. 15 for the determination of solar PV characteristics. In this method for higher accuracy, a large number of panel data at different operating conditions are recorded; hence, it requires larger memory storage. Another alternate method proposed for PV characteristics emulation is the Curve-fitting procedure where every point on I-V characteristics is matched. Even though this method comparatively requires lesser memory space, due to the non-linearity of I-V curves, it involves higher order equations which in turn increase the computational time and complexity. In Ref. 19, a piecewise linear approach using a low cost microcontroller has been proposed to overcome the computational time. The authors in Ref. 22 proposed a parabolic collector rating of 3500 W for application to stirling engine, which was designed and analyzed. A mathematical model is implemented to determine optimum hybrid system for meeting the electrical energy needs of electrical building in Ref. 23.

A DC-DC buck converter employing mathematical model for PV panel simulation is proposed in Refs. 16–20. This approach made the design process simpler and helps in easy implementation. In this method, the predicted characteristic depends on the accuracy of the mathematical model used. In Ref. 24, the authors have proposed a solar PV array emulator using a full bridge structure with high frequency transformers and two proportional integral (PI) controllers. The method has only limited accuracy near short circuit current operation and the system dynamics have acceptable ripple content. Some of the commercially available solar PV Training systems use halogen lamps,²⁵ halide discharge lamps,²¹ and incandescent lamps as solar emulators to simulate the solar cell characteristics and thereby making an attempt to overcome the environmental dependency problem. However, the major drawback of such method is the spectral mismatch, non-uniform distribution of insolation, heat losses, and larger power requirement. Further, most of the commercial solar PV emulators like Ametek Programmable Power supply and Chroma System Solutions can also simulate an I-V curve of the solar module. In addition, software packages like PV-Spice, PV-DesignPro, SolarPro, PVcad, and PVsyst are also available in the market; these simulators can support large array simulations that can be interfaced with MPPT algorithms and power electronic converters. However, they are expensive, unnecessarily complex and rarely support the interfacing of the PV arrays with power converters.²⁶ In Ref. 27, a solar driven, Carnot-like heat engine was optimized using an evolutionary algorithm. Most of the emulators proposed earlier have either any one of the following limitations (1) no provisions for real-time monitoring and control. (2) larger voltage and current ripple, (3) high cost involved, (4) larger memory requirement or computational time, (5) difficulty in hardware interfacing, (6) slower response time, and (7) limited accuracy range.

Therefore, by taking all the above facts into account, in this paper, a near accurate solar PV emulator using dSPACE ds1104controller is proposed. The MATLAB model is linked to dSPACE controller and the model is interfaced to software called Control Desk, which provides graphical user interface (GUI) like feature and an animation mode option wherein real-time values, waveforms, and parameters during experimentations can be monitored and controlled via personal computer. The proposed configuration has provisions for real-time control with better

- (3) The reference value is compared with sensed feedback voltage signal in order to generate the voltage error.
- (4) Finally, the error value is fed to the PI controller, and the required gate pulses are generated.

One of the major advantages with the proposed emulator is its flexibility to accurately derive practically any operating point on the plane of I-V characteristics of a solar PV panel. Previous works on emulator do not have provisions to change panel parameters (R_s and R_p) as well as environmental conditions (G and T) under real time, thereby limiting its applications. The following section (Sec. II A) details about the modeling of solar PV characteristics, an overview of dSPACE controller, and the logic behind Pulse Width Modulation (PWM) pulse generation.

A. A modelling of solar PV characteristics

Perhaps, the most important component of a solar PV emulator is its mathematical model, since the accuracy of the emulated characteristics purely depends on this model. Many approaches were followed in the literature for modelling the I-V characteristics of the solar PV. Among them, the popular methods are the single diode model and double diode model. Single diode model is popular for its ease in implementation and simplicity.²⁸ On the other hand, the double diode model²⁹ includes the recombination effect to have better accuracy. More sophisticated models³⁰ using three diodes are also available in literature. For simplicity and to reduce the computational burden, in this work, the authors have used a single diode model. The single diode model equivalent circuit of solar PV is shown in Fig. 2.

Applying Kirchoff's Current Law (KCL) at node "a," the PV current is given by

$$I = I_{pv} - I_D - (V_D/R_p). \quad (1)$$

Ideal diode current equation is given by

$$I_D = I_o[\exp(V_D/V_t) - 1]. \quad (2)$$

Substituting Equation (2) in (1), we get

$$I = I_{pv} - I_o[\exp\{(V + IR_s)/(aV_t)\} - 1] - [(V + IR_s)/R_p], \quad (3)$$

where I_{pv} is the photon current, G is the irradiation, V is the PV terminal voltage, I_D is the diode current, and I is the solar PV panel current.

The values of I_{pv} and I_o are computed with the help of the following equations:

$$I_{pv} = [I_{scn} + K_i(T - T_n)](G/G_n), \quad (4)$$

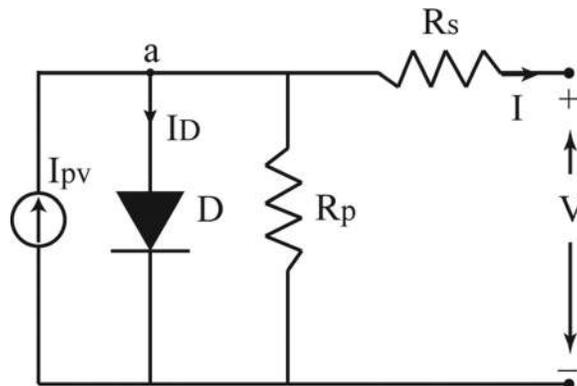


FIG. 2. Single diode model equivalent circuit of solar PV.

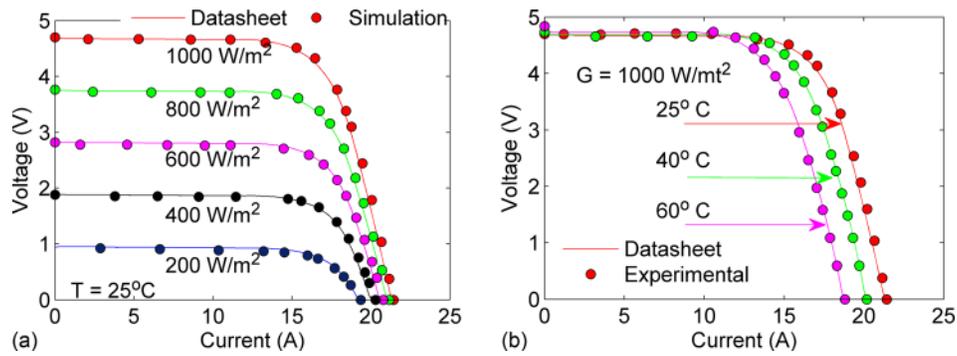


FIG. 3. Comparison of the simulated I-V curves with the datasheet values of shell SP70 solar PV panel.

$$I_o = I_{pv} / [\exp \{ (V_{oc} + k_v dT) / (aV_t) \} - 1]. \tag{5}$$

As from the above equations, it is understood that many unknown parameters are needed to model solar PV characteristics. Hence, the Bacterial Foraging Algorithm (BFA) method is used for solar PV parameter estimation.³¹ Further these parameters control the slope of constant voltage and constant current region.³² The simulated I-V characteristics of shell SP70 panel parameters identified with BFA for different irradiation and temperature are shown in Fig. 3. From the comparison, it is clear that there exists a good agreement between the predicted I-V characteristics and actual one. Henceforth, this model will serve as a reference for the emulation of solar PV characteristics.

B. dSPACE ds1104 controller

The A dSPACE DS1104 controller is suitable for real time control system as it empowers the connecting of the MATLAB/SIMULINK simulated model to the real prototype model. Utilizing the MATLAB/SIMULINK Real-Time Workshop function, the SIMULINK model is compiled, changed over to the C-code, and connected to the real-time dSPACE DS1104 processor board consequently.³³ For the connecting procedure, user needs to incorporate the dSPACE input-output (I/O) interface blocks, e.g., DS1104ADC, DS1104DAC, and DS1104BIT OUT, into the SIMULINK models. With the use of the dSPACE Control Desk GUI software, the monitoring of the performance and behavior of the emulator in real time is made. Indeed, the controller parameters can be changed, and the performance can be observed in real time. A simplified block diagram of the dSPACE DS1104 controller is shown in Fig. 4.

The control desk window of the emulated PV voltage, current, duty cycle, controller constants, PV parameters, irradiation, and temperature is represented in Figures 5–7. The control

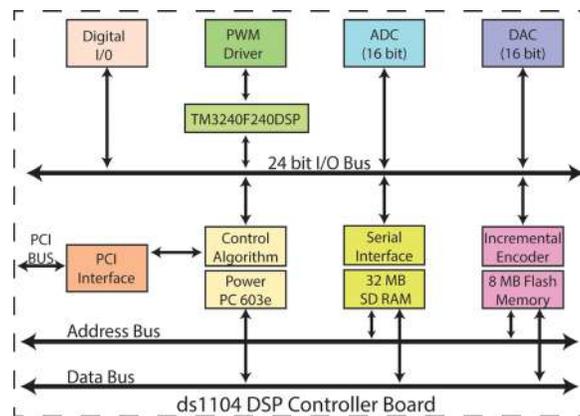


FIG. 4. Block diagram of ds1104 processor board.

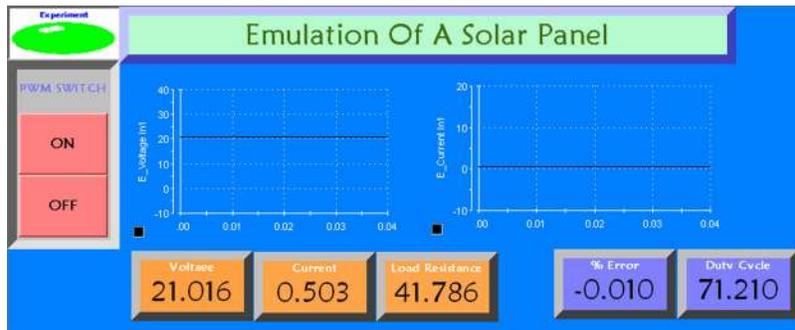


FIG. 5. Control desk window for monitoring system parameters.

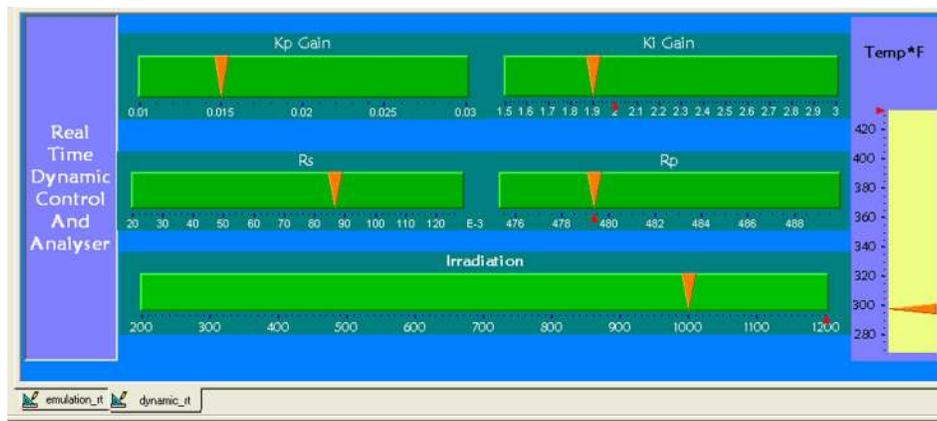


FIG. 6. Control desk window for tuning the parameters.

desk has provisions not only to display the measured value but also works as an interface to change the values instantaneously. From Fig. 5, it can be seen that, along with the values of voltage, current, duty cycle, and the error wave shape of sensed current and voltage can also be viewed. Fig. 6 depicts the control desk window for controlling the parameters such as R_s , R_p , K_p , K_i , irradiation, and temperature in real time; hence, it is possible to simulate the laboratory controlled atmospheric condition. Every single event can be monitored and corrected

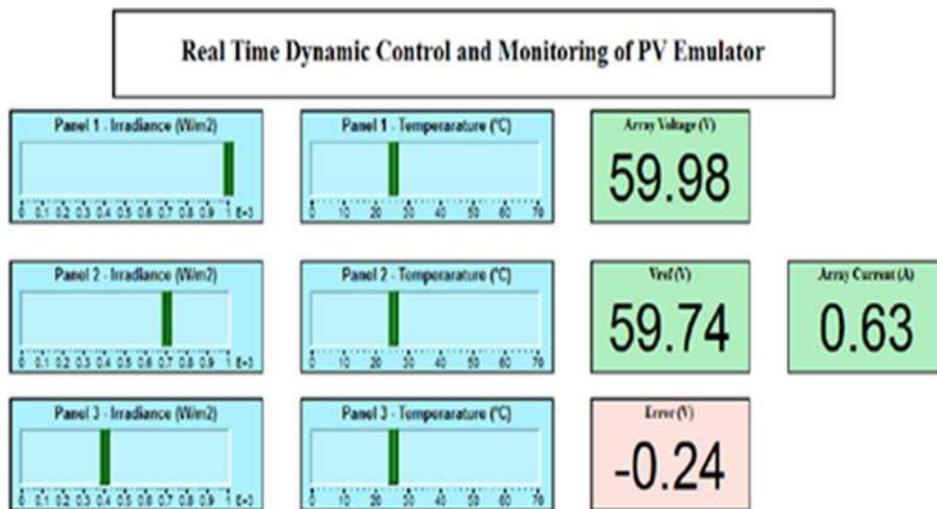


FIG. 7. View of control desk window—monitoring and control for solar array emulation with partial shading capability.

spontaneously. However, this feature is absent in the earlier proposed solar emulators.^{10,11,13,19,20} Fig. 7 illustrates the control desk window during the emulation of 3 series connected panels to form a solar PV array. Individual panel irradiation and temperature can be controlled; hence, an extended feature is supported to test and analyze for the effect of partial shading.

C. PWM generation logic

The closed loop control strategy for the DC-DC buck converter is shown in Fig. 8. The mathematical model developed in MATLAB/SIMULINK generates an equivalent reference voltage to that of the sensed current value and the set values of irradiation and temperature. The reference voltage is compared with the actual buck converter voltage, and the error generated is fed to PI controller. A PI controller acting as a compensator is implemented for (a) output voltage regulation of the DC-DC buck converter and (b) minimal steady state error with a good stability even under sudden load changes.

The PI controller is designed to have the following characteristics:

- (i) high gain at low frequencies to minimize the steady-state error of the output of the converter
- (ii) high crossover frequency to provide good dynamic regulation and low enough to avoid sub-harmonic instability and noise amplification, typically $f_{cmax} < (1/5) * f_s$ (Ref. 34)
- (iii) large phase margin pm yielding well damped transient load responses to ensure good stability for sudden changes in the load and the output voltage.

The converter transfer function $G_p(s)$ and the compensator transfer function $G_c(s)$ are as follows:

$$G_p(s) = \frac{V_{dc}}{s^2LC + s\left(\frac{L}{R} + Cr_L\right) + 1}, \quad (6)$$

$$G_c(s) = \frac{K_p s + K_i}{s}. \quad (7)$$

The designed values of K_p and K_i are 0.01 and 3, respectively. The bode plot of the open loop transfer function $\{G_p(s) \cdot G_c(s)\}$ shown in Fig. 9 depicting a phase margin of 106° at a cross over frequency of 94.5 rad/s with the designed controller constants, experimentations are done and the following observations are made:

- (i) The dynamic response of the emulator is faster for step change in insolation, temperature, and load, and its value is found to be less than $15 \mu s$ whereas it is $50\text{--}150 \mu s$ in Ref. 20.
- (ii) Phase margin is as large as 106° whereas it is only 90.9° in Ref. 20, attributing to better stability.
- (iii) Output voltage with near zero steady state error as the gain in low frequency region is larger.
- (iv) The crossover frequency is 94.5 rad/s and is higher compared to 70.2 rad/s in Ref. 20; as a result, this emulator responds quickly to step changes.

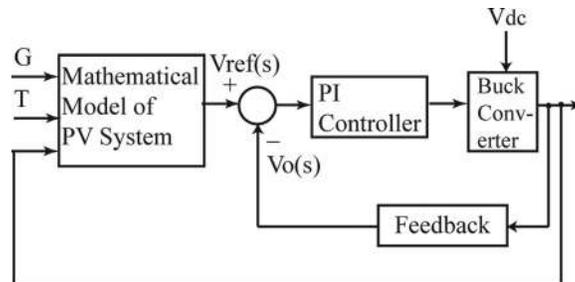


FIG. 8. Feedback control system of DC-DC buck converter.

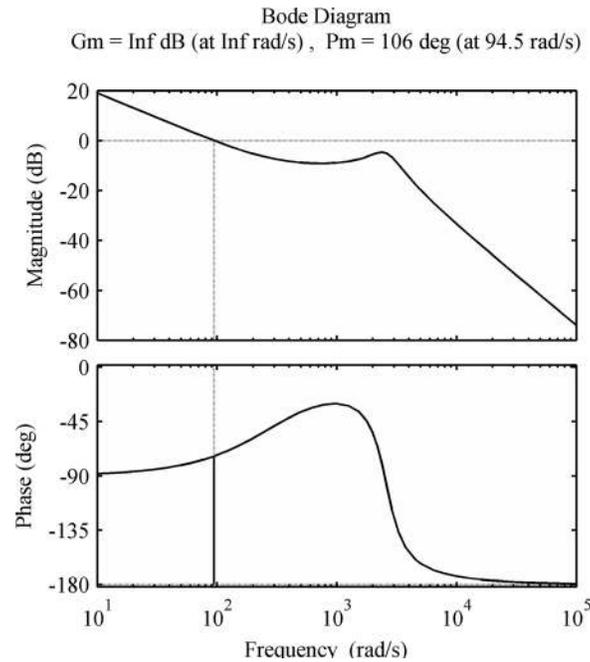


FIG. 9. Bode plot of closed loop system.

III. HARDWARE TEST SETUP

The complete experimental test setup of proposed solar PV emulator is shown in Fig. 10. The DC-DC buck converter is operated at a switching frequency of 10 kHz. For 1% voltage ripple and $<2\%$ of current ripple, the designed L & C values are 1.5 mH and 100 μ F, respectively. By following the procedure given in Ref. 35, the switching frequency (f_s) is selected to reduce the interaction between the solar emulator and the interfacing converter. Further to test the capability of the proposed solar PV emulator, a separate DC-DC boost converter is connected to the output of the emulator and P&O based MPPT method is tested. The designed boost converter of L and C values is 200 μ H and 1000 μ F, respectively.

The MPPT algorithm is programmed using Arduino Uno R3 low cost microcontroller. Both DC buck and boost converters were built using an Insulated Gate Bipolar Transistor (IGBT) (CM 100DU-12H), fast recovery diodes (IXYS DSEI30-06A), LEM LV25P voltage sensor, and LEM LA55P current sensors. From sensed current and voltage feedback signals and built in mathematical model, the required gate pulses for the converter are generated. The generated PWM pulses are sent out through PWM port 7. The generated gate pulses are isolated from the power circuit with the help of optocoupler TLP350 before being applied to the gate



FIG. 10. Hardware setup of solar PV emulator.

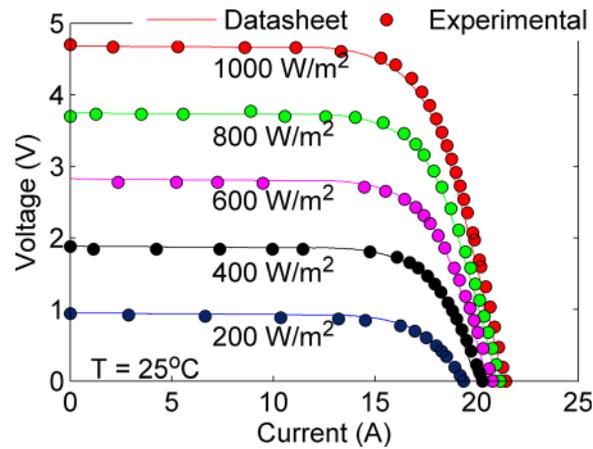


FIG. 11. A comparison of the emulated experimental values and the datasheet I-V curve of shell SP70 solar PV panel.

terminal of the IGBT. The major advantage of this hardware setup is its flexibility of operation for any required changes along with online tuning and ease in implementation.

IV. RESULTS AND DISCUSSION

To know the fidelity of the proposed emulator, various performance tests for different operating conditions have been carried out. To examine the closeness between the emulated and actual PV curve, solar PV emulator is set to operate at different irradiation for Shell SP70 panel, and the panel resultant curve is compared with data sheet values, and it is shown in Fig. 11. From Fig. 11, it is clearly evident that there exists a good agreement between the experimental and datasheet values. In addition, to analyze the emulated characteristics, error graph for every irradiation between the actual and experimental values is plotted, as shown in Fig. 12. From the absolute error curve, it can be observed that PV emulator assimilates the panel characteristics accurately with least error. Moreover, the computed error in the present case is much smaller than the results presented in Ref. 20.

Furthermore, to demonstrate the flexibility of the proposed emulator under real-time scenario, the following experiment is done, and the procedure involved is shown in Fig. 13. Initially, the emulator/DC-DC buck converter is set to operate at 1000 W/m^2 irradiation and 25°C temperature, keeping the irradiation level constant, the load connected to the emulator is varied from point “1” to point “2,” and the corresponding values are noted down. Now at point “2,” the load and temperature are kept constant, and the irradiation level is decreased from

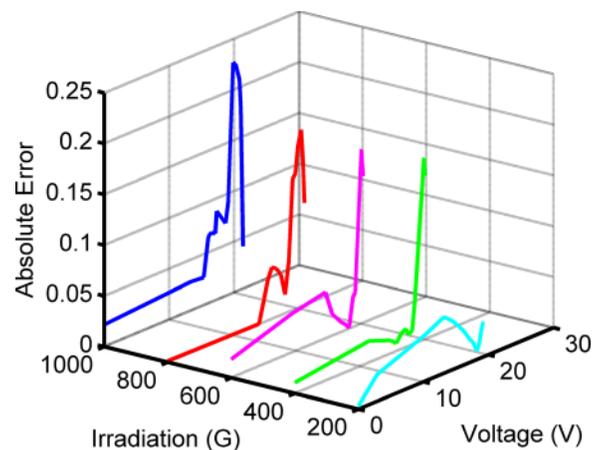


FIG. 12. Absolute error between the emulated values and the datasheet values for different irradiation levels.

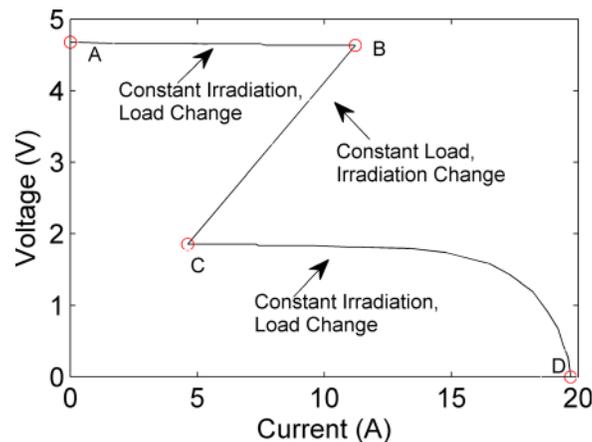


FIG. 13. I-V characteristics under real time control.

1000 W/m² to 400 W/m² until the curve reaches to point “3.” From point “3,” the irradiation is fixed at 400 W/m² and temperature at 25 °C; now the load resistance is gradually increased until the open circuit condition, i.e., the point “4” is increased. For the values obtained between point “2” and “3,” one can infer the dependency of current and voltage values of a solar panel for different irradiation levels for the same load. It can be easily inferred from the above experimentation that practically any value on the I-V plane for different irradiation, temperature, and load levels can be easily obtained with the proposed emulator. It is noteworthy to mention that the changing irradiation and temperature values has been done continuously using the RTI in Control Desk, which is an additional GUI software to interface the Hardware-in-Loop Systems with MATLAB/SIMULINK model. The values can be changed in animation mode while the system is still running; this provision is really helpful to understand the ability of MPPT tracking circuit’s performance for operation under rapid changing environmental condition, which otherwise requires tremendous amount of continuous and repeated field tests to prove an MPP algorithm’s working. Hence, the proposed emulator eases in research prototyping and testing of circuits by acting like an actual solar PV panel with faster and accurate response.

A. Performance analysis with step change in load, irradiation, and temperature

To study the dynamic performance of the system, the following tests such as (1) step change in load, (2) change in irradiation, temperature, and (3) MPPT tracking are performed. Finally, the overall system performance is analyzed. Analysis is done case by case, and the results are discussed in the following sections (Secs. IV A 1–IV A 3).

1. Case 1: Step change in load

To estimate the dynamic stability of the system, a sudden step change in load with constant irradiation and temperature is applied at point a, b, c, and d. During these instants, the load is immediately switched in the following sequence: 10 Ω–58 Ω, 58 Ω–15 Ω, 15 Ω–22 Ω, and 22 Ω–10 Ω, as shown in Fig. 14.

The recorded output voltage variation is shown in Fig. 14. From the figure, it can be seen that the proposed emulator shows good dynamic response with almost zero peak overshoot and steady state error. Further, it also confirms that the designed PI controller shows satisfactory dynamic response with change in operating conditions.

2. Case 2: Step change in both irradiation and temperature

When cloud passes on, it causes both irradiation and temperature to change, and this phenomenon is quiet common under seasonal weather conditions. Hence, to emulate such

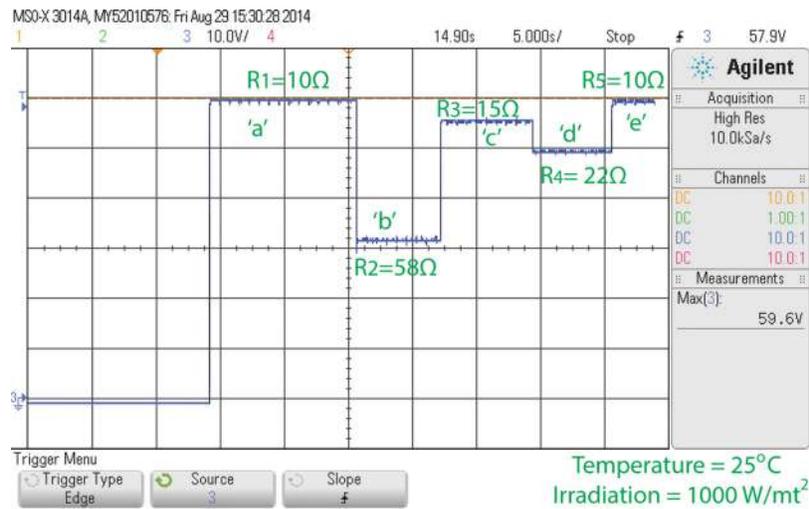


FIG. 14. Dynamic response for a sudden change in load resistance with $T = 25^\circ\text{C}$ and $G = 1000\text{ W/m}^2$.

environmental conditions, both irradiation and temperature is varied keeping the load constant. Further, at time $t = 9\text{ s}$, the temperature and irradiation values are changed from 1000 W/m^2 , 25°C to 400 W/m^2 , 50°C ; again at $t = 21\text{ s}$, irradiation changed to 800 W/m^2 , 30°C , and finally, at $t = 26\text{ s}$, irradiation changed to original values of 25°C , 1000 W/m^2 . This test condition is important with the view point that occurrence of partial shading conditions is very often and the proposed emulator must respond instantaneously without any delay. From the results shown in Fig. 15, it is evident that the emulator is adaptive for change in environmental conditions and responds immediately without any delay; this feature is important in the case of emulator when partial shading conditions are to be tested and analyzed.

3. Case 3: Dynamic response with MPPT Tracking

A commonly required feature of a solar emulator is its ability to evaluate MPPT algorithms.³⁶ To test MPPT algorithm, solar PV emulator is interfaced to the DC-DC boost converter, and P&O method is executed for uniform and partial shading conditions.

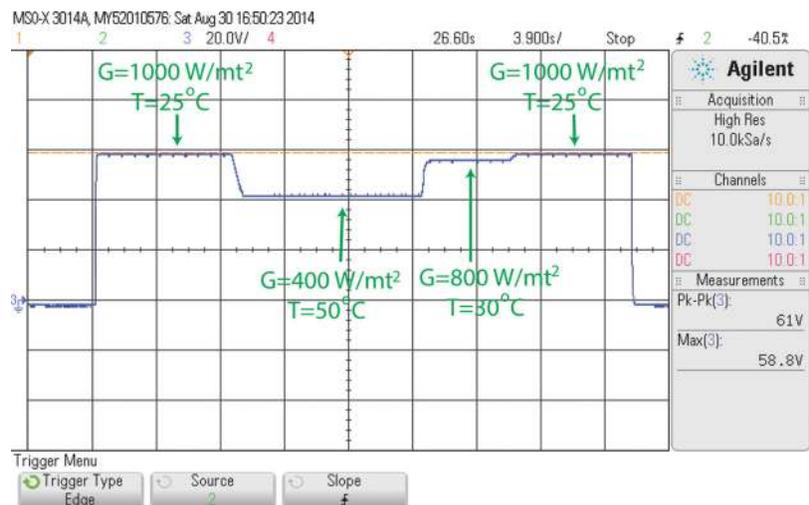


FIG. 15. Rapidity test results with step change in both irradiation and temperature.

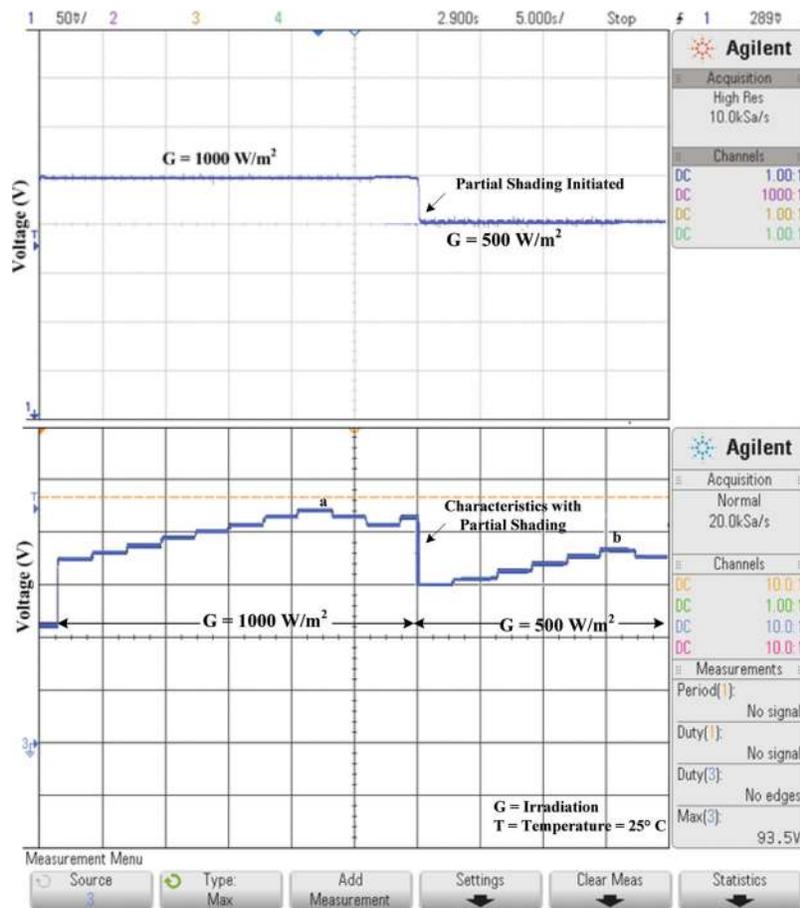


FIG. 16. Voltage waveform of MPPT test under change in irradiation.

Experimentation is done by emulating a PV array consisting of three panels in series, the hardware results taken for the test condition is shown in Fig. 15. The PV emulator is programmed for uniform irradiation of 1000 W/m^2 until time reaches 30 s. After this time interval, partial shading is created by changing the irradiation to 500 W/m^2 . Before shading occurs, the P&O method reaches the maximum power of 95 W. The voltage corresponding to maximum power point is noted down and is marked as point “a” in Fig. 16. Due to the nature of P&O method, it oscillates around MPP. When shading occurs at 30 s, the P&O tries to find the new global peak, but shifts to a new local peak of 60 W. The voltage corresponding to these local maxima is pointed as “b.” This clearly indicates the inability of conventional MPPT scheme to distinguish between global and local maxima. Further, the emulator can also be interfaced with PV inverters for MPPT testing with higher rating.

V. CONCLUSION

A solar PV emulator using a DC-DC buck converter controlled via a dSPACE ds1104 controller is proposed. Modelling, analysis, simulations, and experimentations are carried out, and the results are obtained for various operating conditions. The emulated I-V characteristics are matched with the actual curve for a shell SP70 solar PV panel. From the results obtained, it can be concluded that the proposed emulator has the following characteristics: (1) highly stable output with faster dynamic response, (2) near accurate capability to reproduce the static and dynamic characteristics of a solar PV panel, (3) ease in interfacing with user friendly and simple real-time monitoring and control, (4) ability to replicate any other PV Panels by inputting their characteristic values, and (5) further, the system is also capable of emulating any operating

point of the solar PV curve by changing the solar cell parameters. Furthermore, the result shows that the proposed emulator has the ability to interface with a power electronic converter and has the capability to test the connected power electronic interface and MPPT techniques.

- ¹H. Sridhar and K. S. Meera, "Study of grid connected solar photovoltaic system using real time digital simulator," in International Conference on Advances in Electronics, Computers and Communications (ICAEECC) (2014).
- ²M. Veerachary, "PSIM circuit-oriented simulator model for the nonlinear photovoltaic sources," *IEEE Trans. Aerosp. Electron. Syst.* **42**, 735–740 (2006).
- ³T. Sudhakar Babu, N. Rajasekar, and K. Sangeetha, "Modified particle swarm optimization technique based maximum power point tracking for uniform and under partial shading condition," *Appl. Soft Comput.* **34**, 613–624 (2015).
- ⁴M. Vysakh *et al.*, "Maximum power point tracking using modified PSO with CUK converter," in *International Conference on Advances in Electrical Engineering (ICAEE)* (2014), pp. 1–6.
- ⁵F. Chekired *et al.*, "Intelligent maximum power point trackers for photovoltaic applications using FPGA chip: A comparative study," *Sol. Energy* **101**, 83–99 (2014).
- ⁶N. Chettibi and A. Mellit, "FPGA-based real time simulation and control of grid-connected photovoltaic systems," *Simul. Modell. Pract. Theory* **43**, 34–53 (2014).
- ⁷O. M. Midtgard, "A simple photovoltaic Simulator for testing of power electronics," in *European Conference on Power Electronics and Application* (2007), pp. 1–10.
- ⁸S. Mohammed Azharuddin *et al.*, "A near accurate solar PV emulator using dSPACE controller for real-time control," *Energy Procedia* **61**, 2640–2648 (2014).
- ⁹A. Kora *et al.*, "High efficiency photovoltaic source simulator with fast response time for solar power conditioning systems evaluation," *IEEE Trans. Power Electron.* **29**(3), 1285–1296 (2014).
- ¹⁰O. Nagayoshi, "Novel PV array/module I-V curve Simulator circuit," in *Proceedings of the Photovoltaic Specialists Conference* (2002), pp. 1535–1538.
- ¹¹H. Nagayoshi, "Characterization of the module/array simulator using I-V magnifier circuit of a pn photo-sensor," in *Proceedings of the 3rd World Conference on Photovoltaic Energy Conversion* (2003), 2023–2026.
- ¹²H. Khouzam, "Real-time simulation of photovoltaic modules," *Sol. Energy* **56**, 521–526 (1996).
- ¹³D. Mukerjee, "DC power supply used as photovoltaic Simulator for testing MPPT algorithm," *Renewable Energy* **32**(4), 587–592 (2007).
- ¹⁴Q. Zeng and P. Song, "A photovoltaic Simulator based on DC chopper," *Proc. Can. Conf. Electr. Comput. Eng.* **1**, 257–261 (2002).
- ¹⁵K. Eftichios and K. Kalaitzakis, "Development of an FPGA-based system for real-time simulation of photovoltaic modules," *Microelectron. J.* **40**, 1094–1102 (2009).
- ¹⁶G. Martín-Segura and M. Lopez-Mestre, "Development of a photovoltaic array emulator system based on a full-bridge structure," in *Proceedings of the 9th International Conference on Electrical Power Quality and Utilization* (2002), pp. 214–220.
- ¹⁷M. C. Piazza and G. Vitale, "Photovoltaic field emulation including dynamic and partial shadow conditions," *Appl. Energy* **87**(3), 814–823 (2010).
- ¹⁸D. Dolan, J. Durago, and J. Crowfoot, "Simulation of a photovoltaic Emulator," in *Proceedings of the North American Power Symposium* (2010), pp. 1–7.
- ¹⁹D. C. Lu and Q. N. Nguyen, "A photovoltaic panel emulator using a Buck-boost DC/DC converter and a low cost micro-controller," *Sol. Energy* **86**(5), 1477–1484 (2012).
- ²⁰A. Vijayakumari, T. Devarajan, and N. Devarajan, "Design and development of a model-based hardware Simulator for photovoltaic array," *Electr. Power Energy Syst.* **43**(1), 40–46 (2012).
- ²¹M. Qinglong and Y. Wang, "Irradiance characteristics and optimization design of a large-scale solar simulator," *Sol. Energy* **85**(9), 1758–1767 (2011).
- ²²A. Abdollahpour, M. H. Ahmadi, and A. H. Mohammad, "Thermodynamic model to study a solar collector for its application to Stirling engines," *Energy Convers. Manage* **79**, 666–673 (2014).
- ²³M. A. Ehyaei, M. A. Rosen, and M. H. Ahmadi, "Meeting the electrical energy needs of a residential building with a wind-photovoltaic hybrid system," *World Sustainability Forum* **7**, 2554–2569 (2015).
- ²⁴G. Martín-Segura *et al.*, "Development of a photovoltaic array emulator system based on a full-bridge structure," in 9th International Conference on Electrical Power Quality and Utilisation, IEEE EPQU (2007).
- ²⁵Solar PV Grid Tied Training System[Ecosense.
- ²⁶H. Patel and V. Agarwal, "MATLAB-based modeling to study the effects of partial shading on PV array characteristics," *IEEE Trans. Energy Convers.* **23**(1), 302–310 (2008).
- ²⁷H. Sayyaadi, M. H. Ahmadi, and J. Saeed Dehghani, "Optimal design of a solar-driven heat engine based on thermal and ecological criteria," *Energy Eng.* **141**, 1–7 (2015).
- ²⁸M. G. Villalva and J. R. Gazoli, "Comprehensive approach to modeling and simulation of photovoltaic arrays," *IEEE Trans. Power Electron.* **24**(5), 1198–1208 (2009).
- ²⁹Z. S. Kashifshaque, "A comprehensive MATLAB simulink PV system simulator with partial shading capability based on two-diode model," *Sol. Energy* **85**(9), 2217–2227 (2011).
- ³⁰K. Nishioka, S. Nobuhiro, and U. Yukiharu, "Analysis of multi crystalline silicon SolarCells by modified 3-diode equivalent circuit model taking leakage current through periphery into consideration," *Sol. Energy Mater. Sol. Cells* **91**(13), 1222–1227 (2007).
- ³¹N. Rajasekar, N. Krishna Kumar, and R. Venugopalan, "Bacterial foraging algorithm based solar PV parameter estimation," *Sol. Energy* **97**, 255–265 (2013).
- ³²M. S. Ismail, M. Moghavvemi, and T. M. I. Mahila, "Characterization of PV panel and global optimization of its model parameters using genetic algorithm," *Energy Convers. Manage.* **73**, 10–25 (2013).

- ³³O. Youssef, A.-H., Kamal, and A. G. Luc, "Packed U cells multilevel converter topology: Theoretical study and experimental validation," *IEEE Trans. Ind. Electron.* **58**, 1294–1306 (2011).
- ³⁴R. Ridley, "The purpose of loop gain, switching," in *Power Magazine* (2001), pp. 1–6.
- ³⁵R. Underland, *Power Electronics Converters, Applications and Design*, 3rd ed. (John Wiley & Sons, New Delhi, 2001).
- ³⁶D. M. K. Schofield, M. P. Foster, and D. A. Stone, "Low-cost solar emulator for evaluation of maximum power point tracking methods," *Electron. Lett.* **47**(3), 208–209 (2011).