Programmable DC Power Supply Based Solar PV Module Emulator using LabVIEW and Multisim

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Abstract- The performance evaluation of solar Photo-Voltaic (PV) based energy conversion system under varying environmental conditions is tedious and difficult. Therefore, a Solar Photo-Voltaic Module Emulator (SPVME) based on Programmable DC source is presented in this paper. Multisim software is employed to emulate the PV module characteristics and a Programmable DC power supply is used to replicate the emulated PV module. LabVIEW acts as a Hardware in the Loop platform to integrate the emulated solar PV module developed with the programmable DC power supply. The experimental setup of the proposed SPVME is analyzed with the parameters of 200 W PV string under real-time weather data and the output results are compared with a real-time PV string output. A solar PV system with Perturb and Observe (P&O) Maximum Power Point Tracking algorithm is tested using the SPVME prototype and the system performance is also validated.

Keywords- DC Programmable Power supply; Hardware in the Loop (HIL); Perturb and Observe (P&O) MPPT; Performance Evaluation; Solar Photo-voltaic Module Emulator.

1. Introduction

One of the promising alternative to the fossil fuel based power generation is the solar PV system based energy conversion system [1],[2],[3].To investigate and analyze the performance of the solar PV based energy conversion system, it is mandatory to install solar PV modules, DC-DC converter and loading facilities, which involves high installation cost and requires more space. Performance evaluation of the newly developed Maximum Power Point Tracking (MPPT) algorithm, DC-DC converters and micro inverters using PV module under changing irradiation conditions is difficult [4],[5]. Moreover, it is very difficult to carry out the characteristics study on the solar PV module, because the solar PV module may get damaged, when it is operated in its rated short circuit current. To overcome the above stated issues, Solar Photo-Voltaic Module Emulator (SPVME) is the viable solution.

The SPVME is equipment that can emulate the voltage and current characteristics of the real solar PV module. Any commercial solar PV modules can be tested in the same SPVME without doing any modifications in the emulator. SPVME comes with overload protection; hence this SPVME can be operated under overload and short circuit conditions, which occurs quite often during testing. Further, a researcher can carry out the research even in the cloudy conditions, and at night [6]. SPVME are classified [7] into i) Light source type ii) DC-DC converter type and iii) DC Power Supply type.

Light source type SPVME uses halogen light source to reproduce the irradiation characteristics of sun-light, which in turn illuminates the solar PV cell. PV cell power output is scaled up to the level of PV module with the support of amplification circuit. Light source type SPVME consists of DC halogen light sources, solar PV cell and amplification circuit has been proposed in [8],[9]. The DC-DC buck-boost converter based SPVME that replicate the VI characteristics curve of the solar PV module has been proposed in [10]. A piece-wise linearized model of PV module is implemented using micro-controller in this type of SPVME. The main drawbacks of this type of SPVME are complex circuitry and they require complex calculation to linearize the voltage versus current curve of the solar PV module. In [11],[12],[13] a buck converter based SPVME is developed with MATLAB and D-Space controller has been discussed. In the above mentioned SPVME, MATLAB is utilized to develop the PV module characteristics and PI controller is used to track the simulated characteristic of the PV module. A DC programmable power supply based SPVME has been discussed in [16] [4],[14],[15],[16]which uses software like LabVIEW/ PSIM to reproduces the characteristics of the PV module using pre/JAVAFX determined resistance versus voltage (R-V) relationship lookup table and DC programmable power supply. This type of DC power supply based SPVME uses a predefined lookup table and time-varying iterative loops to simulate the characteristics of the PV module, hence accuracy cannot be achieved under varying load conditions.

Programmable DC power supply based SPVME using Multisim and LabVIEW co-emulation is proposed in this paper. The proposed SPVME emulates the characteristic behavior of the PV module developed in Multisim without the help of predefined lookup table and in turn the developed model is integrated into the DC programmable power supply using LabVIEW. The developed methodology supports emulation of a PV module with real-time irradiation data input. The sensed data can be directly fed into the emulator and the performance of any module can be analyzed online. This SPVME also has the feature to test any commercial solar PV module characteristics without any modifications in the hardware platform. The paper also reports the performance analysis of the Perturb and Observe (P&O) Maximum Power Point Tracking (MPPT) algorithm using proposed SPVME.

2. Solar PV module and its characteristics

A solar PV cell is a P-N junction diode, which converts sunlight into electricity by photovoltaic effect. The solar PV cells absorb the photon energy from the sunlight and the photons which possess higher energy than that of the band-gap energy of semiconductor material leads to the formation of the free electron-hole pairs in the solar PV cell. These electrons are collected by the electrode to form the photocurrent. This phenomenal effect can be expressed with the help of the single diode solar cell connected in series and in parallel configuration. Fig. 1 shows the model of a solar PV module.

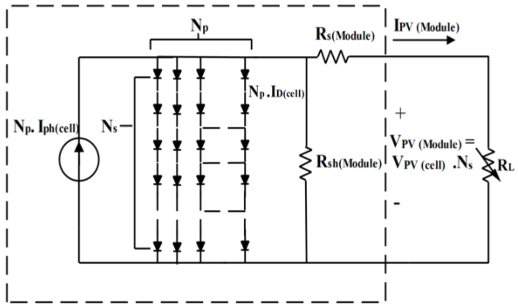


Fig. 1 Model of solar PV module using single-diode solar PV cell.

2.1. Mathematical model of solar PV Module:

The I-V characteristics behaviour of the solar PV module is expressed with reference to the I-V relationship of the single diode solar PV cell given by Eq. (1) [17],[18],[19]

$$I_{PV(Module)} = I_{ph(Module)} - I_{rs(Module)}\left\{\exp\left[\frac{q(V_{PV(Module)} + I_{PV(Module)}R_{s(Module)})}{N_s N_p KAT_c}\right]-1\right\} \quad (1)$$

$$-\frac{(V_{PV(Module)} + I_{PV(Module)}R_{s(Module)})}{R_{sh(Module)})}$$

Where $I_{ph(Module)} = I_{ph(cell)}. N_P$, $I_{rs(Module)} = I_{rs(Cell)} .N_P$ and $V_{PV(Module)} = V_{PV(cell)}.N_s$ are the photocurrent, saturation current and output voltage of the solar PV module, which consist of N_p and N_s number of the parallel and series connected solar PV cells in a PV module respectively. q and K denotes the electron charge and Boltzmann constant. A and TC represents ideality factor and reference temperature of the solar PV cell. The equivalent series and parallel resistance of the module are given by $R_{s\ (Module)} = R_{s(Cell)} .(N_s/ N_p)$ and $R_{sh\ (Module)} = R_{sh(Cell)} .(N_p/ N_s)$.

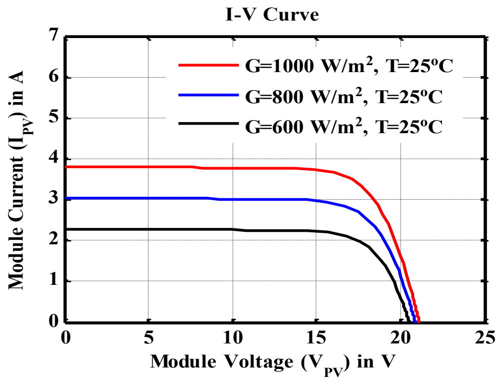
2.2. Effect of Irradiation and Temperature

The characteristics of the solar PV module not only depend on the internal parameters of the solar PV cell but also on the changes in the irradiation and temperature of the light falling on it [20][21].The module voltage $V_{PV(Module)}$ and module current $I_{PV(Module)}$ variation with respect to change in irradiation and temperature can be expressed as follows

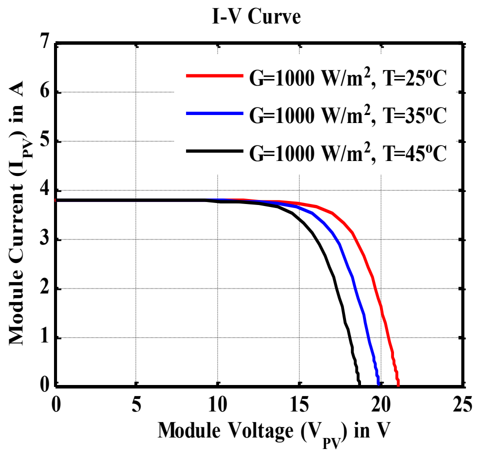
$$V_{PV(Module)} = [V_{PV(Module)} + K_V(T_c - T_{STC})]\frac{T}{T_{STC}} \quad (2)$$

$$I_{PV(Module)} = [I_{PV(Module)} + K_i(T_c - T_{STC})]\frac{G}{G_{STC}} \quad (3)$$

Where T_{STC} represents the temperature and G_{STC} represents the irradiation level at Standard Test Conditions (STC). T_{STC} =25 ^{0}C and G_{STC} =1000 W/m^2. K_i and K_v are the temperature dependence coefficients of the short circuit current and open circuit voltage of the solar PV module. From Eq. (2) and Eq. (3) it can be seen that the output current of the solar PV module is directly proportional to the irradiation level and the atmospheric temperature has negative effect on the output voltage of the solar PV module. Fig. 2(a) shows the characteristics of solar PV module under different irradiation conditions and Fig. 2(b) shows the characteristics of Solar PV module under different temperature conditions.



(a)



(b)

Fig. 2(a) Characteristics of solar PV module under different irradiation Fig. 2(b) Characteristics of solar PV module under temperature conditions

3. Proposed DC Power Source based Solar PV Module Emulator

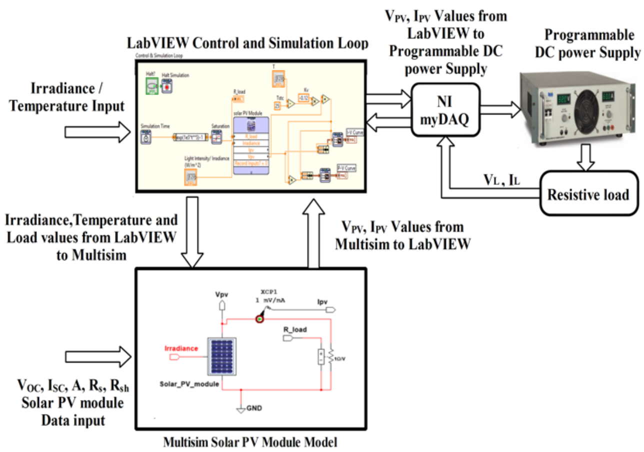


Fig. 3 System description of the proposed SPVME

The block diagram representation of the proposed SPVME is presented in Fig. 3. The proposed SPVME has been designed and developed using the Hardware-in-the-loop (HIL) technique. The components of the proposed SPVME are Multisim model of solar PV module, NI-myDAQ (National Instruments-my Data Acquisition) for data acquisition and programmable DC power supply with the voltage range of 0-64 V and current rating of 30 A .

The solar PV module developed in Multisim using Simulation Program Integrated Circuit Emphasis (SPICE) coding [22][23] mimics the commercial solar PV module; hence it can be used to analyze the characteristics behavior of any PV module available in the market by simply modifying the key parameters of the selected PV module in the software platform. The LabVIEW based HIL environment integrates the emulated solar PV module and the programmable DC power supply in real-time. The irradiation and temperature data are given as input to the emulated PV module through LabVIEW and the emulated PV module voltage and current are observed in LabVIEW. The Programmable DC power supply is connected to the LabVIEW platform through NI-myDAQ. NI-myDAQ sends signal correspond to the emulated V_{PV} and I_{PV} to the DC power supply as input.

Programmable DC power supply used in this work is a Linear DC power supply. The DC power supply works either in constant voltage or constant current mode. The switching of DC power supply from constant voltage mode to constant current mode depends on the load connected to it and maximum current limit. DC power supply generates voltage (V_{PV}), current (I_{PV}) corresponding to emulated V_{PV} and I_{PV} respectively. The resistive load which is kept maximum at the beginning, the value of V_{PV} across the load resistance will be equal to the open circuit voltage (V_{OC}) of the PV module and I_{PV} will be minimum (nearly zero). V_{PV} and I_{PV} are acquired by NI-myDAQ with the support of voltage and current sensing transducers and given to the LabVIEW control and simulation loop. The control and simulation loop computes load resistance ($R_L= V_{PV}/I_{PV}$), module power (P_{PV}) in online and plot I-V, P-V characteristics of the PV module. The computed value of load resistance R_L is fed into the emulated PV module in Multisim. A set of V_{PV} and I_{PV} values will be generated using DC power supply in a similar fashion by adjusting the load resistance value in steps. As resistor value decreases V_{PV} will decrease and I_{PV} will increase accordingly. I_{PV} will become short circuit current (I_{SC}) and V_{PV} will be merely zero when the resistor value become minimum. Fig. 4 shows the V_{PV} and I_{PV} computation using R_L.

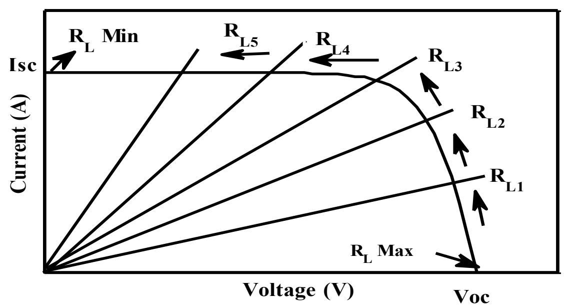


Fig.4 Computing of V_{PV} and I_{PV} using R_L.

4. Result and discussion

In this section, a solar PV string is emulated using the proposed technique and the results are presented. The developed prototype is further tested with real PV string configuration with real-time irradiation and temperature input. To validate the proposed SPVME, a PV system is designed and tested with P&O MPPT algorithm. The output result shows satisfactory performance of developed SPVME under varying irradiation conditions.

4.1 PV string Emulation in Multisim:

A 200 W solar PV string, which consists of two 100 W Sukam module connected in series is chosen for the analysis. The specifications of parameters of a single Sukam PV module are Open Circuit Voltage (V_{OC}) = 21.1 V, Short Circuit Current (I_{SC}) = 5.2 A, Voltage at Maximum Power Point (MPP) (V_{MPP}) = 17.4 V, Current at MPP (I_{MPP}) = 4.62 A and Power at MPP (P_{MPP}) = 80 W, since two modules are interconnected together in the series fashion to get the solar PV string with V_{OC} = 42.2 V, I_{SC} = 5.2 A and guaranteed Peak power of 160 W. Fig. 5 illustrates the emulation model of solar PV string in Multisim. The model receives irradiation and temperature as input from LabVIEW and gives emulated V_{PV} and I_{PV} as output.

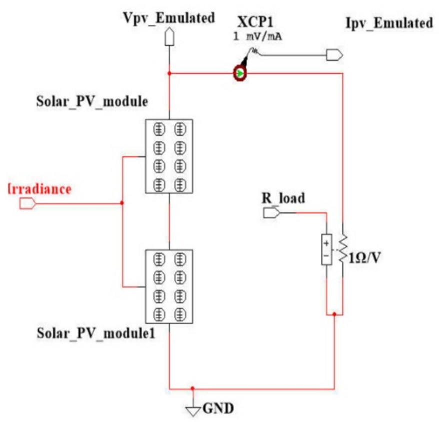
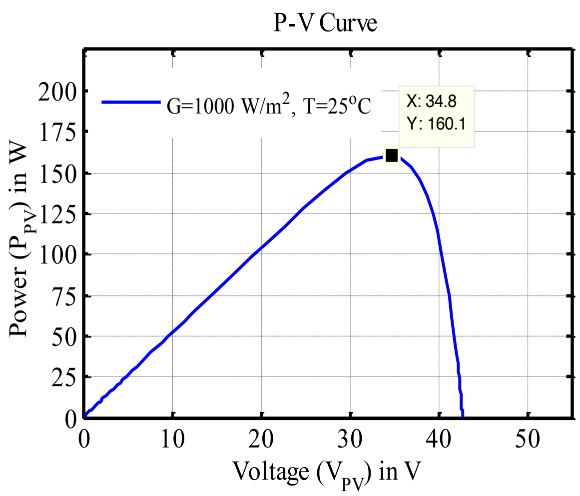
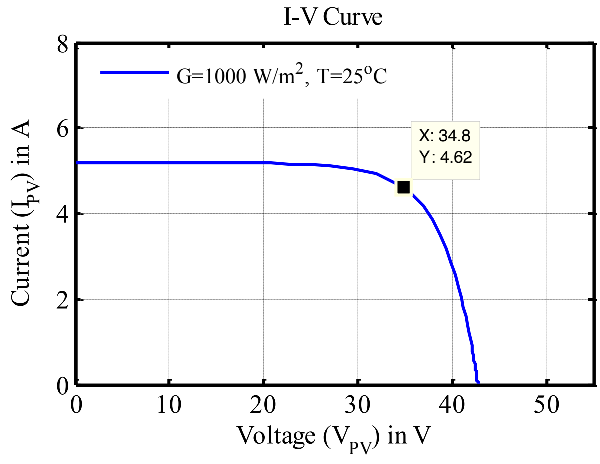


Fig. 5 200 W solar PV string developed using Multisim.



(a)



(b)

Fig. 6 Characteristic of the emulated 200 W solar PV string at STC (a) P-V characteristic (b) I-V Characteristic

Fig. 6(a) and Fig. 6(b) show the P-V and I-V characteristic curve respectively of the emulated PV string. From the characteristics plots it is found that the emulated PV module produces a maximum power of 160.1 W at 34.8 V and 4.62 A, at G = 1000 W/m^2 and T=25 °C.

4.2 Hardware Realization of the proposed SPVME

Programmable DC power supply with the voltage range of 0-64 V and current rating of 30 A is used for the prototype development. Fig. 7 shows the experimental setup of the developed SPVME. Programmable DC power supply receives analog input of 0-10 V and gives appropriate output. For example, the programmable DC power supply produces an output voltage of 42.2 V for the analog input of 6.58 V. Similarly, the output current produces 5.2 A for the analog input of 1.69 V. NI-myDAQ is used as data acquisition and transfer unit between software and hardware platform of the system. The operating range of NI-myDAQ is 0-10 V and hence all the voltage and current data of the LabVIEW environment should be within this range. The inputs like irradiation and temperature data are set in the LabVIEW and then given as input to the emulated PV string in the Multisim. The voltage and current output of the PV string in Multisim are scaled to 0-10 V by LabVIEW. These scaled values are ported out through an analog port of NI-myDAQ. The output of programmable DC power supply is measured across the resistive load using isolation voltage transducer and DC shunt. The measured values are fed into the LabVIEW through an analog port of NI-myDAQ to calculate the load connected to the programmable DC power supply.

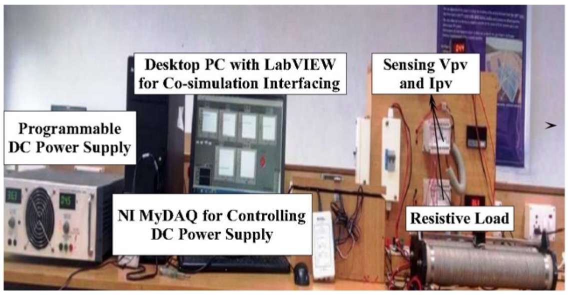


Fig. 7 Experimental setup of the proposed SPVME

4.3 Experimental validation of the SPVME

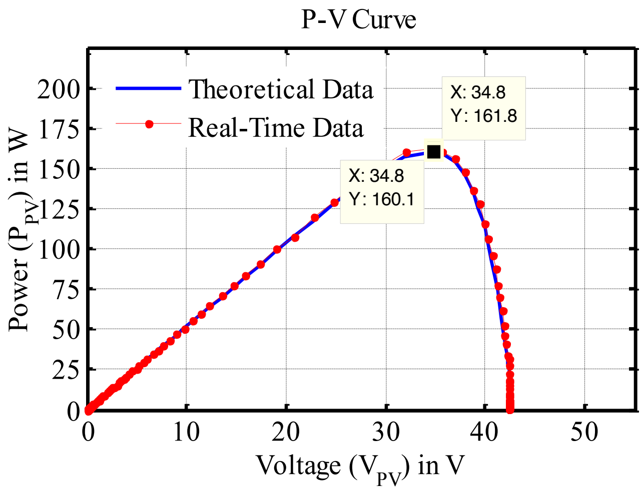
The accuracy of the developed SPVME is evaluated by comparing with the real time solar PV module experimental output. To demonstrate the adoptability of the developed SPVME it is tested with MPPT algorithm and tracking performance are presented in this section.

4.3.1. Steady State analysis under Standard Test Conditions

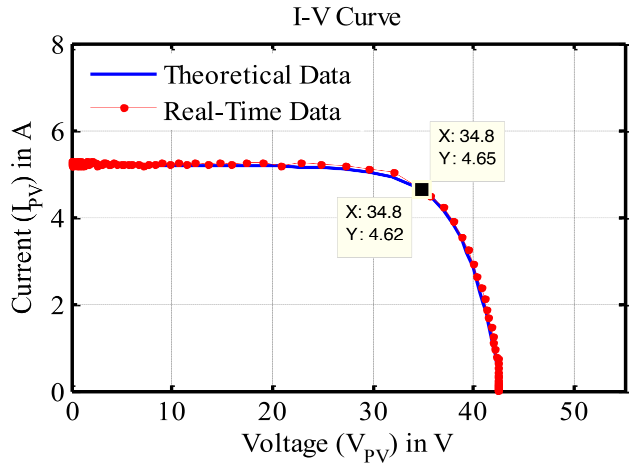
The steady state analysis is carried out with the two Sukam PV modules connected in series under STC. Under STC, Multisim model of Sukam modules is tested with the irradiation level of 1000 W/m^2 and temperature level of 25 ° C. Fig. 8(a) and Fig. 8(b) shows the P-V and I-V characteristics of the theoretical and emulated Sukam PV module using the developed SPVME under STC. In-order to compute the correctness of the SPVME, relative error is calculated between the theoretical and real-time output at various operating points of the PV modules. Table-1 shows the relative error comparison between the proposed SPVME and other PV emulators discussed in [24], [25]

$$\text{Relative Error (X)} = \frac{\left|X_{\text{Real-Time}} - X_{\text{Theroetical}}\right|}{X_{\text{Theroetical}}} X100\ (\%) \quad (4)$$

Where "X" is V_{MPP} , I_{MPP} , P_{MPP} , I_{sc} ,V_{oc}



(a)



(b)

Fig. 8 Real-Time Characteristic of the emulated 200 W solar PV string at STC (a) P-V characteristic (b) I-V Characteristic

Table 1 Relative error comparison between Proposed SPVME and PV emulator under STC proposed in literature.

	Parameter	**Specification of PV modules**	**Real-time data of emulate PV modules**	**Relative Error % of the Proposed SPVME**	**Relative Error % of the PV emulator proposed in [24]**	**Relative Error % of the PV emulator proposed in [25]**
Irradiation - 1000 W/m2 Temperature- 25 ° C	Open Circuit voltage (V_{OC}) in V	42.2	42.46	0.62	0.92	0.88
	Short Circuit current (I_{SC}) in A	5.2	5.23	0.57	0.89	0.65
	Voltage at MPP (V_{MPP}) in V	34.8	34.78	0.05	0.57	1.28
	Current at MPP (I_{MPP}) in A	4.62	4.65	0.64	0.81	0.73
	Power at MPP (P_{MPP}) in W	160.6	161.8	0.75	2.66	0.95

4.3.2. Validation using real time PV module

This study is conducted to validate the functioning of the developed SPVME using the data collected from real-time PV module. Solar PV string voltage and current are acquired by the NI myDAQ which is connected to the PC. The irradiation and temperature data also measured and acquired. The experimental setup of the PV string used for the study is shown in Fig. 9. The real-time characteristics curve of the solar PV string is recorded with the irradiation level of 812 W/m^2 and temperature level of 33 °C. The proposed SPVME is also emulated with the solar PV string configuration and Sukam PV module under the above mentioned real-time environmental inputs. The emulated characteristic of the solar PV string is compared with the real-time solar PV string characteristics and relative error is estimated for the maximum power.

Fig. 9 Solar PV string setup for real time analysis

Fig. 10 and Fig. 11 show the P-V and I-V characteristic curve comparison of the emulated and real-time solar PV string. The maximum power generated by the real solar PV string is 109.1 W, whereas the emulated solar PV string produces a maximum power of 106 W. The estimated relative error of the emulated solar PV string power is in the allowable range of 2.85 %, which exhibits the accuracy of the developed SPVME.

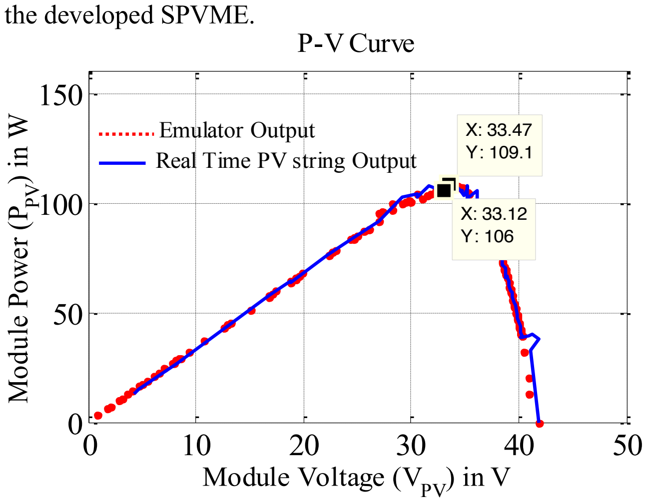


Fig. 10 P-V curve Comparison between emulated and real-time solar PV string

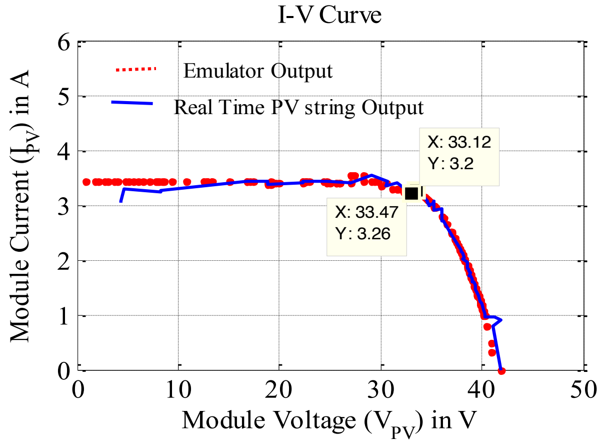


Fig. 11 I-V curve Comparison between emulated and real-time solar PV string

4.3.3. Performance validation with Maximum Power Point Tracking Controller

A Standalone PV system with a DC-DC boost converter and MPPT algorithm is developed using SPVME prototype as shown in Fig. 12. The performance of SPVME based solar PV system with MPPT algorithm is analyzed for different input conditions. The specification of the 200 W PV string is considered as the source for the investigation. The voltage and current output of the PV string under Standard Test Condition (STC) at MPP is V_{MPP} = 34.78 V and I_{MPP} = 4.65 A respectively.

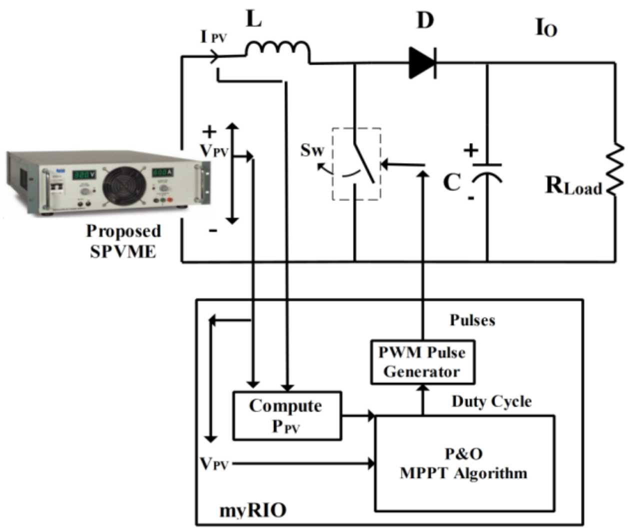


Fig. 12 Experimental setup for Evaluation with MPPT controller

The P&O MPPT algorithm is considered for the analysis [26], [27] and it is implemented using NI-myRIO (my Reconfigurable I/O). P&O senses the V_{PV} and I_{PV} of the selected PV string and adjust the duty cycle accordingly to reach MPP for the selected input conditions. The PWM pulses are generated with the switching pulse of 10 kHZ. The generated pulse drives the MOSFET (IRF 540) in the DC-DC boost converter. The design parameters of the boost converter are given in Table 2.

Table 2 Specification of Boost converter

Parameters	Values
Inductor (L)	540 mH
Output Capacitor (C)	240 µf
Switching Frequency	10 kHz
Resistor (R_L)	12 Ω

The output voltage and current of the PV string with MPPT algorithm under STC is recorded in digital oscilloscope and results are shown in Fig. 13. The developed system with P&O algorithm takes around 8 seconds to reach the MPP from its initial point. The power delivered by the emulated PV source is measured with DC energy meter and the results are presented in Fig. 14. The maximum power delivered by the emulated solar PV string using the SPVME prototype under STC is 161 W. The relative error of maximum power delivered at MPP is 0.49%, which shows the accuracy of the proposed approach.

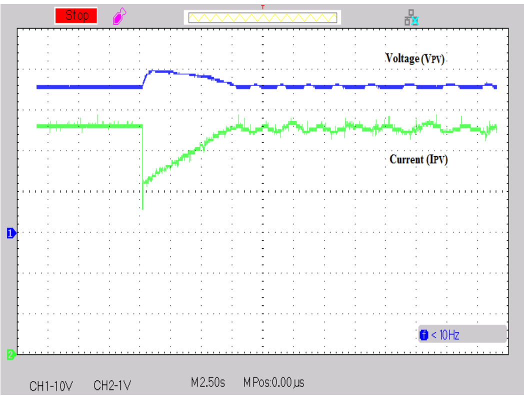


Fig. 13 MPP tracking of P&O MPPT algorithm under STC

Fig. 14. Maximum power delivered by the emulated PV string

The solar emulator is mainly used to evaluate the performance of MPPT algorithm over a period of time. Therefore the proposed SPVME prototype is tested for 1 hour and corresponding power and energy results in interval of 15 minutes are presented in Fig. 15. The load used for the study is a constant resistive load, therefore energy is linearly increasing. The energy consumed by the resistive load for 1 hour is 160 Wh.

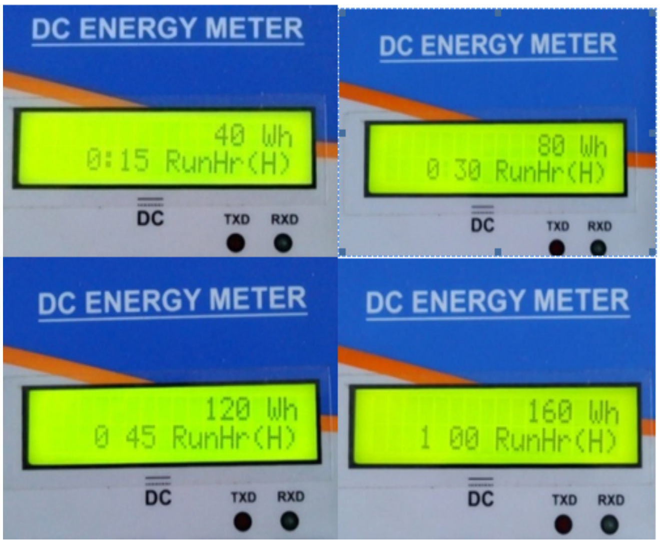


Fig. 15 Power and energy delivered by the proposed prototype for 1 hour

The system is also evaluated under varying irradiation conditions. As shown in Fig. 16, the irradiation is decreased in steps of 100 W/m^2 from 1000 W/m^2 to 700 W/m^2 and increased to 1000 W/m^2 at every 10 seconds. The tracking curve of the P&O MPPT algorithm is shown in Fig. 16.

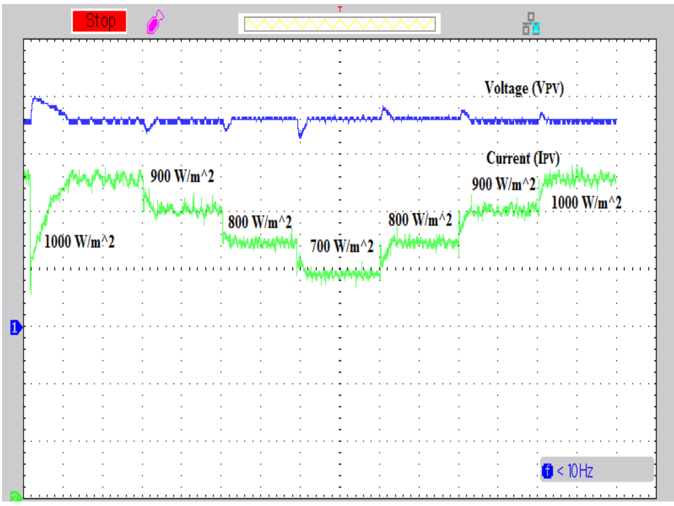


Fig. 16 MPPT Tracking of the system under varying irradiation

G W/m^2	Actual P_{MPP}	P&O MPPT algorithm	
		P_{MPP}	η_{static}
1000	161.8	161	99.50
900	154.5	152.2	98.52
800	146.6	144.3	98.43
700	138.1	136.4	98.76
		Average	98.78

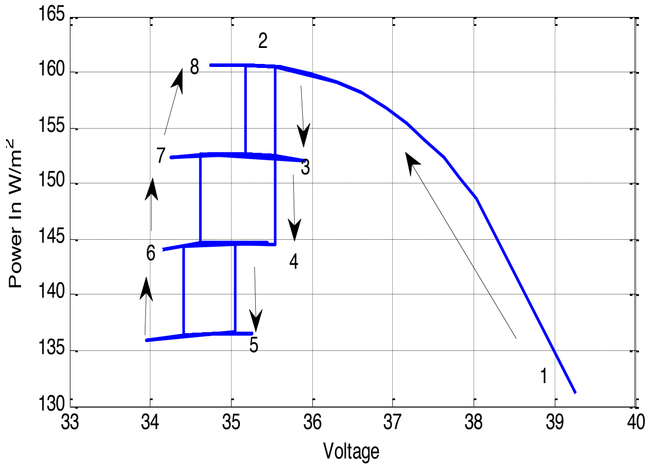


Fig. 17. MPP Tracking curve of the P&O algorithm tested in the Proposed SPVME

To track the MPP of the solar PV string the P&O algorithm always start from the right hand side of the P-V characteristics curve. In this case, the P&O algorithm starts from 131 W, which is shown as the point 1 in Fig. 17. Initially the SPVME is operated with irradiation level of 1000 W/m^2 and temperature level of 25 ^{o}C; hence the P&O algorithm moves from point 1 to point 2 and tracks the MPP of 161 W. With the decrease in irradiation, MPPT algorithm starts to move downwards from point 2 to point 5 and tracks the corresponding maximum power of 136 W. Similarly, with the increase in irradiation MPPT algorithm starts to move upwards from point 5 to point 8 and tracks back the maximum power of 161 W. The static MPPT tracking efficiency of the P&O algorithm is calculated using Eq.(5). The average static efficiency of the P&O algorithm is 98.72%,

$$\eta_{(staticMPPT)} = \frac{P_{PV(out)}}{P_{PV@MPP.}} x100\% \quad (5)$$

Table-3 Overall efficiency of the P&O MPPT algorithm

The output results exhibit the accuracy and adoptability of the developed SPVME under dynamic environmental conditions; therefore the developed prototype can be used for testing the MPPT algorithm under varying irradiation conditions.

5. Conclusion

A Programmable DC power supply based SPVME is proposed in this paper. The Multisim model of the PV module is developed using single-diode model of the PV cell. The DC power supply is programmed to replicate the characteristics behavior of any commercially available PV module. The developed SPVME is emulated with the specifications of 200 W solar PV string. The output of developed SPVME is compared with the real PV string which works under real environmental conditions and the estimated relative error at PV string power is 2.85 %. From the analysis of the test results and operations, the developed system is flexible and yields accuracy better than the other solar PV emulator discussed in the literatures. The developed SPVME supports the performance evaluation and analysis of any PV module, string or array. A standalone PV system along with MPPT controller is emulated with the developed SPVME. The tracking results show that the developed SPVME is an alternative to emulate the PV sources, which can be used to design MPPT algorithm and power converters in the laboratory environment.

References

[1] H. Abdelkader, A. Meriem, C. Ilhami, and K. Korhan, "Smart grid and renewable energy in Algeria," in *2017 6th International Conference on Renewable Energy Research and Applications, ICRERA 2017*, pp. 1166–1171.

[2] M. Veerachary and H. Khas, "PSIM circuit-oriented simulator model for the nonlinear photovoltaic sources," *IEEE Trans. Aerosp. Electron. Syst.,* vol. 42, no. 2, pp. 735-740, 2006.

[3] N. Genc, M. Yesilbudak, and M. Colak, "A Case Study on the Investigation of Solar Regime in Van, Turkey," in *4th International conference on Renewable Energy Research and Application*, 2015, vol. 5, pp. 954–958.

[4] M. Park and I.-K. Yu, "A Novel Real-Time Simulation Technique of Photovoltaic Generation Systems Using RTDS," *IEEE Trans. Energy Convers.,* vol. 19, no. 1, pp. 164-169, mar 2004.

[5] C. G. Katheryn D, Jamer Jimenez, "Hybrid Renewable Energy System based on Intelligent Optimization Techniques," in *5th International Conference on Renewable Energy Research and applications*, 2016, vol. 5, pp. 661–666.

[6] A. Sanaullah and H. A. Khan, “Design and implementation of a low cost Solar Panel emulator,” in *2015 IEEE 42nd Photovolt. Spec. Conf.* IEEE, jun 2015, pp. 1-5.

[7] R. Ayop and C. W. Tan, “A comprehensive review on photovoltaic emulator,” *Renew. Sustain. Energy Rev.,* vol. 80, pp. 430-452, dec 2017.

[8] H. Nagayoshi, “I-V curve simulation by multi-module simulator using I-V magnifier circuit,” *Sol. Energy Mater. Sol. Cells*, vol. 82, no. 1–2, pp. 159–167, 2004.

[9] R. Chandel, “Uncertainty Analysis of Photovoltaic Power Measurements using Solar Simulators,” *Energy Technol.*, vol. 1, no. 12, pp. 763–769, 2013.

[10] V. V. Ramana, D. Jena, and D. N. Gaonkar, “An accurate modeling of different types of photovoltaic modules using experimental data,” *Int. J. Renew. Energy Res.*, vol. 6, no. 3, pp. 970–974, 2016.

[11] B. M. H. Jassim and H. M. Jasim, “Modelling of a solar array simulator based on multiple DC-DC converters,” *Int. J. Renew. Energy Res.*, vol. 8, no. 2, pp. 1038–1044, 2018.

[12] S. Babu, M. Azharuddin, N. Bilakanti, and R. Natarajan, “A dynamic photo voltaic emulator using dspace controller with high accuracy solar photo voltaic characteristics,” *Journal of Renewable and Sustainable Energy,* vol. 8, p. 015503, 01 2016.

[13] A. C. Alejandro C.A. Javier V.C., Jaime O-A, Roberto C , Jesu Gı, “A high-accuracy photovoltaic emulator system using ARM processors,” *J. Sol. Energy*, vol. 120, pp. 389–398, 2015.

[14] A. Chouder, S. Silvestre, B. Taghezouit, and E. Karatepe, “Monitoring, modelling and simulation of PV systems using LabVIEW,” *Sol. Energy*, vol. 91, pp. 337–349, May 2013.

[15] A. Xenophontos, J. Rarey, A. Trombetta, and A. M. Bazzi, “A flexible low-cost photovoltaic solar panel emulation platform,” in *2014 Power Energy Conf. Illinois.* IEEE, feb 2014, pp. 1-6.

[16] K. Arakaki, K. Kuwae, Y. Shimizu, and H. Kitano, “A Microgrid Simulation Software for DC- based Open Energy Systems - The DCOES Simulator,” in *6th IEEE International Conference on Smart Grid, icSmartGrids 2018*, 2019, pp. 136–141.

[17] Suthar, M., Singh, G. K. and Saini, R. P. ‘Comparison of Mathematical Models of Photo- Voltaic Module and effect of various Parameters on its Performance’ in International Conference on Energy Efficient Technologies for Sustainability (ICEETS), 2013, pp. 1354–1359.

[18] Mohapatra, a., Nayak, B. K. and Mohanty, K. B. ‘Comparative study on single diode photovoltaic module parameter extraction methods’ 2013 International Conference on Power, Energy and Control (ICPEC). IEEE, 2013, pp. 30–34.

[19] M. Ulaganathan and D. Devaraj, “Real coded genetic algorithm for optimal parameter estimation of solar photovoltaic model,” in *2016 International Conference on Emerging Trends in Engineering, Technology and Science (ICETETS)*, 2016, pp. 1–6.

[20] D. Sera, R. Teodorescu, and P. Rodriguez, “PV panel model based on datasheet values,” in *2007 IEEE Int. Symp. Ind. Electron.* IEEE, jun 2007, pp. 2392-2396

[21] M. Demirtas, M. Yesilbudak, S. Sagiroglu, and I. Colak, “Prediction of solar radiation using meteorological data,” in *2012 International Conference on Renewable Energy Research and Applications, ICRERA 2012*, 2012, pp. 2–5.

[22] L. Castaner and S. Silvestre, *Modelling Photovoltaic Systems Using PSpice®.* Wiley, sep 2002.

[23] I. Moussa and A. Khedher, “Photovoltaic emulator based on PV simulator RT implementation using XSG tools for an FPGA control: Theory and experimentation,” *Int. Trans. Electr. Energy Syst.*, no. March, pp. 1–16, 2019.

[24] Y. Vagapov and A. Anuchin, “Low-cost photovoltaic emulator for instructional laboratories,” *Proc. - 2016 51st Int. Univ. Power Eng. Conf. UPEC 2016*, vol. 2017-January, pp. 1–6, 2017.

[25] Koutroulis, K. Kalaitzakis, and V. Tzitzilonis, “Development of an FPGA-based System for Real-Time Simulation of Photovoltaic Modules,” in *Seventeenth IEEE International Workshop on Rapid System Prototyping (RSP’06)*, 2006, pp. 200–208.

[26] S. Sheik Mohammed, D. Devaraj, and T. P. Imthias Ahamed, A novel hybrid Maximum Power Point Tracking Technique using Perturb & Observe algorithm and Learning Automata for solar PV system, *Energy,* vol. 112, pp. 1096-1106, oct 2016.

[27] G. Radhia, B. H. Mouna, S. Lassaad, and O. Barambones, “MPPT controller for a photovoltaic power system based on increment conductance approach,” in *Proceedings of 2013 International Conference on Renewable Energy Research and Applications, ICRERA 2013*, 2013, pp. 73–78.