Performance Based Analysis of Solar PV Emulators: A Review

Conference Paper · September 2018

DOI: 10.1109/CCTES.2018.8674082

6 authors, including:

Mohammad Shahabuddin
Integral University
4 PUBLICATIONS **51** CITATIONS
SEE PROFILE

Ahmed Riyaz
Baba Ghulam Shah Badshah University
24 PUBLICATIONS **140** CITATIONS
SEE PROFILE

Mohammed Asim
Integral University
62 PUBLICATIONS **397** CITATIONS
SEE PROFILE

Mirza Mohammad Shadab
Integral University
7 PUBLICATIONS **92** CITATIONS
SEE PROFILE

2018 International Conference on Computational and Characterization Techniques in Engineering & Sciences (CCTES)
Integral University, Lucknow, India, Sep 14-15, 2018

Performance Based Analysis of Solar PV Emulators: A Review

Mohammad Shahabuddin
Department of Electrical Engineering
Integral University,
Lucknow, India
mshahab@iul.ac.in

Mohammed Asim
Department of Electrical Engineering
Integral University,
Lucknow, India
asimamu@gmail.com

Adil Sarwar
Department of Electrical Engineering
Aligarh Muslim University
Aligarh, India
adil.sarwar@zhcet.ac.in

Ahmed Riyaz
Department of Electrical and Renewable Energy
BGSB University
Rajauri, India
riyazamu@gmail.com

Mirza Mohammad Shadab
Department of Electrical Engineering
Integral University,
Lucknow, India
mshahab@iul.ac.in

Anas Anees
Department of Electrical Engineering
Aligarh Muslim University
Aligarh, India
anasanees.amu@gmail.com

***Abstract*—Ever increasing demand of energy and continuous depletion of accessible standard energy resources has diverted the mind of researchers towards the efficient utilization of renewable resources of energy like sun, wind & sea water movement etc. for generation of electrical energy. Among all the renewable energy resources, solar energy is abundantly and almost uniformly available in most part of the world and is seen as a potential player in future energy market around the world. The advantages of electrical energy generation through sun include pollution free electricity generation, negligible maintenance and free availability. Electrical energy can be generated from sun by either directly converting the sunlight into dc electricity or through solar thermal energy. Energy through solar photovoltaic[SPV] has seen a**n enormous funding in research and development with **ministry of new and renewable energy sources [MNRE], government of India, pumping in vital funds for its effective utilization in India. Electrical energy can be extracted from solar photovoltaic module or array during sunny days in the form of dc and can be converted to ac by the use of inverters and can be stored by using batteries for the use in night or in durations of unavailability of solar irradiations in rainy seasons. Solar PV module or array could be a combination of PV cells that can be connected in either series or parallel or combination of both to enhance the power output to the match the load demand. The output power of these photovoltaic modules is affected by varying environmental conditions like variation in irradiations and operating cell temperatures etc. The present work pertains to reviewing the development of solar PV emulator for testing and carrying out research activities on solar PV based system thereby providing the problems posed by its intermittent nature of dependence on the weather conditions. A through and critical analysis of various power electronic and conventional analog technologies in development of solar PV emulator has been carried out. The performance comparison of solar PV emulator presented in literature based on various parameters has also been presented.**

Keywords—Renewable energy system, Solar PV emulator, Maximum power point tracker (MPPT), Buck converter

I. INTRODUCTION

There has been an increase in application of renewable energy in daily uses. Solar photovoltaic system leads other renewable energy sources as potential energy player particularly in the area where grid supply is not available. The output I-V characteristic of solar PV panel is non-linear in nature [1]. Moreover, the characteristics changes, due to change in environmental condition (Fig. 1). This leads to operation at a point away from knee point of I-V curve (where maximum power is available), hence decreasing the overall efficiency of PV panel. The effective installation and utilization of solar PV panel depends on tracking this knee point of operation. So research in solar PV area revolves around to find better materials for solar PV and developing better algorithms (known as maximum power point tracking algorithms) for effective utilization of sun's energy falling on panel. The nonlinear power characteristics of solar PV panel have been modelled by various researchers to understand and study the performance of solar PV based system [1]-[7]. Solar PV emulator refers to the system which emulates the solar PV characteristic and behavior and can be used to power solar PV based systems which is under testing, research or development stage for the purpose of analysis and evaluation of its performance and behavior under varying atmospheric conditions [8]. Various methods have been reported in literature in formulating a practical solar PV emulator [9]-[19]. But there is a lack of concentrated effort to gather all these work at a single platform which provides a central point for the researchers to do innovative work in the development of less costly and simple PV emulator. Only few papers are available which have comprehensively classified the PV emulators [20]. In this paper, the authors administered an avid effort to compile the literature that are otherwise scattered in the area of development of solar PV emulator. Because of the presence of few manufacturers the cost of solar PV emulator in market is very high and hampers the institutions in doing effective research because of the cost constraints.

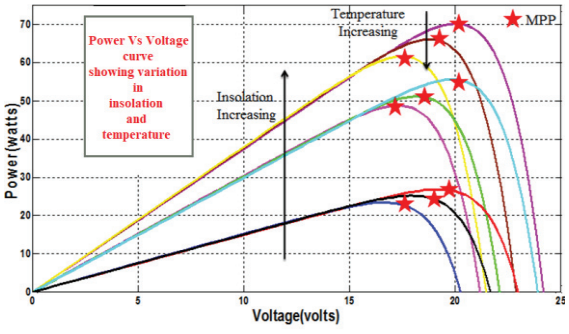

Fig. 1. Power output versus PV Voltage (MPP refers to maximum power point)

II. SOLAR PHOTOVOLTAIC (PV) EMULATOR

A. The need for a PV emulator

The high dependence of output of a PV panel on the atmospheric condition makes it difficult to use it for lab testing of various power electronic interfaces. Thus, there is a requirement of a system which could emulate the actual behavior [I-V and P-V characteristics] of a PV panel under varying atmospheric condition [temperature and solar insolation]. The emulation should also ensure that the desired I-V characteristic corresponding to the real atmospheric condition should be generated depending on the test requirement. This would ensure invariance of the test results and could be replicated again for repeated testing of power electronic interface. Moreover, the space constraint and high cost of installation also limits the use of actual PV panel for testing purpose.

B. Requirements of an ideal PV emulator

- The highly nonlinear IV and PV characteristics of a PV panel should be closely emulated corresponding to the atmospheric temperature and solar insolation
- It should have the ability to be interfaced with any type of power electronic converter for testing purpose.
- It should be programmable and could effectively emulate the panels available from solar panel manufactures.
- The real situation and circumstances like partial shading and rapid changing atmospheric condition could also be replicated without any control issues.
- The cost of the emulator should be low so that it could be procured easily by academic and research institutes for enhanced research activity in the area of solar PV for the benefit of humanity.

III. TYPES OF PV EMULATORS

The development of solar PV emulators has been playing an important role in ascertaining the application area of solar PV system. Various manufacturers of PV emulators like Ecosense, Ametek, itech power etc. are supplying PV emulators and their products are replicating exact PV characteristics of PV panels manufactured by leading companies in area of solar panel. In this section, the PV emulators reported in literature have been grouped under following headings and discussed.

A. Conventional type PV emulator

B. Programmable dc supply based PV emulator and Power electronic converter based PV emulator

C. Microcontroller/DSP/FPGA based PV emulator

D. Hardware in Loop (HIL) based PV emulator

E. Commercial solar PV emulators

A. Conventional type PV emulator

In this section PV emulators based on analog circuits and simple single diode and double diode model has been categorized as conventional PV emulators. PV emulator A PV emulator which is based on basic analog electronic circuit was designed and implemented by the authors of [8]. Among various types of PV emulators available in the literature, emulator based on one diode model approximation is the oldest (Fig. 2). The emulator requires a dc current source and diode in parallel to replicate the IV characteristics of solar cell. Resistances in series and parallel accounts for losses within the cell [21]-[23]. The disadvantage with one diode model it that it doesn't replicate the IV & PV characteristics for varying environmental (temperature and solar insolation) situations effectively [21]. Hence as replacement, a two diode model approximation was proposed (Fig. 3). The results came within the range of effective performance at low irradiation (insolation) level. [21]. But there is great complexity involved in PV panel models available as single diode model and two diode model as they involve evaluation of five parameter and seven parameters respectively.

To reduce the complexity two separate interpolation methods were proposed by author in [24]. The first method requires series resistance to produce accurate model and the second method requires the I-V curve factor and one more point on I-V curve to produced improved result.

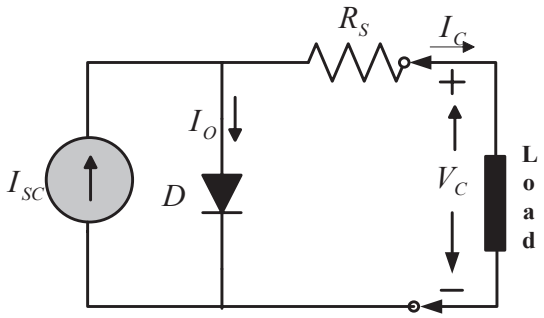

Fig. 2. Model for one diode approximation

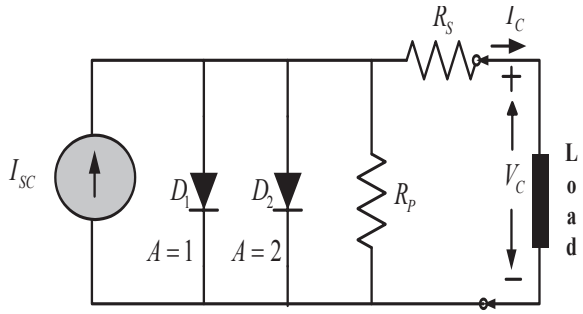

Fig. 3. Model for two diode approximation

B. Programmable dc supply based PV emulator and Power electronic converter based PV emulator

A DC-DC converter is an important part of PV emulator based on converter logic. Different types of converter such as buck converter, SEPIC converter, LLC resonant converter had been used. The basic topology of a PV emulator based on converter logic is shown in Fig. 4. The author in [12] proposed an approach for designing and implementing power electronic based PV emulator which emulates the output characteristics of the PV module using buck converter. A lookup table corresponding to the data of sun power solar panel module has been obtained. A power factor corrected buck converter based on look up table data is used to observe the behavior of panel at various solar irradiance and temperature condition. MATLAB/Simulink based modeling and simulation has been used to obtain the results of the output characteristics which coincides with the actual PV modules characteristics.

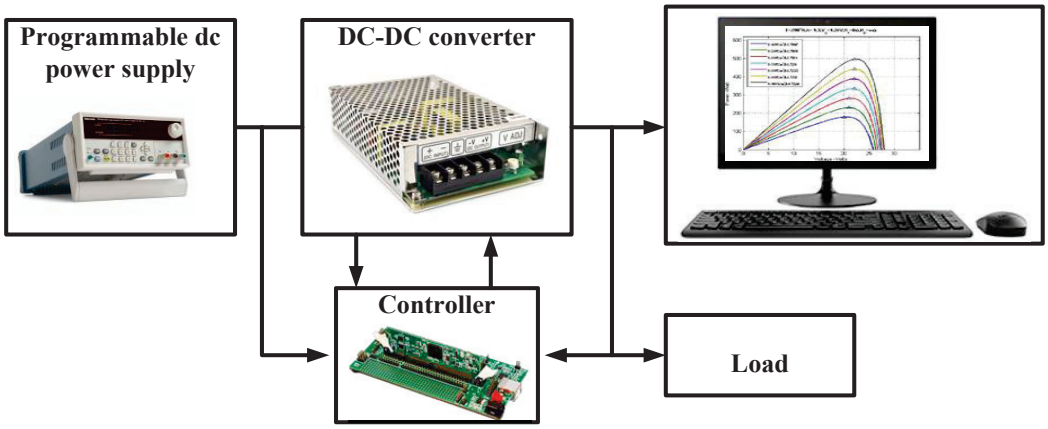

Fig. 4. Block diagram of PV emulator based of converter logic

The role of these converters is generally to ensure operation at maximum power point [13-14]. In the case of buck converter, the generated voltage/current from PV panel is compared with reference voltage/current depending on the type of MPP algorithm. In the case of constant voltage technique, voltage of PV panel is compared with a fraction of open circuit voltage. The error is then passed to the PWM generator and then to the buck converter. The author in [15] proposed a PV emulator based on single ended primary converter [SEPIC] with high accuracy.

C. *Microcontroller/DSP/FPGA based PV emulator*

The real time controllers have increased the effectiveness and accuracy of the PV emulator. The modeling used for it is generally a single diode model except in few cases as in ARM controller based PV emulator double diode model is used [25]. These controllers have the added advantage that they give accurate results for almost every condition such as rapidly changing atmospheric conditions and partial shading conditions. These controllers are also flexible as well as robust. They generally work by collecting data from the manufacturer datasheet with the help of which an interface is build. According to these data, different signals are sent to track the optimum point of operation on the IV characteristic. The various types of real time controllers used by various authors are dspace, FPGA, Microcontroller, ARM controller, and RT-Lab controller [12], [17] and [19]. Digital Signal Controller (DSC) dsPIC33E64MC202 based PV emulator has been developed by [10]. It utilizes the power quasi sliding mode control scheme for implementing the control for fast changing atmospheric condition. Fixed frequency sliding mode control has been investigated further as the filter design for fixed frequency sliding mode control is simple compared to its hysteresis counterpart. A metaheuristic technique (Artificial Bee Colony and Differential Evolution) has beed adopted by authors of [26] to study the faults occurring in a building integrated PV system (BIPV). They had developed a PV emulator based on one diode model. The authors of [27] have shown a PV emulator based on a Digital Signal Processor (TMS320F28335) and DC-DC converter- capable of simulating the IV and PV characteristics of a real solar PV panel. The designed PV emulator has a fast transient response. Moreover, the steady state operating points fits well with the theoretical characteristic.

D. *Hardware in Loop (HIL) based PV emulator*

Hardware-In-the-Loop (HIL) platform has been recognized as a powerful prototyping tool in the testing and validation of renewable energy based system.

The author of paper [28] presented a real time supervision HIL emulator for partial shaded solar PV array. The work emulates the real time behaviour of a shaded PV panel necessary for evaluation of fault detection method using HIL approach. A high level specification of embedded system (HiLeS) for automatic very high-speed integrated circuit hardware description language (VHDL) code generation has been employed for emulating the photovoltaic system behaviour. Experimental results validate a near IV behaviour of the emulator.

A hardware-in-the-loop (HIL) implementation of solar Photovoltaic module has been reported in [29] .It utilizes sliding mode control for the operation of a dc–dc boost converter and a current controlled-voltage source converter. The experimental results promises regulation of voltage and frequency in case of grid connected system and overcurrent protection for standalone storage system like battery.

A real-time simulator of a PV array which is based on self-supervised neural networks Growing Neural Gas (GNG) algorithm has been presented in [30]. Current-voltage-irradiance temperature mapping, given by the growing neural gas algorithm, drives the DC-DC converter and claimed to accurately describe the characteristics of a PV array. The characteristic of solar PV output which depends heavily on the solar insolation and PV cell temperature is also reported to be incorporated. The stability of the said PV emulator was also tested in discrete domain.

The authors of [31] proposed and analyzed a PV active power tracking algorithm and a four phase interleaved boost converter was selected for the implementation. Automatic code generation of MATLAB software is used to generate the codes while HIL device was used to emulate the power stage.

E. *Commercial Solar PV emulators:*

The section gives a brief account of some of the commercial PV emulator available in market. It does not intend to compare the performance of the products nor does

it present a detailed description of the product. The details of the product can be obtained from the respective websites [32]-[36].

The Solar PV emulator from Ecosensense is a programmable dc power supply designed to emulate solar panels [32]. There are four independent channels of 400 Watts each. The IV data has been collected for different manufacturers developing PV panel. The atmospheric data at different longitude and latitude is taken online and can be used to emulate the system. There are three different modes of operation [32]:

1. Fixed Mode –Emulator works like a programmable dc power supply. It can supply controlled voltage in the range 0-50 Volts and 0-8 A from each of the four ports.
2. Table Mode – wherein 12 hours of data can be downloaded and emulated in the four ports of the emulator.
3. Simulator Mode – A maximum of 10 preconfigured table can be downloaded and emulated. There is no time limit for the emulation to run.

Solar array simulator from chroma is a fully programmable solar PV emulator available with Standard USB / RS232 / RS485 interface [33]. Solar cell materials can also be emulated. It is available in variety of voltage and power range. Using parallel operation solar PV output of upto 1.5 MW can be emulated. It has a feature to test algorithms for static and dynamic MPPT. There are provisions for testing solar inverter efficiency. It boasts of very fast dynamic response. Solar array simulators from keysight technologies formerly agilent technologies accurately simulates the I-V curve of solar panels manufactured by different companies under various environmental conditions (such as eclipse, spin, rotation, age and temperature) [34]. The advance emulator has a variety of features including remote programming via GPIB, LAN and USB interfaces. A high-speed high performance photovoltaic / solar simulation power supply, equipped with SAS1000 solar array simulation software is being manufactured by itech power testing solution [35]. It can accurately simulate the solar array I-V curve, up to a maximum voltage of 1000V, power can be extended to 100KW by connecting the emulators is series and parallel. It has a fast response time with better fast control and repeatability features along with other superior characteristics. Solar PV emulator manufactured by AMETEK is another solar simulator for testing energy storage, microgrids and various inverter test applications [36]. It has been specifically designed to emulate the dynamic IV characteristic of solar PV array with low output capacitance and high closed loop bandwidth for easy MPPT tracking. There are other companies in the business of developing solar PV emulators. But the basic issue with all the products is the high cost of procurement [37], [38].

IV. COMPARATIVE ANALYSIS

Various sorts of PV emulators have been developed recently varying from the most basic one diode approximation to the latest IOT based model. In this section criterion based analysis of the PV emulator has been done based on various performance parameters.

The analysis done can be useful for the researchers and students to assist in selection of PV emulator according to their needs depending upon the application and financial constraints. A comparative study taking into consideration the below mentioned factors for different PV emulators have been presented in Table 1. The performance of various groups of PV emulator is gauged quantitatively as low, moderate and high value. The complexity in the hardware has been differentiated in terms of easy, not realizable and difficult.

TABLE I. COMPARATIVE ANALYSIS OF VARIOUS PHOTOVOLTAIC EMULATORS REPORTED IN LITERATURE

S.no	***Techniques***	***Performance for rapidly changing weather condition***	***Accuracy***	***Hardware development***	***Efficiency***	***Price***	***Ease of implementation***
1	*Conventional type PV emulator*	Satisfactory	Less	Easy	Less	Less	Easy
2	*Programmable dc supply based PV emulator*	Good	Moderate	Moderate	Moderate	Moderate	Moderate
3	*Power electronic converter based PV emulator*	Depends on control algorithm	High	Moderate	Moderate	Moderate	Moderate
4	*Microcontroller/DSP/FPGA based PV emulator*	Stable and smooth operation	High	Moderate	High	High	Difficult
5	*Hardware in Loop (HIL) based PV emulator*	Very Good	Very High	Complex	High	Very high	Difficult
6	*Commercial solar PV emulators*	Very Good	Very High	Commercial products with plug n play feature	High	Very high	Manual available

V. CONCLUSION

A thorough review of different PV emulators reported in literature has been done and based on the technology used they have been categorized in this paper. The work is useful for researchers planning to embark research activity in the area of solar PV emulators as research reported in more than three dozen papers and articles have been comprehensively reported here.

On the basis of comparative study, some concrete inference on each emulator has also been given. The pros and cons of all the methods have also been discussed.

REFERENCES

[1] A. Sarwar, M. Hasan and A. Q. Ansari, "Five parameter modelling and simulation of solar PV cell," *2015 International Conference on Energy Economics and Environment (ICEEE)*, Noida, 2015, pp. 1-5.

[2] Y. Liu, Z. Lu and F. Yang, "The investigation of solar PV models," *2018 IEEE Power & Energy Society Innovative Smart Grid Technologies Conference (ISGT)*, Washington, DC, 2018, pp. 1-5.

[3] O. Ibrahim, N. Z. Yahaya, N. Saad and M. W. Umar, "Matlab/Simulink model of solar PV array with perturb and observe MPPT for maximising PV array efficiency," *2015 IEEE Conference on Energy Conversion (CENCON)*, Johor Bahru, 2015, pp. 254-258.

[4] G. Bhuvaneswari and R. Annamalai, "Development of a solar cell model in MATLAB for PV based generation system," *2011 Annual IEEE India Conference*, Hyderabad, 2011, pp. 1-5.

[5] Y. Seo, J. Park and S. Choi, "A rapid I-V curve generation for PV model-based solar array simulators," *2016 IEEE Energy Conversion Congress and Exposition (ECCE)*, Milwaukee, WI, 2016, pp. 1-5.

[6] B. K. Dey, I. Khan, N. Mandal and A. Bhattacharjee, "Mathematical modelling and characteristic analysis of Solar PV Cell," *2016 IEEE 7th Annual Information Technology, Electronics and Mobile Communication Conference (IEMCON)*, Vancouver, BC, 2016, pp. 1-5.

[7] Hyeonah Park and Hyosung Kim, "PV cell modeling on single-diode equivalent circuit," *IECON 2013 - 39th Annual Conference of the IEEE Industrial Electronics Society*, Vienna, 2013, pp. 1845-1849.

[8] P. J. Binduhewa and M. Barnes, "Photovoltaic emulator," *2013 IEEE 8th International Conference on Industrial and Information Systems*, Peradeniya, 2013, pp. 519-524.

[9] D. Chariag and L. Sbita, "Design and simulation of photovoltaic emulator," *2017 International Conference on Green Energy Conversion Systems (GECS)*, Hammamet, 2017, pp. 1-6.

[10] A. F. Ebrahim, S. M. W. Ahmed, S. E. Elmasry and O. A. Mohammed, "Implementation of a PV emulator using programmable DC power supply," *SoutheastCon 2015*, Fort Lauderdale, FL, 2015, pp. 1-7.

[11] U. K. Shinde, S. G. Kadwane, S. P. Gawande and R. Keshri, "Solar PV emulator for realizing PV characteristics under rapidly varying environmental conditions," *2016 IEEE International Conference on Power Electronics, Drives and Energy Systems (PEDES)*, Trivandrum, 2016, pp. 1-5.

[12] A. Rachid, F. Kerrour, R. Chenni and H. Djeghloud, "PV emulator based buck converter using dSPACE controller," *2016 IEEE 16th International Conference on Environment and Electrical Engineering (EEEIC)*, Florence, 2016, pp. 1-6.

[13] B. D. Patel and A. Rana, "A pole-placement approach for buck converter based PV array Emulator," *2016 IEEE 1st International Conference on Power Electronics, Intelligent Control and Energy Systems (ICPEICES)*, Delhi, 2016, pp. 1-5.

[14] M. A. Abdourraziq, S. Abdourraziq, M. Maaroufi, M. Tlemcani and C. Darab, "Experimental results of photovoltaic emulator systems," *2017 International Conference on Electromechanical and Power Systems (SIELMEN)*, Iasi, 2017, pp. 261-265.

[15] M. Hasnaoui, A. Bennani-Ben Abdelghani and I. Slama-Belkhodja, "Control design and experimental set-up for a high-power PV generator emulator," *2018 9th International Renewable Energy Congress (IREC)*, Hammamet, 2018, pp. 1-6.

[16] P. Garg, Priyanshi and G. Bhuvaneswari, "Power electronic circuit based implementation of a solar PV emulator using a power factor corrected buck converter," *2018 IEEMA Engineer Infinite Conference (eTechNxT)*, New Delhi, 2018, pp. 1-6.

[17] I. Moussa, A. Bouallegue and A. Khedher, "Development of a low cost PV simulator based on FPGA technology," *2017 International Conference on Green Energy Conversion Systems (GECS)*, Hammamet, 2017, pp. 1-6.

[18] S. Thale, R. Wandhare and V. Agarwal, "A novel low cost portable integrated solar PV, fuel cell and battery emulator with fast tracking algorithm," *2014 IEEE 40th Photovoltaic Specialist Conference (PVSC)*, Denver, CO, 2014, pp. 3138-3143.

[19] I. Moussa, A. Bouallegue and A. Khedher, "New MPPT algorithm modeling for photovoltaic emulator designed in FPGA," *2017 International Conference on Green Energy Conversion Systems (GECS)*, Hammamet, 2017, pp. 1-7.

[20] J. P. Ram, H. Manghani, D. S. Pillai, T. S. Babu, N. Rajasekar, "Analysis on solar PV emulators: A review," *Renewable and Sustainable Energy Reviews*, Vol. 81, no.1, pp. 149-160, 2018.

[21] K. Ishaque, Z. Salam, Syafaruddin, "A comprehensive MATLAB Simulink PV system simulator with partial shading capability based on two-diode model," *Solar Energy*, vol. 85, pp. 2217–2227, 2011.

[22] A. Sarwar, M. S. J. Asghar, Imdadullah and SK. M. Ahmed, "Development of Solar PV Based Grid Connected Inverters," *Proceedings of International Conference on Electrical Energy System & Power Electronics*, PP. 1172-1177, 2009.

[23] A. Sarwar, "Integrated Maximum Power Point Tracking and Harmonic Reduction in a Grid Interactive Solar PV Inverter," *Journal of Instrumentation Technology & Innovations*, vol. 4, no. 1, pp. 7-15, 2014.

[24] R. Ayop and C. W. Tan, "A comparison study of interpolation and circuit based photovoltaic mathematical models," *2016 IEEE International Conference on Power and Energy (PECon)*, Melaka, 2016, pp. 626-631.

[25] A. C. Atoche, J. V. Castillo, J. O. Aguilar, R. C. Alvarez, A. C. Menchi , "A high-accuracy photovoltaic emulator system using ARM processors," *Solar Energy*, Vol. 120, pp. 389-398, 2015.

[26] O. Hachana, K. E. Hemsas and G. M. Tina, "Fault diagnosis of building integrated PV generator: A metaheuristic technique," *IREC2015 The Sixth International Renewable Energy Congress*, Sousse, 2015, pp. 1-6.

[27] X. R. I. Andrew, M. Anand. and P. Sivakumar., "Modelling and analysis of emulator for distributed generation sourced smart grid using digital signal controller (TMS320F28335)," *ISGT2011-India*, Kollam, Kerala, 2011, pp. 160-166.

[28] A. Gutierrez, M. Bressan, J. F. Jimenez and C. Alonso, "Development of real-time supervision HIL emulator of shaded PV systems," *2017 IEEE 6th International Conference on Renewable Energy Research and Applications (ICRERA)*, San Diego, CA, 2017, pp. 499-504.

[29] M. Rezkallah, A. Hamadi, A. Chandra and B. Singh, "Real-Time HIL Implementation of Sliding Mode Control for Standalone System Based on PV Array Without Using Dumpload," in *IEEE Transactions on Sustainable Energy*, vol. 6, no. 4, pp. 1389-1398, Oct. 2015.

[30] M. Cirrincione, M. C. Di Piazza, M. Pucci and G. Vitale, "Real-time simulation of photovoltaic arrays by growing neural gas controlled DC-DC converter," *2008 IEEE Power Electronics Specialists Conference*, Rhodes, 2008, pp. 2004-2010.

[31] P. Vlado, A. Evgenije, G. Stevan, V. Marko and R. Milan, "Precise PV active power — Converter control rapid prototyping framework," *2017 International Symposium on Power Electronics (Ee)*, Novi Sad, 2017, pp. 1-6.

[32] "Solar PV Emulator | Ecosense", *Ecosenseworld.com*, 2018. [Online]. Available: http://www.ecosenseworld.com/labs/solar-pv-labs/solar-pv-emulator. [Accessed: 24- Aug- 2018].

[33] C. Inc., "Solar Array Simulator | Chroma ATE Inc.", *Chromaate.com*, 2018. [Online]. Available: http://www.chromaate.com/product/62150H-600S_1000S_Solar_Array_Simulator.htm. [Accessed: 24- Aug- 2018].

[34] "E4360 Modular Solar Array Simulators | Keysight [formerly Agilent's Electronic Measurement]", *Keysight.com*, 2018. [Online]. Available: https://www.keysight.com/en/pc-1367756/e4360-modular-solar-array-simulators?cc=US&lc=eng. [Accessed: 24- Aug- 2018].

[35] "Photovoltaic /solar simulator power supply | ITECH", *Itechate.com*, 2018. [Online]. Available: http://www.itechate.com/en/product/dc_power_supply/PV.htm?gclid

=Cj0KCQjw2f7bBRDVARIsAAwYBBtBYj3gCJgN1DZ5HmI4XeCIbFYsBQxuG51O0u9yZP074fB1VjmDf0caAm98EALw_wcB. [Accessed: 24- Aug- 2018].

[36] "Programmable Power Photovoltaic Simulator Provides Higher Output and Power", *Ametek.com*, 2018. [Online]. Available:https://www.ametek.com/pressreleases/news/2015/august/programmable-power-photovoltaic-simulator-provides-higher-output-and-power. [Accessed: 24- Aug- 2018].

[37] Y. Vagapov and A. Anuchin, "Low-cost photovoltaic emulator for instructional laboratories," *2016 51st International Universities Power Engineering Conference (UPEC)*, Coimbra, 2016, pp. 1-4.

[38] A. Sanaullah and H. A. Khan, "Design and implementation of a low cost Solar Panel emulator," *2015 IEEE 42nd Photovoltaic Specialist Conference (PVSC)*, New Orleans, LA, 2015, pp. 1-5.