

**Conference Presentation**

Low-cost photovoltaic emulator for instructional laboratories

Vagapov, Y. and Anuchin, A.

This is a paper presented at the 51st IEEE Int. Universities Power Engineering Conference UPEC-2016

Copyright of the author(s). Reproduced here with their permission and the permission of the conference organisers.

---

**Recommended citation:**

Vagapov, Y. and Anuchin, A. (2016), 'Low-cost photovoltaic emulator for instructional laboratories.' In: Proc. 51st IEEE Int. Universities Power Engineering Conference UPEC-2016, Coimbra, Portugal, 6-9 September 2016, 4p.

# Low-cost Photovoltaic Emulator for Instructional Laboratories

Yuriy Vagapov

School of Applied Science, Computing and Engineering,  
Glyndwr University,  
Plas Coch, Mold Road, Wrexham, LL11 2AW, UK  
y.vagapov@glyndwr.ac.uk

Alecksey Anuchin

Department of Electric Drives,  
Moscow Power Engineering Institute,  
14 Krasnokazarmennaya Street, 111250, Moscow, Russia  
anuchin.alecksey@gmail.com

**Abstract**—This paper discusses a simple and cheap PV emulator based on a linear power supply that does not require a source of light to conduct laboratory experiments. The emulator has been designed to underpin students' understanding the properties of PV cell V-I characteristics and the ways to maximise the output power learned from lectures, tutorial and self-studies. The emulator has been built using “on the shelf” components and tested under rated power conditions. It demonstrated a good emulation of V-I characteristics within the rated range of the sun irradiation and the temperature.

**Index Terms**— instructional laboratory, linear power supply, photovoltaic emulator

## I. INTRODUCTION

Electric power generated using photovoltaic (PV) technologies has dramatically grown over the past decade. International Energy Agency reported that the global capacity of installed PV has been increased in 25% in 2015 and reached the value of 227.1GW [1]. That was achieved due to significant reduction of PV manufacturing and installation cost. It has been also reported that since 2010 the price of solar PV cells per one watt does not exceed 1.0 £/W [2].

In the context of engineering education, the PV technology was not the object for massive research and educational interest prior to the early 2000s. The technology was extremely expensive and, therefore, considered not applicable for mass production and industrial scale installations. A relatively small number of engineers and scientists across the world were involved in research and development in the area of PV solar cells [3]. This is why the study of principles of PV technologies and their applications were not widely integrated into the engineering curriculum in colleges and universities across the world.

Intensive expansion of PV technologies in the recent years demands a significant increase in specialists having skills and professional competences to manufacture, design, develop, install and manage various types of PV applications. Many education providers such as schools, colleges and universities focused on STEM subjects are revising their engineering curriculum to integrate renewable energy and sustainability components including principles of PV technologies into academic programmes [3].

A typical learning and teaching strategy in the area of engineering education comprises both theoretical and

practical elements. Both elements aim to provide the students with appropriate learning outcomes thorough lectures, tutorial and laboratory works. Practical experiments conducted in an instructional laboratory are essential components of the learning process underpinning theoretical knowledge obtained from lectures, tutorial and self-studies. Execution of practical controlled assignments under academic staff supervision requires appropriate laboratory equipment focused on particular aspects of technologies [4]-[7].

As for PV technologies, the laboratory equipment should provide curriculum support for investigation and analysis of volt-ampere (V-I) characteristics of PV cells to cover the main objectives of the practical experiments. The majority of educational equipment produced by manufacturers, colleges and universities are laboratory workstations based on a real PV cell that included a light source to simulate sun irradiation [8]-[11]. However, such a complicated and expensive structure of the workstation is not required if the objective of study is the investigation of PV cell V-I characteristics, particularly, in the context of Maximum Power Point Tracking (MPPT) applications [12]-[17].

Therefore, the paper discusses a simple and cheap PV emulator based on a linear power supply and not requiring a source of light to conduct an experiment. The emulator is designed to support the students in understanding the properties of PV cell V-I characteristics and the ways to maximise the output power, most important learning outcomes of studies in the area of PV technologies.

## II. PV EMULATOR

MPPT methods are widely implemented in PV applications for efficient absorption of power generated by solar cells. The principle of MPPT methods is based on the non-linearity of volt-ampere characteristics of a PV panel where shape of the curve depends on level of sun irradiation and temperature of the panel [18], [19]. Therefore a PV emulator is actually a dc power supply having the non-linear output characteristic corresponding to V-I curve of a real solar cell.

Many power supply based PV emulator utilise switching mode power supplies to reduce power losses and increase efficiency of the device [12], [14], [20]-[24]. These solutions are usually implemented in high power emulators and require

quite sophisticated control. On the other hand, PV emulators based on linear power supplies are much simple and cheaper in terms of hardware. This is why majority of “low cost” emulators are actually linear power supplies. Although these emulators are rated for low power their control is relatively simple [17], [25], [26].

The control of PV emulators is usually digital, based on a microcontroller or DSP board [6], [12], [14], [20]. However some emulators employ computer based control using LabVIEW [13] or dSPACE [27] programming environments. These systems are quite advanced and benefit from ability to be integrated into bigger measurement complexes. Analogue circuits usually used to control the linear power supply emulator at a low power rate [17], [25], [26].

Therefore, the linear power supply structure and simple microcontroller based control has been used to design and built the emulator in order to cut the cost of the device. Fig. 1 shows the functional diagram of the proposed PV emulator.

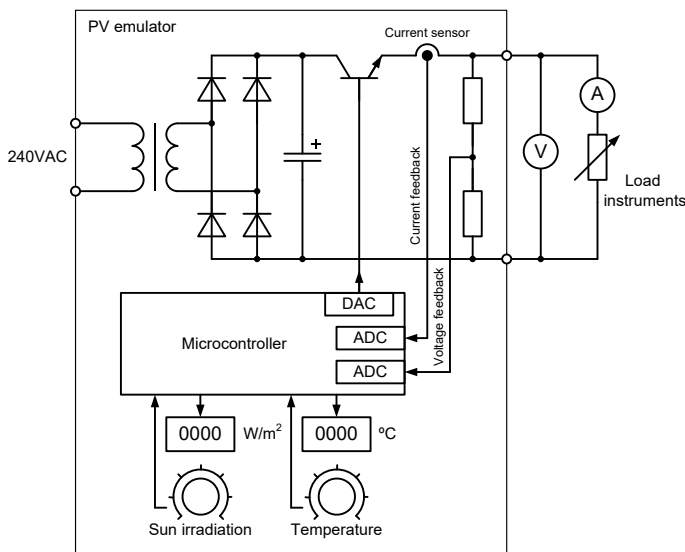


Fig. 1. Functional diagram of PV emulator. The values of sun irradiation in  $W/m^2$  and the cell temperature in  $^{\circ}C$  are input manually and indicated on the front panel of the emulator.

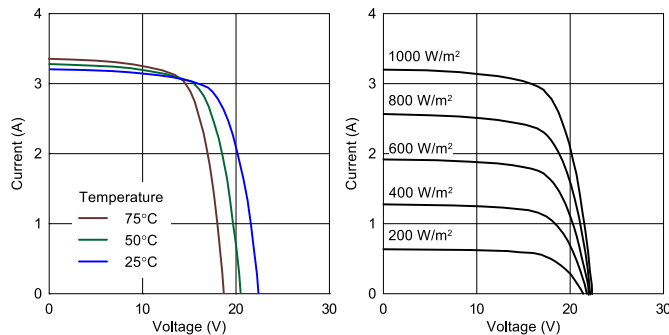


Fig. 2. Examples of V-I characteristics used for the PV emulator [14]; left side – constant sun irradiation of  $1000W/m^2$ ; right side – constant PV temperature of  $25^{\circ}C$ .

The emulator comprises of a simple linear power supply having the output characteristics similar to a PV cell V-I curve. The control circuit of the emulator utilises a microcontroller to process the current and voltage feedbacks from the output of the emulator. The microcontroller employs the modified algorithm of PV simulation suggested by [17]. The inputs for the microcontroller are voltages corresponding to the level of sun irradiation and temperature of emulated PV cell. The microcontroller also provide the indication of the input parameters in  $W/m^2$  for the sun irradiation and  $^{\circ}C$  for the temperature. The emulator is rated at 120 W to provide the output voltage up to 30 V and current up to 4 A.

The device emulates V-I characteristics of the monocrystalline PV cell having peak power of 50W and maximum power point at the current of 2.9A and the voltage of 17.2V [14]. The family of V-I characteristics of the cell for constant sun irradiance and constant temperature are shown in Fig. 2.

### III. TEST RESULTS

The prototype of the PV emulator has been testes in order to verify the approach used for the device design and development. The emulator was tested to simulate V-I characteristic of the real PV cell under wide range of sun irradiation ( $100-1000W/m^2$ ) and the cell temperature ( $25-75^{\circ}C$ ). The test results demonstrated a good emulation of V-I characteristics of the real PV cell.

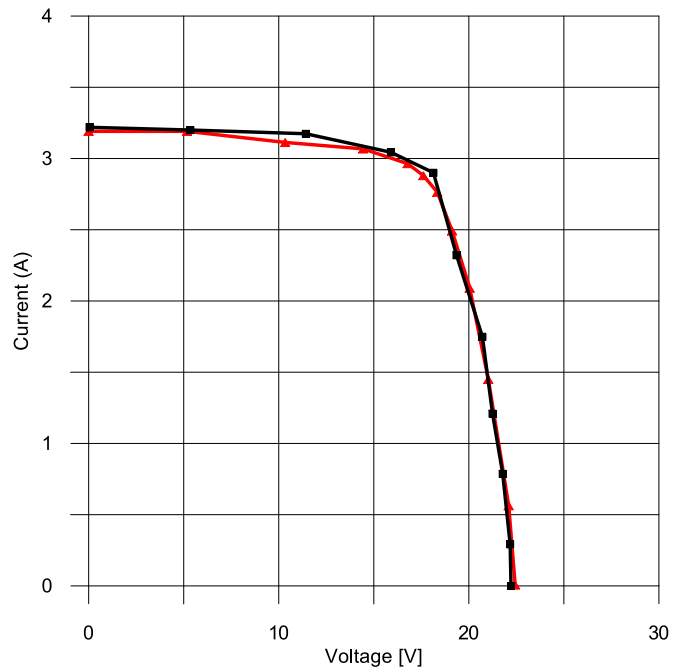


Fig. 3. Two test V-I characteristics of the PV emulator; the sun irradiation is  $1000W/m^2$ ; the PV temperature is  $25^{\circ}C$ .

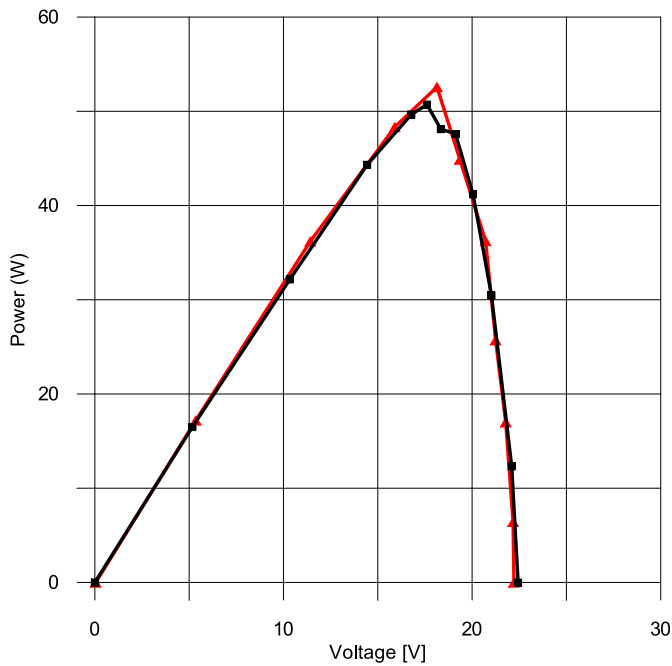


Fig. 4. Two test power characteristics of the PV emulator; the sun irradiation is 1000W/m<sup>2</sup>; the PV temperature is 25°C.

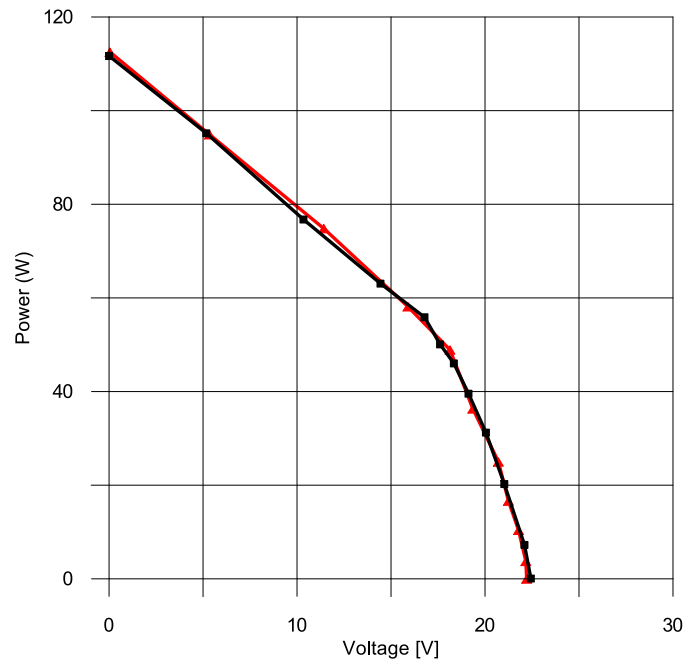


Fig. 5. PV emulator power losses.

TABLE I  
TEST RESULTS OF PV EMULATOR

Voltage (V)	Current (A)	Power (W)	Emulator power loss (W)
Test #1			
22.4	0	0	0
22.1	0.56	12.4	7.3
21.0	1.45	30.5	20.3
20.0	2.09	41.9	31.3
19.1	2.49	47.6	39.6
18.3	2.76	50.7	46
17.6	2.88	50.8	50
16.8	3.07	51.5	55.9
14.4	3.075	44.3	63
10.3	3.11	32.2	76.8
5.2	3.19	16.5	95.2
0	3.2	0	112
Test #2			
22.2	0	0	0
22.1	0.29	6.5	3.8
21.8	0.79	17.1	10.4
21.2	1.21	25.78	16.6
20.7	1.75	36.2	25
19.4	2.32	44.9	36.3
18.1	2.90	52.6	48.9
15.9	3.04	48.4	58.1
11.4	3.17	36.2	74.8
5.4	3.2	17.1	94.9
0.05	3.22	0.16	112.5

The results of two tests discussed in this section are given as an example of the PV emulator performance. Both tests were corresponding to the sun irradiation of 1000W/m<sup>2</sup> and the PV temperature of 25°C.

V-I characteristics of the PV emulates obtained from two testes are shown in Fig. 3. Fig.4 displays the output power of the PV emulator. It can be seen that the maximum power at MPPT is very close to the peak power value of the real PV cell and the value of voltage corresponding to the MPPT is about 17.5V.

The main disadvantage of the linear power supplies is low efficiency under load condition. Fig. 5 demonstrates power loss of the emulator during the tests. It can be seen that power loss has a maximum value of about 112W at the short circuit condition when the PV emulator generates max current at zero terminal voltage. This required installation of an appropriate heat sink to keep the temperature of the power semiconductor below threshold value to provide safe and reliable operation of the device.

#### IV. CONCLUSION

The emulator has been build using “on the shelf” components and tested under rated power conditions. It demonstrated a good emulation of VI characteristics within the rated range of the sun irradiation and the temperature. The non-linearity of V-I characteristic was investigated using conventional load instruments, the same applied for investigation of output characteristic of power supplies. The obtained characteristics were proceeded for further analysis to determine location of the operating point corresponded to MPPT. The emulator has been designed to be compatible with laboratory equipment produced by “Feedback Instruments”.

## REFERENCES

- [1] International Energy Agency. (2016). *Snapshot of Global Photovoltaic Markets. Report IEA PVPS T1-29:2016* [Online]. Available: <http://www.iaea-pvps.org/fileadmin/dam/public/report/PICS>
- [2] M. Gul, Y. Kotak, and T. Muneer, "Review on recent trend of solar photovoltaic technology," *Energy Exploration and Exploitation*, vol. 34, no. 4, pp. 485-526. July 2016.
- [3] R. Ciriminna, F. Meneguzzo, M. Pecorainoc, and M. Pagliaro, "Rethinking solar energy education on the dawn of the solar economy," *Renewable and Sustainable Energy Reviews*, vol. 63, pp. 13-18, Sept. 2016.
- [4] S.V. Levinzon, N.V. Tsarkova, and D.V. Melnikov, "Use of the modern stand equipment in the educational process in the course Electrical Engineering," in *Proc. 49th Int. Universities Power Engineering Conference*, Cluj-Napoca, Romania, Sept. 2-5, 2014, pp. 1-4.
- [5] A.K. Betts, J. Hamilton, S. Ligon, and A.M. Maha, "Integrating solar energy and climate research into science education," *Earth's Future*, vol. 4, no.1, pp. 2-13, Jan. 2016.
- [6] D. Assante, and M. Tronconi, "A remotely accessible photovoltaic system as didactic laboratory for electrical engineering courses," in *Proc. IEEE Global Engineering Education Conference*, Tallinn, March 18-20, 2015, pp. 479-485.
- [7] J. De Las Mercedes, N. Lara, T. Jack, and B. Zoghi, "Innovative Educational Methods in Teaching Sustainable Energy," in *Proc. Int. Energy and Sustainability Conference*, Farmingdale, NY, Oct. 23-24, 2014, pp. 107.
- [8] P.S. Rao, P. Dinesh, G.S. Ilango, and C. Nagamani, "Laboratory course on solar photovoltaic systems based on low cost equipment," in *Proc. IEEE Int. Conf. on MOOC Innovation and Technology in Education*, Jaipur, India, Dec. 20-22, 2013, pp. 146-151.
- [9] D.S. Dolan, L. Friedman, J. Huff, and T. Taufik, "Solar trainer for laboratory photovoltaic systems education," in *Proc. North American Power Symposium*, Champaign, IL, Sept. 9-11, 2012, pp. 1-6.
- [10] C. Young, J. Thelen, and H. Nehrir, "Design and implementation of a low-cost solar photovoltaic experimental station for education enhancement," in *Proc. North American Power Symposium*, Pullman, WA, Sept. 7-9, 2014, pp. 1-5.
- [11] D. Agar, and J. Korppi-Tommola, "Standard testing of photovoltaic modules for use in renewable energy education," *Lumat*, vol. 3, no. 5, pp. 693-701, 2015.
- [12] R. G. Wandhare, and V. Agarwal, "A low cost, light weight and accurate photovoltaic emulator," in *Proc. 37th IEEE Photovoltaic Specialists Conference*, Seattle, WA, June 19-24, 2011, pp. 1887-1892.
- [13] A. Xenophontos, J. Rarey, A. Trombetta, and A.M. Bazzi, "A flexible low-cost photovoltaic solar panel emulation platform," in *Proc. Power and Energy Conference at Illinois*, Champaign, IL, Feb. 28 - March 1, 2014, pp. 1-6.
- [14] S. Gadelovits, M. Sitbon, and A. Kuperman, "Rapid prototyping of a low-cost solar array simulator using an off-the-shelf dc power supply," *IEEE Transactions on Power Electronics*, vol. 29, no. 10, pp. 5278-5284, June 2014.
- [15] Z. Erdem, and M.B. Erdem, "A proposed model of photovoltaic module in Matlab/Simulink for distance education," *Procedia - Social and Behavioral Sciences*, vol. 103, pp. 55-62, Nov. 2013.
- [16] T. Sudhakar Babu, S. Mohammed Azharuddin, B. Nishant, and N. Rajasekar, "A dynamic photo voltaic emulator using dSPACE controller with high accuracy solar photo voltaic characteristics," *Journal of Renewable and Sustainable Energy*, vol. 8, no. 1, 14p., 2016.
- [17] D.M.K. Schofield, M.P. Foster, and D.A. Stone, "Low-cost solar emulator for evaluation of maximum power point tracking methods," *Electronics Letters*, vol. 47, no. 3, pp. 208-209, Feb. 2011.
- [18] A.R. Jordehi, "Parameter estimation of solar photovoltaic (PV) cells: A review," *Renewable and Sustainable Energy Reviews*, vol. 61, pp. 354-71, Aug. 2016.
- [19] S. Lyden, and M.E. Haque, "Maximum power point tracking techniques for photovoltaic systems: A comprehensive review and comparative analysis," *Renewable and Sustainable Energy Reviews*, vol. 52, pp. 1504-1518, Dec. 2015.
- [20] G. Martin-Segura, J. Lopez-Mestre, M. Teixido-Casas, and A. Sudria-Andreu, "Development of a photovoltaic array emulator system based on a full-bridge structure," in *Proc. 9th Int. Conf. on Electrical Power Quality and Utilisation*, Barcelona, Spain, Oct. 9-11, 2007, pp. 1-6.
- [21] J. Chavarria, D. Biel, F. Guinjoan, A. Poveda, F. Masana, and E. Alarcon, "Low cost photovoltaic array emulator design for the test of PV grid-connected inverters," in *Proc. 11th Int. Multi-Conf. on Systems, Signals and Devices*, Barcelona, Spain, Feb. 11-14, 2014, pp. 1-6.
- [22] Y. Erkaya, P. Moses, I. Flory, and S. Marsillac, "Development of a solar photovoltaic module emulator," in *Proc. 42nd IEEE Photovoltaic Specialist Conference*, New Orleans, LA, June 14-19, 2015, pp. 1-3.
- [23] J. Gonzalez-Llorente, A. Rambal-Vecino, L.A. Garcia-Rodriguez, J.C. Balda, and E.L. Ortiz-Rivera, "Simple and efficient low power photovoltaic emulator for evaluation of power conditioning systems," in *Proc. IEEE Applied Power Electronics Conference and Exposition*, Long Beach, CA, March 20-24, 2016, pp. 3712-3716.
- [24] R. Gonzalez-Medina, I. Patrao, G. Garcera, and E. Figueres, "A low-cost photovoltaic emulator for static and dynamic evaluation of photovoltaic power converters and facilities," *Progress in Photovoltaics: Research and Applications*, vol. 22, no. 2, pp. 227-241, Feb. 2014.
- [25] A. Sanaullah, and H.A. Khan, "Design and implementation of a low cost solar panel emulator," in *Proc. 42nd IEEE Photovoltaic Specialist Conference*, New Orleans, LA, June 14-19, 2015, pp. 1-5.
- [26] P.J. Binduhewa, and M. Barnes, "Photovoltaic emulator," in *Proc. 8th IEEE Int. Conf. on Industrial and Information Systems*, Peradeniya, Sri Lanka, Dec 17-20, 2013, pp. 519-524.
- [27] T.S. Babu, S.M. Azharuddin, B. Nishant, and N. Rajasekar, "A dynamic photo voltaic emulator using dSPACE controller with high accuracy solar photo voltaic characteristics," *Journal of Renewable and Sustainable Energy*, vol. 8, no. 015503, 14p., 2016.