Buck Converter based PV Array Emulator for Testing PV Inverters and MPPT Algorithms

Zhongfu Zhou [1*], *John* Macaulay[2]

[1]Swansea University, Department of Electronics and Electrical Engineering, SA1 8EN Swansea, UK
[2] Cardiff Metropolitan University, School of Technologies, Cardiff, CF5, 2YB, UK

Abstract. this paper presents an emulation of PV modules based on the buck DC/DC converter as a replacement of actual solar electricity generation sources for laboratory experiments for testing the conditioners and MPPT algorithms. The buck converter was designed in constant current control mode and the output current of the buck converter is referred to lookup tables constructed based on I-V curves of product datasheets or mathematical equations. Dynamic performance of the current control loop was investigated. To validate the performance simulation and experiment as carried out and a comparison between simulated and practical results obtained from laboratory test with actual sources is performed. It is confirmed the buck converter-based PV simulator is a simple, safe, versatile, and effective way of physically representing of real solar source.

1 Introduction

The demand for solar energy electricity generation system has been continuously increasing due to the improvement of technology of solar panel and power conversion, particularly with growing demand for renewable energy across the world. PV inverters constructed using power semiconductor devices and microcomputer-based control circuit are always required to control the PV system so that the connected PV system can always capture the maximum possible energy by operating it at its maximum power point (MPP) under a given solar irradiance. It is important to adequately evaluate the inverter's efficiency, reliability, and performance to reduce the development time of PV inverters and therefore repeatable test is required for the development PV inverters and MPPT algorithms. Using a real PV array to test PV inverters is known as an efficient method as it would take up more space and not able to carry out repeat test conditions during the continuous variation of solar irradiance. PV emulator-based testing method has been proved a low-cost solution and independent of the weather conditions [1-9].

Various PV emulators have been developed over the years, among these, analog technique-based PV emulator has the advantage of high bandwidth, and it can provide fast response for testing high frequency MPPT algorithms [1], [2], [3], [7], [8]. However, this type of PV emulator suffers the disadvantages of low efficiency and large physical size and

* Corresponding autour : z.zhou@swansea.ac.uk

© The Authors, published by EDP Sciences. This is an open access article distributed under the terms of the Creative Commons Attribution License 4.0 (https://creativecommons.org/licenses/by/4.0/).

higher manufacturing cost. To overcome the disadvantages of analog technique-based PV emulator, switching mode power electronic converter-based PV emulators have been implemented [10-17].

This paper presents a low coat buck converter-based PV emulator. Lookup table approach is adopted for storing current-voltage characteristics of the PV array to be emulated. Proportional & Integral (PI) controller is used for controlling the buck converter to emulate the PV array's electrical characteristics. Detail analysis of the controller performance was analysed in the paper. Simulation results shows the buck converter is controlled well to emulate a PV array.

2 Mathematical Model of PV Array

The equivalent circuit of a conventional PV panel is shown in Fig. 1. It is represented by a current source in parallel with a diode and a parallel resistor, as well as a series connected resistor at the output.

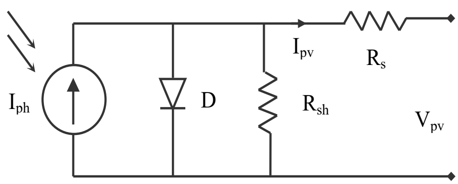

Fig. 1. Equivalent circuit of a photovoltaic panel.

The general I-V characteristic is expressed by (1):

$$I_{\text{pv}} = I_{\text{ph}} - I_0(e^{\frac{V_{\text{pv}}+I_{\text{pv}}R_S}{N_S V_T}} - 1) - \frac{V_{\text{pv}}+I_{\text{pv}}R_S}{R_{\text{sh}}} \quad (1)$$

where, V_T: represents the thermal voltage, $I_{ph:}$ represents the photo current, I_0: represents the dark saturation current, $R_{s:}$ is the series resistance of the PV panel that represents the effect of voltage drop across the semiconductor and contacts, R_{sh}: is the shunt resistance representing the effect of the surface current dispersion of the PV panel N_s is the number of cells connected in series. The photo-generated current is proportional to the solar irradiance reaching the solar panel. In dark or indoor conditions, no current is generated from PV panels and the I-V characteristics of the panel is determined by the diode characteristics I_{pv} =0, and $R_{sh} = \infty$,

3 Buck converter-based PV emulator

Fig.2. shows the block diagram of a single buck converter PV emulator. It consists of a dc power supply, a dc chopper, and a microprocessor-based control circuit. The dc voltage input to the chopper should be larger enough than the open-circuit voltage of the PV array to be emulated. To emulate a real PV array, PV emulator is usually required to have a high switching frequency to allow real-time emulation of the PV array. Therefore, high-speed microprocessors and fast control algorithms are required [10-17].

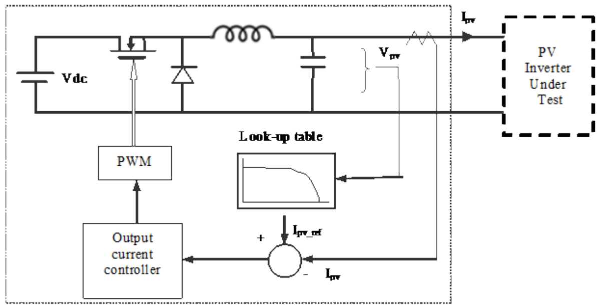

Fig. 2. Buck converter circuit-based PV emulator.

In an actual PV system, the PV array voltage is controlled by its connected PV inverter therefore in Figure 4 the converter output voltage V_{pv} is controlled by the connected PV inverter, this voltage is then input to a look-up table storing the PV array model as described in equation (1), the output of the look-up table will the corresponding PV current of I-V curve, this current can be considered as the current reference output current of the buck converter [12]. If the characteristics of temperature and solar irradiance effects need to be simulated then a 3-D lookup table need to be constructed with input of voltage, temperature, and solar irradiance. To simplify the analysis and focus on the design of PV simulator here only 2-D lookup table (I-V curve at constant temperature and constant solar irradiance condition) is considered as shown in Fig. 3 in which only the voltage is the input variable. In this study, two-phase interleaved buck converter power electronics circuit will be used to emulate PV array's electrical characteristics, which is shown in Figure 3.

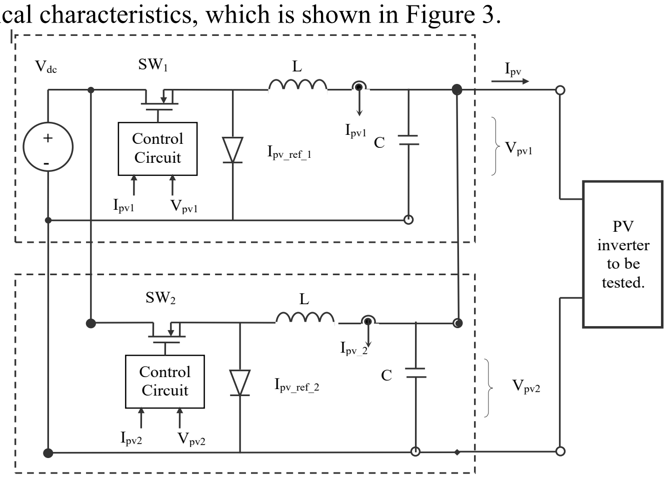

Fig. 3. Two-phase interleaved buck converter-based PV emulator.

Compared to single-phase buck regulator based PVE, interleaved buck converter-based PV emulator offer the advantages of reduction in both input and output capacitance, improvement in thermal performance and efficiency, and enhancement in overshoot and undershoot during load transients, small ripples in output current and higher output current value without increasing the rated current of the components of the converter circuit [18-19]. The parameters of the two-phase interleaved buck converter are shown in Table-1.

Table 1. Parameters of the buck converter and the PV module to be emulated.

Buck converter		PV module to be emulated: A10Green Technology A10J-s72-175	
V_{dc}	60V	Maximum Power	175.9 W
L	2mH	Open circuit voltage	43.99 V
C	200µF	V_{mmp}	36.63 V
$f_{PWM\text{-}sw}$	20kHz	I_{mmp}	4.78 A
		Short circuit current	5.17 A

4 Control loop modelling

Fig. 4 shows the block diagram of buck converter-based PV emulator. The average switching modelling is used to design the current control loop.

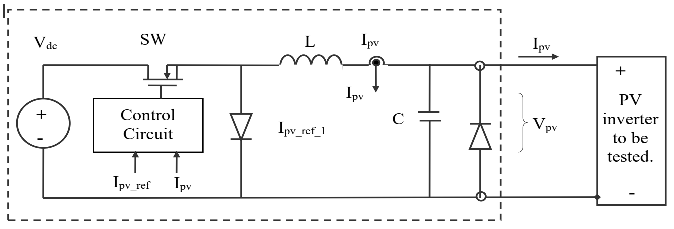

Fig. 4. Block diagram of buck converter-based PV emulator.

The transfer function block diagram of a single buck converter PV-simulator is shown in Fig. 5. The common PI regulator for the current controller is expressed as:

$$PI = K_p + K_i \frac{1}{s} \tag{2}$$

The small signal transfer functions of the buck converter are depending on the load condition. It is found that the zero of the PI controllers is determined primarily by the light load condition, while the gain is determined primarily by heavy load condition. A stable controller for both light and heavy load conditions can be found by

$$PI = K_p + K_i \frac{1}{s} = 20 + 2500 \frac{1}{s} \tag{3}$$

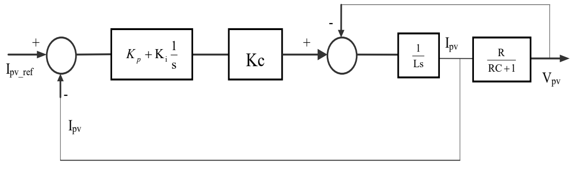

Fig. 5. Transfer function block diagram of buck converter PV-simulator.

The small signal transfer functions of the buck converter are depending on the load condition. It is found that the zero of the PI controllers is determined primarily by the light load condition, while the gain is determined primarily by heavy load condition. A stable controller for both light and heavy load conditions may be found by

$$PI = K_p + K_i \frac{1}{s} = 20 + 2500 \frac{1}{s} \tag{4}$$

 https://doi.org/10.1051/e3sconf/202454502002

5 Simulation results

Figure 6 shows the electrical characteristics of the PV module to be emulated.

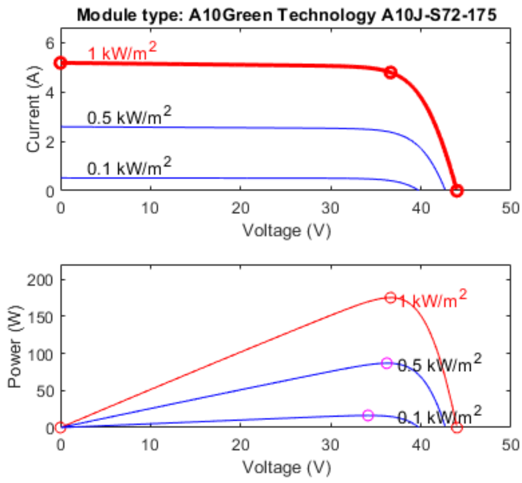

Fig. 6. The electrical characteristics of the PV module to be emulated.

Based on the proposed two-phase interleaved buck converter, the performance of the PV module- A10 Green Technology A10J-S72-175 was emulated at different current points of the operation. **Fig. 7** shows the emulated PV curent with variable reference current at different times (solar irradiance 1000W/m^2). The two curves on the top are the emulated current from the two individual buck converters, respectively. The bottom one is the total emulated current of the interleaved buck converter. It can be seen that the ripple of the output current from the interleaved buck converter has been reduced half compared to that from a single buck converter.

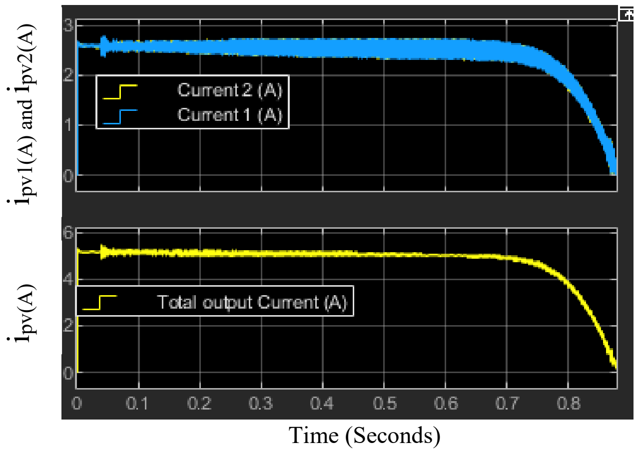

Fig. 7. The emulated PV curents with different reference current (varies at different times) under solar of 1000W/m^2)

6 Conclusion

In this paper the mathematical model of the proposed interleaved buck converter-based PV emulator and simulation circuit were described in detail. PV emulation system with two-phase interleaved buck converter was simulated. Results show that the current ripple has been reduced in half compared to the single buck converter-based PV emulator. All the results have verified the proposed PV module is effective in both single-module application and for multiple series and parallel connections.

References

1. H.Nagayoshi, S. Orio, Y. Kono, H. Nakajima, Novel PV array/module simulator circuit, The 29th IEEE Photovoltaic Specialist Conference, May 2002, pp. 1535-1538.
2. H.Nagayoshi, "I-V curve simulation by multi-module simulator using I-V magnifier circuit," Solar Energy Materials & Solar Cells, vol. 82, pp. 159-167, 2004
3. Hiroshi Nagayoshi and Mani Atesh , Partial shading effect emulation using multi small scale module simulator units, the Thirty-first IEEE Photovoltaic Specialists Conference, 2005. Conference Record of, 2005, pp, 1710 – 1713.
4. Tianxiang Jiang, Ghanim Putrus, Steve McDonald, Matteo Conti, Bowen Li, David Johnston, Generic Photovoltaic System emulator based on Lambert ω function, The 46th international university s power engineering conference, September 2011.
5. Giovanni Petrone, Giovanni Spagnuolo, and Massimo Vitelli A multivariable perturb-and-observe maximum power point tracking technique applied to a single-stage photovoltaic inverter, IEEE Transactions on industrial electronics, vol. 58, no. 1, 2011
6. A.K. Mukerjee, Nivedita Dasgupta, DC power supply used as photovoltaic simulator for testing MPPT algorithms, Renewable Energy 32 (2007) 587–59
7. D.M.K. Schofield, M.P. Foster and D.A. Stone, Low-cost solar emulator for evaluation maximum power point tracking methods, ELECTRONICS LETTERS 3rd February 2011 Vol. 47 No. 3
8. O.-M, Midtgard, A simple photovoltaic simulator for testing of power electronics, Power Electronics and Applications, 2007 European Conference on, 2-5 Sept. 2007, pp, 1 – 10.
9. K. H. Chua, Yun Seng Lim, Phil Taylor, Senior Member, IEEE, Stella Morris, Senior Member, IEEE, and Jianhui Wong , Energy Storage System for Mitigating Voltage, IEEE TRANSACTIONS ON POWER DELIVERY, VOL. 27, NO. 4, OCTOBER 2012.
10. Raúl González-Medina, Iván Patrao, Gabriel Garcerá and Emilio Figueres, A low-cost photovoltaic emulator for static and dynamic evaluation of photovoltaic power converters and facilities, Prog. Photovolt: Res. Appl., vol, 4, 2012.
11. Weichao Zhang and Jonathan W. Kimball, DC-DC Converter Based Photovoltaic Simulator with a Double Current Mode Controller, Power and Energy Conference at Illinois (PECI), 2016 IEEE, 28 April 2016.
12. Vorperian V. Simplified analysis of PWM converters using model of PWM switch-Continuous conduction mode. IEEE Transactions on Aerospace and Electronic Systems 1990; 26(3): pp, 490–496.
13. Yuan. Li, Taewon Lee, Fang. Z. Peng, and Dichen Liu, A Hybrid Control Strategy for Photovoltaic Simulator, Twenty-Fourth Annual IEEE Applied Power Electronics Conference and Exposition, APEC 2009, 15-19 Feb. 2009, pp, 899 – 903.
14. Qingrong Zeng, Pinggang Song, Liuchen Chang, A photovoltaic simulator based on DC chopper, Electrical and Computer Engineering, 2002. IEEE CCECE 2002. Canadian Conference on, 2002, 257 - 261 vol.1.
15. Ankur V. Rana , Current Controlled Buck Converter based Photovoltaic Emulator, Journal of Industrial and Intelligent Information Vol. 1, No. 2, June 2013

16. Maria Carmela Di Piazza, Gianpaolo Vitale , Photovoltaic field emulation including dynamic and partial shadow conditions, Applied Energy 87 (2010) 814–823
17. Jordan G. Trapp, Luciano P. de Lima, Felix A. Farret, Felipe T. Fernandes, Gleisson Balen, PV emulation by buck converter based on experimental I-V curves and dynamic response, Power Electronics Conference (COBEP), 2011 Brazilian, 11-15 Sept. 2011, 984 – 991.
18. Parisi C. Multiphase Buck Design from Start to Finish (Part 1), no. May; 2019:1-20. www.ti.com
19. Baba D. Benefits of a multiphase buck converter. *Texas Instruments*, no. 1, pp. 8–13, 2012. www.ti.com