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An emulated PV source based on an Indoor Solar Panel with external excitement current and voltage compensation

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***Abstract*—This paper presents a novel emulated photovoltaic (PV) source that was constructed by using an indoor solar panel and an external current and voltage source. The mathematical model and electrical characteristics of the emulated PV source were defined and analyzed in detail in the paper. Measures for eliminating the errors of the emulated PV source was also proposed and demonstrated by experiment. The constructed PV source has the advantages of high bandwidth over the switching circuit-based PV simulators. The constructed PV source has used for testing various power electronics converters and various control techniques effectively in laboratory environments for researchers and university students.**

Keywords— PV simulator; solar panel; excitement current; PV inverters; MPPT

I. 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. A large amount of PV electricity is now injected into utility system through a distribution network. A solar electricity generation system often comprises of many PV arrays and PV inverters. A PV generation system could be formed by many parallel and serially connected PV panels to provide sufficient voltage and currents. A PV inverter that is constructed using power semiconductor devices and microcomputer-based control circuit is used in controlling the PV system operation so that it can always operate at its maximum power point (MPP) to capture the maximum possible power under any given solar irradiance. On the other hand, the PV inverters also convert the dc power generated by PV panel to 50Hz ac power at an appropriate voltage suitable for grid connection. PV panels are usually designed with a lifetime of 25 years; however, the PV inverter's lifetime is usually less than that due to the failure of its components. Considerable attention has been paid to the development of advanced PV inverters to achieve higher efficiency, higher reliability, lower cost and advanced control algorithms. Advanced power semiconductor devices, high-quality capacitors, inductors and advanced inverter circuit topologies and control strategies are the keys for high-quality PV inverters [1], [18]. It is imperative to evaluate the inverter's efficiency adequately, reliability and performance to reduce the development period. For the development and experimental test of photovoltaic converters, repeatable test conditions are very often required to justify their control algorithms [10]. It would be tough to carry out the repeatable test by using outdoor installed PV panels as the unpredictable atmospheric conditions affect the repeatability of the test conditions and the high system installation and maintenance cost. Today various PV simulators have been developed to replace actual outdoor PV panels for testing PV inverters, and control algorithms as presented in [2 -16], such as the simple photovoltaic simulator constructed by a dc voltage power supply and a series connected a variable resistor in [7]. The solar simulator implemented by amplifying the small current and voltage of a photo-diode using an analog technique in [2] and [3]. The PV simulator based on the multiple small-scale module units for partial shading effect emulation [4]. The low-cost solar PV simulator was implemented by using discrete operational amplifiers in reference [8], the PV simulator constructed by using several series-connected solar cells to constitute a mini PV-module to provide the reference signal of the PV simulator [9]. The switching mode electronic circuits-based PV simulators were proposed [10-16], and the dynamic, electric-thermal model for a photovoltaic (PV) cell that combines electrical and thermal parameters to accurately emulate PV panels in real time for power-hardware-in-the-loop simulation (PHILS) [17]. This paper presents a novel emulated photovoltaic (PV) source that was constructed by using an indoor solar panel and an external excitement current and voltage source compensation. Details of the mathematical model of the emulated PV source and experimental set up as well as experimental results were presented in the paper.

II. MATHEMATICAL MODEL OF SOLAR PANELS

The equivalent lumped circuit model of solar cells has been widely used for the performance simulation and prediction for designing, manufacturing, and evaluation of PV systems. Fig. 1, shows a single-diode solar cell model. 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 terminal.

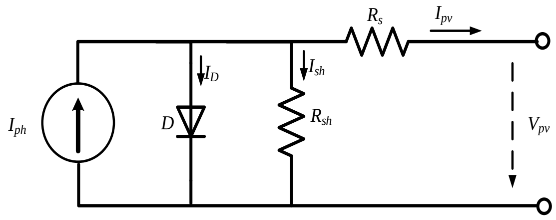


Fig. 1: Equivalent circuit of a single-diode solar cell model

For a solar panel with several series-connected PV cells, it is a widespread practice to assume that the characteristics of the series cells inside the solar panel are nearly identical. A PV panel model, therefore, is considered as a single cell with some multipliers dependent on the number of series-connected cells in the PV panel. Based on the single-diode model, the I-V characteristic of a PV panel is given by (1)

$$I_{pv} = I_{ph} - I_s(e^{\frac{V_{pv}+I_{pv}R_s}{nN_sVt}} - 1) - \frac{V_{pv}+I_{pv}R_s}{R_{sh}} \tag{1}$$

where, I_{pv} and V_{pv} are the terminal current and voltage of the PV panel. I_{ph} is the photocurrent, I_s represents the dark saturation current, R_s *and* R_{sh} are the series and shunt resistances of the solar panel, n is the diode quality factor, Ns is the number of series-connected PV cells in the PV panel, V_t is the solar cell thermal voltage defined as $V_t=kT/q$, where k is Boltzmann's constant *(1.38×10-23J/K)*, q is the elementary charge *(1.6×10-19 C)*, and T is *p-n* junction temperature in Kelvin.

The short circuit current of the solar panel can be calculated by setting V_{pv}=0 and neglecting the current through the diode: as expressed in (2)

$$I_{sc} \approx I_{ph} \tag{2}$$

The short-circuit current is approximately equal to the photo-current. To achieve the maximum output power of a solar panel, the solar panel should be operated at a suitable voltage level at which it can generate its maximum output power. The voltage and current at the MPP can be solved based on (3)

$$\left.\frac{dP}{dV}\right|_{V_{MPP},I_{MPP}} = 0 \tag{3}$$

where, V_{MPP}, I_{MPP} represents the output voltage and output current of the solar panel respectively [1].

III. A MATHEMATICAL MODEL OF THE EMULATED PV SOURCE

The emulated PV source is constructed by using an un-illuminated PV panel and an external current source for testing PV inverters and MPPT algorithms in the laboratory. The circuit connection of the constructed PV source is shown in Fig. 2.

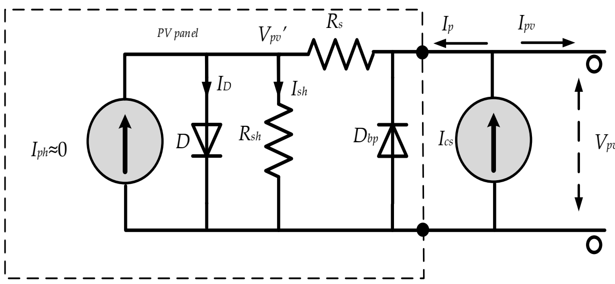


Fig. 2: Equivalent circuit of the emulated PV source

The equivalent circuit of the constructed emulated PV source is shown in Fig. 2, where I_{CS} represents the current source current generated by the external dc power supply, D_{bp} represents the bypass diode installed in the PV panel. From Fig. 2, the current source current is divided into two parts; one current I_p is injected back to the PV panel through the internal series resistance, another current is the output current of the constructed PV source, which is expressed as (4):

$$I_{pv} = I_{CS} - I_p \tag{4}$$

Without sunlight illumination the PV panel will generate zero photo-current, i.e., I_{ph}=0, the I-V equation of the PV simulator will be expressed by (5):

$$\begin{aligned} I_{pv} &= I_{CS} - I_p = I_{CS} - I_s(e^{\frac{V_{pv}-I_pR_s}{N_sV_t}} - 1) - I_{sh} \\ V_{pv} &= I_{pv}R_s + nV_t \ln\frac{I_p - I_{sh} + I_s}{I_s} \\ I_{sh} &= \frac{V_{pv} - I_pR_s}{R_{sh}} \end{aligned} \tag{5}$$

where, I_{pv} and V_{pv} are the PV simulator's output current and voltage, respectively. The electrical characteristics of the constructed PV source are entirely determined by the solar panel's physical properties while the external current source provides the photo-current. Based on (4), for a given I_{cs}, the current injected into the un-illuminated PV source is $I_p=I_{cs}-I_{pv}$.

IV. CHARACTERISTICS OF THE CONSTRUCTED PV SOURCE

Experimental setup of the emulated PV source is shown in Fig. 3, the solar panels used in the setup is 175W commercial PV panels STP175S-24/Ac from SUNTEC [18]. Details of the rated parameters of the PV panel are given in Table-1.

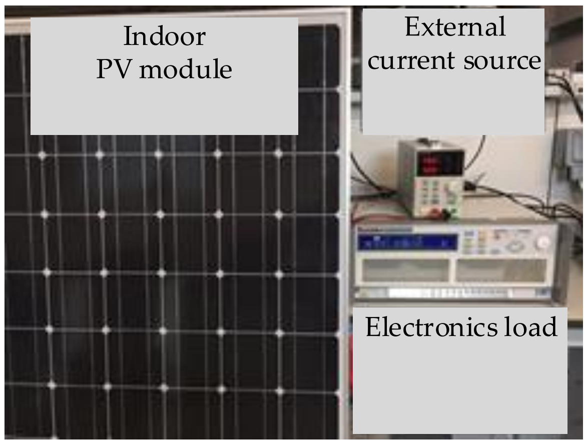


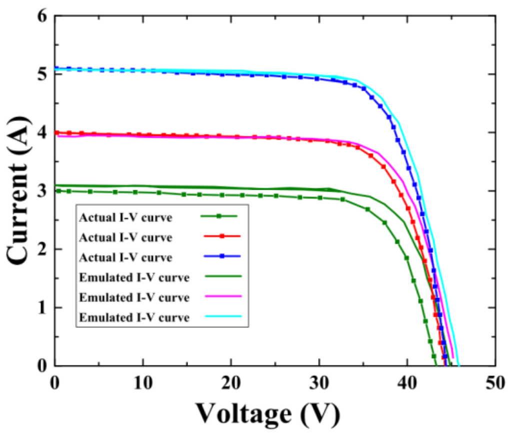
Fig. 3: Experiment setup of constructed PV emulator

A 1250W (TENMA 72-2940) DC power supply is connected in parallel with the solar panel. The photocurrent of the PV panel in an indoor environment is very low and is assumed as zero.

Table-1 The rated parameters of the solar panel STP175S-24/Ac

Rated maximum power	**175 Watts**
Voltage at the maximum power point (V_{mpp})	35.2 Volt
Current at the maximum power point (I_{mpp})	4.95 Amp
Short circuit current (I_{sc})	5.2 Amp
Open circuit voltage (V_{oc})	4.2 Volt
Nominal operating cell temperature	50⁰C

The dc power supply is operated in a current source mode. Three different configurations of the proposed PV source were constructed and tested with single solar panel test, two solar panels in series connection test as well as three solar panels in series connection test. Fig. 4 Comparison of the electrical characteristic between the emulated PV source and the actual solar panel



(a)

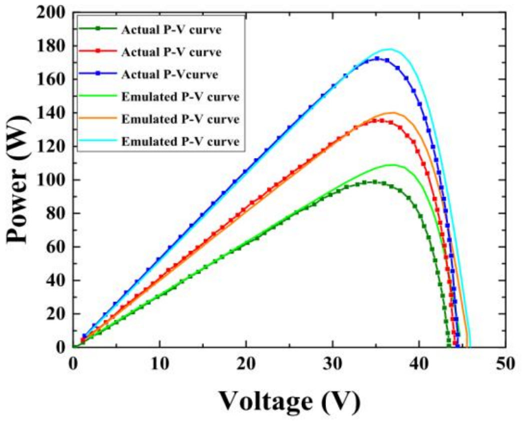
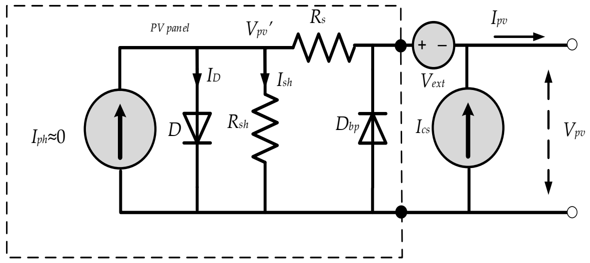


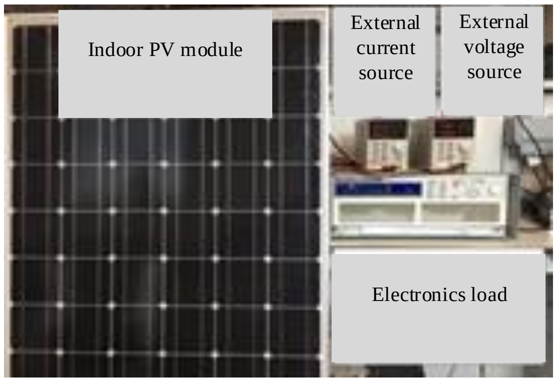
Fig. 4 Comparison of the P-V electrical characteristic between the emulated PV source and the actual solar panel (a) I-V, (b) P-V

Fig. 4, (a) shows measured electrical characteristics of the proposed emulated PV source with a single solar panel at different excitement currents. Fig. 4, (b) shows the comparison of electrical characteristics between the constructed PV source and actual solar panel. There is a small shift for the *I-V* and *P-V* curves between the constructed PV source and the actual solar panel when compared due to the solar panel's series resistance. The difference is approximately determined by the product of the solar panel's series resistance, and the current injected into the solar panel from the external current source, i.e., $\Delta V = I_p \times R_S$.

The experiment of the constructed PV source in previous part is appropriate for a single solar panel. Slight phase shift exists for the I-V and P-V curves of the constructed PV source. To eliminate the difference, a modified PV source emulator is suggested for a more precise emulation. An external voltage source is added to the original emulator circuit as shown in Fig. 5.



(a)

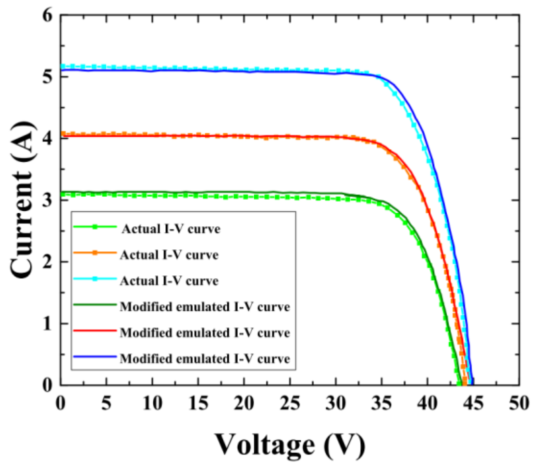


(b)

Fig. 5 Circuit diagram of the modified PV emulator, (b) Experiment set-up of modified PV emulator

The same dc power supply (TENMA 72-2940) was used as the external voltage source. The different voltage and current between the emulation and values from the manual are between 0.5-2V, which was compensated by setting the external voltage source. Results from the modified emulator using the external voltage power supply are shown in Fig. 6.

As demonstrated in Fig. 6, three new *I-V* curves fit quite well with the values from the datasheet although approximately 0.2V of mismatch still occurs. The above result is much more accurate than the original emulator. The result can be explained in the following: as V_{ext} is inserted, the voltage of diode V_d is increasing at the same time. Thus, more current will be sunk by the diode.



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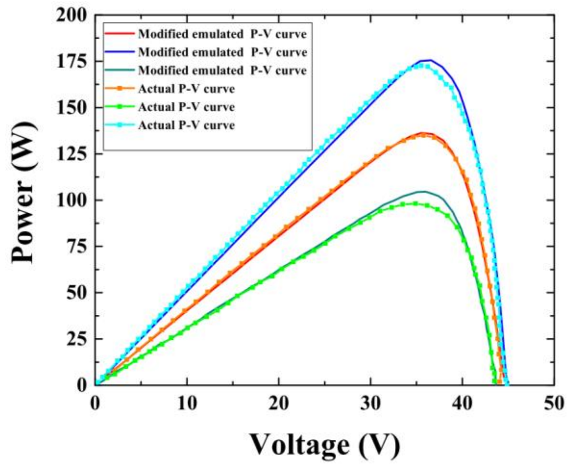
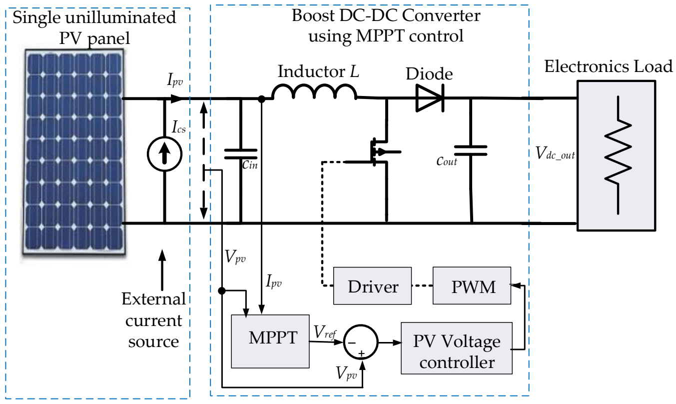


(b)

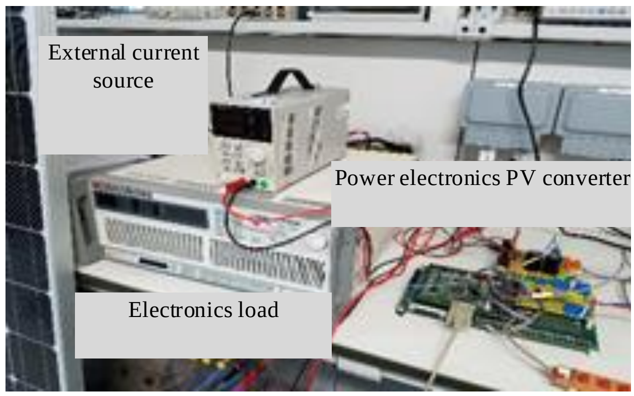
Fig. 6: I-V, P-V characteristics obtained from the modified PV emulator

V. EXPERIMENTAL SETUP FOR TESTING PV INVERTERS AND MPPT ALGORITHMS

A boost dc/dc converter with P&O MPPT algorithm was developed in the laboratory environment. The proposed PV source with a single PV panel was used in testing the PV inverter and MPPT algorithm. The block diagram and circuit connection and experiment set-up are shown in Fig. 7 (a) and (b). The electrical characteristics of the emulated PV source with excitement current of 1A and 2A are shown in Fig. 8. Fig. 9 (a) shows the test result of the boost dc/dc converter controlled by a P&O-MPPT algorithm with a perturbation frequency of 200Hz (time step of 5*ms*) and a perturbation voltage of 0.5V.



(a)



(b)

Fig. 7: (a) circuit connection (b) experiment test set-up of the constructed PV source interfaced with power electronics converter and load.

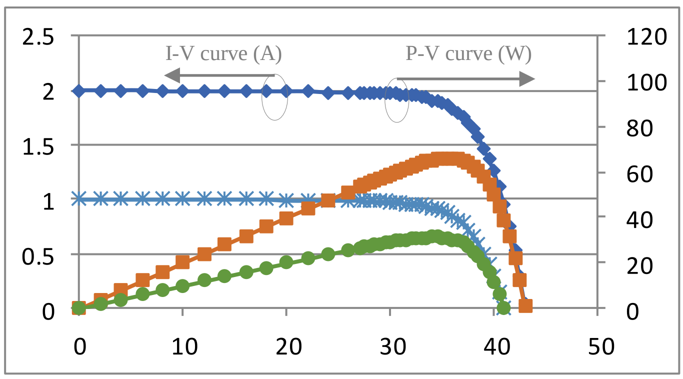
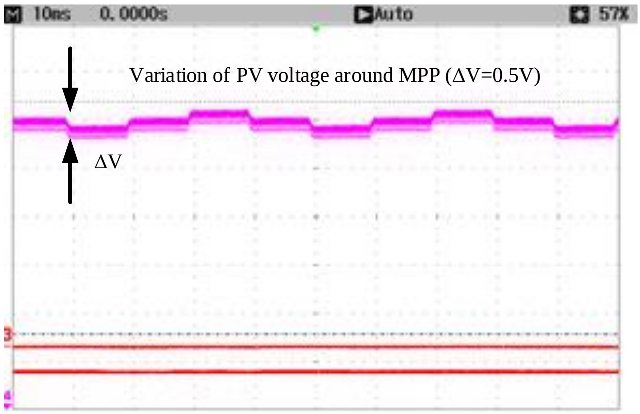
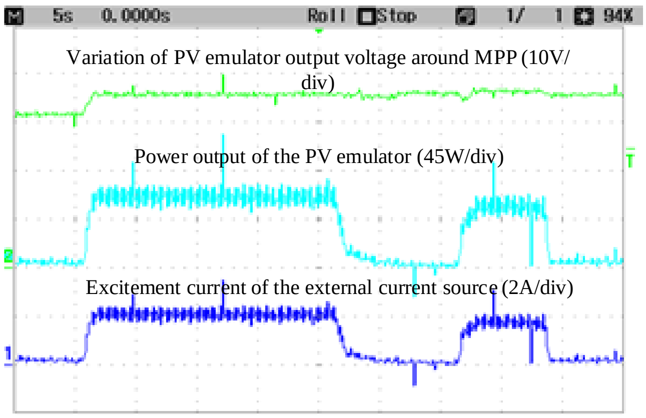


Fig.8: I-V, P-V characteristics of the emulated PV source with excitement current of 1A and 2A, respectively.

The controller was developed using the ADMC401 digital signal processor. It was observed during the test that the terminal voltage of the emulated PV source continuously oscillates around the maximum power point due to the employment of the MPPT algorithm. The measured mean voltage at MPP is 35 V at excitement current I_{cs}=1A, which is corroborated with reference to Figure 8. Test with different excitement currents was also carried out to simulate PV inverter with the variation of solar irradiance. Fig. 9 (b) shows how the constructed PV source output voltage and output power changes with the excitement current from the external current source.



(a)



(b)

Fig. 9: (a) Measured terminal voltage of the constructed PV source for testing a boost dc/dc converter with P&O MPPT algorithm; (b) Test with varied external excitement current (in emulating different solar irradiance).

VI. CONCLUSION

A mathematical model of the constructed PV source with single PV panel and multiple PV panels connected in series were analyzed and presented. The proposed PV source was constructed in a laboratory environment which provides an effective way of testing PV inverters and different MPPT algorithms. The system can provide repeatable test conditions, essential for fast and effective PV inverter development. The proposed PV source has the advantage of high bandwidth which is an essential characteristic for testing high-frequency MPPT algorithms. The dc power supply only provides the exciting current to mimic the photocurrent generated at different solar irradiance. The disadvantages are that an actual PV panel will be required to simulate the PV devices, it is also not very convenient to simulate the temperature effect.

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