Solar Energy 167 (2018) 52–60

Contents lists available at ScienceDirect

Solar Energy

journal homepage: www.elsevier.com/locate/solener

A direct current-voltage measurement method for smart photovoltaic modules with submodule level power optimizers

Qi Gao[a,b], Yating Zhang[a,b], Youlin Yu[c], Zhengxin Liu[a,*]

[a] *Research Center for New Energy Technology, Shanghai Institute of Microsystem and Information Technology (SIMIT), Chinese Academy of Sciences (CAS), 235 Chengbei Road, Shanghai 201800, PR China*

[b] *University of the Chinese Academy of Sciences, 100039 Beijing, PR China*

[c] *School of Physical Science and Technology, ShanghaiTech University, 100 Haike Road, Shanghai 201210, PR China*

ARTICLE INFO

Keywords:
Smart photovoltaic (SPV) module
I-V measurement
Fourier analysis
Power optimizer

ABSTRACT

Mismatch between photovoltaic (PV) devices connected in series, caused by degradation or partial shading, may result in the significant power loss of a PV system. Therefore, smart PV (SPV) modules, integrated with power-optimization converters at the submodule level, have been used to overcome this problem. Due to the complex circuit topology of the integrated converters, the current-voltage (I-V) characteristics of most SPV modules cannot be tested directly using the routine method. This study aims to develop an I-V measurement procedure for SPV modules in the laboratory. The characteristic of the SPV module was investigated through theoretical and experimental analysis. The noise generated from the optimizer circuit was considered as the major hindrance in the I-V measurement for SPV modules, which was tested and then analyzed using Fourier analysis. Then, a filter corresponding to the noise characteristics was applied in the measurements to eliminate the noise. The measured result corresponded with the theoretical analysis; furthermore, the power linearity with irradiance and the field test verified the reasonableness of our method. The proposed method is applicable in the laboratory measurement of SPV modules within a few hundred milliseconds, which may be applied in relevant power sorting and measurements in production line.

1. Introduction

With the rapid development of photovoltaic technology, global PV installation is expected to exceed 100 GW in 2018 (Jaeger-Waldau, 2017; Zoco, 2017). The assessment of these PV technology applications is significantly affected by the performance of PV devices. The actual performance of PV devices is dependent on several factors such as environmental conditions, mismatch losses and system topologies. Among these issues, the irradiance mismatch caused by degradation, limited installation environment, and partial shading could lead to a significant decline in PV power generation (Jordan et al., 2015; Olalla et al., 2014). Moreover, the mismatch caused by uneven degradation or partial shading cannot be eliminated by conventional PV systems based on centralized MPPT converters; thus, more intelligent technologies are necessary for photovoltaic system application (Sanz et al., 2011). Smart photovoltaic (SPV) module, which integrates one or more MPPT (maximum power point tracking) optimization converters comprised of a controller and a DC/DC (direct current-to-direct current) converter, is one of the new products to solve the mismatch issue (Deline, 2010; Doubleday et al., 2016; Pilawa-Podgurski and Perreault, 2013). The primary function of a MPPT optimization converter is to make all the modules or submodules operate independently from each other at their maximum power point (MPP) (Kasper et al., 2014).

The I-V characteristic curves of PV modules are very important for the design of PV power station and the research on the power generation characteristics of PV modules; however, since power optimizer manufacturers rarely consider the I-V measurements of an SPV module, and the circuit structure of SPV modules is much more complicated than that of conventional PV modules, the output current-voltage (I-V) characteristics of most SPV modules are challenging to measure using the conventional method defined in the IEC standard (Gfeller et al., 2016; Standard IEC 60904-1, 2006). The I-V test result measured directly by the conventional method is typically shown as a messy curve or is unmeasurable for SPV modules.

Traceable and comparable measurements are the basis of sorting and pricing for SPV modules. Previous work has explored certain measurement methods of SPV modules. One measurement method is to detach the MPPT converters from the SPV module, and then test the I-V

* Corresponding author at: Shanghai Institute of Microsystem and Information Technology (SIMIT), Chinese Academy of Sciences (CAS), 235 Chengbei Road, Jiading, Shanghai 201800, PR China.

E-mail address: z.x.liu@mail.sim.ac.cn (Z. Liu).

https://doi.org/10.1016/j.solener.2018.03.082
Received 12 January 2018; Received in revised form 7 March 2018; Accepted 29 March 2018
0038-092X/

curve of the bare PV module and the efficiency of the electronics separately (Gfeller et al., 2016). This method can be used to measure the approximate power level of the SPV modules; however, it neglects the output characteristics of the DC/DC converter, the switching losses of the electronic circuit and the electronic noise caused by power electronic switches and cannot acquire the real I-V curve of SPV modules; furthermore, this method is inconvenient for practical measurements.

Testing the PV module and the MPPT converter simultaneously is more reasonable to evaluate the real characteristics of an SPV module. In Grasso et al. (2015), a DC electronic load was used to test an SPV module under constant voltage mode, while in Deline (2010), the AC output of an SPV module was directly tested at the output terminal of the inverter. Using these methods, the output power of SPV modules can be acquired; however, the I-V curves are still unknown. Accordingly, a capacitive load was applied in the I-V characteristics measurement (Orduz et al., 2013). This method can be used to roughly measure SPV modules. However, the measurement time is too long for indoor testing, and the measured I-V curve is not accurate enough according to the result of this work. Furthermore, all these methods require relatively stable light sources, such as sunlight or a continuous solar simulator, which would lead to a significant temperature increase during the measurement process.

Few previous works paid special attention to the problems and methods of the indoor I-V measurement of SPV modules under Standard Testing Conditions (STCs). In this paper, a general I-V measurement procedure is proposed to eliminate interference in the I-V measurement process and to characterize SPV modules under STCs. An SPV module with buck-type power optimizers was used in the analysis and measurement in this work; however, although all measurements were realized using the buck-type SPV module, the theoretical analysis and I-V measurement method are suitable for all topologies of SPV modules. It is important to clarify that the efficiency, circuit parameters and specific topologies of the MPPT converter analysis are outside the scope of this work.

2. Test sample and pre-test

To explore the indoor I-V measurement method for SPV module, a polysilicon SPV module was adopted as the device under test (DUT). The module is composed of five submodules of 12 cells apiece, with each submodule connected with a VT8012 MPPT converter integrated chip (MCIC) manufactured by Maxim Integrated Products company. Fig. 1 presents the structure of the SPV module.

In the I-V measurements, the smart part in the SPV module is

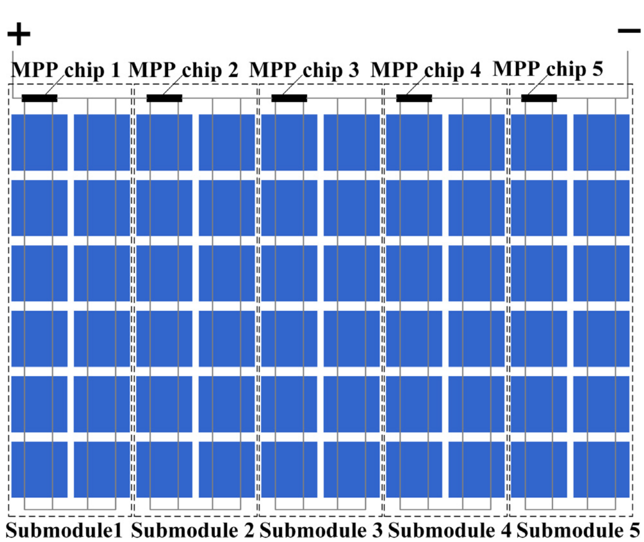

Fig. 1. Schematic diagram of the SPV module with five submodule-level MCICs.

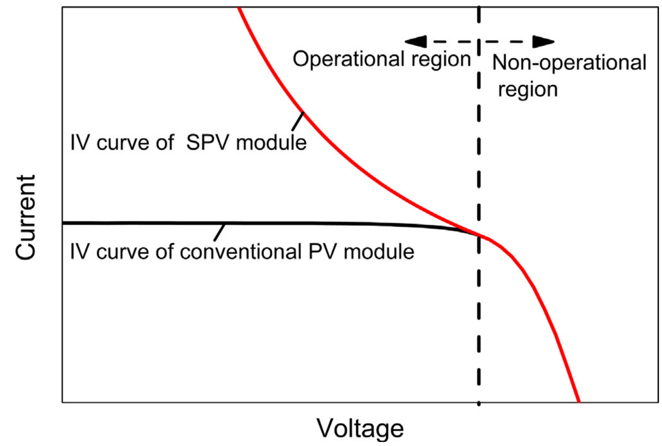

Fig. 2. The theoretical output specifications of the conventional PV module (black) and the SPV module integrated with buck DC/DC converter (red). The operational region for the buck converter is the left part of the first quadrant. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

generally considered to be a black-box, and its specific structure is unknown. Limited information can be obtained from the product specification of SPV modules such as the DC/DC converter type and the limits of the output current/voltage. Therefore, the operating principle of an SPV module is vital in developing the measurement procedure. The DUT in this work is integrated with the buck-type MCICs, which is the layout that is widely adopted by the mainstream MCIC manufacturers, such as Maxim and Tigo, due to its simple structure and comprehensive functions (Khan and Xiao, 2017; Pilawa-Podgurski and Perreault, 2013). Equipped with buck MCICs, the output voltage of mismatched PV submodules can be stepped down to increase their output current until it matches the current of the normal working submodules. Fig. 2 shows the comparison between the theoretical I-V curve of an SPV module integrated with buck power optimizers and the I-V curve of a conventional PV module. Similar curves have also been proposed in previous literatures (Kasper et al., 2014; Tsao, 2010), and there are some explanations in the Appendix A at the end of this paper of how to obtain the theoretical I-V curves. In Fig. 2, the operational region refers to the operating voltage range for the MPPT buck converters, and in this region, the current is inversely proportional to the voltage. In the non-operational region, the I-V curve of the SPV module is the same as that of a conventional PV module.

According to the theoretical I-V curve of the SPV module, the I-V measurement is feasible; however, in the actual I-V measurements of most SPV modules, we cannot obtain the theoretical curves or similar results. The DUT used in this work is a typical SPV module that cannot be tested using the routine I-V measurement method, whose measurement result was shown as unmeasurable in our laboratory flash-testing.

3. Simulation and experiment

3.1. Matlab/Simulink simulation of SPV module

A circuit-structure MATLAB/Simulink program was developed to analyze the effect of the buck MPPT converter on the measurement of an SPV module. Fig. 3 shows an overview of the MATLAB/Simulink model used to simulate the output characteristics of the SPV module with the same structure of the DUT to facilitate the analysis. The characteristic parameters of each submodule in this simulation are shown in Table 1. Although the parameters used in this simulation were different from the actual parameters of the DUT, the simulation model could qualitatively analyze the working principle and output characteristics of SPV modules. A resistive load is applied in circuit model to