Solar Energy Materials & Solar Cells 151 (2016) 60–65

Contents lists available at ScienceDirect

Solar Energy Materials & Solar Cells

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

Portable and wireless IV-curve tracer for >5 kV organic photovoltaic modules

Rafael García-Valverde [a], Samir Chaouki-Almagro [b], Michael Corazza [a], Nieves Espinosa [a], Markus Hösel [a], Roar R. Søndergaard [a], Mikkel Jørgensen [a], José A. Villarejo [b], Frederik C. Krebs [a,*]

[a] Department of Energy Conversion and Storage, Technical University of Denmark, Frederiksborgvej 399, DK-4000 Roskilde, Denmark
[b] Department of Electronics Technology, Technical University of Cartagena, Campus Muralla del Mar, s/n, 30202 Cartagena, Spain

ARTICLE INFO

Article history:
Received 8 December 2015
Received in revised form
6 February 2016
Accepted 23 February 2016
Available online 22 March 2016

Keywords:
Organic/polymer solar cells
High voltage
Wireless control
IV-tracer
Fast recording

ABSTRACT

The practical design of a wirelessly controlled portable IV-curve tracer based on a capacitive load is described. The design is optimized for the measurement of solar cell modules presenting a high open circuit voltage of up to 6 kV and a low short circuit current below 100 mA. The portable IV-tracer allows for on-site/in-situ characterization of large modules under real operating conditions and enables fast detection of potential failure of anomalies in electrical behavior. Currently available electronic loads only handle voltages up to around 1 kV. To overcome cost and safety issues related to high voltage applications, the design is based on low cost components, battery-based isolated supply and wireless communication. A prototype has been implemented and field tested for characterization of different organic photovoltaic modules (OPV) made according to the infinity concept with a large number of serially connected single junctions (~7.450 single junctions) presenting open circuit voltages up to 5.6 kV.

1. Introduction

On-site and in-situ measurement of the IV-characteristics of photovoltaic (PV) arrays is of great interest among PV installers, operators, end users and researchers. It allows for accurate determination of the electrical behavior of the PV device under real conditions and enables validation of performance and comparison with either previous data or expected data. It is an essential tool in the industry for diagnosis and maintenance and for researchers studying failure mechanisms, operational life time and degradation for complete systems. Many programmable loads can be found on the market that can be used as IV-tracers for PV devices in laboratories, from mW to kW. Also some portable IV-tracers are available for on-site evaluation of PV arrays [1]. However, all the available systems on the market only operate up to around 1 kV.

Recently, a concept for fully printable and "infinitely" long organic PV modules with many thousands of serially connected cells was reported [2,3]. This concept supports the idea of increasing PV power by means of increasing voltage but keeping low currents. It minimizes losses and improves the printing process because bus bars or parallel connections are not needed within the PV module. It has already been employed in different settings: solar park installation, solar tube installations and solar balloon installation [4]. OPV modules of 100 m with up to 11.3 kV of open circuit voltage (V_{oc}) and less than 100 mA of maximum current have been built and installed [5]. The characterization of such high voltage OPV modules presents a significant challenge, since there is no available IV-tracer or programmable load on the market in that range of voltage. High voltage components and probes are expensive and in most of the cases designed also for high power/high current applications (kA), which make them inaccurate for low current ranges. In addition, safety is an important issue in high voltage applications for the PV system, the equipment and the operator.

Until now the only generally applicable characterization method has been the use of a resistive load with manual connection (using high voltage gloves) of the OPV module to different high voltage resistive loads and the voltage measurement over the resistance using high voltage probes, and high power resistors with high electrical isolation. This method is accurate as long as the power rating of the resistor is kept significantly higher than the operating power levels (typically 10 times higher) such that the power dissipated does not heat up the resistive element and thus altering the effective resistivity. The method however requires a large number of available resistors to match possible loads and even for low currents (<100 mA) the voltage levels does imply power levels on

* Corresponding author.
E-mail address: frkr@dtu.dk (F.C. Krebs).

http://dx.doi.org/10.1016/j.solmat.2016.02.012
0927-0248/

the order of several hundreds of watts to kilowatts meaning that the resistors are large and bulky. It is however associated with significant risk and safety precautions are imperative. The method is relatively slow and therefore requires conditions of constant weather (i.e. a cloudless day). Under conditions of variable cloud cover the resistive method is impractical and a faster method is needed. Finally, the amount of data acquired using a resistor bank is limited to the I_{sc}, the V_{oc} and 15–20 data points along the IV-curve (depending on the number of combinations of resistors). An automated IV-tracer would be expected to quickly record a large number data points over the entire IV-range.

In this work we present the practical design of a portable IV-curve tracer that allows for rapid measurement of high voltage and low current OPV modules and arrays. The principles and details of the design and the prototype are explained and corroborated by field testing on a large OPV solar park array operating up to 5.6 kV.

1.1. International standards for high voltage PV

At the present 1 kV is the maximum allowable DC voltage in PV utilities according to the European Standards. The PV industry is looking forward to an extension to 1.5 kV according to [6]. In this respect our research includes PV systems with DC voltages higher than 1 kV, which according to the present regulations could not be accepted as a commercial PV plant. However it can be considered a "power installation exceeding 1 kV". This kind of power facilities requires extra safety measurements such as a fence, restricted access, earthing systems etc. and they are feasible and regulated by international standards as described in the European standards [7]. The HV IV-curve tracer can be considered as "medium Voltage (1.5–38 k V) power conversion or measurement equipment", and in case of commercialization it should meet the respective standards [8].

2. Design

2.1. Principles of operation

The IV-tracer is based on the use of a capacitive load. The capacitive load is the most common method used by commercial equipment for measuring the IV-curve of PV devices [9], and its use is recommended by international guidelines and standards for measuring PV arrays up to 50 kW_p [10,11].

The method illustrated in Fig. 1 is quite simple. Under normal operation both switch 1 and switch 2 are open and the capacitor is discharged. When switch 1 is closed the PV array (OPV module) is connected to the capacitive load thus charging it from 0 to V_{oc}. Current and voltage measurements are taken during the charging process, which correspond to the IV-characteristic of the PV array. Finally, the capacitive load must be discharged into a resistor bank for safety reasons and for preparing the tracer for the next measurement. This latter operation is done by opening switch 1 and closing switch 2 until the capacitor is fully discharged. Switch 2 is then opened and the system is ready for the next IV-trace. The method is fully explained by Muñoz et al. in [12,13]. If the IV-curve approximates an ideal rectangular IV-characteristic as shown in Fig. 2, the capacitor charging time, t_C, depends on its capacitance C, and on the instantaneous values of short-circuit current (I_{SC}) and V_{OC}, through the following equation:

$$t_c = \frac{V_{oc}}{I_{sc}} C \quad (1)$$

For real IV-characteristics (Fig. 2) the charging time is slightly longer than the charging time obtained from Eq. (1). Thus, the charging time can be approximated from the known value for the

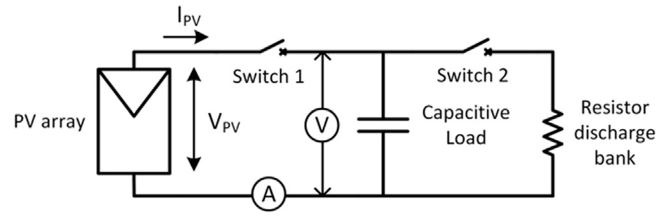

Fig. 1. Simplified schematic of a capacitive load used to trace the IV-curve of a PV array.

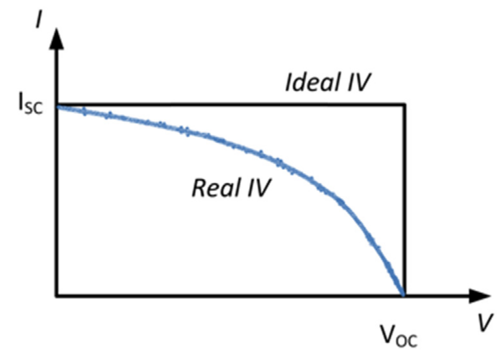

Fig. 2. Ideal and real *I–V* characteristics of a PV array.

capacitance combined with an estimate or a measurement of I_{sc} and V_{oc} (a measurement is preferable). Calculating the charging time and adding an extra margin is quite important for two reasons: 1) it allows more control over the measurement sampling, i.e. the sampling frequency or the number of points to be measured can be changed, improving the quality of the IV-curve, and 2) it makes the switching easier, especially when the switches have to handle an increasingly high voltage since they switch off better when no current is flowing.

The most important point for high voltage IV-tracers is that the capacitance must be high enough to ensure relatively slow charging times to avoid fast transients that can damage the load and the switches. It must however be borne in mind that the energy stored in a capacitor bank scales with the product of the capacitance and the voltage squared so precautionary measures must be taken when operating with capacitors at high voltage since energy levels quickly rise to lethal levels.

2.2. Electronics design

2.2.1. Power circuit

Fig. 3 shows the design schematics for the power circuit. As mentioned above, working with high voltage presents two main challenges, 1) the high cost of the specific components for high voltage applications and 2) operator safety. To overcome the cost problem of high voltage components, we have used parallel and/or series combination of low/mid voltage components when it was possible. This is the case for the capacitor and resistor banks. We dimensioned a HV capacitor bank for 6.6 kV operation and 10 μF consisting of 12 elements rated to 1.1 kV (30 μF for each). The HV resistor bank was comprised of 20 elements rated to 10 kΩ and 700 V which were connected to build a bank of 7 kV and 50 kΩ load.

High voltage switching elements have a high cost because they are specifically designed for high power applications and very demanding applications in terms of switching times. In our application the switching time is not as critical as it can be in converters and also the current is not so high. To avoid expensive switching elements, we scanned the market for HV relays used as safety devices in microwave ovens. Single pole, low current HV relays can be found at moderate cost that allow for operation up to