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Maximum-power-point tracking during outdoor ageing of solar cells

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ABSTRACT

This paper describes how to select a passive load which would the most accurately follow the maximum-power-point (MPP) of small laboratory size solar cells installed outdoors in Central Europe. Either resistor or diode type of passive load have been used as a low-cost alternative to active MPP trackers (designed especially for a long-term outdoor stability study of different types of small size laboratory solar cells). The dye-sensitized solar cells have been chosen as a representative case since they exhibit similar current–voltage (*I–V*) characteristics dependence at different light intensities (*G*) and cell temperatures (T_C) as other solar cell's technologies. The results showed that the most efficient tracking was achieved when the *I–V* characteristic of the optimal resistor or diode cross the MPP of the solar cell measured at $G = 73$ mW/cm^2 and $T_C = 25$ °C. A significantly better tracking could be obtained when instead of a resistor an optimal diode is used; the optimal diode consumes 96.5% of the annual energy that would be potentially produced by the solar cell connected to ideal MPP tracker while the optimal resistor consumes only 83.5% of that energy.

1. Introduction

In recent years emerging solar cell technologies (dye-sensitized solar cells DSSCs (O'Regan and Grätzel, 1991; Hagfeldt et al., 2010; Ye et al., 2015; Sharifi et al., 2014), organic solar cells (Liu et al., 2014; Etxebarria et al., 2015; Yan and Saunders, 2014), *etc.*) and concepts (plasmonic Berginc et al., 2014; Spalatu et al., 2015; Yang et al., 2015; Morawiec et al., 2014; Baek et al., 2014; Yao et al., 2014; Liu et al., 2014; Lu et al., 2014, quantum dots (Kouhnavard et al., 2014; Labelle et al., 2015), *etc.*) have been studied with an aim to improve cell performance and stability. In addition, solar cells that employ halide perovskite absorbers like $CH_3NH_3PbI_3$ have emerged from the field of DSSCs. This novel solar cell technology attracted perceivable attention as a low cost and efficient technology with record efficiencies currently exceeding 20% (Yan and Saunders, 2014; Yang et al., 2015; Park, 2015; Park et al., 2015) but full device stability still needs to be proven (Park, 2015; Snaith, 2013; Niu et al., 2015; Zhang et al., 2015; Leo, 2015). In general the stability of the solar cells is confirmed after several indoor stress tests are passed. However the long-term outdoor tests are also frequently examined since important information about the stability under real operating conditions might be revealed (Li et al., 2015; Berginc et al., 2014). This raises a question which load should be applied to the solar cells during the ageing since the operation condition is expected to influence the degradation as well (Berginc et al., 2014). The short-circuit and open-circuit conditions can be easily obtained but under these conditions the solar cells do not generate any power. On the other hand the degradation under maximum-power-point (MPP) condition is the most relevant since this is a condition where solar cells normally operate. However, the MPP of an individual solar cell is difficult to follow due to constantly changing weather conditions (cell temperature – T_C, light intensity – *G*) and ageing. Normally, active MPP trackers should be employed to follow the actual MPP by constantly adjusting the electronic load (Kamarzaman and Tan, 2014; Lopez-Lapena et al., 2012), but since MPP tracking operates on an individual solar cell, an ageing study with a batch of samples would require numerous low-power active MPP trackers that should be custom designed and build for small-size laboratory cells. Alternatively, a passive load may be used and a fixed resistor or (Schottky) diode(s) could be used as practical solutions to follow the MPP condition of an individual cell during outdoor testing under changing weather (air temperature T_{AIR}, *G*). Such tracking may not be ideally perfect since both, resistor and diode are passive elements. Therefore it is very important to know how to choose the most appropriate value and this is the subject of the present paper. For our analysis we used typical ionic-liquid based DSSCs. We developed the T_C and *G* depended current–voltage (*I–V*) model of the DSSC first and in a combination with the set of one year weather data (T_{AIR}, *G*) we calculated the energy yields

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of the DSSC in Ljubljana (Central Europe) when the cell is loaded with different passive loads (*i.e*. resistors R or diodes D). Further on we describe how to choose the optimal R or diode D in order to obtain the most efficient annual tracking, *i.e*. the highest annual energy yield of the solar cell. Finally the MPP tracking error for different operating conditions (T_C, G) is given if the optimal resistor or diode is connected to the solar cell.

2. Experimental

2.1. Manufacturing of DSSCs

The manufacturing process of the DSSC is shown in Fig. 1. A fluorine-doped SnO_2 coated glass (*i.e.* transparent conductive oxide, TCO) with a sheet resistance of 8 Ω/□ was used for the front and back cell substrate. An optimized Pechini sol–gel TiO_2 paste (based on P25, Degussa) (Berginc et al., 2014) was then applied to the surface of the front TCO glass substrate using a "*doctor blading*" technique to form a rectangular pad of TiO_2 with an area ranging from 0.58 to 0.68 cm^2. The TiO_2 layer was sintered at 450 °C for one hour before being immersed for 12 h in an ethanol solution of a Ruthenium complex based dye N719 (Ru(2,2′bipyridyl-4,4′dicarb oxylate)$_2$ (NCS)$_2$, Solaronix). For a counter electrode, platinum (thickness ~5 nm) was sputtered onto the back TCO glass substrate. The active and counter electrodes were then sealed using 25 μm thick polymer foil frame (Surlyn, DuPont) which also acts as a spacer between the electrodes. The electrolyte is a binary ionic-liquid mixture in a volume ratio 13:7 of 1-propyl-3-methyl-imidazolium iodide (Iolitec) and 1-ethyl-3-methyl-imidazolium tetracyanoborate (Merck), with addition of 0.5 M N-methylbenzimidazol, 0.1 M guanidinium thiocyanate and 0.2 M of I_2; the composition which remains as the best binary ionic liquid electrolyte for DSSCs (Berginc et al., 2014). After injecting the electrolyte through two pre-drilled holes in the counter electrode we sealed the cells and stored them in the dark for 24 h to allow a complete penetration of electrolyte into the TiO_2 pores. The whole manufacturing was processed by hand which caused some variations in active areas and performances.

2.2. Characterization

2.2.1. Indoor characterization

The *I–V* characterization was performed using an Oriel Class ABA solar simulator equipped with a 1.5G air mass filter, the spectrum of which closely matches the required AM1.5 spectrum. In accordance with the IEC60904-3 standard the short-circuit current mismatch parameter was calculated and in conjunction with a calibrated crystalline silicon c-Si reference solar cell, covered with a KG5 glass filter, the level of standard illumination (100 mW/cm^2) was determined. The light intensity was reduced using different neutral density filters (Melles Griot) which had only a negligible influence on the illumination spectrum up to 800 nm. Regardless of the light intensity we used a calibrated c-Si reference solar cell equipped with a KG5 glass filter to determine a specific G. A cooling/heating Peltier element was used to stabilize different T_C including the 25 °C. Before characterization, each cell was placed and secured with a contact tip to a copper plate to assure a good electrical and thermal contact. The cell was then covered by a Styrodur box to insulate it from the heat produced by the solar simulator. The T_C was determined as an average reading of two negative temperature coefficient resistors (NTCs) before and after the measurement; one NTC resistor was placed into the upper copper plate and the other directly onto the glass of the cell. When the temperatures of both NTC resistors equalized and the temperature inside the box stabilized, we removed the box and performed the measurement at certain G and T_C. During the characterization we also masked the cells to leave only the active area of the cell exposed, which is stated as the most rigorous condition regarding the cell's efficiency. The *I–V* characteristics of the cells were then measured using a Keithley 238 source meter by applying a voltage and measuring the current. The cells were scanned stepwise (10 mV) from 0 V (short-circuit condition) to 0.9 V (beyond open-circuit voltage V_{OC}).

2.2.2. Outdoor characterization

Outdoor ageing was performed on the roof of the Faculty of Electrical Engineering, University of Ljubljana (latitude 46°2′39.39″N, longitude 14°29′18.28″E (Berginc et al., 2014) for 7 months (April–October). Cumulatively the DSSCs were exposed to 906 kW h/m^2 irradiation. The cells were stored in a water proof container with a transparent cover (total transmission ranges between 88% and 90% and total reflection between 5% and 10% in the visible wavelength range). Each of the six cells in the batch were then divided into two groups and aged under the (i) quasi maximum-power-point using a shunt resistor (approximately 100 Ω), Fig. 2A and (ii) quasi maximum-power-point using two Schottky diodes and 1 Ω shunt resistor in series, Fig. 2B. The in-house built temperature compensated 24-bit data logger stored in the waterproof container was used to measure the voltages across the shunt resistors in-situ every 10 min which allowed the calculation of the current and the voltage at the quasi maximum-power point (I_{MPP} and V_{MPP}, respectively) at the later stage. During the 7 months outdoor testing the T_C were measured using integrated digital temperature sensors (Dallas Semiconductors). Additionally the G and T_{AIR} were measured every 10 min throughout the same year. A calibrated reference pyranometer CMP 6 (Kipp&Zonen) was used to determine the G in the plane of the samples and a weather station (La Crosse Technology, WS3600) for monitoring the T_{AIR}.

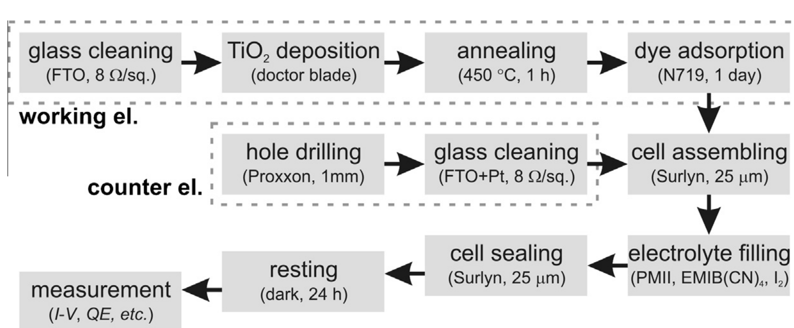

Fig. 1. Manufacturing of dye-sensitized solar cells.