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Low irradiance losses of photovoltaic modules

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ABSTRACT

The efficiency of a photovoltaic cell/module changes, as the intensity of incident irradiance decreases, in a non linear way and these changes are referred to as low irradiance losses. In this study data from field experiments, developed and organized by the National Renewable Energy Laboratory, are used to evaluate the low irradiance losses for a variety of module technologies. The results demonstrate that the ratio of the normalized power divided by the normalized short circuit current provide a good measure of the module's low light efficiency losses after both the maximum power and the short circuit current are adjusted for temperature effects. The normalized efficiencies determined through the field data, spanning for several months, are in good agreement with those determined under controlled conditions in a solar simulator. An analytical relation for the normalized efficiency is proposed based on existing formulation for the fill factor. Despite the approximate nature of the fill factor relation, this approach produces reliable results. It will be shown that a normalized efficiency curve can be used to extract information on the series and shunt resistances of the PV module and that the shunt resistance as a function of solar irradiance can be studied. Alternately, this formulation can be used to study the low irradiance losses of a module when the internal resistances are known.

1. Introduction

Several models are available in the literature that allow one to estimate the power produced by a photovoltaic system (e.g. King et al., 2004; Ayompe et al., 2010; Huld et al., 2011; Mavromatakis et al., 2016). One of the factors that influence the energy production of a photovoltaic cell or module is the loss of conversion efficiency associated with low solar irradiances. Manufacturers quote the efficiency at STC conditions, i.e. at 1000 W/m^2, however, due to parasitic resistances the efficiency is not constant as the intensity of solar irradiance changes.

The shunt resistance is mainly responsible for the decrease of the efficiency towards low light levels although some studies find the series resistance and the diode quality factor also may impact the efficiency changes (e.g. Grunow et al., 2004). On the other hand, Khan et al. (2010) showed variations on both the series and shunt resistance and quality factor as a function of irradiance. However, the silicon solar cell was manufactured for the purposes of their work and was not a commercial one. Chegaar et al. (2013) concluded that the series resistance is invariant with respect to irradiance, while the shunt resistance drops roughly linearly from 200 W/m^2 to 1000 W/m^2. They also reported an increase of the diode quality factor with irradiance. Shen et al. (2016) used a CdTe solar cell manufactured by their lab when they studied different illumination levels. They found power law dependencies for both the series and shunt resistances for the specific cell they examined. Sauer et al. (2015) and Sauer and Roessler (2013) have studied two specific types of multicrystalline modules with respect to their performance as a function of temperature and irradiance. They compared their results with those predicted by commercial software and proposed improvements based on their findings. All measurements from this research were conducted in the lab with a solar simulator. Sentence introduced according to Referee 2 comment.

This study focuses on the change of photovoltaic module efficiency as a function of irradiance. The normalized efficiency (100% at STC) can be used to determine the low light losses of a module. It utilizes the short circuit current and the maximum power of the module, both corrected for cell temperature effects, to estimate the fractional deviation from the STC efficiency. If the incident solar radiation is used to evaluate the module efficiency, the effect of changing plane of array (POA) spectral distribution must be separated from the change in efficiency caused by the low levels of incident radiation. The short circuit current incorporates the effects of changing spectral distribution, as

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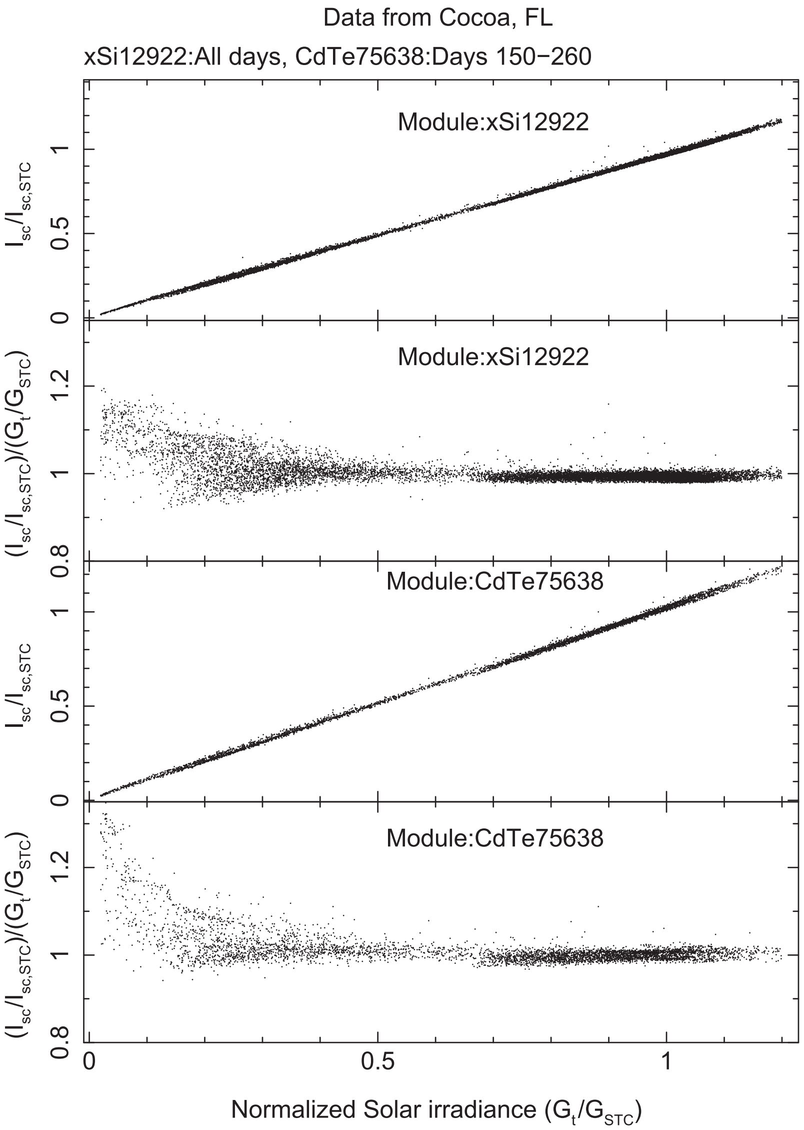

Fig. 1. Actual experimental data from Cocoa, FL of the normalized short circuit current of two modules (c-Si and CdTe) are shown as a function of the incoming irradiance. The irradiance is measured with a broadband pyranometer.

well as angle-of-incidence and soiling losses and provides a less convoluted method for examining the change in module efficiency. Thus, the normalized efficiency (η_{eff}) is defined as

$$\frac{P_{max}}{P_{STC}\cdot(1+\gamma\Delta\theta)}\cdot\frac{I_{sc,STC}\cdot(1+\alpha\Delta\theta)}{I_{sc}} \tag{1}$$

where P_{max} stands for the instantaneous maximum power, I_{sc} stands for the short circuit current, $\Delta\theta$ stands for the offset from the STC temperature, α stands for the temperature coefficient of the short circuit current and γ stands for the temperature coefficient of the maximum power. The absolute efficiency cannot be calculated with this approach but it is not of interest to the current study. The use of the normalized efficiency for the calculation of the low irradiance losses is validated with field data from a NREL experiment which provides a unique opportunity to study this approach (B. Marion et al., 2014).

The paper is organized as follows: In Section 2 the use of the short circuit current as a measure of the solar irradiance is discussed along with details about the experimental data. In Section 3 the approach to determine the normalized efficiency of a module using I-V data is explained and data from four specific modules tested in the NREL experiment are given. In Section 4 the methodology to extract the parasitic resistances from a normalized efficiency curve through approximate analytic relations is presented. In Section 5 the calculated low irradiance losses of modules of different technologies, using the proposed approach, are presented. An example of the proposed methodology to determine the parasitic resistances is also given in this section. Finally, in Section 6 conclusions and recommendations are given.

2. Prerequisite information: ise of I_{sc} and the experimental data

2.1. The I_{sc} as a measure of the incident irradiance

The photocurrent produced in a cell is directly proportional to the incoming solar irradiance. Applying the one-diode model (e.g. Laudani et al., 2014; Hansen, 2015) under short circuit conditions and taking into account the fact that the contribution of the exponential term to the diode current becomes insignificant as voltage approaches zero under short circuit conditions, it is straightforward to show that

$$\frac{I_{sc}/I_{sc,STC}}{G_t/G_{STC}}=\frac{1+r_{STC}}{1+r}\,(1+\alpha_{I_{sc}}\Delta\theta) \tag{2}$$

where I_{sc}, $I_{sc,STC}$ stand for the short circuit current at any solar irradiance (G_t) and at STC conditions ($G_{STC}=1\ \mathrm{kW/m^2}$) respectively, r denotes the ratio of the series resistance of a cell to the shunt resistance with r_{STC} being the same ratio at STC conditions. $\Delta\theta$ denotes the temperature offset from the STC cell temperature of 25 °C, while $\alpha_{I_{sc}}$ stands for the temperature change of short circuit current in 1/°C. Current