Energy Conversion and Management 156 (2018) 329–336

Contents lists available at ScienceDirect

Energy Conversion and Management

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

Performance of a concentrating photovoltaic monomodule under real operating conditions: Part II – Power rating

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ARTICLE INFO

Keywords:
Concentrating photovoltaic
III-V multijunction solar cells
Power rating
Spectral indices
Solar simulator

ABSTRACT

In Part I of this work, a comprehensive outdoor characterisation of a concentrating photovoltaic monomodule was presented where the importance of atmospheric parameters on the performance of such systems was highlighted. In this work, Part II, the power ratings of a concentrating photovoltaic monomodule are determined using different methods and filtering criteria that account for the spectrum. Spectral variations are considered to be a major parameter that contributes to the uncertainty of concentrating photovoltaic power ratings due to the dynamic behaviour of outdoor conditions. In order to address the sensitivity of such variations, Concentrator Standard Operating Conditions (CSOC) and Concentrator Standard Test Conditions (CSTC) power rating estimations are performed using different scenarios and compared with measurements obtained using a Helios 3198 solar simulator. The application of different methods and filtering criteria, in terms of the spectral matching ratio (*SMR*) of the middle to bottom subcell, exhibits differences of up to 3.64% and 1.37% for the CSOC and CSTC estimations respectively. The comparison with the CSTC power rating obtained indoors shows a difference of up to 8.45%; this is attributed to the tracking errors and also the temperature dependence of the refractive optics. The application of the spectral factor (*SF*) as filtering criterion reduces the CSTC power rating difference to 6.74% compared to the corresponding value obtained indoors. In addition, the CSOC power rating estimation using the *SF* filtering exhibits similar results to the standardised procedure using the *SMR* indices (within 1.21%).

1. Introduction

The rating procedures of photovoltaic (PV) devices and modules are important for the comparison of the technologies [1]. Concentrating photovoltaic (CPV) modules can be either rated indoors or outdoors (by translating outdoor current-voltage, *I-V*, measurements to Concentrator Standard Test Conditions [2]) under CSTC (i.e. reference direct spectrum of air mass AM1.5D according to the American Society for Testing and Materials, ASTM G173-03 [3], direct normal irradiance, $DNI = 1000\,\text{W/m}^2$ and cell temperature, $T_{cell} = 25\,^\circ\text{C}$) or outdoors under Concentrator Standard Operating Conditions, CSOC (i.e. AM1.5D, $DNI = 900\,\text{W/m}^2$, ambient temperature, $T_{amb} = 20\,^\circ\text{C}$ and wind speed, $WS = 2\,\text{m/s}$). The CSOC and CSTC power ratings are currently determined according to the recently published International Electrotechnical Commission (IEC) 62670-01 [4] (Concentrator Photovoltaic (CPV) Performance Testing - Standard Conditions) and IEC 62670-3 [5] (Concentrator Photovoltaic (CPV) Performance Testing - Performance Measurements and Power Rating) [6]. Both CSOC and CSTC must be consistent with the AM1.5D spectral irradiance described in IEC 60904-3 [7].

Prior to the publication of the IEC 62670, the CSOC power rating was evaluated using the multiple regression equation of power from ASTM E2527-09 [8] as a function of *DNI*, T_{amb} and *WS*. However, since the publication of IEC 62670-3, the CSOC power determination follows a different methodology. Since many test laboratories do not have an appropriate solar simulator for CSTC measurements, this power rating can also be determined by the translation of outdoor measurements according to the method described by Muller et al. [2] and published in the final version of IEC 62670-3 [5]. Since indoor CSTC power rating is obtained under a controlled environment, while the outdoor characterisations are subject to variable ambient and atmospheric conditions [9], additional uncertainties and deviations from the real CSTC

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https://doi.org/10.1016/j.enconman.2017.11.024
Received 31 August 2017; Received in revised form 2 November 2017; Accepted 11 November 2017

Nomenclature

AM	air mass
AOD	aerosol optical depth
DNI	direct normal irradiance, W/m^2
GNI	global normal irradiance, W/m^2
I	current, A
k_B	Boltzmann constant, eV/K
n	diode ideality factor
N_s	number of cells connected in series
P	power output, W
PW	precipitable water, cm
q	elementary charge, C
SF	spectral factor
SMR	spectral matching ratio
T	temperature, °C
V	voltage, V
WS	wind speed, m/s

Greek letters

β_{Voc}	temperature coefficient of $\underline{Voc}$
δ	temperature coefficient of η
η	efficiency

Subscripts

amb	ambient
avg	average
meas	measured
mod	module
mp	maximum power
oc	open-circuit
ref	reference
sc	short-circuit
sim	simulator

Abbreviations

ASTM	American Society for Testing and Materials
CEAEMA	Centre for Advanced Studies in Energy and Environment
CPV	Concentrating photovoltaic
CSTC	Concentrator Standard Test Conditions
CSOC	Concentrator Standard Operating Conditions
IEC	International Electrotechnical Commission
MJ	Multijunction
PV	Photovoltaic
TTM	Thermal Transient Measurements

power determination can occur. Such uncertainties or deviations might be caused by passing clouds [10], spectrum [11] and temperature [12] variations amongst others. In order to match the spectrum conditions with the reference, a number of filtering criteria, based on the spectral matching ratio (*SMR*) [13], are recommended to be applied on the measured data. However, although the ranges of *SMR* filters are given in IEC 62670-3, they were under a significant debate within the IEC subgroup [2] due to the fact that "tight" ranges of *SMR* might limit the number of available datapoints, especially at locations where the reference conditions are not met frequently. Therefore, the sensitivity of the spectral filtering criteria on the CSTC power determination needs to be further examined. In addition, it is also important to investigate the CSOC power ratings obtained using the newly developed standard against the methods reported in the past.

In order to examine these issues, a comprehensive outdoor characterisation needs to be undertaken where the electrical and spectral characteristics of a CPV module are analysed based on atmospheric, irradiance and meteorological variations. This was the subject of Part I of this work [14] where the results of a CPV monomodule highlighted the importance of considering the influence of the atmospheric parameters on the performance of such technologies. The advantage of using a monomodule rather than a full module is that mismatch losses along cells are neglected [15]. The detailed information obtained from the outdoor characterisation are fundamental to the better understanding of the behaviour of this technology [16] and can provide valuable knowledge of the possible deviations within the power rating procedures. The aim of Part II is to apply both the indoor and outdoor power rating procedures on a CPV monomodule according to IEC 62670-3 [5] and compare the obtained results against the ratings determined by other methods that were reported in the past. In addition, different spectral filtering criteria are applied and deviations within the power rating determinations are examined in order to investigate the influence of the range of spectral filters along with their possible effects. Furthermore, an alternative but widely used spectral index (i.e. the spectral factor, *SF*) [17], is applied on the IEC 62670-3 filtering procedure to examine its applicability in obtaining reasonable CSTC and CSOC power ratings.

2. Indoor characterisation for CSTC power rating

The CPV monomodule (Suncore DDM-1090×) was tested under laboratory (controlled) conditions in order to compare the indoor power rating against the corresponding CSTC rating obtained outdoors by translating *I-V* measurements taken on sun. This is useful to compare both power rating approaches, indoors and outdoors, as well as to better analyse the results presented in the next sections. The system was measured with the multi-flash Helios 3198 pulse solar simulator [18] at the Centre for Advanced Studies in Energy and Environment (CEAEMA) of the University of Jaén. This simulator (see Fig. 1) uses a Xenon flash lamp for generating the solar radiation and a parabolic mirror as a collimator. The spectral irradiance distribution is close to the AM1.5D reference spectrum and the collimation angle is approximately ± 0.3° which, according to IEC 67670-3, is appropriate for this monomodule's acceptance angle of ± 0.7° (i.e. the collimation angle must be at least 10% less than the device's acceptance angle and greater than ± 0.26°). It is worth mentioning, that besides the collimation angle, this simulator meets the requirements defined in IEC 62670-3 for the indoor

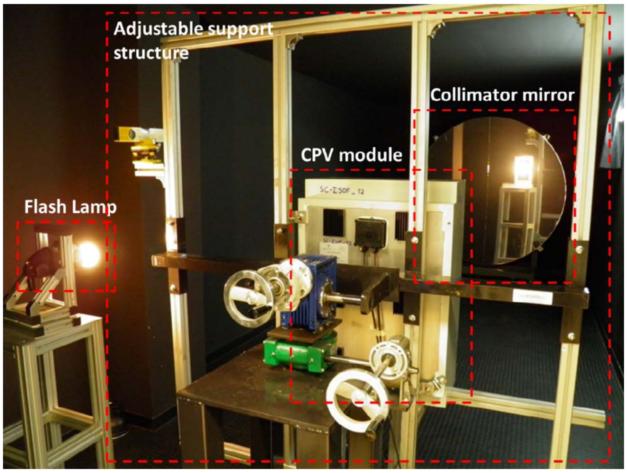

Fig. 1. Photograph and main components of the multi-flash Helios 3198 CPV pulse solar simulator at the CEAEMA of the University of Jaén.