Solar Energy 161 (2018) 163–179

Contents lists available at ScienceDirect

Solar Energy

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

Simulation of large photovoltaic arrays

Z. Abdin, C.J. Webb, E.MacA. Gray*

Queensland Micro- and Nanotechnology Centre, Griffith University, Nathan 4111, Australia

ARTICLE INFO

Keywords:
Photovoltaic
Array model
MPP
Tolerance
Temperature

ABSTRACT

Large photovoltaic arrays are becoming common as the world moves to replace fossil-fuelled electricity generators. As the array size and project cost increase, it becomes increasingly important to know accurately what the array's performance will be before it is built. Large arrays inevitably contain modules with a spread of performance characteristics such as short-circuit current and open-circuit voltage, and suffer from temperature differences between modules. In this first study of these problems, a model has been developed that accurately predicts the behaviour of a photovoltaic array subject to variability between modules and inhomogeneity of cell temperature across the array. The model was applied to a real rooftop array consisting of 912 modules (298 kW nominal peak power). Based on measured string currents, the predicted average string temperature was compared the temperature measured by a radiometric survey using a drone-mounted IR camera and matched very well.

The five-parameter model of cell characteristics was fitted to manufacturer's data, with highest weighting given to the region around the maximum-power point (MPP) where a real array should operate via active MPP tracking. The model was used to explore separately the effects of a spread in module characteristics arising in the manufacturing process and of temperature inhomogeneity across the array. The current in each module of a string was constrained to be the same, and the voltage of every parallel-connected string was also constrained to be the same. These constraints lead to greater power loss than is predicted based on an average module at an average temperature. Compared to a hypothetical array assembled from identical average modules at the same average temperature, variability caused a loss of power of about 2%, depending on the detailed form of the distribution function chosen to represent the spread of characteristics in the manufacturer's tolerance band. As a rule of thumb, de-rating the maximum power to the lower end of the manufacturer's tolerance band is recommended to account for module variability during the design phase. The effect of temperature inhomogeneity is more serious, because temperature affects V_{oc} strongly, causing parallel-connected strings to be pulled away from their ideal operating points to obey the constraint of equal voltage. A modest 10 °C temperature gradient across the studied array was predicted to cause about a 4% loss of power at the MPP. Much higher real temperature differences could be expected in summer and were observed. The study confirmed that temperature inhomogeneity poses a serious design problem for large arrays, requiring careful thermal design to achieve not only acceptably low average array temperature, but also the least possible temperature spread.

1. Introduction

The transition to sustainable electricity supply based on renewable resources is a global project of the utmost importance in responding to climate change. A 2015 study by the Fraunhofer Institute for Solar Energy Systems (Mayer et al., 2015) concluded that global installed photovoltaic (PV) capacity could exceed 30 TW peak power by 2050, well above current predictions and more than enough to supply the world's conceivable electricity requirement. Thus there are sound reasons to anticipate large numbers of large PV arrays connected to national grids in the next several decades. The beginning of this trend is apparent now, with installed PV capacity running well ahead of predictions made just a few years ago.

Given the enormous scale required for PV generators to meet a substantial fraction of global electricity demand, efficient use of finance, materials and manufacturing facilities will be very important, as will efficient operation of the installed facilities. This implies accurate forecasting of the output of very large arrays, so that the return on investment and contribution to total generating capacity can be reliably predicted. Accurate forecasting can only be founded on authoritative modelling, which with large numbers of individual PV modules (panels) involved, and areas large enough to develop temperature gradients

---

* Corresponding author.
E-mail address: e.gray@griffith.edu.au (E.M. Gray).

https://doi.org/10.1016/j.solener.2017.12.034
Received 25 October 2017; Received in revised form 11 December 2017; Accepted 16 December 2017

Nomenclature

AM	air mass
$D_{n/p}$	electron/hole diffusion coefficient
E_g	band gap Energy [eV]
G	radiation [W m^{-2}]
I	current [A]
j	current density
K_T	clearness index
$K_{\tau\alpha}$	angle modifier
K	linear attenuation coefficient
k_B	Boltzmann's constant [1.380 × 10^{-23} J·K^{-1}]
k_I	SC current temperature coefficient
L	glazing/coating thickness
$L_{n/p}$	electron/hole diffusion length
M	air mass modifier
$m^*_{e/h}$	effective electron/hole mass
N_s	number of strings per array
N_m	number of modules per string
N_c	number of cells per module
$N_{a/d}$	acceptor/donor concentration
n	refractive index
n_i	intrinsic carrier density
q	electron charge [1.602 × 10^{-19} C]
R	series resistor [Ω]
R_b	tilt factor
T	temperature [°C]
V	voltage [V]
STC	standard test condition
NOCT	nominal operating cell temperature
LST	local solar time
η	day of the year
θ_{in}	angle of incidence [deg]
θ_z	zenith angle [deg]
ϕ	latitude [deg]
β	tilt angle [deg]
ω	hour angle [deg]
δ	declination
α	altitude [deg]
ψ	solar azimuth angle [deg]
θ_{in}^{d}	angle of diffusion incidence [deg]
θ_{in}^{g}	angle of ground-reflected incidence [deg]
γ	surface azimuth angle [deg]
θ_r	angle of refraction [deg]
κ	ideality factor
$\tau\alpha$	transmittance-absorptance product
ρ	reflectance

Superscripts/subscripts

b	beam
c	cell
d	diffuse
D	diode
e	electron
g	ground
gen	generation
h	hole
in	incidence
mpp	maximum power point
oc	open-circuit
r	refraction
ref	reference
rs	reverse saturation
s	series
sat	saturation
sc	short-circuit
sh	shunt
ph	photon

across the array, implies a need to account for variability in as-received module characteristics and varying module temperatures.

Variability in module characteristics owing to manufacturing tolerance or temperature inhomogeneity appears not to have been addressed in the literature. The five-parameter cell-level model explored in detail by De Soto et al. (2006) has generally been adopted during the past decade (De Soto et al., 2006; Carrero et al., 2007; Dongue et al., 2012; Brano et al., 2010, 2012). The emphasis has since shifted to array-level consideration of operational problems. For example, Chen et al. introduced a fault-diagnosis approach to classify and accurately detect the four most common problems of PV arrays: degradation, short-circuits, open-circuits and partial shading; Belhaouas et al. (2017) proposed three PV array arrangements to mitigate partial shading effects on the array output; Lappalainen and Valkealahti (2017) studied the output power variation of different PV array configurations during irradiance transitions caused by moving clouds; Lee et al. (2017) built a dynamic thermal model for a PV module; Farhat et al. (2017) applied a sliding mode approach to determining the maximum power point of a PV array.

Two important questions arise specifically in relation to large (therefore costly) PV arrays. First, are the effects on array maximum power of manufacturing variability between modules and temperature inhomogeneity across the array large enough to be of concern? Second, can the impacts of module variability and temperature inhomogeneity be assessed simply at the array design stage, without detailed modelling? The objective of this paper is to answer these questions as straightforwardly as possible.

In this paper, therefore, variability in module characteristics within a large array is explored for the first time, based on the 5-parameter PV cell model, scaled to form modules, strings and an array which feeds power conversion electronics with maximum-power-point (MPP) tracking capability. It was felt to be important to base the model on manufacturer's published data, since these are generally available and represent warranted average performance across the production stream. This approach thus avoids the need to measure representative characteristics for the module(s) of interest, although it may restrict the constructed model to using linear temperature coefficients for the short-circuit current and open-circuit voltage. The effects of manufacturer's variability in module characteristics, and differing temperatures between modules, are explored via the clustering of individual module/string MPPs about the string/array MPP. The module-level model is first validated against manufacturer's data, then applied to a real rooftop array with MPP-tracking inverters. Based on a detailed solar radiation model and minute-by-minute global and direct radiation data from a pyranometer and pyrheliometer located within the array area, the electrical power measured at string level is compared to the predicted outputs of individual strings, then summed for comparison at the sub-array level. The temperature inhomogeneity across the studied array, measured by infrared radiometry, is compared to the prediction of the model when cell temperature is taken as a fitted parameter in order to match the predicted output power of each string to the measured power. The results validate the model and confirm that the studied array suffers from significant temperature gradients.