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Thermal–electrical model for energy estimation of a water cooled photovoltaic module

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Abstract

In this paper a theoretical model, which integrates both thermal and electrical aspects, has been developed in order to analyze an unglazed Photovoltaic (PV) module with water cooling. The coolant flow induces higher conversion efficiency due to lower temperatures. However, a non-uniform temperature field of solar cells arises with a consequent impact on their electrical parameters and the corresponding power losses are investigated. Outdoor experimental tests have been carried out to indirectly estimate the temperature of the solar cells at known conditions of irradiance and ambient temperature and to characterize the PV module at Standard Test Conditions (STC). In the outdoor characterization of commercial PV modules without cooling, the current–voltage curves are corrected to STC with a standard procedure, for comparing them with the manufacturer datasheets. In this paper, it is experimentally verified that the STC can be reasonably reproduced in the field in clear sky conditions thanks to a suitable cooling. Finally, by means of daily simulations, the performance improvement with variable coolant flow rates, for two reference sites at different climates, is investigated in details.

Keywords: Photovoltaic modules; Thermal–electrical model; Water cooling; Experimental tests

1. Introduction

Only a fraction of solar radiation is converted by Photovoltaic (PV) systems into electricity, while a large part of the thermal energy is wasted and contributes to the increase of solar (or PV) cell temperature. As a consequence, the electrical efficiency drops (Platz et al., 1997; Kalogirou and Tripanagnostopoulos, 2006; Chow, 2010; Spertino et al., 2014) because the performance of solar cells depends on their ambient conditions, among which the cell operating temperature plays a major role. In general, the PV efficiency loss with temperature depends on the type of cell. A linear dependence of the electrical performance on the operating temperature has been indicated in various references (Kawamura et al., 1997; Omubo-Pepple et al., 2009; Suresh et al., 2013). An indicative value reported in SEI (2004) for the reduction of crystalline silicon (c-Si) efficiency with unitary temperature increment of the solar cell

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Nomenclature

Acronyms

AM	Air Mass
ARC	Anti Reflective Coating
CHP	Combined Heat and Power
DC	direct current
MPP	Maximum Power Point
NOCT	Nominal Operating Cell Temperature
PC	polycarbonate
PCM	phase change material
PV	Photovoltaic
PV/T	Photovoltaic–Thermal
SAHP	Solar Assisted Heat Pump
STC	Standard Test Conditions
TE	thermoelectric
TPU	thermoplastic polyurethane

Symbols

$\mathbf{A}$	matrix
A	heat transfer surface (m^2)
$\mathbf{b}$	vector
c	specific heat of water ($J\,kg^{-1}\,K^{-1}$)
d	hydraulic diameter of water flows passage (m)
E_G	energy gap (eV)
E_{G0}	energy gap at 0 K (eV)
G	solar irradiance ($W\,m^{-2}$)
h	surface heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
I	current (A)
k	thermal conductivity ($W\,m^{-1}\,K^{-1}$)
K_{ph}	spectral-response parameter
m	diode ideality factor
n	step counter
p	perimeter (m)
P	electric power (W)
q	electron charge ($1.60217646 \cdot 10^{-19}$ C)
$\dot{q}$	heat flux ($W\,m^{-2}$)
R	module electrical resistance (Ω)
s	thickness (m)
S	surface (m^2)
SR	spectral response ($A\,W^{-1}$)
T	temperature (K)
T_{sky}	sky temperature (K)
U	overall heat transfer coefficient ($W\,m^{-2}\,K^{-1}$)
$\dot{v}$	volume flow rate of water ($l\,h^{-1}$)
V	voltage (V)
x, y, z	space variables
$\mathbf{x}$	vector for linear system solution
X, Y	height and width of the alveolar polycarbonate layer (m)
w	water velocity ($m\,s^{-1}$)
Z	space derivative of the water temperature ($K\,m^{-1}$)

Greek symbols

α	absorptivity (–)
α_{Isc}	short-circuit current coefficient ($A\,°C^{-1}$)
β	tilt angle of PV module (°)
β_{Uoc}	open-circuit voltage coefficient ($V\,°C^{-1}$)
γ_P	maximum power coefficient ($\%\,°C^{-1}$)
δ	power increase (%)
ε	polycarbonate emissivity (–)
η	efficiency (–)
κ	Boltzmann constant ($1.3806503 \cdot 10^{-23}\,J\,K^{-1}$)
λ	wavelength (μm)
μ	dynamic viscosity of water ($kg\,s^{-1}\,m^{-1}$)
ν	kinematic viscosity of water ($m^2\,s^{-1}$)
ξ	real power gain (%)
ρ	density ($kg\,m^{-3}$)
σ	Stefan–Boltzmann constant ($5.67 \cdot 10^{-8}\,W\,m^{-2}\,K^{-4}$)
τ	transmissivity (–)
φ	constant depending on the cell material
Φ	solar spectral emissive power ($W\,m^{-2}\,\mu m^{-1}$)
χ	power loss (%)
ψ	constant depending on the cell material

Superscripts

T	transposition
iso	isothermal

Subscripts

a	ambient
alv	alveolar
ag	air–gap
C	cell
c	cross-sectional
cond	conductive
conv	convective
D	diode
el	electrical
G	gap
I	ideal
in	input
inw	inlet water
max	maximum
mpp	at maximum power
NC	without coolant
oc	open-circuit
pc	polycarbonate
ph	photo-generated
PVm	PV module
R	real
rad	radiative
ref	reference value, at reference temperature
s	surface
ser	series
sc	short-circuit
sh	shunt
t	thermal
w	water
0	reverse saturation