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Using energy balance method to study the thermal behavior of PV panels under time-varying field conditions

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ABSTRACT

A precise estimate of PV panels temperature is crucial for accurately assessing their electrical performance. Therefore, in this study, one of the main aims has been to significantly improve the prediction accuracy of the PV cell temperature, by using realistic boundary conditions. Unlike previous thermal models in the literature, which usually focus on its mere application, a detailed step by step development and numerical implementation of the complete model has also been provided in great details in this work. The developed model is transient, so it can fully simulate the thermal performance of any PV panel under time-varying field conditions. Once the model is defined for a specific PV panel, the only external inputs it needs are the total incident solar irradiation, wind speed and the ambient temperature. The model has been adequately validated through PV panel's datasheet provided information, literature data and against a versatile set of experimental data under various weather conditions. After thorough validations, the developed model was compared to various other widely used empirical, analytical and numerical thermal models from the literature. The comparison shows that by using realistic boundary conditions, the developed thermal model has far better prediction accuracy than other models from the literature. The methodology presented in this study is completely generic. That is, though it has been implemented and validated here for a silicon-based PV module the approach may be used to model any free-standing plane PV surface, with appropriate modifications to layer thicknesses and material properties. A range of weather conditions may also be accommodated.

1. Introduction

Photovoltaic (PV) panels unlike other solar technologies, have ability to directly convert the incoming solar energy into electricity. PV cells are the building blocks of any PV panel and are the main component responsible for this energy conversion. The rest of the parts comprising the PV panel are there to enhance the solar to electrical power conversion and to provide physical integrity to the overall structure.

The silicon (Si) technology based PV cells have the highest percentage of global market for all PV technologies (almost 93%) [1]. The main reason for this huge market share is the abundant and cheap supply of silicon. The silicon cells are further divided into two main types, i.e. mono-crystalline (mono-Si) and poly-crystalline (poly-Si). As the names suggest, they have different crystal structures. The mono-Si cells due to less crystalline defects have a higher electrical efficiency and are thus, comparatively expensive to produce.

For a typical stand-alone PV panel, PV cells are usually encased in a sheath of Ethylene Vinyl Acetate (EVA), with a glass on the front sun-facing side and a plastic (mostly Tedlar) back-sheet on the rear ground-facing side. The EVA basically binds all the different layers together and provides electrical insulation. The glass is usually tempered to provide mechanical strength to the overall structure and has high transmittance, resulting in reduced reflection/absorption losses. The back-sheet is attached to prevent water ingress from the surroundings and to internally reflect the solar irradiation, to maximize absorption. The silicon-based PV cells also have a very thin layer of Anti-Reflecting Coating (ARC) applied on them to reduce the reflection losses. This is because pure silicon without an ARC can reflect up to 30% of the incident light [2].

Due to the layered structure of the PV panel, not all the incident light reaches the PV cells, as part of it gets reflected and absorbed. Also, a major portion of this transmitted light is not converted to electric current, because of the manufacturing defects and physical limitations of the PV cells [3]. Nowadays, the best laboratory reported solar energy to electrical power conversion efficiency for mono-Si PV cells is around 26.7% [4]. It means that the remaining unutilized absorbed energy, which does not get dissipated to the surroundings fast enough, just

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Nomenclature:

Abbreviations

ARC	anti-reflecting coating
EVA	ethylene vinyl acetate
FD	finite difference
FE	finite element
MBE	mean bias error
NOCT	nominal operating conditions temperature (°C)
POA	plane-of-array
PTC	PVUSA test conditions
PV	photovoltaic
PV/T	photovoltaic thermal
r	correlation factor
RMSE	root mean square error (°C)
Si	silicon
STC	standard test conditions
STF	solar test facility at Doha, Qatar

Symbols

$[A]$	square matrix (of size $N \times N$) in the system of linear equations for FD algebraic equations
$A_{PV,cells}$	total top area of the all PV cells (m^2)
$A_{PV,panel}$	total top area of the entire PV panel (m^2)
$a\&b$	empirically derived PV coefficients by King et al. [8]
α	elevation angle of the sun (°)
α_{fg}	effective absorptivity of front glass
$\widetilde{\alpha}_{PV}$	effective absorptance of the cells
$\{B\}$	vector comprising of known quantities (of size $N \times 1$) in the system of linear equations for FD algebraic equations
β	tilt angle of the PV panel with respect to the horizontal ground (°)
β_{ref}	temperature coefficient of the PV cells (K^{-1})
C	specific heat capacity of each specific layer (J/kg K)
Δ	Del (change in a variable)
$\dot{E}_{in}$	rate of total heat energy entering the control volume of FD grid (J)
$\dot{E}_g$	rate of total internal heat generation in the control volume of FD grid (J)
$\dot{E}_{st}$	rate of total stored energy in the control volume of FD grid (J)
$\varepsilon_{surface}$	emissivity of front/back surfaces
$F_{surface-sink}$	geometric view factor from front/back surfaces towards sky or ground sinks
G_b	beam irradiation (W/m^2)
G_d	diffused irradiation (W/m^2)
G_{HOR}	total global horizontal irradiation (W/m^2)
G_{NOCT}	total incident POA irradiation at NOCT (= 800 W/m^2)
G_{POA}	total incident POA irradiation (W/m^2)
h_{conv}	total heat transfer coefficient (W/m^2 K)
$h_{conv,forced}$	forced heat transfer coefficient (W/m^2 K)
$h_{conv,free}$	free heat transfer coefficient (W/m^2 K)
$h_{rad,surface-sink}$	radiative heat transfer coefficient from front/back surfaces to sky or ground temperature sinks (W/m^2 K)
h_w	wind speed dependent empirical heat transfer coefficient (W/m^2 K)
K	extinction constant of the front glass (m^{-1})
k	thermal conductivity of each specific layer (W/m K)
k_{air}	thermal conductivity of air (W/m K)
L	front glass thickness (m)
$L_{PV,panel}$	characteristic (longest) length of the PV panel
m	node number in the FD grid
N	total number of nodes in the FD grid from top to bottom
Nu_{forced}	Nusselt number for forced convection
Nu_{free}	Nusselt number for free convection
η_{PV}	instantaneous electrical efficiency of the PV panel (%)
$\eta_{PV,Tref}$	reference electrical efficiency of the PV panel (%)
P	instantaneous electrical power produced by the PV panel (W)
p	represents time t in FD heat balance equations
$p+1$	represents time $t+\Delta t$ in FD heat balance equations
ρ	density of each specific layer (kg/m^3)
Q_{fg}	internal heat generation in front glass (W/m^3)
Q_{pv}	internal heat generation in PV cells (W/m^3)
σ	Stefan-Boltzmann constant ($kg\, s^{-3} K^{-4}$)
S	total absorbed irradiation (W/m^2)
T	temperature (K)
ΔT	temperature difference between the front and back side of the PV panel (K)
$\{T\}$	vector comprising of unknown temperature variables (of size $N \times 1$) in the system of linear equations for FD algebraic equations
T_{amb}	ambient temperature (K)
$T_{amb,NOCT}$	ambient temperature at NOCT (= 20 °C)
$T_{backsheet}$	temperature of PV panel's back sheet (K)
T_{cell}	temperature of the PV cells (K)
T_{Gr}	ground temperature (K)
T_{high}	temperature at which the PV panel's efficiency becomes zero (K)
T_m	nodal temperature (K) in the FD grid (K)
T_{NOCT}	rated NOCT temperature of the PV panel (°C)
T_{ref}	reference temperature (K)
T_{Sky}	sky temperature (K)
T_{sink}	sink (sky or ground) temperature for the PV panel (K)
$T_{surface}$	surface temperature (K)
t	time (s)
Δt	change in time (s)
th	thickness of each specific layer (m)
$th_{PV,panel}$	total thickness of the PV panel from top to bottom
τ	transmittivity of the front glass for beam component
θ_b	angle of incidence for beam radiation
θ_r	angle of refraction for the incident beam irradiation (θ_b)
U_0 & U_1	PV cell technology dependent parameters defined by Koehl et al. [13]
U_{PV}	overall heat exchange coefficient defined by Mattei et al. [14]
V_{fg}	total volume of the front glass (m^3)
$V_{PV,cells}$	total volume of all PV cells (m^3)
V_w	wind speed (m/s)
x_m	coordinate number of each node in the FD grid
Δx	distance between adjacent nodes in the FD grid (m)

builds up inside the PV panel and consequently increases the temperature of the entire panel. However, it is a well-documented fact that the temperature rise decreases the electrical efficiency of the PV cells [5]. This temperature build-up depends on the type of PV cells as well as the ambient conditions.

It is because of this increased temperature that the PV panels mostly produce less electrical power than their rated capacity, even at higher levels of solar irradiation. For power predicting electrical models (e.g. in [6,7]), accurate estimate of working temperature of the PV cells is required, which is usually achieved through a thermal model. Thermal models of different nature can be found in the literature. They can be simple empirical correlations, derived analytical equations and detailed