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Real-time simulation model development of single crystalline photovoltaic panels using fast computation methods

Jee-Hoon Jung [a,*], Shehab Ahmed [b,1]

[a] Power Conversion & Control Research Center, HVDC Research Division, Korea Electrotechnology Research Institute, 12 Bulmosan-ro, Seongsan-gu, Changwon-si, Gyeongsangnam-do 642-120, Republic of Korea
[b] Department of Electrical & Computer Engineering, Texas A&M University at Qatar, PO Box 23874, Education City, Doha, Qatar

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Abstract

Real-time simulation and rapid prototyping of power electronics, critical loads, and control systems have prompted recent interest in accurate electrical terminal models of photovoltaic (PV) panels and array systems. Advancement in computing technologies, such as parallel computing and digital signal processing techniques for real-time simulations have allowed the prototyping of novel apparatus to be investigated in a virtual system under a wide range of realistic conditions repeatedly, safely, and economically. This paper accesses numerical iteration methods, selects appropriate techniques, and combines them with model construction methods well suited for boosting the computational speed of an electro-thermal dynamic model of a PV panel. The target computational engine is a parallel processor based real-time simulator to be used in a power hardware-in-the-loop (PHIL) application. Significant improvements resulting from the proposed modeling approach in computation time and numerical convergence speed are verified using experimental results for the target PV panel using Opal-RT's RT-Lab Matlab/Simulink based real-time engineering simulator.

Keywords: Photovoltaic panel; Single crystalline; Dynamic model; Real-time simulation; Fast computation; Numerical iteration

1. Introduction

Photovoltaic (PV) systems do not emit any pollutants during electricity generation, and can therefore be installed in densely populated residential or commercial areas with no health risks (Toledo et al., 2010). In addition, single crystalline silicon cells are the most common in the PV industry (Willeke, 2008). A single crystalline silicon cell has a uniform molecular structure. Compared to noncrystalline materials, its high uniformity results in higher energy conversion efficiency. The higher the energy conversion efficiency of the PV panel, the more electricity it generates for a given area of exposure to sunlight. The conversion efficiency for single-silicon cell commercial modules ranges from 15% to 20%. Moreover, not only are they energy efficient, but single-silicon cell modules are highly reliable in outdoor environments typical of PV system installations.

Significant research effort has been put into the development of elaborate terminal voltage models of PV systems. PV arrays, controllers, battery storage, inverters, and load models have been proposed to predict the performance of a PV system under various load current profiles (Sukamongkol et al., 2002; Joshi et al., 2009; Eltawil and Zhao, 2010). Several PV models were reviewed to select a

* Corresponding author. Tel.: +82 10 9811 3251; fax: +82 55 280 1490.
E-mail addresses: jeehoonjung@keri.re.kr, jung.jeehoon@gmail.com (J.-H. Jung), shehab.ahmed@qatar.tamu.edu (S. Ahmed).
[1] Tel.: +974 4423 0259; fax: +974 4423 0011.

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Nomenclature

α_{ab}	absorbability of cell surface (0.77 for silicon)
α_{sc}	temperature coefficient for short circuit current (AK^{-1})
ρ_{lx}	density of layer x (kg m^{-3})
σ	Stefan–Boltzmann constant (5.67×10^{-8} Wm^{-2} K^{-4})
a_i	coefficient for air mass modifier
a_{ref}	ideality factor parameter at STC (eV)
A_{lx}	area of layer x (m^2)
b_i	coefficient for incidence angle modifier
C_{lx}	total heat capacity of layer x (JK^{-1})
$C_{p,lx}$	specific heat capacity of layer x (Jkg^{-1} K^{-1})
d_{lx}	depth of layer x (m)
E_g	energy bandgap (eV)
$E_{g,T_{\text{ref}}}$	energy bandgap at reference temperature (1.121 for silicon) (eV)
G	total irradiance on horizontal surface (Wm^{-2})
G_b	beam component of total irradiance on horizontal surface (Wm^{-2})
G_d	diffuse component of total irradiance on horizontal surface (Wm^{-2})
G_{ref}	irradiance at STC (1000) (Wm^{-2})
I_d	diode forward current (A)
I_L	photo light current (A)
I_o	output current of a PV panel (A)
I_r	diode reverse saturation current (A)
$I_{L,\text{ref}}$	photo light current at STC (A)
$I_{mp,\text{ref}}$	current of maximum power point at STC (A)
I_{mp}	current at maximum power point (A)
$I_{r,\text{ref}}$	diode reverse saturation current at STC (A)
$I_{sc,\text{ref}}$	Short circuit current at STC (A)
k	Boltzmann's constant (1.381×10^{-23} JK^{-1})
k_{lx}	thermal conductivity of layer x (Wm^{-1} K^{-1})
M	air mass modifier
M_{ref}	air mass modifier at STC
n_I	ideality factor
N_s	number of cells in series
$n_{I,\text{ref}}$	ideality factor at STC
P_{gen}	generated electrical power from PV panel (W)
q	electron charge (1.602×10^{-19} C)
Q_{conv}	heat flow generated by convection (W)
Q_{ele}	heat generated by electric loss (W)
Q_{lx}	heat flow from layer x (W)
Q_{sw}	heat flow generated by short wave radiation (W)
R_s	lumped series resistance (Ω)
$R_{p,\text{ref}}$	lumped shunt resistance at STC (Ω)
R_p	lumped shunt resistance (Ω)
$R_{s,\text{ref}}$	lumped series resistance at STC (Ω)
S	total incident irradiance (Wm^{-2})
$S_{ab,\text{ref}}$	total absorbed irradiance at STC (Wm^{-2})
S_{ab}	total absorbed irradiance (Wm^{-2})
T_c	cell temperature (K)
T_{amb}	ambient temperature of PV panel (K)
$T_{c,\text{ref}}$	cell temperature at STC (K)
T_{lx}	borderline Temperature of layer x (K)
U_{lx}	overall heat transfer coefficient for layer x
V_o	output voltage of a PV cell (V)
$V_{mp,\text{ref}}$	voltage of maximum power point at STC (V)
V_{mp}	voltage at maximum power point (V)
$V_{oc,\text{ref}}$	open circuit voltage at STC (V)
$V_{T,\text{ref}}$	thermal voltage at STC (V)
STC	standard test condition: irradiance 1000 Wm^{-2}, AM1.5 spectrum, module temperature 25 °C

suitable model for PV devices by considering adjustment errors at specific data points (de Blas et al., 2002). The reverse bias model was adopted to explain the breakdown effect of a PV cell with temperature (Alonso-Garcia and Ruiz, 2006). A detailed terminal voltage model of a PV cell was proposed using the five-parameter model (Soto et al., 2006; Chenni et al., 2007). Experimental verification was achieved using mono-crystalline PV modules to evaluate four- and five-parameter models (Celik and Acikgoz, 2007).

The strong correlation between module temperature and electrical terminal characteristics has also prompted significant research into thermal modeling of PV panels. Temperature dependant models of a PV panel were suggested in Sukamongkol et al. (2002), Jones and Underwood (2001), considering heat radiation, heat convection, and power generation. Two dimensional thermal flows for PV panel plates were considered in PV panel models (Ali, 2005; Dehra, 2009). Experimental verification depicting the dependence of panel output power and efficiency on temperature was achieved using commercial PV modules (Tina and Abate, 2008; Gil-Arias and Ortiz-Rivera, 2008; Skoplaki and Palyvos, 2009).

Advancements in computing technology have allowed the prototyping of novel apparatus to be investigated in a virtual system under a wide range of realistic conditions repeatedly, safely, and economically. A five-parameter PV panel is widely used in literature for PV system energy prediction (Soto et al., 2006). However, the model's solution is transcendental in nature; hence it is not possible to solve it for voltage in terms of current explicitly and *vice versa* (Hornbeck, 1975). To solve the four- or five-parameter model of a PV panel, numerical methods are required because the terminal voltage or current equation has no exact analytical solution. Using a Lambert W-function, the solution of the PV model can be expressed as an exact solution (Jain et al., 2004; Jain et al., 2006). In addition, parameter mismatch and model error were investigated (Petrone et al., 2007) and optimum load conditions of PV