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New analytical approach for modelling effects of temperature and irradiance on physical parameters of photovoltaic solar module

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ABSTRACT

In this paper, a new exact method has been presented to extract physical parameters of single diode equivalent circuit modelling a photovoltaic solar module operating at standard test conditions. The method uses four equations, three are linking output current to output voltage in short-circuit, maximum power and open-circuit points, the fourth equation is the first derivative of output power with regard to output voltage in maximal power point. According to this method, we used ideality factor η as variation parameter and solved the system of four nonlinear equations to get values of photocurrent I_{ph}, saturation current I_s, series resistance R_s and shunt conductance G_p. We then varied ideality factor to minimize root mean square error and maximize the coefficient of determination. We assumed series resistance and shunt conductance constant, and derived analytical expressions describing effects of module temperature and incident solar irradiance on photocurrent, on ideality factor and also on saturation current using both temperature coefficients available as well as irradiance coefficients extracted from module datasheet. We considered standard test conditions numerical values of physical parameters as initial conditions and determined numerical models for $I_{ph}(T,G)$, $\eta(T,G)$ and $I_s(T,G)$. We also derived new mathematical expressions of maximum power point voltage and module efficiency. We tested these numerical models as well as mathematical expressions derived on Kyocera KC200GT and Shell SQ80 photovoltaic solar modules under different conditions of module temperature and incident solar irradiance and found good agreement between experimental and forecasted characteristics.

1. Introduction

At the beginning of the third millennium, the use of energy all around the world was equal to 1634 kg of oil equivalent per capita. In 2014, it reached 1919 kg of oil equivalent per capita [1,2]. Today, the world's population needs of energy has been growing rapidly. In the past, energy consumption was mainly due to industrialized high-income per capita countries in America, Western Europe and to Japan. Now, the increase in energy use is also due to emerging low- and middle-income per capita economies such as India, China, Brazil, Russia, Nigeria, South Africa etc…[3]. Unfortunately, world fossil origin fuel reserves like oil, bituminous rocks, coal and natural gas are non-renewable energies. In some cases, their overexploitation led to exhaustion posing the problem of energy security. Meantime, significant natural gas and oil new findings throughout the world are limited and world fossil energy reserves increase slowly.

Moreover, excessive use of fossil origin energy resources results in an increase of levels of greenhouse gas emissions such as nitrogen dioxide, carbon dioxide, and methane in the atmosphere. As a consequence, Earth is facing crucial challenges related to environment such as depletion of natural resources, increase of greenhouse gas emissions rates in the atmosphere leading to global warming and air pollution. This implies a climate change with dramatic involvements like ice melting in the poles, rising of sea levels, acute droughts and disastrous floods.

Today, sustainable and renewable energies are earth alternative solution to meet the increasing need for energy while preserving the environment. Sun is the first source of renewable energy, with its three components (i) Concentrated Solar Power, (ii) Solar Thermal (iii) and Solar Photovoltaic, it is a hope for the entire humanity.

In the present work, we are interested in solar photovoltaic issue. More precisely, we focus on components converting incident solar irradiance into electric current like solar cells, panels and arrays. Until today, the issue of model physical parameters extraction continues to attract attention. In a recent series of papers Xiankun Gao et al. used a Lambert W-function based exact representation (LBER) and traditional

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Nomenclature

STC	Standard Test Conditions (T = 25 °C, G = 1000 Wm^{-2})
SNF	Statistical Nonlinear Fit Method
IFV	Ideality Factor Variation Method
RMSE	Root Mean Square Error
R^2	coefficient of determination
NOCT	Nominal Operating Cell Temperature
η	diode ideality factor
η_{STC}	diode ideality factor at STC
W(x)	Lambert W function
$\Delta\eta$	increment of ideality factor
N_s	number of cells mounted in series
AM	Air Mass
k_B	Boltzmann constant (1.38·10^{-23} J/K)
q	elementary electron charge (1.60217646 10^{-19} C)
I	module output current (A)
I_{ph}	module photocurrent (A)
I_s	module saturation current (A)
I_{sc}	module short-circuit current (A)
$I_{sc}(STC)$	module short-circuit current at STC (A)
$I_{sc}(G_{STC})$	module short-circuit current at reference irradiance (A)
$I_{sc}(T_{STC})$	module short-circuit current at reference temperature (A)
I_{mpp}	module maximum power point current (A)
$I_{mpp}(STC)$	module maximum power point current at STC (A)
$I_{mpp}(G_{STC})$	module maximum power point current at reference irradiance (A)
$I_{measured}$	experimental output current (A)
$I_{calculated}$	calculated output current (A)
ε_{abs}	absolute error of current (A)
V	module output voltage (V)
V_{th}	thermal agitation voltage (V)
V_{oc}	module open-circuit voltage (V)
$V_{oc}(STC)$	module open-circuit voltage at STC (V)
$V_{oc}(G_{STC})$	module open-circuit voltage at reference irradiance (V)
$V_{oc}(T_{STC})$	module open-circuit voltage at reference temperature (V)
V_{mpp}	module maximum power point voltage (V)
$V_{mpp}(T_{STC})$	module maximum power point voltage at reference temperature (V)
$V_{oc}(NOCT)$	module open-circuit voltage at NOCT (V)
P	module output power (W)
P_{mpp}	module maximum power or module peak power (W)
R_s	module series resistance (Ω)
R_{s0}	module dynamic resistance at open-circuit voltage (Ω)
R_{sh}	module shunt resistance (Ω)
G_p	module shunt conductance (Ω^{-1})
G_{p0}	module dynamic conductance at short-circuit current (Ω^{-1})
T	module temperature (K)
T_{STC}	module reference temperature (298.15 K)
T_{NOCT}	NOCT temperature (K)
T_{INI}	initial value of module temperature (K)
T_{FIN}	final value of module temperature (K)
ΔT	increment of temperature (K)
G	incident solar irradiance (W/m^2)
G_{STC}	reference incident solar irradiance (1000 W/m^2)
G_{NOCT}	NOCT incident solar irradiance (800 W/m^2)
G_{INI}	initial value of incident irradiance (W/m^2)
G_{FIN}	final value of incident irradiance (W/m^2)
ΔG	increment of incident irradiance (W/m^2)
K_i	temperature coefficient of short-circuit current (A/°C)
K_v	temperature coefficient of open-circuit voltage (V/°C)
$K_{i,mpp}$	temperature coefficient of maximum power point current (A/°C)
$K_{v,mpp}$	temperature coefficient of maximum power point voltage (V/°C)
α_i	irradiance coefficient of short-circuit current (A/W m^{-2})
$\alpha_{i,mpp}$	irradiance coefficient of maximum power point current (A/W m^{-2})
$\alpha_{v,linear}$	linear irradiance coefficient of open-circuit voltage (V/W m^{-2})
$\alpha_{v,quadratic}$ ($\alpha_{v,q}$)	linear irradiance coefficient of open-circuit voltage for quadratic model (V/W m^{-2})
$\beta_{v,quadratic}$ ($\beta_{v,q}$)	quadratic irradiance coefficient of open-circuit voltage (VW^{-2} m^{-4})
D	diffusion coefficient of saturation current at STC (A K^{-3})
$E_g(T)$	semiconductor band-gap energy at a given temperature (eV)
$E_g(T_{STC})$	semiconductor band-gap energy at reference temperature (eV)
$E_g(0)$	semiconductor band gap energy at T = 0 K (eV)
	first Varshni coefficient (eV K^{-1})
β	second Varshni coefficient (K)
S_{Module}	module front area or top area (m^2)

double diode model (DDM) of solar cells to extract DDM physical parameters [4]. They compared fitness and parameters extraction performance via a series of algorithms using both representations and found that results coming from LBER are always more accurate than those from DDM. Later, Xiankun Gao et al. proposed an improved shuffled complex evolution (ISCE) algorithm for parameters extraction of different PV models, including single diode model, double diode model and single diode solar module model [5]. They compared ISCE algorithm with some state-of-the-art algorithms from the literature and found that the proposed ISCE algorithm always exhibits the highest computational efficiency to get the most accurate parameter values among all compared algorithms. Finally, Xiankun Gao et al. presented a comparison of Special Trans function based single diode model (SBSDM), Lambert W function based single diode model (LBSDM) and exponential-type single diode model (SDM) using modified Nelder-Mead simplex (MNMS) algorithm [6]. The comparison results revealed that the time computational efficiency of SBSDM is inferior to SDM but superior to LBSDM and SBSDM always achieves superior accuracy and convergence speed than LBSDM and SDM.

The topic dealing with effects of module temperature and incident irradiance on model physical parameters stills a promising issue. Effectively, module temperature as well as incident solar irradiance change throughout a day. Temperature and irradiance are at their maximum at solar midday and at their minimum at sunrise and sunset. Therefore, it is crucial to anticipate variation of model physical parameters throughout a sunny, cloudy or rainy day in order to foresee changes of current-voltage characteristics, and to guess accurately peak power coordinates, optimal load resistance value, fill factor and efficiency of photovoltaic solar module operating under real conditions. In this way, Barukcic et al used an evolutionary algorithm to estimate current-voltage characteristics, maximum power point coordinates, open-circuit voltage, as well as short-circuit current at any temperature and irradiance [7,8]. Adel A. Elbaset et al. used Newton Raphson and Runge–Kutta Merson iteration methods to generate non-linear current-voltage and power-voltage characteristics [9,10]. They tested their procedure on three different modules based on multi-crystalline, amorphous and thin film solar cell technologies and found that their model show an excellent agreement with respect to manufacturer's datasheet and to results coming from other works in the literature.

The topics we are dealing with in this work, are the extraction of model physical parameters of photovoltaic solar module equivalent electronic circuit as well as the study of the effects of module