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Novel seven-parameter model for photovoltaic modules

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ABSTRACT

Modeling of PV systems is very crucial for embedded power system applications and maximum power point tracking. This paper presents a proposed two-diode model for PV module with its seven-parameter capable of analytically describing *I–V* characteristic for each generic condition of operative temperature and solar irradiance. Determination of seven-parameter plays an important role in a PV module fabrication, design and an accurate prediction of PV system performance at low and high irradiance levels. Seven-parameter is estimated using the Newton Raphson method with the aid of initial values which are derived from basic equations of the model and manufacturing data sheet at standard test conditions. Newton Raphson and Runge–Kutta Merson iteration methods are proposed to verify the capability of the model to fit non-linear output characteristics of *I–V* and *P–V*. The procedures were tested on three different modules of multi-crystalline, amorphous, and thin film solar cell PV manufacturers. Results are compared with the points taken directly from the manufacturer's published curves and the proposed results of other authors. The results of proposed model show an excellent agreement with respect to data sheet and other works.

1. Introduction

Nowadays, PV systems become popular and have many applications in modern life which extend from remote area energy services up to grid utilities. The rapid growth of PV system utilizations is due to its availability everywhere which avoids transmission costs and losses, free, abundant and pollution free. Silicon is the basic material required for the production of solar cells based crystalline or thin film technology. Most of the world market is based on crystalline silicon and the sharing of thin film technology based solar cells was starting from fewer years. It is expected to gain a much larger share of the PV market in the future due to lower production costs as comparing to the more material-intensive crystalline technology. The available three different types of PV modules in the market are Crystalline Silicon, Amorphous Silicon and other Thin Film technology PV Panels. Crystalline Silicon modules are the oldest, most reliable and highly efficient PV modules in the market today[1–5].

The PV system performance depends on many physical parameters like site latitude of PV systems, typical weather conditions, the panel tilt and its azimuth angles, the air and surfaces surrounding temperatures, the obstruction and shadow, and finally electrical loads. Although PV systems have many advantageous, but unfortunately, they suffered from low efficiency that is hardly reached up to 20% for module, changing the amount of electricity with weather changing, and non-linearity of their electrical characteristics. Therefore, the modeling of PV system has attracted attention of the researchers to facilitate modeling performance of the PV based power systems [6–10].

PV cell is the main building block of PV module which consists of many PV cells connected in series/ parallel manner for each module. Normally PV module represents the main unit of electrical solar power generation system. The non-linear output characteristics of *I–V* and *P–V*, for such PV modules, depend mainly on solar insolation and cell temperature. As PV module has non-linear characteristics, it is important to model a PV module for the purposes of making accurate design, operation and discovering the causes of degradation of PV performance. A complete electrical approach of a PV system simulation should fulfill the following criteria [11–12]:

1- It should be simple, fast and accurate to predict the *I–V* and *P–V* characteristic curves.
2- It should be developed and has a comprehensive tool.
3- It should be validated as PV system design including MPPT control and power converter.

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Nomenclature

PV	Photovoltaic
I	output or load current of PV model (A)
V	output or load voltage of PV model (V)
I_{ph}	photo current (A)
I_{mp}	current at the maximum power point (A)
I_{sc}	short circuit current of the module (A)
V_{mp}	voltage at the maximum power point (V)
V_{oc}	open circuit voltage of the module (V)
I_s	cell reverse saturation current (A)
$I_{s\text{ at STC}}$	cell reverse saturation current (A) at standard test conditions (STC)
I_{s1}	diffusion saturated current of D1 (A)
I_{s2}	recombination saturated current of D2 (A)
$I_{s1\text{ at STC}}$	diffusion saturated current of D1 (A) at standard test conditions (STC)
$I_{s2\text{ at STC}}$	recombination saturated current of D2 (A) at standard test conditions (STC)
Q	electron charge (1.6×10^{-19} C)
K	Boltzmann constant (1.38×10^{-23}J/kelvin)
T	cell working temperature (kelvin)
a	diode ideality factor for single diode model
a_1,a_2	diode ideality factors for two-diode model
R_s	series resistance (Ω)
R_{so}	reciprocal slope of the I–V characteristic for $V=V_{oc}$ and $I=0$ (Ω)
R_{sh}	shunt resistance (Ω)
R_{sho}	reciprocal slope of the I–V characteristic for $V=0$ and $I=I_{sc}$ (Ω)
V_T	thermal voltage (V) (V_T=KT/q)
G	solar irradiance (kW/m^2)
G_{STC}	solar irradiance at standard test conditions (STC) [G_{STC}=1 kW/m^2]
$I_{ph\text{ at STC}}$	photo current at standard test conditions (A)
K_i	short circuit current coefficient (A/C°)
T_{STC}	temperature of PV cell at standard test conditions
E_g	band gap energy of semiconductor (eV)
N_s	number of series cells
N_p	number of parallel cells
X	array of seven-parameter
M	fractional number $0<M<1$

Ref. [1] presents a new five-parameter for single diode model that is capable of analytically describing the I–V characteristic of a PV module for each generic condition of operative temperature and solar irradiance. The parameters of the equivalent electrical circuit are extracted by solving a system equations based on data commonly issued by manufacturers in standard test conditions with a trial and error process. Ref. [2] Operating parameters of the Amorphous Silicon (a-Si) photovoltaic module were studied as a function of solar irradiation and atmospheric conditions using current–voltage curves taken for a year on PV outdoor Test Site. Single diode model has been proposed to explain the current–voltage curves of thin film solar cells and modules. Correlations between internal parameters, namely R_s, R_{sh}, I, I_s, ideality factor of module, solar irradiation and atmospheric data has been investigated. Ref. [3] summarizes the electrical and thermal characterizations of thin film PV modules based on amorphous triple junctions (3 J: a-Si) and Copper Indium Selenide (CIS) thin film solar cells. Ref. [7] presents an efficient and accurate single diode model for the estimation of the solar cell parameters using the hybrid genetic algorithm and Nelder–Mead simplex search method from the given voltage–current data. Ref. [8] presents implementation of a generalized PV model based on single diode model using Matlab/Simulink software package, which can be representative of PV cell, module, and array for easy use on simulation platform. Ref. [9] a Matlab-based modeling and simulation scheme suitable for studying the I–V and P–V characteristics of a PV array under a non-uniform insolation due to partial shading has been studied. Ref. [10] proposes an improved model approach to single diode PV model by the hybrid genetic algorithm particle swarm optimization technique. Several computational methods with different techniques were proposed for single diode model [13–22], but in most of these techniques, new additional coefficients were introduced into the model equations causing increasing their computational burdens. Wolf [23] represented the PV cell with an equivalent electric circuit that composed of different lumped components, each one made up of a current generator, a diode and a series resistance. Wolf modeling has been simplified to a single-diode model as shown in Fig. 1. The I–V characteristic equation of a single diode model is given as [1,8,19,27]

$$I=I_{ph}-I_s\left\{\exp\left(q\left(\frac{V+IR_s}{a.K.T}\right)\right)-1\right\}-\left(\frac{V+IR_s}{R_{sh}}\right) \tag{1}$$

The photo current, I_{ph} is a function of temperature and solar insolation is given as follows [8,17]:

$$I_{ph}=(G/G_{STC})[I_{ph\text{ at STC}}+K_i(T-T_{STC})] \tag{2}$$

The single diode saturation current as function of working PV temperature is given as follows [8,17]:

$$I_s=I_{s\text{ at STC}}\left(\frac{T}{T_{STC}}\right)^3\exp\left[\left(\frac{q.E_g}{a.\,K}\right)\left(\frac{1}{T_{STC}}-\frac{1}{T}\right)\right] \tag{3}$$

Although single diode is more popular for PV modeling, but it has many disadvantageous such as [24]:

1- It exhibits high deficiencies when studying PV performance with temperature variations.
2- It neglects recombination loss in PV cell depletion region.
3- Deterioration its accuracy at low irradiance levels especially at open circuit V_{oc}.

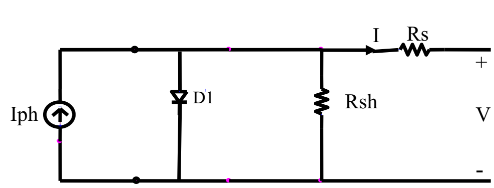

Fig. 1. Single diode circuit model of PV cell.