AN IMPROVED HYBRID COMPUTATIONAL METHOD FOR THE TWO-DIODE MODEL IN PHOTOVOLTAIC SIMULATION APPLICATIONS

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To my beloved parents, sister and brother
for their enduring love, motivation and support

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ABSTRACT

For a successful realization of the solar photovoltaic (PV) system, the availability of an accurate, fast and reliable computer simulation tool is indispensable. The most crucial component that directly affects the accuracy of the simulator is the model of the PV cell (or module) itself. As an improvement over its single diode counterpart, the two-diode model exhibits superior accuracy for wide variations of irradiance and temperature. However, due to the limited number of information that are available on the manufacturer datasheet, the determination of all seven parameters of the two-diode model is very challenging. This thesis proposes a new hybrid method to improve the computation of the two-diode model. Unlike other existing hybrid methods, the proposed method retains the computation speed of the analytical approach and utilizes only standard datasheet information. Furthermore, it does not employ any simplification in the computation of the model parameters. Four parameters are determined analytically, while the remaining three are optimized by using differential evolution. The speed is improved significantly because the parameters are optimized only once, at standard test condition, while the values at other conditions are computed using the analytical equations. Additionally, a procedure to guide the initial conditions of the Newton-Raphson iteration is introduced. For validation, the algorithm is implemented in MATLAB software and its performance is compared with other established computational methods for mono-crystalline, poly-crystalline and thin film modules. When evaluated against the experimental data extracted from the datasheets, the mean absolute error is improved by 10 times, while the speed is increased by approximately three times. The standard deviation of the decision parameters over 100 independent runs is less than 0.1, which suggests that the optimization process is very consistent. Lastly, to prove the applicability of the proposed method in simulation applications, the algorithm is implemented into an in-house PV array simulator and its performance is validated using field data obtained from a PV monitoring station.

ABSTRAK

Untuk merealisasikan kejayaan sistem solar fotovolta (PV), ketersediaan alat simulasi komputer yang tepat, pantas dan boleh dipercayai adalah sangat diperlukan. Komponen terpenting yang mempengaruhi ketepatan simulator secara langsung ialah model sel PV (atau modul) itu sendiri. Sebagai penambahbaikan ke atas pasangan diod tunggalnya, model dua-diod mempamerkan ketepatan yang unggul untuk pelbagai variasi sinaran dan suhu. Walau bagaimanapun, disebabkan bilangan maklumat yang terhad pada lembaran data pengeluar, penentuan kesemua tujuh parameter model dua-diod adalah sangat mencabar. Kajian ini mencadangkan kaedah hibrid baru untuk memperbaiki pengiraan model dua-diod. Tidak seperti kaedah hibrid sedia ada yang lain, kaedah yang dicadangkan ini mengekalkan kelajuan pengiraan pendekatan analitik dan hanya menggunakan maklumat pada lembaran data pengeluar yang piawai. Selain itu, ia tidak menggunakan sebarang penyederhanaan dalam pengiraan parameter model. Empat parameter ditentukan secara analitik, manakala baki tiga dioptimumkan dengan menggunakan evolusi kebezaan. Kelajuan meningkat dengan ketara kerana parameter dioptimumkan sekali sahaja, pada keadaan ujian piawai, manakala nilai pada keadaan lain dikira menggunakan persamaan analitik. Di samping itu, satu prosedur untuk membimbing keadaan awal lelaran Newton-Raphson diperkenalkan. Untuk pengesahan, algoritma ini dilaksanakan dalam perisian MATLAB dan prestasinya dibandingkan dengan kaedah pengiraan lain yang ditetapkan untuk modul filem mono-kristal, poli-kristal dan filem nipis. Apabila dinilai terhadap data eksperimen yang diekstrak daripada lembaran data, min ralat mutlak bertambah baik dengan 10 kali ganda, manakala kelajuan meningkat sebanyak kira-kira tiga kali ganda. Sisihan piawai parameter keputusan lebih 100 larian bebas adalah kurang daripada 0.1, dimana menunjukkan bahawa proses pengoptimuman sangat konsisten. Akhir sekali, untuk membuktikan kebolehgunaan kaedah yang dicadangkan dalam aplikasi simulasi, algoritma ini dilaksanakan ke dalam simulator PV talasusunan dalaman dan prestasinya disahkan dengan menggunakan data lapangan yang diperolehi daripada sebuah stesen permantauan PV.

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LIST OF ABBREVIATIONS

ABSO	-	Artificial Bee Swarm Optimization
AIS	-	Artificial Immune System
AIT	-	Austrian Institute Of Technology
AM1.5	-	Air mass 1.5 spectrum
ANN	-	Artificial Neural Network
BFA	-	Bacterial Foraging Algorithm
BIPV	-	Building-Integrated PV
BMO	-	Bird Mating Optimizer
CS	-	Cuckoo Search
DE	-	Differential Evolution
EA	-	Evolutionary Algorithm
FL	-	Fuzzy Logic
GA	-	Genetic Algorithm
GUI	-	Graphical user interface
HIL	-	Hardware-in-the-loop
HS	-	Harmony Search
MAE	-	Mean absolute error
MOSFET	-	Metal Oxide Semiconductor Field Effect Transistor
MPP	-	Maximum power point
MPPT	-	Maximum power point tracker
NRM	-	Newton Raphson Method
PS	-	Pattern Search Optimization
PSO	-	Particle Swarm Optimization
PV	-	Photovoltaic
PVAS	-	Photovoltaic array simulator
RAID	-	Redundant Array of Independent Disks
RAM	-	Random Access Memory

RES	-	Renewable energy sources
SA	-	Simulated Annealing
SNL	-	Sandia National Laboratory
STC	-	Standard Test Conditions
STD	-	Standard Deviation
UI	-	User interface

LIST OF SYMBOLS

a, a_1, a_2 - Diode ideality factor
$a_{i,STC}$ - Diode ideality factor at STC
CR - Crossover rate
D - Total number of parameters
E_g - Material band gap energy
$E_{g,STC}$ - Material band gap energy at STC
F - Mutation factor
FF - Fill factor
G - Irradiance
G_i - In-plane irradiance
G_{STC} - Irradiance at STC
Gen - Generation index
Gen_{max} - Maximum number of generations
I_D, I_{D1}, I_{D2} - Diode current
I_{DC_FIELD} - DC current measured at the field setup
I_{DC_HIL} - DC current measured at HIL
I_{MPP} - Maximum power point current
$I_{MPP,STC}$ - Maximum power point current at STC
I_o, I_{o1}, I_{o2} - Saturation current
$I_{o1\_array}, I_{o2\_array}$ - Saturation current of PV array model
I_{PV} - Photocurrent
I_{PV_array} - Photocurrent of PV array model
I_{SC} - Short circuit current
$I_{SC,STC}$ - Short circuit current at STC
$I–V$ - Current-voltage
J - Fitness value

k - Boltzmann’s constant

K_i - Temperature coefficient of the short circuit current

K_{ip} - Temperature coefficient of the maximum power point current

K_v - Temperature coefficient of the open circuit voltage

K_{vp} - Temperature coefficient of the maximum power point voltage

M - Ratio between the saturation currents in order of magnitude

N_{mods} - Number of PV modules in series

NP - Population size

Ns - Number of PV cells in series

N_{string} - Number of PV string in parallel

P_{DC_FIELD} - DC power measured at the field setup

P_{DC_HIL} - DC power measured at HIL

P_{MPP} - Maximum power

$P_{MPP,STC}$ - Maximum power at STC

$P\text{–}V$ - Power-voltage

q - Electron charge

R_{cable} - DC cable resistance

r_{cable} - Resistance per unit length

R_p - Shunt resistance

$R_{p,STC}$ - Shunt resistance at STC

R_{p_array} - Shunt resistance of PV array model

R_s - Series resistance

$R_{s,STC}$ - Series resistance at STC

R_{s_array} - Series resistance of PV array model

T - Temperature

T_{amb} - Ambient temperature

T_m - Module temperature

T_{STC} - Temperature at STC

U_i - Donor vector in DE

V_{DC_FIELD} - DC voltage measured at the field setup

V_{DC_HIL}	-	DC voltage measured at HIL
V_{f_bd}	-	Forward voltage drop of the blocking diode
V_i	-	Trial vector in DE
V_{MPP}	-	Maximum power point voltage
$V_{MPP,STC}$	-	Maximum power point voltage at STC
V_{OC}	-	Open circuit voltage
$V_{OC,STC}$	-	Open circuit voltage at STC
V_t	-	Thermal voltage
$V_{t,STC}$	-	Thermal voltage at STC
V_{t_array}	-	Thermal voltage of PV array model
VTR	-	Value-to-reach
x	-	Newton-Raphson approximation
X_i	-	Base vector in DE

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CHAPTER 1

INTRODUCTION

1.1 Overview

The foreseeable depletion of fossil fuels reserves, the increased concerns on the effects of global warming, and the ever-rising global energy demand have positioned mankind in the search of renewable energy sources (RES) that are clean, sustainable and affordable [1, 2]. Among the RES, solar photovoltaic (PV) system has emerged as one of the most promising in the current global energy scenario [3]. It is estimated that, if utilized to the full extent, one-hour of energy received from the sun is sufficient to power the world for a year [4]. Moreover, from the technological viewpoint, solar PV systems are very convenient to install, almost maintenance free, easily scalable, and do not produce greenhouse gases or noise during normal operation. These prospects have encouraged governments around the world to promote this technology by offering attractive initiatives such as generous fed-in tariff schemes, tax-breaks, and capital subsidies [5-7]. Notwithstanding these efforts, PV power is still far from grid-parity, i.e. the point at which the price of PV power per unit is at par with electricity provided by the power utility companies. This is primarily due to the high capital cost and low efficiencies (15 – 20%) of the PV modules [3, 8]. Moreover, in contrast to the conventional energy sources, the energy output of a PV system is highly dependent on the availability of solar irradiance [9].

For these reasons, it is imperative that all available energy that is harvested by the PV modules to be optimally processed. In that regard, the availability of an accurate, fast and reliable computer simulation tool is indispensable to evaluate the performance of the system prior to installation. The simulator can be used for many purposes, for example, 1) to test the behaviour of the maximum power point tracker (MPPT) [10, 11], 2) to estimate the system efficiency [12, 13], and 3) to study the interaction between the power converter and the PV arrays [14, 15]. The first two activities are crucial during the design and development stage of the power converter hardware, while the third is useful for energy yield prediction. The latter is directly related to the investment decision and customer's financing strategies. In addition, the information obtained from simulation can be very valuable to analyse the performance at the system level, i.e. to investigate the characteristics of the PV system under certain (or unusual) meteorological conditions, e.g. partial shading or rapid change of irradiance and temperature.

The most crucial component that directly affects the accuracy of the simulator is the model of the cell (or module) itself. It is always desirable to have a model that closely emulates the behaviour of physical solar cells, i.e. fits the measured current-voltage (I-V) data under all operating conditions. In PV literature, the most widely accepted approach is to utilize the electrical equivalent circuit models. Here, both linear and non-linear electrical elements are used to describe the I-V relationships for any given irradiance (G) and temperature (T). The shape and amplitude of the I-V curve, in turn, are governed by the values of the model parameters, which have to be determined. The complexity of the solution ranges from the most rudimentary ideal single diode model, the single diode R_S-model, the single diode R_P-model, and the two-diode model [16]. Due to their intrinsic simplicity (i.e. fewer parameters), the single-diode models are more popular. However, in recent years, the two-diode version has gained attention owing to its superior accuracy [17, 18]. The improvement is primarily due to the inclusion of an extra diode, which represents the charge recombination process that is neglected in the single-diode models [19]. Notwithstanding the advantage, the two-diode model is more complex and as a consequence the computational burden is increased significantly. The parameters to be determined is seven, compared to only five for the single-diode R_P-model.

Furthermore, due to the presence of two exponential terms and the transcendental nature of the equations, obtaining the solution for these unknown seven parameters is very challenging. These, perhaps explain the limited reported works on the two-diode model.

The values of model parameters are normally determined in two ways: the numerical extraction or the analytical approach. In the numerical extraction, a point-by-point fitting of the computed *I-V* values to the experimental dataset is performed—mainly by certain types of mathematical or optimization algorithms. The evolutionary algorithm (EA) techniques are widely used due to their global search capability and effectiveness in handling non-linear function without requiring gradient information. By defining an objective function, the model parameters are extracted by minimizing the error between the computed values and experimental dataset [20-23]. Despite its accuracy, the approach inherits several drawbacks which makes it impractical to be used as the computational engine for the PV simulator. First, to perform the comparison, it is mandatory that the entire experimental *I-V* dataset of the specific module is available. However, this information is not always provided in the manufacturer datasheets [24]. As a result, the application of the numerical extraction approach is highly situational. Second, due to the point-by-point comparison, the computation process is very time-consuming. This is especially true when a large number of unknown parameters are involved in the optimization [20].

On the other hand, the analytical approach computes the model parameters by solving a system of equations, derived from several key points of the *I-V* curve. These points, namely the short circuit point (I_{SC}, 0), maximum power point (I_{MPP}, V_{MPP}), open circuit point (0, V_{OC}), temperature coefficients for short circuit current (K_i) and open circuit voltage (K_v), are commonly available in the standard datasheet. Therefore, the analytical method is more practical. Furthermore, since there is no requirement to analyze the entire *I-V* curve, the number of iteration is much reduced. This leads to significantly rapid computations, which is an important feature for any simulator. Nonetheless, the analytical methods always rely on various mathematical assumptions and simplifications to solve for the two-diode model [18, 25, 26]. This is inevitable, since the number of equations that can be formulated from the model based on the standard datasheet information are insufficient to determine all the seven parameters. Although these approximations simplify the computation, they tend to result in compromised and at times, unrealistic solutions.

Recently, a new hybrid approach has been proposed to overcome the aforementioned shortcomings. It incorporates both analytical and numerical extraction. The analytical approach is employed to define a system of equations which relates the parameters to several key points on the *I–V* curve and their variations with respect to *G* and *T*. Meanwhile, EA is used to optimize the model parameters based on a suitable objective function. By doing so, the model parameters can be solved simultaneously, without requiring the availability of the *I–V* information. Moreover, since fewer number of assumptions are required, the hybrid methods are, in general, more accurate than the conventional analytical approach [27-30]. With these advantages, it has been applied quite extensively for the computation of the single-diode model. However, up till now there has been very limited works on its two-diode model counterpart. There is an absence of a reliable and sufficiently fast hybrid computational method for the latter.

1.2 Problem Statement

In comparison to its single diode counterpart, the two-diode model is a more realistic representation of the PV cell. The model is known for its superior accuracy in a wide range of operating conditions. However, due to the presence of the seven unknown model parameters and two exponential terms in the model equation, solving for the two-diode model is particularly challenging. The numerical approach, which is based on point-by-point comparison of the *I-V* curves, is time-consuming and requires graphical information that are normally not provided in the datasheet. As a result, it is not practical to be used as the computational engine of a PV simulator. On the other hand, due to the complexity of the two-diode model and the limited number of information available on the datasheet, using the analytical approach often involves numerous assumptions and simplifications which lead to compromised, and sometimes, unrealistic solutions. Therefore, it is crucial to obtain a solution for the two-diode model without the aforementioned shortcomings.

1.3 Objective of Research

In view of the potential of the hybrid modelling approach, the main objective of this research work can be formulated as follows:

(i) To propose, design and implement a fast and reliable hybrid computational method for the two-diode model. The expected outcome is a practical algorithm that is able to accurately estimate the PV module output under any environmental conditions. Furthermore, the proposed method should require only information that are readily available from the standard module datasheet.

(ii) To implement the proposed method as a new PV model option in the Photovoltaic Array Simulator (PVAS). The idea is to prove the applicability of the proposed modelling method as the computational engine of a workable PV simulator. To be more realistic, the results from the simulator are validated by the data from an actual PV system in the field.

1.4 Scope of Research and Limitations

To achieve the objective of the research, the scope of work for this research is defined as follows:

(i) The method is developed to model monocrystalline, polycrystalline, and thin-film PV modules. Other types of modules such as organic and multi-junction are not considered.

(ii) To compute the PV module/array output, all the PV cells are assumed to be identical and work under the same operating conditions.

(iii) To prove the applicability of the proposed method in practical simulation applications, it is implemented as a new PV model option in an existing in-house PV simulator, known as the Photovoltaic Array Simulator (PVAS). Due to software limitations, only series-parallel array configuration is considered. The maximum power that can be emulated by the PVAS is 7 kW, with an open circuit voltage range of 0–800 V and short circuit current range of 0–24 A.

1.5 Research Methodology

The overall flow of the research work that is described in this thesis is as depicted in Figure 1.1. In the initial phase, a comprehensive survey and review of the literature is carried out. The aim is to identify the research gap through an in-depth understanding of the latest development in PV modelling and simulation. Based on the findings, the objectives, scope, and limitations of the research are carefully defined. Next, in accordance to the research objectives, a hybrid computational method for the two-diode model is developed. The performance of the proposed method is evaluated against other well-established computational methods using six PV modules of different technologies (i.e. mono-crystalline, poly-crystalline, and thin film) for a wide range of operating conditions. As input to the computational methods, the specifications of each PV modules are obtained from the manufacturer datasheet. At this stage, any shortcomings of the proposed method are examined and improved. The process is reiterated until satisfactory modelling performance is achieved. Overall, two distinct computational methods are introduced. The first method, termed “proposed method A” in the thesis, describes an initial attempt to solve for the two-diode model based on the conventional hybrid approach. In the second method, “proposed method B”, several critical improvements are made to eliminate the drawbacks found in the first. Subsequently, to prove the applicability of proposed method B in PV simulation applications, it is implemented as a new PV model option in the Photovoltaic Array Simulator (PVAS). The PVAS is configured as a part of the hardware-in-the-loop (HIL) setup which emulates a grid-tied PV system. For validation, the measurement data from the HIL setup is evaluated using a set of field data that is collected from an actual grid-tied PV system installed at Universiti Teknikal Malaysia Melaka (UTeM).

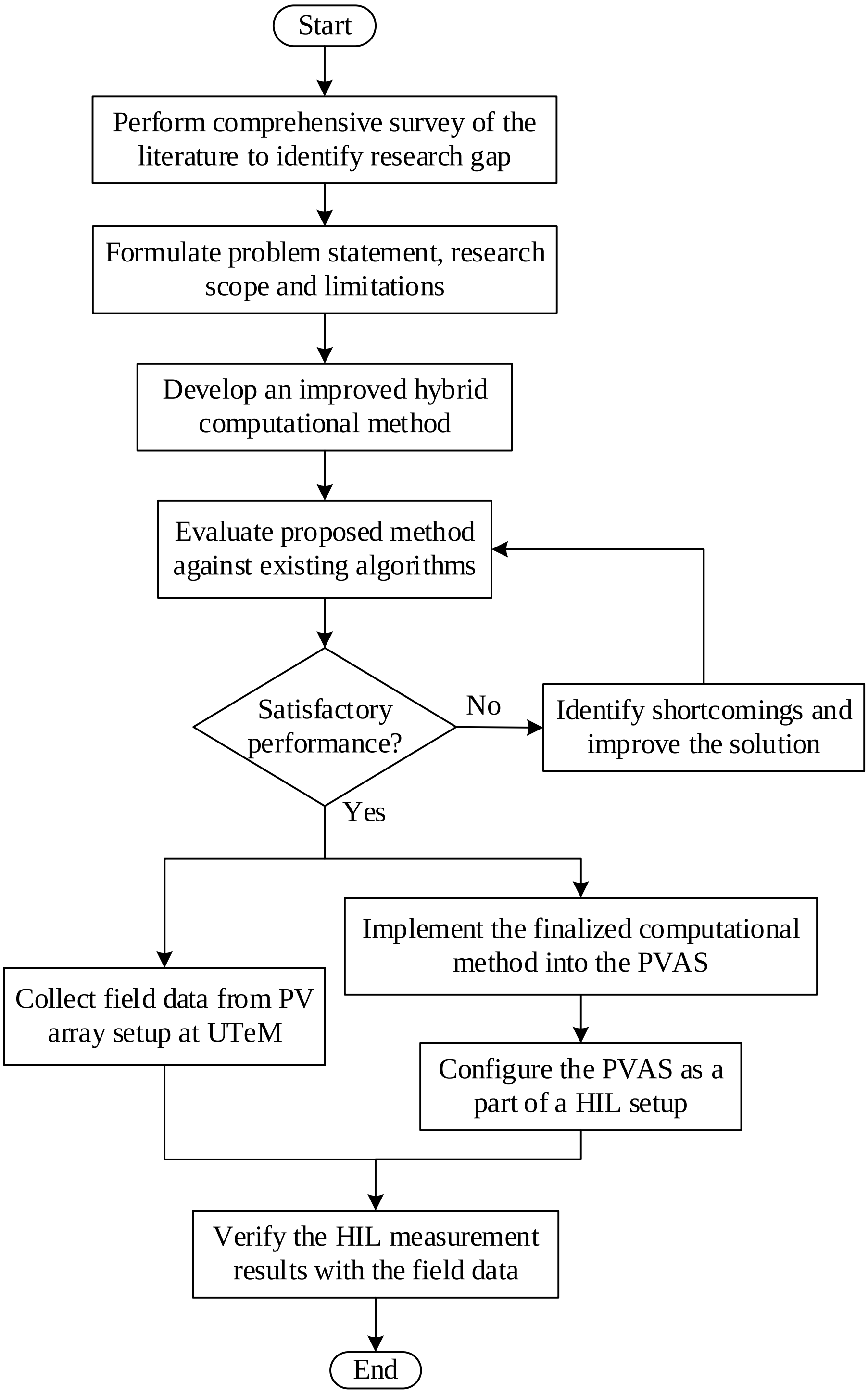

Figure 1.1 Flowchart of research methodology

1.6 Organization of Thesis

This thesis is organized into 5 chapters. The contents of the subsequent chapters are outlined as follows:

Chapter 2 provides a relevant background knowledge and extensive review of the modelling methods that are used in PV simulation. The methods are broadly categorized into various groups, i.e. the analytical approach, the numerical extraction approach, and the hybrid approach. The merits and drawbacks of each approach are discussed and highlighted.

Chapter 3 describes the main contribution of the thesis. It proposes two different hybrid computational methods for the two-diode model. The working principles of the algorithms and the derivation of equations are described in detail. The performances of the proposed methods are compared with other well-established computational methods in terms of accuracy, speed, and consistency. The results are validated by using six modules of different technologies. Based on these assessments, the superior method is selected, and its improvements are justified.

Chapter 4 presents the incorporation of the proposed method in a hardware-in-the-loop (HIL) setup. The idea is to show the applicability of the proposed computational method in a PV simulator. Furthermore, the results from the HIL setup are verified using actual field data. The working principle of PVAS system and the added PV model are described in detail. For validation, the output of the HIL setup is compared with field data measurement from an actual PV string.

Chapter 5 concludes the works undertaken and highlights the contributions of this research. Several suggestions on possible directions of future work are also given.

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