UNIVERSITI PUTRA MALAYSIA

MODELING AND MULTI-OBJECTIVE OPTIMAL SIZING OF STANDALONE PHOTOVOLTAIC SYSTEM BASED ON EVOLUTIONARY ALGORITHMS

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By

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The standalone photovoltaic (SAPV) system is one of the most widely used applications of the PV system. However, the main drawbacks of this system are the high capital investment and low energy efficiency mainly due to the simple PV model and the ineffective sizing method of SAPV system. Therefore, precisely modeling method to determine the unknown parameters of the PV module is essential to give a realistic evaluation for the extracted energy of the PV array. Moreover, optimization of the standalone PV system is necessary to maximum the reliability and minimize the total cost of the system in both urban and rural areas.

The research presented in this thesis is divided into two phases, namely, modeling of the PV module, and optimal sizing of the entire system to obtain reliable and cost-effectiveness SAPV system. Due to the effective attraction-repulsion mechanism of electromagnetic-like (EM) algorithm and reliable exploration and exploitation phases of differential evolution (DE), these two methods were used to determine parameters of the single diode PV model and finding optimal sizing of the SAPV system. Firstly, an improved EM (IEM) algorithm is presented to estimate the five parameters of the single PV-module system. The IEM algorithm uses the attraction-repulsion mechanism to change the positions of solutions towards the optimality. The key to improvement is performed by adding a nonlinear equation to adjust the length of the particle. Moreover, the total force formula is simplified to speed up the exploration for an optimal solution. Six statistical tools are used to show the superiority of the proposed PV model as compared to other models proposed in the literature. Secondly, the modeling method of the proposed PV module is validated by experimental data. In the sizing of the SAPV system, the mutation adaptive DE (MADE) algorithm based multi-objective functions minimizes three constraint objective functions. A new mutation vector inspired by the two-opposite path (2-Opt) algorithm with adaptive

mutation scalar (F) and crossover rate (CR) control parameters were employed to enhance the exploration and exploitation phases of the proposed algorithm. The objective functions are loss of load probability (LLP) and life cycle cost (LCC) and levelized cost of energy (LCE). In the current sizing optimization problem, the three individual objectives are normalized, weighted, and then aggregated by a single function which is minimized to select the optimal configuration of the SAPV system. Moreover, the performance of the SAPV system is carried out based on three types of storage batteries which are lead-acid battery, crown battery, and lithium-ion battery using hourly meteorological data for one year.

Performance results show that the MADE algorithm based on lead-acid battery has a high level of LLP and minimum cost among other types of storage batteries. The LLP value of lead-acid is 0.0019 which describes the availability of the proposed SAPV system. Moreover, the LCC and LCE values are 54895.68 USD, and 1.5803 USD, respectively. Finally, the proposed sizing method is compared with a numerical sizing method to show the accuracy and efficiency of the proposed method. The results of the comparison indicated that the MADE method has an excellent level of accuracy and outperforms the iterative method in terms of CPU-execution time.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Master Sains

PEMODELAN DAN PENSAIZAN OPTIMAL BERBILANG OBJEKTIF SISTEM FOTOVOLTA KENDIRI BERDASARKAN ALGORITMA EVOLUSI

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Sistem fotovolta berdiri sendiri (SAPV) adalah salah satu sistem aplikasi PV yang paling banyak digunakan. Walau bagaimanapun, kelemahan utama sistem ini adalah pelaburan modal yang tinggi dan kecekapan tenaga yang rendah terutamanya disebabkan oleh model PV sederhana dan kaedah ukuran sistem SAPV yang tidak berkesan. Oleh itu, kaedah pemodelan tepat untuk menentukan parameter modul PV yang tidak diketahui adalah penting untuk memberikan penilaian yang realistik untuk tenaga yang diekstrak dari susunatur PV. Lebih-lebih lagi, pengoptimuman sistem PV mandiri diperlukan untuk memaksimumkan kebolehpercayaan dan meminimumkan jumlah kos bagi sistem di kawasan bandar dan luar bandar.

Penyelidikan yang dibentangkan dalam tesis ini terbahagi kepada dua fasa iaitu, pemodelan modul PV, dan ukuran optimum dari keseluruhan sistem untuk mendapatkan sistem SAPV yang dapat dipercayai dan menjimatkan kos. Oleh kerana mekanisme tarikan-tolakan yang berkesan dari algoritma seperti elektromagnetik (EM) dan fasa eksplorasi dan eksploitasi yang boleh dipercayai dari evolusi kebezaan (EK), kedua kaedah ini digunakan untuk menentukan parameter model PV dioda tunggal dan mencari ukuran SAPV yang optimum sistem. Pertama, algoritma EM yang diperbaiki (IEM) dibentangkan untuk menganggarkan lima parameter modul sistem-PV tunggal. Algoritma IEM menggunakan mekanisme tarikan-tolakan untuk mengubah kedudukan penyelesaian ke arah optimum. Kunci penambahbaikan dilakukan dengan menambahkan persamaan tak setara untuk menyesuaikan panjang zarah. Tambahan lagi, formula kekuatan keseluruhan dipermudah bagi mempercepatkan penerokaan untuk mendapatkan penyelesaian yang optimum. Enam alat statistik digunakan untuk menunjukkan keunggulan model PV yang dicadangkan berbanding dengan model lain yang dicadangkan dalam literatur. Kedua, kaedah pemodelan modul PV yang dicadangkan telah disahkan oleh data ujikaji. Dalam

ukuran sistem SAPV, fungsi multi-objektif berasaskan algoritma mutasi adaptif DE (MADE) meminimumkan tiga fungsi objektif kekangan. Vektor mutasi baru yang diilhamkan oleh algoritma dua-laluan bertentangan (2-Opt) dengan parameter kawalan skalar mutasi adaptif (F) dan kadar *crossover* (CR) yamg digunakan untuk meningkatkan tahap eksplorasi dan eksploitasi algoritma seperti yang dicadangkan. Fungsi objektif adalah kehilangan kebarangkalian beban (LLP) dan kos kitaran hayat (LCC) dan *levelized* kos tenaga (LCE). Dalam masalah pengoptimuman ukuran sekarang, tiga objektif individu telah dinormalisasi, ditimbang, dan kemudian digabungkan oleh satu fungsi yang diminimumkan untuk memilih konfigurasi optimum sistem SAPV. Selain itu, prestasi sistem SAPV dijalankan berdasarkan tiga jenis bateri simpanan iaitu bateri asid-plumbum, bateri *crown* dan bateri *lithium-ion* menggunakan data meteorologi setiap jam selama setahun.

Keputusam prestasi menunjukkan bahawa algoritma MADE berdasarkan pada bateri asid-plumbum mempunyai tahap LLP yang tinggi dan kos yang minimum berbanding kalangan jenis bateri simpanan yang lain. Nilai LLP asid-plumbum adalah 0.0019 yang menerangkan ketersediaan sistem SAPV yang dicadangkan. Tambahan pula, nilai LCC dan LCE masing-masing adalah 54895.68 USD, dan 1.5803 USD. Kaedah ukuran yang dicadangkan akhirnya dibandingkan dengan kaedah ukuran berangka untuk menunjukkan ketepatan dan kecekapan kaedah yang dicadangkan. Hasil perbandingan menunjukkan bahawa kaedah MADE memiliki tingkat ketepatan yang sangat baik dan mengungguli kaedah berulang dari segi masa pelaksanaan CPU.

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LIST OF SYMBOLS

d	Ideality factor of diode
I	Current conducted by the PV module (A)
I_o	Saturation current of the diode (A)
V_e	Experimental voltage conducted by the PV module (V)
I_e	Experimental current conducted by the PV module (A)
I_P	Proposed current of the PV module (A)
I_{Ph}	Photocurrent (A)
N	Length of dataset
R_p	Shunt resistance (Ω)
K_B	constant of Boltzmann (1.380603e-23 J/K)
R_s	Series resistance (Ω)
V	Voltage conducted by PV module (V)
R^2	Determination coefficient
V_T	Diode thermal voltage (V)
d_i	Deviation of RMSE
ξ_{avg}	Average error
$\%rerr$	Relative percentage error
M	Number of initial particles
MAXITER	Maximum number of local iterations
LISTER	Maximum number of local search iterations
δ	Local search operator
$S1 - S7$	Operational condition (solar radiation and cell temperature)
F^i	Total force calculation
q	Charge particle
F	Total force vector
n	Total dimension of the particle
N	Length of dataset
λ	Randomly distributed between 0 and 1
V_T	Diode thermal voltage (V)
V	Voltage conducted by PV module (V)

X	Population set
X^i	Vector whose components limited between L_k or U_k bound
L_k	Lower bound of EM-like algorithm
U_k	Upper bound of EM-like algorithm
R_p	Shunt resistance (Ω)
R_s	Series resistance (Ω)
R^2	Determination coefficient
$f(X^{best})$	Objective value of each particle
ϵ	Switching control parameters ($\epsilon \in [0,1]$)
η_{PV}	Efficiency of PV array
A	Area of PV array (m^2)
G_T	Hourly solar radiation falls on the PV array surface (W/m^2).
PV_{INV_R}	Rated power of the inverter
C_1 to C_3	Coefficients of model of the inverter
C_{bat}	Capacity of the battery
AD	Autonomy days
DOD	Depth of discharge
ηb	Efficiency of the battery
ηinv	Efficiency of the inverter
SOC	State of charge of the battery
E_{bat_min}	Minimum energy of the battery
SOC_{max}	Maximum state of charge
IC_{cap}	Initial cost of the SAPV system
C_{rep}	Value of replacement
$C_{O\&M}$	Value of operation and maintenance
C_{PV}	Total capacity (W)
$C_{Unit,PV}$	Unit cost of PV array ($/W)
C_{Batt}	Total capacity of the battery (W)
$C_{Unit,Batt}$	Unit cost of the battery ($/W)
C_{Bidi}	Total capacity of the inverter (W)

$C_{Unit,Bidi}$	Unit cost of inverter ($/W)
C_{CH}	Total capacity of converter
$C_{Unit,CH}$	Unit cost of converter ($/W)
C_O	Total constant cost with civil work and installation
LP	Lifetime of the SAPV system (year)
IR	Interest rate
FR	Inflation rate
S	Set of population
X_i	Target vector
G	Generation index
$rand$	Random number in the range [0,1] interval
$\hat{X}_i^G$	Mutant vector
$X_\propto^G$	Based vector
F	Scaling control parameter within [0.5,1]
$y_{j,i}^G$	Trail vector
CR	Crossover control parameter [0.5,1]
x	Vector of decision variable
k	Number of individual objectives
w_i	Weighting coefficient
$f_i^{min}(x)$	Minimum bounds of the ith individual objective function
$f_i^{max}(x)$	maximum bounds of the ith individual objective function

LIST OF ABBREVIATIONS

AE	Absolute error
AC	Alternative current
Amor-Si	Amorphous-crystalline silicon
AI	Artificial intelligence
AGM	Absorbent glass mat
ABC	Artificial bee colony
AEC	Annual electrical cost
ANN	Artificial neural network
BSA	Backtracking search algorithm
BFA	Bacterial foraging algorithm
CdTe	cadmium telluride
CIS	copper-indium-diselenide
CIGS	copper-indium-gallium-diselenide
CC	Cycle charge
CFNN	Cascaded forward neural network
DC	Direct current
DD	Double diode
DE	Differential evolution
EA	Evolutionary algorithm
ESP	Energy shortfall probability
EA	Evolutionary algorithm
EQE	External quantum efficiency
ELM	Extreme learning machines
EPBT	Energy payback time
FF	Fill factor
FFNN	Feed forward neural network
FPA	Flower pollination algorithm
FL	Fuzzy logic
GA	Genetic algorithm
HOMER	Hybrid optimization model for electric renewable

HS	Harmony search
IAE	Individual absolute error
IEM	Improved electromagnetic-like algorithm
ITAE	Integral time absolute error
LCOE	Levelized cost of energy
LCC	Life cycle cost
LCE	Levelized cost of energy
LLP	Loss of load probability
LPSP	Loss of power supply probability
LPS	Loss of power supply
LL	Loss of load
LOLH	Loss of load hours
LM	Levenberg Marquardt
LMSE	Least mean square error
MADE	Mutation adaptive differential evolution
MBE	Mean bias error
MTM	Markov transition matrices
MPP	Maximum power point
Mono-Si	Mono-crystalline silicon
Multi-Si	Multi-crystalline silicon
μc-Si	micromoph-silicon
MSPCOA	Mutative-scale parallel chaos optimization algorithm
MOO	Multiple objective optimization
MCDM	Multi-criteria decision making
NM	Nelder-mead
NR	Newton Raphson
NPC	Net present cost
NFFEs	number of fitness evaluations
PS	Pattern search
PISM	Physical model simulator
PSO	Particle swarm optimization
QN	Quasi-Newton

RACF	Residual autocorrelation function
RBFNN	Radial basis function neural network
RETScreen	Clean energy management software
REFF	Residual error of fitness function
RMSE	Root mean square error
SA	Simulated annealing
SAM	System advisor model
SAPV	Standalone photovoltaic system
SSE	Sum square error
SSA	Salp swarm algorithm
SOC	State of charge
SD	Single diode
STC	Standard test condition
TLBO	Teaching learning-based optimization
TS	Test statistical
TRANSYS	Transient system simulation model
TR	Trust-Region
VOLL	Value of lost load

CHAPTER 1

INTRODUCTION

1.1 Research background

The electrical energy demand is rapidly increasing due to the growth in population. Along time ago, conventional energy sources such as crude oil, natural gas, and coal are considered the main sources for supplying electricity. However, these conventional energy resources have negative impacts on the environment, which substantially contribute to global warming [1]. Moreover, the conventional energy resources are going to depletion as well as the oil prices are fluctuating. These reasons stimulate many researchers in the world to focus on clean and friendly environment energy sources such as photovoltaic systems, wind turbines, and fuel cells. The development of these technologies gives a good opportunity to increase efficiency and reduces system costs. In the meanwhile, the deployment of new capacity storage techniques leads to a boost in battery storages growth in 2016 by (150%) [2]. As a result of that, researchers cooperate with governments and companies to improve the requirements of renewable energy and decrease CO_2 emission. Furthermore, energy technology perspectives are expected to increase all share of the electricity of the energy demand across all sectors from 18% to 26% by 2060 [2]. Stern [3] has mentioned that the hazards of climate change can be mitigated if the greenhouse gas (GHG) levels in the atmosphere are limited between 450 and 550 ppm-CO_2. In general, RESs are suffering from two key limitations which are the variability and low availability. These reasons result in low capacity utilization with a high capital cost of the system and intermittent energy sources such as solar radiation, wind, biomass, etc.

Solar energy is one of the promising emerging technology, sustainable, and eco-friendly energy sources [4]. The standalone PV (SAPV) system is an attractive and effective source of electricity in both the remote and resident areas [5]. Furthermore, the SAPV system is a clean, environmentally friendly, and secure energy source. Moreover, the long lifetime of the PV system and low (replacement and maintenance) of subsystems carried out the governments and researchers to spend more concerns on the SAPV system [6].

1.2 Problem statement

An accurate model and design method give more value to increasing SAPV system reliability [7]. Standalone PV systems have been designed and conducted by many research works in rural and remote areas, but they remain serious problems and need for improving [8]. Low energy conversion and high initial cost are the main obstacles to the spread of SAPV systems [9].

The parameters of the equivalent electric circuit of the PV system directly affect on the output power and I-V characteristic curve [10]. Thus, the PV module's parameters take essential impacts on modeling and designing a SAPV system which can influence the availability of the system [11]. The methods were utilized for modeling a PV array in the SAPV systems are inaccurate and simple [12]. Several conventional methods have been employed to estimate the parameters of PV modules such as numerical, analytical, and artificial neural networks. However, evolutionary methods (EMs) have been proven their ability in extraction the parameters of the PV module in terms of efficiency, fast convergences, reducing the time of execution. The values of the parameters and I-V characteristics curve are determined under different weather conditions [13]. Consequently, inefficient modeling of the PV system can lead to undesirable performance and design of the SAPV system which means that the system will be not only unreliable but also costly [14].

Another challenge is the current sizing methods of a SAPV system. The intuitive method is simple and imprecise, which is not taking into consideration the relationship between the components of the subsystem and using the average monthly meteorological data [15]. Therefore, this method is suitable to give an initial estimation and a rough approximation of a SAPV system [16]. In meanwhile, the numerical method is the most common in the sizing of SAPV system: it uses the meteorological data and electrical load demand to describe the performance of the system over a large set of configurations. However, the numerical method takes very long execution time as it explores all possible configurations of the SAPV system in a search space. Moreover, the numerical method gives a single configuration selected from the search space [8,17]. In the analytical method, the SAPV system's components are calculated by computational mathematical models to describe the reliability of the system. The advantage of analytical methods is the simplicity in sizing calculation while the main obstacle in estimating coefficients of these equations which are local dependent [18, 19]. Several studies have conducted in the sizing of a SAPV system using artificial intelligence methods. These methods can successfully fix the unavailability of the meteorological data because they use a population-based search algorithm to find the optimal solutions. However, the complexity of these methods is in designing the components of a SAPV [20].

Therefore, an appropriate modeling method to identify the unknown parameters of the PV module is necessary to obtain an efficient SAPV model. Optimization of a SAPV system is required to increase system reliability and minimizing the capital cost.

1.3 Objectives

This research study was carried out under to achieve the following specific objectives:

1. To develop an accurate method of parameters extraction of the PV module's model based on improved electromagnetic-like (IEM) algorithm.
2. To optimize the size of the SAPV system using mutation adaptive differential evolution (MADE) algorithm based on multi-objective optimization for various types of storage batteries.
3. To validate the MADE method for sizing of the SAPV system by using numerical method based on techno-economic criteria.

1.4 Significance and contribution of the study

Based on the previous objectives, the significant contributions of this thesis are described in the following:

1. Proposing improved electromagnetic-like (IEM) algorithm to identify the five parameters of the single PV-module system. Six statistical tools are utilized to show the superiority of the proposed model which are root mean square error (RMSE), deviation of RMSE of each solar radiation level (d_i), standard test deviation of RMSE (STD), absolute error (AE), mean bias error (MBE), and test statistic (TS).
2. Proposing mutation adaptive differential evolution (MADE) algorithm using techno-economic criteria for determining optimal sizing of the SAPV system considering three types of storage batteries.
3. Proposing a new flow chart energy management for a SAPV based on a numerical approach considering multi-objective optimization.

1.5 Scope and limitations of work

Nowadays, the global electricity demand is increased due to the rapid developing in the industry, increasing population, and the rising cost of bills [21]. However, most of the rural and remote areas are without electricity. Therefore, this research focuses on providing the right solutions for predetermined problems. The scopes and limitations of this thesis work are:

1. An accurate PV model is obtained by estimating the five parameters of a single PV-module system using improved electromagnetic-like (IEM) algorithm to achieve lower root mean square error (RMSE), lower deviation of RMSE of each solar radiation level (d_i), lower standard test deviation of RMSE (STD), lower absolute error (AE), and lower mean bias error (MBE). The solar

radiation and ambient temperature are obtained as inputs for the proposed model.
2. The MADE algorithm is proposed to optimize the SAPV system size based on techno-economic criteria.
3. A new flowchart for a SAPV system based on a numerical approach to find a set of optimal configurations considering techno-economic perspectives.
4. The IEM algorithm is time-consuming. This phenomenon occurs because exploration is performed for all particles.
5. The proposed MADE algorithm has the main obstacle which is: The results of optimization are strongly dependent on the weights and the individual objectives are represented by a single-objective function.
6. The actual data of load demand are not available in this research. Therefore, the performance of the SAPV system was evaluated by using a typical load demand for one day and then duplicated for one year.

1.6 Thesis outline

This thesis consists of five chapters, where chapter 1 shows the overview of the thesis and contains the introduction, problem statement, objectives, significance, and contribution of the study, and scope.

Chapter 2 outlines the literature review, which contains methods for estimating the parameters of PV modules. Then, the components of the SAPV system are explained. Furthermore, it also includes the mathematical model of the output power prediction of PV mode. In addition to that, the types of methods used for sizing a SAPV system are discussed. Finally, the limitations and challenges of a SAPV system's performance are summarized.

The methodology of this research work is presented in Chapter 3. The proposed improved electromagnetism-like (IEM) model to identify unknown parameters of a single-diode (SD) PV module is explained. The criteria used for evaluation of the accuracy of the proposed IEM model is presented. Furthermore, the proposed mutation adaptive differential evolution (MADE) algorithm using multi-objective optimization to find the optimal configuration of a SAPV system is explained. Loss of load probability (LLP), life cycle cost (LCC), and levelized cost of energy (LCE) are obtained as objectives of the MADE algorithm. Finally, the flow chart energy management of a SAPV system based on the numerical method is presented. A new flow chart energy management based on the numerical approach is proposed and used for validation of the proposed MADE method.

In chapter 4, the results of the proposed methods to extract the five parameters of the PV module's model and prediction of I-V and P-V data curves are presented. The proposed PV modeling model is compared with the different methods available in the literature. The IEM method is verified by using experimental data and the various statistical criteria. The optimization results based on the MADE algorithm are explained. The analysis of the MADE algorithm is performed based on hourly meteorological data for one year. The optimal configurations based on the numerical approach and their relationships with the techno-economic criteria for the sizing of a SAPV system are presented. The results and discussions of findings are explained with figures, and tables in this chapter.

Chapter 5 focuses on the conclusion and shows how the objectives of this study are fulfilled. Finally, research contributions, limitations, and a direction for future work are presented.

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