Faculty of Engineering

OFF-GRID SOLAR PHOTOVOLTAIC (PV) DESIGN BASED ON FUZZY TECHNIQUE FOR ORDER PERFORMANCE BY SIMILARITY TO IDEAL SOLUTION (TOPSIS) APPROACH

Nur Afiqah binti Jahilan

Bachelor of Engineering

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UNIVERSITI MALAYSIA SARAWAK

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NUR AFIQAH BINTI JAHILAN

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ABSTRACT

The primary energy source, fossil fuels are finite and the other alternative energy sources are costly. Due to this, the solar sector is constantly growing worldwide to generate tremendous demand for electrification. PV technology comprises the grid-connected PV systems and off-grid PV systems. Off-grid PV systems generate and distribute electrical energy independently, unlike the grid-connected PV systems. In this project, the modelling of the off-grid PV system is presented via LabVIEW graphical programming. The design process involved studies on the major components associated with the off-grid PV system such as the PV modules, batteries, solar charge controllers, and inverters to meet the load demand. Specifications and sizing of these PV components play a crucial role to prevent the most common issues in PV system design which are the under and oversizing. Thus, an optimum sizing technique is implemented in this project to overcome the said issue. The aforementioned technique is the MCDM method, particularly the fuzzy TOPSIS algorithm. This algorithm is embedded in the PV system to select the best PV components' configuration based on multiple criteria. To add, the multiple criteria being utilized in the algorithm consists of benefit criteria and cost criteria. Precisely, the fuzzy TOPSIS algorithm has selected the best configuration of PV system with financial optimization feature. Moreover, this project also stressed the graphical user interface design for the off-grid PV system. The designed GUI displayed the input and output data of the PV system, assisted the user to enter input values for the required PV parameters, and allowed the user to perform data analysis for the PV system design. To summarize, the off-grid PV system designed in LabVIEW is viable and readily available for future use.

ABSTRAK

Sumber tenaga utama iaitu bahan bakar fosil adalah terbatas dan kos untuk sumber alternatif adalah sangat tinggi. Oleh kerana itu, sektor solar sentiasa berkembang di seluruh dunia untuk menjana permintaan yang besar untuk elektrifikasi. Teknologi PV terdiri daripada sistem PV yang disambungkan ke grid dan sistem PV luar grid. Sistem PV luar grid menjana dan mengedarkan tenaga elektrik secara bebas, tidak seperti sistem PV yang disambungkan ke grid. Dalam projek ini, sistem PV luar grid telah dimodelkan menggunakan pengaturcaraan grafik LabVIEW. Proses reka bentuk melibatkan kajian mengenai komponen utama yang berkaitan dengan sistem PV luar grid seperti modul PV, bateri, pengawal caj, dan penyongsang untuk memenuhi permintaan beban. Spesifikasi dan saiz komponen PV ini memainkan peranan penting untuk mengelakkan isu yang paling sering berlaku dalam reka bentuk sistem PV iaitu saiz yang tidak mencukupi atau berlebihan. Oleh itu, teknik saiz optimum akan difokuskan dalam projek ini untuk mengatasi isu tersebut. Teknik tersebut adalah kaedah MCDM, terutamanya algoritma *fuzzy TOPSIS*. Algoritma ini digunakan di dalam sistem PV untuk memilih konfigurasi komponen PV terbaik berdasarkan pelbagai kriteria. Kriteria yang digunakan oleh algoritma ini ialah kriteria manfaat dan kriteria kos. Lebih tepatnya, algoritma tersebut telah memilih konfigurasi yang terbaik sekaligus mengutamakan aspek kewangan. Selain itu, projek ini juga menekankan reka bentuk antara muka pengguna grafik untuk sistem PV luar grid. GUI memaparkan data input dan output sistem PV, membantu pengguna memasukkan nilai input untuk parameter PV yang diperlukan, dan membolehkan pengguna melakukan analisis data untuk reka bentuk sistem PV. Kesimpulannya, sistem PV luar grid yang direka menggunakan LabVIEW ini adalah berdaya maju dan sedia ada untuk kegunaan di masa hadapan.

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LIST OF SYMBOLS

a_j^-	:	cost criteria
A^-	:	fuzzy negative ideal solution
A^*	:	fuzzy positive ideal solution
A_{dc_cable}	:	CSA of DC cable used (mm^2)
$A_{min\_dc\_cable}$	:	minimum CSA of the cable (mm^2)
αV_{oc}	:	open circuit voltage temperature coefficient (%/deg C)
C_{Ah_batt}	:	battery capacity (Ah)
C_{Ah_req}	:	charge storage capacity required (Ah)
CC_i	:	closeness coefficient
c_j^*	:	benefit criteria
d_i^-	:	distance from each alternative to the FNIS
d_i^*	:	distance from each alternative to the FPIS
$DOD_{max}(\%)$	:	maximum depth of discharge of storage unit
E_{ac}	:	AC daily energy required (Vah)
E_{dc}	:	DC daily demand required (Wh)
E_{req}	:	total energy required
η_{con}	:	efficiency of converter
η_{coul}	:	coulombic efficiency of battery
η_{inv}	:	efficiency of inverter
η_{ss}	:	efficiency of subsystem
f_o	:	oversizing factor
H_{poa}	:	daily irradiation on plane of array (poa) (kWh/m^2)
I_{bat_md}	:	continuous discharge current (A)
I_{bat_tsd}	:	surge demand current (A)
$I_{blocking\_diode}$	:	minimum blocking diode current (A)
I_{bypass_diode}	:	minimum bypass diode current (A)
$I_{cc_{nom}}$	:	nominal charge controller DC current (A)
I_{dc}	:	maximum operating current in the cable (=$I_{mp_{stc}}$)(A)
I_{dc_ms}	:	DC main switch current
I_{load}	:	continuous discharge current (A)
I_{min_array}	:	minimum array current (A)
I_{min_string}	:	minimum string current (A)
I_{mp_stc}	:	current at maximum power (A)
I_{sc_stc}	:	short circuit current at STC (A)

I_{trip}	:	fuse tripping current (A)
k_{dir}	:	soiling deration factor (decimal)
k_{mm_p}	:	derating factor due to module power mismatch
k_{mp_imp}	:	current tolerance (decimal)
k_{tem_p}	:	power deration factor due to temperature
k_{sto}	:	correction factor of storage unit
L_{dc_cable}	:	length of the longest string cable (m)
$Loss$	:	loss in the cable (0 to 0.03) (decimal)
N_{MPPT_req}	:	number of MPPT required (minimum)
N_p	:	number of parallel connection
N_{p_batt}	:	number of batteries in parallel
N_{P_max}	:	maximum number of PV module in parallel (per charge controller)
N_{PWM_req}	:	number of standard PWM required
N_{P_PV}	:	number of PV module in parallel connection (PWM)
N_{tot_PV}	:	total number of PV module
N_s	:	number of series connection
N_{s_batt}	:	number of batteries in series
N_{s_max}	:	maximum number of PV module in series (per charge controller)
N_{s_PV}	:	number of PV module in series connection (PWM)
P_{dc}	:	power loss in DC cable (W)
P_{mp_stc}	:	maximum power at STC (W)
P_{nom_cc}	:	maximum power of charge controller (W)
$\%Power\ loss$	:	percentage of power loss
$\%V_{drop\_dc}$	:	percentage of voltage drop in DC cable
$\tilde{R}$	:	normalized fuzzy decision matrix
r_{ij}	:	normalized fuzzy decision matrix
ρ	:	resistivity of the cable
T_{aut}	:	number of autonomy days
$T_{cell_{min}}$	:	minimum temperature of PV cell (deg C)
T_{disch}	:	discharge rate
T_{stc}	:	PV standard temperature (deg C)
$V_{blocking\_diode}$	:	minimum blocking diode voltage (V)
V_{bypass_diode}	:	minimum bypass diode voltage (V)
V_{dc_ms}	:	DC main switch voltage (V)
V_{drop_dc}	:	voltage drop in DC cable (V)
V_{fuse}	:	minimum fuse voltage (V)
V_{max_cc}	:	maximum PV array open circuit voltage (V)
$V_{mp\_min\ \_string}$	:	minimum voltage at maximum power (V)

V_{mp_stc}	:	voltage at maximum power (V)
V_{oc_stc}	:	open circuit voltage (V)
V_{PV_std}	:	PV standard voltage (V)
$\tilde{V}$	:	weighted normalized fuzzy decision matrix
$\tilde{v}_{ij}$	:	weighted normalized fuzzy decision matrix for each criterion
V_{nom_batt}	:	nominal battery voltage (V)
V_{sys}	:	system's voltage (V)
$\tilde{x}_{ij}$	:	fuzzy decision matrix
$\widetilde{w}_j$	:	weightage for each criterion

LIST OF ABBREVIATIONS

AC	:	Alternating Current
AGM	:	Absorbent Glass Mat
AHP	:	Analytic Hierarchy Process
ANN	:	Artificial Neural Network
BOS	:	Balance of System
CSA	:	Cross-Sectional Area
DC	:	Direct Current
FiT	:	Feed-In Tariffs
FL	:	Fuzzy Logic
FNIS	:	Fuzzy Negative Ideal Solution
FPIS	:	Fuzzy Positive Ideal Solution
GA	:	Genetic Algorithm
GoM	:	Government of Malaysia
GUI	:	Graphical User Interface
HTFs	:	Heat Transfer Fluids
LabVIEW	:	Laboratory Virtual Instrument Engineering Workbench
MCDM	:	Multi Criteria Decision Making
MECM	:	Ministry of Energy, Communications and Multimedia
MPPT	:	Maximum Power Point Tracker
NI	:	National Instruments
NIS	:	Negative Ideal Solution
NOCT	:	Nominal Operating Cell Temperature
PIS	:	Positive Ideal Solution
PV	:	Photovoltaic
PWM	:	Pulse Width Modulation
RE	:	Renewable Energy
RTL	:	Resource to Load Ratio
STC	:	Standard Test Condition
TB	:	Tabu Search
TMD	:	Total Maximum Demand
TOPSIS	:	Technique for Order Performance by Similarity to Ideal Solution
TSD	:	Total Surge Demand
VI	:	Virtual Instrument
VIKOR	:	*Visekriterijumska Optimizacija I Kompromisno Resenje*

CHAPTER 1

INTRODUCTION

1.1 Project Background

Fossil fuel-based power plants generated the majority of energy in 2013, accounting for 67.2% of total global electricity generation which resulting in pollution [1]. The limited supply and rising expense of fossil fuels, alongside the environmental consequences have prompted a worldwide growth in awareness of renewable energy supplies, particularly in the recent decade [2, 3]. REN21 reported that by the end of 2019, the installed renewable energy capacity was adequate to generate 27.3% of worldwide power output [4]. Renewable energy, particularly solar power generation utilising PV technology has risen in popularity due to the low maintenance, minimal amounts of carbon emission and energy savings potential [5-7].

As solar PV becomes the most cost-effective alternative for electricity generation, demand for this source of energy as well as the location of installation are significantly increased throughout the years [5]. Solar PV systems are divided into two categories which are the off-grid PV systems and grid-connected PV systems [6, 7]. The off-grid PV system generate and distribute the solar power independently, while the operation of grid-connected PV systems is dependent on the main utility grid. The off-grid PV system appear to be the best alternative to generate electricity due to the ubiquity and long-term viability [8, 9]. Off-grid PV systems are projected to minimise carbon dioxide emissions, building costs, and the danger of blackouts due to natural catastrophes [10]. The dispersion and intensity of solar radiation are two important elements that influence the efficiency of the solar PV sector [11]. These two elements significantly vary across the nations as depicted in Figure 1.1. In comparison to other countries, Asian countries have the greatest potential for receiving solar radiation due to the longer sunshine duration throughout the year.

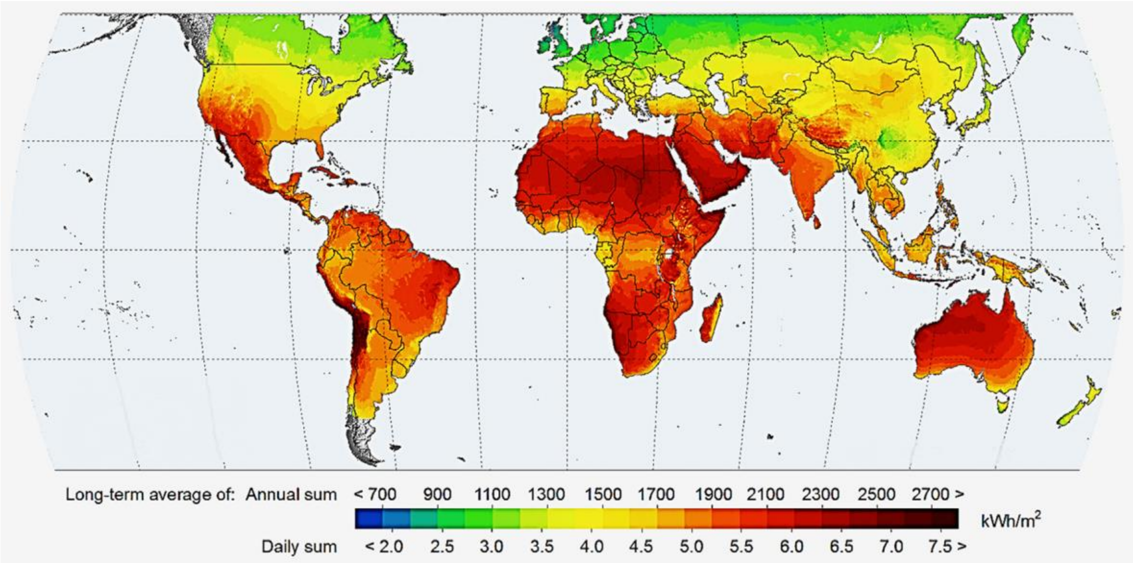

Figure 1.1: Global irradiation [11].

The design and development of PV systems require a detailed analysis to produce a reliable and effective system. This can be achieved by considering the components needed to design the PV system such as the PV modules, inverters, solar charge controllers, load demand, and battery capacity. The specifications of these components highly influenced the performance and overall cost of the PV systems. Moreover, the other important aspects that need to be considered when designing the PV systems are the solar irradiation at the installation point, the maximum demand, power loss within the system due to the mismatch between the components, and component sizing.

In this project, the software used to design the PV system is LabVIEW graphical programming. LabVIEW consists of two main parts which are the block diagram and the front panel. The PV system is programmed in the block diagram to model the overall system and perform calculations for the needed parameters. Meanwhile, the graphical user interface designed in the front panel will be used by the user to choose and key in input data for their components and display the calculated values of all parameters obtained from the block diagram where the results can be examined thoroughly. Selection of the best PV components' configuration is carried out with the integrated Multi Criteria Decision Matrix (MCDM) technique where it evaluates the best configuration based on multiple criteria.

1.2 Problem Statement

Due to the rapid growth of current technology, the utilization of RE sources for electrifications becomes financially practical [12]. Off-grid solar PV systems have been hailed as promising and fast-developing RE sources, particularly in rural area. It is due to the high reliability, wide availability and free of noise [7]. However, the major drawbacks of the off-grid PV systems are the poor energy conversion, large capital costs, and improper subsystem sizing. These drawbacks can be overcome when the PV system is designed and modelled with the consideration of several factors. These factors include the specification of PV components, optimum sizing technique, technical and economical parameters, and the selection of the best PV configuration [13-15]. This project aims to model the off-grid PV system in LabVIEW where the factors inducing the drawbacks are minimized.

The optimum sizing technique is one of the factors that potentially induced the drawbacks of off-grid PV system. With that, it is deemed important to consider various aspects so that the optimum size of PV system can be achieved. In PV system design, selecting the best PV configuration requires complex decision-making. The process becomes complex due to the ambiguity, vagueness, and subjectivity of human judgements [13]. Given these complexities, the fuzzy set theory is utilized to tackle the complicated energy system evaluation and consensus challenges when language variables and phrases are used for decision-making [14]. Therefore, the fuzzy TOPSIS algorithm is incorporated in LabVIEW software at the end of the design process to aid in achieving the optimum sizing of PV system. This is due to its capability in selecting the best PV configuration based on MCDM technique with financial optimization feature.

Moreover, the accuracy of data for all PV components is crucial as it can affect the final design of PV system. It is important to yield a precise data for all PV components as the required parameters are dependent on each other. Thus, the graphical user interface is designed in the front panel of LabVIEW. The GUI assists the user to perform a comprehensive data analysis for the PV system from the initial design stage until the configuration selection of PV components.

1.3 Objectives

The completion of this paper is mainly focusing on computer visualization where a graphical programming software, LabVIEW is used to simulate the concept and design of the off-grid solar PV system. Moreover, an optimization feature will be embedded into the solar PV system through the incorporation of mathematical modeling for the fuzzy TOPSIS algorithm. The objectives of this project are listed as follows.

- To model solar PV system design via programming.
- To optimize solar PV system design with financial optimization feature using fuzzy TOPSIS algorithm.
- To create a graphical user interface for solar PV system design programming.

1.4 Project Scope

In this project, the main element in modelling a solar PV system comprises the design and implementation of graphical programming emphasizing the financial optimization feature. The modelling involves research on the off-grid solar PV system and the associated PV components. The aim of this project is to optimize the sizing of the PV system whilst minimizing the financial aspect. Precisely, LabVIEW software is used to model the off-grid solar PV system. Then, the optimization feature is executed by incorporating fuzzy TOPSIS algorithm in LabVIEW where the mathematical modelling of this algorithm is coded in MATLAB. The proposed methodology offers a streamlined design process to produce an effective design of the PV system and the optimization feature provide the selection of the best PV configuration from several available options. Then, benchmarking is executed to investigate the viability of the software and algorithm used in this project.

1.5 Thesis Outline

This paper is specifically organized into five chapters. Chapter 1 describes the introduction of the project including a brief description of solar PV, annual installation, and global growth. Chapter 1 also encompasses the problem statement, project goals, the scope of the research, as well as the predicted outcomes from the implemented methodology.

Chapter 2 elucidates a comprehensive summary of implementing the solar PV system. This chapter further reviews the theoretical and significant elements from the previous research to accomplish the project objectives.

Chapter 3 demonstrates the methodology being utilized to execute the project. The process of designing the solar PV system as well as the reconstruction of mathematical modeling was executed by the LabVIEW graphical programming. Then, the expected outcome of the graphical interface of the programming is discussed for better comprehension.

Chapter 4 discusses the outcome of the designed project where the simulation of the solar PV system was validated based on real data. Further analysis was conducted to ensure the accuracy and functionality of the system.

Chapter 5 concludes the research with a succinct summary and recommendation for future works.

Chapter 2

LITERATURE REVIEW

2.1 Introduction

Designing a solar PV system requires thorough research in every aspect that contributes to the advantages as well as minimizing the disadvantages. Solar PV system is not widely implemented a few decades ago since they were expensive to manufacture, and their applications had not yet been established. This chapter stresses the components needed to establish an efficient approach to design the solar PV system. Moreover, this chapter entails the previous designs and methodology proposed by other researchers to improve comprehension and to assist in the design phase.

2.2 Solar Irradiation

Solar irradiation quantifies the energy per unit area of incoming solar radiation on a surface. Solar radiation is known as the power received over time ($\mathrm{J/m^2}$ or $\mathrm{Wh/m^2}$). The quantity of energy generated by a PV system is affected by solar radiation and the ambient temperature of the PV array. PV systems directly convert solar radiation into electric energy via the photovoltaic effect, therefore their output rises as the solar radiation incidence on their surface rises. A study from 2010 claimed that Malaysia has an annual average daily solar irradiation of 4.21–5.56 $\mathrm{kWh/m^2}$ and a sunlight duration of more than 2,200 hours per year [15]. According to the Ministry of Energy, Communications and Multimedia (MECM), the advantageous geographical location of Malaysia being in the equator has sustained a tremendous solar irradiation with an average of 4.5 $\mathrm{kWh/m^2}$ daily, sunny duration of around 10 hours and a typical ambient temperature ranging from 27°C to 33°C [16, 17]. From [17], several studies are discussed where solar irradiation in both East and West Malaysia are obtained. From the study, it was discovered that the Northern part of Peninsular Malaysia has the greatest potential for solar energy utilisation since it receives the most monthly solar radiation as compared to East Malaysia. However, it has been shown that some regions in East Malaysia have the potential to use solar energy systems since these regions are more exposed to radiation from May to November, and the lowest from December to January. According to the Kuching Weather Station, Kuching, Sarawak is said to have 15.44 $\mathrm{MJ/m^2}$ (= 4.29 $\mathrm{kWh/m^2}$) of daily global solar irradiation and 1470 $\mathrm{kWh/m^2}$ of yearly average solar irradiation. Moreover, the fluctuations of solar irradiation and air temperature at Kuantan Airport over the course of a month are shown in Figure 2.1 where SolarGis was used to get historical values of the concern parameters [18]. Due to the varied amount of solar radiation throughout the year, the amount of energy generated by the solar plant varies as well.

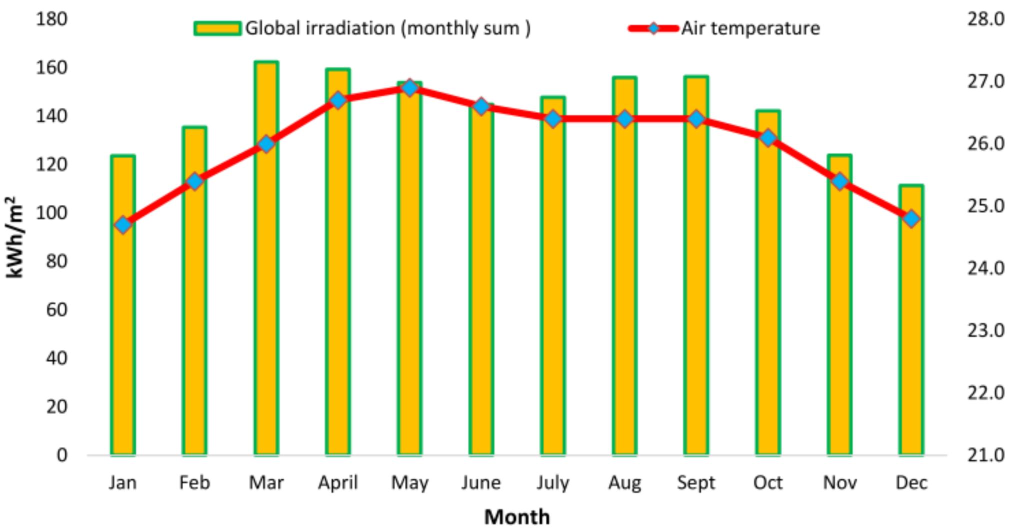

Figure 2.1: Fluctuations of solar irradiation and air temperature [18].

2.3 General Principle of Photovoltaic Systems

Solar PV transforms sunlight into electrical energy. PV technology allows for the generation of power and its distribution throughout the country. Solar PV systems are divided into two categories which are off-grid connected systems (standalone PV systems) and grid-connected systems. The classification is depending on their component configuration, functional and operational needs, and linkages to other power sources and loads.