THE MATHEMATICAL MODEL OF PHOTOVOLTAIC ARRAY IN MATLAB/SIMULINK

NURLIYANA BINTI RADZALI

BACHELOR OF ELECTRICAL ENGINEERING WITH HONOURS
UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2019

THE MATHEMATICAL MODEL OF PHOTOVOLTAIC ARRAY IN MATLAB/SIMULINK

NURLIYANA BINTI RADZALI

A report submitted
in partial fulfillment of the requirements for the degree of
Bachelor of Electrical Engineering with Honours

Faculty of Electrical Engineering

UNIVERSITI TEKNIKAL MALAYSIA MELAKA

2019

DECLARATION

I declare that this thesis entitled "THE MATHEMATICAL MODEL OF PHOTOVOLTAIC ARRAY IN MATLAB/SIMULINK is the result of my own research except as cited in the references. The thesis has not been accepted for any degree and is not concurrently submitted in candidature of any other degree.

Signature :

Name : NURLIYANA BINTI RADZALI

Date :

APPROVAL

I hereby declare that I have checked this report entitled "THE MATHEMATICAL MODEL OF PHOTOVOLTAIC ARRAY IN MATLAB/SIMULINK" and in my opinion, this thesis it complies the partial fulfillment for awarding the award of the degree of Bachelor of Electrical Engineering with Honours

Signature : ----------

Supervisor Name : ----------

Date : ----------

DEDICATIONS

To my beloved mother and father

ACKNOWLEDGEMENTS

Alhamdulillah, I have completed this project as planned. Firstly, I would like to express gratitude to Allah for His grace the consent and aid until I have finished this project.

During preparing this report, many people was contributed toward my understanding. In particular, I wish to express my sincere appreciation to my supervisor, Encik Mohd Saifuzam Bin Jamri for encouragement, guidance critics and friendship. I very appreciate his advice, valuable time and ideas in completion this report. Without his support, this project would not have been same as presented here.

I also like to wish thanks to my beloved parents. They always give me the moral support and understand with my schedule until I have completing this paper. I also does not forgotten to my friend who have help me get the information and understanding about my project. Thank you for the shared knowledge and moment with me when I face the challenges.

Lastly, thank you for all hand and heart that help me made this project. Without any assistance, I cannot completion this project as planned.

ABSTRACT

Photovoltaic (PV) is a material that can convert the solar energy from sun into electrical energy. The PV array may consists of multiple connected modules to form the PV generating system. This project proposed an approach to model and simulate the photovoltaic array. The photovoltaic module was modeled by using combination of circuit and mathematical technique. The interconnected of PV module in series or parallel will formed the PV array which yield the higher operating point in I-V and P-V characteristic curve. The modeled PV arrays was validated with multiple solar irradiant and ambient temperature input conditions.

ABSTRAK

Photovoltaic (PV) adalah bahan yang boleh menukar tenaga matahari dari matahari menjadi tenaga elektrik. Array PV mungkin terdiri daripada pelbagai modul yang disambungkan untuk membentuk sistem penjanaan PV. Projek ini bertujuan untuk memodelkan dan mensimulasikan array fotovoltaik. Modul fotovoltaik dimodelkan dengan menggunakan gabungan litar dan teknik matematik. Sambungan modul PV siri atau selari akan membentuk array PV yang menghasilkan titik operasi yang lebih tinggi dalam lengkung ciri I-V dan P-V. Array PV yang dimodelkan telah disahkan dengan pelbagai keadaan input iradiasi suria dan ambien.

TABLE OF CONTENTS

PAGE

DECLARATION

APPROVAL

DEDICATIONS

ACKNOWLEDGEMENTS **2**

ABSTRACT **3**

ABSTRAK **4**

TABLE OF CONTENTS **5**

LIST OF TABLES **7**

LIST OF FIGURES **8**

LIST OF SYMBOLS AND ABBREVIATIONS **11**

CHAPTER 1 INTRODUCTION **12**
1.1 Overview 12
1.2 Project Background 12
1.3 Motivation 14
1.4 Problem Statement 14
1.5 Objective 15
1.6 Scope 15

CHAPTER 2 LITERATURE REVIEW **16**
2.1 Overview 16
2.2 Basic of Photovoltaic 16
2.2.1 Operation of Photovoltaic 17
2.2.2 The Photovoltaic cell effect 18
2.2.3 Cell, module and array 18
2.3 Type of Photovoltaic cell 19
2.3.1 Monocrystalline Silicon Cell 19
2.3.2 Polycrystalline Silicon Cell 20
2.3.3 Thin Film 20
2.4 Types of Photovoltaic system 21
2.4.1 Grid-connected solar PV system 21
2.4.2 Off-grid solar PV system 22
2.5 Photovoltaic Array 22
2.5.1 Connecting of Photovoltaic Array 23
2.6 Mathematical Model Of Photovoltaic 25
2.6.1 Equation Of Photovoltaic Cell 25
2.6.2 Equivalent Circuit For Photovoltaic Array 29
2.7 Resistance in PV circuit 29

2.7.1 Series resistance 29
2.7.2 Shunt Resistance 30
2.8 Effect of Solar Radiation variation 31
2.9 Effect of variation in cell Temperature 31

CHAPTER 3 METHODOLOGY 32
3.1 Overview 32
3.2 Proposal Gantt 32
3.3 Flowchart of workplan 34
3.3.1 Literature Review 35
3.3.2 Reference Photovoltaic (PV) Model 35
3.4 Modelling proses 37
3.4.1 Mathematic model of Photovoltaic cell 37
3.4.1.1 Simulation process of PV module 38
3.4.2 Mathematical of Photovoltaic array 43
3.4.2.1 Simulation of Photovoltaic Array 44
3.4.2.2 Test for PV array module 45
3.5 Summary 46

CHAPTER 4 RESULTS AND DISCUSSIONS 47
4.1 Overview 47
4.2 Result and analysis of Photovoltaic module 47
4.2.1 Result for test 1 49
4.2.2 Result for test 2 51
4.2.3 Result for test 3 53
4.2.4 Result for test 4 54
4.3 Result and analysis of Photovoltaic Array model 55
4.3.1 Case 1: All scenarios are tests on the input of PV array model 55
4.3.1.1 Scenario 1: Fixed the value input of radiance and temperature. 56
4.3.1.2 Scenario 2: Fixed the value input of irradiance, different value input of temperature. 57
4.3.1.3 Scenario 3: Difference radiance, fixed temperature. 58
4.3.1.4 Scenario 4: Difference value input of irradiance and temperature. 59
4.3.2 Case 2: All scenarios are tests on each PV module 59
4.4 Summary 62

CHAPTER 5 CONCLUSION AND RECOMMENDATIONS 63
5.1 Overview 63
5.2 Conclusion 63
5.3 Recommendation 64

REFERENCES 65

LIST OF TABLES

Table 3-1: Project Gantt Chart 33

Table 3-2: Datasheet of PV model ETA-L080 36

Table 3-3: List of parameter for model 38

Table 3-4 : Input value for PV array model 46

Table 3-5: Input value for PV module connecting in PV array model 46

Table 4-1: Value for PV module 47

Table 4-2: Result for test 1 56

Table 4-3: Result of scenario 2 57

Table 4-4: Result for scenario 3 58

Table 4-5: Result for scenario 4 59

LIST OF FIGURES

Figure 1-1: Photovoltaic Model 13

Figure 2-1: Photovoltaic system 17

Figure 2-2: Photovoltaic cell, module, panel, array 19

Figure 2-3: Monocrystalline cells in a solar panel 19

Figure 2-4: The comparison of polycrystalline silicon (left) and a monocrystalline silicon cell (right) 20

Figure 2-5: Grid-connected configuration 21

Figure 2-6: Off-grid system configuration 22

Figure 2-7: Equivalent circuit of solar array 23

Figure 2-8: PV-cell operating point 23

Figure 2-9: PV panel in parallel connection 24

Figure 2-10: PV panel in series connection 24

Figure 2-11:Equivalent circuit model of PV cell[13] 25

Figure 2-12: Resistance in series circuit[18] 30

Figure 2-13: the graph current density vs voltage 30

Figure 2-14: A solar cell circuit with shunt resistance 31

Figure 3-1: Flowchart plan of project 34

Figure 3-2: Solar Panel ETA-L080 35

Figure 3-3: Developing the PV module model 37

Figure 3-4: Simulink block of temperature operating module 38

Figure 3-5: Simulink block of photo-current module 39

Figure 3-6: Simulink block of saturation current module 40

Figure 3-7: Simulink block of output current module 41

Figure 3-8: Simulink block of circuit PV module 41

Figure 3-9: Simulink block of Photovoltaic module 42

Figure 3-10: Flowchart of developing PV array model 43

Figure 3-11: PV circuit model 44

Figure 3-12: PV module panel in series connection 44

Figure 3-13: PV array in parallel 45

Figure 3-14: PV array Model 45

Figure 4-1: Simulink block for test 1 48

Figure 4-2: Simulink block for test 2 48

Figure 4-3: Simulink block for test 3 49

Figure 4-4: Simulink block for test 4 49

Figure 4-5 : I-V characteristic with variable irradiance and constant temperature 50

Figure 4-6: P-V characteristic with variable irradiant and constant temperature 51

Figure 4-7: I-V characteristic of photovoltaic with varying temperature 52

Figure 4-8: P-V characteristic of photovoltaic with varying temparature 52

Figure 4-9: I-V characteristic output with difference irradiance and temperature 53

Figure 4-10 : P-V characteristic output with difference irradiance and temperature 53

Figure 4-11: I-V characteristic output with constant irradiance and temperature 54

Figure 4-12: P-V characteristic output with constant irradiance and temperature 54

Figure 4-13: PV array model 55

Figure 4-20: PV array series vs PV array in parallel 60

LIST OF SYMBOLS AND ABBREVIATIONS

PV	-	Photovoltaic
FYP	-	Final Year Project
I-V	-	Voltage vs current
P-V	-	Power vs voltage
I	-	current
V	-	Voltage
MATLAB	-	Matrix laboratory
Ø or G	-	Irradiance
T	-	Temperature
N_s	-	Number cell in series
N_p	-	Number cell in parallel
R	-	Resistance
I_{ph}	-	Photovoltaic current
q	-	Electron charge
IEEE	-	Institute of Electrical and Electronic Enginering

CHAPTER 1

INTRODUCTION

1.1 Overview

Chapter one explained about the introduction of this project. This chapter is divided into subtopic which described about the motivation and formulation of problem statement, objective and scope of project.

1.2 Project Background

Photovoltaic (PV) is a semiconductor material that can convert the light to electricity[1]. The light has come directly from sunlight. The material is absorbed proton and released electron is known as a photoelectric effect. The effect can be considered the prerequisite and essential sustainable resource among renewable energy. This is because it's produced solar irradiates that can be sustainability, ubiquity, and abundance. Electric current came from the free electron. The cell recharged the battery when direct current electricity is produced. Edmond Becquerel, in 1829, French physicist has noted the effects of photoelectric. He found the material that can produced the small electric current when there is light existed. Bell Laboratories in 1954 is the first-person who created the photovoltaic module. The module is known as a solar battery and too expensive. The industry began in the 1960s, to make the first technology that provides power aboard spacecraft. The space program was established and the cost decline. At long-term, the future economic increase depends on the affordable portable operation also the energy from a renewable source. Wind energy and solar energy is the utilization of the prime energy source. The portable operation are also the advantages connecting the number of solar cell that is connected [2].

A photovoltaic module is the connecting the number of the solar cell. The design of module followed by the certain voltage and current. PV generator system of the fundamental power unit represented by PV module. The solar irradiance, output voltage, and temperature cell effect the output of the PV module characteristic. The

multiple modules can from an array by connecting wire together. More electricity can produced when the large module array created. The array of PV module can be arranged in series and parallel by the combination of voltage and current. Photovoltaic can produced two type of module. The first module is crystalline silicon (c-Si) PV module. Crystalline silicon can produce two type of PV module in single crystalline (monocrystalline silicon) and polycrystalline silicon (multi-crystalline). Both c-Si module have high efficiencies about 10 percent to 12 percent. Amorphous silicon (a-Si) is the second module of PV and it have efficiency around 6 percent. This module is made thinner than crystalline silicon and it can absorbed more light energy from the sunlight.

To enable researchers to have a great understanding of photovoltaic working, the mathematical modelling of PV module has continuously created. The simulation MATLAB is used to develop PV models. The data of voltage, solar irradiation and temperature in the study of (Walker 2001) and (Gonzalez-Longatt 2005) has been developed in MATLAB to calculate the current output. Figure 1 show the photovoltaic panel model.

Figure 1-1: Photovoltaic Model

1.3 Motivation

Photovoltaic is a material that has an ability to convert the solar irradiance from sun into an electrical energy. It is play an essential role in an electrical power grid. However, in order to consider this renewable energy source in the network model, it is important to understand its characteristic and describe its behavior in mathematical equation. This project proposed a technique to model the PV using combination between circuit and mathematical approach. By applying several parameters stated in the manufacturer datasheet, the proposed PV model yields the I-V and P-V characteristics curve with follow the manufacturer specification.

1.4 Problem Statement

Analyzing the PV system through mathematical model is the simplest way because it only require the simulation software instead of costly hardware. The hardware model needs a larger space to create a single PV module. The equipment for the model of PV systems such as real sensor are difficult to handle and require complicated data communication. Furthermore, the PV array has nonlinear characteristics and its operating power under varying irradiance and temperature conditions gives the larger results. To overcome this problem, the model of solar panel and array has been developed and integrated in the common engineering software. This project is conducted in MATLAB Simulink software.

This project focuses on developing the mathematical model for PV array which consist of a combination of multiple PV module connected in series and parallel. The performance is analysed in terms of output power and output voltage under the variations of solar irradiance and ambient temperature.

1.5 Objective

The objectives of this project are:

a) To develop the photovoltaic modelling equation using Simulink.

b) To study the combination of photovoltaic array model.

c) To observe the effect of photovoltaic model in terms of output power and voltage towards the variations of irradiance and temperature

1.6 Scope

This project is will focus on the standard mathematical equation of photovoltaic module using Simulink in MATLAB. Next, the photovoltaic array consist of five interconnected modules.

CHAPTER 2

LITERATURE REVIEW

2.1 Overview

This chapter discussed on the basic of photovoltaic with the operation of cell and the different characteristic of the type module. Furthermore, the mathematical equation of photovoltaic and the type of resistance will affect the modelling demand also included in chapter 2. The advance information research about photovoltaic modelling will study further.

2.2 Basic of Photovoltaic

A photovoltaic or solar cell is created to convert the solar radiation energy into electrical energy for electrical load and the other electrical system. Photovoltaic (PV) array is assembled from PV modules that change the light energy from sunlight to direct current (DC). The array is often mounted on building or set up in open space. The more cell is used more electricity is generated. The electricity can use to run appliances such as a heater, toaster and fan until the sun goes behind the cloud. A more practical idea connects the PV array with the batteries. The energy stored in the batteries is commonly used in stand-alone system, but only design for the grid-tied system. There are many ways to use this technology. Figure 2.1 shows the energy conversion of the PV system on its application.

Photovoltaic (PV) cells is often used to supply power, such as streetlights and building. It's also often used in conjunction with other electricity sources. Arrays for large-scale power generation can be huge in solar farms. The most PV cell is silicon based. Silicon has chosen for its semiconductor potential. The silicon wafer is very thin.

The fundamental power conversion unit of a photovoltaic system is represented by PV module. The characteristic of the photovoltaic output depends on the solar irradiance and cell temperature [3]. Since the photovoltaic module characteristic is non-linear, it is necessary to model it for the design and simulation of maximum power

point tracking (MPPT) for photovoltaic system. Figure 2 1 shows the operation of Photovoltaic system. PV array absorbs energy from sunlight and converts to electrical energy for load.

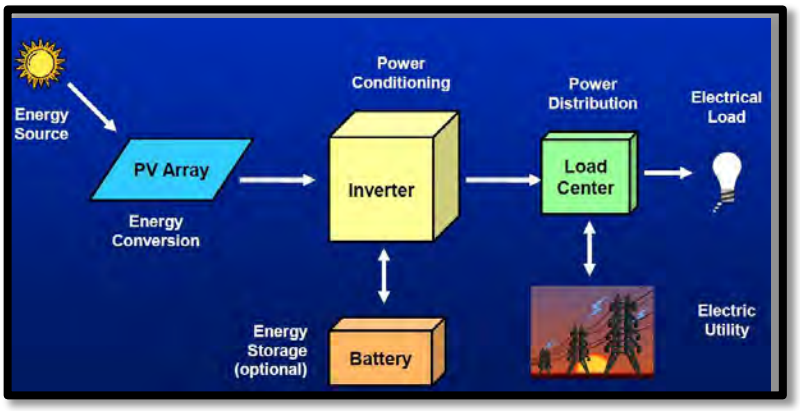

Figure 2-1: Photovoltaic system

2.2.1 Operation of Photovoltaic

The phenomenon of light energy generating electrical energy is called the photovoltaic effect. When the light was exposed in a semiconductor material, free electron will absorb and create electricity[2]. Photovoltaic effect utilized light energy to electricity system. The system is a basic unit of a photovoltaic cell. Photovoltaic cell is conducted by silicon and generate electricity used the Michael Faraday's principle of a magnet spinning of wire. The atom in photovoltaic cell is bonded together and produce covalent bond. The electron in atom produces a negative charge and the proton from the nucleus of atom carried the positive charge. The energy move randomly inside the atom of silicon. These moving electrons produce a current of electricity. This electricity can be used for a load, such as a hair dryer. The current generates is depends on how much light strikes the PV module.

Photovoltaic system operation is same like other electrical power. The equipment uses are better for conventional electromechanical generating system[3]. A PV array system needs other components to properly conduct, control, convert, distribute, and store the energy produced when it produce energy from sunlight. The operational and functional requirements are depending on the system. DC-AC power inverter, battery bank, system and battery controller, auxiliary energy sources and the specified electrical load is included in the system requirement.

For the purpose of storing energy produced by the PV array, batteries usually use during the night and cloudy weather. The batteries also use of the PV array operate near its maximum power point and it can control the voltage and current to electrical load and inverters. To keep the battery from overcharge and over discharge, a battery charge controller is used in systems.

2.2.2 The Photovoltaic cell effect

The photovoltaic effect is the process to expose the electromagnetic radiation[4]. The proton energy in a semiconductor material moves freely and generates the electricity. The motion of light through a wave and difference type of radiation are characterized as the individual wavelength. A frequency and an energy are matched up with the solar spectrum for each wavelength. A PV device created the amount of the electricity depends on the efficiency of device and solar radiation.

2.2.3 Cell, module and array

Photovoltaic cell produce the higher power, voltage and current. It is connected in series and parallel or both of position. The modules of photovoltaic consist of larger photovoltaic cell group and make the block of photovoltaic systems. The photovoltaic panel is a combination of one or more photovoltaic modules. The PV modules are gathering the electricity and mechanically to produce the power of DC. The complete power-generating unit consists of photovoltaic modules and panel is called photovoltaic array. An array is designed to construct a specified electrical output. Photovoltaic modules and array have rated under Standard Test Condition (STC). It is 25º C of temperature, 1000 W/m2 of solar irradiance level and 1.5 spectral under air mass. The usually actual performance of photovoltaic is around 85 to 90 percent[5]. The service lifetime of photovoltaic is 20 to 30 years. Figure 2-2: Photovoltaic cell, module, panel, array This figure shows a combination of photovoltaic cells to form a photovoltaic array[6].

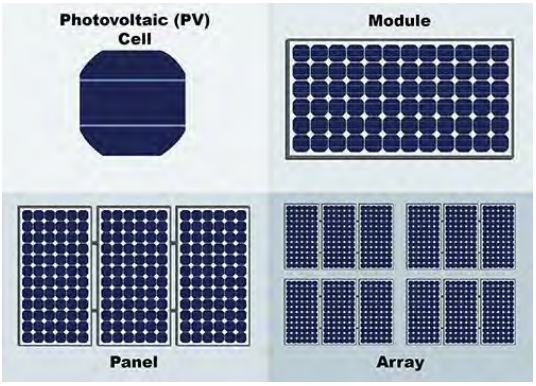

Figure 2-2: Photovoltaic cell, module, panel, array

2.3 Type of Photovoltaic cell

2.3.1 Monocrystalline Silicon Cell

This is the first type of solar cell, made from the pure silicon. These cell has a single crystal lattice structure. Monocrystalline can convert the energy from the sun to electricity around 15% and it's more efficient technology[7]. The manufacturing process of this cell is complicated and high cost. Figure 2-3: Monocrystalline cells in a solar panel shows the description of the monocrystalline cell in a solar panel.

Figure 2-3: Monocrystalline cells in a solar panel

2.3.2 Polycrystalline Silicon Cell

Polycrystalline or Multicrystalline cell is a single uniform crystal structure. It is made from molten silicon that is formed into a cube shape. Polycrystalline form is cut and packaged similar to monocrystalline cell. The manufacturing process of polycrystalline is simpler and cheaper than monocrystalline but it is less efficient. Figure 2-4 show the comparison monocrystalline and polycrystalline.

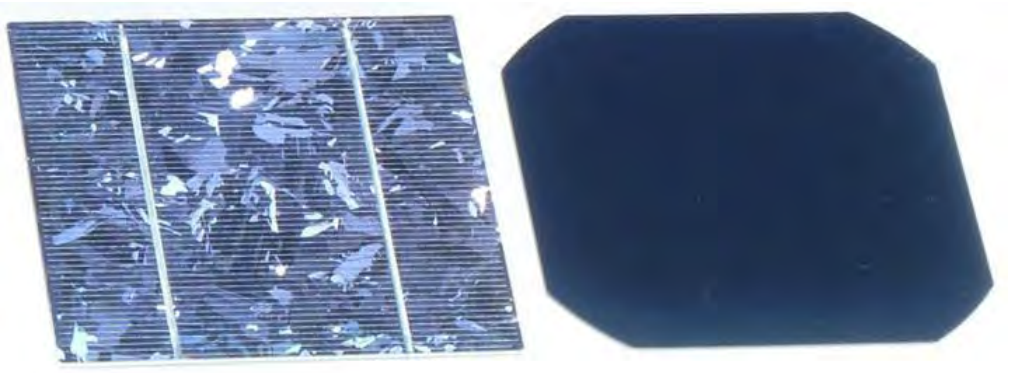

Figure 2-4: The comparison of polycrystalline silicon (left) and a monocrystalline silicon cell (right)

2.3.3 Thin Film

Thin film cell are more flexible, durable and thinner than crystalline cell. Amorphous silicon (a-Si) is a type of thin film cell, it makes from the depositing of the silicon layer to the glass substrate. It is cheaper and thinner produce because of the less raw material needed. Amorphous silicon is ideal for the curved surface. However, it is less efficient than crystalline. The combination atom are not stabile and easy inactive into electricity. The first month of use, the cell will reduce the efficiency around 20% before it stabilizes.

Copper indium gallium diselenide (CIGS) and cadmium Telluride (CdTe) are also the type of thin film cell. It requires extra precaution during manufacture, it is because this cell contains the rare and toxic element. This type is more efficiency that offer in technologies than the amorphous silicon.