I-V CURVE TRACER BASED ON CAPACITOR CHARGING METHOD FOR PHOTOVOLTAIC (PV) POWER SYSTEM

by

ABDULHAMID SAAD ALFITOURI MAHMOUD
(1732222340)

A dissertation submitted in partial fulfillment of the requirements for the degree of
Master of Science in (Electrical Power Engineering)

School of Electrical System Engineering
UNIVERSITI MALAYSIA PERLIS

2018

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ACKNOWLEDGMENT

First and foremost, **Alhamdulilah**, the creator, the cherisher, the wisest, the lord of the world. I am extremely thankful to almighty Allah for giving me the chance, strength and courage to complete this work, and without his willing, this dissertation will never have done.

I would like to express my utmost and deepest gratitude to my advisor, **Dr. Mohammad Faridun Naim Tajuddin**, for his guidance in academic research and his support in daily life. He has widened my view in research areas, especially in Photovoltaic systems and renewable energy area. His motivation and support have guided me towards the successful completion of my dissertation.

I would like to convey my deepest gratitude and thanks to my family (**my parents, my brothers and sisters**) for their support spiritually and financially in order to finish this dissertation.

I would also like to extend my gratefulness to my friends and entire staff in the **School of Electrical System Engineering**, UniMAP for their fully support me all these period.

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LIST OF ABBREVIATIONS

PV	Photovoltaic
STC	Standard Test Condition
PS	Partial Shading
MOSFET	Metal Oxide Semiconductor Field Effect Transistor
BJT	Bipolar Junction Transistor
IGBT	Insulated Gate Bipolar Transistor
UTC	Uniform Test Conditions
PSTC	Partial Shading Test Conditions
MPP	Maximum Power Point

LIST OF SYMBOLS

I_{sc}	Short circuit current
V_{oc}	Open circuit voltage
FF	Fill Factor
P_{mpp}	Maximum power point
I_{mp}	Current at maximum power
V_{mp}	Voltage at maximum power
R_{sh}	Shunt resistance
R_s	Series resistance
n	Diode ideality factor
I_{ph}	Photo-induced current
I_o	Operating current
V_o	Operating voltage
N_s	Number of series strings
N_p	Number of parallel strings
R_{eq}	Equivalent resistance of solar cell module
α	Temperature coefficient
τ	Time constant
V_C	Load capacitor voltage
V_R	Discharging resistance voltage
t_{ch}	Capacitor charging time
t_{dis}	Capacitor discharging time
t_{total}	Total time period is taken to starting next trace

I-V CURVE TRACER BERDASARKAN METODE CHARGING CAPACITOR UNTUK SISTEM POWER PHOTOVOLTAIC (PV)

ABSTRAK

Mengukur ciri *I-V* adalah sangat penting kerana ia boleh dianggap sebagai sijil kualiti dan prestasi untuk setiap penjana PV. Kaedah pengecasan kapasitor dianggap sebagai kaedah pengukuran yang paling murah dan tepat bagi penjana PV. Litar penjana PV yang digunakan bersama kapasitor berfungsi sebagai beban dan kemudian analisis transien dilakukan pada litar untuk mendapatkan voltan dan arus pengisian kapasitor sebagai fungsi masa. Kaedah ini juga boleh digunakan untuk mendapatkan perbezaannya sebagai fungsi saiz kapasitor dan arus litar pintas. Kaedah ini dicadangkan sebagai penyelesaian kepada masalah pengesanan lengkung *I-V* berkelajuan rendah dalam kaedah perintang. Ia juga disyorkan sebagai penyelesaian kepada isu tenggelam kuasa yang sering dikaitkan dengan penukar DC-DC. Untuk mencapai maklumat lengkung yang pantas, lancar dan tepat, saiz kapasitor dianggap sebagai kebimbangan utama dalam kaedah yang dicadangkan ini. Pengiraan yang telah digunakan membantu untuk mengira saiz kapasitansi yang betul bagi mengukur ciri-ciri *I-V*. Ia juga mengambil kira pemerolehan kelajuan sistem pengukur seperti digambarkan menggunakan sampel pengukuran yang diberikan dalam kajian ini untuk lengkung *I-V* dengan ketepatan yang boleh diterima. Saiz kapasitor adalah berkadar terus dengan arus litar pintas dan berkadar tidak terus dengan voltan litar terbuka bagi penjana PV. Tempoh pengecasan kapasitor yang akan mewakili keluk ciri *I-V* akan disimulasikan melalui simulasi berkomputer menggunakan perisian MATLAB. Hasil tesis ini menunjukkan bahawa tempoh pengesanan untuk kedua-dua syarat UTC dan PSTC adalah kurang dari satu saat untuk mengesan sepenuhnya dan menggambarkan kurva *I-V*.

I-V CURVE TRACER BASED ON CAPACITOR CHARGING METHOD FOR PHOTOVOLTAIC (PV) POWER SYSTEM

ABSTRACT

Measuring the *I–V* characteristics is of high importance since it can be considered as a quality and performance certificate for each PV generator. The capacitor charging method is considered as the cheapest and most precise measuring methods for PV generators. The equivalent circuit of the PV generator is utilised with a capacitor serving as the load and then a transient analysis is performed on the circuit to obtain the charging voltage and current of the capacitor as a function of time. This method can also be used to obtain their differentials as a function of the capacitor size and the short-circuit current. This method was proposed as a solution to the low-speed *I-V* curve tracing problem in the resistor method. It was also suggested as a solution to the power sinking issues that are often associated with DC-DC converters. In order to achieve a fast, smooth and accurate curve information, the capacitor size is considered the main concern in this proposed method. The utilized equations help to calculate the proper capacitance size to measure the *I-V* characteristics. It also takes into consideration the speed acquisition of the measuring system as illustrated using the measurement samples given in this study for the *I-V* curve with acceptable accuracy. The capacitor size is directly proportional to the short-circuit current and indirectly proportional to the PV generator's open circuit voltage. The capacitor charging durations that will represent the *I-V* characteristics curve will be simulated through a computerised simulation using the MATLAB software. The results of this thesis shows that the tracing durations for both performed conditions of UTC and PSTC was less than one second in order to fully trace and graph the *I-V* curve.

CHAPTER 1 : INTRODUCTION

1.1 Introduction

The ever-increasing world energy demand and the fast depletion of fossil fuels and the unpredictable weather pattern have prompted the world to look for alternative source of energy. Since the sun produces more energy per hour than the world can consume per year, that making photovoltaic (PV) industry more viable than any other source (Yunas Erkaya, 2016). A photovoltaic module/array comprises of a multiple solar cells connected into a single unit. The solar cell is a device that converts solar energy into electricity. A photovoltaic module or array may have cells connected in series or parallel as a string. When connected in series a higher voltage is realized while solar cells in parallel would give a greater current than a single cell (Lorenzo, 2006). Photovoltaic electrical energy is the most favored source of electrical energy since it's environmentally friendly and inexhaustible since its present everywhere and the conversion process is noise free and emits no pollutants to its surrounding.

During operation, PV performance can be monitored by measuring the array's current-voltage (*I-V*) characteristic curve at the ambient temperature and actual solar irradiance. Measuring the *I-V* principle curve involves reading and drawing various current and voltage data that were generated at different load conditions. Doing so also offers the ability to understand the performance and quality of a PV module. The curve offers a description of the important PV module parameters, including short circuit current (I_{sc}), open circuit voltage (V_{oc}), and maximum power point where the PV module will function at optimum efficiency (Brito, Antônio, Cupertino, & Pereira, 2013). Given these considerations, it becomes very important to gain an understanding of the *I-V* curve parameters.

However, in certain circumstances, the PV array may not be experiencing uniform irradiance and could be undergoing partial shading as a result of different factors like trees, shadows of nearby buildings, dirt, etc. Given practical conditions, the partial shading problem is almost unavoidable. The shaded modules use up power as a result of reverse voltage polarity, which leads to reduced extractable power from the array (Bai et al., 2015). Furthermore, power dissipation in shaded modules results in hot spot problems and local overheating. In order to address this problem, bypass diodes are linked throughout the terminals of the cell groups found in every string module. This protection allows for the generation of an additional current path when there is a slight reversal of the voltage throughout the terminals of the shaded modules (or clusters of cells) (Lu, Guo, Walsh, & Aberle, 2013).

With taking these considerations in account, developing a simple and fast device for tracing *I-V* curve of PV system allowing PV users to know its performance and conditions. A common method to trace the *I-V* curve utilize by using resistor as a load to PV module. This help to measure the stepwise current and voltage, however, due to resistor load manual charge and its slowness during measuring process has led to this work using a capacitor-based *I-V* curve tracer. Capacitor method have found more to be suitable than resistor method because it is fast and very useful for high power with reasonable capacitor values (Durán, Piliougine, Galán, & Andújar, 2008).

Moreover, as a rule of thumb, the chosen charging times are normally range between 20 and 100ms (Blaesser, 1997). These short periods lower the risk of overheating and reduce the size of components like capacitors and switches. It also makes it possible to assume that the array operating conditions such as the cell temperature and irradiance remain constant during the *I-V* sweep. Therefore, the capacitor size must not be too large as this increases the component size and the tracing time. It also leads to the tendency of having to collect a large amount of unnecessary I-V samples. However, the capacitor size should also be high enough so that relatively slow charging times can be achieved and fast transients can be avoided since they damage the switches and the load (Durán, Andújar, Enrique, & Pérez-Oria, 2012).

1.2 Objectives

The objectives of this project are:

1) To design a capacitor-based *I-V* curve tracer for a photovoltaic system.

2) To determine the appropriate size of the capacitor based on charging and discharging time.

3) To model and simulate the proposed *I-V* curve tracer connected to the PV module/array using MATLAB/Simulink software.

1.3 Problem Statement

For the past several years, different researchers have proposed several approaches to develop compatible techniques that can be used for tracing the *I-V* curve. The utilisation of a variable resistor is one of the popular techniques for doing this. The resistor's value will be made to differ in the various steps so that the points of the *I-V* curve can be measured from the short to the open circuit. However, this method is not highly accurate since measuring the *I–V* process by manually changing the load resistor slows down the process significantly. Thus, one can change the solar radiation and thermal conditions during the measurement. Moreover, this approach can only be applied to PV generators that possess very low peak power (<1 kW) since higher power resistors are largely unavailable (Durán et al., 2008).

Another method is based on the DC-DC converter. There are three topology examples utilize for *I-V* curve tracer with this method, these include the design of three different topologies such as buck, boost and buck-boost converter. However, these three methods take more time to trace full curve leading the overall system performance and large power sinking issue (Issac, 2013).

Capacitor *I-V* curve tracing is proposed to solve the problem of power limitation tracing in resistor based *I-V* curve tracer, yet still providing a high-speed curve trace. It is also proposed to solve the power sinking issues related to DC-DC converters. The sizing of capacitor in order to achieve accurate uniform and smooth curve is another issue in the proposed system. This project aims to investigate on solving these problems in order to optimize the overall performance of the proposed *I-V* curve tracer using capacitive charging technique.

1.4 Project Scope

The primary target of the project is to optimize a capacitor-based *I-V* curve tracer which is capable of tracing an *I-V* curve up to 7 kW PV array. The project will obtain and investigate different mathematical formulas related to capacitor sizing of the tracer. Mathematical approach is utilized to select suitable capacitor size based on its charging and discharging period that is needed to trace sufficient data in order to plot the overall *I-V* curve in less than (one second). Simulation analyses of different irradiance conditions at standard ambient temperature of 25^0C will be carried out using MATLAB/Simulink software.

1.5 Organization of Chapters

Chapter 1: Introduction

This chapter provides the introduction to the thesis along with the system details, project objectives, research question, the problem of research, introductory part also discusses the reason of implementing the research and provide an equivalent instruction of what required to complete the project.

Chapter 2: Literature Review

This chapter is where the relative development or work approaches by other researchers; most of the work in this section is sort of related systems, method, result and research comparison.

Chapter 3: Methodology

Project concept and idea toward the implementation is provided in this chapter, the detail instruction includes the system functionality, design concept, mathematical equation and initial results of the proposed system.

Chapter 4: Results and Discussion

Mainly discussion about the results obtained through analysis and simulation of the designed circuit for different stages of capacitor capacitance and variable irradiance levels.

Chapter 5: Conclusion and Future work

The overall conclusion including the earlier four chapters and potential improvement recommendation for future work.

CHAPTER 2 : LITERATURE REVIEW

2.1 Introduction

Photovoltaic is a device that has gained widespread application especially due to its ability to convert directly sun rays to electricity. There is extensive research on the fabrication of cheap and efficient solar cells that need to be electrically characterized to ascertain its power output (Spertino, Sumaili, Andrei, & Member, 2013). This chapter presents some earlier contribution and studies on designing *I-V* curve tracers used in the characterization of photovoltaic modules/array.

2.2 Modelling Photovoltaic Modules

Modeling the behavior of photovoltaic modules is important for module characterization, *I-V* curve measurements, and PV module emulation. The model used must represent photovoltaic modules accurately without prohibitively difficult mathematical operations that make the solutions hard to obtain (Laurent, 2016). PV module measurements taken outdoors are under an uncontrolled solar irradiance and ambient temperature. For consistent results, these measurements must be converted to standard testing conditions (STC) for proper characterization of PV modules. Similarly, with *I-V* curve measurements, the measured curves need to be transposed to STC for meaningful and comparable results (Lineykin, Averbukh, & Kuperman, 2014).

2.3 PV Module Models Overview

There are three main ways of modeling photovoltaic modules in the literature (Laurent, 2016): (1) ideal diode, (2) single-diode, and (3) dual-diode models. These models slightly differ among themselves in theory, but there is a large discrepancy when it comes to mathematical complexity. Among these, the ideal single diode model provides the simplest mathematical equation that is easily solvable without using iterative methods, which both the single diode and the dual-diode require (Ciulla, Lo Brano, Di Dio, & Cipriani, 2014).

2.3.1 Ideal Diode Model

The ideal diode model ignores the non-ideal effects of series and shunt resistances as it shows in Figure 2.1, and simplifies both the schematic and the equations.

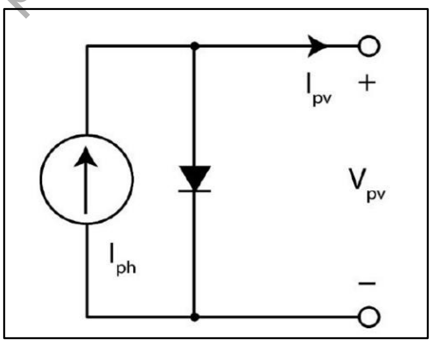

Figure 2.1: Ideal diode model of solar cell without resistances (Ciulla et al., 2014).

A few assumptions are made for the ideal single diode model: the series resistance is assumed to be zero, the shunt resistance is assumed to be infinitely large, the photon current I_{ph} is assumed to equal to the short-circuit current I_{sc} and the exponential term is assumed much larger than one, allowing the removal of the "-1" term (Ciulla et al., 2014).

The new equation describing the diode therefore as Equation 2.1:

$$I_{PV} = I_{sc}\left[1 - exp\left(\frac{ln\left(1 - \frac{I_{mpp}}{I_{sc}}\right)(V - V_{oc})}{V_{mpp} - V_{oc}}\right)\right] \quad 2.1$$

In the end, the current equation can be simply derived from the open-circuit voltage V_{oc}, the short-circuit current I_{sc}, the maximum power point voltage V_{mpp}, and the maximum power point current I_{mpp}. This eliminates the requirement for knowing I_o and temperature coefficient a, values which are not provided by module manufacturers (Erkaya, 2016).

2.3.2 Single Diode Model

The single diode model is the most commonly used model in solar cells owing to its relative simplicity and good correlation. The solar cell is modeled as a current source with I_{ph}, a series anti-parallel diode, the series resistance R_s that models the series losses in the device, and the shunt resistance R_{sh} that models the recombination losses in the device (Goss, Cole, Betts, & Gottschalg, 2014). The schematic of the model is given in Figure 2.2.

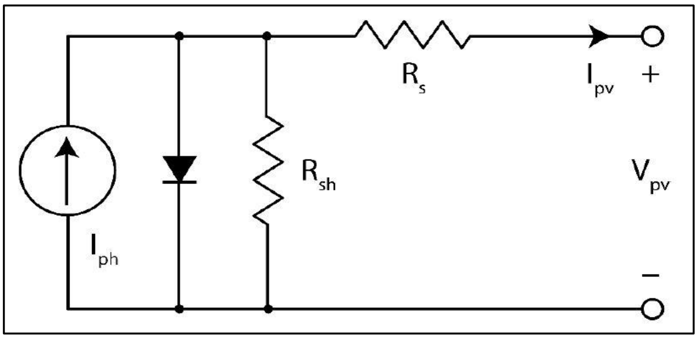

Figure 2.2: Single diode model with series and shunt resistances (Goss et al., 2014).

The equation for the single-diode model is given by Equation 2.2.

$$I_{PV} = I_{ph} - I_0 \left(e^{\frac{V + I.R_s}{m\frac{kT}{q}}} - 1 \right) - \left(\frac{V + I\ R_s}{R_{sh}} \right) \qquad 2.2$$

Where the model parameters as follows: the output voltage of PV cell V, Reverse saturation current of the diode I_o, Electron charge q, Boltzmann constant k, Junction temperature in Kelvin T, Diode quality factor m, series resistance R_s, and shunt (or parallel) resistance R_{sh}.

For modern PV cells and modules, the effects of R_s and R_{sh} are not as significant as they used to be, due to the improvements in manufacturing processes in recent years (Lu et al., 2013).

2.3.3 Dual Diode Model

Both the single diode and the ideal single diode solar cell model assume a fixed value for the diode ideality factor n. This assumption does not hold in reality since the diode ideality factor is dependent on the bias voltage across the solar cell. Figure 2.3 shows the dual diode model.

When V_{pv} is large, the recombination of the charge carriers (holes and electrons) is dominated by surfaces and bulk regions, therefore the ideality factor n converges to (1). On the other hand, when the cell voltage V_{pv} is low, the recombination at the junction dominates and n converges to (2). The second diode in the two diode model is necessary to account for junction recombination effects (Ciulla et al., 2014).