ANALYSIS OF SEPIC DC/DC CONVERTER USING PERTURB & OBSERVE ALGORITHM FOR PHOTOVOLTAIC CHARGE CONTROLLER

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ABSTRACT

The solar energy is one of the renewable energy sources that plays an important part in our daily life nowadays. The solar energy harvesting system usually consists of solar panels and inverters. The inverter consists of many subsystems; solar charge controller is one of them. As the name suggests, solar charge controller plays a crucial role in harvesting maximum energy from the sun’s irradiation. This thesis focuses on solar charge controller area; which presents theoretical studies on the photovoltaic (PV) module characteristics and Maximum Power Point Tracking (MPPT) capability. This study uses real irradiation data to analyze the PV module characteristics and the MPPT algorithm in MATLAB. The simulations in PSIM software is to verify the Single Ended Primary Inductor Converter (SEPIC) circuit with Perturb & Observe (P&O) MPPT algorithm method. This simulation provides an information on the charge controller capability to produce an output power as close as the input power on the changement of the solar irradiation intensity. This simulation provides an information on how the P&O algorithm reacts to the changement of solar irradiation and how long it took for this MPPT to track the Maximum Power Point (MPP). The SEPIC hardware analysis is likely to be the determination of the losses in the SEPIC circuit at certain working frequency parameters and component selections. This experiment also contributes to the knowledge on the switching and conduction losses, where in reality depending on many parameters. On the ideal SEPIC circuit (lossless converter), the efficiency can reach as high as 98% at maximum solar irradiation. By comparison, given the same components with the same value, the experimental SEPIC circuit can obtain an efficiency of only 77%.
ABSTRAK

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## LIST OF SYMBOLS

- $k$: Boltzmann constant ($1.3806503 \times 10^{-23} \text{J/K}$)
- $M$: Conversion ratio
- $D$: Duty cycle
- $n$: Diode ideality factor
- $I_0$: Reverse saturation current of the diode
- $q$: Electron charge ($1.60217646 \times 10^{-19} \text{C}$)
- $T$: Cell temperature in Kelvin = (273+25)
- $\alpha$: Temperature coefficient of short circuit current ($\%/\degree \text{C}$)
- $G$: Irradiance ($\text{W/m}^2$)
- $f_{sw}$: Switching frequency (kHz)
- $P_m$: Maximum power
- $V_{mp}$: Voltage at maximum power point
- $I_{mp}$: Current at maximum power point
- $V_{oc}$: Open circuit voltage
- $I_{sc}$: Short circuit voltage
- $R_s$: Series resistance
- $C_s$: Coupling capacitor
- $V_{th(min)}$: MOSFET minimum threshold voltage
- $V_D$: Diode forward voltage drop
- $I_L$: Inductors current
- $R_{D\text{son}}$: MOSFET drain-source resistance
- $Q_{GD}$: MOSFET gate-drain charge
- $DCR$: DC resistance
- $Q_{rr}$: Diode reverse recovery charge
- $V_{cf}$: Voltage across diode during turn off condition
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<td>BJT</td>
<td>Bipolar Junction Transistor</td>
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<tr>
<td>CCM</td>
<td>Continuous conduction mode</td>
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<td>DC</td>
<td>Direct current</td>
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<td>ESR</td>
<td>Electrostatic charge resistance</td>
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<td>IGBT</td>
<td>Insulated Gate Bipolar Transistors</td>
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<td>IncCond</td>
<td>Incremental Conductance</td>
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<td>I-V curve</td>
<td>Current versus Voltage curve</td>
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<td>kWp</td>
<td>Kilowatt peak</td>
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<td>MOSFET</td>
<td>Metal Oxide Silicon Field Effect Transistors</td>
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<td>NREL</td>
<td>National Renewable Energy Laboratory</td>
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<td>PV</td>
<td>Photovoltaic</td>
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<td>P-V curve</td>
<td>Power versus voltage curve</td>
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<td>PWM</td>
<td>Pulse-width modulation</td>
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<td>P&amp;O</td>
<td>Perturb and Observe</td>
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<td>RMS</td>
<td>Root Mean Square</td>
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<tr>
<td>SCRs</td>
<td>Silicon-Controlled Rectifiers</td>
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<tr>
<td>SEPIC</td>
<td>Single Ended Primary Inductor Converter</td>
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<td>SMPS</td>
<td>Switch Mode Power Supplies</td>
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<td>STC</td>
<td>Standard Test Condition</td>
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CHAPTER 1

INTRODUCTION

1.1 OVERVIEW

Over the past few years, there was plenty speculation of fuel price hikes, a world energy crisis and concerns of global warming. The increasing demand of energy and the growing concern about the environment has sparked enormous interest in the utilization of renewable energy. For the time being, renewable energy represents only 7% of the global energy consumed and it will slightly increase as the need for the global energy increased (Bose, 2010). One of the alternative energy sources that are recently flourishing is the sun, mainly because it is free, sustainable, environmental friendly and maintenance free.

The sun's energy, which is converted to solar electricity, or photovoltaic (PV), is likely being one of our major energy sources in the near future. PV is energy from the sun, which the light is converted directly into electricity without creating any air or water pollution. It consists of silicon, which going through a doping process to produce positive and negative type semiconductor materials. When light enters the cell, some of the photons from the light are absorbed by the semiconductor atoms, freeing electrons from the cell’s negative layer to flow through an external circuit and back into the positive layer. The main electrical characteristics of a PV cell or module are summarized in the relationship between the current and voltage. The solar radiation that is absorbed by the cell controls the current (I), while the increases in the temperature of the solar cell reduce its voltage (V). A single PV cell is basically a direct current (DC) source, where the current is determined by the area of the cell and the amount of
exposed solar irradiation. One of the examples of the PV module structure is as shown in Figure 1.1.

**Figure 1.1: PV Module construction**

Source: Kroposki, Margolis et al. 2009

There was a long list to show a chronological history of solar PV, but it is important to know that in 1839, French scientist, Edmond Becquerel, discovered the photovoltaic effect while experimenting with an electrolytic cell made up of two metal electrodes placed in an electricity-conducting solution; the electricity-generation increased when exposed to light. In 1876, William Adams, a British physicist, discovered a material of photovoltaic which is selenium with his student, Richard Day. They, altogether, then made it to solid cells with 1 % – 2 % efficiency. And in 2008, scientists at the U.S. Department of Energy's National Renewable Energy Laboratory (NREL) have achieved a new world record in solar cell efficiency. They managed to get a photovoltaic device have 40.8 % of efficiency. The achievement and evolution in PV industry are really outstanding and exceptional. The PV system is gaining an important as a renewable source due to advantages such as the absence of fuel cost, little maintenance and no noise and wear due to the absence of moving parts. Even though solar energy constitutes a very small percentage of our energy system today, the size of the resource is enormous which we can state that the earth receives more energy from the sun in one hour than the global population uses in an entire year (Kroposki, Margolis et al., 2009).
Although the PV system has many advantages, there are still two major disadvantages to the use of photovoltaic systems; the high installation cost and the lower energy conversion efficiency. Efficiency is the main component in solar PV technology as the solar energy that disappears without converting to electrical energy is considered a loss. As PV installation averagely at a cost of around RM5000/kWp (Ali, 2013), thus every power that loss during the process are costly. The relatively high cost of photovoltaic power systems has required system designers to maximize efficiency wherever possible. Even modest gains in overall efficiency can result in significant savings in the cost of operating the power system. Compared to the cost of electrical energy available from conventional sources the cost of energy from photovoltaic is still fairly high so it is important that the maximum available amount of energy be extracted from the solar array. To maximize the power output of the PV system, a DC/DC converter with an appropriate Maximum Power Point Tracking (MPPT) algorithm is commonly employed within a controller device named Solar Charge Controller. Together, the DC/DC converter and MPPT algorithm control the terminal voltage of the PV system at optimal values in various solar radiation conditions, where at a certain weather condition; the output power of a PV panel depends on the terminal voltage of the system. Figure 1.2 shows the PV system block diagram that works to ensure the PV module operation point always at the MPP.

![PV system block diagram from charge controller’s perspective](image-url)
1.2 PROBLEM STATEMENT

In this thesis, the solar charge controller is being studied in terms of efficiency and performance. Questions have been raised about the efficiency where it is actively discussed as one of the main issues which is causing either by MPPT algorithm or DC/DC converter topology (J.M. Enrique, 2006; Esram and Chapman, 2007; A. Dolara, 2009; Patarau, Daraban et al., 2011). Research on the converter efficiency arises in many scopes, but the one that should be concerned of, is the design of the converter itself (Kimball, Flowers et al., 2004). There are increasing concerns that apart from the PV system, there are also a need for analysis on DC/DC converters’ efficiency in a wind farm technology (Prabhakar, Bollinger et al., 2008) which triggered that the efficiency issue of the DC/DC converters needs to be taken into consideration for the designers regardless on which applications it will be used. While there has been considerable research on the efficiency analysis of DC/DC converter, only certain studies have proposed a new method of DC/DC to improve the converter efficiency (Kim, Lee et al., 2013; Kawaguchi, Yamaguchi et al., 2008; Al-Saffar, Ismail et al., 2008). One major issue arose that the converters used for photovoltaic applications had a common reliability issue, which is a failed electrolytic capacitor used in filters (Lahyani, Venet et al., 1998). Thus, it is important for the designers not only to maximize the extracted energy, but also to ensure that the converter does not require failure prone components like large capacitors. Previous studies of Martin A. Green (2013) on PV module, the efficiency of conversion of the incident radiation to electrical energy in the PV cell is low and could be as high as 24.1% for thin film type module at Standard Test Condition, STC.
1.3 OBJECTIVES

The objectives of this study are:
1. To develop a model of PV module in computer simulation based on varying solar irradiation at a specific geographical location.
2. To realize a charge controller in computer simulation; consists of PV module, SEPIC DC/DC converter and control system.
3. To analyze the efficiency and the losses of a SEPIC DC/DC converter via practical experiment.

1.4 SCOPE AND LIMITATIONS

To achieve the objectives, this study is conducted on a best efforts basis. Like all other studies, this study is focused at a specific scope and is bounded by limitations. It should be noted that the study covers the overall study of solar charge controller; from the solar irradiance, solar panel, DC/DC converter and its controller. The inverter is not part of the study, and will be looked at as a load from the solar charge controller's perspective.

Objective 1:
Geographical and time scope: The context of the study is based on data logged from the UMP's weather station at Pekan, Pahang. The data spans for over the period of one year and three months; from Jan 2011 to March 2012.
Lab resource limitation: The model of PV is based on a readily available PV panel during the study, the Mitsubishi PV-TE125MF5N.

Objective 2:
For Objective 2, a thorough literature study is conducted, mainly on choosing the appropriate DC/DC converter topology and the suitable control algorithm. This is explained in detail in Chapter 2. At the end of the literature review, the study narrowed to focus on SEPIC DC/DC converter and Perturb & Observe (P&O) algorithm, hence the title of the thesis. A simulation is conducted to achieve Objective 2, where the SEPIC with P&O system is tested using the cloudiest and the sunniest data set from the Objective 1 study.
Objective 3:

Objective 3 is about the efficiency and the losses of SEPIC DC/DC converter. To achieve this objective, a SEPIC DC/DC converter is constructed with the same parameters and same component sizing as in Objective 2. As for the controller, open-loop control is sufficient for efficiency analysis, where an Arduino board is used as the controller. The limitation of the Arduino board applied to the study, especially on the switching frequencies, where the maximum possible is 62.3 kHz. The converter is normally operate at switching frequency higher than 50 kHz (Burmester, Rayudu et al., 2013).

1.5 OVERVIEW OF THE THESIS

This study has been divided into two parts. The first part deals with the simulation of solar charge controller while the second part deals with the DC/DC converter efficiency analysis experiment. The charge controller has a DC/DC converter that using a Single Ended Primary Inductor Converter (SEPIC) topology. This study includes a simulation of the PV module and SEPIC circuit model in MATLAB and PSIM respectively, plus a hardware testing for the SEPIC. The PV module used is the modules that available in the Fakulti Kejuruteraan Elektrik & Elektronik, Universiti Malaysia Pahang, which is Mitsubishi PV-TE125MF5N. This thesis is organized in five chapters. Chapter 1 is a brief introduction of Renewable Energy as a whole and specifically on the use of the PV system with the concern over its price compare to efficiency. In Chapter 2, literatures that relevant to the issue are presented along with the reviews of various books, journals and articles. The literatures focused on the PV cell characteristics, MPPT algorithm (P&O) and DC/DC converter (SEPIC). Chapter 3 presents the methodology of the study. This chapter includes simulation procedures and component selection for experimental purposes which involve some calculations. Chapter 4 is relate or a continuation of Chapter 3 where the results that obtained from simulation and experiment are presented and discussed. Graphs and figures are included to be observed and discussed. In the last chapter (Chapter 5), the study is concluded and summarized based on the methodology used and the results obtained. Moreover, further works that can be conducted are also recommended.
CHAPTER 2

LITERATURE REVIEW

2.1 INTRODUCTION

French physicist, Edmund Becquerel, discovered the first photovoltaic effect when he illuminated a metal electrode in an electrolytic solution back in 1839. Then, William Adams, a British physicist, discovered a material of photovoltaic which is selenium thirty-seven years later with his student, Richard Day. They, altogether then made it to solid cells with 1 % – 2 % efficiency (Masters, 2004). The PV timeline evolution is as per attached in APPENDIX B which is prepared by United States Department of Energy. PV systems are comprised of photovoltaic cells, devices that convert light energy directly into electricity. The word photovoltaic comes from “photo,” meaning light, and “voltaic,” which refers to producing electricity. Therefore, the photovoltaic process is producing electricity directly from sunlight (S.E.C.O, 1997).

The uses of solar energy become more demanding year by year. PV based installation demand has grown consistently by 20 %–25 % per annum over the past 20 years (Carrasco, Franquelo et al., 2006). Today, the production of PV cells is following an exponential growth curve since technological advancement of the late ‘80s that has started to rapidly improve efficiency.

Despite its rapid growth, there remain several challenges that hinder the widespread use of PV power systems. The main limitation is the high cost of the module. It is difficult to ignore that the cost is basically determined by the economics of scale of a certain country, supply-demand, price of basic material and the cell manufacturing processes (Taheri, Salam et al., 2010). To ensure that the installation of
PV is effective, there is a need to ensure that the power output of the PV modules should be at its optimum. Several attempts have been made to overcome the problem, where one evidence suggests that this can be achieved by employing a specific circuit, famously known as Maximum Power Point Tracker (MPPT) (Rebei, Gammoudi et al., 2014; Zanotti, dos Santos et al., 2013; Durgadevi, Arulselvi et al., 2011; Coelho, Concer et al., 2009). Therefore, an efficient PV module requires the MPPT to assured that the maximum power is delivered at the operation point, where the magnitudes of the PV generator and load circuit resistances are equal as shown in Figure 2.1.

![Figure 2.1: Load and generation curves intersection](source: Coelho, Concar et al. 2009)

### 2.2 PHOTOVOLTAIC

Photovoltaic (PV) is a method of generating electrical power by converting solar radiation into direct current electricity using semiconductors that exhibit the photovoltaic effect. Photovoltaic power generation employs solar panels composed of a number of solar cells containing a photovoltaic material. Mainstream materials presently used for photovoltaic include mono-crystalline silicon, poly-crystalline silicon, amorphous silicon, cadmium telluride and copper indium gallium selenide/sulfide. Due to the increased demand for renewable energy sources, the manufacturing of solar cells and photovoltaic arrays has advanced considerably in recent years.
2.2.1 Photovoltaic Cell

PV cells convert sunlight directly into electricity without creating any air or water pollution. PV cells are made of at least two layers of semiconductor material. One layer has a positive charge, the other negative. When light enters the cell, some of the photons from the light are absorbed by the semiconductor atoms, freeing electrons from the cell’s negative layer to flow through an external circuit and back into the positive layer. This flow of electrons produces electric current (S.E.C.O, 1997). The main electrical characteristics of a PV cell or module are summarized in the relationship between the current and voltage. The solar radiation that is absorbed by the cell controls the current (I), while the increases in the temperature of the solar cell reduce its voltage (V).

Figure 2.2: Photovoltaic cells

Source: (MITSUBISHI 2007)

A single PV cell is basically a direct current (DC) source, where the current is determined by the area of the cell and the amount of exposed solar irradiation. The voltage of an individual silicon cell is in the order of 0.5 V. Therefore, the cells have to be connected in series to constitute a module with reasonable voltage levels.

2.2.2 Photovoltaic Module

PV modules (the type of mono and poly-crystalline) consist of PV cells that connected in series by two wires and normally attached in a series of 36 or 72. The amount of available light falling on these solar cells affects the production of electric
current. The temperature of the cell affects its voltage and the larger the cell, the more current it will produce. There are various types (Mono-crystalline, Poly-crystalline and Amorphous) and sizes (typically sized from 60 W to 170 W) of PV module that available in the PV market worldwide.

The reason to connect the cells in series is to provide a suitable voltage for battery charging as well as storage (non grid-tied system). Furthermore, it was also needed for the use of DC/DC converters in the solar charge controller system which required a specific voltage. Typical PV module use 36 solar cells connected in series and will have a total voltage of around 16 V (36 x 0.5 V) and this is why the individual solar PV cells which make up a solar module have a standard size (156 mm x 156 mm) (Yingli, 2013; KYOCERA, 2011; MITSUBISHI, 2007). There are also available modules with 30, 54, 60 and 72 cells connection. A 60 cells module will operate at a higher voltage than the 54 cells module which allows them to overcome the reduction in output voltage when the modules are operating at high temperatures. Figure 2.3 shows the different of form $I-V$ curve under different type of cell connections.

![I-V curve for various types of PV cell connections](image)

**Figure 2.3:** $I-V$ curve for various types of PV cell connections

Source: (Articles 2013)

There are three main panel types come from the three different forms of crystalline materials. In 2012, mono-crystalline module and poly-crystalline module are the most modules sold globally, approximately 93 % of all modules type while
Amorphous silicon module is approximately only 4.2 % sold globally (EvoEnergy, 2012).

2.2.3 The $I$-$V$ Curve and Maximum Power Point

The $I$-$V$ curve is a characteristic of any PV module which consists of the PV module current and voltage on its x-axis and y-axis respectively. A PV module can produce the power at an operating point, anywhere on the $I$-$V$ curve where the coordinates of the operating point are the operating voltage and current. There is a unique point near the knee of the $I$-$V$ curve, called a maximum power point (MPP), at which the module operates with the maximum efficiency and produces the maximum output power. The rectangle area as in Figure 2.4 is equal to the output power which is a product of voltage and current.

![Figure 2.4: $I$-$V$ and $P$-$V$ curve of a typical PV module working under Standard Test Condition (STC)](Source: (Articles 2013))
2.3 MAXIMUM POWER POINT TRACKING

Dang (1990), from California Polytechnic State University, Pomona was the first person that made an attempt to study MPPT on his research. The maximum power point tracker (MPPT) is now prevalent in grid-tied PV power systems and is becoming more popular in stand-alone systems. MPPT plays an important role in photovoltaic (PV) power systems because they maximize the power output from a PV system for a given set of conditions, and therefore maximize the array efficiency (Abdelmoula, Moughamir et al., 2014; Durgadevi, Arulselvi et al., 2011). MPPT’s found and maintain operation at the maximum power point, using an MPPT algorithm. Nowadays, this algorithm is executed using a microcontroller that used the PV current and voltage data to control the duty cycle that applied to the DC/DC converter circuit. There are many researches done on tracking the MPP with the entire algorithm proposed (Burmester, Rayudu et al., 2013; Muoka, Haque et al., 2012; Hohm and Ropp, 2000) but there is lack of source on which algorithm is appropriate for a suitable topology of a DC/DC converter. However, one particular algorithm, the perturb and observe (P&O) method, claimed by many in the literature to be inferior to others, continues to be by far the most widely used method in commercial PV MPPT (Charfi and Chaabene, 2014; Byunggyu, Gwonjong et al., 2011; Kazmi, Goto et al. 2009; Femia, Petrone et al., 2004; Hohm and Ropp, 2000).

2.3.1 Perturb & Observe Algorithm

The P&O algorithm is a simple method for MPPT. The algorithm is an iteration based approach to MPPT (Elgendy, Zahawi et al., 2012; Salas, Olías et al., 2006). A flowchart of the method can be seen in Figure 2.5. The first step in this algorithm is to sense the current, $I_k$ and voltage, $V_k$ coming out of the PV panel and these values is used to calculate the output power, $P_k$ of the panel. The algorithm then compares the present output power with the power from the previous iteration that has been stored in memory. If the algorithm is just in the first iteration the current power will be compared against some constant, $k$ placed in the algorithm during programming. The system compares the difference between the present power and the previous power against a predefined constant. This constant is placed within the algorithm to ensure that when
the method has found the MPP on the PV panel, the duty cycle will remain constant until any condition changes large enough to change the location of the MPP. If this step is not included the algorithm would constantly change the duty cycle, causing the operating point of the panel to move back and forth across the MPP. The movement across the MPP is an unwanted oscillation that can be disruptive to power flow and could also cause unwanted loss from not having the operating point right over the MPP at all times.

The next step in the algorithm is determining whether the current power, $P_k$ is greater than or less than the previous power, $P_{k-1}$. The answer to this tells the algorithm which branch of the flowchart to take next. No matter which direction the algorithm takes, the next step is to compare the voltage in the current, $V_{in(k)}$ and the voltage in the previous, $V_{in(k-1)}$ iterations. The voltage comparison tells the algorithm which side of the MPP the operating point is at thereby allowing the algorithm to adjust the duty cycle in the right direction, either a positive or a negative addition to the current duty cycle. The final step of the method is to actually change the duty cycle being output to the converter, and wait for the converter to stabilize before starting the process all over again.

The main advantage of choosing the P&O as an algorithm is easier and simple to implement and its low computational method. However, there are some limitations that cannot be ignored such like the oscillations around the MPP in steady state operation and slow response speed. But, these limitations can be reduced by optimizing the sampling rate depends on the converters’ dynamic (Kollimalla and Mishra, 2014; Sharma and Purohit, 2012; Femia, Petrone et al., 2004; Liu and Lopes, 2004).