**UNIVERSITI PUTRA MALAYSIA**

# *DUAL SEARCH MAXIMUM POWER POINT ALGORITHM BASED ON MATHEMATICAL ANALYSIS UNDER PARTIALLY- SHADED CONDITIONS*

**SHAHROOZ HAJIGHORBANI**

# DUAL SEARCH MAXIMUM POWER POINT ALGORITHM BASED ON MATHEMATICAL ANALYSIS UNDER PARTIALLY- SHADED CONDITIONS

By

SHAHROOZ HAJIGHORBANI

Thesis Submitted to the School of Graduate Studies. Universiti Putra Malaysia, in Fulfillment of the Requirements for the Degree of Doctor of Philosophy

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# DEDICATION

I would like to dedicate this thesis to my parents for their endless love, support, and encouragement. Thank you both for giving me strength to reach for the starts and chase my dreams. My sister, Neda, brother-in-law, Hamid, nephew, Arshan, and best friend, Alireza Azadpour, deserve my wholehearted thanks as well.

Abstract of thesis presented to the Senate of Universiti Putra Malaysia in fulfillment of the requirement for the Doctor of Philosophy

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**July 2016**

**Chairman : Mohd Amran Mohd Radzi, PhD**
**Faculty : Engineering**

Solar energy has drawn much attention in recent years because of high demand for green energy resources. Electrical power can be generated by using semiconductors in photovoltaic (PV) cells to convert solar irradiance into DC current. Each PV module has its own optimum point at which the power delivered from the PV is at its maximum value. Since the initial cost for using PV is high, it is essential to make the PV module to operate at its maximum power point (MPP). However, the non-linear relation between current and voltage for the PV system is a challengeable issue that results in a unique MPP for its power-voltage (*P-V*) curve. Under uniform conditions or without shading, there is a unique MPP on the *P-V* curve. By changing the irradiance and temperature, the value of MPP will be changed. The PV system is troubled with the weakness of nonlinearity between current and voltage under partially shaded conditions (PSCs). Under PSCs, there are multi-peak powers. Only one of these peak powers has the highest power, which is called global maximum power point (GMPP), and other peak powers are the local maximum power point (LMPP).

The maximum power point tracking (MPPT) algorithms under PSCs can be categorized generally in two groups. In the first group, the conventional techniques are combined with other techniques and the second group is based on the optimization methods. One of the main challenges of MPPT techniques under PSCs is ability of the algorithms to find the GMPP faster with minimal oscillation in power. Moreover, it is very important that the algorithms should be general and not so complicated which could be implemented for all systems.

Therefore, this research presents design and development of a novel method, which is called dual search maximum power point (DSMPP) algorithm, for tracking the GMPP under PSCs. The proposed method is based on mathematical analysis that reduces the search zone and simultaneously identifies the possible MPPs in the specified zone that leads to determining the GMPP in minimum time. In this work, the perturb and

observation (P&O) method based on duty cycle adjustment is introduced, which is modified to increase speed of the search and also to reduce the oscillation.

The simulation and experimental works have been performed to investigate behavior and performance of the proposed algorithm. The PV array in series-parallel (SP) configuration is considered as an input of the standalone system and mathematical model of this PV array under PSC has been developed. Moreover, the load sizing method for PSCs is also presented to avoid controller failure when detecting the GMPP. In evaluation part, the DSMPP algorithm has been compared with two other methods.

According to both simulation and experimental results, by implementing the DSMPP technique, the GMPP can be obtained faster. Moreover, the oscillation in power is reduced significantly. Interestingly, the experimental results under different irradiances also show that the proposed algorithm can detect the GMPP faster in comparison with other methods. The significant reduction of oscillation in power is observed to be due to implementation of the modified P&O.

As a conclusion, the DSMPP algorithm has successfully been performed to detect the GMPP under PSCs in minimum time, with low oscillation in power, and high accuracy as detecting the GMPP for different scenarios of shadowing.

Abstrak tesis yang dikemukakan kepada Senat Universiti Putra Malaysia sebagai memenuhi keperluan untuk ijazah Doktor Falsafah

**ALGORITMA DUAL CARIAN TITIK KUASA MAKSIMUM BERDASARKAN ANALISIS MATEMATIK DI BAWAH KEADAAN SEPARA TEDUHAN**


Oleh

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**Julai 2016**


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Tenaga suria telah menarik banyak perhatian dalam beberapa tahun kebelakangan ini kerana permintaan yang tinggi untuk sumber tenaga hijau. Kuasa elektrik boleh dihasilkan dengan menggunakan semikonduktor dalam sel fotovolta untuk menukar sinaran suria kepada arus DC. Setiap modul fotovolta mempunyai titik optimum sendiri yang mana kuasa yang dibekal daripada fotovolta adalah ada nilai maksimumnya. Oleh sebab kos permulaan menggunakan fotovolta adalah tinggi, adalah penting untuk memastikan modul fotovolta beroperasi pada titik kuasa maksimumnya. Walau bagaimanapun, hubungan tidak linear antara arus dan voltan bagi sistem fotovolta adalah isu mencabar yang membuatkan wujudnya titik kuasa maksimum yang unik bagi lengkung kuasa-voltannya. Di bawah keadaan seragam atau tanpa teduhan, terdapat satu titik kuasa maksimum pada lengkung kuasa-voltan. Dengan menukar sinaran dan suhu, nilai titik kuasa maksimum akan bertukar. Sistem fotovolta disukarkan lagi dengan kelemahan ketaklelurusan antara arus dan voltan di bawah keadaan separa teduhan. Di bawah keadaan separa teduhan, terdapat pelbagai kuasa puncak. Hanya satu daripada kuasa puncak ini mengandungi kuasa tertinggi, yang dipanggil titik kuasa maksimum global, dan kuasa puncak yang lain adalah titik kuasa maksimum tempatan.

Algoritma titik penjejakan titik kuasa maksimum di bawah keadaan separa teduhan boleh dikategorikan umumnya dalam dua kumpulan. Dalam kumpulan pertama, teknik konvensional akan digabungkan dengan teknik lain dan kumpulan kedua berdasarkan kepada kaedah pengoptimuman. Salah satu cabaran bagi teknik titik penjejakan kuasa maksimum di bawah keadaan separa teduhan adalah kebolehan algoritma berkenaan untuk mencari titik kuasa maksimum global lebih pantas dengan ayunan minima dalam kuasa. Tambahan lagi, adalah sangat penting bagi algoritma berkenaan bersifat umum dan tidak terlalu rumit yang boleh digunakan pada semua sistem.

Oleh itu, penyelidikan ini membentangkan reka bentuk dan pembangunan satu kaedah novel, yang dipanggil algoritma carian dual titik kuasa maksimum, untuk menjejak titik kuasa maksimum global di bawah keadaan separa teduhan. Kaedah yang dicadangkan adalah berdasarkan analisis matematik yang mengurangkan zon pencarian dan sekaligus mengenal pasti titik kuasa maksimum yang mungkin dalam zon ditetapkan yang membawa kepada penemuan titik kuasa maksimum global dalam masa yang minima. Dalam kerja ini, kaedah usik dan cerap berdasarkan pelarasan kitaran tugas diperkenalkan, yang diubah suai untuk meningkatkan kelajuan carian dan juga mengurangkan ayunan.

Kerja simulasi dan eksperimen telah dilaksanakan untuk menilai kelakuan dan prestasi algoritma yang dicadangkan. Jajaran fotovolta dalam susunan sesiri-selari ditetapkan sebagai masukan kepada sistem berdiri sendiri dan model matematik jajaran fotovolta ini di bawah keadaan separa teduhan telah dibangunkan. Tambahan lagi, kaedah pensaizan beban bagi keadaan separa teduhan turut dibentangkan untuk mengelak kegagalan pengawal apabila mengesan titik kuasa maksimum global. Dalam bahagian penilaian, algoritma carian dual titik kuasa maksimum telah dibandingkan dengan dua kaedah lain.

Berdasarkan kedua-dua keputusan simulasi dan eksperimen, dengan melaksanakan teknik dual carian titik kuasa maksimum, titik kuasa maksimum global boleh dicapai dengan lebih pantas. Tambahan lagi, ayunan dalam kuasa berkurang dengan ketara. Menariknya, keputusan eksperimen di bawah sinaran berlainan juga menunjukkan algoritma yang dicadangkan boleh mengesan titik kuasa maksimum global dengan lebih pantas jika dibandingkan dengan kaedah lain. Pengurangan ketara pada ayunan dalam kuasa dapat dilihat oleh sebab perlaksanaan usik dan cerap yang diubah suai.

Kesimpulannya, algoritma dual carian titik kuasa maksium telah berjaya beroperasi untuk mengesan titik kuasa maksimum global di bawah keadaan separa teduhan dalam masa yang minima, dengan ayunan rendah dalam kuasa, dan ketepatan tinggi dalam mengesan titik kuasa maksimum global bagi senario teduhan yang berlainan.

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This thesis is only a beginning of my journey.

I certify that a Thesis Examination Committee has met on 1 July 2016 to conduct the final examination of Shahrooz Hajighorbani on his thesis entitled "Dual Search Maximum Power Point Algorithm Based on Mathematical Analysis under Partially-Shaded Conditions" in accordance with the Universities and University Colleges Act 1971 and the Constitution of the Universiti Putra Malaysia [P.U.(A) 106] 15 March 1998. The Committee recommends that the student be awarded the Doctor of Philosophy.

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This thesis was submitted to the Senate of Universiti Putra Malaysia and has been accepted as fulfillment of the requirement for the Doctor of Philosophy. The members of the Supervisory Committee were as follows:

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## LIST OF ABBREVIATIONS

| | |
|---|---|
| ANN | Artificial neural network |
| ACO | Ant colony optimization |
| ADC | Analog-to-Digital converter |
| BL | Bridge-link |
| CV | Constant voltage |
| CCM | continuous conduction mode |
| CE | Change of error |
| CCS | Code Composer Studio |
| DSP | Digital signal processor |
| DSMPP | Dual search maximum power point |
| DC | Direct current |
| DCM | discontinuous conduction mode |
| DE | Differential evaluation |
| FL | Fuzzy logic |
| FLC | Fuzzy logic controller |
| FS | Fibonacci search |
| FA | Flashing fireflies |
| GA | Genetic algorithm |
| GMPP | Global maximum power point |
| GTO | gate-turn off thyristor |
| HC | Honey-comb |
| IC | Incremental conductance |
| IGBT | insulated-gate bipolar transistor |
| LMPP | Local maximum power point |
| MPP | Maximum power point |
| MPPT | Maximum power point tracking |
| MOSFET | metal–oxide–semiconductor field-effect transistor |
| NB | Negative big |

| | |
|---|---|
| NM | Negative medium |
| NS | Negative Small |
| OC | Open-circuit |
| PV | Photovoltaic |
| P&O | Perturb and observation |
| PSO | Particle swarm optimization |
| PSCs | Partially shaded conditions |
| PI | proportional-integral |
| PID | proportional-integral-derivative |
| POC | Perturb, observe, and check |
| PB | Positive big |
| PM | Positive medium |
| PS | Positive small |
| PCB | Printed circuit board |
| PWM | Pulse width modulation |
| SP | Series-parallel |
| STC | Standard test condition |
| SC | Short-circuit |
| SRC | Standard reporting condition |
| SOP | Status of operation |
| TCT | Total-cross-tied |
| ZE | Zero |

# CHAPTER 1

# INTRODUCTION

## 1.1 Research Background

Fossil fuels are sources of non-renewable energy that are finite; as a result, the sources of fossil fuels will eventually become depleted, resulting in a high cost of fuel while also affecting the environment, in particularly global warming [1]. In contrast, there are certain types of renewable energy resources, such as solar and wind energy, that are continually resupplied and are virtually inexhaustible [2, 3]. Among renewable energy resources, energy from the sun is commercially viable because of its potential for high productivity and low emissions [4]. A photovoltaic (PV) system generates electricity by the direct conversion of the sun's energy into electricity [5]. This simple principle involves advanced technology used to build efficient devices, namely solar cells, which are the key components of a PV system and require semiconductor processing techniques in order to be manufactured at low cost and high efficiency. In PV systems, there are certain factors that can create power losses, such as current and voltage mismatch [6, 7], the accumulation of dust on a PV module's surface [8], the angle of prevalence of such radiation, and the maximum power point (MPP) of a PV system. So, by considering all the advantages and disadvantages of this source of energy, it is necessary to increase the efficiency to become more commercial [9, 10].

The PV system can be categorized in three general types: standalone, grid connected, and hybrid systems [11-13]. The standalone PV system includes dc-dc converter and specific load such as water pump and lighting [14]. The grid connected PV system can include dc-dc and dc-ac converters, in which the output current and voltage of the system are connected directly to grid. Hybrid PV systems most commonly take the form of PV systems combined with wind turbines or diesel generators. They would most likely be found on island, yet they could also be built in other areas.

In this work, the standalone system is considered which includes the dc-dc boost converter to increase the output voltage to supply the load. The PV system contains a controller which performs maximum power point tracking (MPPT) algorithm. The general schematic of system is shown Figure 1.1.

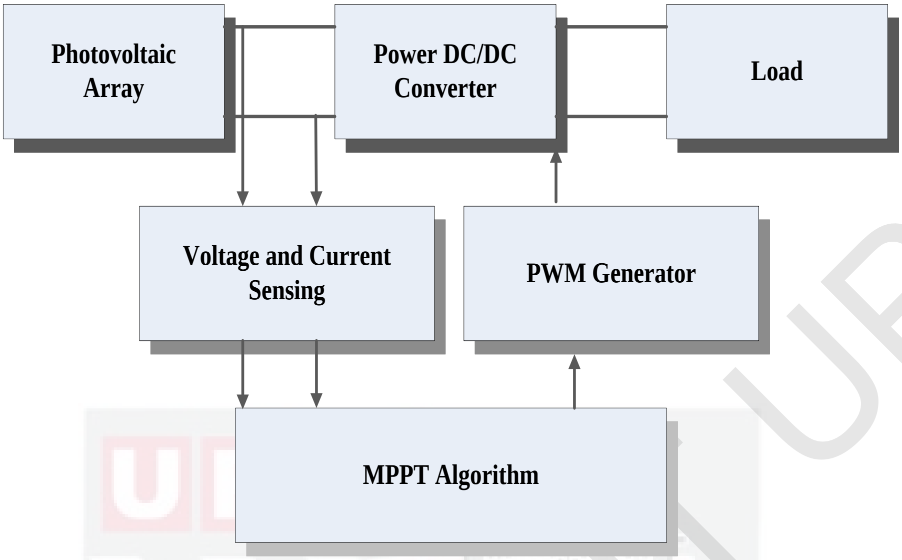


**Figure 1.1: The general schematic of considered standalone system**

PV systems are distinguished by their *I-V* and *P-V* characteristics, where *I*, *V*, and *P* are the current, voltage, and power of the PV system, respectively. Each type of load connected to a PV system has a load line characteristic. As shown in Figure 1.2, the intersection point between the load line and *I-V* characteristic of a PV system defines the operating point, which can be varied by changing the load value [15]. Thus, the output power of a PV system, which is defined by multiplying the current by the voltage, ranges from nearly zero to the maximum value of the PV system. To solve this problem of variable power output and to simultaneously avoid further power losses, a MPPT algorithm is used to determine the maximum available power of a PV system which is as interface between the PV system and load [16, 17]. According to previous studies, the PV system with MPP tracker is able to save 30%-40% more energy in comparison with the system without tracker [18-20].

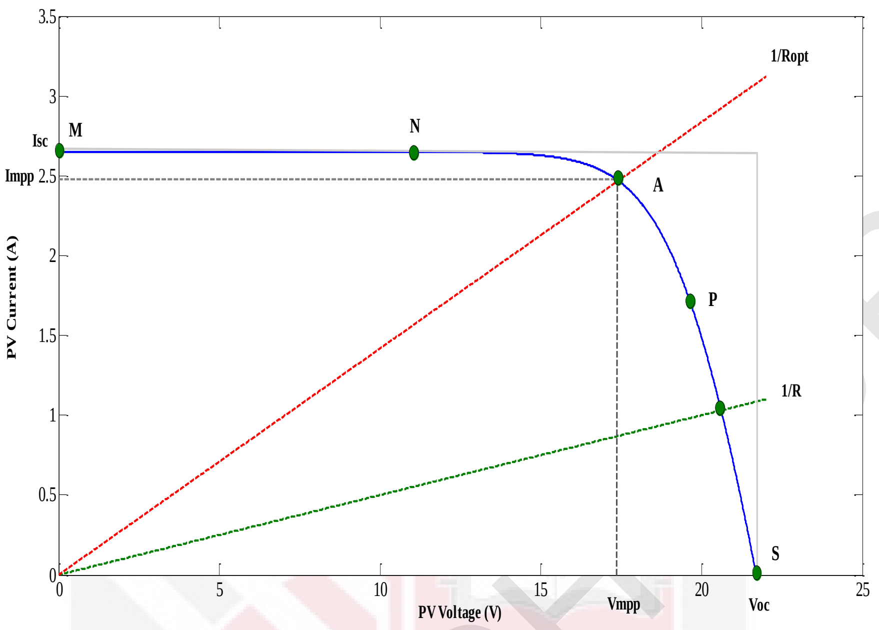


**Figure 1.2: *I-V* curve of PV system for different load lines**

In recent years, many different MPPT algorithms [21] have been presented and can be classified into two general groups. The first group is conventional methods, such as perturb and observation (P&O) [22-25], incremental conductance (IC) [26, 27], sliding mode [28, 29], and constant voltage (CV) [30, 31], and the second group is artificial intelligence methods, such as fuzzy logic (FL) [32-36], artificial neural network (ANN) [37, 38] , ant colony optimization (ACO) [39], genetic algorithm (GA) [40, 41], and particle swarm optimization (PSO) [42, 43]. Among the conventional methods, P&O is the most frequently used because it is easy to be implemented in PV system controllers.

Under uniform conditions, in which there is only a single peak power point, generally, all of the above-mentioned methods are successful in finding the MPP, and some of them have their own particular advantages, such as a short time required to obtain the MPP and acceptable with oscillations [44-46]. However, in some cases, especially under partially shaded conditions (PSCs), there are multiple power peaks; one of these peaks is the global maximum power point (GMPP), which has the highest power, and the other peaks are local maximum power points (LMPPs). According to some studies [47-49], the power loss can vary from 10 to 70% due to PSC. To determine the GMPP, smart techniques should be combined with the above-mentioned methods. In Figure 1.3, the *P-V* curve with multiple peaks of power which includes the LMPPs and GMPP is shown.

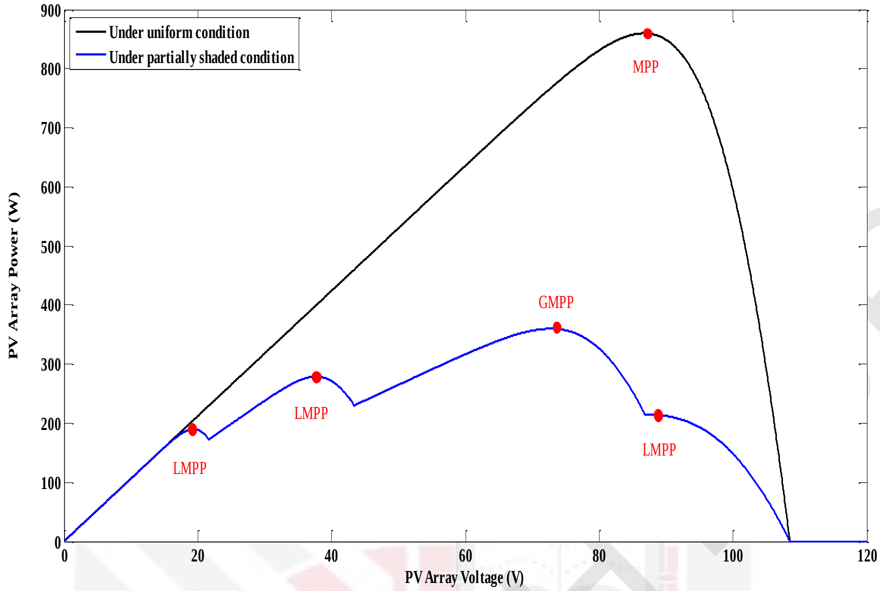


**Figure 1.3: *P-V* curve of PV array under shaded condition**

## 1.2 Problem Statement

As mentioned earlier, the PV system suffers from nonlinearity between current and voltage under PSC. In recent years, many researchers have presented different strategies for finding the GMPP under shaded conditions. Generally, the presented methods can be categorized in two general groups. The first group is hybrid methods like two stage methods which are based on combination of classical methods with other techniques, and the second group is the methods based on artificial intelligent methods. In the first group, those methods usually look for all possible MPPs by scanning the whole *P-V* curve, which increases the searching time [50, 51], especially in the PV systems with large number of the modules in strings, and subsequently increases the power loss as well [52].

The second group is based on artificial intelligent methods such as ANN, FL, PSO, and ant colony optimization (ACO). These methods are quite efficient, but each has its own drawbacks. For example, ANN must provide enough experimental data to be trained. In the FL method, there are certain primary components, such as fuzzification and defuzzification that require large computational memory; in addition, the specific range of membership functions and rules should be varied according to the specific application. The PSO method is more useful in large PV systems with a large number of strings, but this method requires experience for setting the parameters. In some works, specific conditions are assumed for designing a new MPP algorithm and only specific *P-V* and *I-V* curves are considered. In MPPT methods based on PSO, by increasing number of the particles [53], the accuracy can be increased, but it leads to increasing of the calculation burden. The complexity of the PSO method is another disadvantage of MPPT; in reality, the practical controllers such as microcontroller and digital signal processor (DSP) need to have bigger memory if the algorithm is complicated. Another artificial intelligent method used for MPPT is the ACO method, also has its own disadvantage. In this method [39], if the generated ants are distant from the GMPP, the likelihood of failing in detecting the GMPP is very high.

Therefore, by considering all advantages and drawbacks of the above mentioned existing methods, finding a new method which can reduce searching zone and consequently identifying the GMPP in the minimum amount of time is essential.

## 1.3 Aim and Objectives

The main aim of this work is to design a novel hybrid method which is called dual search maximum power point (DSMPP) algorithm for a standalone PV system to detect the GMPP under PSCs. The detailed objectives in order to achieve the aim are listed as follows:

1. To model PV array in series-parallel (SP) configuration and to design dc-dc boost converter for the considered PV array.
2. To design, develop, and integrate a novel MPPT algorithm which can detect the GMPP under PSCs.
3. To simulate and evaluate performance of the MPPT algorithm with the PV array under various PSCs in terms of to reach the GMPP, oscillation in power and accuracy.
4. To experimentally validate the MPPT controller in terms of time to reach the GMPP, oscillation in power and accuracy.

The proposed MPPT algorithm is implemented in the control unit of the PV system and its performance is evaluated by simulation in MATLAB/Simulink and then tested and verified in the laboratory by developing the experiment prototype.

## 1.4 Scope and Limitations

This work aims to simulate and implement a novel hybrid MPPT algorithm for PV system operating under PSCs. The considered PV module in this work is based on KC40T PV modules connected in the SP configuration. In actual PV power plants, the SP configuration is the most common connection since there are advantages to both series and parallel connections. In recent years, different topologies have been presented but most of them rely on SP and total-cross-tied (TCT) configurations. The main important note for dealing with the re-configurable topologies of the PV array is the number of switches and sensors used in the selected configuration. In SP configuration, the number of switches is much lower than TCT configuration. In the considered PV array, one diode is connected in parallel with each PV module to avoid the hotspot phenomenon and also to reduce the effect of mismatch which leads to increase output power of the system.

For practical validation, the programmable solar array simulator power supply 62100H-600S series is used to generate *I-V* and *P-V* curves under PSCs. This solar array simulator provides simulation of open-circuit voltage up to 1000 V and short-circuit current up to 25 A. The dc-dc boost converter is used as interface between PV array and load and then, the whole system is simulated, tested and verified under PSCs. The temperature effect is neglected since change of temperature is very slow in comparison with change of irradiance.

## 1.5 Thesis Organization

The remainder of this thesis is organized as follows:

**Chapter 2** presents an overview on PV system which is describing the PV cell, equivalent circuit of PV cell, and mathematical model of PV array under uniform and PS conditions. After that, a comprehensive study of boost, buck, and buck-boost converters in order to select the proper topology for this work has been done. Finally, the different MPPT algorithms and further analyses under PSC are explained.

**Chapter 3** describes the methodology of the work which includes the mathematical model of the PV module and array under uniform and PSCs, development of the dc-dc boost converter for the considered system, design of the proposed method by describing the mathematical analysis, explanation on the PV simulator, and description on implementing experiment setup and operation of DSP via Simulink/MATLAB for the proposed method.

**Chapter 4** presents the simulation results for the completed PV system by implementing the proposed method which has been done via Simulink/MATLAB. Then, the experimental setup with details of experiment design and implementation are presented. Finally, the experimental results for the proposed method by comparing with other methods are presented.

**Chapter 5** summarizes the findings obtained from implementation of the proposed method, and also recommends the potential future works.

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