SOLAR PHOTOVOLTAIC SYSTEM BASED ON PERTURB AND OBSERVE MAXIMUM POWER POINT TRACKING WITH TRAPEZOIDAL RULE APPROACH UNDER PARTIAL SHADING CONDITIONS

By

ALTWALLBAH NEDA MAHMOD MOHAMMAD

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

November 2022

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DEDICATION

This thesis is dedicated to

My lovely kids:

With love, respect and a bunch of memories
Indeed, we belong to Allah and indeed to Him we will return.

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

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Chairman : Professor Mohd Amran Mohd Radzi, PhD
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Photovoltaic (PV) energy has grown enough to be the most popular renewable energy source due its sustainability and advantageous properties. However, the performance of the PV panels is highly sensitive to weather variations and the incident illumination. PV system performance is highly impacted by partial shading conditions (PSCs), The shading affects the pattern of the power- voltage (P–V) characteristic curve to contain more than one power peak, which creates difficulties on extracting the maximum power point (MPP), and hence, the generated power will reduce. Many maximum power point tracking (MPPT) algorithms were proposed in literature, such as conventional and soft computing algorithms.

Among all proposed algorithms, perturb and observe (P&O) algorithm is the most popular due to its simplicity and good convergence. However, P&O suffers from considerable oscillation in the output power, and in the original form, P&O is not capable to perform efficiently under PSC, and needs improvement to be prosperous. Several works proposed different modifications on P&O algorithm to handle the main drawbacks, in addition to combine the P&O algorithm with a soft computing algorithm to track global peak under PSC, which is known as the hybrid approach. These improvements presented an enhanced performance, but the performance enhancement comes at the expense of the algorithm simplicity, computational overhead, requirements and tracking speed. Therefore, the proposed work has the main target on improving P&O by three sequenced phases. The first is to introduce a modification in conventional P&O algorithm, to be able to achieve the global maximum power point (GMPP) effectively in the presence of shading conditions. The second is to propose a hybrid MPPT algorithm based on modified P&O algorithm assisted by Extremum Seeking Control (ESC) approach, in order to maximize the extracted PV power under complex PSC. The third is to present a novel P&O GMPP tracking algorithm. Employing trapezoidal rule concept as a new consideration in the P&O tracking process is successful to result a highly

efficient approach in extracting the extreme available power from the PV array under PSCs and severe cases of weather fluctuation. The three proposed algorithms are tested under different cases of PSC, considering a comprehensive weather fluctuation such as sudden and fast change in incident radiation levels. The algorithm is validated using two different methodologies: a simulation model in MATLAB/Simulink and hardware implementation. Both simulation and hardware results confirm that the proposed algorithm provides excellent efficiency of 100% and 99.6% respectively. The GMPP is achieved within less than 100 ms, which is extremely advantageous tracking time, that avoids the power losses. In addition, the minimal steady-state oscillation has been achieved, with the desired level of simplicity without the need to complicated computations or random particles.

In this research, the performance of the P&O algorithm is gradually improved, starting with modified P&O and progressing to hybrid P&O and finally to a new version of P&O that can be efficiently applicable under PSC as well as under uniform weather conditions.

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

SISTEM FOTOVOLTA SURIA BERASASKAN PENJEJAKAN TITIK KUASA MAKSIMUM USIK DAN CERAP DENGAN PENDEKATAN PERATURAN TRAPEZOIDAL DI BAWAH KEADAAN SEPARA TEDUHAN

Oleh

NEDA MAHMOD MOHAMMAD ALTWALLBAH

November 2022

Pengerusi : Profesor Mohd Amran Mohd Radzi, PhD
Fakulti : Kejuruteraan

Tenaga fotovolta (PV) telah cukup berkembang untuk menjadi sumber tenaga boleh diperbaharui yang paling popular kerana sifatnya yang mampan dan berkelebihan. Walau bagaimanapun, prestasi panel PV sangat sensitif terhadap perubahan cuaca dan pencahayaan kejadian. Prestasi sistem PV sangat dipengaruhi oleh keadaan teduhan separa (PSC), Teduhan mempengaruhi corak lengkung sifat ciri kuasa–voltan (P–V) untuk mengandungi lebih daripada satu puncak kuasa, yang menimbulkan kesukaran untuk mengekstrak titik kuasa maksimum (MPP), dan oleh itu, kuasa yang dijana akan berkurangan. Banyak algoritma penjejakan titik kuasa maksimum (MPPT) telah dicadangkan dalam literatur, seperti algoritma konvensional dan pengkomputeran lembut.

Antara semua algoritma yang dicadangkan, algoritma usik dan cerap (P&O) adalah yang paling popular kerana keringkasannya dan penumpuan yang baik. Walau bagaimanapun, P&O mengalami ayunan yang besar dalam kuasa keluaran, dan dalam bentuk asal, P&O tidak mampu untuk beroperasi dengan cekap di bawah PSC, dan memerlukan penambahbaikan untuk berjaya. Beberapa kerja mencadangkan pengubahsuaian berbeza pada algoritma P&O untuk mengendalikan kelemahan utama, ditambah dengan menggabungkan algoritma P&O dengan algoritma pengkomputeran lembut untuk menjejaki puncak global di bawah PSC, yang dikenali sebagai pendekatan hibrid. Penambahbaikan ini memberikan prestasi yang dipertingkatkan, tetapi peningkatan prestasi datang dengan mengorbankan keringkasan algoritma, beban pengiraan, keperluan dan kelajuan penjejakan. Oleh yang demikian, kerja yang dicadangkan mengandungi sasaran utama pada penambahbaikan P&O dengan tiga fasa tersusun. Pertama ialah memperkenalkan pengubahsuaian dalam algoritma P&O konvensional, untuk dapat mencapai titik kuasa maksimum global (GMPP) yang berkesan dengan kehadiran keadaan teduhan. Yang kedua ialah mencadangkan algoritma MPPT hibrid berdasarkan algoritma P&O yang diubah suai dibantu oleh pendekatan Kawalan Mencari

Ekstrem (ESC), untuk memaksimumkan kuasa PV yang diekstrak di bawah PSC yang kompleks. Yang ketiga ialah membentangkan algoritma pengesanan P&O GMPP novel. Menggunakan konsep peraturan trapezoid sebagai pertimbangan baharu dalam proses penjejakan P&O berjaya menghasilkan pendekatan yang sangat cekap dalam mengekstrak kuasa tersedia yang melampau daripada tatasusunan PV di bawah PSC dan kes turun naik cuaca yang teruk. Tiga algoritma yang dicadangkan diuji di bawah kes PSC yang berbeza, dengan mengambil kira turun naik cuaca yang menyeluruh seperti perubahan mendadak dan pantas dalam tahap sinaran kejadian. Algoritma ini disahkan menggunakan dua kaedah berbeza: model simulasi dalam MATLAB/Simulink dan pelaksanaan perkakasan. Kedua-dua keputusan simulasi dan perkakasan mengesahkan bahawa algoritma yang dicadangkan memberikan kecekapan yang cemerlang masing-masing dengan 100% dan 99.6%. GMPP dicapai dalam masa kurang daripada 100 ms, yang merupakan masa penjejakan yang sangat berfaedah, yang mengelakkan kehilangan kuasa. Tambahan pula, ayunan keadaan mantap yang minimum telah dicapai, dengan tahap keringkasan yang dikehendaki tanpa memerlukan pengiraan yang rumit atau zarah rawak.

Dalam penyelidikan ini, prestasi algoritma P&O dipertingkatkan secara beransur-ansur, bermula dengan P&O diubah suai dan berkembang kepada P&O hibrid dan akhirnya kepada versi baharu P&O yang boleh digunakan dengan cekap di bawah PSC serta dalam keadaan cuaca yang seragam.

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

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This is to confirm that:

- the research conducted and the writing of this thesis was under our supervision;
- supervision responsibilities as stated in the Universiti Putra Malaysia (Graduate Studies) Rules 2003 (Revision 2012-2013) are adhered to.

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LIST OF ABBREVIATIONS

ABC	Artificial bee colony
ACO	Ant colony optimization
ADC	Analog to digital converter
ANN	Artificial neural network
BOA	Butterfly optimization algorithm
CS	Cuckoo algorithm
CSO	Chicken swarm optimization
DAC	Digital to analog converter
DLCI	Dynamic leader based collective intelligence
DSP	Digital signal processor
ESC	Extremum Seeking Control
ePWM	Enhanced pulse width modulator
FL	Fuzzy logic
GA	Genetic algorithm
GMPP	Global maximum power point
GWO	Grey wolf optimizer
HC	Hill climbing
HPF	High-pass filter
IC	Incremental conductance
DSP	Digital Signal Processor
I-V	Current- voltage
ISSA	Improved squirrel search algorithm
LA	Learning Automata

LMPPs	Local maximum power points
LPF	Low-pass filter
LPSO	Levy flight based particle swarm optimizations
MFO	Moth-flame optimization
MKE	Monkey king evolution
MPP	Maximum power point
MPPT	Maximum power point tracking
MSSA	Memetic salp swarm algorithm
OD	Overall distribution
OP	Operating point
P&O	Perturb and observation
PCB	Printed circuit board
PSC	Partial shading condition
PSO	Particle swarm optimization
PV	Photovoltaic
P–V	Power–voltage
PWM	Pulse width modulator
RM	Measuring resistance
S	Series
SP	Series-parallel
SSA	Salp swarm algorithm
THD	Total harmonic distortion
WOA	Whale optimization algorithm

LIST OF SYMBOLS

I_{max}	Maximum current
I_{PV}	Photovoltaic current
I_{ref}	Reference current
I_{SH}	Short circuit current
P_{Ref}	Reference Power
V_{Ref}	Reference Voltage
A_{ref}	Reference Area
V_{max}	Maximum voltage
C_{out}	Output capacitor
N_S	Series number of cells
N_P	Parallel number of cells
R_{mpp}	Resistance of PV array at MPP
Rs	Series resistance
Rp	Parallel resistance
T	Temperature
Voc	Open circuit voltage
V_T	Thermal voltage of PV module
K	Boltzmann constant
q	Electron charge
a	Diode ideality factor
D	Duty cycle
f_S	Switching frequency
L	Inductor

C	Capacitor
ω	Sinusoidal perturbation frequency
ω_L	Low-pass filter frequency
ω_H	High-pass filter frequency

CHAPTER 1

INTRODUCTION

1.1 Research Background

The electrical power generation from fossil fuel sources have been threatened of being no longer sufficient due to the increased energy demand throughout the world. The enhancement of living standards and the significant development in industry besides the considerable growth of population are the main factors that aid to exhausting the energy resources based on the fossil fuels such as oil, gas and coal while the time passing [1]. Therefore, the primary universal attention is to realize new energy resources, which are renewable and sustainable, having no noise or any bad effect on the environment, and promising the world with safe future. These features are fulfilled through renewable energy sources, such as solar and wind energy, that are continually available and are practically unlimited [2]. Among the efficient renewable energy sources, photovoltaic (PV) solar energy has been grown enough to be the most popular due to its sustainability, purity and simplicity [3].

The sunlight is converted into direct current using semiconductor materials without any harmful dissipation or carbon release. However, there are several factors that can impact the PV performance, such as irradiation level, temperature and the panel age itself [4]. Therefore, many researchers are interested in optimizing the power extraction from PV systems. The main target is to boost the conversion efficiency, and that can be approached by controlling the operating point of the PV panel to be conformable with the maximum power point (MPP). Therefore, maximum power point tracking (MPPT) control is significant and essential target in PV system. Hence, identifying the suitable MPPT system that is able to deliver the maximum possible power to the load at all times is a big challenge [5].

In general, PV power systems are classified based on their functions, operations, components, configurations, and how the equipment are connected with electrical loads. The two main classifications are grid-connected systems and stand-alone systems [6]. Grid-connected PV systems are interconnected in parallel with the electric utility grid, and can incorporate dc-dc and dc-ac converters, in which the output current and voltage of the system are connected directly to grid. Stand-alone PV systems are operated independently of the electric utility grid. It can be designed and sized to supply dc electrical loads, and consist of dc-dc converter and specific load such as lighting [7]. These types of PV systems can be powered by a PV array only, or can use wind, engine-generator or utility power as additional power sources in what is known as a PV-hybrid system. The standalone PV system is considered in this work, including its significant components; the dc-dc boost converter and the controller for MPPT algorithm. The general block diagram of the stand-alone PV system is shown Figure 1.1.

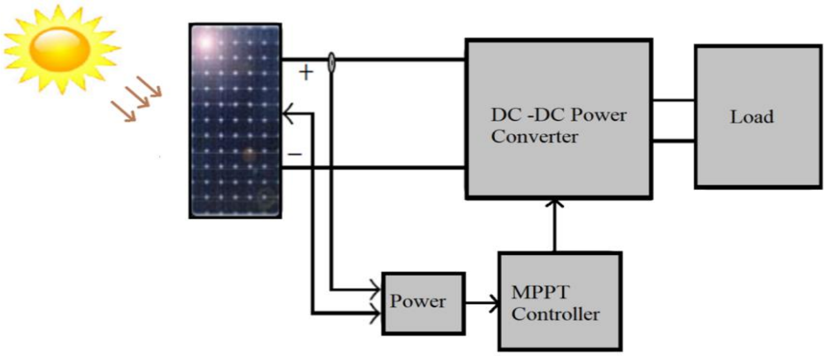

Figure 1.1 : The block diagram of the stand-alone PV system

PV systems can be described precisely by their characteristics curves of current- voltage (I-V) and power- voltage (P-V). These curves can give important information about PV modules performance, such as, open circuit voltage V_{oc}, short circuit current I_{sh}, maximum power point (MPP), operating point (OP), maximum current I_{max}, and maximum voltage V_{max}, as shown in Figure 1.2. These parameters are essentials for using, testing, designing, and controlling PV systems [8]. As observed, the OP is the point of intersection between the load line and I-V curve.

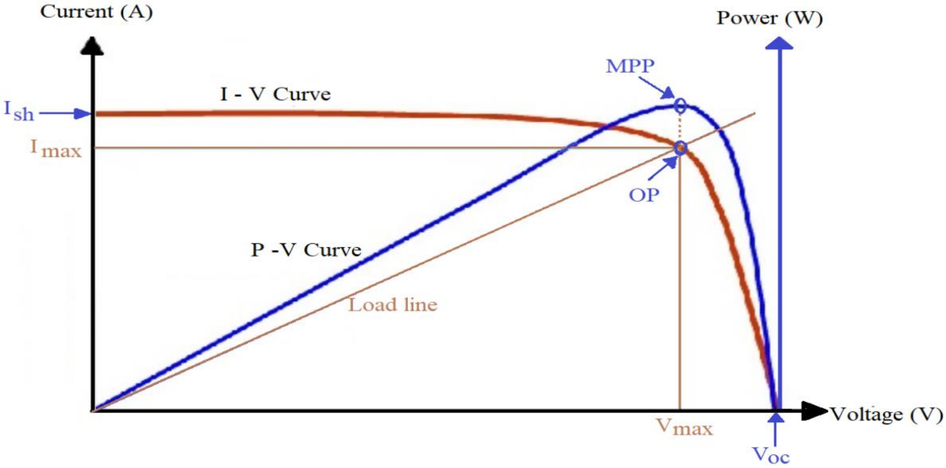

Figure 1.2 : I-V and P-V characteristics curves for PV modules

PV systems performance is affected by the surrounding weather conditions, which can impact the power conversion efficiency. PV system can work under both uniform irradiance and partially shaded conditions. When PV modules receive uniform radiation, then single MPP will be presented in the P-V curve. Meanwhile, in the presence of PSCs, the P-V curve of PV array will contain multiple power peaks which are called local maximum power points (LMPPs), while the peak of the highest power is known as global maximum power point (GMPP), as presented in Figure 1.3.

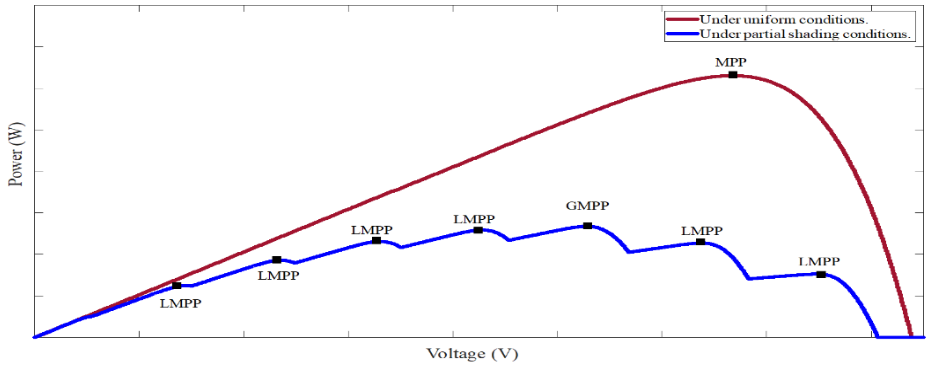

Figure 1.3 : P-V curve of PV array under uniform and PSCs

Based on the nonlinear electrical characteristics and dependence on weather conditions, the PV arrays may have failed to operate at its actual MPP [9]. Therefore, MPPT controlling is essential to overcome such problem and to check whether the PV system operates at the correct MPP [10]. MPPT systems are controlled by different algorithms and techniques. Many different MPPT algorithms have been proposed in recent years, and can be categorized into two main groups. The conventional MPPT algorithms and the intelligent soft computing algorithms, considering the modified algorithms as well as the hybrid algorithms. Conventional MPPTs are extremely popular. The key benefits of these are their simplicity and ease of use. These approaches can work efficiently under uniform irradiation, when a single MPP is existed. Soft computing is a term that refers to the optimization, bio-inspired, and artificial intelligence algorithms. These algorithms are more complicated than conventional algorithms, but they provide better tracking results. Hybrid MPPT methods are frequently used to overcome the drawbacks of single algorithms and generate superior outcomes. Hybrid MPPT approaches have been presented in the literature as a solution to the problems with conventional and soft computing methods. Hybrid methods can be two conventional methods combined, a soft computing-based algorithm combined with a conventional algorithm, or two soft computing-based algorithms.

Perturb and observe (P&O), hill climbing (HC), and incremental conductance (IC) are the most popular conventional algorithms and are extensively investigated in literatures. Beside of their low cost, simplicity and the low computation time, they are able to work efficiently under uniform weather conditions and can track the MPP [11]. Nevertheless, these algorithms have two main drawbacks. First, persistent oscillation around the achieved MPP is produced, and secondly, the direction of the correct tracking under PSC can be missed and clings to the nearest LMPP [12]. Moreover, several modifications have been introduced on conventional MPPT algorithms, such as considering more than one stage P&O [13] and scanning search MPPT [14] algorithms. In addition, some researchers have given their attention to apply the extremum seeking control (ESC) method, which is performed to seek the maximum or the minimum of a nonlinear map [15]. This method and modified conventional algorithms are still not efficient enough under PSCs. To overcome these limitations, researchers have turned on the soft computing algorithms. For the soft computing algorithms, the fuzzy logic control (FLC) and artificial neural network (ANN) have presented good performance. However, FLC algorithm requires pre knowledge of the system for tracking process with complex fuzzy rules [16], and a separate sensor arrangement is needed to be presented in ANN, which increases the cost [17]. An advantageous enhancement in tracking efficiency has been obtained by some of nature-inspired soft computing algorithms such as the genetic algorithm (GA) and the particle swarm optimization (PSO) algorithm. However, they are complex and require high computation time and low convergence speed. Furthermore, a big attention is paid on a hybrid MPPT algorithms. Enhancing the energy conversion efficiency is the main target of all hybrid MPPT, that each of the incorporated algorithms have its own advantages and disadvantages.

Based on reviewing most of the MPPT algorithms suggested in literature, it can be concluded that one of the performance aspects is being improved at the expense of the other. Therefore, making a comprehensive enhancement on the MPPT algorithm performance is a major challenge, tacking in account the algorithm complexity, tracking speed, stability, accuracy, oscillations around the maximum tracked power and the PV array's configuration dependency under any weather fluctuation.

1.2 Problem Statement

P&O is the most frequently used MPPT algorithm due to its simplicity, precision, and low cost. The idea of the P&O algorithm is based on the observation of the array output power and on the perturbation on the array voltage. Hence, it is periodically perturbing the operating voltage and comparing the power with the previous instant. If the changes in power is positive, then the operating point is in the correct direction towards the MPP. If the change is negative, then the perturbation sign has to be reversed. The same for the next cycle until the first MPP is tracked. The perturbation step size is an important factor in determining the system's performance. The larger the step size, the faster the reaction, but the higher the oscillation around the monitored MPP. Smaller step sizes, on the other hand, result in less power loss but slower reaction. This difficult trade-off became a key weakness in the P&O MPPT algorithm. The most significant disadvantage takes place under the occurrence of PSC. The multiple maximum peaks cause confusion to the P&O MPPT. The perturbing and observing process cannot continue after the first local MPP, where the power change begins to be negative. Then the perturbation direction must be reversed, without considering any higher MPPs. As a result, the extracted maximum possible power is highly impacted.

Briefly, the conventional P&O MPPT method has two main flaws: The generated steady state oscillation and the inability to distinguish the actual MPP under PSC. These shortcomings affect the power generation and the system performance efficiency. Therefore, the algorithm need to be modified properly to enhance the performance under any weather fluctuations. To address these two limitations, numerous researchers devised various modifications to the method, however, enhancing the performance while keeping the beneficial original features is still a big challenge. This work will present a clear enhancement on P&O algorithm performance under PSC and other weather fluctuations, without losing the simplicity or adding complicated computations and procedures.

1.3 Aim and Objectives

The main aim of this work is to improve the P&O MPPT algorithm to be able to perform efficiently under PSCs as well as any case of weather fluctuations. This main aim can be achieved by three essential objectives:

1. To design an enhanced and adaptive P&O algorithm which is able to achieve the extremely maximum power effectively in the presence of shading conditions.
2. To formulate a hybrid MPPT algorithm based on modified P&O algorithm assisted by ESC approach, in order to perform under complex PSC.
3. To develop P&O tracking algorithm based on trapezoidal rule with simplicity of implementation for the fastest tracking speed and accurate performance of GMPP.

1.4 Scope and Limitations

This research primarily focuses on improving the performance of the conventional P&O MPPT under PSC and any case of weather variations. Three proposed MPPT algorithms are designed for controlling the PV system. The performance of the proposed algorithms along with well-designed boost converter is validated and simulated in MATLAB/Simulink, and then tested and verified in the laboratory by developing the experiment prototype using TMS320F28335 microprocessor. The dc-dc boost converter is used as interface between PV array and load, and then, the whole system is simulated, tested and validated under PSCs. Temperature is fixed at 25C° in all considered tests, and effect of temperature variation is neglected since change of temperature is very slow in comparison with change of irradiance.

The detailed scopes in order to achieve the aims of this work are established by several steps, starting by modeling different configurations of PV arrays, connected in series and series-parallel. A proper dc-dc boost converter is designed based on the considered PV array configuration and the system requirements. The proposed MPPT algorithms which can detect the GMPP under PSC are designed and simulated to evaluate their performance with the different PV arrays configurations under various PSCs and more complicated radiation profiles. Finally, the high performance and robustness of the proposed MPPT controller is validated experimentally in terms of tracking time to reach the GMPP, oscillation in power and accuracy.

1.5 Thesis Organization

The remainder of this thesis is organized as follows. Chapter 2 presents a comprehensive overview on PV, including PV cells history, operation, equivalent circuit, and mathematical model of PV array under uniform and PSC. After that, a comprehensive survey of the main dc-dc converters topologies such as boost, buck, and buck-boost converters are presented and the boost converter which is selected as the proper topology for this work is highlighted. Finally, the most popular existing MPPT algorithms are explained, considering their operation principles, advantages, and disadvantages, with the most recent related works in literatures.

Chapter 3 presents the first proposed algorithm, an enhanced adaptive P&O MPPT algorithm for efficient tracking under PSC. The operation principles and full design of simulation model which is executed in MATLAB/Simulink are included. The simulation results, performance evaluation and comparison of the proposed enhanced P&O algorithm with the conventional P&O and IC algorithms are discussed, considering execution of various configuration tests with comprehensive comparison in overall performance, in addition to the main conclusions can be obtained from this work.

Chapter 4 presents the second proposed algorithm, a novel hybrid approach for maximizing the extracted PV power under complex PSC. The operation principles of the proposed hybrid MPPT with both of ESC and P&O algorithms, and the full design of simulation model which is executed in MATLAB/Simulink are included. The simulation results, performance evaluation and comparison of the proposed hybrid algorithm with the conventional P&O and IC algorithms are discussed under various PV array configurations, in addition to the main conclusions can be obtained from this work.

Chapter 5 presents the third proposed algorithm, a novel P&O GMPP tracking algorithm based on trapezoidal rule which is able to work under uniform, PSC and sudden change in radiation levels. The operation principles of the proposed MPPT with detailed explanation of the considered numerical integration approach, trapezoidal rule, are included. Then, the full design of simulation model which is carried out in MATLAB/Simulink is presented. Several weather fluctuations covering both uniform and partial shading levels are simulated and discussed such as uniform irradiation (zero shading), weak and strong shading, in addition to a three comprehensive tests of irradiation change profiles, considering the sudden and gradual changes in irradiation levels and the transition between shading patterns. The simulation results and the detailed experimental setup of design and implementation are presented. Finally, the experimental results for the proposed method by comparing with other methods are presented, considering various PV array configurations, in addition to the main conclusions that can recap this work.

Chapter 6 summarizes and concludes the findings that can be obtained from this research, and also presents recommendations of potential future works.

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