MODIFIED ADAPTIVE PERTURB AND OBSERVE MAXIMUM POWER POINT TRACKING ALGORITHM FOR HIGHER EFFICIENCY IN PHOTOVOLTAIC SYSTEM

JUBAER AHMED

UNIVERSITI TEKNOLOGI MALAYSIA

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JUBAER AHMED

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Specially dedicated to my beloved *Mom, Dad and my Wife.*

For their enduring love, care and motivation

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ABSTRACT

Due to the continuous variation in temperature and solar irradiance, *P–V* characteristics curve of a photovoltaic (PV) system exhibit a non-linear, time-varying Maximum Power Point (MPP). Furthermore, the tracking becomes more complicated when the PV array is partially shaded due to the presence of multiple peaks. This work proposes a Maximum Power Point Tracking (MPPT) algorithm named Modified Adaptive Perturb and Observe (MA-P&O) to address two main limitations of the conventional Perturb and Observe (P&O), namely the steady state oscillation and the divergence from the MPP. At the same time, it locates the global peak during partial shading. The MA-P&O is equipped with an intelligent mechanism to detect the steady state oscillation, and then deploy an adaptive perturbation procedure to reduce it to the minimum. Furthermore, to avoid operating voltage from diverging from its locus, a dynamic boundary condition is imposed. For partial shading, an effective checking mechanism to precisely detect partial shading occurrence is suggested. In addition, an improved set of equation is developed to detect the exact position of local peaks under partial shading. To assess its feasibility, the proposed ideas are simulated using comprehensive PV simulator. For practical validation, the algorithm is implemented in hardware using a buck-boost converter in conjunction with dSPACE DS1104 DSP board. It is demonstrated that under the dynamic irradiance and partial shading test, the MA-P&O ensures the MPPT efficiency is 99.5%. Furthermore, when evaluated against the European Standard EN 50530 test, the MA-P&O records a 98.6% efficiency; this is up to 18% higher than the conventional and other adaptive P&O. Finally, MA-P&O is tested with a tropical daily irradiance and temperature profile. It is found that MA-P&O successfully ensures 99.2%, which is on average 3% higher than the other P&O based algorithms.

ABSTRAK

Berdasarkan perubahan suhu dan sinaran solar yang berterusan, ciri-ciri lengkungan *P–V* sistem fotovolta (PV) mempunyai Titik Kuasa Maksimum (MPP) yang tidak linear dan berubah dengan masa. Tambahan pula, pengesanan MPP menjadi lebih rumit apabila PV mengalami fenomena bayangan separa, yang menyebabkan lengkungan P-V mengalami puncak yang berganda. Sebuah algoritma pengesan MPP (MPPT) yang digelar *Modified Adaptive Perturb and Observe* (MA-P&O) direka untuk memastikan kendalian voltan sentiasa berada di MPP. Skema yang diusulkan dapat menangani dua kekangan utama *Perturb and Observe* (P&O) konvensional, iaitu ayunan keadaan mantap dan kelencongan dari MPP, di samping keupayaan mengesan puncak global semasa bayangan separa. MA-P&O dilengkapi dengan mekanisme pintar mengesan ayunan keadaan mantap dan kemudian menggunakan satu prosedur adaptif untuk mengurangkannya kepada tahap minimum. Selain itu, bagi mengelakkan kelencongan kendalian voltan dari lokusnya, sempadan dinamik telah dikenakan, lantas memaksa titik operasi untuk tetap berada berhampiran MPP. Untuk masalah bayangan separa, pengawalan yang efektif disarankan bagi mengesan dengan tepat berlakunya kejadian litupan separa tersebut. Tambahan pula, satu set persamaan yang lebih mantap dibentuk untuk mengesan kedudukan sebenar puncak global. Bagi menilai kesesuaiannya, idea tersebut disimulasikan menggunakan simulator PV yang komprehensif. Untuk pengesahan praktikal, algoritma ini dilaksanakan dalam perkakasan dengan menggunakan penukar *buck-boost* bersama sistem dSPACE DS1104 DSP. Keputusan menunjukkan bahawa di bawah sinar dinamik dan ujian bayangan separa, MA-P&O memastikan kecekapan MPPT adalah 99.5%. Di samping itu, apabila diuji menggunakan ujian Piawai Eropah EN 50530, MA-P&O merekodkan kecekapan 98.6%; ini adalah sehingga 18% lebih tinggi daripada P&O konvensional dan adaptif lainya. Akhir sekali, MA-P&O diuji dengan profil tipikal sinaran dan suhu tropika. Didapati bahawa MA-P&O berjaya mencecah kecekapan sehingga 99.2% iaitu, secara purata, 3% lebih daripada algoritma P&O yang lain.

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LIST OF ABBREVIATIONS

ANN	-	Artificial neural network
ACO	-	Ant colony optimization
BIPV	-	Building integrated photovoltaic
CS	-	Cuckoo search
DE	-	Differential evolution
DSP	-	Digital signal processor
EA	-	Evolutionary algorithm
FF	-	Flashing fireflies
FLC	-	Fuzzy logic control
FOV	-	Fractional open-circuit voltage
FSC	-	Fractional short-circuit current
GA	-	Genetic algorithm
GP	-	Global peak
HC	-	Hill climbing
IC	-	Incremental conductance
IDB	-	Interleaved dual boost
MPP	-	Maximum power point
MPPT	-	Maximum power point tracking
MRAS	-	Maximum ripple attenuation system
NB	-	Negative big
NS	-	Negative small
PB	-	Positive big
PI	-	Proportional-Integral

P&O	-	Perturb and observe
PSO	-	Particle swarm optimization
PS	-	Positive small
PV	-	Photovoltaic
PVAS	-	PV array simulator
RCC	-	Ripple correlation control
SP	-	Series-parallel
STC	-	Standard Test Conditions
VSI	-	Voltage source inverter
ZE	-	Zero

LIST OF SYMBOLS

a, a_1, a_2	-	Diode ideality factor
A_v	-	Converter gain
C	-	Capacitor
c_1, c_2	-	Acceleration coefficients in PSO
d	-	Duty cycle
dP/dI	-	Derivative of power to current
dP/dV	-	Derivative of power to voltage
Δd	-	Change in duty cycle
E	-	Error signal
ΔE	-	Change in error signal
F_n	-	Fibonacci numbers
G	-	Solar insolation
G_{STC}	-	Solar insolation at STC
I_{MPP}	-	Current at maximum power point
I_m	-	Current at MPP
I_o, I_{o1}, I_{o2}	-	Saturation current
I_{PV}	-	Photovoltaic current
I_{sc}	-	Short circuit current
I_{sc_array}	-	Short circuit current of the whole PV array
$Isc_{\_STC}$	-	Short circuit current at STC
$I–V$	-	Current versus voltage

itr	-	Iteration
K_i	-	Short circuit current coefficient
K_v	-	open circuit voltage coefficient
L	-	Filter inductor
$N_{BD,M}$	-	Number of Bypass diode in a single module
Np	-	Number of parallel modules in PV array
n_s	-	Number of series cell in PV module
Ns	-	Number of series modules in PV array
P	-	Power
P_{MPP}	-	Maximum power
P_{old}	-	Recorded power in previous iteration
$P–I$	-	Power versus current
$P–V$	-	Power versus voltage
R_{load}	-	Load connected to PV array
R_{Lmax}	-	Maximum PV load
R_{Lmin}	-	Minimum PV load
R_m	-	Ratio between V_m and I_m
R_{PVmax}	-	Maximum reflective impedance of PV array
R_{PVmin}	-	Minimum reflective impedance of PV array
R_s	-	Series resistance of PV module
R_p	-	Parallel resistance of PV module
T	-	Temperature
T_{STC}	-	Temperature at STC
V_{high}	-	Highest boundary for voltage is MA-P&O
V_{low}	-	Lowest boundary for voltage is MA-P&O
V_{Lim}	-	Maximum limit for searching voltage

V_{PV}	-	Photovoltaic voltage
V_{MPP}	-	Voltage at maximum power point
V_m	-	Voltage at MPP
V_{mppoc}	-	Voltage of local peak nearest to V_{oc_array}
V_{oc}	-	Open circuit voltage of a single module
V_{oc_STC}	-	Open circuit voltage at STC
V_{oc_array}	-	Open circuit voltage of the whole PV array
V_T	-	Thermal voltage
w	-	Inertia weight in PSO
X_i	-	Generated Population is DE
ΔI	-	Change in current
ΔP	-	Change in power
ΔV	-	Change in voltage
Δd	-	Change in duty cycle
ϕ	-	Perturbation direction

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CHAPTER 1

INTRODUCTION

1.1 Background of the Research

With the continuous decline in the price of photovoltaic (PV) modules and the rising concern about the greenhouse gas emissions, solar energy is rapidly becoming an important power source in the global energy scenario. Technologically, PV system is relatively easy to install, very safe, almost maintenance free and environment friendly. Large PV power systems are being installed worldwide due to their medium and long term economic prospects [1]. Meanwhile, unused spaces–such as rooftops of homes, factories and large buildings can be effectively utilized to harvest solar energy. These are demonstrated by the success of the building integrated PV (BIPV) initiatives in various countries [2-4]. Notwithstanding these advantages, PV power systems in general, still could not attain the grid-parity due to the high initial investment cost. Despite the continuous efforts to improve the efficiency of PV cells, its manufacturing and fabrication processes, as well as the inverter electronics, one should not overlook the potential of enhancing the system throughput by improving its Maximum Power Point Tracking (MPPT) capability. The solution is cost effective because it does not require additional hardware circuitry. Only few line of codes are needed to enable the controller to operate the PV system in such a way that ensures the optimized extraction of power under any circumstances.

Due to the continuous variation in the environmental condition (primarily the temperature and solar irradiance), the *P–V* characteristics curve exhibits a non-linear, time-varying maximum power point (MPP) problem. To ensure that the maximum power from PV system is always achieved, the MPPT algorithm/controller is employed in conjunction with the power converter (dc-dc converter and/or inverter). To date, numerous MPPT algorithms have been reported in the literature; they are broadly classified into two categories, namely 1) the conventional and 2) soft computing methods. [5] and [6] have reviewed various techniques in both categories excellently. For conventional MPPT, the widely used methods include perturb and observe (P&O) [7], hill climbing (HC) [8] and incremental conductance (InCond) [9]. Besides these, there are other simpler methods such as the fractional short circuit current [10], fractional open circuit voltage [11], ripple correlation control [12], sliding control [13] and mathematical-graphical approach [14]. Under normal conditions, i.e. uniform irradiance, they are capable of tracking the MPP quite efficiently and exhibit very good convergence speed. Despite these advantages, each of these methods exhibit some serious drawbacks. These methods fail to track the MPP under varying environmental conditions and partial shading (when some part of the PV array experiences different irradiance than the other parts).

Among these conventional method, the P&O is the most popular and widely used for industrial and research purposes. The operation of P&O is simple. It provides a perturbation (duty cycle or voltage) in one direction and checks the change of power. If the change of power is positive then the algorithm provides perturbation in the same direction, otherwise it provides perturbation in the opposite direction. As a result, when the algorithm reaches near the MPP it keeps on moving back and forth around the MPP, resulting in steady state oscillation. If perturbation size is large, so does the oscillation and energy loss. On the other hand, if perturbation size is small, then the energy loss can be reduced. In that case, the tracking speed is compromised. To resolve this trade-off, an adaptive approach is required. Numerous works are carried out to minimize the oscillation, but it is achieved at the expense of reduced tracking speed [15].

Apart from the steady state oscillation, P&O is prone to provide perturbation in one direction only when irradiance starts increasing gradually. The reason is, in every perturbation, the algorithm realizes that the power is increasing; thus it keeps on providing perturbation in the same direction. Consequently, the operating point will keep moving away from the actual MPP point. On the other hand, if adaptive P&O

with small perturbation is deployed instead of conventional P&O, then the operating point will not move much from its position. However, another problem will arise due to the change of location of the MPP because of increasing irradiance. So the adaptive P&O will remain in the wrong position while MPP keeps on moving away. To resolve this limitation of both conventional and adaptive P&O, an intelligent technique is required that will track MPP under gradual change of irradiance. Additionally, P&O is not capable of handling partial shading [16] in its original form. To make it capable of handling partial shading, an improved adaptive methodology is required.

To alleviate some of these problems of conventional methods, the MPPT techniques based on soft computing (SC) are proposed. Among them are the artificial neural network (ANN) [17], fuzzy logic controller (FLC) [18], genetic algorithm (GA) [19], differential Evolution (DE) [20], particle swarm optimization (PSO) [21] and ant colony optimization (ACO) [22]. Despite their flexibility, SC algorithms are generally more complex and slower than the conventional methods. For example, ANN requires very specific and prolonged training period to produce accurate results. Furthermore, due to its computational intensive nature, ANN needs to be implemented using expensive microprocessor. On the other hand, FLC shows excellent convergence speed but its performance is subjected to the programmer's experience and understanding of a specific PV module and the environmental conditions in which the system is being installed. Other algorithms such as GA and ACO are being used, but mainly as an optimizer for the conventional MPPT; this approach is popularly known as the hybrid MPPT. However, in spite of these successes, the limitations of the SC methods remain. Most of the SC methods like PSO, ACO, DE and CS etc. are highly dependent on the random searching methods inspired by natural distribution, such as the Gaussian distribution, Levy distribution, normal distribution, Cauchy distribution etc. Due to the evolutionary nature of these distributions, the converging time is usually higher than the conventional methods. Searching for the global peak under partial shading using random numbers in soft computing techniques results longer convergence time and sometimes the algorithms even fail to locate the global peak if the number of locals peaks are many. Besides, most of the SC methods suffer from the trade-off between convergence speed and the convergence efficiency. The convergence efficiency can be improved by using large step sizes in the iteration. However, increasing the step size may cause the algorithm to miss certain local maxima points during the searching and force the MPPT to settle down at a local peak under partial shading.

Due to these drawbacks of SC techniques, conventional methods–mainly P&O is still the most popular algorithm in the industry and research. Thus, although P&O algorithm was developed over 25 years ago, contemporary researchers are still working to remove its limitations from different angles. In [23-31], researchers proposed different adaptive versions of the P&O that attempts to reduce the steady state oscillation. However, the divergence problem under ascending irradiance has remained unsolved. Few other algorithms [32-34], dealt with the divergence issue along with the steady state oscillation. The proposed solutions are, nevertheless, highly case dependent and may fail under different environmental conditions. Apart from that, the simulation and experiments carried out in these works are very simple and does not properly reflect the adverse environmental situations. It is also important to note that, none of these adaptive approaches mentioned above provide solution for partial shading conditions.

Other researches [35-39] enable P&O algorithm to cater partial shading, though these works completely ignore the steady state oscillation and divergence problem. Up to this date, no MPPT technique enables conventional P&O to handle all three limitations at the same time. Besides, the scanning techniques under partial shading proposed by these methods are not flawless and often fail under partial shading [40].

Another common problem for the adaptive P&O which cater partial shading is, almost all of the MPPT approaches ignore the precise detection of partial shading. Majority of the algorithms set a threshold value on the sudden power change to detect the partial shading. The problem of such approach is, sudden power change can happen due to the sudden change of irradiance (irradiance level falls from one to another level due to the movements of the clouds) as well. Throughout the day irradiance changes suddenly multiple times and more frequently than the occurrence of partial shading. If MPPT is unable to differentiate between the sudden change of irradiance and the occurrence of partial shading, then the MPPT is subjected to search for the global peak unnecessarily many times a day. Thus, an innovative approach is required to detect the occurrence of partial shading precisely, which will remove many unnecessary searching initiations.

Apart from that limitation, all the adaptive P&O which choose to control the voltage of the PV array (the configuration of PV modules) require temperature and irradiance sensors to update the open circuit voltage of the PV array continuously [25, 32, 39]. Some researches ignored the use of irradiance sensors by approximation techniques but still could not get rid of the temperature sensors [36]. The implication of sensors in the MPPT makes the overall system very expensive and often requires extra circuitry to interface the sensors with the MPPT algorithm.

Having these limitations in mind, this thesis aims to clarify all the limitations of conventional P&O and provide the solutions for the problems in a single MPPT named Modified Adaptive P&O (MA-P&O). Apart from solving the steady state oscillation, divergence problem and partial shading, the proposed scheme will be equipped with an intelligent mechanism that will precisely detect the occurrence of partial shading. Moreover, a smart technique will be proposed to update the open circuit voltage of the PV array without using any temperature and irradiance sensors. Besides, the proposed scheme will be tested against very stringent tests like standard EN 50530, various partial shading patterns and a realistic daily profile of irradiance and temperature. The outcome of the MA-P&O will be compared with both conventional and other adaptive P&O approaches to clarify the improvement. It is envisaged that, the MA-P&O will be capable of handling any environmental adversity and ensure the maximum extraction of the power from the PV array under any circumstances.

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1.2 Objective of the Research

The objective of this research is to Design and implement the Modified Adaptive P&O (MA-P&O) to simultaneously resolve all the limitations of conventional P&O. These includes

- The steady state oscillation problem.
- Loss of tracking direction during ascending irradiance.
- Tracking under partial shading.
- In addition to that, MA-P&O is envisaged to be equipped with smart and dynamic techniques that can detect the occurrence of partial shading accurately.
- Besides, algorithm should be capable of updating the open circuit voltage of the PV array without using any sensors.

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1.3 Scope of the Research

To achieve the objective of the research the following scope of the work is carried out:

I. A critical and strategic review on the MPPT methods is performed. In this review, almost all the existing MPPT methods are covered. Besides, their advantages and limitations are also clarified. Particular focus is given on both conventional and adaptive P&O and the limitations of the existing approaches. Literary gaps found through the review have functioned as the basis for the work that had been carried out.

II. Behaviour of the PV systems under varying environmental conditions and partial shading is critically analysed. Based on the analysis, critical relations have been developed that work as the fundamental to design the intelligent technique for updating open circuit voltage of the PV array without any sensors. In addition to that, a novel prediction model is developed to accurately identify the position of the local peaks under partial shading.

III. In the process of developing MA-P&O algorithm, an intelligent checking mechanism is proposed that is capable of detecting the steady state oscillation precisely. Thus, appropriate measures are taken to evade the power loss due to such oscillation. A dynamic boundary condition is imposed on the operating voltage that guides it to remain near to the MPP position all the time.

IV. A smart scanning method is proposed that can precisely detect the occurrence of the partial shading. Under partial shading, the novel prediction model to locate the peaks is incorporated to ensure the detection of the global peak in a faster and flawless way.

V. The proposed algorithm is implemented in MATLAB Simulink platform using two diode model of the solar cell. Besides, the algorithm is implemented in the hardware level using dSPACE DS1104 board and buck-boost dc-dc converter. To clarify the improved performance step irradiance test, sinusoidal irradiance test several partial shading tests are carried out. Along with that, MA-P&O is subjected to the EN 50530 profile to be scrutinized under fast changing irradiance profile. Finally the algorithm is applied to a one-day irradiance and temperature profile to justify the behaviour under real environmental conditions.

1.4 Importance of the Research

Due to the non-linear characteristics of *I–V* and *P–V* curve, the tracking of the maximum power point (MPP) at various environmental conditions is a challenging task. The issue becomes more complicated when the entire PV array is subjected to partial shading. In both circumstances (uniform and partial shading), conventional and SC techniques exhibit several limitations that results in dropping the efficiency by a significant margin. However, due to the simplicity in structure and implementation, conventional P&O based MPPT is most widely used in both research and commercial purposes. This research intends to mitigate all the limitations of the conventional P&O approach withstanding the similar simple structure. To achieve that, no additional sensors are used for the implementation. However, based on the critical analysis of the *P–V* curve under different environmental conditions several relations are utilized to measure irradiance and update open circuit voltage continuously. Besides, an improved scanning technique is developed to ensure the tracking of the global peak under partial shading. Thus, few additional lines in coding is sufficient to enable P&O to handle varying irradiance and temperature along with the partial shading. Therefore, the implementation of the proposed MA-P&O ensures the optimum power extraction from the PV system throughout the operation lifetime.

1.5 Organization of the Thesis

The thesis is organized into six chapters in total. This chapter describes the backgrounds, objectives and scopes of the research. The problem statements are also clearly mentioned and clarified.

Chapter 2 is composed of extensive review on the MPPT methods reported in the literature. These are broadly classified into two groups, namely conventional method and soft computing approaches. All the MPPT methods are briefly described in their generalized structure along with their advantages and drawbacks.

In Chapter 3, behaviour of the PV system under different environmental conditions is presented. The analysis is divided into two major segments–uniform irradiance and partial shading. In addition to the analysis under partial shading a new prediction model is proposed to predict the position of the local peaks during partial shading.

In Chapter 4, MA-P&O is developed to mitigate the limitations of the conventional P&O. The working principal of the algorithm, design structures, flowcharts etc. are described in details. Besides, the working principles of the proposed schemes are explained step by step in conjunction with a tracking example.

In chapter 5, the implementation in software and hardware is explained elaborately. Along with that, the proposed MA-P&O is tested with several tests, namely step irradiance change, sinusoidal irradiance test, EN 50530 standard test, several partial shading patterns and a daily profile. The performance of the proposed MPPT is compared with the conventional P&O and other adaptive P&O approaches side by side and the improved performance of the MA-P&O is clarified.

Chapter 6 concludes and summarises the research and the contributions are highlighted again. Besides, some probable direction towards the future works are also provided.

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