

**RESEARCH ON PHOTOVOLTAIC MPPT
CONTROL METHOD BASED ON IMPROVED
BAS ALGORITHM AND VARIABLE STEP-SIZE
INC METHOD**

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UNIVERSITI SAINS MALAYSIA

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by

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LIST OF SYMBOLS

I_{ph}	Photo-Current Generated by Absorbed Light
I_{VD}	Current Flowing Through the Diode
I_{sc}	Short-Circuit Current
G	Irradiance of The Incident Light
G_{ref}	Reference Irradiance, Typically 1000 W/m ²
I_0	Reverse Saturation Current of The Diode
q	Electric Charge of The Electron, $1.6 \times 10^{-19}C$
R_s	Series Resistance of PV Cell
n	Diode Constant Factor
K	Boltzmann Constant, $1.38 \times 10^{-23}J/K$
T	Thermodynamic Temperature
R_{sh}	Parallel Resistance of PV Cell
U_{oc}/V_{oc}	Open-Circuit Voltage of The PV Cell
P_{max}	Maximum Power
V_{mp}/U_{MPP}	Voltage at MPP
I_{mp}	Current at MPP
U_L	The Output Voltage of PV Module
U_{PV}	The Output Voltage of PV Cell
D	Duty Cycle
R_{PV}	Internal Resistance of PV Module
R_L	External Load Resistance.
K	Ratio Coefficient
dP/dU	First-Order Derivative of P/U

dI/dU	First-Order Derivative of I/U
Δ	Delta - Variable Quantity
C_i	Input Capacitor
C_o	Output Capacitor
L	Inductor
R	Electric Resistance
s	Sec
W	Watt
m^2	Square Meter
$^{\circ}C$	Degree Celsius
μH	Microhenry
μF	Microfarad
Ω	ohm

LIST OF ABBREVIATIONS

PV	photovoltaic
MPPT	MPP Tracking
CVT	Constant Voltage Tracker
P&O	Perturb and Observe
INC	Increment Conductance
MPP	Maximum Power Point
LCM	Load Current Maximization
CSA	Crow Search Algorithm
TLC	Tent-Logistic-Cosine
PSO	Particle Swarm Optimization
I-U	Current-Voltage
P-U	Power-Voltage
DC	Direct Current
IGBT	Insulated Gate Bipolar Transistor
P	Power
U/V	Voltage
I	Current
PWM	Pulse-Width Modulation
BAS	Beetle Antennae Search Algorithm
IBAS	Improved BAS
VSINC	Variable Step-Size INC
VSP&O	Variable Step-Size P&O

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**KAJIAN TENTANG KAEDAH KAWALAN MPPT FOTOVOLTAN
BERDASARKAN ALGORITMA BAS YANG DIPERBAIKI DAN KAEDAH
INC LANGKAH-SAIZ BERUBAH**

ABSTRAK

Tenaga solar telah mendapat perhatian meluas dan telah dibangunkan kerana kelebihannya yang jelas, seperti bekalan yang mencukupi dan tidak terhad oleh geografi. Walau bagaimanapun, modul PV mudah terjejas oleh persekitaran luar dalam aplikasi praktikal, menyebabkan penurunan kuasa PV. Teknologi MPPT untuk sistem kuasa PV adalah kaedah yang berkesan untuk meningkatkan keberkesanan penukaran elektrik PV. Kaedah kawalan yang biasa digunakan termasuk kaedah CVT, kaedah gangguan dan pemerhatian, dan kaedah konduktans tambahan. Kaedah-kedah ini berbeza secara ketara dari segi parameter yang diperlukan, kekompleksan algoritma, kelajuan penjejakan, ketepatan penjejakan, keperluan perkakasan, dan lain-lain. Dalam kajian ini, satu kaedah kawalan MPPT berdasarkan IBAS dan VSINC dicadangkan untuk mencapai prestasi yang lebih baik dalam MPPT. Bagi mencerminkan perubahan amplitud cahaya dan suhu sepanjang hari, suhu berubah antara 30°C dan 60°C, dan irradiance berubah dari 500W/m² hingga 1000W/m². Prestasi kaedah kawalan MPPT yang dicadangkan dibandingkan dengan modul PV monokristal silikon 360W yang banyak digunakan. Algoritma ini dimodelkan dan disimulasikan menggunakan perisian MATLAB/Simulink dan dibandingkan dengan kaedah MPPT lain (P&O, INV, PSO) untuk mengesahkan bahawa algoritma ini secara signifikan meningkatkan kelajuan dan ketepatan penjejakan di bawah pelbagai keadaan dengan gelombang yang lebih kecil di MPP. Kerja penyelidikan utama adalah seperti berikut: Pertama, prinsip asas sel PV dijelaskan, dan kemudian model

matematikanya dibina. Satu model matematik kejuruteraan ditetapkan, dan model matematik disimulasikan menggunakan MATLAB/Simulink untuk mendapatkan kurva ciri P-U dan I-U di bawah perubahan suhu dan intensiti cahaya. Pengaruh kuasa PV terhadap perubahan suhu dan cahaya dianalisis. Kedua, prinsip MPPT diperkenalkan, dan litar penukaran Boost dipilih untuk mencapai MPPT untuk sistem kuasa PV. Kemudian, penyelidikan tentang teknologi MPP dijalankan, dan prestasi beberapa kaedah, seperti kaedah P&O, kaedah INC, dan algoritma PSO, dibandingkan dan dianalisis; namun, mereka tidak dapat menyediakan MPPT yang lebih cepat dan stabil. Berdasarkan data simulasi, dapat disimpulkan bahwa di bawah keadaan penyinaran seragam, kaedah VSINC dan VSP&O memiliki beberapa kesalahan dalam menanggapi perubahan intensitas cahaya dan suhu, dan akan ada beberapa gelombang kuasa setelah mencapai titik kuasa maksimum, mempengaruhi prestasi penjejakan mereka. Kaedah VSINC dan langkah P&O mempunyai beberapa kesalahan dalam menanggapi perubahan intensitas cahaya dan suhu, dan akan ada beberapa gelombang kuasa setelah mencapai titik kuasa maksimum di bawah keadaan penyorotan, mempengaruhi prestasi penjejakan mereka. Walaupun algoritma PSO menunjukkan gelombang yang relatif kecil setelah mencapai titik kuasa maksimum, ia mengalami gelombang yang signifikan semasa perubahan intensitas cahaya dan suhu, mengakibatkan beberapa kerugian tenaga. Akhirnya, kaedah kawalan MPPT baru berdasarkan kaedah IBAS dan VSINC dicadangkan untuk mencapai penjejakan yang lebih cepat dan stabil dalam persekitaran luar yang berubah-ubah. Menggunakan MATLAB/Simulink untuk menguji dan mengesahkan algoritma yang dicadangkan telah secara signifikan meningkatkan kelajuan dan ketepatan penjejakan di MPP. Dalam kajian ini, dalam simulasi puncak tunggal, kaedah IBAS dan VSINC dapat menjejaki titik kuasa maksimum dalam 0.41 saat, mengatasi kaedah P&O dalam 0.43

saat; kuasa purata kaedah IBAS dan VSINC adalah 231.5W, mengatasi kaedah P&O pada 228.7W dan kaedah INC pada 230.6W. Dalam simulasi puncak berganda, kaedah IBAS dan VSINC dapat menjejaki titik kuasa maksimum dalam 0.43 saat, mengatasi kaedah P&O dan kaedah INC dalam 0.55 saat; kuasa purata kaedah IBAS dan VSINC adalah 558.8W, melampaui kaedah P&O dan kaedah INC pada 552.5W. Kaedah IBAS dan VSINC hampir tidak memiliki kesalahan dalam menanggapi perubahan lingkungan luar sementara memiliki prestasi penjejakan yang jauh lebih baik secara keseluruhan. Kaedah IBAS dan VSINC adalah kaedah yang lebih robust dan boleh dipercayai untuk penjejakan titik kuasa maksimum untuk MPPT fotovoltaiik berganda-puncak.

RESEARCH ON PHOTOVOLTAIC MPPT CONTROL METHOD BASED ON IMPROVED BAS ALGORITHM AND VARIABLE STEP-SIZE INC METHOD

ABSTRACT

Solar energy has received widespread attention and has been developed due to its distinct advantages, such as abundant reserves and not restricted by geography. However, the PV module is easily affected by external environments in practical applications, leading to a decrease in PV power. MPPT technology for the PV power system is an effective method to improve the efficacy of PV electricity conversion. Commonly used control methods include CVT method, perturbation and observation method, and incremental conductance method. These methods differ greatly in terms of required parameters, algorithm complexity, tracking speed, tracking accuracy, hardware requirements, etc. In this study, a MPPT control method based on IBAS and VSINC was proposed to obtain a better performance in MPPT. In order to reflect the changes in light amplitude and temperature during the day, the temperature varied between 30°C and 60°C, and the irradiance shifted from 500W/ m²to 1000W/m². The performance of the proposed MPPT control method was compared with a widely used 360W monocrystalline silicon PV module. The algorithm was modelled and simulated using MATLAB/Simulink software and compared with other MPPT methods (P&O, INV, PSO) to verify that the algorithm significantly improved the tracking speed and accuracy under various conditions with smaller oscillations at the MPP. The main research work is as follows: First, the fundamental principle of a PV cell is described, and then its mathematical model is constructed. An engineering mathematical model is established, and the mathematical model is simulated using MATLAB/Simulink to

obtain the P-U and I-U characteristic curves under temperature and light intensity changes. The influence of PV power on temperature and light changes is analysed. Secondly, the principle of MPPT is introduced, and a Boost conversion circuit is selected to achieve MPPT for the PV power system. Then, research on MPP technology was carried out, and the performance of some methods, such as the P&O method, the INC method and the PSO algorithm, were compared and analysed; however, they cannot provide faster and more stable MPPT. Based on the simulation data, it can be concluded that under uniform illumination conditions, the VSINC and VSP&O methods have some errors in response to light intensity and temperature changes, and will be certain power oscillations after reaching the maximum power point, affecting their tracking performance. The VSINC and step-size P&O methods have some errors in response to light intensity and temperature changes, and will be certain power oscillations after reaching the maximum power point under shading conditions, affecting their tracking performance. Although the PSO algorithm exhibits relatively small oscillations after reaching the maximum power point, it experiences significant oscillations during variations in light intensity and temperature, resulting in some energy losses. Finally, a new MPPT control method based on the IBAS and VSINC method is proposed to achieve faster and more stable tracking in continuously changing external environments. Using MATLAB/Simulink to test and verify the proposed algorithm has significantly improved the tracking speed and accuracy at the MPP. In this study, in the single-peak simulation, the IBAS and VSINC algorithm can track the maximum power point in 0.41 seconds, outperforming the P&O algorithm at 0.43 seconds; the average power of the IBAS and VSINC algorithm is 231.5W, surpassing the P&O algorithm at 228.7W and the INC algorithm at 230.6W. In the multi-peaks simulation, the IBAS and VSINC algorithm can track the maximum

power point in 0.43 seconds, outperforming the P&O and INC algorithms at 0.55 seconds; the average power of the IBAS and VSINC algorithm is 558.8W, exceeding the P&O and INC algorithms at 552.5W. The IBAS and VSINC method have almost no errors in response to changes in the external environment while have much better tracking performance overall. The IBAS and VSINC methods are more robust and reliable methods for maximum power point tracking for multi-peak photovoltaic MPPT.

CHAPTER 1 INTRODUCTION

1.1 Background and Significance

For a long time, traditional fossil fuels have played a promoting role in economic development and have held a dominant position in the energy market. These fuels, while converting their energy into electricity when burned, also produce highly polluting chemicals, causing ongoing harm to the natural environment and threatening the lives and work of people in various countries. With the progress of industrialization in different nations and the continuous and stable growth of the global population, countries are gradually entering a historical peak in energy demand. However, the known reserves of fossil fuels cannot sustain an unlimited and continuous supply. The energy consumption structure, which is predominantly based on traditional fossil fuels, faces severe challenges [1-2]. Environmental degradation and the scarcity of energy supply make it extremely urgent to develop a diversified energy consumption structure and accelerate the development of new energy sources [3]. Currently, fossil fuels still account for a significant proportion of the global energy supply, representing 85.7% of the total energy required by humanity [4-5]. As non-renewable energy sources, fossil fuels will eventually be depleted as humans continue to extract them. According to the latest statistics from the International Energy Agency (IEA), as shown in Table 1.1, most of the world's known fossil fuel reserves will be consumed within this century.

Table 1.1 Global Known Fossil Fuel Reserves and Extraction Timelines [6]

Energy Source	Coal	Oil	Natural Gas
Reserves	84.75 billion tons	1.7 trillion barrels	177 trillion cubic meters
Extraction Timeline	200 years	50 years	80 years

On the other hand, a large amount of greenhouse gases are emitted into the atmosphere, accompanying the use of fossil fuels, causing global climate warming and

threatening the ecological environment. With the increasing severity of the energy crisis and the continuous deterioration of the living environment, changing the energy structure predominantly based on fossil fuels and achieving sustainable energy development is a problem that the international community must face. Therefore, in order to prevent global climate warming and the survival crisis caused by energy depletion, vigorously developing renewable and clean energy is the future direction and an important path to achieving sustainable development of energy and the ecological environment.

Renewable energy is increasingly valued for its renewable and pollution-free advantages. Compared to fossil fuels, renewable energy can be regenerated in nature and is an energy source that is inexhaustible and renewable. The use of renewable energy does not face the problems of environmental pollution and resource depletion. Common renewable energy sources include solar energy, wind energy, tidal energy, and nuclear energy. Among these, solar energy has the most promising development and application prospects. It has significant advantages, such as being clean, non-polluting, widely distributed, and inexhaustible. Solar energy has become the most promising renewable energy source [7].

The dual crisis of energy shortage and environmental problems has prompted countries around the world to continuously increase their support and investment in the development of renewable energy. At the same time, a series of policies and regulations have been enacted and implemented to support the renewable energy industry. With the strong promotion of laws, regulations, and relevant policies, the renewable energy industry has witnessed vigorous development. Among them, the solar PV industry, which is a key focus in the field of renewable energy development, will play an important role in global energy consumption. It will not only serve as an alternative to

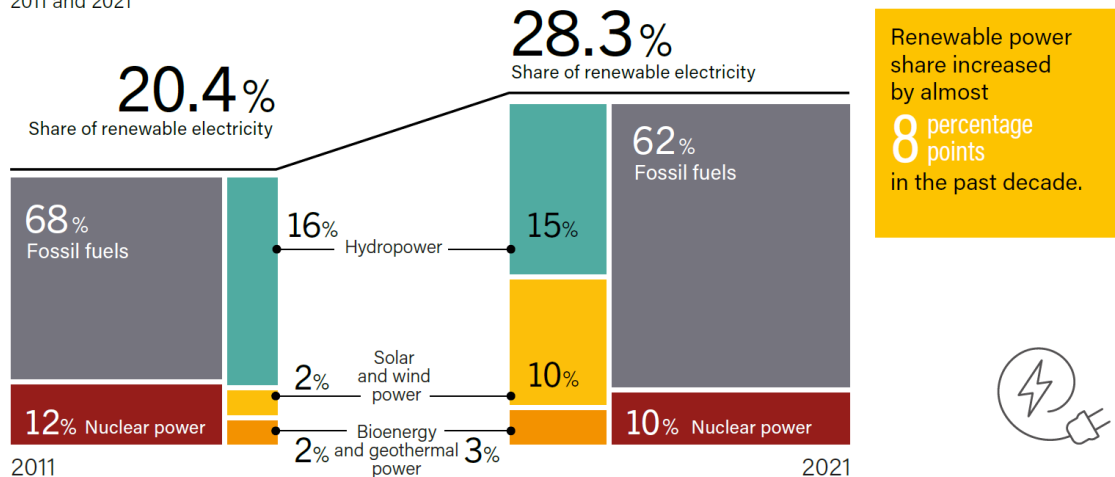
some conventional energy sources but will also gradually replace fossil fuels as the primary energy source in the world's energy supply. It is estimated that by the end of the 21st century, solar PV systems will account for more than 60% of the world's total energy consumption, reflecting the vast development potential and strategic significance of the solar PV industry in the global energy field.

Therefore, proposing a more mature and efficient MPPT method is crucial as one of the effective approaches to improve the efficiency of PV power generation systems, considering the limited photoelectric conversion efficiency of PV cells [8]. Researching algorithms for MPPT in complex environments holds significant importance in maximizing the power conversion capability of PV cells, thereby increasing the electricity generation efficiency of PV systems, reducing power wastage, and lowering the overall cost of electricity generation.

1.2 Development Status of PV Power

In response to environmental pollution, global climate change, and energy strategies, countries worldwide are actively promoting the transformation of clean, sustainable energy and low-carbon systems [9]. In Europe, a roadmap has been proposed to achieve 100% renewable energy power system in Europe and North Africa by 2050 [10]. Wind and solar are the leading forces in the development of non-hydro renewable power sources [11]. 2021 saw an increase of 175 GW of solar PV generation to a cumulative total of about 942 GW [12], with solar power generation set to gradually overtake wind power in the future. Solar energy is regarded as the most promising source of energy. PV energy has the advantages of high efficiency, clean and pollution-free, abundant resources, and low maintenance costs, etc [13].

**Share of Renewable Energy in Power,
2011 and 2021**



Source: Based on IEA data. See endnote 60 for this chapter.

Fig. 1.1 Share of Renewable Energy in Power 2011 and 2021 [10]

The PV industry in Western countries started early, and governments began large-scale promotion of distributed solar PV projects in the 1990s, leading to the thriving development of PV power generation. In June 1997, the US government launched the "Million Solar Roofs" program, aiming to install solar power systems on one million building roofs. In July 2010, the US Senate passed the "Ten Million Solar Roofs Act," with the goal of installing ten million solar roofs by 2020 [14].

In 1998, the German government introduced the "100,000 Roofs Program," further expanding the proportion of solar energy in the overall energy structure and promoting the prosperity and development of the PV industry. In the 21st century, the German government enacted relevant laws, regulations, and incentives, promoting the implementation of the Renewable Energy Sources Act, strictly controlling greenhouse gas emissions, and providing strong support for the vigorous development and large-scale application of solar PV power generation in Germany [15].

The Japanese government has been actively promoting solar power generation programs since the 1970s, with a focus on promoting renewable energy projects,

particularly solar PV systems. It explicitly prioritized the development of solar energy among all renewable energy applications. By the year 2000, Japan's total solar PV power generation capacity reached 120 megawatts. By 2020, Japan's total solar PV capacity was increased by about ten times compared to 2005, and it is projected to grow to about 40 times the 2005 level by 2030.

China's photovoltaic (PV) power generation industry started later, with the application of PV cell technology to the aviation sector occurring after 1970. With economic development and the introduction of energy-saving and emission reduction policies, the PV industry in China found favourable market opportunities, and in 2002, large-scale PV production began. Currently, as resources become increasingly scarce and the environment continues to deteriorate, China is intensifying efforts to promote the development of the PV industry. With a series of favourable policies introduced by the government, China has made significant breakthroughs in the research and development of PV technology. As of the end of 2022, China's cumulative grid-connected PV installed capacity reached 392.6 GW, ranking first globally in both new and cumulative installed capacity. The annual PV electricity generation was 427.6 billion kilowatt-hours, representing a year-on-year growth of 30.8% and accounting for approximately 4.9% of the total national electricity generation. It is projected that in 2023, the new PV installed capacity in China will exceed 95 GW, with the cumulative installed capacity expected to surpass 487.6 GW. The country continues to play a leading role in the global PV industry.

Currently, thanks to the application of new technologies and the transformation in the energy sector, solar PV technology and related industries have gradually gained attention from countries around the world. With support and promotion from governments, the global solar PV market has tremendous growth potential and shows a

promising development trend. The global cumulative installed capacity of solar PV is expected to continue its rapid growth in the coming years, according to the International Energy Agency.

1.3 Status and problems of MPPT

Photovoltaic Maximum Power Point Tracking (MPPT) is a critical technology in solar photovoltaic systems, designed to ensure that photovoltaic cell components can efficiently output electrical energy at maximum efficiency under varying light conditions. Currently, photovoltaic MPPT technology has made significant advancements, yet it still faces several challenges and issues.

Cost Issues:

High-cost algorithm implementation: Advanced MPPT algorithms like fuzzy logic control and artificial neural networks may demand more computational resources and specialized hardware, contributing to increased system costs.

High-performance sensor costs: Employing high-performance sensors for environmental monitoring can escalate costs, especially when real-time monitoring of multiple parameters is required.

Adaptability to Environmental Conditions and Complex Scenarios:

Overcast days and shadow effects: Traditional MPPT systems may struggle to accurately track the maximum power point in low light conditions or partial shading, as the current-voltage characteristics of photovoltaic cells become unclear.

Temperature impact: Elevated temperatures in high-temperature environments can alter the electrical characteristics of photovoltaic cells, causing performance degradation in traditional MPPT systems.

Reliability Issues:

Long-term operational stability: MPPT systems operating over extended periods may be susceptible to circuit component aging, failures, and environmental changes, emphasizing the need for long-term operational stability.

Tolerance under adverse weather conditions: In extreme weather conditions such as heavy rain or storms, MPPT systems must exhibit sufficient tolerance to ensure reliability and safety.

Standardization and Compatibility Concerns: Lack of unified communication protocols and standards: Different manufacturers producing MPPT controllers may adopt diverse communication protocols, leading to compatibility issues and limiting system scalability and interoperability.

Balancing Efficiency and Performance: Computational complexity of high-efficiency algorithms: Some high-efficiency MPPT algorithms may increase computational complexity in the pursuit of the maximum power point, requiring a balance between efficiency and computational cost.

Challenges: Addressing these challenges requires ongoing research and innovation to advance photovoltaic MPPT technology, enhance system performance and reliability, and reduce costs, thereby better meeting the diverse requirements of various application scenarios.

1.4 Research Status of MPPT

Distributed generation of renewable energy sources such as solar power exhibits certain intermittency and randomness due to the constantly changing irradiance and temperature conditions experienced by PV cells, resulting in lower efficiency. Over the past 20 years, there have been significant advancements in traditional silicon-based PV

cells in terms of material quality, auxiliary materials, and processing techniques. Currently, the average "light-to-electricity" conversion efficiency in the PV industry is generally around 18% - 19% for commercial silicon PV cells, while high-efficiency silicon PV cells can achieve over 20% efficiency [16].

To improve the conversion efficiency of PV systems, there are primarily two approaches: developing solar cell materials and enhancing the control algorithms of PV systems. The theoretical upper limit for the light-to-electricity conversion efficiency of silicon PV cells is around 30% [17]. To fully leverage the conversion capabilities of PV cells and effectively improve the efficiency of PV systems, one critical avenue is the development of more mature and efficient MPPT methods [18]. MPPT plays a key role in optimizing PV system performance by tracking the maximum power output point of the PV array based on its operating conditions.

The input and output characteristics of PV cells show a non-linear correlation in PV power systems. The power output of PV is closely related to changes in light intensity, temperature and load [19]. Improving the efficiency of light conversion while reducing the cost of PV power generation has been pressing issues [20-23]. MPPT research aims to enable PV power systems to operate quickly and continuously at their MPP, maximize photoelectric conversion efficiency, reduce energy losses due to oscillations, improve the efficiency and effectiveness of PV power generation, promote the widespread adoption and application of large-scale, high-efficiency, high-effective PV power generation and ultimately provide important support for replacing fossil fuels and solving global environmental pollution problems [24].

Currently, there are various types of MPPT algorithms for uniform irradiance conditions, including typical methods such as the INC method, the Constant Voltage Tracking, and the Perturbation and Observation method [25-27]. The Constant Voltage

Tracking method, although stable, lacks dynamic adjustment capability and cannot adapt to environmental changes. The P&O method, which is commonly used for power tracking, can converge to the optimal value but tends to oscillate around the optimal point, resulting in unstable output and insufficient tracking accuracy. Although the INC method has smaller voltage fluctuations, it still cannot effectively meet the dual requirements of tracking speed and accuracy.

Factors such as weather conditions, clouds, and partial shading caused by buildings can cause the output characteristics of the PV array to transition from a single peak under uniform irradiance to multiple peaks. The multi-peak output characteristics pose significant challenges for finding and tracking the MPP, and traditional tracking algorithms often find local MPPs that do not meet the required accuracy. To address this issue, new intelligent algorithms capable of achieving nonlinear global optimization can be applied based on the nonlinear characteristics of the PV array's output power. Other algorithms, such as the Fruit Fly Algorithm, PSO Algorithm, and others have been applied in research on MPPT for multi-peaks curves [28-30].

Research on single-peak MPPT algorithms is relatively mature, but the study of multi-peak MPPT algorithms under partial shading conditions is still in the exploratory stage. Currently, there is no algorithm that can achieve fast and accurate multi-peaks MPPT. Despite the emergence of many new control methods, multi-peaks MPPT technology still holds great research value and development potential.

1.5 Objectives of This Study

This article focuses on the research of MPPT control technology for PV arrays under uniform illumination and partial shading conditions, aiming to address the

problem of traditional MPPT algorithms failing to accurately track the MPP. The main objectives of this article are as follows:

Investigate MPPT Control Challenges: Explore the challenges in MPPT control technology for PV arrays, specifically under uniform illumination and partial shading conditions. Analyse the current status and future prospects of the PV power generation industry. Examine the research status and major issues related to MPPT control algorithms for PV systems.

Enhance MPPT Algorithms and Strategies: Understand the working principles and simulation modelling of PV cells, focusing on characteristics under various conditions. Evaluate traditional MPPT control algorithms and identify their limitations, particularly in PV array MPPT control under partial shading. Introduce and validate an advanced MPPT control strategy based on the IBAS Algorithm and VSINC Method, addressing identified shortcomings.

Validate and Verify Developed Strategy: Apply the proposed IBAS Algorithm and VSINC Method to MPPT control of PV arrays. Conduct comparative simulation experiments to verify the feasibility and effectiveness of the developed MPPT control strategy. Systematically summarize research findings, highlighting encountered problems, and provide directions for future research and improvements.

1.6 Scope of Study

The scope of study in a thesis or research report is typically outlined in the following manner:

Introduction: Introduce the main topic or problem under study. Provide a brief overview of the background and significance of the research.

Scope: Clearly define the scope of the study, including the objectives, timeframe, geographic limitations, and the subjects under investigation. Any constraints or exclusions should also be mentioned.

Methodology: Explain the research methods and data sources to be used. This can include details about the research techniques, data collection, and analysis methods that will be employed.

Conclusion: Summarize the anticipated outcomes and significance of the study, as well as any potential limitations and avenues for future research.

In summary, when describing the scope of study, it is important to clearly articulate the goals, parameters, and methodology of the research, enabling readers to understand the content and limitations of the study, as well as its significance and potential for future research.

CHAPTER 2 LITERATURE REVIEW

2.1 Introduction

The power output of PV is closely related to the change in light intensity, temperature and load [31]. Improving the efficiency of light conversion and reducing the cost of PV power generation have always been urgent questions to be solved. PV material improvement and MPPT technology are researching by technicians. at present, the research of PV materials has made a significant breakthrough. The research of MPPT focuses on improving its control algorithm, which can increase the efficiency of PV power generation and decrease its expense [32]. In recent years, domestic and foreign scholars have developed a large number of effective MPPT control algorithms; these research results have great differences in the required parameters, algorithm complexity, tracking speed, tracking accuracy, hardware requirements and so on.

2.2 Review Previous Literature

Currently, the commonly used control algorithms include the CVT method, the P&O algorithm, the INC method, and so forth.

The CVT method, introduced in the 1980s, is characterized by its simplicity and ease of implementation. However, it comes with notable drawbacks. Firstly, its tracking accuracy is subpar, making it less effective in optimizing power output. Additionally, the CVT method overlooks the influence of temperature on the open-circuit voltage of photovoltaic (PV) systems. This limitation can result in inefficient energy conversion, particularly in environments with varying temperatures. Furthermore, the CVT method exhibits poor adaptability to external conditions, limiting its performance when faced with dynamic environmental changes. One of its significant shortcomings is the

inability to automatically track the Maximum Power Point (MPP) as environmental factors evolve, leading to energy losses over time.

The P&O algorithm is favored for its simpler structure, fewer measured parameters, and higher conversion efficiency. However, it is not without its drawbacks. The P&O algorithm tends to oscillate around the MPP, introducing challenges in maintaining precision and speed of control. The step size used in the algorithm has a critical impact on its performance, requiring careful tuning. Moreover, the P&O algorithm demonstrates a poorer response to changes in the external environment, reducing its effectiveness in optimizing power generation under varying conditions.

The INC method is known for its rapid tracking of MPP changes, superior control results, and higher stability. Despite these advantages, its complex control algorithm poses challenges. The intricacy of the algorithm may hinder its practical implementation in certain contexts. Similar to the P&O method, the INC method is susceptible to oscillations at the MPP, which can affect its overall performance. While it excels in tracking MPP changes efficiently, the increased complexity may limit its applicability, especially in scenarios where simplicity and ease of implementation are crucial considerations.

Liqun Shang designed an improved CVT method; the method compensates the open-circuit voltage to reduce the voltage deviation when the temperature changes, but this method does not consider the influence of irradiation on the open circuit voltage. tracking accuracy is affected by the accuracy of temperature sensor and temperature difference between the temperature sensor and PV array. In this research, a contrast can be seen in that when the irradiance increases from 0.3 kW/m^2 to 0.5 kW/m^2 , the response time of the traditional algorithm is 0.39s while for the proposed algorithm it is

0.30s, indicating a tracking speed increase of 23.1%. The average output powers of the PV array are 25.09W and 25.1W, respectively. When the irradiance increases from 0.5 kW/m² to 0.8 kW/m², the response time is 0.43s for the traditional algorithm and 0.35s for the proposed algorithm, indicating a tracking speed increase of 18.6%. The average output powers of the PV array are 40.01W and 40.18W, respectively [33].

Saberi Ali et al adjusted the step size of the P&O method according to the optimal gradient method, and the tracking accuracy and effect are significantly improved; however, this method only targets even lighting environment, and the tracking accuracy and effect under local shading are poor. In this study, the irradiance pattern changes from 600 W/m² to 1000 W/m² with the step and the slope changes, the length is 3.5s. The irradiance pattern used in the simulation includes step and slop, increasing and decreasing patterns, and the proposed algorithm obtained an overall efficiency of 98.54% [34].

Lieping Zhang et al combined the conventional LCM method and the P&O method, using variable step size. The experimental results show that the LCM-P&O method with variable step size has a higher tracking efficiency, about 90%–92%, and has higher stability and lower power consumption [35].

Weifeng You proposed an improved INC method of variable step size; the step size will become larger at the beginning to enhance tracking speed while using a smaller step size to improve tracking accuracy in a later stage; although its control effect is improved, it is challenging to balance the tracking speed and accuracy. In this study, the simulation results show that the algorithm can accurately track the MPP with shadow. The average tracking time is only 0.13 seconds, and the power tracking efficiency reaches 98% [36].

Zhen Gao et al proposed a variable step size P&O method based on power prediction; the step size is larger in the early stage and smaller in the later stage; although the control effect is improved, it is difficult to balance the accuracy and tracking speed. In this study, the P&O with variable step size based on power prediction can be well applied to photovoltaic power generation systems with three-level DC/DC converters under conditions of changing light intensity and temperature. It not only completes the task of maximum power tracking, but also improves the tracking accuracy from 97.2% to 98.1% and obtains higher output power [37].

Fathi Milad et al applied the nerve network algorithm and fuzzy control on MPPT control to improve the tracking accuracy, but it takes a long time to train. In this study, the difference between the maximum and minimum RMSE obtained via the fuzzy system is $15 \times 10^{-4} \text{W}$, while this difference for the other methods is even $87 \times 10^{-4} \text{W}$, which is 5.5–5.8 times than the difference in the fuzzy logic. Regarding MAE, the difference between the maximum and minimum values in artificial neural networks based on GA, PSO, and ICA is 2.5–2.8 times compared to the fuzzy logic [38].

Guerra Maria I.S. et al uses the fuzzy control algorithm on MPPT control, which does not need to consider the accuracy of parameters and better effect in the application; however, the user's experience has a great influence on the tracking effect. In this study, the power generation recovery was more expressive. When the P&O algorithm was changed for the ANN algorithm, the performance was better because the power generation increased from 15.11 to 16.61 kWh, i.e., 9.9% [39].

Chunguang Zhou et al designed the standard PSO algorithm and the P&O method to track the MPP, the tracking performance is significantly improved, and the deviation is smaller; however, it requires better hardware, and the algorithm is complex.

In this study, when the light intensity changes suddenly, the response time of the maximum power point tracking under the PSO algorithm is about 0.006s, and the response time of the maximum power point tracking under the P&O algorithm is about 0.03s, it can be further inferred that when the number of cells connected in series in the photovoltaic PV array increases, the response speed of the maximum power point under the PSO algorithm is much lower than the response speed of the maximum power point under the P&O algorithm [40].

Ravinder Kumar proposes a hybrid fuzzy particle swarm optimization (FPSO) technique with a photovoltaic fed shunt active power filter (SAPF) to improve power quality and deliver clean electricity. In this study, the proposed control scheme was simulated and real-time tested on the Hardware-in-the-Loop using OPAL-RT 4510 system. The planned system has a total harmonic distortion of 2.22% and a sampling time of 30 μ s. The results reveal that the proposed controller performs well under various load conditions [41].

Aranzazu D. Martin et al proposed a new method to accomplish the MPP under partial shading conditions using artificial vision is presented. The artificial vision uses a webcam to identify in real time the shadow irradiance and provide the reference voltage that supplies the maximum power, regardless of the number of peaks that the P–V curve presents. Then, the reference voltage is used by a robust and non-linear control, the backstepping controller, to regulate the DC/DC converter input voltage and to guarantee the PV modules maximum energy extraction. Experimental tests carried out outdoor validate the proposed method, obtaining a MPP tracking efficiency that ranges from 98.1% to 99.6% [42].

2.3 Gap Analysis

Regardless of the operating conditions of the PV array, the application of MPPT control algorithms aim at enabling the PV power system to work at its MPP quickly and continuously, maximizing the photoelectric conversion efficiency, reducing energy loss caused by oscillations, improving the efficiency and benefits of PV power generation, promoting the widespread adoption and application of PV power of large-scale, high-efficiency and high-benefit, ultimately providing vital support for replacing fossil fuels and addressing global environmental pollution issues.

In recent years, photovoltaic systems have gained significant attention as a sustainable energy source. The efficiency of these systems heavily relies on MPPT algorithms that track and maintain the maximum power output from the solar panels. While substantial research exists in this area, there are gaps and shortcomings that need to be addressed for further advancements.

A significant gap in the current research surrounds the adaptability of MPPT algorithms to varying environmental conditions. Most studies focus on idealized scenarios, neglecting real-world factors such as partial shading, temperature variations, and panel aging. Additionally, the comparison of MPPT algorithms under different climatic and operational conditions is still limited, leading to a lack of comprehensive understanding.

Furthermore, there is a notable absence of research on the integration of MPPT with energy storage systems and hybrid energy sources. Exploring the optimal operation of MPPT in conjunction with energy storage technologies and multi-source input could significantly enhance the overall system efficiency but remains relatively unaddressed.

Several published works present conflicting or inconclusive results when comparing the performance of various MPPT algorithms. The lack of standardized testing procedures and performance metrics makes it challenging to draw clear conclusions and hinders the reliable assessment of algorithm effectiveness.

To address the identified gaps and issues, it is crucial for future research to focus on developing MPPT algorithms that are robust and adaptable to diverse operating conditions. Additionally, standardization of testing methodologies and performance metrics is imperative to enable meaningful comparisons between different algorithms. Moreover, expanding research to incorporate hybrid energy systems and storage integration will be pivotal in advancing the practical implementation of MPPT in real-world applications.

In conclusion, this gap analysis emphasizes the need for comprehensive and robust research in MPPT for photovoltaic systems. Addressing these gaps and improving the methodologies will not only enhance the understanding of MPPT algorithms but also contribute to the increased efficiency and practical viability of photovoltaic systems.

2.4 Principles in This Study

2.4.1 Physics Principle of PV Cell

According to the conductivity, materials can be classified into three categories: conductors, semiconductors, and insulators. Among them, semiconductors are widely used in various electronic components due to their unique doping characteristics, thermal sensitivity, and photosensitivity. Solar cells, which are based on semiconductor materials, utilize the PV effect for "light-to-electricity" energy conversion. Since the discovery of the PV effect in liquids by Becquerel in 1839, the basic principles and

structure of solar cells have remained relatively unchanged. Unlike other types of rechargeable batteries, solar cells cannot store energy in advance. The process of converting light energy into electrical energy is instantaneous and simultaneous. For this conversion to occur, the surface illumination intensity of a solar cell must exceed a certain minimum threshold and reach a specific temperature.

The PV effect, which is the capacity of some materials to create an electric current when exposed to light, is the basis of the PV power principle. PV cells, referred to as solar cells, are constructed from semiconductors like silicon. Electrons in the semiconductor material are excited and made to move when light strikes the cell's surface, producing an electrical current. The PV effect is the name of this mechanism.

In a semiconductor material, the absorption of light photons causes the generation of free electrons and holes, which may later be separated by an internal electric field and gathered as an electric current. This process is known as the PV effect. The following processes form the basis of the PV cell's operating principle:

Photon absorption: When light photons hit the PV cell's surface, the semiconductor material absorbs them and generates an electron-hole pair.

Separation of charges: The electric field within the PV cell separates the holes and electrons, generating a potential difference between the two sides of the cell.

Collection of charges: The separated electrons and holes are collected by the electrodes located at the two sides of the cell, creating a flow of electrical current.

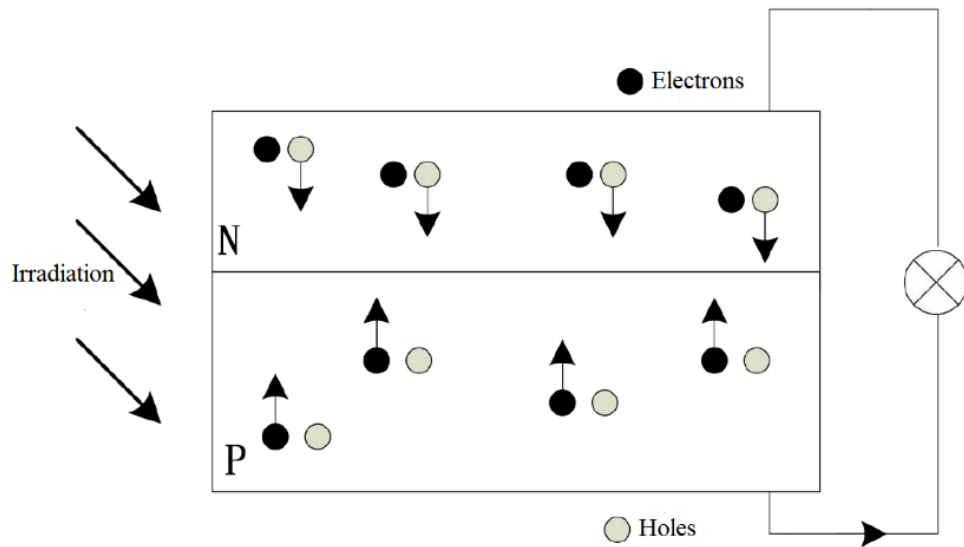


Fig. 2.1 Schematic Diagram of the PV Effect [43]

2.4.2 Mathematical Model of PV Cell

PV cells are instruments for converting light energy into electrical energy. A mathematical model of a PV cell has been developed based on the physical properties of semiconductor materials and electrochemical principles. A current source in parallel with a diode represents the basic model of a PV cell. The current source denotes the photo-current generated by light absorption in the semiconductor material, and the diode indicates the P-N junction's current-voltage characteristics that form the PV cell. PV cells, as devices that directly convert light energy into electrical energy, are often represented by an equivalent circuit in practical applications to facilitate the analysis of their output characteristics [43]. The equivalent circuit of a PV cell is shown in Figure 2.2.

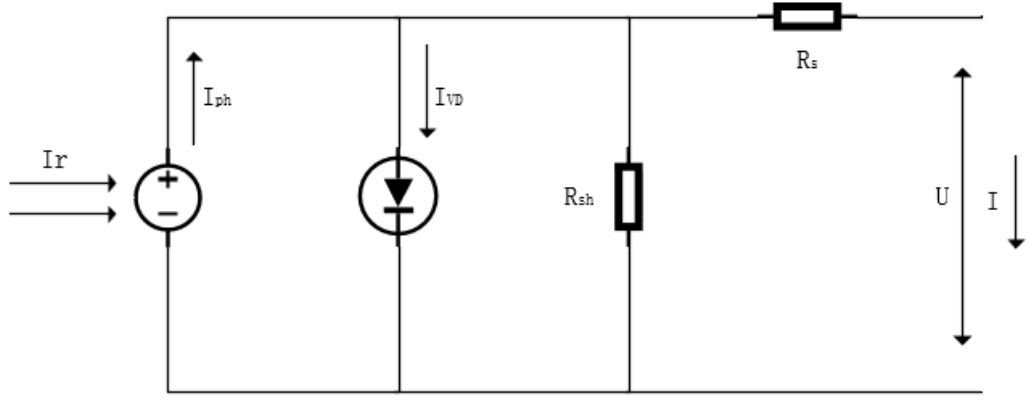


Fig. 2.2 Equivalent Circuit of PV Cell [44]

According to Figure 2.2, the mathematical model of the PV cell is shown in equations (2.1), (2.2), (2.3), (2.4) and (2.5).

$$I = I_{ph} - I_{VD} - I_{sh} \quad (2.1)$$

$$I_{ph} = I_{SC} \times \frac{G}{G_{ref}} \quad (2.2)$$

$$I_{VD} = I_0 \left\{ \exp \left[q \left(\frac{U + I R_s}{n K T} \right) \right] - 1 \right\} \quad (2.3)$$

$$I_{sh} = \frac{U + I R_s}{R_{sh}} \quad (2.4)$$

$$P = I \times (U - U_{oc} + I R_s) \quad (2.5)$$

In the formulas [44]:

I - Current generated by PV cell;

I_{ph} - Photo-current generated by absorbed light;

I_{VD} - Current flowing through the diode;

I_{SC} - Short-circuit current of the PV cell;

G - Irradiance of the incident light;

G_{ref} - Reference irradiance, typically 1000 W/m²;

I_0 - Reverse saturation current of the diode;

q - Electric charge of the electron, $1.6 \times 10^{-19} \text{C}$;

U - Voltage across the PV cell;

R_s - Series resistance of PV cell;

n - Diode constant factor;

K - Boltzmann Constant, $1.38 \times 10^{-23} \text{J/K}$;

T - Thermodynamic temperature;

R_{sh} - Parallel resistance of PV cell;

P - The power output of PV cell;

U_{OC} - Open-circuit voltage of the PV cell.

The performance of PV cell is affected by various factors such as temperature, the spectral distribution of the incident light, and shading effects [45]. The mathematical models described above therefore provide a basic framework for understanding the behavior of PV cells. Still, more detailed models are often used in practice to accurately predict PV system performance.

Equations (2.1) - (2.5) in the theoretical analysis of solar PV cells exhibit a high degree of fitting to the basic principles of actual solar cell operation. Hence, they are widely applied in the research and modeling of PV cells. However, due to the presence of uncertain parameters in (2.1) - (2.5), namely R_s , R_{sh} , I_{sh} , I_{ph} , and I , they are inconvenient for engineering applications. These parameters not only depend on the intensity of sunlight and cell temperature but also possess significant randomness and unpredictability, making them difficult to determine in practical settings. Therefore, to facilitate research, this paper adopts a simplified mathematical model derived from the circuit model represented by equations (2.1) - (2.5). This model better meets the

requirements of practical engineering applications [46]. The simplified model is as follows:

$$\mathbf{I} = \mathbf{I}_{sc} \left[1 - \mathbf{C}_1 \left(e^{\frac{\mathbf{U}}{\mathbf{C}_2 \mathbf{U}_{oc}}} - 1 \right) \right] \quad (2.6)$$

$$\mathbf{C}_1 = \left(1 - \frac{\mathbf{I}_m}{\mathbf{I}_{sc}} \right) e^{\frac{\mathbf{U}}{\mathbf{C}_2 \mathbf{U}_{oc}}} \quad (2.7)$$

$$\mathbf{C}_2 = \frac{\frac{\mathbf{U}_m}{\mathbf{U}_{oc}} - 1}{\mathbf{I}_n \left(1 - \frac{\mathbf{I}_m}{\mathbf{I}_{sc}} \right)} \quad (2.8)$$

$$\mathbf{I}_{sc_r} = \mathbf{I}_{sc} \frac{\mathbf{S}}{\mathbf{S}_{ref}} (1 + \mathbf{a} \Delta \mathbf{T}) \quad (2.9)$$

$$\mathbf{U}_{oc_r} = \mathbf{U}_{oc} \cdot \ln(\mathbf{e} + \mathbf{b} \Delta \mathbf{S}) (1 - \mathbf{c} \Delta \mathbf{T}) \quad (2.10)$$

$$\mathbf{I}_{m_r} = \mathbf{I}_m \frac{\mathbf{S}}{\mathbf{S}_{ref}} (1 + \mathbf{a} \Delta \mathbf{T}) \quad (2.11)$$

$$\mathbf{U}_{m_r} = \mathbf{U}_m \cdot \ln(\mathbf{e} + \mathbf{b} \Delta \mathbf{S}) (1 - \mathbf{c} \Delta \mathbf{T}) \quad (2.12)$$

In the formulas [46]:

$\mathbf{I}_{sc_r}$ - Short-circuit current under current working conditions;

$\mathbf{U}_{oc_r}$ - Open-circuit voltage under current working conditions;

$\mathbf{I}_{m_r}$ - Maximum power point current under current working conditions;

$\mathbf{U}_{m_r}$ - Maximum power point voltage under current working conditions;

$\mathbf{S}_{ref}$ - The reference sunlight intensity, where $\mathbf{S}_{ref}=1000 \text{ W/m}^2$;

$\mathbf{T}$ - The reference temperature of the solar cell, where $\mathbf{T}=25\text{C}$;

$\mathbf{AS}$ - The difference between the actual sunlight intensity and the reference sunlight intensity, $\mathbf{AS}=\mathbf{S}-\mathbf{S}_{ref}$;

$\mathbf{AT}$ - The difference between the actual temperature of the photovoltaic cell and the reference temperature, $\mathbf{AT}=\mathbf{T}-\mathbf{T}_{ref}$;

E - The base of the natural logarithm, approximately equal to 2.71828;

I_m - The current at the maximum power point (MPP);

U_m - The voltage at the maximum power point (MPP);

a - Compensation coefficient, where $a = 0.0025C^{-1}$;

b - Compensation coefficient, where $b = 0.5(W/m^2)^{-1}$;

c - Compensation coefficients, where $c = 0.00288^\circ C$.

By analyzing the PV cell model and utilizing the mathematical model of the PV cell, it is possible to create a model of the PV cell using the MATLAB/Simulink module.

Figure 2.3 illustrates the simulation model of the PV cell.

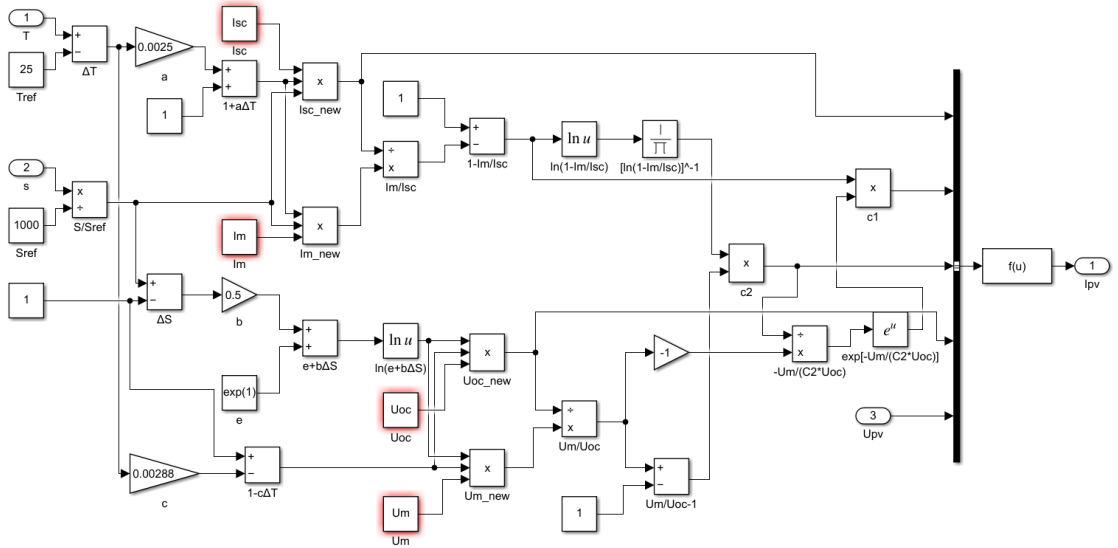


Fig. 2.3 Simulation Model of PV Cell

2.4.3 The Principle of MPPT

In a PV power system, the characteristic curve of a PV cell in a constant environment is a single-peak curve. The highest point on the nonlinear output curve is the MPP [47]. MPPT detects the output power of the PV array in real time and tracks