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ANALYSIS OF THE FACTORS INFLUENCING THE PERFORMANCE OF PV MODULE

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ABSTRACT

The rapid depletion of non-renewable energy supplies has made it necessary to extract energy from renewable sources. Over the past few decades, the use of renewable energy, particularly solar energy, has received a lot of attention. Photovoltaic power generation projects are implemented in very large number in many countries. The performance of a photovoltaic (PV) module is mostly affected by array configuration, irradiance, and module temperature. Solar energy presents a challenge because of the sun's fluctuating position and characteristics, which cause variations in the daytime irradiance and ambient temperature. The production of power levels fluctuates as a result. It is important to understand the relationship between these effects and output power of the PV array. Due to the reasons mentioned, it is essential to maximize the output power available from PV cell. Several MPPT (Maximum Power Point Tracking) techniques have been proposed which is used to extract the maximum output power from a PV cell. In order to obtain maximum power from a PV cell with the help of MPPT control, the understanding and modelling of PV cells is necessary. To utilize PV power or extract maximum power from PV array, the maximum power point tracking (MPPT) technique is essential to study and implement. This paper provides insights into the methodologies, system modelling and various MPPT techniques involved in PV modules.

I. INTRODUCTION

Natural resources that can be naturally replenished and never run out include wind, sunlight, rain, tides, and geothermal heat. These resources are referred to as renewable energy. Fossil fuel reserves are depleting at a startling rate, and burning them produces significant pollution. When compared to non-renewable energy sources, renewable energy sources generate more energy and less pollution. With the development of human society, the environment and energy has become a major issue that people are facing nowadays. Solar energy as a kind of widely distributed 'clean energy' has good applications. PV cells are the core of solar power generation since it generates power from abundantly available sunlight, without any pollution and have potential as a clean energy source for future power demand [1]. During the last decades, there is huge growing interest in for renewable energy resources. Among all the renewable energy resources, solar energy can be considered as the most promising, widely available and essential resource. Solar photovoltaic is one of the most growing technologies with a growth of 35-40 % per year [2]. An essential power conversion device that produces electricity from sunlight is a photovoltaic cell. PV cells normally generate voltages between 0.5 and 0.8 V, which is far too low for direct use in a home or business. Consequently, a PV module is made up of a series-connected number of PV cells (between 36 and 72 cells). PV module output characteristics are nonlinear because they depend on temperature, solar irradiance, and other environmental factors like wind and humidity in addition to climate conditions [3]. Solar irradiance and PV cell temperature are pointed out to be the major factors affecting PV cell output to a much greater extend than other conditions. The amount of power extracted from a PV system is a function of the PV array voltage and current set point. Due to the reasons mentioned above, it is essential to maximize the output power available from PV cell. Several MPPT (Maximum Power Point Tracking) techniques have been proposed which is used to extract the maximum output power from a PV cell. In order to obtain maximum power from a PV cell with the help of MPPT control, the understanding and modelling of PV cells is necessary. The simulation evaluation and development of PV systems can be simplified by an accurate robust model of PV cells [4]. When compared to other methods, perturb & observe and incremental conductance algorithm are widely used due to their simplicity and easiness in implementation. Other MPPT techniques used are open circuit voltage, short circuit current method and intelligent technique based MPPT algorithms such as fuzzy MPPT, artificial neural network. These MPPT techniques differ from each other in terms of input parameters, tracking speed and accuracy.

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II. THEORETICAL BACKGROUND

Irradiance and temperature are the key factors that determine the operating conditions of a PV cell. The standard test conditions (STC) for PV cells specify an irradiance (G) of 1000 W/m^2 and a temperature (T) of 25°C. During manufacturing, PV modules are tested under these conditions. However, the actual conditions at the PV installation site differ from these standards, leading to corresponding changes in peak power. While the module voltage (Vpv) remains almost constant, the module current (Ipv) is directly proportional to the irradiance level, causing PV power to increase with higher irradiance. Conversely, the module voltage (Vpv) is inversely proportional to temperature, and the module current stays nearly constant, resulting in a decrease in PV power as the temperature rises [5]. A PV system comprises solar PV arrays and electric converters. A PV array is constructed from a series/parallel combination of solar modules. Various operating conditions, such as shadows, clouds, dirt, debris and different orientations and tilts, can result in nonuniform irradiance across the PV array. When several solar cells within a series PV module are mismatched due to nonuniform irradiance, these cells limit the output current of the unaffected cells. This results in a decrease in output power, the formation of hot spots, and potential damage to the affected cells. To mitigate the destructive-affects of hot spots, a bypass diode is connected in parallel with a PV module or within certain series connected solar cells within the module, providing an alternate path. When the bypass diode is activated, the output power of the mismatched cells is cut-off. Consequently, the output characteristics become more complex and some energy loss occurs when the PV characteristics under conditions of nonuniform irradiance [6].

III. PHOTOVOLTAIC MODULE MODELING

A. Mathematical equation of PV cell

The mathematical model of the PV module can be useful for the following purposes:

1. For studying the characteristics of photovoltaic systems with change in operating condition i.e temperature, irradiance, partial shading conditions.
2. For studying Maximum power point tracking (MPPT) algorithms.
3. Dynamic analysis of converters and optimizing their design for specified power quality standards.
4. Designing hybrid systems with PV in combination with other energy sources.
5. Designing grid-connected systems and examining the dynamic influences of PV systems in both sub-transmission and distributed levels.

An ideal PV cell behaves like a diode which is described using Shockley diode equation with the Eq.1, where IL is the photocurrent, Io is the reverse saturation current of the diode and the N is the diode ideality factor.

$$I = IL - Io.\,[\exp\,(qv/NKT) - 1] \qquad (1)$$

The equivalent circuit of a PV cell is shown in Fig 1. It can be seen that, it consists of a current source, a diode, a shunt resistance and series resistance. G and T represents solar radiation and temperature respectively. The ideal PV cell can be defined as a diode with anti-parallel diode. However, metal contacts (RS) and leakage of the PN junction (RSH) have to be considered in case of practical circuit.

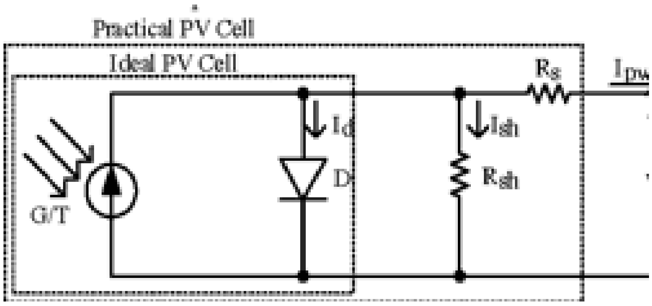

Fig 1. The electrical equivalent circuit of a PV cell [7].

The output current of a PV cell is derived using Kirchhoff's current law (KCL) as derived in the Eq. 2.

$$Ipv = Iph - Id - Ish \qquad (2)$$

The V_{PV} voltage and I_{PV} current characteristics can be described by the following equations 3 and 4.

$$I_{pv} = I_{ph} - I_s.\,[\exp\frac{(q(Vpv + IpvR)}{NKT}\,] - \frac{Vpv + IpvRs}{Rsh} \qquad (3)$$

$$V_{pv} = \frac{NK}{q}\,[\frac{Iph+Id-Ipv}{Ipv}] - R_s I_{pv} \qquad (4)$$

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Where;

Iph: Photocurrent or light-generated current

Is: Saturation current

q: electron charge (1.6x10^ (-19) C)

K: Boltzmann constant (1.38x10^ (-23) j/k)

T: cell temperature in Kelvin degrees (273.15 +°C)

N: Ideality factor of diode

Rs and Rsh represents losses of metal contacts and leakage
of the PN junction

Ipv: PV cell output current (A)

Vpv: PV cell output voltage (V)

Values such as Ish and Io are calculated from the following equations:

Iph = G/Gn [Iphn + α (T – Tn)]

Is = Isn. (T/Tn) ¬¬3. exp[(q.Eg.)/ (n.k) (1/Tn - 1/T)]

Isn = Isc. 1/ (exp. (Voc/ (n. Vtn)) -1)

Vt = NKT/q

In Fig 2, a typical I-V characteristic of the PV cell for a certain irradiation (G) and a certain cell temperature (T) has been shown. The I-V characteristic of the PV cell effected by G and T. It is also affected by the series resistance in the near open circuit voltage and parallel resistance in the near short circuit current, respectively. From Fig 2, it can be seen that the open circuit voltage increases logarithmically with the irradiation.

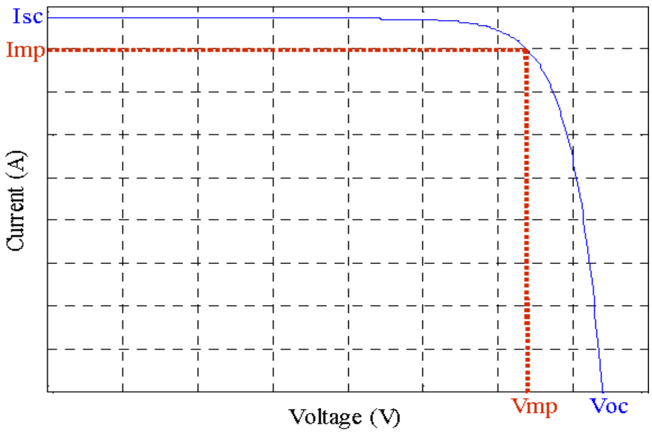

Fig 2. A typical current-voltage I-V curve for a PV cell [7].

B. MATLAB based modelling of PV module

Partial shading, caused by obstacles like clouds, trees, or buildings, leads to significant power losses and complex current-voltage (I-V) and power-voltage (P-V) characteristics in PV module. Shading on even a small portion of the module can lead to significant power losses. The configuration of the array and the shading pattern critically influence the extent of these losses. The authors developed a MATLAB-based simulation model to analyse the behaviour of PV module under partial shading conditions. The model incorporates the effects of shading on individual solar cells and their interconnections within the module. The simulation uses detailed mathematical modelling of solar cells and includes the affects of temperature, irradiance, and shading patterns. Different shading scenarios are considered to evaluate their impact on the overall module performance. Partial shading causes multiple peaks in the P-V characteristic curve, complicating the maximum power point tracking (MPPT) process. The use of bypass diodes is effective in reducing power losses under partial shading by allowing current to bypass shaded cells, though it introduces multiple peaks in the P-V curve. The MATLAB-based model provides a powerful tool for studying and understanding the complex effects of partial shading on PV modules. The insights gained can help in designing better MPPT algorithms and optimizing PV array configurations to minimize power losses due to shading [8]. The model developed is incorporated with the affects of partial shading. The model simulates the electrical characteristics of solar cells, including current-voltage and power-voltage curves under various shading conditions. The study examines

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different shading scenarios, such as uniform shading and non-uniform shading patterns, to understand their impact on the solar cell's performance. The model allows for the simulation of shading on different parts of solar cell array, providing insights into how shading affects individual cells and the overall module. The results obtained indicated that partial shading leads to multiple peaks in the P-V curve, indicating a drop in maximum power output. The I-V characteristics are also significantly altered, showing reduced current and voltage outputs under shaded conditions. The study highlights the importance of bypass diodes in mitigating the adverse effects of partial shading. These diodes help in maintaining better performance by allowing current to bypass the shaded cells. Understanding the behaviour of solar cells under partial shading can help in designing more efficient solar power systems and developing strategies to minimize power losses [9]. The MATLAB model incorporates real-world parameters and allows for simulation under different conditions. Factors considered for analysis include temperature, solar irradiance, and load conditions. The effect of ambient temperature on the PV module's efficiency and power output is examined. Different levels of sunlight intensity are simulated to see how they influence the performance and the impact of connecting different electrical loads to the PV module is analysed. The study finds that both temperature and solar irradiance significantly affect the performance of PV modules. Increased solar irradiance generally improves performance, but this relationship is not linear and varies with other conditions. Load variations also impact the PV module's output, highlighting the importance of optimizing load connections for better efficiency. The research underscores the importance of considering multiple factors simultaneously to accurately predict and optimize the performance of solar PV systems. This study provides insights that can help in the design and optimization of solar PV systems, ensuring they perform efficiently under diverse environmental and operational scenarios [10]. The author developed a PV module model based on the single-diode equivalent circuit. This model incorporates key parameters such as short-circuit current, open circuit voltage, and temperature coefficients. The model examined how changes in temperature affect the voltage, current, and overall efficiency of the PV module. Different levels of solar irradiance were simulated to observe their impact on the power output and efficiency of the module. The simulation results show a clear relationship between environmental conditions and PV module performance. Increased temperature leads to a decrease in the open-circuit voltage and a slight increase in the short-circuit current, resulting in overall reduced efficiency, while higher irradiance levels increase the current output, thus enhancing the power output of the PV module. The developed model was validated by comparing its output with real-world data and existing theoretical models. The comparison showed good agreement, indicating that the Simulink model is accurate and reliable for predicting PV module performance under varying conditions. This model can be used to optimize PV system design and improve the efficiency of solar energy systems by accurately predicting how different factors influence performance [11]. The simulation model was incorporated with different scenarios, including uniform shading, single-cell shading, and multiple-cell shading, to observe their respective impacts on the overall performance of the solar cell. The simulation demonstrated significant changes in the I-V and P-V curves under partial shading. There was a notable reduction in the peak power point and a shift in the maximum power point. The use of bypass diodes was examined as a mitigation strategy. These diodes help in redirecting the current around the shaded cells, thus reducing power losses. The formation of hot spots due to uneven heating was highlighted as a potential issue, which could lead to further degradation of the solar cells. The results underscore the importance of addressing partial shading in the design and placement of solar panels. The implementation of bypass diodes and other strategies were recommended to mitigate the affects of partial shading and improve the overall efficiency of solar power systems [12].

C. MATLAB based PV module combined with DC-DC converters

DC-DC converters are used in PV systems to regulate the voltage generated by PV modules. DC-DC boost converters are used in grid connected applications in order to step up the module voltage. The circuit diagram of DC-DC boost converter is shown in Fig 3.

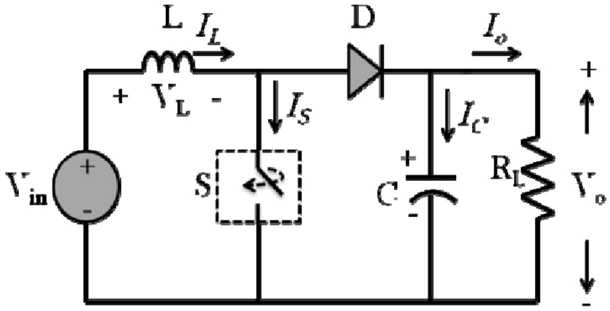

Fig 3. DC-DC Boost Converter [13]

The DC-DC boost converter circuit consists of Inductor(L), diode(D), capacitor(C), load resistor (RL), the control switch(S). These components are connected in such a way with the input voltage source (Vin) so as to step up the voltage. The output of the converter depends on the duty cycle of the control switch. So, the output voltage can be varied by varying the ON time of the switch. Hence, for a duty cycle "D" the average output voltage can be calculated using, Vo/Vin = (1/(1-D)) where Vin, Vo are the input and output voltage of the converter respectively and D is the duty cycle of the control switch. The output power of the converter is equal to input power which yields in an ideal circuit. The boost converter operates in two distinct modes. The first mode starts when the switch is turned on (t=Ton). During this phase, the increasing input current flows through the inductor and switch, storing energy in the inductor. The second mode begins when the switch is turned off (t=Toff). In this phase, the current flows through the inductor, diode, capacitor, and load. The inductor current decreases until the start of the next cycle, transferring energy to the load. The study implements a control strategy for the boost converter to ensure stable and efficient operation, adjusting the duty cycle to maintain desired output voltage levels. The simulation results are analysed to evaluate the performance of the PV system with the boost converter. Key performance metrics such as output voltage, current, and power are assessed under varying conditions of solar irradiance and temperature. The efficiency and stability of the boost converter in maintaining consistent power output despite fluctuations in environmental conditions are examined. The simulation demonstrates that the designed PV system with a boost converter effectively regulates the output voltage and can adapt to changes in irradiance and temperature. It highlights the practical applicability of such systems in off-grid scenarios, providing a reliable and sustainable power solution [13]. A DC/DC converter is a crucial component of any MPPT system. It is used in DC power supplies and DC motor drives to convert unregulated DC input into a controlled DC output at the desired voltage level. In MPPT implementation, the converter regulates the input voltage of the photovoltaic panel and ensures load matching for maximum power transfer. A DC/DC converter can either be a step-down converter, where the output voltage is less than the input voltage, or a step-up converter, where the output voltage is higher than the input voltage. Specifically, a boost converter, which is a type of step-up converter, provides an output voltage greater than the input voltage. MPPT algorithms are essential for optimizing the power output of PV systems, and the P&O method is one of the most commonly used techniques. The P&O MPPT algorithm, when combined with a boost converter, provides an efficient solution for maximizing the power output from PV systems under partial shading conditions. The detailed analysis shows how the P&O MPPT algorithm successfully tracks the maximum power point even with the presence of multiple peaks in the P-V curve [14].

IV. MAXIMUM POWER POINT TRACKING TECHNIQUES FOR PHOTOVOLTAIC ARRAYS

When utilised as an optional electrical load for a photovoltaic (PV) cell, a maximum power point tracker is an effective DC to DC converter that delivers power, voltage, or current levels in line with the load level it is designed to drive. A maximum power point tracker can be used to monitor the maximum power point (MPP) on the characteristic curve of photovoltaic arrays in order to maximise the compatibility of the solar arrays with utility grids or battery banks. A maximum power point tracking device detects and corrects variations in the current-voltage characteristics (I-V) of solar cells (MPPT). To get the most power possible, the MPPT controller forces the PV module to run at voltages that are near the maximum power point (MPP). When a PV module serves as the energy source, there are numerous applications for the maximum power point tracking (MPPT) technique. Perturb and Observe (also known as the hill climbing method), the incremental conductance method, fuzzy control of fractional short circuit current, fractional open circuit voltage, and neural network control are a few popular MPPT techniques. The most popular techniques are incremental conductance and perturb and observe because they are easy to implement, take less time to track the MPP, and have a number of other advantages [15].

A. Perturb and observe

In the perturb and observe (P&O) method, the sensor detects voltage levels and the controller adjusts the voltage to increase power. Adjustments continue in this direction as long as the power rises. When the output power begins to decrease, adjustments are made in the opposite direction. This method, also known as the hill climbing method, relies on the power curve's increase with respect to voltage. P&O is a straightforward and cost-effective maximum power point tracking (MPPT) algorithm. However, it has drawbacks, including continuous oscillations near the maximum power point (MPP) and difficulty in accurately finding the MPP under the changing weather conditions [16].

B. Incremental conductance method

This method utilizes two sensors to detect voltage and current. The controller measures the incremental changes in voltage and current, thereby determining the conductance of the array and predicting the impact of voltage changes. By comparing the incremental conductance with the array conductance, the controller identifies the maximum power point (MPP) voltage when both conductance is equal. However, a significant drawback of this method is its tendency to lose track of the MPP when irradiation levels changes [17].

C. Fuzzy logic control

Fuzzy logic control is a method that handles the uncertainty and imprecision associated with real-world systems. Three steps make up this method: defuzzification, rule base table, and fuzzification. This method's advantage is its ability to handle non-linearity and operate with ambiguous and imprecise inputs. The findings are significant for the development of more reliable and efficient PV-powered micro-grids, which are crucial for sustainable energy solutions, especially in areas with intermittent solar availability. This approach offers a promising direction for future advancements in renewable energy management systems [18].

D. Power curve slope

In this method, the sign of dP/dV at various points is used to locate the global maximum. It leverages the fact that a change in the dP/dV sign from positive to negative on the P-V curve indicates the presence of another maximum to the left of an existing one. Conversely, a change from negative to positive suggests another maximum to the right. This technique searches for the global maximum on both sides of the last recorded maximum. Initially, the search is conducted near the maximum power point (MPP) identified under uniform insolation conditions. If a local maximum is detected, as indicated by a change in the dP/dV sign, it is compared to the stored maximum. If the newly detected local maximum is greater, stored maximum is updated. If not, the search in that direction is immediately terminated. This process continues until the global maximum is found. Therefore, encountering a local maximum with lower power indicates no higher maximum power exists beyond that point, significantly reducing the tracking time. The search subroutine continues in one direction until a smaller local maximum is found or the voltage threshold, the lowest voltage below which the global maximum is unlikely to exist, is reached. The power curve slope technique works in conjunction with a dc-dc converter and can be simply implemented by an inexpensive microcontroller and current and voltage sensors. The tracking speed has been improved to the order of couple of seconds by applying a feed-forward control scheme for the dc-dc converter. However, this technique is not fast enough for the portable PV applications due to rapid change of partial shading condition. This technique is effective under both uniform and nonuniform insolation of the PV array [19].

E. Neural network method

Another tool for soft computing is the neural network method. Three layers are necessary for it to function: input, hidden, and output. Neural networks can be trained with parameters like temperature, irradiance, Voc, or Isc as input. Typically, the output serves as a reference signal for power converter operation in close proximity to the MPP. Neural network implementation complexity is extremely high. Results indicate that the neuro-fuzzy MPPT method significantly improves tracking speed and accuracy compared to traditional MPPT techniques, demonstrating its potential for real-world PV applications [20].

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F. Hybrid MPPT techniques

In these types of techniques, the MPP is tracked using a technique that combines multiple traditional MPPT techniques. PV cell efficiency at varying solar irradiation has been increased through the hybridization of P&O and Inc Cod techniques. When the weather is changing quickly, P&O is used to prevent oscillation losses, and the Inc Cod method is used when the normalized solar radiation is greater than 30%. P&O is also utilized in conjunction with solar trackers to increase system efficiency by causing solar radiation to strike PV cells vertically [21].

G. MPPT for mismatched conditions

As previously mentioned, a photovoltaic array consists of multiple solar cells that may differ in orientation, manufacturing specifications, ambient temperature due to air pressure differences, and shadowing caused by clouds moving through space. Variations in these parameters have a noticeable effect on PV performance, and PV arrays can occasionally have multiple MPPs. By addressing these issues, distributed MPPT (DMPPT) makes sure that every PV cell operates on the same MPPT. DMPPT tracks MPP using five different methods. When there is a mismatch, this approach guarantees greater efficiency than other MPPT algorithms [22].

H. Analytical based MPPT technique

The observations derived from the experiment's outcomes serve as the foundation for this approach. Voc and Isc are observed based on the experiments. For every panel, a ball with radius R is chosen based on these observed values. R is chosen to have a value that places MPP inside the ball. The MPP from that ball is obtained by applying the mean value theorem. An observation-based heuristic strategy is the analytically based MPPT [23].

I. Estimated perturb-perturb technique

Compared to P&O, this method offers superior accuracy and tracking speed. Between two perturb modes in this method, there is a single estimate mode. In different irradiance levels, the estimate mode compensates for the perturb mode, which carries search. Compared to the P&O technique, this technique's implementation is much more complicated [24].

V. CONCLUSION

In this paper, the increasing demand for renewable resources of energy has been emphasized. The PV module simulation model allows us to investigate the characteristics of a PV module under various conditions of different irradiance and temperature, especially under condition of nonuniform irradiance. The model provides easy interface for changing the model parameters and observe the impact of changing the parameters on the I-V and P-V characteristics of the PV module. Another important performance of the model is that, it allows to be combined with an electronic circuit to simulate the behavior of circuit and control strategy. The PV cell's mathematical model is described, along with the necessity of MPPT to produce the maximum amount of power. The model is not only useful to study the behavior of PV module, but also to validate new electronic circuit and MPPT strategies. This paper offers a classification of different MPPT techniques along with a list of their benefits and drawbacks. Improvement can be done by tracking the maximum power point in changing environment conditions such as variation in solar irradiance as well variation in temperature.

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