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A Review of Fault Detection Techniques in Photovoltaic Systems

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A B S T R A C T

This paper provides an overview of different types of faults that are present in large-scale solar Photovoltaic (PV) systems. This paper provides a comprehensive review of conventional approaches for fault detection in photovoltaic (PV) systems, as well as an overview of relevant research conducted in the field of PV system monitoring and fault detection. The advantages of PV module-level monitoring over array or string monitoring are evident. The surveillance of photovoltaic modules is of paramount significance to minimize losses and optimize the efficiency of a photovoltaic plant system. Numerous methodologies have been investigated and examined to identify and acknowledge defects and failures. Several factors contribute to the performance degradation of photovoltaic (PV) modules. These factors encompass the variability of solar radiation levels and discrepancies in operating temperature that affect the parameters of the PV modules. Additionally, errors in maximum power point tracking, shading effects, aging, snow and dust accumulation on PV modules, and power converter losses also play a role in the decline of PV module performance. The faults are assessed and categorized into different classes according to their geographical distribution and structural characteristics.

Keywords: PV Module level faults, Wireless Sensor Networks, Solar Energy, Renewable Energy.

1. Introduction

The energy demand is consistently increasing because of the growth in industrial activities, socio-economic activities, and lifestyles. The necessity of researching green energy has been underscored by this development. The primary objective of research in renewable energy technology is to facilitate the conversion of renewable energy sources into electrical energy, which can be either integrated into the utility grid or utilized on a local scale. Undoubtedly, solar energy is a significant and indispensable form of renewable energy. Nevertheless, the performance of the solar system may be compromised due to its installation in an outdoor setting, where it is subjected to adverse climatic and environmental factors. The phenomena that hinder the efficiency of the solar system are commonly referred to as faults. According to the findings presented in reference [1], it has been observed that the annual power loss resulting from faults amounts to approximately 18.9%. To address these deficiencies, it is imperative to possess a comprehensive comprehension of climatic data, alongside the ongoing surveillance of solar modules. In addition, there is a need for solutions that can effectively detect faults in real time.

The monitoring of photovoltaic modules is of utmost importance to minimize losses and enhance the efficiency of a photovoltaic plant system [2]. Various methodologies have been explored to identify and acknowledge defects and failures. According to the authors (3), the diagnostic approach can be established by analyzing the deviation of feature curves. This entails conducting a comparative analysis between the experimental measurements of the photovoltaic (PV) system and the data derived from a model.

2. Faults in PV Systems

Faults can be described as elements that reduce the performance of a photovoltaic (PV) module. Faults can manifest as either temporary or enduring in nature. Several factors contribute to the loss of energy in photovoltaic (PV) systems. These factors include variable solar radiation levels and operating temperature mismatches in PV module parameters, errors in maximum power point tracking, shading effects, aging, snow and dust accumulation on PV modules, and power converter losses [1,4]. A separate study conducted in Spain has identified several photovoltaic (PV) deficiencies, including yellowing and browning, delamination, the presence of bubbles in solar modules, cracks in cells, defects in the anti-reflective coating, hotspots resulting from solar panels functioning as a load, delamination at the edge of cells, delamination over cells and interconnections, split encapsulation over cells and interconnections, as well as protruding interconnections [5,6]. The identification and description of defects in PV systems can be categorized according to their specific location and structural characteristics. This review aims to enumerate prevalent flaws observed in photovoltaic (PV) modules on the direct current (DC) side, as documented in reference [7].

2.1. Arc Faults and Line to Line Faults

Arc faults occur as a result of a disruption in the flow of electric current through conductors that are carrying current. These disruptions can be attributed to various factors such as solar disjoint, cell delamination, connection corrosion, or abrasion from external sources. Insulation failure in current-carrying conductors can also be a contributing factor in the occurrence of this phenomenon. The occurrence of an unintended short circuit current between two points in a series with varying voltage potentials results in line-to-line faults.

2.2. Degradation Faults

The degradation and increase in the internal resistance of solar modules can be attributed to various factors, including delamination, cell cracks, yellowing and browning, bubbles formation, faults in the anti-reflective coating, as well as delamination occurring over cells and interconnections.

2.3. By-pass Diode Faults and Bridging Faults

Defects in by-pass diodes may arise due to erroneous connections, thereby leading to the occurrence of short circuits. Bridging failures occur as a result of a diminished resistance connection between two locations with dissimilar voltages within a series of modules or cabling.

2.4. Open Circuit Faults and Mismatch Faults

Open circuit issues can occur due to various factors, including the physical damage of panel-to-panel cables or joints, the impact of objects falling on PV panels, loose cable termination, and improper handling of connections at junction boxes. Mismatch flaws are frequently attributed to factors such as partial shading, soiling, coverage by snow or mud, and exposure to high temperatures.

3. Review Of External PV System Fault Detection Techniques

In recent years, there has been a concerted effort to comprehend the various categorizations of faults to devise methodologies for detecting and pinpointing the specific fault type within a photovoltaic (PV) system. The aim of these endeavors is to enhance the dependability and longevity of the system. This review primarily examines fault detection in photovoltaic (PV) modules, with a particular focus on techniques documented in reference [1].

3.1 Independent Meteorological Data Collection Technique

The methodology employed in this study involves the utilization of external instruments, such as LCR meters and signal generators, which are not reliant on climate data, to detect faults. In a previous study [8], a method was introduced that utilizes earth capacitance measurement to identify discontinuities within a string of photovoltaic (PV) modules. The application of time domain reflectometry (TDR) was utilized in this technique to detect and locate faults within photovoltaic (PV) strings. TDR involves the application of a voltage signal to the string and the subsequent observation of the signal response waveforms. This technique facilitated the identification of faults such as degradation and disconnection that may occur between strings of modules.

3.2 Measurement of Current-Voltage (I-V) Characteristics

Faults can be identified by conducting measurements of the current voltage (I-V) characteristics at the output terminals [9]. Numerous scholars have employed this methodology to identify deficiencies. In the study conducted by [10], a system based on a microcontroller is employed to effectively monitor, supervise, and control the photovoltaic (PV) system in real-time. Moreover, the developed system exhibits seamless integration with network infrastructure, facilitating the retrieval of data from photovoltaic (PV) systems that are geographically dispersed. A comparable methodology was introduced in a prior study [11], wherein the automatic identification of defect location in grid-connected photovoltaic (PV) systems was achieved through the utilization of voltage and current indicators, as well as monitoring the AC to DC power ratio. The program that has been developed is capable of identifying faults in both the alternating current (AC) and direct current (DC) components of the photovoltaic (PV) installation. The aforementioned methodology can identify anomalies within a solar string, an inverter, as well as a broader fault that encompasses partial shading, PV-aging, or maximum power point tracking (MPPT) error.

3.3 Comparing the Actual Output and Simulated Output of the PV system

This methodology entails the comparison of the simulated photovoltaic (PV) output obtained through modelling with the empirically measured output. The distinction functions as an indicator for detecting malfunctions. The anticipated power output is determined by employing photovoltaic (PV) models and various parameters to establish a threshold during the typical operation of a PV system. If the measured output surpasses the predetermined threshold, the system is deemed to be defective.

3.4 Analyzing the power losses

The identification of faults in a photovoltaic (PV) system relies on an analysis of power losses within the system. This is achieved through the computation of the disparity between the measured or monitored power and the simulated results. The approach described in reference [12] was proposed for monitoring and identifying faults in photovoltaic (PV) systems. The technique outlined in this study enables the identification of faults occurring on the direct current (DC) side of the photovoltaic (PV) system. The system defines two indicators of power loss, namely thermal capture losses and miscellaneous capture losses. The examination of these indicators allows the supervisory system to produce a faulty signal as a means of detecting faults in the operation of the photovoltaic system.

3.5 Artificial Neural Networks Techniques

The fault detection technique involves instructing the system model to acquire knowledge about various scenarios that are associated with a particular data type. The identification of new conditions is predicated on prior training and can serve as a means to detect and uncover faults. The determination of theoretical boundaries for fault detection in PV systems can pose challenges due to the variability of system output influenced by climatic conditions. Nevertheless, the constraint can be overcome by constructing a model that is tailored to identify specific input-output relationships. The researchers employed a trained system to identify photovoltaic (PV) array defects that arise from partial shadowing and inverter losses [13]. The utilization of this technology serves to streamline the maintenance framework of photovoltaic (PV) systems. The aforementioned technology employs diagnostic criteria databases to analyze data obtained from photovoltaic (PV) systems. These databases undergo regular updates and checks to ensure their accuracy and reliability. After a thorough diagnostic analysis, a maintenance recommendation is provided. This technique offers significant advantages as it greatly streamlines the servicing and maintenance of PV systems. Furthermore, the authors of [14] employed an artificial neural network to categorize diverse issues encountered in photovoltaic arrays. The Artificial Neural Networks (ANN) model incorporates various parameters, including voltage, current at the maximum power point, and temperature of the photovoltaic (PV) system, to determine and classify the specific fault within the system.

3.6 Infrared or Thermal Imaging

The utilization of this method is widely recognized for the identification of faults in photovoltaic (PV) systems. Thermal imaging relies on the detection of localized heat generation resulting from various types of flaws, including weak conductors, short circuits, and joule heating effects. When specific photovoltaic (PV) cells within a series exhibit fault, they exhibit reduced energy generation compared to their counterparts, resulting in reverse biasing. Consequently, these faulty cells function as loads, leading to the dissipation of heat. Consequently, the presence of a temperature gradient gives rise to a discernible luminous region when observed through thermal imaging. There exist two distinct methodologies for conducting thermal imaging.

3.6.1 Forward Bias Imaging

In the context of imaging in forward bias, the module is operating in a state of forward bias and is connected to the power source. The current flowing through the module, which is twice the magnitude of the short circuit current, will increase the temperature. The infrared (IR) images are subsequently acquired using the IR camera, followed by the application of image processing techniques to ascertain the characteristics and spatial coordinates of the identified problem. This methodology proves to be advantageous in identifying issues such as hotspots, loose connections, and increments in series resistance.

3.6.2 Reverse Bias Imaging

Reverse bias imaging employs a similar procedure to forward bias imaging, with the exception that the module is connected to the power source in a reverse-biased condition. This methodology is capable of identifying faults, such as ohmic shunts.

4. PV Module Level Monitoring and Fault Detection

It is imperative to acknowledge that the defect detection techniques elucidated in the preceding sections primarily pertain to the PV systems in isolation, without consideration of the converters or the AC side. The subsequent section examines the importance of fault detection in photovoltaic (PV) modules.

There are several advantages associated with photovoltaic (PV) module-level monitoring and defect detection.

- Enhancing fault localization techniques in large-scale photovoltaic (PV) systems. Consequently, the expenses associated with maintenance are diminished due to the ability to identify issues at the individual photovoltaic module level.
- To enhance operational efficiency and optimize energy production, it is imperative to mitigate the consequences of failure in large arrays, thereby minimizing downtime and maximizing energy output.
- Data presentation offers comprehensive visibility of technical performance at the module level, enabling accurate prediction of the overall performance of photovoltaic (PV) systems.
- Remote troubleshooting and real-time access to system data are utilized to assist in the analysis of root cause faults [15].

5. Review Of Monitoring and Fault Detection On PV Systems Using Wireless Sensor Networks

Extensive research has been conducted and continues to be carried out in the field of PV system module monitoring and defect detection. The monitoring and evaluation of electrical characteristics and climatic variables on the photovoltaic (PV) array involve both instantaneous and continuous sensing. This process also includes the transfer of data between sensors and an external gateway for further analysis. Wireless Sensor Networks (WSN) refer to the collection of sensors or nodes that communicate with each other through a wireless network. The authors introduced a fault detection technique for defect diagnosis in photovoltaic arrays, utilizing Zigbee wireless sensor networks [16]. A circuit to measure the values of different attributes was developed. The fault meter for accurately assessing the PV power generation system was constructed using a combination of a PIC microcontroller and a ZigBee module, in addition to incorporating neural networks. Nevertheless, the detection of defects at the photovoltaic (PV) module level was not conducted, and the wireless sensor network (WSN) only covers a limited distance of 100 meters. Sholehi et al. (2017) developed an internet-based monitoring and protection solution for photovoltaic (PV) smart grid systems. In this design, a voltage and current sensor apparatus were employed to observe and record voltage and current measurements, subsequently transforming them into electrical power. The system is capable of offering power protection to the load through the utilization of a relay mechanism, ensuring that the power supplied does not surpass the load's power demands. The monitoring and protection system utilizes wireless internet communication through a Wi-Fi module. Nonetheless, the process of monitoring is conducted at the array level, thereby resulting in inefficiencies in terms of both time and financial resources.

The authors in reference [18] introduced a monitoring and control system for detecting malfunctions in solar panels, utilizing the Internet of Things (IoT) as its underlying technology. Data acquisition sensors are primarily utilized for the collection of various types of data, including current, voltage, temperature, light, and dust measurements. Due to its wireless nature, Zigbee is limited to short-range communication capabilities. The method for monitoring photovoltaic (PV) modules from a string is outlined in the reference [19]. The monitoring of the open circuit voltage and current, as well as the short circuit voltage and current, of the panels connected in a series configuration, is conducted at this location, irrespective of their operational state. The photovoltaic (PV) panel is disengaged from the string, and measurements are conducted under open-circuit and short-circuit conditions. The aforementioned parameters are transmitted wirelessly to the coordinator node for analysis, and they are also stored in the data memory of the microcontroller unit. The monitoring of the PV system's reliability is achieved through the utilization of a wireless sensor network. This network enables the identification of faults in individual PV panels within a string, facilitating the localization of malfunctions. The authors proposed a solution in reference [20] that aims to automate the detection of faults by leveraging the Internet of Things (IoT) technology. The panel is equipped with current sensors to gather data on the electrical current. The recorded measurements are transmitted to the monitoring centre through the utilization of a Wi-Fi module. The data is assessed at the monitoring centre, where any anomalies are detected. A study conducted in reference [21] involved the development of a monitoring system specifically designed for online fault detection and classification in photovoltaic (PV) plants. A proposed monitoring system is suggested to assess the efficiency of the photovoltaic (PV) plant by analysing electrical and environmental data in real time as well as over a period of time.

When contemplating the implementation of a substantial photovoltaic (PV) system comprising a significant quantity of solar PV modules, the task of attaining monitoring capabilities at the module level may seem to entail a considerable investment of time and financial resources. Efficient monitoring of PV modules at the module level is essential for analysing performance and health. This requires real-time observations of the individual modules within the system, as well as the ability to remotely analyse the collected data. To effectively localize errors and resolve them, it is necessary to perform the procedure mentioned earlier for each module in the system. The implementation of the Internet of Things (IoT) alongside low-power, low-cost communication, and wireless sensor networks presents a viable and economically efficient approach for enabling photovoltaic (PV) module-level monitoring within large-scale PV systems. Wireless communication offers a multitude of advantages in comparison to its wired counterpart.

Consequently, the benefits of wireless sensor networks encompass a cost-benefit analysis, the capability for continuous parameter monitoring, the ability to access and evaluate the output from individual modules, a reliable and secure communication and data transfer mechanism, scalability to accommodate new nodes or devices as needed, flexibility, and accessibility facilitated by a centralized monitoring system that enables access to all WSN nodes. Table I compares all low-power wide-area network (LPWAN) options for PV module monitoring and defect detection. The comprehensive examination of the system's design and development will be deferred to subsequent research endeavours, as it falls beyond the scope of this paper.

TABLE I: COMPARISON OF LPWAN NETWORKS

Specification	ZigBee	Sigfox	Bluetooth	Dash 7
Low Cost of System Components	X		X	
High Interference Immunity				
Long Distance Coverage				
Low Power Consumption	X		X	
Multipoint Connection	X	X		X
High Security	X	X		
Sensor Direct Connectivity	X		X	
Expansion Capability	X		X	

6. Conclusion

This study examined various flaws and fault detection systems employed in photovoltaic (PV) technology. The study also examined the benefits of PV module-level monitoring, an important application for optimizing the performance of solar PV systems by accurately identifying defects within the system. In the design, our objective is to measure the voltage, current, temperature, and solar irradiance level of each photovoltaic (PV) module within a string of a large-scale solar system. In our future work, we will use a modern deep learning technique to overcome the existing research gaps in the current works.

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