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Towards Smart Monitoring Systems: Fault Detection and Diagnosis-Based Artificial Intelligence Algorithms in Solar PV Power Plants

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Solar photovoltaic (PV) power plant reliability and efficiency are always hot topics. During the operating period as all industrial systems, these plants are susceptible to malfunctions and failures in their equipment or operations. Faults occurrence in solar PV system components can significantly affect the efficiency, power generation yield, safety, and stability of the entire PV power plant if not detected and corrected promptly. Furthermore, if any faults persist, they can increase the fire hazard. For these reasons, incorporating a smart diagnostic system is required, where its primary goal is to provide accurate indicators for detecting faults and thus maintaining the stability of the solar PV power plant energy production. Given the importance of this topic, the present literature starts with a description of various fault mechanisms that occur in solar PV power plants before providing a consistent review about fault detection and diagnosis strategies-based artificial intelligence to boost the progress and the transition towards smart grid-based green energies.

Keywords: Fault detection and diagnosis, Artificial Intelligence, Solar photovoltaic, Energy transition, Microgrids, Smart grids.

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1. INTRODUCTION

The energy landscape is undergoing profound changes due to the increase in decentralized electricity production associated with the development of renewable energies [1], the appearance of new uses (heat pumps, electric vehicles, self-consumption, etc.), targets for reducing greenhouse gas emissions. Addressing these challenges and achieving the energy transition at the best cost require making more flexible and smarter energy networks. Indeed, a smart grid integrates new information and communication technologies to develop a multitude of new uses [2].

For electrical network operators, smart grids make the network more adaptable, which increases the resilience of the electrical system, optimizes the level of reliability and quality of the electricity supply, and facilitates the insertion of new means of production into the electricity networks, in particular renewables energies, such as wind, solar energy, which are both intermittent and decentralized [3]. For consumers, smart grids make them real players in the energy system. With smart grids, they can monitor their consumption in real-time and, if necessary, control it and modify their behavior by playing an active role in the operation of the electrical system [4].

Smart microgrids are the starting point in the emergence of the smart grid from the current power infrastructure [5]. Indeed, a microgrid is an electricity distribution network, consisting of multiple generations, storage and load managed from the more extensive transmission network. The primary goal is to provide affordable, stable localized electric supply to urban and rural areas, coastlines, and distant businesses that have little or no connectivity to the main power grid. The more electricity generated locally, the less a community will need to import it from outside generation plants or the primary grid.

Green energy sources are environmentally friendly and sustainable, and the integration of these energy sources into microgrids is rapidly spreading worldwide. Solar photovoltaic (PV) systems are one of the most used renewable energy systems.

The reliability and efficiency of renewable energy systems are always a hot topic. As all industrial systems, renewable energy systems are subject to malfunctions and failures in their installations or work, resulting in significant yearly expenditures [6]. These systems fail and deteriorate during the operating period, which requires the development of a diagnostic system; its main objective is to provide indicators to detect faults and thus maintain the energy production of the renewable energy system. Furthermore, the data collected from the fault detection and diagnosis (FDD) module would be further analyzed and employed by controllers to accommodate failure effects using adequate fault-tolerant control (FTC) techniques [7]. In this sense, it is crucial to understand various failures mechanisms in microgrid modules before analyzing the various fault diagnostic methodologies and techniques.

The present research focuses on microgrids integrating solar PV systems. It starts with an overview of several failure mechanisms that occur in different elements of solar PV plants, followed by an investigation of state of the art in FDD methods based artificial intelligence techniques mainly applied to solar PV systems in microgrids.

The following is how the remainder of this paper is

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organized: Section 2 discusses the various fault types in solar PV power systems. Section 3 reviews different FDD methods based artificial intelligence techniques presented in the relevant literature, and Section 4 draws some conclusions and perspectives.

2. TYPES OF PV FAULTS

To conduct a literature study on FDD techniques in solar PV plants, it is necessary to characterize probable failure and fault types, along with their relative causative factors. Faults can manifest themselves in various microgrid modules, comprising distribution wires, power converters, distributed generation sources, and sensing technologies. The most prevalent types of faults in PV systems are classified as depicted in Fig. 1 [8]. In the following sub-sections, essential information about failure mechanisms of solar PV installations is shown.

Faults in the PV system are defined as temporary or permanent. Shading effects and module fouling often cause temporary defects. Permanent module defects are delamination, bubbles, PV cell yellowing, burnt and scratched PV cells.

Permanent defects are addressed by changing or fixing faulty PV modules. Severe defects in solar PV panels are often caused by a short circuit, grounding, line-to-line, and arcing defects [8].

Maximum power point tracking (MPPT) fault, joule losses in wiring, and malfunctioning devices are all reasons that might cause yield loss [8]. Faults in solar PV installation can be categorized as modules, strings, or networks defects, based on the solar PV plants concerned.

2.1 Hotspot Fault

The hotspots on the PV panels are mainly due to the increased resistance of the cells due to a lousy welding process between the bus bars. Poor solder connections result in low resistance in the PV module, which absorbs the PV cell electricity. As a consequence, panels with hotspots reduce the efficiency and lifetime of the solar PV system. In this case, the panels must be replaced, which incurs additional system costs). This fault causes short circuits that damage the ethylene vinyl acetate (EVA) film and the back sheet and then ignite [6].

2.2 Microcracks

The microcracks are mainly caused by poor quality cells, a problem during the production of PV modules, a problem during shipping (due to poor quality packaging and incorrect loading of the container) or improper handling of the panels when unloading the container or installing the panels.

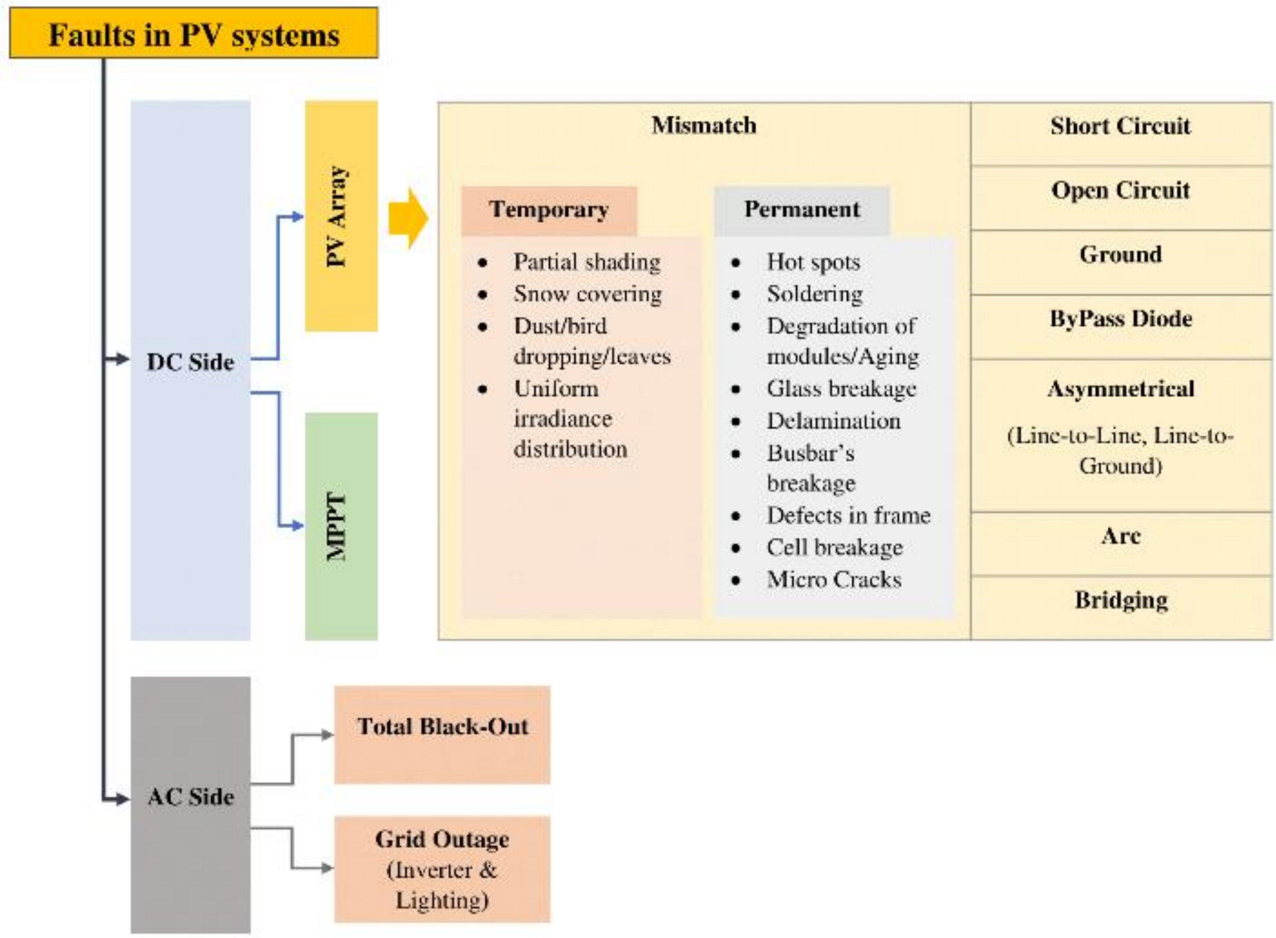

Fig. 1 – Classification of faults in PV power plants in DC and AC sides

Panel's cells are connected in a series configuration. Finally, the microcracks will impact the efficiency of all PV modules and systems, resulting in a performance loss. Changing the panel is usually advised in this situation [9].

2.3 Ground Fault

A DC ground fault is among the most common issues in PV installations. A DC ground fault is an undesired condition caused by the current that flows via the instrument grounding conductor in DC power lines. Ground faults often cause serious safety problems, including arc faults and high voltage arc flashes. Ground faults presented a fire danger with a safety issue when short-circuited current heats exposed metal [10].

2.4 Line-to-Line Fault

A line-to-line (LL) fault is a short-circuit defect that occurs between the wires of a PV installation. Faulty cable insulator and mechanical stress can also induce LL problems [11].

2.5 Diode Fault

Bypass and blocking diodes are vital in maintaining the performance of PV installation. Bypass diodes (Bp-D) provide reverse voltage protection, whereas reverse current protection is provided by blocking diodes (Bk-D). These diodes have two electrical faults: short-circuit diode and open-circuit diode. These failures can result when a PV module/array is partially shaded for an extended time. Bp-D is a crucial component for safe system operation,

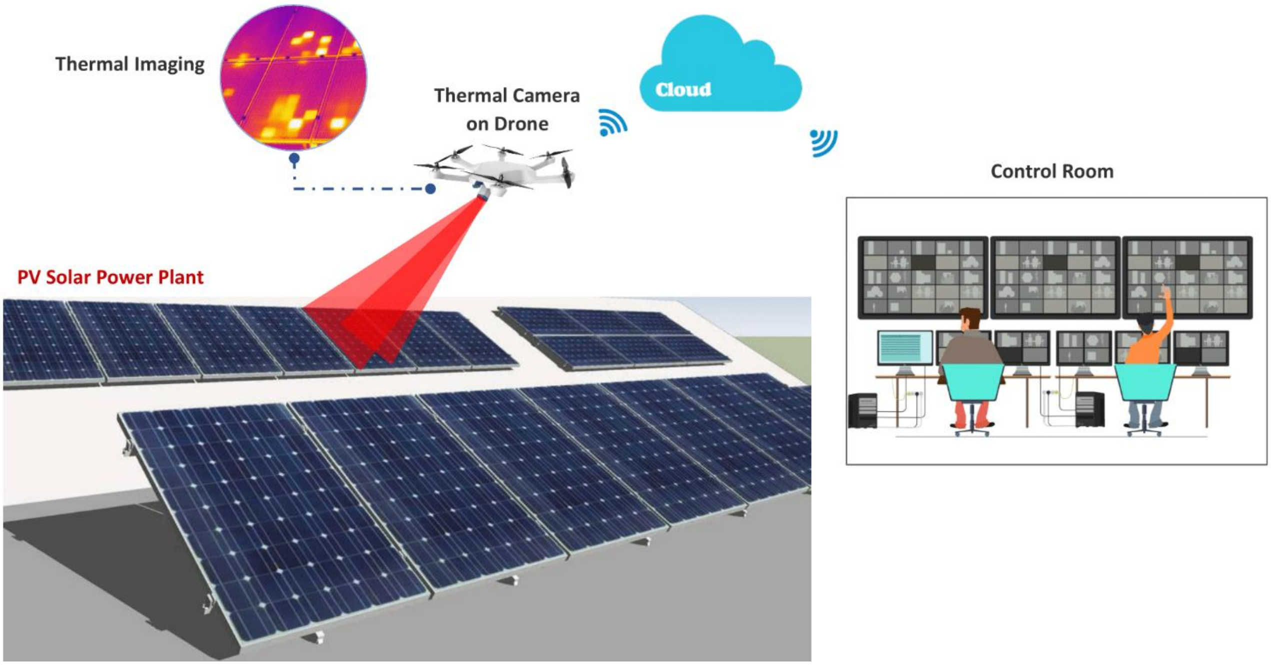

Fig. 2 – Drone equipped with infrared camera for PV power station inspection

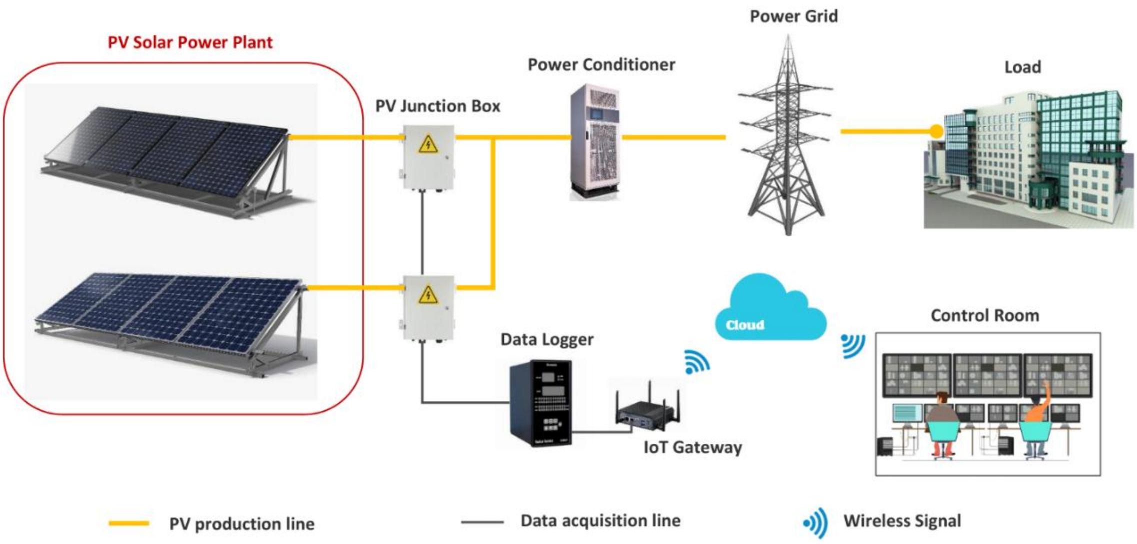

Fig. 3 – IoT platform for solar PV power plant monitoring

whereas Bk-D in series with PV module prevents over current. Bk-D will block the reverse current under LL fault, breaking down the system. For that reason, both Bp-D and Bk-D should be carefully selected and thoroughly verified [10].

2.6 Arc Fault

An arc fault is the unintentional passage of a spark across air or cables insulators [12]. Arc hazards can arise between electric cable discontinuities and cables with differing potentials. Electric arcs in a solar photovoltaic installation can cause severe dangers [13].

2.7 Junction Box Fault

The reliability of the junction box (JB) is one of the most critical issues for PV modules during performance testing and outdoor functioning. Fretting corrosion in JB can result in a rapid rise in contact resistance. As presented in [10], an electric arc between the contacts causes the JB to wear out and melt. This fault would eventually destroy the panels and the entire string, costing the solar PV system's owners additional losses due to energy production loss [10].

3. ARTIFICIAL INTELLIGENCE-BASED FAULT DETECTION AND DIAGNOSIS METHODS

Solar PV power plants have increased dramatically over the last few years. The output efficiency of these plants degrades over time due to various factors such as microcracked cells, snail trails, hotspots, shaded cells, panels, and so on. For that reason, it is necessary to implement an automated system to identify faults in solar PV power plants [3]. As a solution, scientists have recommended using drones integrated with infrared cameras for PV power station inspection, Fig. 2, as drone technology advances and benefits from the internet of things (IoT) technology's sensors and platforms as depicted in Fig. 3.

Based on the literature reviews, these technologies are using artificial intelligence (AI) methods to detect automatically the incidence of faults in solar PV panels or strings based on infrared image processing or on picks presented in the residual series that is calculated based on the variance between the real and the estimated PV power measurements.

Most developed AI-based FDD approaches involve machine learning (ML) algorithms, including support vector machines for regression and classification, artificial neural networks, fuzzy inference systems, decision trees, random forests, metaheuristics, etc. It enables the creation of models and algorithms designed to infer the correlations between PV system's inputs and outputs features. The data is derived from experimentally precise PV module observations and then divided into training and testing sets. The study presents the application of different AI algorithms for fault detection and diagnosis. Table 1 summarizes different AI methodologies applied for FDD, highlighting the detected fault types.

Based on the conducted literature review in detecting and diagnosing faults in PV systems, several steps are required in the ML regressors and classifiers' development process. These steps are presented as follows:

- PV generator modeling;
- Collection of data sets covering the most probable scenarios for each fault and the proper operation of the PV system;
- Creating a knowledge base of various faults;
- Selection of AI classifiers and regressors to classify the measurements taken in real-time among different faults' classes and patterns;
- Selection of triggering criteria for AI classifiers and regressors;
- Training and testing of AI classifiers and regressors;
- Merging of AI classifiers and regressors' decisions for making an accurate decision.

Table 1 – AI techniques applied for FDD

References	Years	Fault types	ML technique
[14]	2021	General	Adaptive neuro-fuzzy inference
[7]	2018	• String • Short circuit • Line-to-Line	C4.5 decision tree algorithm
[15]	2020	Partial shading	Artificial neural network
[3]	2020	General	Hybrid deep artificial neural network
[16]	2021	Bird's drops	Deep convolutional encoder-decoder approach
[13]	2020	Arc	Data-augmented neural network
[17]	2019	Hotspots	Mamdani-fuzzy inference system
[9]	2021	• Microcrack • Hotspots	• Artificial neural network • Support vector machine • Binary tree – support vector machine
[11]	2022	• Intra string Line-to-Line • Inter string Line-to-Line • Degradation fault in array • Degradation fault in string • Open circuit	• Categorical boosting • Light gradient boosting method • Extreme gradient boosting

AI with classification and regression properties makes it possible to identify faults in real time with excellent tolerance to noise associated with climatic conditions and sensing devices.

4. CONCLUSIONS AND PERSPECTIVES

This article presents an overview of solar PV plant defects and FDD techniques. An accurate automated monitoring system needs to be developed and integrated with these plants to boost their efficiency and reduce the operating costs. Recent approaches based AI techniques for FDD have been presented in this paper to overcome this problem. Based on the reviewed papers, detecting faults in solar PV systems was accomplished using either AI regressors or classifiers models, both of which demonstrate an excellent precision compared to traditional strategies.

Approaches based on data-driven models can efficiently detect and classify the fault type with similar patterns. Nevertheless, the primary disadvantage of these approaches is that they require more technical expertise in terms of experimental realizations of different cases' scenarios to build a large dataset of different fault types, which are not always available or accessible.

As perspectives, first, large databases need to be created for FDD applications based time series and labelled images to overcome this issue efficiently with an automated system-based AI. Second, boost traditional AI methods' accuracy and robustness by hybridizing them with metaheuristics and other techniques.

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На шляху до інтелектуальних систем моніторингу: алгоритми штучного інтелекту на основі виявлення та діагностики несправностей на сонячних фотоелектричних електростанціях

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Надійність та ефективність сонячних фотоелектричних (PV) електростанцій завжди залишаються актуальними темами. Протягом періоду експлуатації, як і всі промислові системи, ці установки сприйнятливі до збоїв у своєму обладнанні або роботі. Поява несправностей в компонентах сонячної PV системи може суттєво вплинути на ефективність, вихід електроенергії, безпеку та стабільність усієї PV електростанції, якщо їх не виявити та не усунути вчасно. Крім того, якщо залишаються будь-які несправності, вони можуть збільшити небезпеку пожежі. З цих причин необхідне включення інтелектуальної діагностичної системи, основною метою якої є надання точних індикаторів для виявлення несправностей і, таким чином, підтримання стабільності виробництва енергії сонячною PV електростанцією. Стаття починається з опису різних механізмів несправностей, які виникають на сонячних PV електростанціях, перш ніж надати послідовний огляд штучного інтелекту на основі стратегій виявлення та діагностики для прискорення прогресу та переходу до зеленої енергії з урахуванням інтелектуальних мереж.

Ключові слова: Діагностика несправностей, Штучний інтелект, Сонячна фотоелектрика, Перехід енергії, Мікромережі, Інтелектуальні електромережі.