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Challenges during commissioning and operation in photovoltaic power plants by electrical faults

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ABSTRACT

Problems such as increasing environmental pollution and global warming due to fossil fuels used in energy production have revealed the requirement for renewable energy sources. In addition to this situation, the decreasing fossil fuel reserves, and the need to diversify energy production resources to ensure energy supply security for countries have made the use of renewable energy sources a necessity. Therefore, demand for solar energy will continue to increase, considering the increasing renewable energy need. To increase energy efficiency, the uninterrupted production of photovoltaic power plants during production hours is important to reduce the consumption of fossil fuels. For this reason, situations and malfunctions that prevent uninterrupted operations should be detected. Fault classification contributes to the rapid identification of problems by providing fast diagnostics for possible faults. When the previous studies in this field are examined, there are publications about general faults in photovoltaic power plants and publications about electrical faults separately. However, there are limitations in academic studies that deal with the difficulties encountered in the commissioning and operation of photovoltaic power plants in detail and examine electrical faults. In this context, there is a need for relevant studies. In this study, the possible failures that may occur during the commissioning and operation of photovoltaic power plants will be categorized and this study is intended to be a resource for studies on this subject. It is aimed to create a resource for academic studies and to contribute to field applications to companies in the sector.

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1. INTRODUCTION

The methods and resources used to produce energy are changing and diversifying day by day. Photovoltaic (PV) power plants are among the alternative energy sources that have seen the most investment recently [1]. PV power plants have become the most efficient and sustainable option against power plants using fossil fuels [2]. Inverters are used to transform the direct current (DC) electricity generated by solar panels into alternating current (AC) power, which allows PV power plants to be connected to the grid. Depending on the application area there are also PV power plants that operate without being connected to the grid. One of the biggest advantages of PV power plants is that they can be sized for any application. While this sizing can be as large as conditions, it can even be small enough to meet the energy needs of only one house [3]. According to the application method, PV power plants can be connected to the grid usually, from a low voltage level or medium voltage level by adjusting the voltage level with the help of transformers [4]. PV power plants can be used for voltage and frequency regulation purposes as grid-regulating auxiliary facilities [4-6].

To analyze the problems encountered in PV power plants, it is necessary to identify the causes of the problems by categorizing the problems first. Identifying faults will help to classify faults. Classifying the faults will help to see the causes of the faults more clearly and thus develop the measures to be taken against to faults. Taking measures during commissioning and operation can prevent the loss of time and money because less fault means more power production. Different methods can be used to categorize the difficulties encountered [7]. Alsharif et al. in [8], the difficulties encountered in PV power plants are classified as cost, discontinuity of energy production, technical problems, ecological-social effects, and performance constraints. To categorize the faults in more detail, it is necessary to define the fault first. Any effect that reduces the output voltage of a PV power plant can be called a fault [9]. Faults can be named temporary or permanent faults according to their duration of action. Madeti et al. in [9], the most commonly used headings in the classification of electrical faults in PV power plants are examined. In this study, the faults are examined under two main headings as AC and DC faults. Diminish et al. in [10], while

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classifying the faults in PV power plants, in addition to the AC and DC faults, the faults experienced during the data collection phase for the control system are included and discussed under three headings. Electrical faults in PV panels used in PV power plants in [11]; earth faults, phase-to-phase faults, and PV arc faults were examined in the upper headings and divided into subgroups according to the reasons for the occurrence of the faults in each heading. Chen et al. in [12], electrical faults in PV panels are modelled on the MATLAB/Simulink program. Kurukuru et al. [13] deal with the faults in PV power plants differently and comprehensively than other studies. Faults in their study were classified as environmental faults, electrical faults, and physical faults. Among these topics, electrical faults were also separated as inverter faults and PV string faults and detailed the faults in this way and made a comprehensive grouping. Then, by modelling the PV plant on the MATLAB/Simulink program, the algorithm created for the classification of faults was examined on Kurukuru's model [13]. In Berghout et al.'s study [14], in PV power plants, machine learning techniques are utilized to find defects. In a study by Demirel et al. [15], a model was created for a sample PV power plant using a simulation program, and the effects of lightning strikes were examined on the model. Bosman et al. [16] stated that although PV power plants are plants with a low risk of failure, the widely known "Install and Forget" perspective for PV power plants is wrong. Within PV power plants, several different kinds of failures can happen. Classification of failures according to their types and modelling of their possible effects are important in terms of convenience in applications and a source for future academic publications.

This study is aimed at the classification of electrical faults in PV power plants during commissioning and operation. For this purpose, this study is a literature review that contains the publications related to the subject and comments according to the information in these publications.

2. MATERIAL AND METHOD

In [24], a fault is described as, "an abnormal condition that may cause a reduction in, or loss of, the capability of a functional unit to perform a required function". The development of fault classification and detection has become an essential research area in recent years since faults in PV power plants might influence their ability to produce electricity [43]. The reason for examining and classifying the electrical faults in PV power plants in this study is the low number of studies that are specialized under the heading of electrical faults in PV power plants.

2.1. Literature Research

In this study, academic study search engines such as Google Scholar, and ProQuest were used. The main resources were related academic studies such as articles, papers, master's theses, and doctoral theses published between 2010 and 2023. In addition, experiences from the field were also used. Different types of publications containing keywords are used to provide resource diversity. Publication date and keywords are the main criteria in the selection of the studies used.

One of the most important steps to evaluate the causes of failure and the effects of failures is to examine the most common failures in PV power plants. In this context, it is possible to examine faults under two headings, DC side faults and AC side faults. AC side faults can occur according to issues with the inverter or power grid. DC side faults are more in number than the faults on the AC side, and they include faults in the cell, bypass diode, module, junction box, open circuit, short circuit, arc fault and ground fault [1]. As shown in Figure 1, the classification of electrical faults that occur in PV plants is given to understand the subject better and to facilitate the physical follow-up of the fault occurrence zones in this study.

There are different ways of fault classification [44]. In this study, the main criterion is electrical faults. The causes of electrical failures are categorized, and a table is created. There are two main categories according to the location of the fault. In the following section, these main branches and sub-headings are examined [14, 22, 42].

3. RESULTS AND DISCUSSION

Challenges in PV power systems by electrical faults are mainly defined in this section based on Figure 1.

3.1. Results

In this section electrical faults in PV power plants are examined according to classification heading.

3.1.1. Fault Types on the AC Side of PV Power Plants

The inverter and grid fail, which falls under the system's AC side fault. The DC power in this scenario is unchanged from the power in a fault-free condition [17]. On the AC side, two different fault categories can be distinguished: total power cuts, which are classified as system external faults, unbalanced voltage, and lighting or grid outages for faults in AC parts like weaker switches, overcurrent, or overvoltage. [29-31, 36].

Inverter faults: Under the inverter fault conditions, the DC power remains constant while the AC output power decreases. This information demonstrates that there is no chance that a module or string failure or a broken wire between the modules and inverter occurred. Thus, the inverter's problem is to blame for the power outage [17].

Grid faults: Grid faults include malfunctions at power plants, damage to substations, electrical transmission lines, or other distribution system components, a short circuit, or an overload of the energy mains [17]. Grid faults affect directly the PV power plant's connection to the grid [26]. Grid faults even can disrupt the synchronization state and cause the power plant to fail.

Environmental Faults (Lightning): Whenever lightning strikes, a pole-to-ground fault happens [22]. Lightning strikes may damage electronic components and may cause temporary or permanent problems.

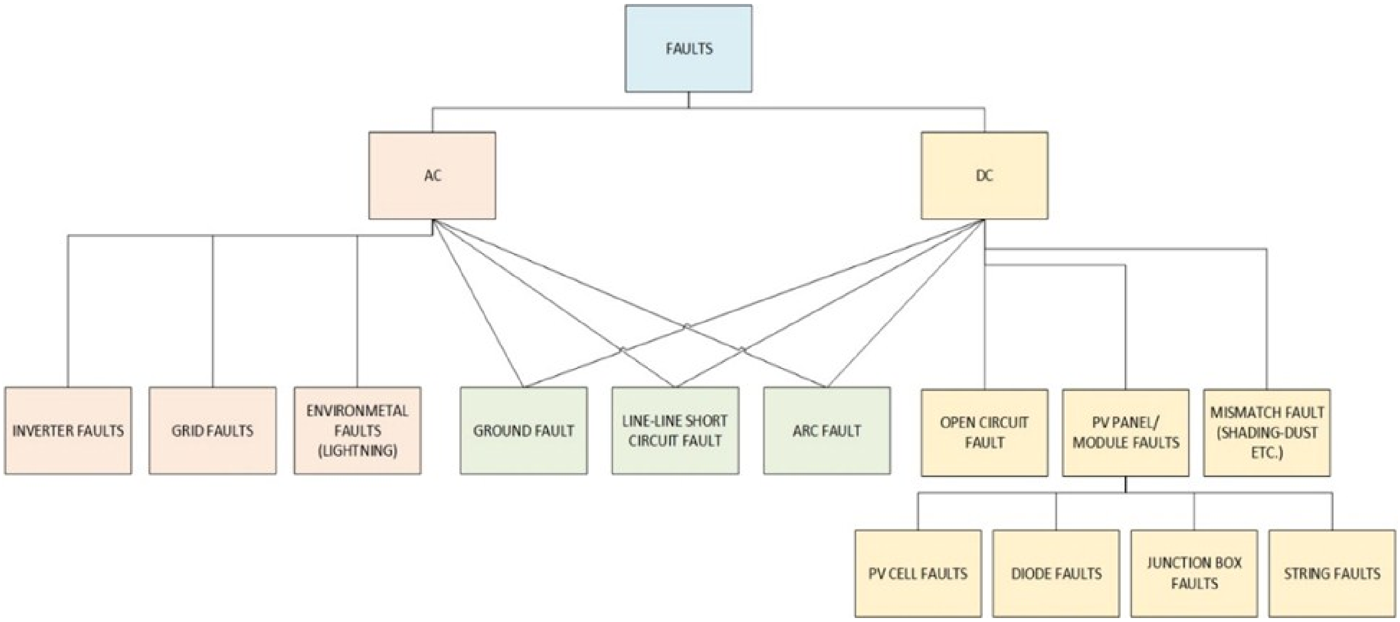

Fig. 1. Classification of electrical faults in PV power plants.

3.1.2. Fault Types in AC & DC Side of PV Power Plants

Ground Fault: A ground fault occurs when the circuit unintentionally creates a path to the ground [13, 27]. For instance, wrong operation, dust, and water leaks may occur due to cracks in the cells. And also, damage to the insulation of the conductors that transport current and transmit electricity to PV systems is a common reason for ground faults. National electrical regulations often mandate ground fault detection and interruption equipment installation that identifies excessively leaking current to the ground to prevent ground problems. Also, typical solar inverters have insulation testing circuits that can spot ground leaks. PV systems must have two different types of grounding, such as system grounding and equipment grounding [18].

Line-Line Short Circuit Fault: An unintended short circuit between any two points with different voltage potentials is referred to as a line-line fault [19]. Accidental short circuits in a PV array could occur either within a PV string or across PV strings, resulting in an intra-string line-line fault [20]. Also, these faults are brought on by the cables' insulation failing, which can happen due to corrosion, mechanical harm, water intrusion, or animal damage.

Arc Faults: In ideal conditions, the resistance between the interconnections of the modules in PV arrays is practically low. Cable insulation failure or weak connections at a conductor's joint are the two main causes of arc failures. Arc faults come in two varieties: parallel and series arc faults [28]. In case of a loose wire connection at the junction point or between modules, series arcs are frequently seen within the module itself. Parallel arcs are produced when two parallel conductors with different potentials are positioned close to one another. Series arc fault electrical simulations have been carried out [20]. Arc faults are shown in Figure 2.

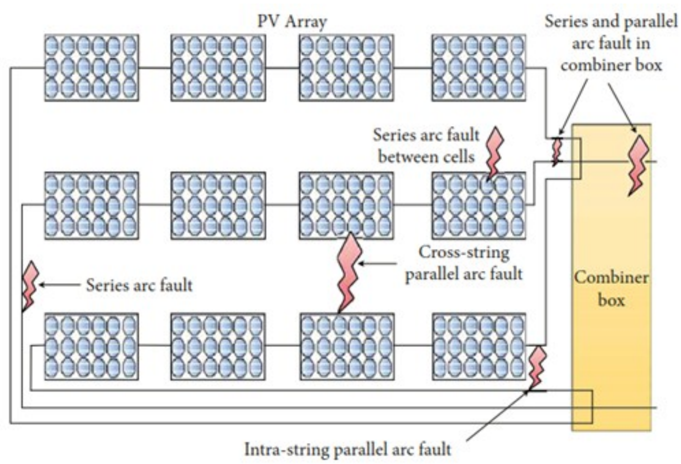

Fig. 2. Series and parallel arc faults [19].

3.1.3. Fault Types on the DC Side of PV Power Plants

Figure 3 gives a brief description of the DC side faults of a PV system [32-40].

Open Circuit Fault: The disconnecting of wires in one or more branches of a PV circuit results in open circuit faults [21]. A failure known as an open circuit can occur between more than one phase and ground wires or it may simply happen between two phases [14]. The improper connections at PV cells, faulty connector connections at junction boxes, or fractures in cables create these failures [9].

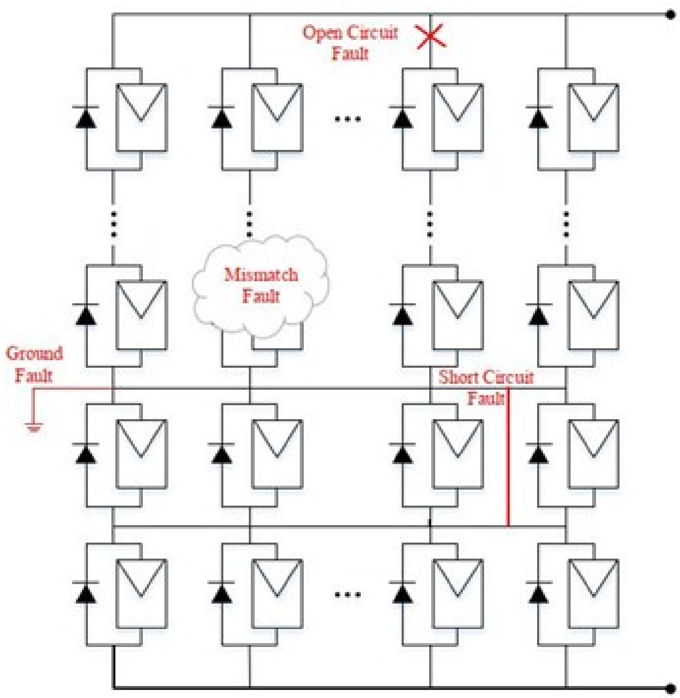

Fig. 3. Example of faults in PV system [25, 41].

Mismatch Faults: Mismatches in PV modules happen when the electrical parameters of a single cell or a group of cells are altered from one another. PV modules are irreparably harmed by this problem, and there is significant power loss. Mismatch faults that are both permanent and temporary can be seen in these problems [17, 21].

When a section of the PV panel array is covered by the shade of trees, buildings, dirt, cloud, snow, or other light-blocking impediments, there will be temporary mismatches. Snow cover makes it possible to identify temperature variations.

To explain in more detail, sunlight is the main energy source for solar panels. Solar panels cannot be used effectively when the sun's rays are obstructed. Due to passing clouds, and snow, the panel is covered with water, mud, bird droppings, and tree shadow, the majority of solar panels are unable to receive sunlight, which ultimately causes a loss of power production [22].

Hotspot, soldering, and degrading errors lead to permanent mismatches. When a shaded or defective cell or group of cells inside the module's operational current surpasses their lowered short circuit current, hot spot heating results.

PV Panel / Module Faults: Can be examined according to the component and location of faults in PV panels and PV cells. These faults are photovoltaic cell faults, diode faults, junction box faults and string faults.

Photovoltaic Cell Fault: Photovoltaic cell fault is the case of cracks on the cell surface, dust, snow, intercellular current imbalance, co-ageing problems caused by partial shading, premature completion of some cells' life, and a decrease in efficiency due to overheating and corrosion in the cells [23].

Diode Faults: The diode included in solar PV panels serves as a feed check valve. The two types of diodes that are most frequently used are blocking and bypass diodes. Blocking diodes are used in series with the solar cell to restrict the flow of electrical current to just one direction. To stop electricity from flowing backwards from a solar cell that has been exposed to a lot of sunlight to a weaker solar cell, bypass diodes are utilized. They are connected in parallel. Thus, it is crucial to identify solar panel diode faults. Diode failures are mostly caused by overheating and incorrect connection [19, 27, 28]. Diode placements are shown in Figure 4.

Junction Box Faults: The wiring connection between PV strings and an external terminal is maintained by a junction box [27]. Junction box faults are caused by disconnections in the junction box, improper installation, and corrosion on connection points [13].

String Faults: The expression string failure is used to describe failures that occur in strings. It causes a decrease in the power produced as a result of the string being disabled [7, 27].

3.1.4. An Overview of the Literature on Fault Types

More than 45 studies were reviewed for literature review. Among these studies, the most used studies are references [7, 9, 12]. Table 1 shows the fault types, location, possible effects, and description of faults in PV power plants. Table 1 also contains references that have been described related to PV power plant faults before.

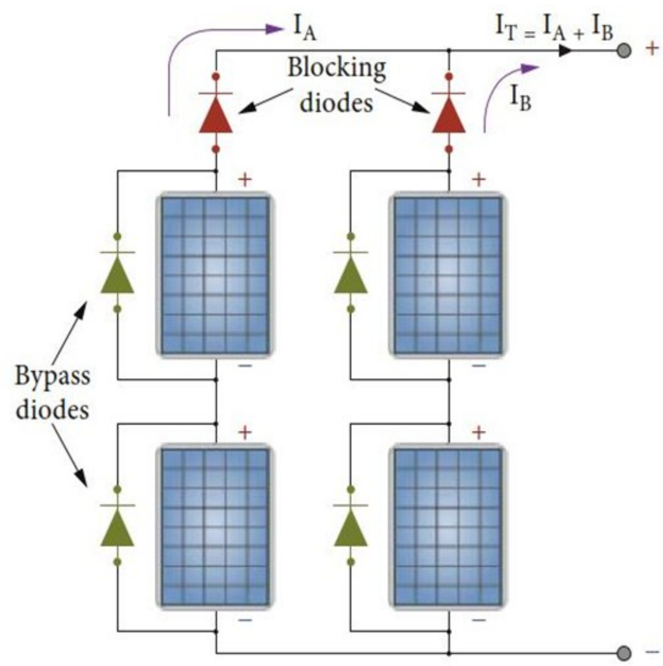

Fig. 4. Blocking and bypass diodes [19].

Table 1. Photovoltaic power plant fault classification and explanations

Fault Types	*Location*	*Description*	*Effected Components / Effects*	*Reference*
Inverter faults	AC side	Caused by any inverter component malfunction	Inverter	[2, 13, 17, 22, 28, 38]
Grid faults	AC side	Caused by equipment malfunctions, line tripping, network configuration, maintenance issues, incidents, or human error	Whole PV Plant	[13, 17, 22, 26]
Environmental faults	AC side	Lightning, storm, or any other natural calamities caused	Various damages to the whole PV plant	[8, 9, 15, 17, 22]
Ground fault	AC and DC side	Unintentional connections between current-carrying conductors and ground/earth ground.	Damage to the PV array and PV string, the possibility of fire	[1, 2, 7, 9, 11-13, 17, 19, 21, 22, 26, 28, 33, 35, 41, 44]
Line-Line fault	AC and DC side	Between two places, an unintentional low-impedance current path.	Damage to conductors and PV array, the possibility of fire	[1, 2, 7, 9, 11, 13, 14, 17, 19-22, 27, 28, 33, 35, 37, 41, 44]
Arc fault	AC and DC side	Caused when there is a gap between current-carrying conductors as a result of connector corrosion, cell damage, solder separation, loosening of screws, mechanical damage, ageing, wild animals, etc.	Damage to PV string, the possibility of fire	[1, 2, 7, 9, 11, 13, 14, 17-22, 27, 28, 41]
Open circuit fault	DC side	Broken cells, poor connections between PV cells, unsecured connectors in junction boxes, hot spots, outdated cables, etc. are the main causes of this.	Damage to PV modules, diodes, junction boxes	[9, 12-14, 17, 20, 21, 28, 35, 41]
PV panel/module faults	DC side			
PV cell faults		Low power output from the modules, open-circuited or short-circuited conditions	Damage cells	[2, 7, 13, 14, 17, 19, 21-23, 43, 44, 46, 47]
Diode faults		Open-circuited or short-circuited diode situations, partially shaded cells, overheating	Damage diodes	[7, 9, 13, 14, 17, 22, 27, 28, 43, 44]
Junction box faults		Fretting corrosion, loosening connection and oxidation	Damage junction box, the possibility of fire, decreased efficiency, and reliability	[7, 13, 17, 27, 43, 44]
String faults		Unwanted current passing via the device grounding conductor in circuits supplying DC power	Damage string, reduce efficiency and reliability	[7, 11, 13, 17, 43]
Mismatch fault	DC side	External causes; shadow, soiling, dust and snow Internal causes; cell-to-cell current flow mismatch, cell fragmentation, the ageing and deterioration of cells, and high resistance or "cold" solder spots	Solar cell damage, decreased efficiency, and reliability, temporary loss of power	[1, 2, 9, 12, 13, 14, 17, 19-22, 28, 32, 37, 41, 43, 44]

3.2. Discussion

Standardization is the beginning of development and innovation; therefore, standardization is needed in every part of the operation. Since the priority for PV power plants is the continuity of the operation, the prevention of failures is of critical importance. Based on this priority, it is important to classify and standardize faults in PV power plants. Studies in this field have started to increase in recent years.

However, PV power plant investments started in the 1980s and increased rapidly after the 2000s. These data show that studies on fault classification started to increase lately. Fault classification is the first step in solving faults because preventing and diagnosing faults starts with identifying the situation. Despite this fact, the recent increase in the studies is due to the increase in the maintenance need of the sector over time. Increasing PV power plant investments show that this need will continue in the future.

Different fault classifications have been developed for PV power plants over the years. Every fault classification method has its perspective on faults. For instance, in [44] faults are classified under two headings as temporary faults and permanent faults, this indicates that this study prioritizes the duration of the fault rather than locating it. Study [38] examines PV power plant faults according to efficiency effects, in this type of classification faults with different root causes may be in the same category. In [19], only PV array faults are examined. These comparisons show that this study is a comprehensive study of PV power plants' electrical faults.

Due to faults in PV plants as shown in Table 1, permanent and/or temporary damage may occur, fires may occur in the place where the fault occurred or in the sections related to this part, or there may be a loss of efficiency. Fault classification enables faults to be diagnosed quickly, thus preventing a decrease in the power production of PV power plants and an increase in fossil fuel use.

This study will benefit the sector in terms of not losing information and creating written sources for countries, where PV plant installations are on the rise.

4. CONCLUSION

This study presents a classification of every electrical fault that could occur in PV power plants. Fault types are classified according to AC and DC voltage types to show the exact reason and the place of faults. Classification is the first step in identifying faults. This study can be a reference document for identifying faults and taking precautions before a fault occurs.

In the future, it is possible to create a computer-based model to examine these failures on this model and compare the results to create a resource for academic studies and to contribute to the field applications to the companies in the sector. Also, it is possible to create complete documentation about PV power plant failures and solution methods. Additionally, computer-based tools may be developed in the future to detect faults before they occur with the help of the measurement signals, according to fault detection algorithm which will work based on classified fault types.

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