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USO DA INTELIGÊNCIA ARTIFICIAL NA SEGURANÇA CONTRA INCÊNDIO EM SISTEMA SOLAR FOTOVOLTAICO

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ABSTRACT

Photovoltaic solar energy, especially in the form of Distributed Generation (DG), plays an essential role in the global energy matrix, including the Brazilian scenario. This article aims to analyze the application of Artificial Intelligence (AI) in fire safety in photovoltaic solar systems, focusing on improving and optimizing prevention, detection and response processes to fire-related incidents. Therefore, it becomes essential to implement comprehensive measures, especially intelligent arc detection and rapid shutdown technologies, in order to improve the safety and management of PV plants, whether in residential, commercial and industrial installations or even in solar farms. As a methodology, it adopts a descriptive approach and case study, of a qualitative nature, as well as bibliographical sources in books, articles and online journals, seeking to understand the application of AI in the safety of photovoltaic solar systems, as well as case analysis. specifications that exemplify the effectiveness of AI in preventing and responding to fire incidents in solar installations. Among the results, we seek to demonstrate the contributions of AI in a significant way to maximize safety and reliability for users of solar PV systems, protecting lives and properties. It is concluded that the application of AI in this context contributes not only to the protection of users and their properties, but also to the ongoing sustainability and reliability of solar PV power generation. Therefore, its use must be encouraged and regulated in accordance with current safety standards.

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INTRODUCTION

The use of Artificial Intelligence in Security for Photovoltaic (PV) Systems - *Arc Fault Circuit Interrupter* (AFCI). This work explores how artificial intelligence can be applied to enhance the safety and life protection of users in PV solar systems. The Brazilian electrical grid, totaling 221,992 MW, is highlighted by the Brazilian Photovoltaic Solar Energy Association (ABSOLAR), revealing the significant contribution of solar energy. With 35,739 MW, or 16.1% of the total, photovoltaic solar energy ranks second, surpassed only by hydropower, representing 109,909 MW (49.5%). This rise of solar energy is a testament to the growing role of renewable sources in diversifying and sustaining the national electrical sector. While hydropower remains predominant, it is making way for cleaner and more innovative alternatives. The advancement of solar energy strengthens the resilience of the system, reducing greenhouse gas emissions and promoting the transition to a more sustainable energy matrix. This scenario reflects Brazil's commitment to promoting clean energy sources and underscores the ongoing importance of investing in renewable technologies to address environmental challenges and ensure a greener energy future. After the publication of Resolution 482/2012 in Brazil, which granted the end consumer the right to generate their own energy through a clean and sustainable source, there was a gradual and exponential growth of the Photovoltaic (PV) source within the Distributed Generation (GD) modality. At that time, the safety of users, installers of PV systems, and properties was not yet a priority, and even international standards did not emphasize the demand for fault tolerance. As the global scenario expanded with the generation of energy through the PV source, clean and sustainable energy also became economically viable for end consumers. However, along with the installations, issues started to arise, especially electrical failures, whether due to poor installation or product malfunctions leading to fires. According to the standards set by UL1699b, which pertains to electrical safety and devices used in PV systems, the term refers to standards for electrical safety and devices used in PV systems. The DC (direct current) photovoltaic arc fault circuit protection is employed to prevent fire hazards caused by electrical arcs in PV systems. UL *Subject* 1699B is a specific standard that defines requirements and testing procedures for DC arc fault protection devices in PV systems, ensuring that they can effectively detect and interrupt electrical arcs in such systems. These standards and devices are essential to ensure the safety of PV systems and the prevention of electrical fires. Adhering to UL *Subject* 1699B and using DC arc fault protection devices are fundamental in the design and installation of PV systems to meet safety requirements and regulations. It is important to check with relevant authorities and follow local electrical codes and standards when working with PV systems to ensure compliance and safety (Zgonena; Dini, 2011). The application of UL1699B in PV solar systems addresses the importance of compliance with safety standards, such as UL1699B, in PV solar systems. It will be discussed how this standard contributes to ensuring electrical safety and preventing risks in PV systems.

In this case, we will be analyzing a failure that occurred in a commercial PV solar system installed on the roof property of a commercial establishment located in the city of Santo Antônio de Leverger MT, analyzing the performance of the *Arc Fault Circuit Interrupter* (AFCI) protection system. The mentioned system, valued at around R$135,000.00, updated to the "*Turn-Key*" service and equipment prices, consists of 64 solar panel modules, covering a total area of 162.99 m² and has an installed capacity of 24.9 kWp. It is installed with a 20 kW inverter. Therefore, a crucial aspect is the development of a predictive model for solar energy generation forecasting. Through the analysis of meteorological data, sunlight patterns, and other environmental factors, artificial intelligence can create accurate models that predict the amount of energy a PV system can generate at a given time. This is essential for planning energy supply efficiently and reliably during the long operational period of the PV system. Artificial intelligence is used in both safety and Operations and Maintenance (O&M) demands for better efficiency in PV systems. It is considered that the inverter, by converting direct current into alternating current, generates data and alarms for overvoltage, current, power, frequencies, among other information and supervisory signals, ensuring that the installing company can effectively analyze the daily performance of an installed solar system. With the goal of incorporating technologies into some inverters as an international standard, the use of Artificial Intelligence is also being established to ensure the lives and properties of users and installers of PV solar systems (Canal Solar, 2020). The application of artificial intelligence aims to provide an advanced layer of protection, ensuring greater safety in residential, commercial, industrial, and rural installations, both in Distributed Generation (GD) and Centralized Generation (GC). This article aims to analyze the application of Artificial Intelligence (AI) in fire safety for photovoltaic solar systems, with a focus on enhancing and optimizing the processes of prevention, detection, and response to fire-related incidents.

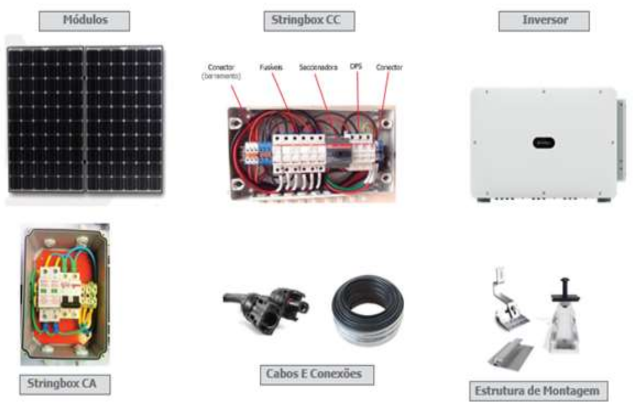
METHODOLOGY

The methodology employed involves bibliographic research through consulting books, articles, and online journals, covering topics such as photovoltaic solar energy, energy transition, energy policies, sector regulation, tax and financial incentives, technological innovation, among other relevant subjects. Reference sources included not only academic publications but also technical reports, normative documents, and publications from governmental bodies. The interpretation of results was conducted through a thorough analysis of the data, directly relating them to the specific objectives outlined in the research (Gil, 2017). The case study methodology, as outlined by Yin (2015, p.58), was implemented, defining a case study as "an investigation of a contemporary phenomenon within its real-life context, especially when the boundaries between the phenomenon and the context are not clearly defined." In terms of the methodology's nature, the proposed case study is predominantly qualitative, seeking an in-depth and contextualized understanding of string inverters with AFCI technology. The qualitative approach allows for a detailed analysis of the characteristics, performance, and impact of this technology in practical situations. Qualitative methods involve research approaches centered on the interpretation and in-depth understanding of the studied phenomenon, emphasizing the researcher's subjectivity. In this type of method, the researcher takes an active role in data collection and analysis, incorporating their own perspectives and opinions. A case study is a detailed analysis of a specific case highlighting particular features, providing an in-depth understanding of the situation. Under the Case Study approach, various investigations are encompassed, forming a wide variety of contexts and scenarios. These studies offer valuable insights into specific phenomena, allowing a meticulous analysis of circumstances and factors contributing to the uniqueness of the case at hand (Pereira et al., 2018). This article focuses on a case study highlighting the safety of string inverters, even without power optimizers or microinverters when equipped with AFCI technology in compliance with UL1699B standard. The implementation of this technology is crucial to ensuring the quick and automatic disconnection of the system in the event of an electrical arc failure, aiming to protect both the lives of users and their properties. The study was conducted at the 24.9 kWp Photovoltaic Solar Plant located in Santo Antônio de Leverger (MT). To conduct the research, access to the projects and electrical systems of this commercial installation was necessary. The obtained results provide valuable insights into the effectiveness of string inverters when combined with AFCI technology, reinforcing confidence in the safety of these photovoltaic systems. The scope of the analysis included not only publications on photovoltaic solar energy sector data, but also legal provisions, resolutions, guidelines, incentives, and specific requirements established by current legislation, notably technical standards. The analysis of the performance of the direct current side electrical arc safety system in photovoltaic solar systems (PV), as established by the UL16699B standard, reveals significant advances in safety. The tested inverter manufacturer integrated Artificial Intelligence (AI) with embedded hardware, a crucial innovation preventing flame propagation, providing a higher level of safety in residential, commercial, industrial, and rural installations in both Distributed Generation (GD) and Centralized Generation (GC). Thus, the evaluation of the importance of AI presence in the security system hardware is a proactive and effective approach, as it empowers the system to quickly identify and respond to electrical arc situations. The ability to prevent flame propagation represents an additional layer of protection, significantly reducing fire risks in diverse environments. Additionally, studies and reports from governmental and non-governmental institutions focusing on the sector in question were considered. The collection of relevant data aimed to ensure a well-founded analysis based on reliable and up-to-date sources, with the purpose of obtaining accurate information about photovoltaic solar energy, current legislation, and market practices.

DISCUSSION

Photovoltaic solar energy systems generate electricity by converting sunlight irradiation, and there are two basic types of systems: Isolated (*Off-grid*) or connected to the grid (*On-grid*) of the Utility. Recently, the approval of Law 14,300 on January 7, 2022, allowed the use of hybrid inverters (on-grid with battery coupling) in accordance with Inmetro Ordinance 140, published on March 19, 2021. The distinctive feature of hybrid inverter technology is its ability to be used in both *off-grid* and *on-grid* systems. It allows obtaining energy through the battery when there is a power outage from the local utility or no irradiation, providing power to a specific load, or even, according to sizing, powering the entire load. Isolated Systems can be used in remote locations such as country houses, public lighting, telecommunications stations, etc. There is no connection to the utility grid in *off-grid* mode (Brazil, 2022). Since April 17, 2012, with the enactment of Regulatory Resolution ANEEL No. 482/2012, Brazilian consumers gained the right to produce their own electricity from renewable sources or qualified cogeneration through *On-Grid* systems. Additionally, these consumers were allowed to deliver the surplus energy generated to the local distribution grid, with the intention of later offsetting energy consumption (ANEEL, 2019). These innovations are associated with Microgeneration and Distributed Mini generation of Electrical Energy (MMGD) and the Energy Compensation System (SCEE). The guidelines governing MMGD have been subject to adjustments by ANEEL over time, including changes in installed power limits and participation modalities in the SCEE. These changes were implemented through Regulatory Resolutions, such as No. 687, dated November 24, 2015, and No. 786, dated October 17, 2017, as indicated by the Ministry of Mines and Energy (MME, 2023). The Regulatory Resolution No. 1,059, dated February 7, 2023, adjusted ANEEL regulations in accordance with Law No. 14,300, dated January 7, 2022, as well as studies conducted since 2018. Additionally, it consolidated the provisions related to MMGD and SCEE in the general conditions of energy supply, as established in Regulatory Resolution No. 1,000/2021 (MME, 2023). In this way, the regulatory changes aimed to better encourage decentralized energy generation, promoting the use of renewable sources, financial savings for consumers, a sense of socio-environmental responsibility, and the promotion of energy self-sustainability. As a result, Brazilian consumers have more opportunities to participate in the production of clean and efficient energy.

The PV systems have the following basic components: PV Modules: They are responsible for capturing solar irradiation and converting it into electricity. b) Inverters - On-grid, Off-grid, and Hybrid: These are electronic devices used to convert direct current (DC) electricity to alternating current (AC) in a solar system, playing a crucial role in energy conversion and management. It is important to highlight the hybrid inverter technology's differential; they control battery charging and provide automation. In case of a power outage from the utility, they automatically supply power to the loads added to the battery, ensuring a continuous energy supply. c) Batteries: Lithium-ion batteries play a central role in providing innovative solutions to enhance energy efficiency. Faced with these challenges, we are motivated to pave the way toward new possibilities, contributing to the construction of a more ecological and sustainable future for all (Solar Channel, 2023). The transition from lead-acid battery technology to lithium-ion batteries represents a significant revolution in the energy sector. Now, with the approval of Law 14,300 and Inmetro Ordinance 140, lithium-ion batteries take a prominent position, serving as the foundation for energy storage systems. This development requires a greater emphasis on inverter safety since they play a crucial role in connecting energy generation and storage (Solar Channel, 2023). Inverters play a vital role in efficient communication between energy generation, storage, and the electrical grid. They ensure that energy is converted, stored, and distributed effectively and safely. It is in this context that the importance of using AFCI (Arc Fault Circuit Interrupters) stands out. AFCIs are safety devices with the ability to detect and disconnect circuits in the event of dangerous electrical arcs, preventing fires and ensuring the safety of the electrical system. They are particularly relevant in energy storage systems, where safe electricity handling is crucial (Solar Channel, 2023). Therefore, the transition to lithium-ion batteries, coupled with regulations and an emphasis on inverter safety, highlights the continuous evolution of the energy sector towards more efficient and secure systems, including the generation, storage, and distribution of electricity from renewable sources. Figure 1 belowillustrates a solar PV energygeneration system:



Source: Oca Solar, 2023.

Figura 1. Solar PV Energy Generation System

Figure 1 depicts the solar PV energy generation system, highlighting the following components:

a) **Modules:** These are the solar panels that capture sunlight and convert it into electricity through PV cells.
b) **DC String Box:** This component is responsible for gathering the protection and operation outputs of solar module circuits into a single point before connecting them to the inverter.
c) **Inverter:** The inverter converts the direct current (DC) generated by the solar modules into alternating current (AC), which is used to power electrical appliances and equipment in homes or businesses.
d) **AC String Box:**Similar to the DC string box, the AC string box gathers the output cables with protections and operations of the inverter circuits and connects them to the electrical grid.
e) **Cables and Connections:** Electrical cables and connections are essential for connecting all system components, ensuring efficient electricity transmission.
f) **Mounting Structure:** The mounting structure provides physical support for the solar modules, keeping them securely in place, usually on rooftops or ground-mounted structures.

This solar PV system is an effective solution for generating electricity from sunlight, contributing to the use of cleaner and more sustainable energy sources. Each of these components plays a crucial role in collecting, converting, and distributing the electricity generated by the system. In Figure 2, the high-voltage lithium battery is presented.

Source: Goodwe, 2023.

Figure 2. High-voltage Lithium Battery

This high-voltage lithium battery, built with lithium-ion technology, is known for its ability to efficiently store and supply energy in applications that require higher voltages. Figure 3 highlights the essential components of the battery, such as lithium cells, protective casing, and connection terminals.

Source: Goodwe, 2023.

Figure 3. Residential Low-Voltage Lithium Battery

These batteries find wide applications, including electric vehicles, renewable energy storage systems, and many others, due to their high energy density and ability to reliably supply power at significantly elevated voltage levels (Solar Channel, 2023). Figure 4 presents the hybrid PV system, which can be used both as Off-Grid or On-Grid, a retrofit inverter for energy storage only, with or without installed solar.

Source: Goodwe, 2023.

Figure 4. Hybrid PV Solar System

Figure 4 illustrates the *on-grid* PV solar system, where the inclusion of a retrofit inverter allows for determining a specific load exclusively for energy storage. This inverter can be a solution for PV systems installed without a hybrid inverter or independently of having solar panels installed. It serves as a solution solely for energy storage, meaning it recharges the batteries with electricity from the utility grid. This flexibility makes the system highly adaptable to the user's needs and preferences, enabling the maximization of clean energy utilization and storage for future use, whether in scenarios connected to the conventional power grid or operating independently. Figure 5 presents an *on-grid* PV solar system connected to the electrical grid.


Source: Usina solo – MT (2023)

Figure 5. On-Grid PV Solar System

It has been observed that this system combines photovoltaic solar power generation with the ability to be connected to the conventional electrical grid, allowing energy to be supplied to the grid or used locally as needed. This flexibility is highly advantageous, as it enables the maximization of clean solar energy use while also providing the option to earn energy credits or use the grid as a supplementary power source when solar production is insufficient. The integration of on-grid solar systems with Building-Integrated Photovoltaics (BIPV) technology represents an innovative approach to clean energy generation in buildings. In this context, Figure 6 may describe the specific configuration of this system. BPIV technology involves the incorporation of thin-profile PV solar cells, where these modules, much lighter than traditional ones, are directly installed on building structures such as facades, windows, or roofs. This seamless integration allows buildings to generate electricity from sunlight using functional solar panels integrated into their facades. This not only optimizes space usage but also contributes to energy efficiency by reducing internal temperatures and carbon emissions. The term "*on-grid*" indicates that the system is connected to the conventional electrical grid. This enables the excess energy generated by the BPIV system to be exported to the grid, often resulting in energy credits or financial compensation for the owners. Additionally, the on-grid system ensures a continuous electricity supply even when solar generation is insufficient. Together, BPIV technology and the on-grid system provide an effective solution to address the challenges of increasing energy demand while promoting sustainability and reducing electricity costs. Figure 6 likely describes how these components come together to form an innovative and efficient solar energy system in buildings (Solar Channel, 2023). With the energy sector undergoing a transition and the emergence of various technologies entering the photovoltaic solar market for energy generation and storage, as well as BIPV technologies, the safety prerequisites for fire protection are elevated. Naturally, all these solutions require equipment such as String inverters, central inverters, or micro-inverters, which convert energy captured by solar panels into direct current with characteristics suitable for alternating current, commonly used in residences, businesses, and industries. Increasingly incorporating technologies that utilize AI or any other mechanism to reduce the chances of a fire occurring in a photovoltaic solar installation is crucial, and we will discuss this further in the next image. Figure 7 illustrates an incident of a fire in PV solar modules due to an electrical arc caused by a DC cable chewed by a rodent. This incident reportedly took place in the city of Cuiabá (MT), in April 2022.


Source: Project in São Paulo 523 involves installing 523 panels on the facade of a building with an inverter equipped with AFCI (Arc Fault Circuit Interrupter) to ensure safety.

Figure 6. On-grid system with BIPV technology (Building-Integrated Photovoltaics) on the building façade


Source: Autor, 2023.

Figure 7. Fire in PV Solar Panels due to an Electrical Arc

As seen in Figure 7, incidents of this nature are concerning as they pose a significant risk of fire in PV solar systems. Rodents can damage electrical cables, exposing conductive wires and creating conditions conducive to electrical arcs. These electrical arcs can generate intense heat and flames, potentially leading to fires. In

Figure 8, it becomes evident that the absence of a shutdown system in the solar panels' energy production caused the flames to reignite, necessitating urgent action from the operational team. The crew had to physically remove adjacent solar panels and cut the wires responsible for conducting the generated energy to isolate the source of the fire and enable a safe extinguishment. This incident occurred in the municipality of Porto Murtinho-MS on 02/02/23 (CBMMS, 2023).

Source: Military Fire Department of the State of Mato Grosso do Sul - CBMMS, 2023.

Figure 8. Fire in a solar energy system

It was found that this intervention was necessary to prevent the fire from spreading, as the continued energy production could fuel the flames. The action underscored the critical importance of safety protocols and efficient shutdown systems in solar installations to prevent and control emergency incidents. Figure 9 presents the outcome of a fire in PV solar panels due to an electrical arc.

Source: Liang Ji (2015).

Figure 9. Fire in PV Solar Panels due to an Electrical Arc

Figure 10 depicts an electrical arc occurrence in a metal conduit due to issues with the insulation of electrical cables. This type of incident poses a serious risk to electrical safety and can be highly dangerous.

Source: Bakesfield/USA, 2009

Figure 10. Arc in the metal conduit due to insulation issues with the cables

Arcs in PV systems mainly occur in two ways: a) improper connections, and b) cables with compromised insulation. The market has been improving equipment to interrupt electrical arcs and prevent fire propagation. The formation of electrical arcs poses a significant risk in PV systems as it can lead to fires and equipment damage. Therefore, regular maintenance, safety inspections, and hiring qualified professionals for installation and maintenance are crucial measures to minimize these risks in PV systems. To prevent incidents of this nature, regular maintenance and inspection of solar systems are essential. This includes checking for cable damage, ensuring proper insulation, and implementing measures to protect against animals, such as rodents. Additionally, solar systems should comply with electrical safety standards and be installed by qualified professionals. It becomes evident that among the main causes of a fire in photovoltaic panels, the failure of one of the solar panels resulting from internal electrical problems, inverter failures, mechanical damage, or connection issues, as shown in Figure 11. This accident occurred in a shoe store in the city of Patos de Minas (MG).

Source: Canal Solar (2023)

Figure 11. Fire in the PV system at a shoe factory in Patos de Minas (MG)

There is a need for investments in training to gain greater insights from experiences in other countries, especially the United States, and to promote a safety culture that is constantly evolving to address specific challenges related to fires. The electrical arc is a phenomenon in which electric current jumps from one point to another through the air, often accompanied by sparks, heat, and even fire. In the context of a metal conduit, the electrical arc can spread rapidly, causing significant damage to the structure and posing a fire risk. The failure in cable insulation is the underlying cause of this incident. Proper insulation of cables is crucial to prevent short circuits, electrical arcs, and other electrical issues. Degradation or damage to cable insulation can allow electric current to escape into the environment, resulting in dangerous arcs. To prevent such incidents, it is essential to conduct regular inspections of electrical systems, ensure the integrity of cable insulation, and implement safety measures by installing devices for protection against electrical arcs. Therefore, electrical safety becomes fundamental for accident prevention, safeguarding lives and properties, as well as maintaining the integrity of electrical systems.

The *Arc Fault Circuit Interrupter* (AFCI) protection is a crucial safety feature in PV solar systems, especially concerning direct current (DC) circuits. It plays a fundamental role in fire prevention and the overall safety of the system. It is essential for professionals and PV solar system installers to be aware of and adhere to the technical standards and regulations applicable in their region, ensuring that systems are installed safely, reliably, and in compliance with established quality standards. This is crucial for the long-term safety and performance of PV solar systems.

The following are the main regulations and technical instructions establishing basic criteria for fire prevention in PV solar system installations, including:

a) Technical Instruction No. 30/2022 from the Military Fire Department of the State of Minas Gerais;
b) Technical Standard No. 49/2022 - Military Fire Department of the State of Mato Grosso;
c) Technical Standard No. 44/2023 from the Military Fire Department of the State of Goiás.

Technical Instruction No. 30/2022 addresses the topic of Electrical Installations and Equipment, specifically focusing on Substations, Photovoltaic Panels, and Power Generation Groups. The standard provides technical and practical guidelines related to these elements, aiming to ensure safety, efficiency, and compliance in electrical installations (MG, 2022). The objective of this regulation is to define fire safety measures for electrical substations, installations containing photovoltaic panels, and power generation groups, in compliance with the Fire Safety Regulation applicable to buildings and spaces intended for collective use in the State of Minas Gerais. Covering substations, the instruction deals with procedures and requirements for the proper implementation and operation of these crucial points in electrical power distribution. In the context of photovoltaic panels, the standard addresses specific guidelines for the installation and operation of solar power generation systems, considering the unique characteristics of these equipment. Additionally, power generation groups are discussed, focusing on relevant technical aspects for the installation and operation of these devices (MG, 2022).

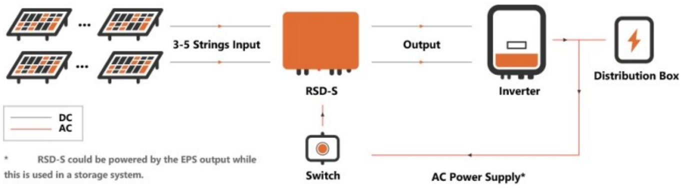
The mentioned Technical Instruction No. 30/2022-MG presents the following requirements:

a) Installation and maintenance of photovoltaic system components must adhere to Brazilian reference standards, notably NBR 16690 and NBR 5410, or other suitable standards in their absence. In the absence of these, recognized international standards may be adopted.
b) Photovoltaic installations for distributed energy generation must include solar panels, inverters, and other necessary devices, all in compliance with INMETRO requirements.
c) Arc fault protection equipment and rapid shutdown devices must be installed. In the absence of INMETRO regulations for these devices, accepted international standards or manufacturer specifications can be followed.
d) The sizing and execution of precautions related to the installation of photovoltaic panels, as outlined in reference standards, are the sole responsibility of the Technical Responsible (RT) and are not subject to analysis or inspection by the Military Fire Department of Minas Gerais (CBMMG).
e) Inspection requests must include the presentation of the technical responsibility document for photovoltaic installations.

Regarding the installation of photovoltaic modules:

a) Photovoltaic modules should not be installed on roofs or coverings that are flammable. In exceptional situations where the roof or covering is made of combustible material, the application of retardant or intumescent products may be accepted, provided it is supported by a report from the professional responsible for applying the product and accompanied by the corresponding technical responsibility document.
b) In buildings and spaces intended for collective use that have installed photovoltaic panels, the following requirements must be observed:
- Rapid shutdown devices must be designed and installed in secure locations within the building, providing easy access. The device should be accompanied by additional signage containing the written message: "RAPID SHUTDOWN DEVICE FOR PHOTOVOLTAIC SYSTEM."

The Rapid Shutdown (RSD) system plays a crucial role in the safety and efficiency of a photovoltaic system. Its nomenclature reflects its primary function: to provide a quick and effective shutdown of the photovoltaic modules in case of failure or emergency situations. This component is designed to respond promptly to adverse events, minimizing risks associated with solar electricity generation. In incidents such as fires, short circuits, or other electrical issues, the ability to rapidly disconnect the photovoltaic modules becomes essential to mitigate potential hazards (Solar Channel, 2022). The signage should be reflective, in uppercase letters, with a minimum height of 10 mm, in white letters on a red background (Figure 12).



Source: TSDM (80 V UL) / NEC 2020 / NT 44 (2023)

Figure 12. Example of a Rapid Shutdown Device

In Figure 12, the Rapid Shutdown (RSD) unit for photovoltaic arrays is observed, which is an essential device to ensure safety in critical situations, such as fires. Its implementation complies with the technical standard NT44-2023 of the Fire Department of Goiás, specifically for installations classified as Type 1. The key highlights of this unit are: i) Automatic shutdown by thermal protection: provides automatic shutdown in response to excessive temperatures, protecting the photovoltaic array against thermal damage; ii) Multiple shutdown methods: offers various shutdown methods, allowing a flexible response to different scenarios and operational requirements; iii) Multiple voltage options: supports a variety of voltage options, ensuring adaptation to the specific characteristics of the photovoltaic array; iv) Plug and play, easy installation: designed with the "plug and play" concept, the device facilitates installation, reducing the time required to integrate it into the existing photovoltaic solar system. The Rapid Shutdown (RSD) system in photovoltaic systems is responsible for quickly interrupting the operation of the photovoltaic modules in case of failures. This concept was introduced by the National Electrical Code (NEC) in the United States, with regulations that have evolved over time. Initially proposed in 2014 by NEC 2014 690.12, rapid shutdown regulations set limits for the distance to the photovoltaic panel, fixing it at 3.05 meters. In the 2017 revision, the NEC intensified these requirements, requiring that within 30 seconds of activating rapid shutdown, the system voltage be reduced to below 30 V outside the panel limits and 80 V in the module circuit. This necessitated "module-level rapid shutdown," ensuring that each module receives an individual shutdown command.

In the latest 2020 version, NEC expanded the term "rapid shutdown" and proposed "photovoltaic hazard control systems." Now, the standard requires a "photovoltaic hazard control system," ensuring that the system can be controlled in critical situations. Within 30 seconds of initiating the shutdown, the voltage at the limits of the photovoltaic modules must drop below 80 V. The emergence of RSD technology was motivated by the concern to prevent electrical risks for firefighters during firefighting in photovoltaic plants. RSD has become an essential technology to ensure safe rescue conditions after incidents. Therefore, the implementation of module-level rapid shutdown varies depending on the type of inverter. Microinverters, due to their low working voltage, naturally meet the requirements. In conventional inverters, the addition of a rapid shutdown box, readily available in the market, provides a simple and cost-effective solution. In compliance with NT44-2023, installations classified as Type 1 should seek the best rapid shutdown solution on the market to integrate into the photovoltaic solar system. This integration is crucial to ensure that, in case of failure, especially during fires, the system is rapidly shut down. This allows effective action by firefighters, emergency responders, and other trained professionals, who can perform initial interventions, including the complete shutdown of the photovoltaic solar system. This proactive approach is essential to preserve personal safety and minimize the risks of electrical accidents in emergencies. In situations where the projection of safety measures by the Fire Brigade is mandatory, it is crucial that the brigade members are fully informed about the location of solar panels, batteries, and the rapid shutdown device for photovoltaic panels. If there is no Fire Brigade present, it is highly recommended that the public be aware of these elements, including the precise location of panels, batteries, and the rapid shutdown device. This awareness is crucial to ensure safety in emergencies, facilitating quick and effective actions to prevent or deal with potential incidents related to photovoltaic systems.

c) In easily accessible locations, such as entrances, information for rescue teams must be provided, including the layout of the site with the location of photovoltaic panels and their rapid shutdown device, along with instructions on how to proceed. Additionally, contact details for the system's responsible party should be provided. In addition to the locations specified in NBR 16690, signage to identify the presence of a photovoltaic system in the building should be installed next to sign M1, as illustrated in Figure 10. The signage should convey the written message: "THIS BUILDING HAS A PHOTOVOLTAIC SYSTEM INSTALLED." The signage illustrated in Figure 10 should have a minimum dimension of 100 mm in width and 150 mm in height, in black letters on a yellow background. The signage with the written message should be reflective, in uppercase letters, with a minimum height of 10 mm, in white letters on a red background. In all locations where there is a risk of electrical shock, the A5 warning signage must be allocated, as established by IT 15 (MG, 2022).
d) The Intervention Plan, if mandatory for the building or space intended for collective use, must include actions to be taken with the panels and their equipment before the actual firefighting begins.
e) For panels installed on roofs or coverings, as well as for inverters and battery rooms, the use of fire extinguishers designated for the building is allowed, provided they are suitable for combating Class C fires. This practice must adhere to the walking distances stipulated in IT 16.

The areas where photovoltaic panels are installed must be clearly represented on the plan. However, these areas will not be considered as built-up areas for the following purposes (MG, 2022): a) Definition of the total area for the Fire and Panic Safety Plan (PSCIP); b) Definition of security measures; c) Definition of the type of PSCIP; d) Calculation of the Prevention Service Fee (TSP) for analysis and inspection purposes; e) Area to be reported in the Certificate of Fire Department Inspection (AVCB). For battery installation areas, the security measures outlined for the building or space intended for collective use must be designed. Compliance with the provisions of item 6.10.2 of NBR 13231, or its substitute, should be evaluated at the discretion of the Responsible Technician (RT). Regarding Technical Standard No. 49/2022 from the Military Fire Department of the State of Mato Grosso, included as fire safety for photovoltaic solar systems, it has been standardizing commercial and industrial installations in the state of Mato Grosso. Two items among all addressed in this technical standard are noteworthy (MT, 2022):

5.4.1.4 Arrays/lots of PV modules classified as Type 3 must have a device that disconnects the current and/or voltage in the modules and *string* conductors.

5.4.1.5 Installation of PV arrays is prohibited in:

5.4.1.5.1 Roofs of locations that store/handle or trade flammable and/or combustible liquids or gases.

No item 5.4.1.4 quando específica TIPO 3, seriam telhados comerciais e industriais, onde o sistema solar FV teria que ter um dispositivo que desliga a corrente e ou/ a tensão nos módulos.

It is understood that currently, in the Brazilian market, both microinverters and optimizers can address the requirement to disconnect the voltage at the module level, meeting one of the prerequisites suggested by the item. The other aspect, disconnecting the current, can be achieved with AFCI according to UL1699b. This involves the use of artificial intelligence to interrupt the current flow in the string, preventing electrical arcs that could lead to a fire. However, it would be beneficial if the firefighters could provide more specific guidance, as the term "device" is not clear in the market. Apart from the two options mentioned (microinverters and optimizers), it would be helpful to understand what other string-level devices could be equally effective. In this context, AFCI appears to be the most efficient since it directly acts on the current, principle in the separation of two poles of an electrical arc. While other devices, like microinverters and optimizers, operate within international voltage standards, avoiding and minimizing high voltages at the module level, AFCI directly addresses current issues. The other item, 5.4.5.1, concerning installations, especially in gas stations, emphasizes the importance of safety measures. Several solar systems installed in gas stations without proper equipment care serve as a warning. The firefighter's regulations provide guidance on fire safety, not only in solar installations but also in various scenarios where electrical faults and arcs in alternating current can lead to fire incidents. Finally, Technical Standard 44/2023, which addresses safety in PV systems, was introduced by the Military Fire Department of the State of Goiás. This standard aims to establish safety measures against fire and panic in buildings with PV energy systems, and it is necessary to follow the guidelines of the State Code of Fire and Panic Safety (Law No. 15802, dated September 11, 2006). Therefore, it becomes necessary to implement specific measures to mitigate risks associated with PV systems, considering aspects such as secure installation, protection against short circuits, proper training for emergency interventions, and ensuring access for firefighters in case of necessity. These measures aim to ensure the safety of both solar installations and the people occupying the space, aligning with local regulations for fire prevention and control (GO, 2023). To establish fire and panic safety measures in buildings with PV energy systems, it is necessary to follow the guidelines of the State Code of Fire and Panic Safety (Law No. 15802, dated September 11, 2006). This involves the implementation of specific measures to mitigate risks associated with PV systems, considering aspects such as secure installation, protection against short circuits, proper training for emergency interventions, and ensuring access for firefighters in case of necessity. These measures aim to ensure the safety of both solar installations and the people occupying the space, aligning with local regulations for fire prevention and control (GO, 2023).

The solar panel, or PV (Photovoltaic) panel, refers to a module with a nominal power of 5V or more, commonly composed of silicon cells, thin-film semiconductor layers, or hybrid (heterojunction) cells. It can have a frame or be frameless, be monofacial or bifacial, and can be rigid, flexible, or semi-flexible. It can operate independently, be applied to, or integrated into buildings. On the other hand, the PV system is a set of devices that convert solar energy into electricity, connected to the local power grid (On Grid). Finally, the standalone PV system refers to a system that is not connected to the local power grid (Off Grid), storing the energy produced through batteries. For Type 1 Systems, it is necessary to implement electrical protection measures, including an Arc Fault Protection Equipment (AFPE) and a Ground Fault Circuit Interrupter (GFCI). Additionally, it is essential to install a Rapid Shutdown Device (RSD) near the solar panels, with specific location requirements. The RSD switch should be in a secure and easily accessible location, with constant human surveillance and visibility. If there is no constant human surveillance, the switch can be installed at a maximum distance of 3 meters from the string inverters. The installation should allow operation without the need for ladders or tools. The switch should be accompanied by reflective signage with uppercase letters, indicating "PHOTOVOLTAIC SYSTEM RAPID SHUTDOWN SWITCH," with a minimum letter height of 10 mm, with white letters on a red background, as shown in Figure 13.

Source: GO (2023) - Goiás State Military Fire Department

Figure 13. Warning Sign

Government decree No. 515, issued on November 10, 2023, proposes amendments to PortariaInmetro No. 140, dated March 21, 2022, which deals with the technical regulation of quality and conformity assessment requirements for generation equipment, as well as the conditioning and storage of electrical energy in photovoltaic systems (Brazil, 2023). This proposal aims to adjust and improve the previous guidelines to ensure the quality and compliance of equipment used in photovoltaic systems (PV) in Brazil. The rationale for these modifications is based on the conclusions of the technical meeting "Risks and Fire Protection Measures in PV Equipment and Systems," held by Inmetro on July 1, 2022, and the public hearing "Fire Risks in Photovoltaic Generation Installations," conducted by the Committee on Mines and Energy of the Chamber of Deputies on July 6, 2022. These events identified the need to strengthen regulations related to arc flash protection in photovoltaic systems, aiming to enhance safety and prevent potential fire risks. The demand for stricter regulations aims to meet international safety standards and mitigate the risks of fires in this context. Therefore, it is imperative to introduce new requirements for arc flash protection for inverters, contributing to the enhanced safety of PV systems. Thus, it was stipulated a period of 12 months after the publication of the ordinance for all inverter manufacturers to comply with the arc flash safety requirements.

Regarding international technical standards for AFCI (Arc Fault Circuit Interrupter) devices in PV systems, they include:

a) UL 1699B Standard: The UL Outline standard was first issued by UL in 2011 and subsequently updated several times. The latest version is UL 1699B-2018. This standard specifies the testing requirements and performance indicators for arc fault protection devices (AFCI) in photovoltaic systems;
b) IEC 63027 Standard: The international standard developed by the International Electrotechnical Commission (IEC) in 2017, specifying the final performance requirements for AFCI in PV power generation systems;
c) AS/NZS 5033 Standard: The standard issued by Australia and New Zealand for the first time in 2019 under the code AS/NZS 5033-2019 specifies the functional requirements and test methods for AFCI in PV systems;
d) NEC 2017 Section 690.11: The 2017 edition of the National Electrical Code (NEC) introduced for the first time the requirements that AFCI in compliance with UL 1698B standard should be installed in DC circuits of PV systems.
e) CSA C22.2 No. 293 Standard: PV system safety standard issued by the CSA Group of Canada. Since the 2019 edition, it has incorporated the functional requirements and testing provisions of AFCI devices, requiring reference to the UL 1699B standard.

It has been possible to observe a progressive increase in specifications related to the installation of PV systems in various European countries. This trend is marked by the gradual introduction of Arc Fault Circuit Interrupters (AFCIs) in regulatory requirements. This development reflects the growing awareness of the importance of electrical safety in PV systems and the pursuit of international standards to ensure the effectiveness of these protective measures. In this context, the international standard IEC 63027 has played a central role. Developed by the International Electrotechnical Commission (IEC) in 2017, this standard establishes final performance requirements for AFCIs in PV energy generation systems. Its incorporation into installation specifications highlights the global recognition of the need for effective devices that detect and respond to electrical arc faults in PV systems. AFCIs play a crucial role in preventing fires and protecting against electrical risks associated with PV systems. Their introduction into installation standards reflects the evolution of safety practices to keep pace with the rapid growth and adoption of solar technologies. By specifically addressing electrical arc faults, these devices contribute to the integrity and reliability of systems, minimizing potential risks to properties and human lives. The trend of referencing IEC 63027 in European regulations emphasizes the importance of a harmonized approach across the continent to ensure consistent and high safety standards in PV installations. This movement not only promotes compliance with internationally recognized practices but also strengthens confidence in the sustainability and safety of PV systems, thus driving the ongoing advancement of solar energy in Europe.

In summary, UL 1699B and IEC 63027 emerge as the leading international standards for arc fault circuit interrupter (AFCI) detection and protection. Both demonstrate notable consistency in terms of defining AFCI functions, technical requirements, test methods, and other relevant aspects. These standards play a central role, often being referenced by regulations in countries and regions around the world. The high cohesion between UL 1699B and IEC 63027 is crucial to promote interoperability and the internationalization of AFCI technology and products. Consistency in the guidelines established by these standards facilitates global compliance, ensuring that AFCI devices meet uniform standards of performance and safety. This alignment contributes significantly to the global acceptance and widespread adoption of AFCI technology, promoting a common approach to preventing electrical risks in various contexts and applications. Currently, there is no global solution or unified international regulatory policy for regulating and establishing test standards for direct current (DC) arc faults in PV systems. The United States has led the research and development of standards to address fire issues in PV systems, with Underwriters Laboratories (UL) issuing the UL Outline standard in 2011, later updated to the latest version, UL 1699B-2018. This standard specifies test requirements and performance indicators for Arc Fault Circuit Interrupters (AFCIs) in PV systems. The 2017 edition of the National Electrical Code (NEC) in the United States introduced requirements for the first time, mandating the installation of AFCIs in compliance with the UL 1699B standard on DC circuits of PV systems.

Simultaneously, in several European countries, specifications for the installation of PV systems have been gradually increasing, incorporating requirements for implementing AFCIs based on the international standard IEC 63027. The growing emphasis on the operational safety of PV plants has highlighted the urgency of addressing challenges related to testing technology and protection against DC arc faults in PV systems. Therefore, developing an effective DC arc fault testing solution has become a crucial research area to assess and improve inverters, aiming to enhance the reliability and safety of PV systems. This research field has emerged as a relevant and pressing issue in the solar energy sector. In the application of Artificial Intelligence (AI) for fire prevention in PV systems, when evaluating its complexity and exposure to various environmental conditions, they are susceptible to a variety of faults and failures. Identifying these occurrences is crucial for the effective maintenance of the system. In this context, the first step is to conduct a comprehensive classification of possible faults, with a special focus on solar modules.

Photovoltaic modules, known as solar panels, operate in a simple and effective manner: when exposed to light, their cells absorb electromagnetic energy, generating free electrons that, in turn, use this energy to traverse the cell. These electrons are then connected in an internal circuit, resulting in the generation of an electric current (Conrado, 2021). The structure of a photovoltaic module is composed of various essential elements, each playing a specific role. The protective glass, for example, serves to safeguard the solar cells against external elements such as wind, rain, and dust. Encapsulation plays the role of keeping the cells safe and preventing moisture entry. Another vital component is the backsheet, which acts as an additional protective layer. It prevents external factors such as rain and wind from interfering with the electric current generated by the cells. Additionally, electrical connectors are responsible for connecting the modules to the power system, allowing efficient transfer of electricity generated by the solar panel to the rest of the system (Conrado, 2021). The application of Artificial Intelligence (AI) for fault detection in photovoltaic systems (PV) represents an innovative and effective approach to the intrinsic complexity of these systems. The nonlinear nature of solar energy sources adds an additional level of operational challenge, making the implementation of fault detection strategies a priority. Solar energy utilization systems face unique complexities due to the direct dependence on climatic and environmental conditions for the availability of solar resources. This dependence, in turn, directly influences the performance and efficiency of PV systems. Factors such as clouds, shading, and variations in solar radiation can significantly impact energy production. Thus, artificial intelligence techniques have played a crucial role in addressing complex challenges associated with solar energy utilization systems. Among the various applications highlighted in the literature, problems such as power generation prediction, solar irradiance prediction, water heating through solar energy, sizing of photovoltaic systems, improvement of Maximum Power Point Tracking (MPPT), and fault diagnosis in photovoltaic systems are prominent (Kalogirou & Senc, 2012). The enhancement of Maximum Power Point Tracking (MPPT) is essential for maximizing efficiency in converting solar energy into electricity, and artificial intelligence plays a significant role in this process by continuously optimizing MPPT. Additionally, the detection and diagnosis of faults in photovoltaic systems are facilitated by the ability of artificial intelligence to learn and analyze patterns. This enables rapid responses to potential issues, contributing to the reliability and longevity of photovoltaic systems.

of dealing with the inherent variability in these systems. Machine learning algorithms and advanced data processing techniques can analyze complex patterns and nonlinear behaviors, enabling early identification of faults. By employing AI models, it is possible to create intelligent monitoring systems that dynamically adjust to constantly changing conditions. This adaptive capability is particularly crucial in environments where solar conditions can vary rapidly, impacting energy production in short periods. Therefore, integrating artificial intelligence into fault detection in photovoltaic systems not only enhances the ability to identify irregularities but also contributes to the continuous optimization of system performance. This represents a significant advancement in the efficient management of PV systems, mitigating risks and maximizing the sustainable utilization of solar energy. The operation of the rapid shutdown system involves the activation of specific devices that immediately and safely interrupt solar energy generation. These devices may vary, but often include disconnect switches and specialized controllers. The swift action of these components is essential to reduce the risk of electrical shocks, prevent equipment damage, and ensure the overall safety of the system. The implementation of Rapid Shutdown is often guided by specific standards and regulations, ensuring that photovoltaic systems meet established safety standards. Compliance with these guidelines not only reinforces safety but also facilitates the integration of photovoltaic systems into existing electrical grids (Canal Solar, 2022). This case study aims to evaluate the level of protection against electrical arcs in DC solar photovoltaic (PV) systems using both direct and indirect parameters outlined in UL1699B. The focus is on the PV Generation Solar System, consisting of 64 PV panel modules installed in a commercial establishment, covering a total area of 162.99 m², with a installed capacity of 24.9 kWp. The study takes into account the unique occurrence of an electrical arc and the response time of the AFCI protection in a location adjacent to the solar plant.

Board 1. Project structure

Item	Material	Quantity	Ud	Cost R$	Observation
1	Solar plant FV de 24,9 kWp (MT)	1	Ud	N.A.	Existing (MT)
2	Specifications and Data of the electrical and electronic characteristics of the 24.9 kWp PV Solar Plant	1	Ud	N.A.	Installation project information and manufacturer details. Note: Alternative supplementary support in the academic and scientific community.
3	On-site analysis	1	Ud	N.A.	Existing system
4	Real-time PV Generation Analyses	1	Ud	N.A.	Author-conducted technical survey option.
5	Real-time Logging through the SUN2000 App	1	Ud	N.A.	Author-conducted technical survey option.

Source: Author, 2023.

Fonte: O autor (2021), Arquivo de entrega da instalação.

Figure 14. PV Solar systems FV - 24,9 KWp

The breadth of these applications reflects the growing importance of artificial intelligence in the ongoing evolution of the efficiency and reliability of solar energy utilization systems (Kalogirou & Senc, 2012). Artificial intelligence emerges as an adaptive solution capable

The project includes an analysis of the real risk situation of this system, aiming to provide a technically appropriate protection solution. Additionally, data collection on all types of electrical transients experienced by the solar plant during the initial 12 months is considered. This involves installing a Solar View electronic device and monitoring with the SUN2000 application, enabling the activation of the AFCI protection function for the solar system. Data on detected issues related to the quality and power disturbances in the installations are stored and made available in memory as event logs. These logs serve for later retrieval, studies, and analysis using the SUN2000 application. The successful execution of this work required access to the projects and electrical systems of the 24.9 kWp PV Solar Plant in the commercial establishment located in Santo Antônio de Leverger MT. The provision of a Solar View electronic device and the SUN2000 application, pre-installed for operation during the 12 months of this project, was also planned. Table 1 provides a summary of the entire structure (materials) made available for the execution and completion of this case study project.

This article explores a case study demonstrating that string inverters, even without power optimizers or microinverters, can be safe when equipped with AFCI technology according to the UL1699B standard.This ensures that, in the event of an electrical arc fault, the system is quickly and automatically shut down, protecting the lives of users and their properties. The study at hand provides solid evidence that string inverters, traditionally considered less safe due to the lack of module-level optimization technologies, can be reliable and secure when equipped with AFCI systems. This electrical arc detection technology is crucial for promptly identifying and interrupting any potential faults, mitigating safety-related risks. By adhering to the UL1699B standard, which establishes guidelines for arc fault detection and interruption, string inverters can offer security levels comparable to their counterparts with power optimizers or microinverters. This has significant implications for the solar energy industry, especially considering that safety is a crucial priority in PV installations. The ability to ensure that the system is automatically shut down in the event of electrical arc faults not only protects the lives of users but also safeguards their properties from potential damage. This case study highlights that AFCI technology, combined with string inverters, can be a safe and viable option, even in the absence of power optimizers, contributing to a safer and more reliable solar industry. Figures 14 and 15 that follow provide a visual representation of the system in full operation, showcasing a PV solar system with a total capacity of 24.9 kWp. These images capture the efficiency and operation of the system, allowing a direct view of how solar energy is being converted into electricity. Figure 14 presents the solar system in all its magnitude, revealing the complete installation with its solar panels in position, ready to capture sunlight. This image is a vivid representation of the scale of the installation and the involved infrastructure. Figure 15 offers a closer and more detailed view of the solar system, demonstrating the photo of the 20 kW (kilowatts) capacity inverter installation. The 20 kW capacity indicates the power the inverter can convert from the PV solar panels. This visual representation is valuable for monitoring, maintenance, and documentation of the PV solar system, enabling a detailed analysis of the inverter's configuration and connections.

Source: The author (2021)

Figure 15. Photo of the String Inverter Installation – 20 kW

In the context of solar photovoltaic (PV) energy, the inverter is a critical component that converts the direct current generated by solar panels into alternating current, making it suitable for use in homes, businesses, and industries. Therefore, the visual capture of the installation of the 20 kW inverter is valuable for monitoring the performance and functionality of the solar system. These visual illustrations are crucial for understanding the operation of the solar PV system, demonstrating how the technology converts solar energy into usable electricity. These images provide a tangible representation of the contribution of solar energy to the generation of clean and renewable electricity. The occurrence of a failure in the monitoring application, with the notification of "Unexpected Shutdown," is a scenario that can be challenging for users. This message suggests that the application encountered an unforeseen error, resulting in its abrupt closure. Internet connectivity is also a critical point to be evaluated. Connection issues can trigger failures in monitoring applications. Additionally, it is advisable to review the settings of the device where the application is installed and ensure that the operating system is up to date. Sometimes, problems arise from incorrect settings. Figure 16 presents the failure in the monitoring application, indicating an unexpected shutdown.

Source: Sun 2000, 2023.

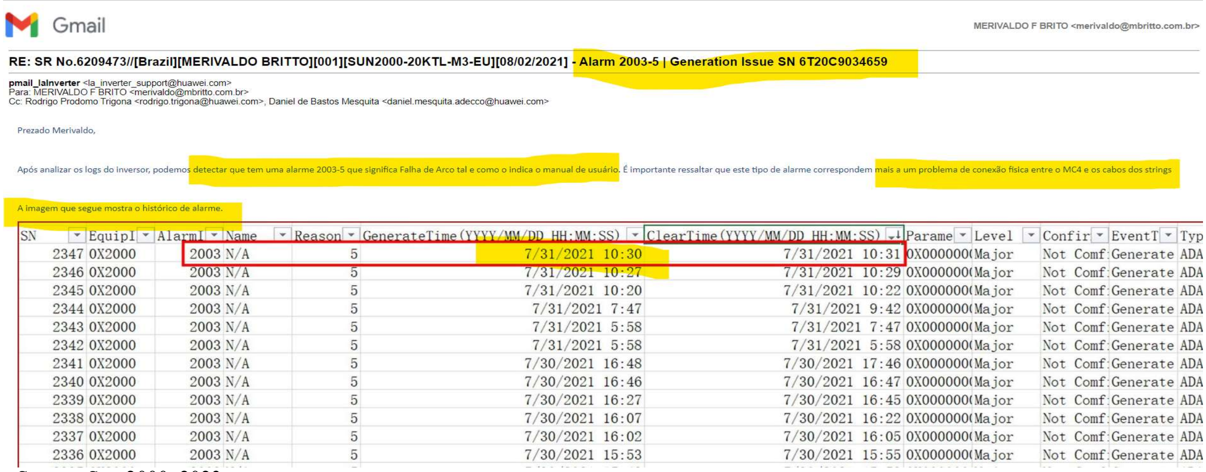
Figure 16. Monitoring Application Failure (indicating unexpected shutdown)

The alarm issued by the inverter monitoring system, indicating an "Unexpected inverter shutdown failure," is an alert that deserves attention. This message indicates that an unplanned interruption occurred in the inverter's operation. Verifying the integrity of the components of the solar PV system is another crucial step. This involves inspecting cables, connections, and solar panels for potential physical or connection issues that may have triggered the failure. Additionally, it is advisable to assess the inverter settings and ensure they align with the recommended specifications. Sometimes, inappropriate adjustments can result in unexpected shutdowns. Figure 17 illustrates an alarm in the inverter monitoring system, indicating an unexpected inverter shutdown failure.

Source: Sun 2000, 2023.

Figure 17. Alarm in the inverter monitoring system indicating unexpected inverter shutdown failure

It is noted that the unexpected shutdown failure of the inverter requires a careful approach to determine the underlying cause and take appropriate measures to restore the normal operation of the solar energy system. The inverter experienced a failure situation that triggered an alarm with the code 2003-5, indicating the activation of the AFCI (Arc-Fault Circuit Interrupter). This specific circumstance generated a critical alert that was immediately communicated via email. Figure 18 illustrates an inverter failure with the error "alarm 2003-5." message provided crucial information about the nature of the failure and the specific alarm code. This level of detail is essential for understanding the root cause of the problem and determining necessary corrective actions. Based on this notification, system operators were able to investigate and take appropriate measures to address the inverter failure.The installation verification involves a comprehensive analysis of all components in the solar PV system. This includes inspecting solar panels, cables, connections, and related electrical components.



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RE: SR No.6209473//[Brazil][MERIVALDO BRITTO][001][SUN2000-20KTL-M3-EU][08/02/2021] - Alarm 2003-5 | Generation Issue SN 6T20C9034659

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Cc: Rodrigo Prodomo Trigona <rodrigo.trigona@huawei.com>, Daniel de Bastos Mesquita <daniel.mesquita.adecco@huawei.com>

Prezado Merivaldo,

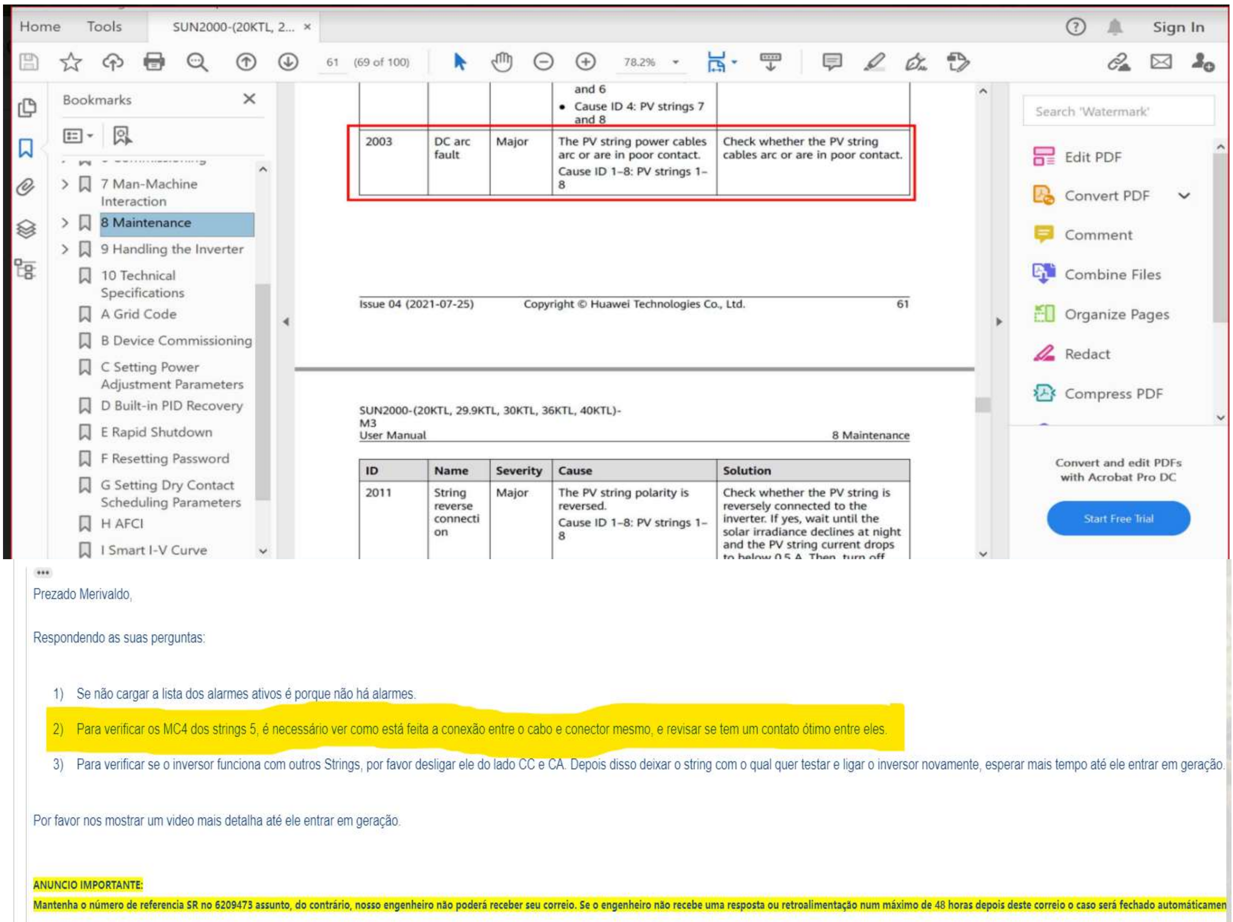
Após analizar os logs do inversor, podemos detectar que tem uma alarme 2003-5 que significa Falha de Arco tal e como o indica o manual de usuário. É importante ressaltar que este tipo de alarme correspondem mais a um problema de conexão física entre o MC4 e os cabos dos strings

A imagem que segue mostra o histórico de alarme.

SN	EquipI	AlarmI	Name	Reason	GenerateTime(YYYY/MM/DD HH:MM:SS)	ClearTime(YYYY/MM/DD HH:MM:SS)	Parame	Level	Confir	EventT	Typ
2347	0X2000	2003	N/A	5	7/31/2021 10:30	7/31/2021 10:31	0X000000(	Major	Not Comf:	Generate	ADA
2346	0X2000	2003	N/A	5	7/31/2021 10:27	7/31/2021 10:29	0X000000(	Major	Not Comf:	Generate	ADA
2345	0X2000	2003	N/A	5	7/31/2021 10:20	7/31/2021 10:22	0X000000(	Major	Not Comf:	Generate	ADA
2344	0X2000	2003	N/A	5	7/31/2021 7:47	7/31/2021 9:42	0X000000(	Major	Not Comf:	Generate	ADA
2343	0X2000	2003	N/A	5	7/31/2021 5:58	7/31/2021 7:47	0X000000(	Major	Not Comf:	Generate	ADA
2342	0X2000	2003	N/A	5	7/31/2021 5:58	7/31/2021 5:58	0X000000(	Major	Not Comf:	Generate	ADA
2341	0X2000	2003	N/A	5	7/30/2021 16:48	7/30/2021 17:46	0X000000(	Major	Not Comf:	Generate	ADA
2340	0X2000	2003	N/A	5	7/30/2021 16:46	7/30/2021 16:47	0X000000(	Major	Not Comf:	Generate	ADA
2339	0X2000	2003	N/A	5	7/30/2021 16:27	7/30/2021 16:45	0X000000(	Major	Not Comf:	Generate	ADA
2338	0X2000	2003	N/A	5	7/30/2021 16:07	7/30/2021 16:22	0X000000(	Major	Not Comf:	Generate	ADA
2337	0X2000	2003	N/A	5	7/30/2021 16:02	7/30/2021 16:05	0X000000(	Major	Not Comf:	Generate	ADA
2336	0X2000	2003	N/A	5	7/30/2021 15:53	7/30/2021 15:55	0X000000(	Major	Not Comf:	Generate	ADA

Source: Sun 2000, 2023.

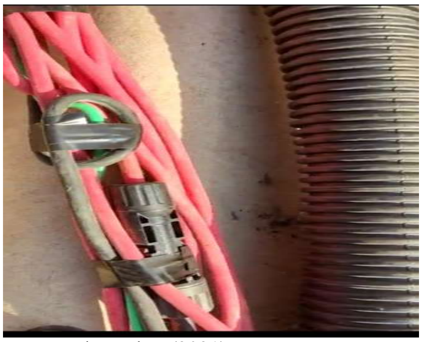
Figure 18. Inverter Failure (Alarm 2003-5 – AFCI)



Source: Sun 2000, 2023.

Figure 19. Orientação para verificar a instalação

The inverter monitoring system detected the occurrence of alarm 2003-5 related to the AFCI, and an email notification was generated and sent to those responsible for the operation of the solar system. This type of notification is crucial as it allows for a prompt response to potentially dangerous issues, such as electrical arcs. The email The goal is to identify any anomalies, such as loose connections, physical damage, or other issues that may impact system performance. Additionally, this guidance implies a review of inverter settings. Ensuring that the settings align with recommended specifications is crucial, as incorrect adjustments can lead to operational issues. In Figure 19, the guidance for thorough installation verification is illustrated. It was determined that after the alarm indicated a fault in connector MC4 in String 5, a team was needed to conduct an on-site inspection.An investigation revealed that the underlying cause of the problem was, in fact, related to an installation failure. This type of failure is commonly associated with inconvenient or faulty connections that may occur during the solar PV system assembly process. The identification of the failure in the MC4 connector in String 5 was a crucial step in resolving the issue. Once the field team identified the installation failure, corrective measures could be immediately implemented, as shown in Figure 20.



Source: The author (2021)

Figure 20. Falha conector MC4 na String 5

These measures may include replacing the faulty MC4 connector, reevaluating connections throughout the installation to ensure they are properly tightened and secure and taking any other necessary actions to restore the functionality of the system. This situation highlights the importance of regular maintenance and detailed inspections in PV solar energy systems. Installation issues, such as loose or faulty connections, can have significant impacts on system operation and safety. Prompt identification and correction of installation failures are crucial to ensure proper performance and reliability of solar systems. A connector exhibiting symptoms of overheating was identified. This discovery is of utmost importance, as overheating of connectors in PV solar energy systems can pose a significant risk for electrical arc initiation. Thus, the safety and performance of the system were ensured with AFCI, identifying the failure. The overheating of connectors can be caused by various factors, such as faulty connections, electrical overload, or inadequate sizing issues. Regardless of the cause, this condition can lead to damage to the connectors, increasing the risk of fire and affecting the system's operation. Figure 21 presents the connector with signs of overheating.

Surce: The author (2021)

Figure 20. Faulty MC4 Connector in String 5

Given this scenario, it is crucial that immediate measures be taken to address the overheating connector issue. This may involve replacing the defective connector, assessing adjacent connections for possible damage, and implementing adjustments to the system sizing if necessary. Therefore, the identification of the connector with signs of overheating underscores the importance of preventive maintenance in photovoltaic (PV) solar energy systems. Regular inspection and early detection of issues, such as overheating, play a fundamental role in preventing more serious damage and maintaining the safety and efficiency of the system. Therefore, this discovery should be treated with due attention and prompt action.

RESULTS

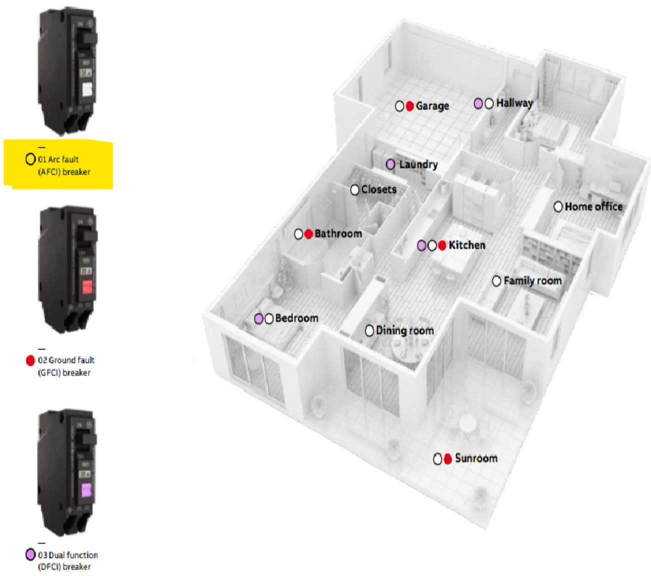
With the completion of literature review stages, collection of project information, and specifications of solar generation systems in a commercial establishment, followed by the real-time on-site measurement using the Sun2000 application:

a) We identified the Performance Level of the solar generation system and system failure alarms.
b) Through the application, with the sending of fault codes via email, we identified and demonstrated in the figures showing arc fault alarms (Figures 13, 15, and 17) in the 24.9 kWp Solar Generation System, considering the characteristics obtained from the Sun2000 application.

All data were obtained where the inverter had an unexpected shutdown, i.e., ceasing to generate the reverse flow of current, as shown in Figure 14. It was observed that there was voltage existence, with the inverter automatically shutting down the reverse flow of the current through AI. It's worth noting that for an arc fault to occur, there must be a break in two poles. That is, it is an event that occurs due to an electrical discharge between two poles, exceeding the resistance of the air and maintained by the formation of gases that act as a conductor for the electric current. This can be caused by human error (technicians during the connection) or product failure, leading to an electrical arc on the DC side, potentially causing a fire and resulting in losses and damage to users. In contrast to the extensive experience accumulated over decades in photovoltaic (PV) installations in more temperate climates, we are starting to observe the effects of extreme operational temperatures and extreme levels of solar irradiance as large-scale PV energy absorption expands into regions known as the "solar belt." One of these effects is triggered by extreme solar irradiance events, which, until recently, were more a subject of scientific interest than a potential problem affecting the performance of PV plants (Nascimento et al., 2019). The nonlinear output characteristics of PV arrays and maximum power point tracking (MPPT) techniques present significant challenges in fault diagnosis. An effective approach to overcome these challenges is the fault diagnosis model based on the analysis of electrical transients in the time domain. However, many previous studies using transient processes required extensive and labeled datasets to train their models, and some approaches involved normalization with environmental condition sensors or reference PV panels (Xi et al., 2021). The detection algorithm analyzes a unique symmetrical energy profile generated by an arc fault. Experimental results confirm that the harmonics generated by the ignition and extinction of an arc fault can be identified through voltage measurements at the voltage source where arc fault protection devices (AFCI) are installed (Kim et al., 2022). In this case, Figure 17 revealed an issue due to an incorrect installation in the MC4 connector connection. The installing technician made a faulty connection by winding over 10 meters of direct current cables around the connector, creating a coil. This resulted in overheating, almost leading to the rupture of the connection, which could have caused an electrical arc failure, subsequently resulting in a fire that would have endangered the lives of users and property. Upon evaluation, it was determined that by applying AFCI to the inverter's hardware before the pole rupture occurred, in less than 300 milliseconds, using AI, the inverter achieved an instantaneous shutdown, preventing the rupture in the MC4 connector, which, as previously observed, has a higher rate of fire propagation failures in solar PV systems. Arc faults in PV systems, especially series arc faults, are becoming more frequent. Without timely detection and interruption, these hazardous events have the potential to trigger catastrophic fires, posing a serious threat to the safety of individuals and properties (Lu et al., 2022). As the adoption of PV systems grows, concerns about arc faults also increase. These faults can be triggered by various factors, including connection issues, component damage, or adverse environmental conditions. When not identified and addressed promptly, arc faults can result in substantial damage and jeopardize lives and property. Therefore, it is crucial to implement arc fault detection and interruption measures in PV systems to mitigate these risks. Human safety and property protection are essential priorities in the solar energy industry, and preventing arc faults plays a crucial role in this process. Ensuring compliance with safety standards and regulations is fundamental to minimizing the hazards associated with arc faults in PV systems (Lu et al., 2022). Arc faults present significant reliability and safety challenges in PV systems. This study introduced an effective method based on discrete wavelet transform and support vector machines (SVM) for detecting arc faults in DC photovoltaic systems. Due to its advantages in processing time-frequency signals, the wavelet transform is applied to extract characteristic features from the voltage/current signals of the system. SVM is then used to identify arc faults. The proposed technique demonstrates promising results for arc fault detection in PV systems using discrete wavelet transform for feature extraction and support vector machine for decision-making. As the developed classifier is designed for DSP/MCU applications, computing load involved in classification and the memory space used for storing support vectors are two major concerns (Wang; Balog, 2022).

With the expansion of the photovoltaic (PV) solar sector, particularly in the Distributed Generation (DG) mode, there has been an observed gap in safety practices. Professionals have entered the industry without adequate training and knowledge of technical standards such as ABNT5410, ABNT5419, ABNT16690, as well as safety regulations like NR10 and NR35, which are essential for electrical installations and work at heights (ABNT, 2018). The increasing number of fires in photovoltaic systems, especially on residential and commercial rooftops, has drawn the attention of Brazilian authorities. A recent example was a fire at a shoe factory in Patos de Minas (MG), attributed to a potentially improper installation of solar panels. In response to this concern, the Fire Department sent a letter to ABNT requesting urgent development of safety standards to mitigate the risks of fires in solar power plants. The document emphasizes the importance of sustainable practices and the use of photovoltaic systems, acknowledging the positive evolution these technologies have brought to society. However, it highlights that several fire departments have reported incidents of fires associated with photovoltaic systems, especially in direct current circuits between the panels and inverters.

The National Council of Internal Control (CONACI) proposes measures, including regulatory evolution to require additional protective devices, the use of appropriate materials, and commissioning and inspection procedures to reduce risks. Additionally, it emphasizes the need for de-energizing direct current circuits, enabling safer firefighting procedures (Canal Solar, 2023). The organization emphasizes the importance of recycling and training firefighters to deal with fires in photovoltaic systems. It also suggests a normative and regulatory approach focused on fire safety and the protection of professionals involved. Developed countries have already adopted such measures after similar events, indicating a proactive approach to prevent accidents and deaths related to fires in solar installations. The market previously offered short-duration online courses, often insufficient to adequately address crucial topics. Legislation now requires more extensive courses, such as 40 hours for NR10 and a minimum of 160 hours for electricians. Products in the market also lacked adequate protection against electrical risks, such as arc faults. The recent Inmetro Ordinance establishes a 12-month deadline for all inverters to implement fire protection, concluding discussions and promoting significant advancements in the safety of the PV sector in Brazil. As a result, it can be concluded that through Artificial Intelligence, the inverter detected disturbances on the DC side and when it identified a spectrum with an electric arc due to an installation failure in the MC4 connector in String 5, the DC circuit is immediately interrupted, thus ensuring the safety of property and users' lives. The introduction and mandatory use of Arc Fault Circuit Interrupters (AFCI) in electrical installations are essential measures to improve fire safety. The National Electrical Code (NEC) in the United States is a significant reference for safe practices in electrical installations, and its updates reflect continuous advancements in technology and knowledge about safety. Figure 22 presents Arc Fault Circuit Interrupters (AFCIs) installed in residential environments. This visual representation highlights the specific layout or configuration of these electrical safety devices in a domestic context. The purpose is to provide a clear and understandable view of the implementation of AFCIs, emphasizing their importance in preventing electrical fires in homes.



Source: AFCI - ABB Group (2023)

Figure 22. Arc Fault Circuit Interrupters (AFCI) in residential environments

Arc Fault Circuit Interrupters (AFCIs) help prevent electrical arc faults, reducing the risk of electrical fires in residences. The NEC requirement until the year 2023 mandates the use of AFCIs in specific residential spaces. The mandatory installation locations include the following residential spaces: a) family room; b) dining room; c) living room; d) bedroom; e) sunroom; f) library; g) den; h) office hallways; i) closets; j) recreation room; k) Kitchen (except as otherwise specified). Therefore, there is a recognized need to install AFCIs in various residential spaces to enhance electrical safety and prevent fires related to electrical arc faults. The mandatory implementation of AFCIs on all residential electrical circuits in the United States is a crucial measure to prevent accidents related to electrical arcs and strengthen safety in homes. AFCIs are designed to detect electrical arc faults, which can be caused by issues such as worn-out wires, loose connections, or cable damage. These conditions can lead to fires if not detected and interrupted in time. The inclusion of AFCIs in circuit breakers and other electrical devices is a proactive measure to mitigate the risks of electricity-related fires. This demonstrates a growing commitment to residential safety and occupant protection. Therefore, it is essential for electrical professionals, builders, and property owners to be aware of these updates and adhere to standards to ensure safer environments. Fire prevention in electrical installations is crucial to protecting lives and properties, and the adoption of technologies such as AFCIs plays a fundamental role in this effort.

FINAL CONSIDERATIONS

In the final considerations, it is important to emphasize the relevance of the research and analysis conducted within the scope of photovoltaic solar power generation systems. Several significant aspects impacting the efficiency, performance, and safety of these systems were identified. It was found that the ability to perform measurements and monitor systems in real-time, as demonstrated with the Sun2000 application, is fundamental for identifying faults, performance issues, and ensuring system safety. This allows for immediate action and helps prevent more serious problems. In the detection of electrical arc faults, as indicated in the analyses, it is crucial to ensure system safety. The use of arc fault detection technology (AFCI) is highly recommended, even in conventional string inverter systems. The analysis reinforces the importance of preventive maintenance in solar power generation systems. This includes regular inspections, continuous monitoring, and swift action in case of issues. Considering the continuous expansion of photovoltaic solar generation, it is suggested that additional research be conducted to enhance arc fault detection technology, improve monitoring methods, and deepen the understanding of distributed generation systems. Standards and regulations related to the safety and performance of photovoltaic solar systems were also addressed, emphasizing the need for continuous review and updates to reflect best practices and technological advancements. This article demonstrated the importance of continuous monitoring and fault detection in photovoltaic solar power generation systems. The implementation of advanced technologies, such as arc fault detection, is crucial to ensure the safety and efficiency of these systems. The future of photovoltaic solar energy depends on continuous research, technological innovation, and compliance with standards and regulations. The implementation of AI is a promising approach to enhance fire safety in photovoltaic solar power systems.

This technology offers effective solutions for early detection of arc faults and triggering rapid shutdowns, significantly reducing the risks associated with fires in photovoltaic plants. Proposed areas for future work include a) The AFCI in circuit breakers, widely used in the United States, is not limited to fire protection in power generation but also plays a crucial role in distribution. Implemented in distribution panels of residential, commercial, and industrial electrical installations, the AFCI acts as a fire protection system by detecting electrical anomalies, such as electrical arcs, that can result in fires; b) developing an AI system to diagnose faults in residential electrical installations, optimize energy efficiency, and integrate renewable sources. An environmental impact analysis guided by AI will assess and reduce the environmental impact of electrical installations, promoting more sustainable practices; c) implementing predictive maintenance plans for electrical equipment performed through AI systems, preventing failures and reducing repair costs. Intelligent algorithms will be created to optimize energy consumption, considering usage patterns, weather conditions, and tariffs, including automation to maximize efficiency. When analyzing future projections, it becomes important to highlight that by 2040, photovoltaic solar energy is expected to represent approximately 32% of the global energy matrix. Furthermore, it is estimated that about 75% of solar energy will be generated by distributed generation systems. These projections reflect the growing importance and adoption of solar energy as a significant source of electricity. Distributed generation highlights the trend of decentralized energy systems, where electricity generation occurs on a small scale and close to points of consumption. This can include solar installations in homes, businesses, and communities, contributing to a more resilient and sustainable grid. These estimates reflect the growing recognition of the fundamental role of solar energy in transitioning to cleaner and renewable sources. The expansion of distributed generation also reflects the pursuit of more decentralized and resilient solutions, reducing dependence on large traditional power plants.

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