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Protection Challenges and Fault Diagnosis in PV Systems: A Critical Review

Prakash Kumar[1], Amit Kumar Sinha[2]
[1, 2]Department of Mechanical Engineering, Assistant Professor, R.V.S. College Of Engineering and Technology, Jamshedpur, Jharkhand, India

Abstract: With the rapid expansion of global photovoltaic (PV) power capacity, ensuring the protection of PV systems has become increasingly crucial over the past few decades. Despite the incorporation of standard protection devices, certain faults within PV arrays may go undetected. Motivated by the growing demand for reliable fault detection methods, numerous advanced techniques have been proposed in recent years. This paper provides a comprehensive analysis of various fault occurrences, the challenges associated with protection, and the potential consequences of undetected faults in PV systems. Additionally, it critically reviews a wide range of fault detection algorithms and techniques that have been proven to be both effective and practical for implementation. Beyond merely surveying existing methods, this study evaluates each technique based on key factors such as: 1) Methodology, 2) Sensor requirements, 3) Fault diagnosis and localization capability, 4) Integration complexity, 5) Accuracy, 6) Applicability, and 7) Implementation cost. Ultimately, this paper serves as a valuable resource for researchers in the field of PV systems, assisting them in advancing their work and developing more reliable fault detection strategies.

I. LITERATURE REVIEW

The rapid expansion of PV power generation, particularly in the distribution sector, has led to a complex mix of electricity production on a large scale. At the same time, PV technology plays a crucial role in mitigating global warming by reducing reliance on fossil fuels and lowering greenhouse gas emissions. Over the past few decades, extensive research efforts have been directed toward three key areas: 1) Enhancing PV cell efficiency, 2) Lowering PV panel costs, and 3) Maximizing power extraction from PV panels. Despite these advancements, PV systems remain susceptible to various faults that significantly impact their efficiency, reliability, and safety. To address this issue, conventional international protection standards have been revised, and specific protection guidelines have been introduced to ensure the safe operation of PV power plants. However, it is important to note that while these standards effectively safeguard the AC side of a PV system, they fall short in detecting faults on the DC side. As a result, faults in PV systems persist and often go unnoticed. According to the National Electric Code (NEC) Article 690, the DC side of all PV systems must be protected against overcurrent faults, ground faults, and arcing faults. This is achieved through the use of Overcurrent Protection Devices (OCPDs), Ground Fault Detection and Interruption (GFDI) fuses, Ground Fault Protection Devices (GFPDs), and Arc Fault Circuit protection mechanisms. Interrupters (AFCIs). Additionally, string-level Arc Fault Detectors (AFDs) can be used to detect arcing faults. However, studies have shown that these protection devices often fail to identify faults within the PV array due to several factors, including: 1) Low fault current magnitudes, 2) The presence of Maximum Power Point Trackers (MPPTs), and 3) The nonlinear characteristics of PV systems, which are highly dependent on insolation levels.

Moreover, electrical faults occurring on the DC side of a PV system can have severe consequences on its output characteristics, often leading to unpredictable behavior. In some cases, these faults can cause extensive damage, potentially resulting in the complete burnout of the system, despite the presence of protection mechanisms. Additionally, faults that occur under low irradiation conditions may go undetected, leading to significant energy losses and long-term degradation of PV panels.Energy audit reports indicate that such faults can cause annual energy losses of up to 18.9% in domestic PV systems in the UK. To address these issues, researchers have conducted Failure Mode and Effect Analysis (FMEA) on various PV system faults, emphasizing the critical need for early fault detection to enhance system reliability. In response, design guidelines have been proposed for optimizing the use of protection devices, considering the complex nature of PV systems, which includes: 1) Unique fault characteristics that are difficult to distinguish, and 2) The presence of dynamic operational conditions that affect fault detection accuracy.

However, existing guidelines rely on multiple combinations of protective devices, which not only increase costs but also fail to guarantee precise fault detection. Additionally, the presence of MPPT controllers in PV systems further complicates these protection strategies by influencing system behavior.

A critical limitation of current protection devices is their inability to detect partial shading in PV modules—a prevalent and severe issue. While partial shading is often considered a fault, it is typically temporary. Therefore, protection systems must be capable of distinguishing between temporary shading and actual faults to prevent unnecessary tripping. Overall, to overcome these challenges and ensure accurate detection, diagnosis, and localization of multiple faults in PV systems, advanced fault detection techniques are essential. Over the years, numerous methods have been proposed to enhance fault detection and diagnosis. A comprehensive analysis of various fault detection approaches in PV systems is provided in which also reviews available monitoring systems designed to track system performance. Some papers presents key insights into selecting appropriate monitoring strategies to improve the reliability and accuracy of fault detection in PV systems.

Survey of fault diagnostics in microgrids is presented but these studies focus primarily on the analysis of physical and environmental faults in PV systems, without reviewing the performance of advanced fault detection techniques. Electrical faults in PV arrays are particularly hazardous and require immediate attention.

The development of reliable fault detection schemes began with improved protection devices and was followed by physical testing of PV systems using fault detection tools and instruments. Over the past decade, several advanced fault detection algorithms have been developed to achieve both accurate and rapid fault detection in PV systems. While an overview of conventional methods for fault detection, including their advantages and disadvantages, is provided in a more detailed analysis—specifically on their accuracy, integration complexity, and cost-effectiveness—has not been thoroughly discussed. Additionally, the computational effectiveness, detection procedures, and applicability of each algorithm or technique remain underexplored. There is a clear need for a comprehensive evaluation of these detection methods to fully understand their potential and limitations in the context of modern PV systems.

II. TYPICAL FAULTS IN A PV SYSTEM AND PROTECTION CHALLENGES

Photovoltaic (PV) systems are generally reliable, but like any technology, they can experience faults that affect performance. The faults in a PV system can be broadly categorized into electrical, mechanical, and environmental issues. Here are some of the typical faults and protection challenges:

A. Common Faults in PV Systems

1) Module Failures

- Cracks and Delamination: Mechanical stress or extreme weather can cause the solar cells or modules to crack or delaminate, reducing efficiency or causing failure.
- Hot Spots: When a part of a solar panel is shaded or damaged, it can lead to excessive heating, causing localized damage and reducing the panel's lifetime.
- PID (Potential Induced Degradation): This occurs when the potential difference between the solar cell and the frame leads to leakage currents, resulting in a gradual loss of power output over time.

2) Inverter Faults

- Inverter Failure: Inverters are the most complex and failure-prone components in a PV system. They can experience issues such as power supply malfunctions, cooling problems, or component wear over time.
- Overvoltage and Undervoltage: Inverters may trip or stop working if the voltage exceeds safe operating limits or falls below the minimum threshold.

3) Wiring and Connection Faults

- Loose Connections: Corrosion or poor maintenance can lead to loose or faulty connections in wiring, causing system inefficiency, overheating, or electrical fires.
- Short Circuits: Damaged wires or insulation can cause short circuits, leading to system shutdown or further equipment damage.

4) DC Circuit Issues

- Ground Faults: A DC ground fault happens when there is unintended contact between the ground and an active conductor in the DC circuit, which can lead to malfunction or electrical hazards.
- Arcing: DC circuits can generate arcs when switches are made or broken under load, posing safety risks and causing damage to circuit components.

5) Environmental Factors

- Shading: Partial shading from trees, buildings, or debris can lead to underperformance in certain parts of the system, often resulting in hot spots.
- Dust and Dirt: Accumulation of dust, dirt, or snow on solar panels can significantly reduce energy generation.
- Lightning Strikes: Direct or nearby lightning strikes can cause surge damage to the electrical components of the PV system.

B. Protection Challenges in PV Systems

1) Overcurrent Protection

- Challenges: Overcurrent protection is critical to prevent damage due to excess current flowing through the system. PV systems often have varying output based on sunlight, so designing protection circuits that can handle high currents during peak output without frequent trips is complex.
- Solution: Use fuses or circuit breakers in key locations like the DC side, the inverter, and AC distribution board to prevent overloads or short circuits.

2) Ground Fault Protection

- Challenges: Ground faults in PV systems are often difficult to detect, especially if the system is not properly grounded. This makes it harder to protect the system from electrical hazards.
- Solution: Using ground fault detection units or monitoring systems is necessary to detect and locate faults quickly and safely.

3) Surge Protection

- Challenges: PV systems, especially in remote areas, are at risk of lightning strikes or power surges from grid disturbances. Surge protection needs to be robust and effective.
- Solution: Surge protective devices (SPDs) can be installed at the inverter and distribution panels to protect against high-voltage transients.

4) Voltage Fluctuations and Frequency Instability

- Challenges: PV inverters must be able to handle voltage fluctuations in both the DC and AC sides. Voltage spikes, drops, or frequency instability can cause inverters to trip or malfunction.
- Solution: Inverters with advanced protection features, such as under/overvoltage protection, frequency regulation, and fault tolerance, are necessary for maintaining stability.

5) DC Isolation and Disconnects

- Challenges: A common protection challenge is the safe isolation of the DC system for maintenance or emergency scenarios. DC isolation is more complex than AC due to the constant current flow in the system.
- Solution: DC disconnects and isolation switches are essential for ensuring that the system can be safely de-energized for maintenance or repairs.

6) Temperature Monitoring and Cooling

- Challenges: Overheating of the system components (especially the inverter) is a major issue in PV systems, especially in hot climates. Excessive heat can reduce the life span of components or even cause failures.
- Solution: Adequate ventilation, cooling systems, and temperature sensors in key parts of the PV system are crucial for ensuring optimal operation.

C. Monitoring and Diagnostics

Regular monitoring of both the performance and safety aspects of a PV system is crucial for early detection of faults. This includes:

1) Performance Monitoring: Continuous data logging and comparison against expected outputs can help detect underperformance.
2) Remote Diagnostics: Remote monitoring systems can provide real-time fault detection and preventive maintenance suggestions.
3) AI and Machine Learning: Some advanced systems use AI to predict faults based on historical data and trends, helping to prevent issues before they occur.

By addressing these common faults and protection challenges, the reliability and safety of PV systems can be significantly improved.

III. OVERALL REVIEW

Comprehensive comparison of each method within a unified framework. As shown in Table 4, these techniques have been assessed based on eight key features that significantly contribute to making a fault-tolerant PV system both efficient and compact. The following features have been examined and briefly explained:

1) Approach – Describes the general methodology used for fault detection.
2) Sensor Requirement – Determines whether additional sensors are necessary beyond the standard current and voltage sensors used for MPPT operation, and if so, specifies the number required.
3) Fault Diagnosis Capability – Evaluates the technique's ability to differentiate between faults with similar characteristics.
4) Ability to Locate Faults – Assesses whether the method can accurately pinpoint the fault location, facilitating easier and more efficient maintenance.
5) Integration Complexity – Measures how seamlessly the proposed technique can be incorporated into existing PV systems, considering factors such as detection rules, required components, and overall system structure.
6) Applicability – Determines the technique's relevance to PV systems with or without MPPT, based on the detection parameters it employs. Some methods, for example, rely on MPP data for fault detection, limiting their use to PV systems with MPPT.
7) Accuracy – A critical factor in any detection technique, analyzed based on the reliability of detection rules, choice of detection variables, and overall performance across various environmental conditions.
8) Cost of Implementation – Assessed by considering the expenses associated with additional components and sensors required for the technique.

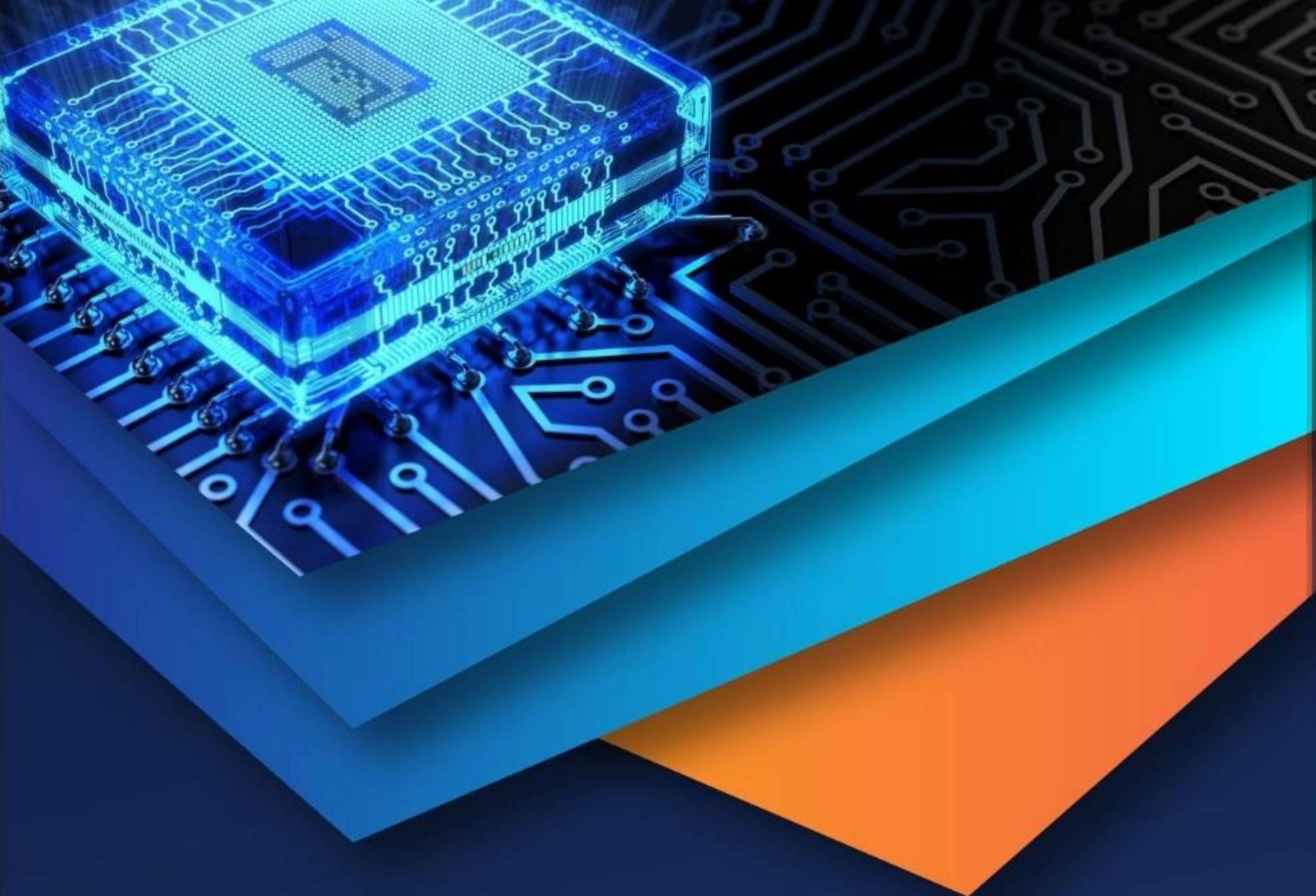
IV. CONCLUSION

This paper, inspired by the growing interest in fault detection, reviews several fault detection techniques proposed for photovoltaic (PV) systems. The aim is to provide researchers and industry professionals in the PV field with valuable data and benchmarks for their work. The authors present a thorough analysis of various fault occurrences and their potentially catastrophic effects on PV systems. Additionally, the paper examines the challenges in detecting each type of fault and the limitations of conventional protection devices. Fault detection approaches are categorized into six main types, with a detailed study and extensive comparative analysis of the techniques proposed in each category. In conclusion, the paper summarizes the key findings and insights from the work. For PV systems that have already been installed with conventional protective devices, great care must be taken to protect the system from double ground faults, which are typically associated with blind spots. Installing Residual Current Devices (RCDs) in combination with the existing Ground Fault Detection Indicators (GFDIs) appears to be a more effective and feasible solution. While numerous studies have been conducted to detect various faults in PV systems, a practically viable technique for detecting the presence of parallel arcs is still lacking. Any fault detection scheme should address this gap to ensure effective protection. A significant portion of existing research has focused on detecting and diagnosing faults. However, for large PV systems, even if a fault is detected, it is often challenging to pinpoint its exact location. Therefore, a fault detection method should not only detect faults but also be capable of identifying the fault points within the system, facilitating proper maintenance and mitigation. For future work, the performance of each fault detection technique presented in the literature could be analyzed for detecting similar faults across different environmental conditions. This would help identify the most effective technique for detecting specific faults.

REFERENCES

[1] Biagi M, Falvo MC Smart micro grid programming for renewable resources: from communication to dispatching.
[2] Brenna M, Falvo MC, Foiadelli F, Martirano L, Poli D. Sustainable energy microsystem (SEM): preliminary energy analysis. In: Innovative Smart Grid Technologies (ISGT), IEEE PES; 26 Jan 2012. p. 1–6.
[3] Capparella S, Falvo MC. Secure faults detection for preventing fire risk in PV systems. In: Proceedings of International carnahan conference on security technology (ICCST); 13 Oct 2014. p. 1-5.
[4] EPIA. Connecting the Sun: Solar Photovoltaics on the road to large scale grid integration. [Online], Sept; 2012. Available: ⟨http://www.epia.org/news/publications/⟩.
[5] Masson G, Latour M, Biancardi D. Global market outlook for photovoltaics until 2016. European Photovoltaic Industry Association; 2012.
[6] Zahedi A. Solar photovoltaic (PV) energy; latest developments in the building integrated and hybrid PV systems. Renew Energy 2006;31(5):711–8.
[7] Protection against electric shock—common aspects for installation and equipment, IEC Standard 61140; 2005.
[8] LV Electrical Installations—Part 41: protection for safety—protection against electric shock, IEC Standard 60364-4-41; 2005.

[9] Electrical Installations of Buildings—Part 7: requirements for special installations or locations—section 712: solar PV power supply systems, IEC Standard 60364-7- 712; 2002.
[10] Installation and safety requirements for PV generators, IEC Standard 62548.
[11] Article 690—solar photovoltaic systems of national electrical code, NFPA70; 2011.
[12] Albers MJ, Ball G. Comparative evaluation of DC fault-mitigation techniques in large PV systems. IEEE J Photovolt 2015;5(4):1169–74.
[13] Zhao Y, de Palma JF, Mosesian J, Lyons R, Lehman B. Line–line fault analysis and protection challenges in solar photovoltaic arrays. IEEE Trans Ind Electron 2013;60(9):3784–95.
[14] Alam MK, Khan FH, Johnson J, Flicker J PV faults: Overview, modeling, prevention and detection techniques. In: Proceedings of the 14th workshop on control and modeling for power electronics (COMPEL). IEEE; 23 Jun 2013. p. 1–7.
[15] Capparella S, Falvo MC Secure faults detection for preventing fire risk in PV systems. In: Proceedings of international Carnahan conference on security technology (ICCST). IEEE; 13 Oct 2014. p. 1–5.
[16] Brooks B. The bakersfield fire-A lesson in ground-fault protection. Sol Pro Mag 2011:62–70.
[17] Collier DE, Key TS Electrical fault protection for a large photovoltaic power plant inverter. In: Proceedings of conference record of the twentieth photovoltaic specialists conference. IEEE; 26 Sep 1988. p. 1035–42.
[18] Zhao Y, Lehman B, DePalma JF, Mosesian J, Lyons R Fault evolution in photovoltaic array during night-to-day transition. In: Proceedings of the 12th workshop on control and modeling for power electronics (COMPEL). IEEE; 28 Jun 2010. p. 1–6.
[19] Zhao Y, Lehman B, de Palma JF, Mosesian J, Lyons R Fault analysis in solar PV arrays under: Low irradiance conditions and reverse connections. In: Proceedings of the 37th photovoltaic specialists conference (PVSC). IEEE; 19Jun 2011. p. 002000–5.
[20] Firth SK, Lomas KJ, Rees SJ. A simple model of PV system performance and its use in fault detection. Sol Energy 2010;84(4):624–35.
[21] Colli A. Failure mode and effect analysis for photovoltaic systems. Renew Sustain Energy Rev 2015;50:804–9.
[22] Hernandez JC, Vidal PG. Guidelines for protection against electric shock in PV generators. IEEE Trans Energy Convers 2009;24(1):274–82.
[23] Falvo MC, Capparella S. Safety issues in PV systems: design choices for a secure fault detection and for preventing fire risk. Case Stud Fire Saf 2015;3:1–6.
[24] Zhao Y Fault analysis in solar photovoltaic arrays (Doctoral dissertation, Northeastern University).
[25] Ram JP, Babu TS, Rajasekar N. A comprehensive review on solar PV maximum power point tracking techniques. Renew Sustain Energy Rev 2017;67:826–47.
[26] Forman SE. Performance of experimental terrestrial photovoltaic modules. IEEE Trans Reliab 1982;31(3):235–45.
[27] Bower WI, Wiles JC Analysis of grounded and ungrounded photovoltaic systems. In: Proceedings of the first world conference on photovoltaic energy conversion, conference record of the twenty fourth. IEEE photovoltaic specialists conference. IEEE, Vol. 1; 5 Dec 1994. p. 809–12.
[28] Zhao Y, Lyons Jr R. Ground-fault analysis and protection in PV arrays. Proc Photovolt Prot 2011:1–4.
[29] McEvoy A, Markvart T, Castañer L, Markvart T, Castaner L, editors. Practical handbook of photovoltaics: fundamentals and applications. Elsevier; 2003.
[30] Brooks B. The ground-fault protection blind spot: Safety concern for larger PV systems in the US. Solar American Board for Codes and Standards Jan; 2012.
[31] Kuznetsova VA, Gaston RS, Bury SJ, Strand SR Photovoltaic reliability model development and validation. In: Proceedings of the 34th photovoltaic specialists conference (PVSC). IEEE; 7Jun 2009. p. 000432–6.
[32] Dhople SV, Davoudi A, Chapman PL, Domínguez-García AD Reliability assessment of fault-tolerant Dc-Dc converters for photovoltaic applications. In: Proceedings of energy conversion congress and exposition, ECCE. IEEE; 20 Sep 2009. p. 2271–6.
[33] Bazzi AM, Kim KA, Johnson BB, Krein PT, Dominguez-García A Fault impacts on solar power unit reliability. In: Proceedings of twenty-sixth annual applied power electronics conference and exposition (APEC). IEEE; 6 Mar 2011. p. 1223–31



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