Faults in a Photovoltaic System

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Photovoltaic systems are prone to breaking down due to harsh conditions. In photovoltaic systems, various types of faults can cause power loss in some way. To improve the reliability of these systems, diagnostic methods using Machine Learning (ML) have been developed.

Keywords: diagnosis ; faults ; photovoltaics ; machine learning ; supervised learning

1. Introduction

In recent years, renewable energy sources have gained popularity, with photovoltaic solar energy ranking as the third most developed technology behind hydroelectricity and wind power. According to the “TrendForce Feb2023” report, photovoltaic solar energy is experiencing remarkable growth, with an estimated world installed capacity of 350.6 GW by 2023 [1]. The annual evolution of the global installed capacity of PV systems is shown in **Figure 1**. This growth can be attributed to various factors, including reduced production costs, government support policies, reliability, and the desire for localized energy production. However, despite these benefits, photovoltaic installations may face challenges related to aging and environmental constraints that can impact their efficiency and long-term safety. Exposure to difficult environmental conditions can lead to malfunctions and anomalies that result in power losses or even the risk of fire, depending on the severity of the issue [2]. When the surface of a solar panel system is covered with dust for two months, its performance can be reduced by 8.4% compared to a clean system according to studies [3][4]. Therefore, it is crucial to be aware of any faults, control them to minimize their occurrence, recover the maximum amount of energy produced, and reduce maintenance costs for the PV system.

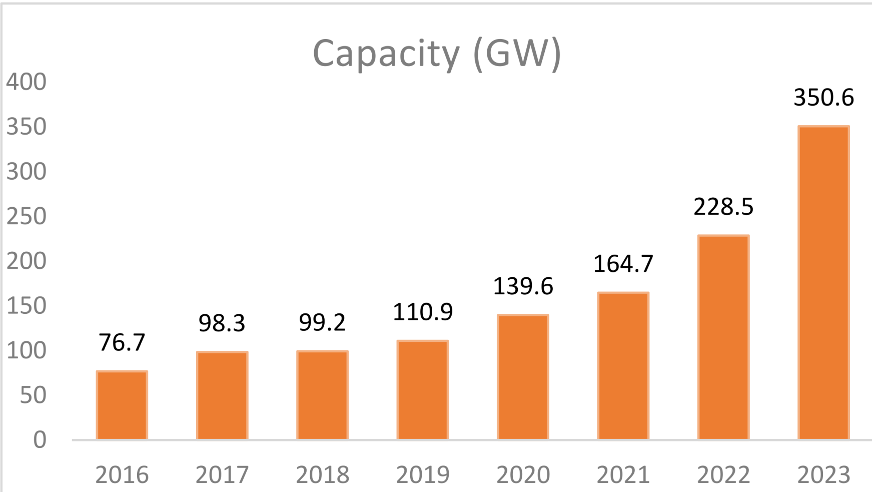

Figure 1. Annual evolution of the global world capacity of PV installations (TrendForce, 2023).

Several research studies have been conducted to identify the categories of faults and diagnostic techniques for detecting various faults in photovoltaic (PV) systems. Some of these techniques use climate data-independent methods based on the circuit resistance, inductance, capacitance (RLC) and a signal generator to predict faults in PV systems, while others rely on electrical parameters based on current and voltage indicators [3][5][6]. It is noteworthy that these methods are not affected by climate data. In recent years, there has been a renewed interest in the industrial applications of digital methods, such as the use of machine learning for vehicle autonomy on public roads and fault diagnosis using data [7]. In the field of photovoltaics, various machine learning models, such as artificial neural networks (ANN), k nearest neighbors (kNN), the Adaptive Neuro-Fuzzy Inference System (ANFIS), Naïve Bayes (NB), decision trees (RF), and fuzzy logic, have been successfully employed for fault diagnosis [3][8][9][10][11][12][13]. Several articles have demonstrated the effectiveness of supervised learning algorithms in improving the diagnosis of PV systems with the application of artificial intelligence [14][15]. Compared to traditional techniques that require more computing time and human expertise, Machine Learning (ML) and Deep Learning (DL) supervised learning algorithms are faster and more efficient in providing diagnostic solutions [14][16][17][18]. For example, Amiri et al. proposed a Deep Learning algorithm that combines convolutional and bidirectional recurrent neural networks to detect faults in a PV system [19]. Additionally, several authors have conducted reviews to highlight the effectiveness of Machine Learning and Deep Learning algorithms in diagnosing PV systems, as they accelerate and improve diagnostic solutions for PV systems [20][21][22][23][24][25][26][27].

In photovoltaic systems, various types of faults can cause power loss in some way. To classify the faults in PV systems, some authors have categorized them according to the components involved [5]. **Figure 2** represents the description of faults likely to occur in a photovoltaic system.

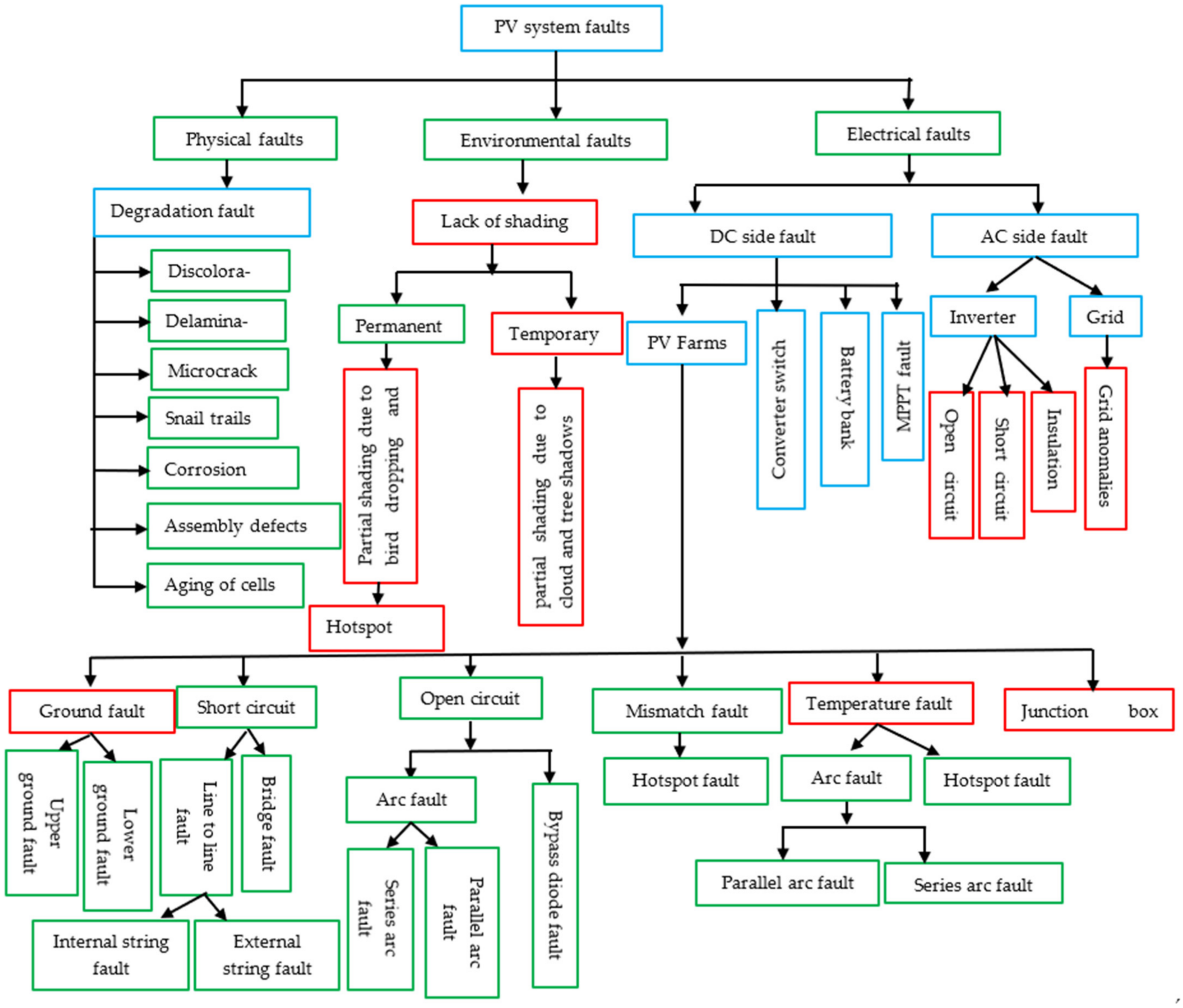

Figure 2. Classification of fault types in a PV system.

2. Photovoltaic Generator Faults

In a photovoltaic system, a fault refers to an atypical behavior that signals a potential loss of power or complete system unavailability. Given the challenging environmental conditions that photovoltaic systems operate in, defects can arise across various components, each with a unique set of issues. These faults may manifest themselves in the photovoltaic array and/or in the inverter, which can partially identify them [28]. PV generators can experience different types of faults, which are classified based on the area they affect. These categories comprise electrical, physical, and environmental faults [29]. However, faults can occur in photovoltaic systems, with the most common being on the solar panel side. These include shading, mismatch, potential-induced degradation, hotspot, open circuit, short circuit, line-to-line, line-to-ground, arc, bypass, and anti-reverse diode faults. Also, there are different types of faults that can occur in an inverter, which include open-circuit faults, short-circuit faults, insulation faults and so on [30][31]. The following section provides a detailed explanation of the most common faults provides a detailed explanation of the most common faults found in a photovoltaic installation. This information will help in the diagnostic process.

Based on the analysis of **Figure 2**, the following subsections describe some of the most common faults that can affect a PV installation.

2.1. Ground Fault

Ground fault (F_1) is an accidental short circuit between one or more current conductors and the earth. It is the most common type of fault that occurs due to cable insulation failure. This fault poses a serious risk as it can produce current arcs at the points of failure, leading to electric shocks. Furthermore, it causes an increase in current in the affected conductors, resulting in imbalances and changes in the architecture of the PV array [32].

2.2. Short-Circuit Fault (SCF)

A short-circuit fault occurs when two points in a circuit of different potentials accidentally connect [33]. This fault can happen within the same module string (intra-string fault F_2) or between two modules of different strings (inter-string fault F_3). Poor wiring between the generator PV and the inverter, animal damage to cables, and water infiltration into the PV modules are the causes of this fault [34]. Short-circuited modules result in a drop in network voltage while the current significantly increases. Generally, a short-circuit fault circuit causes a line-to-line fault [35].

2.3. Line to Line Fault

According to Pillai et al. [30], a line-to-line fault happens when there is an unintended short circuit between two points of a PV array with different potentials. This type of fault can occur between modules of the same string or between modules of adjacent strings. It can also occur between conductors of the same circuit with different potentials, without involving any earthing point. Furthermore, when this fault occurs between two modules of the same order from different strings, it is sometimes referred to as a bridging fault [36]. The outcome of this fault is a decrease in the open circuit voltage, while the short circuit current may remain unchanged. This voltage reduction results in a modification of the current-voltage characteristics of the photovoltaic field. Please see **Figure 3** for a summary of the most common faults in a PV system.

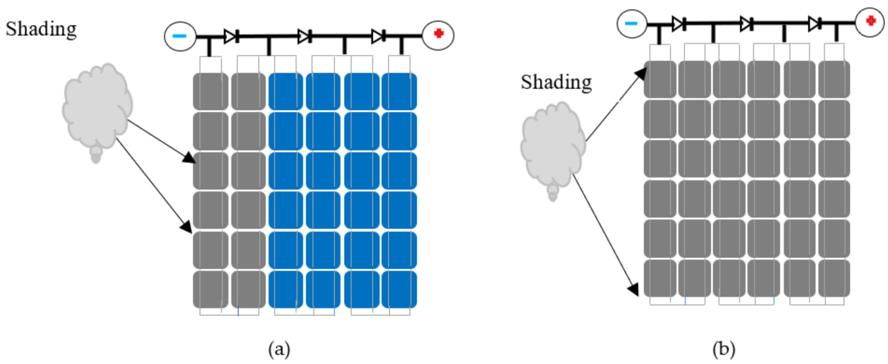

Figure 3. (**a**) Partial shading of a PV module (**b**) Total shading of a PV module.

2.4. Open-Circuit Fault (OCF)

An open-circuit fault (F_4) occurs when a cable inside a module or a PV module string accidentally disconnects. This fault affects the total resistance of the PV generator and causes a significant increase in the short circuit current [37]. However, an open-circuit fault is more damaging than a short-circuit fault due to the increased current flow. The breakage of connection wires between cells or PV modules, faulty diodes, and the deterioration of connection cables usually cause this fault [35]. An open-circuit fault is a result of the line-to-line fault, which itself is caused by the short-circuit fault [22].

2.5. Arc Fault

An arc fault is a type of fault that occurs when an electrical current passes accidentally through air or another dielectric material [31]. Detecting arc faults is a complex process because they occur intermittently. Arc faults can happen within a single conductor (series arc fault F_5) or between two parallel conductors (parallel arc fault F_6). Additionally, faults can occur due to the breakage of insulation cables, which can cause significant noise in the output voltage and current of the PV network [32].

2.6. Mismatch/Shading Defects

A mismatch fault occurs when a group of photovoltaic cells has different electrical characteristics [38]. This type of fault can be permanent, like an open-circuit fault, or temporary, like partial shading. Partial shading is a specific type of mismatch fault and is one of the main causes of failures in a PV system. The shading phenomenon can be classified as uniform or non-uniform [38]. The source of uniform shading can be adjacent buildings, passing clouds, trees, other signs, bird droppings, dirt and so on. Non-uniform or partial shading defects occur when some cells or modules receive direct irradiation and temperature in a non-uniform manner. On the other hand, uniform or total shading occurs when all cells or modules receive uniform but reduced exposure, resulting in a constant reduction in the output current and voltage of individual cells in a string. It is important to note that technical abbreviations should be explained the first time they appear [39]. **Figure 3** shows a partially shaded and fully shaded module.

The setting of the sun causes shading of the photovoltaic (PV) module, which reduces its power output. It is important to note that although shading has a negligible impact on the PV module's overall performance, it should still be avoided. Shaded cells can become reverse polarized, consuming energy instead of producing it, leading to a drop in power and the hotspot phenomenon [40]. The hotspot phenomenon can accelerate the aging process of the PV system and may even lead to an open-circuit fault or fire risks [41]. **Figure 4** provides an illustration of the various faults described above.

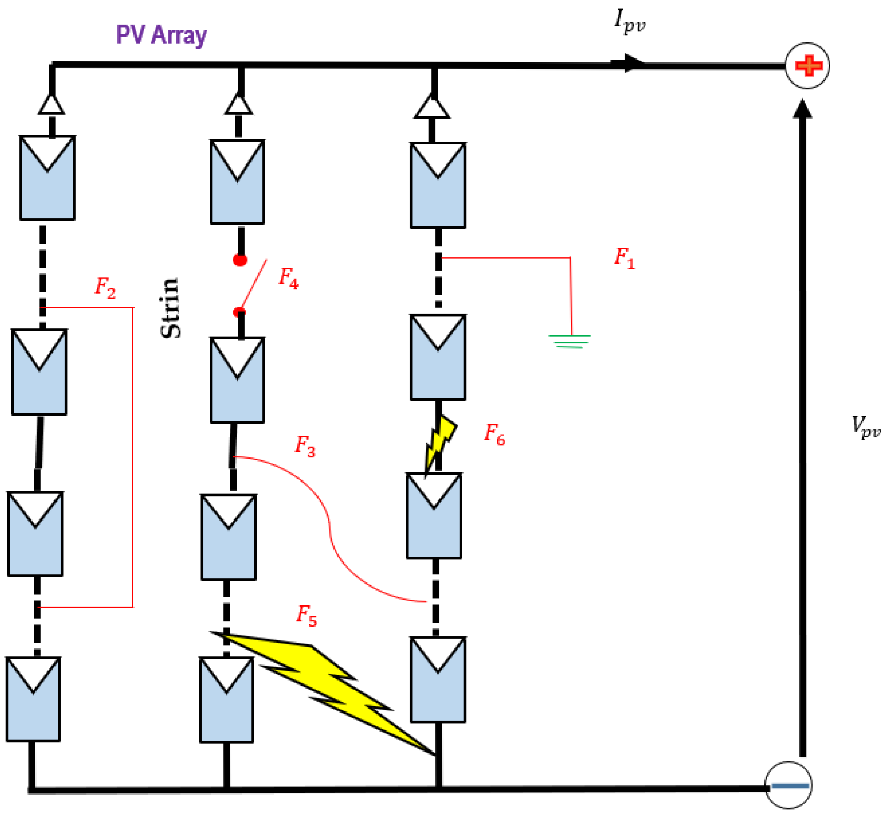

Figure 4. Illustration of ground faults F_1, short-circuit faults F_2, F_3, open-circuit faults F_4 and arcing faults (F_5, F_6in a PV array).

In the case of a short circuit, the output voltage drops significantly while the output current slightly increases. Short-circuit faults can affect cells, modules, and bypass diodes [42]. Bypass diodes are protection devices against shading and are connected in parallel to each group of cells as show in **Figure 5**. However, these diodes can be damaged during factory electrical discharge and high reverse voltage due to any fault [43]. If the bypass diode is faulty, there will be a sudden drop in power due to the absence of the voltage chain. The fault may be caused by non-functioning diodes, diodes reversed during assembly, poor diode connection, disconnection, or corrosion of the junction boxes. A bypass diode fault can cause damage such as hot spots, electric arcing, and the risk of fire if the diode is in an open circuit [44].

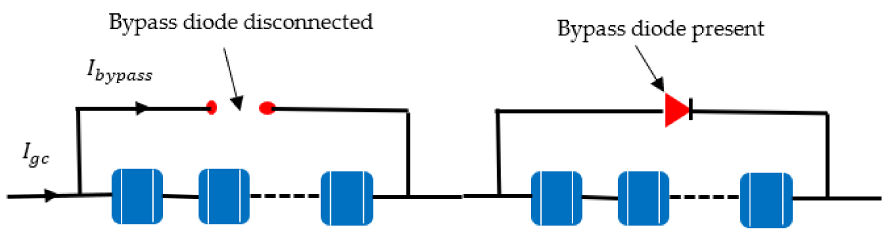

Figure 5. Illustration of a group of cells with bypass diode disconnected.

PV modules can degrade in several ways, including discoloration of the encapsulant due to exposure to UV rays, which causes the PV cells to turn brown or yellow. Another form of degradation is delamination or the separation of different layers of the PV module. There are also two specific types of degradation to be aware of. Potential Induced Degradation (PID) occurs when there is a potential difference between the metal frame of the PV module and the solar cell, which can significantly degrade the electrical characteristics of the PV cell. Light-induced degradation (LID) is a loss of performance that occurs when the boron–oxygen effect and the boron–iron effect are activated after the PV modules have been exposed to sunlight [5]. In addition to the breakdowns observed at the PV generator level, the photovoltaic inverter is also a vulnerable component with unreliable performance [44]. Therefore, it is necessary to have knowledge of the common faults associated with this component.

3. PV Inverter Faults (PVI)

In photovoltaic applications, one of the biggest challenges is ensuring that power electronics are reliable in order to optimize energy production. The inverter serves as the interface between the photovoltaic generator and the network and/or load. Its main function is to convert the continuous energy produced by the photovoltaic modules into alternating energy that is identical to the network. This allows the inverter to access electrical information from the generator and the electrical network, making it an intermediary between the two. Additionally, the inverter is equipped with a high level of data granularity, which enables it to detect electrical anomalies in real-time and alert the user through an audible signal or a message. However, despite its advantages, the inverter is vulnerable and subject to faults. During its operation, it is exposed to overvoltage and overcurrent constraints due to transient operating conditions, mechanical turbulence, temperatures, and humidity [44]. The IGBT (insulated gate bipolar transistor) power switch, being the main energy transfer component, is the most likely source of failure in the photovoltaic inverter [45]. The most common faults that can occur during the inverter's operation are open-circuit, insulation faults and short-circuit faults [46].

3.1. Short-Circuit Fault

A fault can occur due to breakage of the connection wire, deterioration of the gate circuit, or overcurrent. However, a short circuit happens very quickly, making it difficult to detect. Shortly after appearing, it transforms into an immediate open-circuit fault [47]. Short-circuit faults automatically shut down the system, making them more dangerous than open-circuit faults.

3.2. Open-Circuit Fault

An open-circuit fault can occur in a photovoltaic system due to a disconnection of the jumper wire, overheating, or a device driver fault, resulting in a broken connection. Unlike a short-circuit fault, an open-circuit fault may not immediately affect the inverter, but if left unaddressed, it can lead to serious accidents with other components [47]. This is because an open-circuit fault distorts the output current of the inverter, causing an increase in the total harmonic ratio, which does not meet the grid connection requirements. **Table 1** provides a list of main faults that can occur in a photovoltaic system, and **Figure 6** illustrates an overview of the open-circuit fault that can occur in the IGBT transistor of a PV inverter.

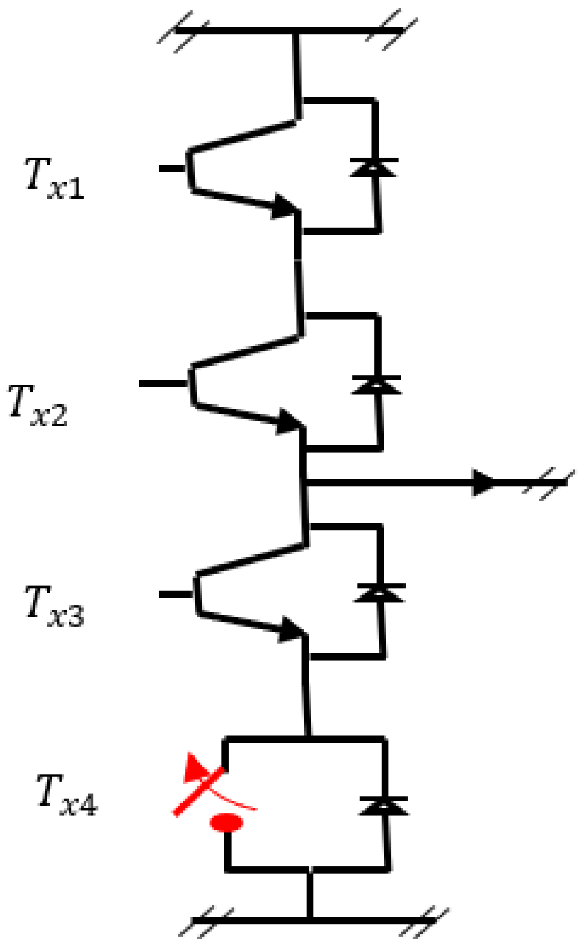

Figure 6. Representation of an open-circuit fault on an inverter arm.

Table 1. Summarizes the various faults, their causes, and the resulting consequences.

Type of Defects		Causes	Effects	Consequences
Internal	Short circuit	Manufacturing defect	Low impedance, blocked path between internal power rails	Reduction of power produced
	Cell microcracks	Manufacturing defect	Difference in module characteristics	Unable to deliver power to the load
	Broken modules	Shock during transport		
	Degraded modules	Aging	Drop in power delivered	Low production
	Bypass diode	Manufacturing defect, wiring defect	Can't drive	Unable to prevent the appearance of hot spots, electric arc, fire risk
	Open circuit	Manufacturing defect, wiring defect	Lack of access path for the power produced	No power produced

Type of Defects			Causes	Effects	Consequences
External	Mismatch fault	Temporary	Temporary shading	Cloud	Drop in production, risk of fires
		Permanent	Equipment damage	Blackout	No production
	Shading	Temporary	Passage of clouds, weather conditions	Uneven distribution of irradiation on the surface of the modules	Drop in power produced
		Permanent	Natural disaster Partial shading	Module reverse bias	Hot spot/fire hazard
PV field	Short circuit		Bad wiring between inverter and PV field, chewing of cables by animals, water infiltration into modules	Drop in network voltage and increase in current	Drop in production
	Open circuit		Accidental breakage of connecting cables	Drastic drop in short-circuit current	Drop in production
	Line to line		Faulty connection link between the different rail circuits	Power loss	Reduction of open circuit voltage, modification of characteristic IV of the PV field
	Arc fault		Accidental passage of current in a dielectric	Strong noise in currents and voltages	Fire hazard
	Line to ground		Ground wiring fault, corrosion	Drop in network voltage and increase in current	Risk of electrocution, variable voltage

Type of Defects		Causes	Effects	Consequences
PV inverter	Inverter open circuit	Absence of gate control, connection wire breakage due to high short-circuit current, external disconnection due to vibrations	Deterioration of phase current and torque	External radiation
	Inverter short circuit	High gate voltage, delamination and cracking in the solder layer, static locking and high temperature	Excessive leakage current, affected phase current close to zero	Temperature variation
	Insulation fault	Humidity, high heat, poor connection in the solar panel junction box, aging of solar panels		No power
Grid	Grid anomalies	Electrical overload, deterioration of conductive insulators	Network disruption, voltage dips and peaks, harmonics	Interruption of current flow, short circuit

References

1. TrendForce. Global Solar Installation May Hit 350.6 GW. Available online: https://www.pv-magazine.com/2023/03/09/pv-product-prices-resume-downward-trend-says-trendforce/ (accessed on 25 April 2023).
2. Livera, A.; Theristis, M.; Makrides, G.; Georghiou, G.E. Recent advances in failure diagnosis techniques based on performance data analysis for grid-connected photovoltaic systems. Renew. Energy 2019, 133, 126–143.
3. Madeti, S.R.; Singh, S.N. Modeling of PV system based on experimental data for fault detection using kNN method. Sol. Energy 2018, 173, 139–151.
4. Oh, W.-G. A Fault Detection Scheme in Acoustic Sensor Systems Using Multiple Acoustic Sensors. J. Korea Inst. Electron. Commun. Sci. 2016, 11, 203–208.
5. Abubakar, A.; Almeida, C.F.M.; Gemignani, M. Review of artificial intelligence-based failure detection and diagnosis methods for solar photovoltaic systems. Machines 2021, 9, 328.
6. Jiang, Y.; Yin, S.; Kaynak, O. Optimized design of parity relation-based residual generator for fault detection: Data-driven approaches. IEEE Trans. Industr. Inform. 2021, 17, 1449–1458.
7. Mohammad, S.; Sudhakar, K. Machine Learning-Autonomous Vehicles. Int. J. Manag. 2018, 8. Available online: http://www.ijmra.us (accessed on 29 December 2023).
8. Livera, A.; Theristis, M.; Makrides, G.; Georghiou, G.E.; Sutterlueti, J.; Georghiou, G.E. Advanced Diagnostic Approach of Failures for Grid-Connected Photovoltaic (PV) Systems PV-Estia-Enhancing Storage Integration in Buildings with Photovoltaics View Project Modeling and Optimization of Advanced Energy Systems View Project Advanced Diagnostic Approach of Failures for Grid-Connected Photovoltaic (PV) Systems. 2018. Available online: https://userarea.eupvsec.org/proceedings/35th-EU-PVSEC-2018/6BO.6.5/ (accessed on 8 May 2023).
9. Karatepe, E.; Syafaruddin; Hiyama, T. Controlling of artificial neural network for fault diagnosis of photovoltaic array. In Proceedings of the 16th International Conference on Intelligent System Applications to Power Systems, Hersonissos, Greece, 25–28 September 2011; pp. 1–6.
10. Bendary, A.F.; Abdelaziz, A.Y.; Ismail, M.M.; Mahmoud, K.; Lehtonen, M.; Darwish, M.M.F. Proposed anfis based approach for fault tracking, detection, clearing and rearrangement for photovoltaic system. Sensors 2021, 21, 2269.
11. Soffiah, K.; Manoharan, P.S.; Deepamangai, P. Fault detection in grid connected pv system using artificial neural network. In Proceedings of the 7th International Conference on Electrical Energy Systems, ICEES, Chennai, India, 11–

13 February 2021; pp. 420–424.

12. Gong, S.; Wu, X.; Zhang, Z. Fault diagnosis method of photovoltaic array based on random forest algorithm. In Proceedings of the 2020 39th Chinese Control Conference (CCC), Shenyang, China, 27–29 July 2020; pp. 4249–4425.
13. Hussain, M.; Dhimish, M.; Titarenko, S.; Mather, P. Artificial neural network based photovoltaic fault detection algorithm integrating two bi-directional input parameters. Renew. Energy 2020, 155, 1272–1292.
14. Alimi, O.A.; Meyer, E.L.; Olayiwola, O.I. Solar photovoltaic modules' performance reliability and degradation analysis: A review. Energies 2022, 15, 5964.
15. Romero, H.F.M.; Rebollo, M.G.; Cardeñoso-Payo, V.; Gómez, V.A.; Plaza, A.R.; Moyo, R.T.; Hernández-Callejo, L. Applications of artificial intelligence to photovoltaic systems: A review. Appl. Sci. 2022, 12, 56.
16. Xie, C.; Chen, S.; Guo, F.; Liu, X. A deep residual recurrent neural network model-augmented attention with physical characteristics: Application to turntable servo system. IEEE Trans. Ind. Electron. 2022, 69, 489.
17. Yau, H.T.; Prior, S.D.; Wang, Y.; Li, Y. IEEE Access Special Section Editorial: Advanced artificial intelligence technologies for smart manufacturing. IEEE Access 2021, 9, 119232–119234.
18. Fei, Z.; Zhang, Z.; Tsui, K.L. Deep learning powered online battery health estimation considering multi-timescale ageing dynamics and partial charging information. IEEE Trans. Transp. Electrif. 2023.
19. Amiri, A.F.; Kichou, S.; Oudira, H.; Chouder, A.; Silvestre, S. Fault detection and diagnosis of a photovoltaic system based on deep learning using the combination of a convolutional neural network (cnn) and bidirectional gated recurrent unit (Bi-GRU). Sustainability 2024, 16, 1012.
20. Rocha, H.R.O.; Fiorotti, R.; Fardin, J.F.; Garcia-Pereira, H.; Bouvier, Y.E.; Rodríguez-Lorente, A.; Yahyaoui, I. Application of AI for short-term pv generation forecast. Sensors 2023, 24, 85.
21. Li, B.; Delpha, C.; Diallo, D.; Migan-Dubois, A. Application of artificial neural networks to photovoltaic fault detection and diagnosis: A review. Renew. Sustain. Energy Rev. 2021, 138, 110512.
22. Berghout, T.; Benbouzid, M.; Bentrcia, T.; Ma, X.; Djurović, S.; Mouss, L.H. Machine learning-based condition monitoring for pv systems: State of the art and future prospects. Energies 2021, 14, 6316.
23. Al Smadi, T.; Handam, A.; Gaeid, K.S.; Al-Smadi, A.; Al-Husban, Y.; Khalid, A.S. Artificial intelligent control of energy management PV system. Results Control. Optim. 2024, 14, 100343.
24. Boubaker, S.; Kamel, S.; Ghazouani, N.; Mellit, A. Assessment of Machine and Deep Learning Approaches for Fault Diagnosis in Photovoltaic Systems Using Infrared Thermography. Remote Sens. 2023, 15, 1686.
25. Mansouri, M.; Trabelsi, M.; Nounou, H.; Nounou, M. Deep learning-based fault diagnosis of photovoltaic systems: A comprehensive review and enhancement prospects. IEEE Access 2021, 9, 126286–126306.
26. Kuo, W.C.; Chen, C.H.; Hua, S.H.; Wang, C.C. Assessment of different deep learning methods of power generation forecasting for solar pv system. Appl. Sci. 2022, 12, 7529.
27. Hichri, A.; Hajji, M.; Mansouri, M.; Nounou, H.; Bouzrara, K. Supervised machine learning-based salp swarm algorithm for fault diagnosis of photovoltaic systems. J. Eng. Appl. Sci. 2024, 71, 12.
28. Vai, V.; Chhorn, S.; Chhim, R.; Tep, S.; Bun, L. Modeling and Simulation of PV Module for Estimating Energy Production under Uncertainties. In Proceedings of the 2020 8th International Electrical Engineering Congress, IEECON 2020, Chiang Mai, Thailand, 4–6 March 2020.
29. Arani, M.S.; Hejazi, M.A. The comprehensive study of electrical faults in PV arrays. J. Electr. Comput. Eng. 2016, 2016, 8712960.
30. Pillai, D.S.; Rajasekar, N. A comprehensive review on protection challenges and fault diagnosis in PV systems. Renew. Sustain. Energy Rev. 2018, 91, 18–40.
31. Aouchiche, N. Défauts Liés Aux Systèmes Photovoltaïques Autonomes et Techniques de Diagnostic-Etat de l'art. 2018. Available online: https://www.researchgate.net/publication/328577571 (accessed on 14 June 2023).
32. Garoudja, E.; Chouder, A.; Kara, K.; Silvestre, S. An enhanced machine learning based approach for failures detection and diagnosis of PV systems. Energy Convers. Manag. 2017, 151, 496–513.
33. Madeti, S.R.; Singh, S.N. A comprehensive study on different types of faults and detection techniques for solar photovoltaic system. Sol. Energy 2017, 158, 161–185.
34. Trejo, D.R.E.; Bárcenas, E.; Díez, J.E.H.; Bossio, G.; Pérez, G.E. Open- and short-circuit fault identification for a boost DC/DC converter in PV MPPT systems. Energies 2018, 11, 616.
35. Guerriero, P.; Piegari, L.; Rizzo, R.; Daliento, S. Mismatch based diagnosis of pv fields relying on monitored string currents. Int. J. Photoenergy 2017, 2017, 2834685.

36. Abdulmawjood, K.; Refaat, S.S.; Morsi, W.G. Detection and prediction of faults in photovoltaic arrays: A review. In Proceedings of the 2018 IEEE 12th International Conference on Compatibility, Power Electronics and Power Engineering, CPE-POWERENG 2018, Doha, Qatar, 10–12 April 2018; pp. 1–8.
37. Roger, P.Y.; Emilio, C.C.J.; Rubén, R.H. Fault diagnostic methodology for grid-connected photovoltaic systems. J. Multiapp. 2021, 2, 10–30.
38. Maghami, M.R.; Mutambara, A.G.O. Challenges associated with hybrid energy systems: An artificial intelligence solution. Energy Rep. 2023, 9, 924–940.
39. Khalil, I.U.; Ul-Haq, A.; Mahmoud, Y.; Jalal, M.; Aamir, M.; Ahsan, M.U.; Mehmood, K. Comparative analysis of photovoltaic faults and performance evaluation of its detection techniques. IEEE Access 2020, 8, 26676–26700.
40. Bhimrao, B.; Vishwakarma, S. Study of partial shading effect on solar module using MATLAB development of a MATLAB. Int. J. Adv. Res. Electr. Electron. Instrum. Eng. 2017, 6, 5303–5308.
41. Malvoni, M.; Chaibi, Y. Machine learning based approaches for modeling the output power of photovoltaic array in real outdoor conditions. Electronics 2020, 9, 315.
42. Dhakshinamoorthy, M.; Sundaram, K.; Murugesan, P.; David, P.W. Bypass diode and photovoltaic module failure analysis of 1.5kW solar PV array. Energy Sources Part A Recovery Util. Environ. Eff. 2022, 44, 4000–4015.
43. Platon, R.; Martel, J.; Woodruff, N.; Chau, T.Y. Online fault detection in pv systems. IEEE Trans. Sustain. Energy 2015, 6, 1200–1207.
44. Kim, S.; Kim, S. Performance estimation modeling via machine learning of an agrophotovoltaic system in South Korea. Energies 2021, 14, 6724.
45. Im, W.S.; Kim, J.S.; Kim, J.M.; Lee, D.C.; Lee, K.B. Diagnosis methods for IGBT open switch fault applied to 3-phase AC/DC PWM converter. J. Power Electron. 2012, 12, 120–127.
46. Puthiyapurayil, M.R.M.K.; Nasirudeen, M.N.; Saywan, Y.A.; Ahmad, M.W.; Malik, H. A Review of Open-Circuit Switch Fault Diagnostic Methods for Neutral Point Clamped Inverter. Electronics 2022, 11, 3169.
47. Gunda, T.; Hacket, S.; Kraus, L.; Downs, C.; Jones, R.; Mcnalley, C.; Bolen, M.; Walker, A. A Machine learning evaluation of maintenance records for common failure modes in PV inverters. IEEE Access 2020, 8, 211610.