HOTSPOT PATTERNS IN PHOTOVOLTAIC MODULES: CLASSIFICATION, IMPACTS AND MONITORING STRATEGIES

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Summary

This study evaluates hot spots in photovoltaic (PV) modules ground-mounted in PV power plants in Minas Gerais, Brazil. The paper emphasis is on fault characteristics identification and preventive detection. The visual inspection, infrared thermographic imaging, I-V curve measurements and electroluminescence analysis were employed as diagnostic methods. The results revealed that the hot spots were caused by polarization potential-induced degradation (PID), microcracks, and shading effects. These findings highlight the importance of early detection to extend module lifespan and enhance the operational reliability of photovoltaic systems.

Keywords: Photovoltaic Modules, Hot Spots, Preventive Maintenance, Thermal Imaging, Reliability

1. Introduction

Photovoltaic (PV) technology plays a central role in the global transition toward cleaner and more sustainable energy sources. Driven by the urgency of climate change, its adoption has expanded rapidly across a variety of configurations—from ground-mounted systems to innovative solutions such as floating photovoltaic (FPV) power plants. However, as these installations grow in scale and complexity, ensuring the long-term performance and reliability of PV modules becomes increasingly critical (Wohlgemuth & Herrmann, 2005). Among the most pressing operational challenges are hot spots, typically caused by partial shading, manufacturing defects, or electrical installation faults. The occurrence of hot spots compromises not only system efficiency but also operational safety and longevity (Moretón et al., 2014; Dhimish et al., 2023).

In Brazil, the expansion of PV systems has been accelerated by public policies and regulatory incentives, such as the ANEEL Strategic R&D Program (Call 13/2011) and the Distributed Generation Framework. According to the Agência Nacional de Energia Elétrica – ANEEL (2025), there are currently 18,594 centralized PV systems totaling 17.95 GW, and approximately 3.725 million distributed generation systems reaching 41.43 GW. This results in a total installed PV capacity of about 60 GW, positioning Brazil among the world's leading nations in solar power deployment.

Traditional monitoring approaches at the string or inverter level are insufficient to detect localized hot spots in operating PV modules. Therefore, module-level inspection and diagnostic tools are required to identify incipient faults before they propagate. Techniques such as infrared thermography (IR), electroluminescence (EL), and I–V curve tracing have proven to be effective non-destructive methods for this purpose. Nevertheless, most of these procedures are performed offline, providing only periodic assessments rather than continuous monitoring (Tsanakas, Ha & Buerhop, 2016).

Several studies have reported that hot spots may cause power losses of up to 30–50% in affected modules, in addition to potential fire and safety risks (Moretón et al., 2014; Bouraiou, 2018; Li et al., 2022). Factors such as potential-induced degradation (PID), bypass diode malfunction, and partial shading are among the main contributors to these phenomena. Recent analyses using thermography and electroluminescence imaging confirm that hot-spot formation is not limited to aged systems; it is also observed in newly deployed high-efficiency PERC and bifacial modules (Tsanakas et al., 2016; Mellit et al., 2018; Oliveira et al., 2023).

Advanced diagnostic techniques are now being developed to detect and classify thermal anomalies in real time. IR thermography, I–V curve tracing, and EL imaging are increasingly being combined with data-driven methods to improve early fault identification (Kalogirou, 2020; Deng et al., 2017). Artificial intelligence (AI) and machine learning (ML) models have demonstrated high accuracy in automatic fault classification from IR images (Tang et al., 2024; Zhao et al., 2022). In parallel, the implementation of module-level monitoring

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architectures enables predictive maintenance and enhances operational safety (Olalla et al., 2018; Campos et al., 2024).

Within this context, this research presents an in-depth technical analysis of the mechanisms behind hot-spot formation, along with detection methods and performance impact assessment associated with preventive maintenance strategies. Based on experimental field data, the study aims to identify recurring patterns of thermal failure and propose proactive mitigation guidelines, thereby contributing to the reliability and efficiency of photovoltaic systems. The integration of advanced diagnostics and continuous monitoring seeks to support predictive maintenance strategies, improving system reliability, performance, and lifespan.

2. Materials and Methods

Data were collected from more than one hundred photovoltaic (PV) modules installed in PV power plants located in Minas Gerais, Brazil, Thea region has tropical climate with high solar irradiation (annual average of 5.5–6.0 kWh/m² day) and average ambient temperatures between 20 °C and 32 °C. PV modules with different technologies, monocrystalline PERC, polycrystalline Al-BSF, and bifacial PERC were selected for the research. The installed PV generators were mounted in fixed and floating configurations.

Each inspected site was equipped with a lufft WS600-UMB and SRA30-M2-D1 albedometer, recording global irradiance (W/m²), ambient temperature (°C), relative humidity (%), and wind speed (m/s), ensuring traceable environmental conditions during field testing. Measurements were carried out during clear-sky conditions between 10:00 and 14:00 h, irradiance > 700W/m² and wind speed was below 10 km/h, to minimize convective cooling effects.

Initially a visual inspection was conducted following IEC 61215-2 and IEC 61730 guidelines to identify physical damage such as cracked glass, delamination, corrosion, or junction box defects. Surface issues such as soiling, bird droppings, and discoloration were also documented photographically. These visual indicators provided initial evidence of mechanical or environmental stress.

Following the visual inspection, the Infrared thermography (IR), I-V curve measurement, Electroluminescence imaging on the PV modules to detect temperature anomalies. The infrared thermography was the primary non-invasive diagnostic technique. Two imaging systems were employed:

Fluke Ti-450 handheld camera (resolution ≥ 320 × 240 px) for close-range inspections and DJI Matrice 200 drone equipped with a FLIR Zenmuse XT-2 (640 × 512 px) for large-scale aerial mapping were used for inspections. Images were captured perpendicular to the module plane with emissivity set to 0.90 (for tempered glass) and background.

Thermal images were processed using FLIR Tools+ including noise filtering, and histogram equalization to improve contrast between defective and healthy cells. Following IEC TS 62446-3, the temperature gradient ΔT was given by:

$$\Delta T = T_{max} - T_{avg} \quad \text{eq.(1)}$$

Where Tmax - maximum temperature measured by the camera and Tavg - average of operational PV module temperature to classify fault severity The following criteria were used:

- *Normal: $\Delta T < 10$ °C*
- *Moderate: 10 °C $\leq \Delta T \leq$ 20 °C*
- *Severe/Critical: $\Delta T > 20$ °C*

Modules exhibiting elevated temperature gradients were selected for electrical characterization by I-V curve measurement, using the Daystar DS-1000 I-V tracer. The device measures open-circuit voltage (Voc), short-circuit current (Isc), maximum-power voltage and current (Vmp, Imp), and power (Pmax) under standardized test conditions (STC). The data were corrected to STC values using reference irradiance and temperature recorded simultaneously by a pyranometer SR30-M2-D1 and a Pt100 sensor mounted on the module rear surface. Electroluminescence imaging was performed on modules identified as defective through IR or I–V testing. The setup used a Sony Alpha 7 II camera with the infrared filter removed, capturing emissions in the 900-1100 nm wavelength range under forward bias (0.7–0.8 × Voc). EL imaging provided insight into micro-cracks, shunted cells, and interconnection failures not visible in thermal maps.

2.1 Operational Monitoring Module (MMO)

To extend diagnostics beyond periodic inspections, an embedded monitoring system, the Operational Monitoring Module (MMO), was developed. The MMO comprises three subsystems:

- *PVMed – local sensor node measuring voltage, current, and surface temperature of each PV module.*
- *PVRtr – wireless router that aggregates data from several PVMed nodes.*
- *PVGtw – central gateway responsible for data storage, synchronization, and SCADA integration.*

The MMO enables real-time acquisition of thermal and electrical data with ±1.0 % measurement accuracy. It supports early fault detection and facilitates predictive maintenance strategies for utility-scale PV installations.

3. Results and Discussion

3.1 Hot Spot Study

The visual inspection identified PV modules mainly with shading, microcracks, soiling, and bypass diode failure. Table 1 shows hotspot pattern found on PV modules analyzed consistent with literature trends (Tsanakas et al., 2016; Mellit et al., 2018).

Table 1- Hot-Spot Patterns

Pattern	Description	Main Cause	Typical ΔT (°C)
Singular	One isolated cell overheated	Microcracks, local soiling	10–20
Linear	Heating along interconnect/busbar	Soldering or interconnect failure	15–25
Patchwork	Scattered cells with high temperature	PID, partial shading	20–30
String-End Heating	Cells near string ends hotter	PID-polarization or mismatch	15–30

Figure 1 shows the severity of gradient temperature (ΔT range). Fig. 1(a) <10°C (normal temperature), Fig. 1(b) 10-20°C (moderate) and Fig. 1(c) >20°C (critical/fire risk). A direct correlation was found between hotspot ΔT and power loss (up to 30–40%).

(a) Normal temperature **(b) Moderate/mild** **(c) Critical/fire risk**

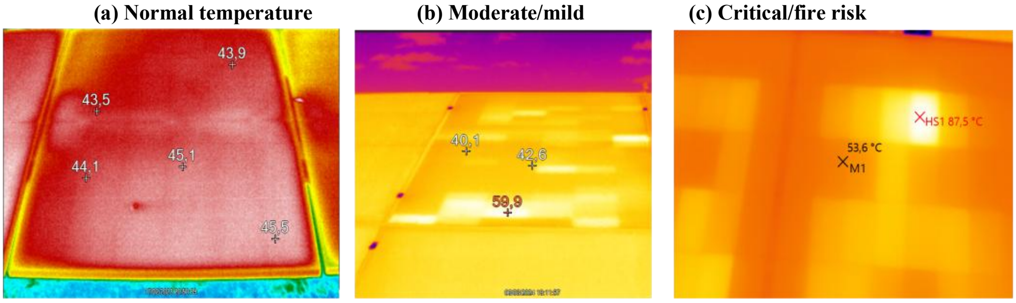

Figure 1- ΔT range severity at bypassed substring

The thermographic imaging survey revealed multiple fault mechanisms across the inspected PV plants. Four predominant thermal signatures were identified and are shown in Figure 2. These patterns were used as the basis for fault classification and for correlating temperature gradients with electrical performance degradation.

Figure 2 illustrates representative thermal images of the main fault categories identified in this study. One can possibly identify Potential Induced Degradation-polarization (PID) (Figure 2a)exhibited the highest severity, with ΔT exceeding 30 °C and characteristic thermal patchwork patterns across multiple cells. Figure 2b shows Bypass diode failure produced linear heating. As a consequence, there was reduced open-circuit voltage.

Design-related issues (Figure 2c) caused uniform heating at the bottom rows due to inadequate spacing and reflected irradiance. Finally, partial shading (Figure 2d) generated asymmetric temperature gradients with ΔT ≈ 15 °C, often related with shading caused by vegetation and tracker alignment.

(a) PID **(b) Bypass diode failure** **(c) Design/installation fault** **(d) *Shading effect***

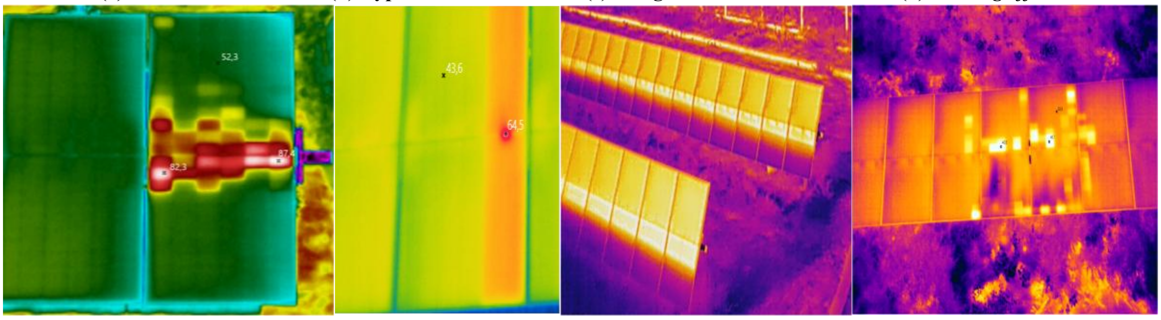

Figure 2 - Thermographic examples of typical hot-spot patterns observed in field inspections: (a) PID-shunt degradation in floating PV module (ΔT ≈ 35 °C); (b) bypass diode failure causing localized overheating (ΔT ≈ 21 °C); (c) design and layout fault leading to systematic heating along lower module rows; and (d) partial shading by vegetation resulting in non-uniform temperature distribution.

Table 2 summarizes the effects on the electrical parameters as a function of ΔT range and summarizes the main causes of diagnosed hot spots found in this study.

Table 2- Summary of electrical parameter variations as a function of ΔT*

Parameter	**Module without hotspot (baseline)**	**With mild/moderate hotspot (distributed or transient)**	**With severe hotspot (localized or permanent)**
Isc (short-circuit current)	100% (nominal current)	Moderate reduction partially shaded or defective cells reduce the string current, typically a 5–20% drop depending on the shaded fraction.	Significant reduction if a cell is severely limited and bypass is inactive; current may drop sharply (>50%). If a bypass diode conducts, current may recover near normal, but at the cost of deactivated segments.
Voc (open-circuit voltage)	100% (sum of all healthy cell voltages)	Slight reduction – heated or damaged cells have reduced open-circuit voltage; several slightly hot cells may reduce total Voc by a few percent.	Significant reduction in extreme cases, an entire substring may be bypassed even at open circuit (fully open cell or diode shorted), reducing Voc by ~1/3 (e.g., from 36 V to 24 V). Even without bypass, a permanently damaged cell may contribute much lower voltage.
Pmpp (maximum power)	100% (nominal power under STC)	Notable reduction – due to lower Isc and slight Voc drop, maximum power decreases. Case studies show Pmpp losses of 5–15% for moderate distributed hotspots.	Major power loss – the module may be unable to deliver power from one or more substrings. Losses may exceed 30–50%. For example, a module with 1/3 of its cells bypassed may have 30–35% lower Pmpp. If the defective cell limits current without bypass, loss may be even greater (~50% reported). Over time, Pmpp may decline further due to permanent damage.
FF (fill factor)	~75–80% (typical for healthy modules)	Slight to moderate reduction the I–V curve becomes more "arched" due to current drop and minor dissipation in some cells; FF may drop to ~70% depending on mismatch severity.	Pronounced reduction – severe hotspots introduce non-linearities ("knees") in the I–V curve, especially when bypass diodes activate, producing dual current plateaus. FF may fall to 60% or lower, as power output becomes much lower than Isc·Voc. Modules with one inactive substring and two active ones may show a "two-stage" curve with greatly reduced FF.
Efficiency (η, relative)	100% (nominal efficiency, e.g., 18%)	Reduction proportional to Pmpp loss, Pmpp drops 10%, efficiency drops by 10% (from 18% to ~16.2%).	Drastic reduction e.g., 50% Pmpp loss implies efficiency ~50% of original (from 18% to 9%). Moreover, hotspots increase the average operating temperature of the module, further reducing efficiency due to the negative temperature coefficient of power.

*The analysis of the results identified in the PV modules mainly shading, microcracks, soiling, PID, PID Shunt, bypass diode failure. A direct correlation was found between hotspot ΔT and power loss (up to 30–40%).

Table 3 summarizes the electrical impacts of different failure types. PID and diode failures exhibited the highest ΔT and corresponding losses. The floating systems showed higher defect incidence (2.3×) compared to ground-mounted ones, confirming the influence of humidity and temperature causing PID-shunt.

Table 3- Electrical impacts of failure modes.

Failure Mode	Average ΔT (°C)	Avg. Pmax Loss (%)	Frequency (%)
PID-shunt	25.4	47	32
Partial shading	17.8	21	28
Diode failure	22.5	34	14
Micro-cracks	11.2	13	18
Soiling	9.3	9	8

3.2 Evaluation of the Operational Monitoring Module (MMO)

To acquire and record data on electrical and thermal parameters of PV modules, the Operational Monitoring Module (MMO) shown in Figure 3, was developed. It is defined as an embedded system responsible for continuous monitoring of variables measured in PV modules. The following parts encompass the proposed MMO solution: i) PVMed-Measurement terminal module, ii) PVRter-Communication router module, and iii) PVGtw-Control, registration and communication gateway module (CEMIG/ANEEL, 2023).

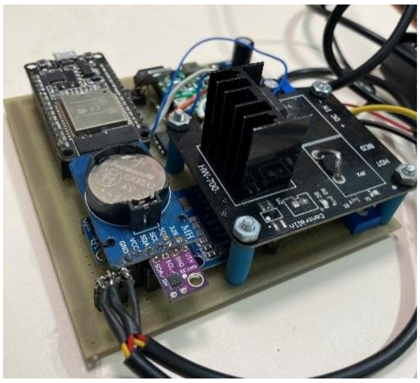

Figure 3- Operational Monitoring Module (MMO)

The PVMed modules are equipped with wireless data processing and communication units, as well as dedicated instrumentation for measuring electrical, thermal and movement parameters of PV modules. The PVRtr modules act as routers, connecting the PVMed modules to the PVGtw gateway concentrator unit. The PVGtw unit is responsible for coordinating the field sensor network, maintaining measurement information in buffers and implementing interface services with the local SCADA server.

The measurement system includes two meteorological stations, one of which will be installed on the photovoltaic modules. This local station will be managed by the PVGtw unit. The station installed in the local server shelter building will be managed by this server and will provide reference climate and irradiation data.

As the MMO monitors continuously the variables measured in photovoltaic modules, it can anticipate failures and losses in operational performance. This information is essential for developing preventive and corrective maintenance plans, in addition to estimating operational costs.

Preliminary tests with the MMO prototype demonstrated successful wireless data acquisition for > 24 h without interruption and detection of early abnormalities before visible hot spots appear in IR images. Therefore, the MMO enables a transition from reactive to predictive maintenance, reducing downtime and improving safety and energy yield. The proposed MMO system represents a viable path toward real-time module-level monitoring, enabling predictive maintenance and improving the long-term reliability of photovoltaic power plants in Brazil.

4. Conclusions

This study and analyses conducted highlight that hotspots in photovoltaic modules are well-known phenomena, with clear mechanisms and identifiable patterns. Today, it is possible to detect them effectively using multiple techniques. Existing classification methods support both scientific research and the implementation of more efficient maintenance practices. However, there are significant opportunities for future research aimed at making photovoltaic plants more resilient and intelligent. These include the integration of advanced sensors, sophisticated management algorithms, the use of new materials to prevent or mitigate the occurrence of hotspots, and the development of the special MMO instrumentation for monitoring.

This study confirms that the detection and classification of hotspots are essential for the reliability of photovoltaic systems. Thermal imaging, especially when integrated into automated monitoring, enables predictive maintenance, extends module lifespan, and minimizes safety risks. Photovoltaic installations benefit significantly from this proactive diagnostic approach. The integrated diagnostic approach (visual + IR + I–V + EL) proved effective in identifying and quantifying thermal anomalies in PV modules under tropical field conditions. The findings confirm that temperature gradients above 20 °C indicate critical failure stages associated with significant energy losses.

Future work will focus on AI-enhanced image classification and the integration of real-time operational monitoring data with SCADA systems using MMO. The goal is to move from reactive management to a predictive approach, ensuring higher energy yield, operational safety, and mitigation of the adverse effects of hotspots throughout the lifetime of photovoltaic modules.

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