Uncertainty Zone in PV Systems Fault Detection due to Temperature Variation and Measurement Error

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I declare that this document is an original work of my own authorship and that it fulfils all the requirements of the Code of Conduct and Good Practices of the Universidade de Lisboa.
Abstract

This thesis focuses on defining the error associated with voltage and current measurements on PV cells and the impact of temperature-related power loss in fault detection. The influence of temperature on the electrical parameters of solar cells has been studied. Experimental results show that all electrical parameters of solar cells such as maximum output power, open-circuit voltage, short circuit current, and fill factor change with temperature variation. The variation of these parameters with temperature throughout the year has been obtained. According to the results, the most significant is the temperature dependence of the voltage, which decreases with increasing temperature while the current of cells slightly increases with temperature. An analysis of these temperature-related power loss in parallel with fault associated power loss allows the definition of an uncertain origin power loss zone, and to give recommendations for the development of a possible fault detection method.

Keywords: Monitoring, Maximum output power, Open circuit voltage, Short circuit current, Solar cells, Temperature
Resumo

Esta tese foca-se na definição do erro associado às medições de tensão e corrente em células fotovoltaicas e no impacto da perda de energia produzida relacionada com a temperatura na deteção de falhas. O papel da influência da temperatura nos parâmetros elétricos das células solares foi estudado. Os resultados experimentais obtidos mostram que todos os parâmetros elétricos da célula solar, como a potência máxima de saída, a tensão de circuito aberto, a corrente de curto-circuito e o fator de preenchimento, mudam com a variação de temperatura. A variação desses parâmetros com a temperatura foi obtida mensalmente ao longo do ano. De acordo com os resultados, a dependência com a temperatura mais significativa é a da tensão, esta diminui com o aumento da temperatura, por outro lado a corrente das células aumenta ligeiramente com a temperatura. Uma análise das perdas de energia relacionadas com a temperatura, paralelamente à perda de energia associada a falhas, permite a definição de uma zona de perda de energia de origem incerta e recomendações para o possível desenvolvimento de um método de deteção de falhas.

Palavras-Chave: Monitorização, Potência máxima de saída, Tensão de circuito aberto, Corrente de curto-circuito, Células solares, Temperatura
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List of Abbreviations

AC – Alternating Current
AF – Arc Fault
AFCI – Arc Fault Circuit Interrupter
AFD – Arc Fault Detector
AI – Artificial Intelligence
AM – Air Mass
BGBC – Broken Glass Broken Cell
BGHC – Broken Glass Healthy Cell
CEC – California Energy Commission
DAQ – Data Acquisition
DC – Direct Current
DF – Diodes Fault
EVA – Ethylene Vinyl Acetate
GF – Ground Fault
GFPD – Ground Fault Protection Devices
GFPI – Ground Fault Protection Interrupters
GPIB – General Purpose Interface Bus
H – Healthy Cell
HS – Hot Spot
IEA – International Energy Agency
IEC – International Electrotechnical Commission
IR – Infrared
I-V – Current-Voltage
JB – Junction Box
JBF – Junction Box Fault
LL – Line-to-Line
LLF – Line-to-Line Fault
LS-PVPP – Large Scale - Photovoltaic Power Plant
MPP – Maximum Power Point
MPPT – Maximum Power Point Tracking
NASA – National Aeronautics and Space Administration
NREL – National Renewable Energy Laboratory
OC – Over Current | Open Circuit
OCPD – Over Current Protection Device
O&M – Operations and Maintenance
PR – Performance Ratio
PV – Photovoltaic
PVMF – Photovoltaic Module Fault
RCD – Residual Current Detector
SAM – System Advisor Model
SDS – Sustainable Development Scenario
STC – Standard Test Conditions
TDR – Time Domain Reflectometry
UV – Ultraviolet
List of Symbols

A – Ampere, Area

a – Modified Nonideality Factor

$\alpha_{sc}$ – Short-Circuit Current Temperature Coefficient

B – Temperature Independent Constant

$\beta_{oc}$ – Open-Circuit Voltage Temperature Coefficient

°C – Degree Celcius

D – Diffusivity

$\delta$ – Standard Deviation

E – Alternating Current Power Output

$E_g$ – Energy Band Gap

$E_{GO}$ – Energy Band Gap Extrapolated to Absolute Zero

FF – Fill Factor

Ge – Germanium

$G_{stc}$ – Yield for Standard Test Conditions

GW – Gigawatt

H – Total In-Plane Solar Irradiation

$I_0$ – Reverse Saturation Current

$I_{1a}$ – Primary Current Entering

$I_{1b}$ – Primary Current Leaving

$i_{1a,b}$ – Secondary Currents

$I_L$ – Photoelectric Current

$I_{mp}$ – Maximum Power Current

$i_{op}$ – Relay’s Operating Current

$I_{sc}$ – Short-Circuit Current

$k_B$ – Boltzmann Constant
kg – Kilogram
L – Diffusion Length
Lc – System Capture Losses
Lc_cm – Miscellaneous Capture Losses
Lc_mes – Measured Capture Losses
Lc_sim – Simulated Capture Losses
Lc_th – Thermal Capture Losses
m² – Square Meter
me – Mass of Electrons
mh – Mass of Holes
mm – Millimeter
mono-Si – Monocrystalline Silicon
n – Ideality Factor
Np – Doping
ni – Intrinsic Carrier Concentration for Silicon
Ns – Number of cells in series
Ω – Ohm
P0 – Nominal Photovoltaic Power
P_{actual} – Actual Output Power
Pm – Maximum Power Output
P_{max} – Maximum Power for STC
P_{mvar} – Maximum Power Output Variation
P_{sim} – Simulated Output Power
q – Electron Charge
R – Resistance
Rs – Series Resistance
R_{sh} – Shunt Resistance
Si – Silicon

T – Temperature

T_{Cell} – Cell Temperature

T_{n_{oc}} – Normal Operating Condition Temperature

T_{Wh} – Terawatt Hour

V – Volt

V_{mp} – Maximum Power Voltage

V_{oc} – Open-Circuit Voltage

W – Watt

\gamma – Maximum Power Point Temperature Coefficient

Y_{A} – Daily Array Energy Output

Y_{f} – Final Yield

Y_{r} – Reference Yield
1. Introduction

The worldwide growth of photovoltaics has been close to exponential between 1992 and 2018. During this period, photovoltaics (PV), also known as solar PV, evolved from a niche market of small scale applications to a mainstream electricity source. When solar PV systems were first recognized as promising renewable energy technology, subsidy programs, such as feed-in tariffs, were implemented by several governments in order to provide economic incentives for investments. For several years, growth was mainly driven by Japan and pioneering European countries. As a consequence, the cost of solar declined significantly due to experience curve effects like improvements in technology and economies of scale [1].

Power generation from solar PV is estimated to have increased by more than 30% in 2018, to over 570 TWh. With this increase, the solar PV share in global electricity generation exceeded 2% for the first time. It remains the fourth-largest renewable electricity technology in terms of generation, after hydropower, onshore wind and bioenergy [2].

In 2018, solar PV capacity additions globally were 97 gigawatts (GW), accounting for around half of total net renewable capacity growth. Solar PV capacity additions had doubled from 2016 to 2017, but in 2018 they remained stable as a result of policy changes and uncertainties in critical markets such as China, the United States, and India. The average selling prices of solar PV modules continued to decline by around 10% globally [2].

Despite slower capacity growth in key markets in 2018, solar PV is well on track to reach the Sustainable Development Scenario (SDS) level by 2030, which will require electricity generation from solar PV to increase 16% annually, from 570 TWh in 2018 to almost 3.300 TWh in 2030 [2].

With greater cost-competitiveness and continuous policy support, robust solar PV growth is expected in the next five years, led by China, the United States, India, and Japan. Growth in Latin America, the Middle East, and Africa is also expected to accelerate because of improved economic attractiveness and continued policy support [2].

PV systems, such as PV power plants or smaller-scale PV applications, rely on continuous operations and maintenance (O&M) routines to ensure long term up-time, higher system efficiencies, and economic viability. The continuous growth of this industry enhanced the importance of O&M activities. Augmented challenges are found in solar PV plants located in remote places, with difficult access and poor communication infrastructures. One main O&M issue in the PV industry is the number of components that need to be inspected in large PV plants, especially solar panels. A study done for grid-connected systems in Germany in the 1990’s revealed that solar panels, or PV modules, accounted
for 15% of the total system failures, whereas inverters contributed with 63% and other system components contributed with 22% Despite being only 15% of total system failures, PV modules failures affect the overall system’s efficiency and can jeopardize the energy production. Well maintained PV systems present in average 6% higher performance than poorly maintained ones [3].

Currently, plenty of PV module failures are known, but their rapid detection is not an easy task. The sooner a faulty module is identified and replaced, the lower is the energy loss it causes. Hence, it is essential to develop robust and accurate monitoring systems and manage how faults impact energy production.

There are three kinds of monitoring systems for PV system:

- **Quantitative-Model based solutions** - Offer compact representations of the system dynamics, where a difference or differential equation may describe the system for a broad set of input functions and initial states.
- **Process-History Based Solutions** - Collect, store, and replay historical and continuous system data, using it to analyze and understand system performance.
- **Signal-Processing Based Solutions** - Focuses on fault detection through signal analyzing and processing.

All these methods are applied to employ scheduled routines; some of them even demand the disconnection of the solar panels. Thus, they are called off-line methods. On the other hand, an on-line method – capable of continually monitor the PV systems status – offers apparent advantages in terms of response time. On-line methods are typically based on measurements of the electric characteristics, e.g., current, voltage, and power, at some point in the circuit [4].

In this work the problems regarding current and voltage measurements in online monitoring will be studied as well as a set of recommendations on quantitative model-based monitoring systems which use electrical measurements of current, voltage, and power. It will focus on characterizing the error in voltage and current measurements of PV cells and the study of their impact of the temperature in the cell output power voltage and current

### 1.1. Objectives

The main objectives of this work are the following:

- Define the errors associated with current and voltage measurements.
- Evaluate how these errors and temperature influence fault detection.
• Recommend practices to improve the accuracy of monitoring and fault detection.

1.2. Thesis Structure

This thesis has 6 Chapters described as follows:

Chapter 1 introduces the work as well as presenting the objectives of this thesis.

Chapter 2 provides an overall view of photovoltaic systems with an emphasis on solar panels and solar cells. It also describes the different types of PV monitoring systems and the temperature impact on PV power generation.

Chapter 3 focuses on defining the error associated with voltage and current measurements by carrying out various PV cell experiments, as well as an I-V curve and fault simulations.

Chapter 4 describes temperature and manufacturing-related power variations that occur in PV modules and how they affect their performance and possible fault detection.

Chapter 5 focuses on recommendations for the development of a possible fault detection method based on temperature-related power variation.

Chapter 6 concludes the work and summarizes the obtained results as well as recommendations for future works.
2. Literature Review

2.1. Photovoltaic Systems

Photovoltaic (PV) panels have been widely exploited in today's environmentally conscious world. As the amount of energy generated by the panels mainly depends on the environmental conditions, such as insolation level and ambient temperature, the last four decades have witnessed a great deal of research effort devoted to advancing the semiconductor materials for increasing the PV cell efficiency and system architecture, so as to maximize the output power of the panels. Apart from producing electricity, the diagnosis of PV panels is equally essential, as it can provide users with a warning of a system failure or high failure risks. The information can thus help shorten the time interval with reduced or no energy production, so the overall system reliability and efficiency are improved. Diagnosis generally includes performance monitoring and tracking of the drift in the panel parameters. The panel's health state can sometimes be concluded by comparing the actual estimated value to the base value [5].

2.1.1. Basic Concepts

PV systems are energy conversion systems. These are designed to generate electricity by converting sunlight into electricity, the physical phenomenon that occurs is the photovoltaic effect, and it is the basis of this conversion. This effect is a specific case of the photoelectric effect, where electrons are excited to a higher energy level when exposed to sunlight (photons). What distinguishes these effects is that in the photovoltaic effect, excited carriers, or free electrons, are still contained within the material and are not emitted to the exterior.

This effect happens in photovoltaic cells and can be described simply as follows: Light, pure energy, enters a photovoltaic cell and transfers enough energy to release some electrons (negatively charged atomic particles). The photovoltaic cell consists of semiconductor material typically in the form of a p-n junction, this junction is the interface between two semiconductors made of the same material: the "n" (negative) side contains electrons in excess, and the "p" (positive) side contains a shortage of electrons, also known as holes. Because the p-n junction is composed of inversely polarized materials, an electric field is formed. This electric field causes the electrons to flow in one direction (n side) and the holes in the other direction (p side). The movement of the electrons in one direction is what constitutes the electric current in the cell. The characteristics of the electric field depend on the semiconductor material. The potential difference associated with this electric field is typically 0.6 V to 0.7 V for silicon (Si) semiconductors and 0.3 V to 0.35 V for germanium (Ge) semiconductors [6].
Most of the energy that reaches the cell in the form of sunlight is lost before it is converted into electricity. Light-to-electricity conversion reaches peak values in the order of 30% (much higher values are achieved for other more complex cell design types), but typically panel efficiencies are 15% - 20%. Certain physical phenomena limit the efficiency of solar cells; some are inherent and cannot be avoided; others can be improved by changes in design and the production processes [6].

The phenomena that most limit the efficiency of the photovoltaic cell are the following:

- Reflection of the cell surface;
- The light that does not contain enough energy to separate the electrons from their atomic bonds;
- The light that has too much energy, beyond what is needed, to separate the electrons from their bonds;
- Electrons and holes (empty links) that randomly meet and recombine before they can contribute to cell performance;
- Electrons and holes that recombine in the surface and defects of the cell material.
- Resistance to current flow.
- Performance degradation due to non-optimal operating temperatures.
2.1.2. PV Panel Structure

The materials and structures used in the PV panel manufacturing process are very similar independently from different types of solutions. That is why the manufacturing process plays a fundamental role, experience, and research in order to achieve the best photovoltaic modules. The assembly process of a PV panel is related to integrating each raw material best, adopting all the optimizations required to improve the quality of the final product [7-8].

![Image of PV panel structure]

*Figure 2.2 - PV panel structure [8]*

The currently used photovoltaic panels are commonly formed with the following structure:

- Photovoltaic solar cell;
- Front glass;
- Back sheet;
- Encapsulant material;
- Frame;
- Junction Box.

2.1.2.1. Photovoltaic solar cell

Photovoltaic Cells are semiconductor devices and the main component in a module, they have the role of capturing the sunlight and convert it into electricity. Crystalline cells can be monocrystalline or...
polycrystalline, depending on their manufacturing process. This, however, does not affect the photovoltaic module production process. The main technical characteristics are, color, size, number of bus-bar, and above all, the conversion efficiency. The latter is the parameter that most affects the power output of the panel [7-8].

2.1.2.2. Front Glass

The front glass is the most massive part of the photovoltaic module, and it has the function of protecting and ensuring robustness to the entire photovoltaic module, maintaining high transparency. The thickness of this layer is usually 3.2 mm, but it can range from 2 mm to 4 mm depending on the type of glass chosen. It is essential to pay attention to features such as quality of hardening, spectral transmittance, and light transmittance. For photovoltaics, some special glasses have been studied with a unique pattern on their surface ensuring a higher degree of light trapping. Choosing the glass carefully, checking these features, or adding anti-reflective layers, can bring an overall improvement of the efficiency of the module [7-8].

2.1.2.3. Back-sheet

The term back-sheet means the sheet on the back. It is made from plastic material that has the function to electrically isolate, protect, and shield the PV cells from weather and moisture. This particular sheet is usually white and is sold in rolls or sheets. Particular versions can be different in thickness, in color and the presence of particular materials for a more excellent shielding or a higher mechanical strength [7-8].

2.1.2.4. Encapsulating material

One of the most important materials is the encapsulant, which acts as a binder between the various layers of the PV panel. The most common material used as an encapsulant is EVA – Ethylene-vinyl acetate. It is a translucent polymer sold in a roll. It must be cut in sheets and deposited before and after the photovoltaic cells. When subjected to a thermal process of vacuum cooking. This particular polymer becomes similar to a transparent gel and incorporates the photovoltaic cells. The quality of this process, called lamination, ensures a high service life to the module itself, while the encapsulant quality affects the light transmission, the process speed and resistance to yellowing due to UV rays [7-8].

2.1.2.5. Frame

One of the last parts to be assembled is the frame. It is generally made of aluminum and has the function to ensure robustness and a practical and safe coupling to the photovoltaic module. Together with the frame, also a layer of sealant is deposited around the walls of the panel as a moisture barrier. For this purpose, the most widely used material is silicon, although sometimes a special sealing tape is used [7-8].
For special applications, also frameless modules or special plastics solutions are available. These solutions usually involve the use of supports glued in the rear side and modules with glass-glass technology [7-8].

2.1.2.6. Junction box

The junction box has the function of bringing the electrical connections of the PV module outside. It contains the protection diodes for shadows and the cables for the connection of the panels in the field. In choosing the Junction, the plastic quality is crucial, the goodness of sealing, the type of connection of the ribbon, and the quality of by-pass diodes. In these years also boxes with special low-loss diodes or integrated with micro-inverters were born. The price of these solutions has not yet allowed a mass distribution, although the potentiality is interesting [7-8].

2.1.3. PV Systems Topologies

The connection of PV inverters with PV panels and transformers considers four basic topologies: (i) central, (ii) string, (iii) multi-string and (iii) ac module integrated. The power produced by different topologies is affected by solar radiation and shading effect, becoming very important the correct choice of the topology according to the power output, location, reliability, cost, and efficiency [9].

In this section, a review of these configurations is developed, describing, and analyzing their main characteristics, advantages, disadvantages, and applications [9].

The interconnection between PV panels and the inverters is illustrated in Fig. 2.3. The central topology (Fig. 2.3(a)) interconnects several thousands of PV panels to one inverter. The disposition of these PV panels is clustered into PV arrays. Each array has hundreds of PV strings connected in series [9].

The string topology (Fig. 2.3(b)) connects one PV string with one inverter. The multi-string topology (Fig. 2.3(c)) connects one PV string to a dc-dc converter, then 4 or 5 DC-DC converters are connected to one inverter which may or may not be close to the dc-dc converter. The fourth topology, the ac module integrated (Fig. 2.3(d)), has one inverter per each PV panel. The inverters utilized on these topologies take the name of the topology used: central, string, multi-string, and ac module integrated [9].
The electrical characteristics of these inverters are described in (Table 2.1).

**Table 2.1 - Electrical characteristics of PV inverter topologies [9]**

<table>
<thead>
<tr>
<th>Inverter topology</th>
<th>P (kW)</th>
<th>Vin MPPT DC (V)</th>
<th>Vout AC (V)</th>
<th>f (Hz)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Central</td>
<td>100-1500</td>
<td>400-1000</td>
<td>270-400</td>
<td>50,60</td>
</tr>
<tr>
<td>String</td>
<td>0.4-5</td>
<td>200-500</td>
<td>110-230</td>
<td>50,60</td>
</tr>
<tr>
<td>Multistring</td>
<td>2-30</td>
<td>200-800</td>
<td>270-400</td>
<td>50,60</td>
</tr>
<tr>
<td>Module Integrated</td>
<td>0.06-0.4</td>
<td>20-100</td>
<td>110-230</td>
<td>50,60</td>
</tr>
</tbody>
</table>

These topologies are differentiated by four categories: general characteristics, power losses, power quality, and cost (Table 2.2).
### Table 2.2 - Main characteristics of PV inverter topologies [9]

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Central</th>
<th>String</th>
<th>Multistring</th>
<th>Module</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Performance</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Reliability</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
<td>Very High</td>
</tr>
<tr>
<td>Robustness</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
<td>Very Low</td>
</tr>
<tr>
<td>Flexibility</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
<td>Very High</td>
</tr>
<tr>
<td>MPPT efficiency</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
<td>Very High</td>
</tr>
<tr>
<td><strong>Power losses</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Mismatching</td>
<td>High</td>
<td>Low</td>
<td>Low</td>
<td>Very Low</td>
</tr>
<tr>
<td>Switching</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
<td>Very Low</td>
</tr>
<tr>
<td>AC power losses</td>
<td>Low</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>DC power losses</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
<td>Very Low</td>
</tr>
<tr>
<td>AC voltage variation</td>
<td>Low</td>
<td>High</td>
<td>Medium</td>
<td>Very High</td>
</tr>
<tr>
<td><strong>Power quality</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>DC voltage variation</td>
<td>Very High</td>
<td>Medium</td>
<td>High</td>
<td>Very Low</td>
</tr>
<tr>
<td>Voltage balance</td>
<td>High</td>
<td>Medium</td>
<td>Low</td>
<td>Low</td>
</tr>
<tr>
<td><strong>Cost</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Installation cost</td>
<td>Medium</td>
<td>High</td>
<td>Medium</td>
<td>Very High</td>
</tr>
<tr>
<td>DC cables</td>
<td>High</td>
<td>Low</td>
<td>Medium</td>
<td>Very Low</td>
</tr>
<tr>
<td>AC cables</td>
<td>High</td>
<td>Medium</td>
<td>Medium</td>
<td>High</td>
</tr>
<tr>
<td>Maintenance</td>
<td>Low</td>
<td>Medium</td>
<td>High</td>
<td>Very High</td>
</tr>
</tbody>
</table>

The first category, general characteristics, considers robustness, reliability, flexibility, and MPPT efficiency. Each topology presents its general characteristics that depend primarily on the power rating, the number of PV inverters, and the number of PV strings. For instance, the central topology has low levels of reliability, flexibility and MPPT efficiency but its robustness is higher than other topologies [9].

The second category, power losses, consider mismatching, switching, AC, and DC losses. Mismatching losses are inevitable in any PV array. These depend on uneven degradation along the PV string, shading, cloud coverage, dust, cooling, MPPT efficiency, among others. In this case, central topology presents higher mismatching losses due to several strings being connected to a single inverter. The switching losses are also a concern that depends on the devices and the control of the PV inverter. The length of the cables in the DC or AC side influences the cumulative losses of PV systems. Central inverters have very high losses at the DC side as many strings are connected in parallel. In contrast, the ac losses in the central inverter are low, as the transformers (Tn) are connected very close to the inverter [9].

The third category, power quality, is influenced by the DC and AC voltage variations and voltage balance. In the case of central topology, the DC voltage variation is very high because many strings are connected in parallel. In this case, the AC voltage variation is low, and the voltage balance is high as it has only one inverter. The voltage is unbalanced, especially when many inverters are connected in parallel as the case of module integrated. Due to losses, distances, and voltage sags, the three-phase voltage balance at the point of connection with the transformer (Tn) could be affected. Therefore, when
several inverters are connected in parallel, it is necessary to develop a master control for a group of PV inverters to reduce the ac voltage variation and to improve the voltage balance [9].

The fourth category, the cost, involves the installation, maintenance, land cost, and length of cables in the DC or the AC side. The comparison of costs for each topology is detailed in Table 2.2, but the land cost is not included as it depends on the location of the system [9].

![Diagram showing comparison between different PV inverter topologies characteristics for LS-PVPP](image)

*Figure 2.4 - Comparison between different PV inverter topologies characteristics for LS-PVPP [9]*

Because of comparison analysis, Figure 2.4 is developed considering each characteristic for every topology presented in Table 2.2. It can be stated that the central topology has the following advantages: robustness, low AC power losses, low AC voltage variation, and a flexible installation and maintenance cost in contrast to other topologies. The general characteristics of string and multi-string topologies are desirable, but the main drawback is the installation and the maintenance cost as the number of inverters increases. String topology has similar characteristics as the multi-string topology, but it is recommended to use it when each PV string has different orientation angles. Regarding module integrated, it has excellent characteristics considering flexibility, MPPT efficiency, and reliability. The robustness, power losses, power quality, and the general cost are several drawbacks for the module integrated topology [9].

### 2.1.4. Faults in PV Systems

A fault in a photovoltaic panel origins one of two events, it causes the power degradation of the module, which is irreversible through standard procedures, or it creates safety problems. A purely aesthetic problem that does not give rise to one of the two events mentioned above is not considered a...
fault. A failure in a module is relevant regarding insurance when the fault occurs under normal and expected operating conditions [10].

Some defects in the modules occur during their production. These defects may be the reason why some modules do not function as well as expected, as long as these defects are not relevant to the safety or the labeled power level, taking into account the loss of power rating for imperfections due to production, these defects are not considered a module failure [10].

A photovoltaic system can be subject to a wide variety of faults, including those of the photovoltaic array, those of the inverter and those of the electricity grid. This thesis focuses on photovoltaic arrays, which have non-linear characteristics of limited current and voltage, (I-V) curves. Failures in photovoltaic systems require special attention and careful evaluation. As shown in Fig. 2.5 [10].

A wide variety of faults are usually found within photovoltaic arrays. In this thesis, it is considered that the PV array is the only source of fault current since most of the inverters are endowed with galvanic isolation between the PV arrays and the electric power grid. Among these faults, ground faults and line-to-line faults are those that have the greatest potential to cause high fault currents [10].

Without proper protection and fault detection, these defects can cause serious problems in the PV array, such as DC arcs and even fire hazards. Also, parallel or serial DC arcs can fall into these four categories of failures. Especially for series arcs, as these have a behavior similar to a variable resistance, they can be difficult to identify or to extinguish [10].

Defects in PV modules can include discoloration, cracking, snail tracks, antireflection coating damage, bubbles, soiling, busbar oxidation, and corrosion, and split encapsulation over cells interconnections, back sheet adhesion loss, among others. Generally, faults in PV modules can be
classified into two main categories: permanent and temporary. Permanent faults are, for example, delamination, bubbles, yellowing of cells, scratches, and burnt cells. So, this category of faults can be eliminated simply by replacing the faulty modules. While, transient faults are basically due to partial shading effects, dust accumulation (soiling), dirt on the PV module, and snow that can be removed by operators without replacing the faulty module. The cause of the fault could be external or internal, and both may lead to a decrease in the output power, efficiency, and reliability of the PV system [10].

2.1.4.1. Hot Spot (HS) Fault

Hot Spot (HS) can be caused when some cells in a PV string/array have different I-V curves, mismatch, i.e., there are variations in the I-V characteristics of the PV modules, high resistance or cold solder points due to manufacturing processes. The I-V characteristic can be affected by dust accumulation and soiling, incomplete edge insolation by transparent module materials, degradation of the cells or by the manufacture’s tolerance, and the non-uniform insolation. The partial shadow effect can be considered as a particular case of the mismatch fault. The HS phenomenon can result when the bypass diode of the shaded cell is damaged/disconnected; thus its current decreases and its voltage becomes negative, so the shaded cells consume power, if this phenomenon persists, the affected solar cells will be damaged and eventually need replacement [10].

2.1.4.2. Diodes Fault (DF)

Bypass and blocking diodes play a critical role in maintaining the performance of PV systems. The bypass diodes are used for reverse voltage protection; while blocking diodes are used for reverse current protection (Figure 2.6). The electrical faults associated with these diodes are short-circuit and open-circuit diodes. These faults may occur when a PV module/array is partially shaded for a long period. Bypass diodes are a key element for safe system operation; however, blocking diodes in series with PV modules will stop Over Current Protection Devices (OCPD) to operate correctly. The reverse current under line-to-line fault will be cut off by the blocking diode, and the system fails. To avoid this type of fault, both bypass diodes and blocking diodes should be chosen carefully and tested adequately [10].
2.1.4.3. **Junction Box Fault (JBF)**

Junction box (JB) reliability is one of the most crucial issues for PV modules during verification testing and operation in the field. Fretting corrosion that occurred in JB may lead to a quick increase in contact resistance. An electric arc between the contact leads to wearing out and melting of the JB. This would finally damage the modules and the whole string, causing the PV system owner further damages due to loss of energy production [10].

2.1.4.4. **PV Module Fault (PVMF)**

The faults on the PV module can occur when the array is isolated from the ground, due to corrosion, delamination of the PV module, leakage currents within a module and manufacturing defects which may lead to shunted modules and short circuit within a module. Generally, faults in PV modules may cause electrical shock hazard and fire risk [10].

2.1.4.5. **Ground Fault (GF)**

A ground fault (GF) in a PV array can be considered as an accidental electrical short-circuit involving ground and various normally designated current-carrying conductors. GF in PV arrays often draws people’s safety concerns because they may generate DC arcs at the fault point on the GF path. If the
fault is not removed properly, the DC arcs could sustain and cause a fire hazard. GF is the most common fault in PV systems. Ground fault detection interrupters (GFDI) (sometimes also called ground fault protection devices, GFPD) are the conventional solution to detect and interrupt ground faults in PV arrays in grounded PV systems [10].

PV systems are system-grounded when the negative conductors are intentionally grounded. Another grounding is called equipment grounding: non-current carrying conductive parts, such as metallic module frames, equipment, and conductor enclosures, should be grounded. A small fuse is usually integrated inside the PV inverters to detect ground faults by sensing the ground-fault leakage current, the ground-fault current in the closed fault path will always return through the GFDI. When the fault current is large enough, the GFDI (e.g., fuse) will be blown. Then the PV inverter will shut down, and the PV array will be de-energized into open-circuit conditions [6].

2.1.4.6. Arc Faults (AF)

An Arc Fault (AF) is the unintended flow of current through the air or another dielectric. AF is generally divided into two categories:

- Series AF: arc from discontinuity in an electrical conductor
- Parallel AF: electrical discharge between conductors with different potentials.

This produces plasma as a consequence of the spark that ionizes the surrounding air. If the current is high enough, sufficient plasma is created to maintain the current flowing across the gap in the conductive path. An AF Detector (AFD) should be included in each system if the system has a maximum voltage of 80 V or higher [10].

2.1.4.7. Line-to-Line Fault (LLF)

A line to line fault (LLF) is an accidental low-resistance connection between two points of different potential in an electrical network or system. In a PV system, a LLF is usually defined as a short-circuit fault among PV modules or array cables with different potential. LLF in PV arrays may be caused by, insulation failure of cables, an incidental short circuit between string connectors in DC string box and mechanical damage. To protect the PV array from LL incidents, many companies have developed protecting devices [10].
2.2. PV Monitoring Systems

Monitoring systems are a crucial part of any electrical installation; it allows to collect, analyze, and use the information to manage the system and track faults. Monitoring is conducted throughout the operation period of the PV system [12].

The three main areas of best practices for system monitoring are the following: quality of monitoring equipment, data presentation, and transparency of measurement protocols and procedures. The approach to monitoring and the associated cost depends on the revenue associated with the performance of the asset. IEC 61724 classifies monitoring systems (A, B, C); the O&M related to monitoring depends on the system class [12].

Data are valuable, and it should be established who owns the monitoring data and who will have access to the data for what purpose. Data analysis is a powerful tool for understanding PV system performance, but it is fundamentally limited by the quality of sensors and models being used, in addition to the condition of the array [12].

Fault detection is defined as "the indication that something is wrong in the monitored system." In addition to fault detection, classification can automatically identify the type of fault. To help maintenance teams look for the fault, the fault detection system can estimate the fault location on the cable, making it easier to perform corrective maintenance after a default. The detection, classification, and locating faults are essential to monitor and identify unexpected problems in PV systems [13].

2.2.1. Quantitative-Model Based Solutions

In this subchapter, four quantitative analysis methods will be briefly explained: current-voltage (I-V), performance comparison, performance ratio, and capture loss [13].

2.2.1.1. Current-Voltage (I-V) Analysis

Current vs. Voltage (I-V) curve analysis can provide most of the operating points of a PV module, string, or array. As illustrated in Figure 2.7, the I-V curve reveals major PV characteristics [13].
It is possible to detect and classify PV faults based on the I-V curve shape and its characteristics. This analysis allows the detection of faults such as series losses, which corresponds to the losses in the metallic parts of the system, mismatch losses, reduced current and reduced voltage [12].

2.2.1.2. Performance Comparison

In addition to fire hazards and safety issues, faults in PV systems may cause a large amount of energy loss. Therefore, it is necessary to monitor PV system performance, study the fault pattern, and develop the fault detection methods [13].
Performance comparison technique compares the actual PV performance with the simulated one under real-time operation. Recently, performance comparison has been proposed for fault detection. Generally, it compares the actual performance with the expected performance. The fault detection rule is straightforward: a significant difference in produced and measured output performance may indicate a fault. As shown in Figure 2.9, the performance evaluation usually has several components, including weather information such as solar irradiance and temperature, expected PV performance as a benchmark, actual measured PV performance, performance comparison, and fault detection [13].

![Figure 2.9 - Performance comparison inputs](image)

For example, to prevent energy and subsequent financial losses in PV systems, an automatic PV performance comparison can be used. It monitors the difference between the simulated and actual energy yield in real-time. The fault detection system gathers satellite-derived solar irradiance and ambient temperature, which are fed into the simulation model to predict the PV’s AC output power $P_{\text{sim}}$. Meanwhile, it monitors the actual AC output power $P_{\text{actual}}$ and compares it with $P_{\text{sim}}$. Four general categories can be established: constant energy loss, changing energy loss, snow cover, and total blackout. There is a limitation, since it monitors the PV power over some time (equivalent to energy yield), it has a slow response. For example, this fault detection method may take at least one day [13].
2.2.1.3. **Performance Ratio (PR)**

Performance ratio (PR) is a normalized parameter of the PV system energy yield to evaluate the system performance. Independent of the orientation and inclination of the panel, PR considers the overall effects of the system losses so that it can be used for fault detection. It is usually defined as the final yield \( Y_f \) over the reference yield \( Y_r \) (1) [13].

\[
PR = \frac{Y_f}{Y_r} \quad \text{dimensionless}
\]  

(1)

Figure 2.10 illustrates how to obtain \( Y_f \) and \( Y_r \) in a grid-connected PV system. Accurately, \( Y_f \) represents the normalized AC energy output to the utility grid. It is defined in (2), where \( E \) is the net AC power output and \( P_0 \) is the nominal PV power [13].

\[
Y_f = \frac{E}{P_0} \quad \text{(kWh/kW)or(hours)}
\]  

(2)

On the other side, \( Y_r \) represents the normalized solar irradiation conditions. It is defined in (3), where \( H \) is the total in-plane solar irradiation (kWh/m²) and \( G_{stc} \) is 1 kW/m² [13].
\[ Y_r = \frac{H}{G_{STC}} \text{ (hours)} \] (3)

Performance ratios values for PV systems are commonly reported on a monthly or yearly (long-term) basis. For a short-term basis, such as daily or weekly, PR gives better resolution, and it can be used for fault detection in PV systems [13].

2.2.1.4. Capture Loss Analysis

To overcome the limitation of previously discussed PR (performance ratio), the system capture loss \( L_c \) is used to understand the abnormality on the system level further. Parameter \( L_c \) represents the losses due to PV array operation. It is defined in (4), where \( Y_r \) is the reference yield and \( Y_A \) is the daily array energy output per kW of the installed PV array. Besides, \( L_c \) can be divided into two types of losses, namely the thermal capture loss \( L_{ct} \) and miscellaneous capture loss \( L_{cm} \) in (5) [13].

\[ L_c = Y_r - Y_A \] (4)

\[ L_c = L_{ct} - L_{cm} \] (5)

The measured capture loss \( L_{c,\text{mes}} \) should remain in a theoretical boundary if the PV array is normal. Therefore, (6) can be used for fault detection, where \( \delta \) is the standard deviation of the simulated capture losses \( L_{c,\text{sim}} \) [13].

\[ [L_{c,\text{sim}} - 2\delta] < L_{c,\text{mes}} < [L_{c,\text{sim}} + 2\delta] \] (6)
As can be seen in Figure 2.11, module parameters, plant configuration, irradiance and module temperature are inputs for the simulation model, this simulation has as output the instantaneous simulated energy produced which is subtracted to the reference yield, obtaining the corresponding losses, the simulated losses are then compared with the measured losses obtained through electrical measurements of voltage and current. This comparison allows to decide on whether a fault does or does not exist. It is then possible to classify faults based on ratios of voltage and current between their simulated and measured values [13].

2.2.2. Process-History Based Solutions

In this subchapter, three process-history analysis methods, statistical methods, and machine learning will be briefly explained [13].

2.2.2.1. Statistical Methods

Statistical methods are proposed to detect abnormality in PV systems based on energy generation. Correctly, descriptive and inferential statistics are applied to the measured energy generation of each subarray of a PV plant [13].
2.2.2.2. Machine Learning

Machine learning is a subarea of AI, which automatically extracts knowledge from the given PV data set. One category of machine learning uses supervised learning approaches. As shown in Figure 2.12, depending on a large amount of labelled data, supervised learning algorithms can learn the system and predict after it is trained [13].

![Supervised learning diagram](image)

*Figure 2.12 - Supervised learning [13]*

2.2.3. Signal-Processing Based Solutions

In this subchapter, six signal-processing solutions, DC arc-fault circuit interrupter (AFCI), insulation resistance monitor, residual current detector (RCD), time-domain reflectometry (TDR), infrared (IR) thermography and internal series resistance, will be briefly explained [13].

2.2.3.1. DC Arc-Fault Circuit Interrupter (AFCI)

DC arc-fault circuit interrupter (AFCI) is required to fill the protection shortcomings of conventional GF detection interrupters and OC protection devices. If GFDI and OCPD do not correctly clear the fault, the DC arc may occur in PV arrays [13].

An electric arc is defined as “an electrical breakdown of a gas which produces an ongoing plasma discharge, resulting from a current flowing through normally nonconductive media such as air.” In real PV fields, as the current and voltage rating increases, DC arcs may have a much higher power level that can easily ignite fire hazards [13].

As shown in Figure 2.13, the DC arc will generate a significant amount of ac noise that can be used as a fault detection signature. An AFCI should detect and interrupt series and parallel arcing faults in DC PV sources and output circuits [13].
2.2.3.2. Insulation Resistance Monitor

Insulation resistance monitor is used as ground-fault protection in un-grounded PV systems when the system is de-energized. Insulation resistance of the PV array ranges from kΩ to MΩ, and it decreases dramatically when insulation faults or direct contact faults (e.g., hazardous ground fault) occur. Therefore, significantly reduced insulation resistance may indicate a ground fault [13].

Figure 2.14 shows a commercial product of an insulation resistance monitor. It monitors both the positive-ground and negative-ground insulation resistance in real-time for ground-fault detection [13].
This approach can be used for both energized and de-energized PV system [13].

2.2.3.3. **Residual Current Detector (RCD)**

Residual current detector (RCD) acts as a differential relay in the power system by monitoring the current difference between input and output terminals of the protected zone (see Figure 2.15). If the current difference is higher than a threshold, the fault alarm will be sent out. However, the parasitic capacitance of the PV array may cause considerable leakage current when inverters without transformers are used. This may lead to nuisance tripping on RCD [13].

![Figure 2.15 - Concept of differential relays for internal fault detection](image)

The differential protection is known as the best protection technique now and for more than 50 years for transformers, motors, generators, and reactors in power systems. The idea of differential relays is to monitor the electrical quantities (usually current) entering and leaving the protected zone. As shown in Figure 2.15, the primary current coming in and leaving from the protected zone are $I_{1a}$ and $I_{1b}$, respectively. The corresponding secondary currents are $i_{1a}$ and $i_{1b}$. Their difference is the relay’s operating current $i_{op} = i_{1a} - i_{1b}$. If the magnitude $|i_{op}|$ is higher than zero or a small threshold, a fault alert will be sent out [7].

2.2.3.4. **Time Domain Reflectometry (TDR)**

Time-domain Reflectometry (TDR) is a measurement approach to determine the electrical wire or cable characteristics by injecting specific waveforms (usually step or impulse signals) and observing reflected waveforms. TDR compares the reflections from an unknown line environment to those generated by standard or given impedance. Therefore, TDR can be used to troubleshoot faulty wires or cables. In addition to fault detection and classification, TDR can locate the fault, which is especially useful in an extensive electrical system [13].
Fault location using TDR is used in PV fields. The waveforms differ with the type of conditions, such as open-circuit fault, short-circuit fault, and resistance load. However, TDR has several drawbacks. First, the PV system under test must be off-line, which will affect the energy yield. Second, it requires human input (labor cost) to observe and learn the reflected waveforms, which hinders its effectiveness of automatic fault detection [13].

2.2.3.5. Infrared (IR) Thermography

Infrared (IR) thermography is used to identify specific mismatch faults, such as hot spots on PV modules, which may cause irreversible damage and power loss on PV modules. Since IR inspection is periodic and repetitive, it may be costly if it requires PV maintenance personnel to increase labor costs over the lifespan PV modules [7].

2.3. Temperature Effect

Like all other semiconductor devices, solar cells are sensitive to temperature. Increases in temperature reduce the bandgap of a semiconductor, thereby affecting most of the semiconductor material parameters. The decrease in the bandgap of a semiconductor with increasing temperature can be viewed as increasing the energy of the electrons in the material. Lower energy is therefore needed to break the bond. In the bond model of a semiconductor bandgap, a reduction in the bond energy also reduces the bandgap. Therefore, increasing the temperature reduces the bandgap [6].
In a solar cell, the parameter most affected by an increase in temperature is the open-circuit voltage. The impact of increasing temperature is shown in the figure below [6].

![Figure 2.17 - The effect of temperature on the I-V characteristics of a solar cell [6]](image)

The open-circuit voltage decreases with temperature because of the temperature dependence of $I_0$ [6]. The equation for from one side of p-n junction is given by:

$$I_0 = qA \frac{D}{L} \frac{n_i^2}{N_D}$$

(7)

Where:

- $q$ is the electronic charge;
- $A$ is the area;
- $D$ is the diffusivity of the minority carrier given for silicon as a function of doping;
- $L$ is the minority carrier diffusion length;
- $N_D$ is the doping; and
- $n_i$ is the intrinsic carrier concentration given for silicon.

In the above equation (7), many parameters have some temperature dependence, but the most significant effect is due to the intrinsic carrier concentration, $n_i$. The intrinsic carrier concentration depends on the bandgap energy (with lower bandgaps giving higher intrinsic carrier concentration), and on the energy which the carries have (with higher temperatures giving higher intrinsic carrier concentrations) [6]. (8) is the equation for the intrinsic carrier concentration is:

$$n_i^2 = 4 \left( \frac{2\pi kT}{\hbar^2} \right)^3 \left( m_r^* m_i^* \right)^{3/2} \exp \left( - \frac{E_{gd}}{kT} \right) = B T^3 \exp \left( - \frac{E_{gd}}{kT} \right)$$

(8)
Where:

- \( T \) is the temperature;
- \( h \) and \( k \) are constants
- \( m_e \) and \( m_h \) are the effective masses of electrons and holes respectively;
- \( E_{GO} \) is the bandgap linearly extrapolated to absolute zero; and
- \( B \) is a constant which is independent of temperature.

Substituting these equations back into the expression for \( I_0 \) and assuming that the temperature dependencies of the other parameters can be neglected, gives:

\[
I_0 = qA \frac{D}{LN_D} BT^3 \exp \left( - \frac{E_{GO}}{kT} \right) = B'T^\gamma \exp \left( - \frac{E_{GO}}{kT} \right)
\]  

(9)

Where \( B' \) is an independent temperature constant. A constant, \( \gamma \), is used instead of the number 3 to incorporate the possible temperature dependencies of the other material parameters. For silicon solar cells, \( I_0 \) approximately doubles for every 10 °C increase in temperature [6].

The impact of \( I_0 \) on the open-circuit voltage can be calculated by substituting the equation for \( I_0 \) into the equation for \( V_{oc} \), as shown below:

\[
V_{oc} = \frac{kT}{q} \ln \left( \frac{I_{sc}}{I_0} \right) = \frac{kT}{q} \left[ \ln(I_{sc}) - \ln(I_0) \right] = \frac{kT}{q} \ln(I_{sc}) - \frac{kT}{q} \ln \left( B'T^\gamma \exp \left( - \frac{qV_{GO}}{kT} \right) \right)
\]

\[
= \frac{kT}{q} \left( \ln(I_{sc}) - \ln(B') - \gamma \ln(T) + \frac{qV_{GO}}{kT} \right)
\]

(10)

Where \( E_{GO} = qV_{GO} \). Assuming that \( dV_{oc}/dT \) does not depend on \( dI_{SC}/dT \), \( dV_{oc}/dT \) can be found as:

\[
\frac{dV_{oc}}{dT} = \frac{V_{oc} - V_{GO}}{T} - \frac{k}{q}
\]

(11)

The above equation shows that the temperature sensitivity of a solar cell depends on the open-circuit voltage of the solar cell, with higher voltage solar cells being less affected by temperature. For silicon, \( E_{GO} \) is 1.2, and using \( \gamma \) as 3 gives a reduction in the open-circuit voltage of about 2.2 mV/°C [6].

\[
\frac{dV_{oc}}{dT} = - \frac{V_{GO} - V_{oc} + \gamma \frac{k}{q}}{T} \approx -2.2 \text{ mV per °C for Si}
\]

(12)
The short-circuit current, $I_{SC}$ increases slightly with temperature, since the bandgap energy, $E_G$ decreases, and more photons have enough energy to create e-h pairs [6]. However, this is a small effect, and the temperature dependence of the short-circuit current from a silicon cell is shown in (13).

$$\frac{1}{I_{SC}} \frac{dI_{SC}}{dT} \approx 0.0006 \text{ per } ^\circ \text{C for Si}$$ (13)

Or $0.06\%$ per $^\circ \text{C}$ for silicon.

The following equation approximates the temperature dependency of the fill factor (FF) for silicon;

$$\frac{1}{FF} \frac{dFF}{dT} \approx \left( \frac{1}{V_{OC}} \frac{dV_{OC}}{dT} - \frac{1}{T} \right) \approx -0.0015 \text{ per } ^\circ \text{C for Si}$$ (14)

The effect of temperature on the maximum power output, $P_m$, is:

$$\frac{P_{Max}}{P_M} = \frac{1}{P_M} \frac{dP_M}{dT} = \frac{1}{V_{OC}} \frac{dV_{OC}}{dT} + \frac{1}{FF} \frac{dFF}{dT} + \frac{1}{I_{SC}} \frac{dI_{SC}}{dT} \approx -(0.004 \text{ to } 0.005) \text{ per } ^\circ \text{C for Si}$$ (15)

Or $0.4\%$ to $0.5\%$ for silicon.

The performance of solar cells is dependent on environmental conditions and their output parameters such as output voltage, current, power, and fill factor vary by temperature. As can be observed the values obtained for $\alpha_{SC}$, $\beta_{OC}$ and $\gamma$ are very close to the ones specified in the datasheet for the PV panel STP190S-24/Ad+ used later in this thesis for experimental results and simulation purposes [6].
3. Healthy and Faulty Solar Cell Characterization and Modelling

In order to test the possible detection of the most usual faults, gain sensibility with this subject, learn how to draw an I-V curve, and to make an analysis on how voltage and current vary from healthy to faulty cells, a set of experimental measurements and simulations were carried out in the laboratory.

3.1. Experimental Analysis of a Solar Cell

A series of laboratory tests were made in order to obtain voltage and current curves for different irradiance values. For this analysis, two SUNTECH photovoltaic panels were used, one in perfect condition and another one damaged with the glass cracked and with a broken cell, this allowed to perform this experiment. The corresponding pictures can be found below:

![Healthy and Damaged Cells PV Panels](image)

*Figure 3.1 - Healthy and Damaged Cells PV Panels*

The Broken cell is presented in Figure 3.2.
The panel used in the experiments has the technical characteristics listed in Table 3.1.

Table 3.1 - STP190S - 24/Ad+ PV Panel characteristics [13]

<table>
<thead>
<tr>
<th>Characteristics</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Model number</td>
<td>STP190S-24/Ad+</td>
</tr>
<tr>
<td>Maximum power voltage (V_{mp})</td>
<td>36.6 V</td>
</tr>
<tr>
<td>Maximum power current (I_{mp})</td>
<td>5.20 A</td>
</tr>
<tr>
<td>Open-circuit voltage (V_{oc})</td>
<td>45.2 V</td>
</tr>
<tr>
<td>Short-circuit current (I_{sc})</td>
<td>5.62 A</td>
</tr>
<tr>
<td>Maximum power for STC (P_{max})</td>
<td>190 W</td>
</tr>
<tr>
<td>Module efficiency</td>
<td>14.9%</td>
</tr>
<tr>
<td>Normal operating condition temperature (T_{noct})</td>
<td>45°C ± 2°C</td>
</tr>
<tr>
<td>Weight</td>
<td>15.5 Kg</td>
</tr>
<tr>
<td>Size</td>
<td>1580mmx808mmx35mm</td>
</tr>
<tr>
<td>Maximum system voltage</td>
<td>1000 V</td>
</tr>
<tr>
<td>Cell technology</td>
<td>mono-Si</td>
</tr>
<tr>
<td>Number of cells</td>
<td>72 (6x12)</td>
</tr>
<tr>
<td>Data presented in standard test conditions (STC)</td>
<td></td>
</tr>
</tbody>
</table>
In order to have access to the cell terminals, the EVA coating was melted, allowing to perform the desired voltage and current measurements.

The full I-V curve could not be observed at first; this was due to high resistance in the sensors and cabling. Taking into account that the cell electrical characteristics at STC conditions are, $V_{oc}=0.63\, V$; $I_{sc}=5.62\, A$, and that the maximum observable current value was around 0.5 A, knowing that $V=R.I$; this means that the resistance of the measuring system was around 1Ω. Hence it had to reduced 10 times to around 0.1Ω, in order to observe the full I-V curve until the short circuit current value $I_{sc}$ was reached. To be able to observe the full I-V curve, sensor connections were then remade in order to reduce its resistance and improve its accuracy. It was verified that the voltage drops in the sensors and the respective cabling were significant and did not allow us to obtain the totality of the I-V curve for the solar cells.

Sensor connections were changed; nonetheless, high voltage drops in the cables were still verified and did not allow to obtain the full I-V curve. Having reduced the sensor resistance to its maximum, connectors were removed, and cables were weld directly in the terminals; also parallel cables were added to reduce the resistance of the cables. The setup can be seen in Figure 3.4.
In that way, it was possible to obtain the I-V curve almost entirely, for that we used current and voltage hall sensors and a variable resistance of 1 Ω with a maximum current of 16 A, enabling to vary the load and obtain different operating points in order to trace the I-V curve, and a thermal sensor to measure the cell temperature in the center of the back of the cell. An irradiance sensor was used to place marks on the wooden stand, built to stabilize the 500W spotlight. Two multimeters were necessary, one that was connected to the thermocouple and another one used to make the corrections due to voltage drops in the series resistance. To measure the short-circuit current ($I_{sc}$), a current clamp was used. The experimental is listed in 3.1.1.
3.1.1. Current-Voltage Measurement Procedure

1. Placement of the spotlight in the chute according to the desired irradiance.
   a. G=1000, 800, 600, 400, 230 [W/m²]

2. Turn on the spotlight and let the temperature stabilize.
   a. Average necessary time for stabilizing: 30 minutes;
   b. Register the final temperature.

3. Obtaining data for computing the corrections in the I-V curve.
   a. Short-circuit the load;
   b. Measure Vcc, the voltage at the terminals of the voltage sensor;
   c. Measure VR1, the voltage between the positives of the cell and sensor;
   d. Measure VR2, the voltage between the negatives of the cell and sensor;
   e. Measure Icc, short-circuit current that flows through the circuit.

4. Prepare the DAQ for data acquisition.
   a. Run the Matlab code.

5. Initiate the process of obtaining the I-V curve;
   a. Begin in open circuit;
   b. Connect the circuit and move the handle of the variable resistance from its maximum to its minimum value;
   c. Finish in a short circuit;
   d. Repeat this process at least ten times.

6. Correction of the measured data:
   1. Compute the cabling resistance;
   2. Correct the errors associated with this resistance plotting a new I-V curve.

3.2. Computing the Error of the Measuring System

3.2.1. Computing the Error Associated with the Cabling and Sensors Losses

The cabling connectors and sensors all have associated losses due to its resistance this leads to the decrease of the accuracy in fault detection.

In order to correct this phenomenon, measurements were made. They can be found in Table 3.2, where G is the incident irradiance from the spotlight, Icc is the current when the cell terminals are short-
circuited, \( V_m \) is the voltage at the terminals of the voltage sensor, \( V_R1 \) is the voltage between the positive terminal of the cell and the positive output of the voltage sensor, \( V_R2 \) is the voltage between the negative terminal of the cell and the negative output of the voltage sensor, \( V_R \) is the sum of \( V_R1 \) and \( V_R2 \), \( T_{cell} \) is the temperature of the solar cell at the time of measurement and \( R \) is the resulting resistance value of the cabling, connectors and sensor obtained in the measuring system.

Table 3.2 - Healthy cell measurements for resistance correction

<table>
<thead>
<tr>
<th>Healthy Cell</th>
<th>( G (\text{W}/\text{m}^2) )</th>
<th>( I_{cc} (\text{A}) )</th>
<th>( V_m (\text{V}) )</th>
<th>( V_R1 (\text{V}) )</th>
<th>( V_R2 (\text{V}) )</th>
<th>( V_R (\text{V}) )</th>
<th>( T_{cell} (\degree \text{C}) )</th>
<th>( R (\Omega) )</th>
</tr>
</thead>
<tbody>
<tr>
<td>1000</td>
<td>4.37</td>
<td>0.21</td>
<td>0.0484</td>
<td>0.0685</td>
<td>0.1169</td>
<td>64</td>
<td>0.026751</td>
<td></td>
</tr>
<tr>
<td>800</td>
<td>3.25</td>
<td>0.1425</td>
<td>0.0384</td>
<td>0.0562</td>
<td>0.0946</td>
<td>55</td>
<td>0.029108</td>
<td></td>
</tr>
<tr>
<td>600</td>
<td>2.46</td>
<td>0.0946</td>
<td>0.0285</td>
<td>0.0382</td>
<td>0.0667</td>
<td>47</td>
<td>0.027114</td>
<td></td>
</tr>
<tr>
<td>400</td>
<td>1.595</td>
<td>0.0701</td>
<td>0.0192</td>
<td>0.026</td>
<td>0.0452</td>
<td>39</td>
<td>0.028339</td>
<td></td>
</tr>
<tr>
<td>230</td>
<td>0.903</td>
<td>0.0373</td>
<td>0.0109</td>
<td>0.0136</td>
<td>0.0245</td>
<td>32</td>
<td>0.027132</td>
<td></td>
</tr>
</tbody>
</table>

These unwanted voltage drops in the monitoring system can eventually bring problems in fault detection, e.g. if 0.05 V in the positive side of the cabling sums up with 0.05 V on the negative side this will lead to an error voltage of 0.1 V. Knowing that the output voltage of the cell is 0.21 V the voltage drop in the measuring system accounts for around 50% of the output. These values reduce as the irradiance decreases since the current is smaller and so is the voltage drop in the measuring components.

This experiment was made for just one cell, if this is applied to an entire PV array or string, much more cabling will be involved and thus the error will be higher.

As it can be seen in Table 5.1, a short-circuited cell is equivalent to losing 0.5 V, which also means that if 5 cells present the above mentioned error a false alarm of a SC fault could appear.

The values of the voltage drops in all these components were used to correct the plots of the I-V curves. The voltage drops on the measuring system were added to the voltage output of the cell, correcting the obtained I-V curves.

The example given was for the healthy cell situation; these same corrections were performed for the other two cases corresponding to the damaged panel.

A corrected and non-corrected I-V curve for a \( G = 1000 \text{ W/m}^2 \) for the Broken cell is shown below:
As it can be seen in the figure 3.5, the series losses have decreased significantly with the correction.

3.2.2. Computing the Error Associated with the Resistance Correction

The instruments used in the measurements of the values of Table 3.2, were the following:

1. Multimeter, CENTER 120 RS-232[^C];
2. Multimeter, CENTER 120 RS-232 [V];
3. Clamp Meter, CENTER 223 AC-DC [I];
4. Irradiance sensor, RS PRO ISM400;
5. DAQ, NIUSB-6008-12bits;
6. Current sensor, LA25-NP;
7. Voltage sensor, LV25-P.

An error propagation analysis along the measuring chain was performed. The accuracies of the measuring equipment are presented in the following tables:
Table 3.3 - Center 120 RS-232 Multiometer Characteristics

<table>
<thead>
<tr>
<th>CENTER 120 RS-232 MULTIMETER</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Range</strong></td>
<td><strong>Resolution</strong></td>
<td><strong>Accuracy</strong></td>
</tr>
<tr>
<td>4V</td>
<td>0.001V</td>
<td>+/-0.3%rdg+2dgt</td>
</tr>
</tbody>
</table>

Table 3.4 - LA 25-NP Current Transducer characteristics

<table>
<thead>
<tr>
<th>Current Transducer LA 25-NP</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accuracy</strong></td>
<td>+/-0.5%</td>
</tr>
</tbody>
</table>

Table 3.5 - LV 25-P Voltage Transducer LV 25-P

<table>
<thead>
<tr>
<th>Voltage Transducer LV 25-P</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Accuracy</strong></td>
<td>+/-0.9%</td>
</tr>
</tbody>
</table>

Table 3.6 - DAQ characteristics

<table>
<thead>
<tr>
<th>DAQ - Absolute accuracy at full scale, differential</th>
<th></th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Range</strong></td>
<td><strong>Typical at 25°C (mV)</strong></td>
<td><strong>Maximum over Temperature (mV)</strong></td>
</tr>
<tr>
<td>+/-5</td>
<td>4.28</td>
<td>58.4</td>
</tr>
<tr>
<td>+/-1</td>
<td>1.53</td>
<td>37.5</td>
</tr>
</tbody>
</table>

In order to compute the error associated with the resistance correction the following rules that can be derived from the Gauss equation for errors with a normal distribution were used. Where $a, b, c, ...$ are measured quantities and $\delta a, \delta b, \delta c, ...$ are the uncertainties associated with those measurements [15].

Computing the error in sums and subtractions:

If $Q$ is a combination of sums and subtractions, i.e.

$$Q = a + b + ... + c - (x + y + ... + z),$$

(16)

So,

$$\delta Q = \sqrt{(\delta a)^2 + (\delta b)^2 + ... + (\delta c)^2 + (\delta x)^2 + (\delta y)^2 + ... + (\delta z)^2}. \quad (16)$$
Computing the error in multiplication and divisions:

If,

\[ Q = \frac{a \cdot c}{x \cdot y \cdot z} \]

So,

\[ \delta Q = \sqrt{\left(\frac{\delta a}{a}\right)^2 + \left(\frac{\delta b}{b}\right)^2 + \ldots + \left(\frac{\delta c}{c}\right)^2 + \left(\frac{\delta x}{x}\right)^2 + \left(\frac{\delta y}{y}\right)^2 + \ldots + \left(\frac{\delta z}{z}\right)^2} \cdot |Q| \]

We can then compute the error propagation in the correction:

<table>
<thead>
<tr>
<th>Calculating the error</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>VR1 error</td>
<td>VR2 error</td>
</tr>
<tr>
<td>0.000345</td>
<td>0.000406</td>
</tr>
<tr>
<td>0.000315</td>
<td>0.000369</td>
</tr>
<tr>
<td>0.000286</td>
<td>0.000315</td>
</tr>
<tr>
<td>0.000258</td>
<td>0.000278</td>
</tr>
<tr>
<td>0.000233</td>
<td>0.000241</td>
</tr>
</tbody>
</table>

These values represent the error associated with measuring equipment and process. These instruments were used to measure the values that led to the correction of the voltage drop across the connections, they are significant and must be accounted for.

As it is possible to conclude there are many errors associated with measuring and they appear across all stages of monitoring. They can have a serious impact in fault detection and in the accuracy of monitoring systems.

### 3.3. I-V curves

Solar Cell I-V Characteristic Curves are graphs of output voltage versus current for different levels of insolation and temperature and can tell a lot about a PV cell or panel's ability to convert sunlight into electricity. The most fundamental values for calculating a particular panel power rating are the voltage and current at maximum power rating.
3.3.1. Healthy Cell I-V Curves

Below the I-V and Power-Voltage curves for the healthy cell for all the proposed irradiances are presented.

![Figure 3.6 - Healthy Cell I-V curves](image1)

![Figure 3.7 - Power-Voltage curves for Healthy Cell](image2)
It can be observed that the I-V curves correspond to a healthy cell. The power produced scales with the irradiance available, the slopes of the curve are small, which indicates small shunt and series resistance losses as shown in Figure 2.7. The $I_{SC}$ observed for the irradiance of 1000 W/m$^2$ is of around 4 A; this is smaller when compared with the one given at STC of 5.2 A; this is mainly because the spotlight light quality (radiation spectrum amplitude) is not the same as the sun. The voltage $V_{OC}$ is also far from the one at STC conditions; this is mainly related to the temperature increase since in this experiment, the module temperature was 64 °C and not 25 °C.

The $V_{OC}$ value is 0.63 V at STC conditions, as it was expected the value closest to this one corresponds to the irradiation of 230 W/m$^2$ since the module temperature was at the lowest among the others for higher irradiations. In this situation the temperature of the cell was roughly above 32 °C, which leads to an open-circuit voltage loss of -0.018 V and so a $V_{OC}$ of 0.61 V; this value is still far from the one observed in Figure 3.6, this might be due to other reasons like performance degradation and aging.

The slope of the I-V curve is affected by the amount of shunt resistance in the electrical circuit. Reduced shunt resistance results in a steeper slope in the I-V curve near $I_{SC}$ and a reduced fill factor. A decrease in shunt resistance may be due to changes within the PV cells or modules. Potential causes are:

- Shunt paths exist in PV cells;
- Shunt paths exist in the PV cell interconnects;
- Module $I_{SC}$ mismatch.

The slope of the I-V curve between $V_{MP}$ and $V_{OC}$ is affected by the amount of series resistance internal to the PV modules and in the array wiring. Increased resistance reduces the steepness of the slope and decreases the fill factor. Potential causes are:

- PV wiring has excess resistance, or it is insufficiently sized;
- Electrical interconnections in the array are resistive;
- The series resistance of PV modules has increased.

### 3.3.2. Broken Glass but Healthy Cell I-V Curves

Below the I-V and Power-Voltage curves for the healthy cell with broken front glass for all the proposed irradiances are presented.
Here we can observe a slight reduction in the current since the irradiance that reaches the cell is reduced due to reflections caused by the cracked glass. No significant difference can be observed comparing the curves in Figure 3.8 with the previous one in Figure 3.6 of the healthy cell. The same expected $V_{oc}$ loss due to temperature increase with higher irradiance is visible.
3.3.3. Broken Glass and Damaged Cell I-V Curves

Figure 3.10 shows the I-V and Power-Voltage curves for the damaged cell with broken front glass for all the proposed irradiances are presented.

Figure 3.10 - Broken glass with a damaged cell I-V curves

Figure 3.11 - Broken glass with a damaged cell Power-Voltage curves
In this last case, the I-V (Figure 3.10) curve presents a reduction in the power produced by the cell, as it can be seen in Figure 3.11, with a much flatter slope. The fill factor reduced tremendously, thus indicates that this cell has some defect. The cell can be broken in an infinite amount of ways, and so it could not be characterized for simulation purposes. In order to evaluate the three previous scenarios, the maximum power points were plotted and compared with the reference values from the datasheet for the irradiance of 1000W/m².

3.3.4. I-V Curves and MPP for all 3 Scenarios

In this section, the I-V curves and maximum power points for all three previous scenarios of, healthy cell (H), broken glass with a healthy cell (BGHC) and the broken front glass with a broken cell (BGBC) for 1000W/m² are presented.

Figure 3.12 - I-V curves with MPP for H, BGHC and BGBC scenarios with G=1000W/m²

It is possible to observe in Figure 3.12 that the defects analyzed have a significant impact on the I-V curve of the cell, i.e., in the output parameters such as output voltage, current, power, and fill factor.

The experiments; despite being conducted at the same irradiance of 1000 W/m², they differed in module temperature (Table 3.2) as seen before the increase of temperature leads to a decrease in \( V_{oc} \).
The maximum power point values for power, voltage, and current that correspond to the crosses in Figure 3.12 are listed in Table 3.8.

<table>
<thead>
<tr>
<th>MPP</th>
<th>Healthy</th>
<th>BGHC</th>
<th>BGBBC</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Power (W)</td>
<td>1.4849</td>
<td>1.3153</td>
<td>0.6843</td>
<td>2.6389</td>
</tr>
<tr>
<td>Voltage (V)</td>
<td>0.3863</td>
<td>0.3615</td>
<td>0.3670</td>
<td>0.5083</td>
</tr>
<tr>
<td>Current (A)</td>
<td>3.8438</td>
<td>3.6383</td>
<td>1.8647</td>
<td>5.6200</td>
</tr>
</tbody>
</table>

Comparing the MPP values with the reference ones, given in the datasheet for STC conditions, we get the following variations:

<table>
<thead>
<tr>
<th>δMPP</th>
<th>Healthy</th>
<th>BGHC</th>
<th>BGBBC</th>
</tr>
</thead>
<tbody>
<tr>
<td>δP (W)</td>
<td>-1.1540</td>
<td>-1.3236</td>
<td>-1.9546</td>
</tr>
<tr>
<td>δV (V)</td>
<td>-0.1220</td>
<td>-0.1468</td>
<td>-0.1413</td>
</tr>
<tr>
<td>δI (A)</td>
<td>-1.7762</td>
<td>-1.9817</td>
<td>-3.7553</td>
</tr>
</tbody>
</table>

As can be concluded from the data obtained, the broken glass condition affects the voltage mainly due to the broken glass whilst the current decreases significantly in the broken cell scenario.

3.4. Simulation of I-V curves

3.4.1. PV cell simulation model

In this chapter, the solar cell electric model and the introductions made by the CEC model for changes in temperature and irradiance are briefly explained.

A solar cell can be modelled through an equivalent electric circuit. The simplest version is the one shown in Figure 3.13.
The electric current generated by the photoelectric effect is represented by the source current \( I_L \). The semiconductor p-n junction is represented by the diode that has a current given by (19):

\[
I_D = I_0 \left[ \exp \left( \frac{q \cdot V_{pv}}{n \cdot k_B \cdot T_{cell} \cdot N_S} \right) - 1 \right]
\]  

Applying Kirchhoff’s law, the electric current supplied by the solar cell is given by:

\[
I = I_L - I_0 \left[ \exp \left( \frac{q \cdot V_{pv}}{n \cdot k_B \cdot T_{cell} \cdot N_S} \right) - 1 \right]
\]  

Equation (20) represents the ideal solar cell. It is said to be an ideal model because it does not take into consideration the power losses due to imperfections of the semiconductor and the non-zero resistance of the metallic cell interconnections. Those losses are modeled by adding a parallel resistance \( R_{sh} \) and a series resistance \( R_s \) whose effects on the I-V curve were explained in chapter 3.1.1. This model with the added resistances is called the 5-parameter model \( (I_L, I_0, R_s, R_{sh}, n) \) and its output current expression is given by (21) [15].

\[
I = I_L - I_0 \left( \exp \left( \frac{V_{pv} + I_{pv} \cdot R_s}{a} \right) - 1 \right) - \frac{V_{pv} + IR_s}{R_{sh}}
\]  

The modified nonideality factor \( a \) defined in (22) encapsulates the diode thermal voltage \( V_T \), the number of cells in series in the photovoltaic module \( N_s \) and the diode nonideality factor \( n \) [16]. Given that the thermal voltage is defined as \( V_T = k \cdot T_{cell} / q \), where \( k \) is the Boltzmann constant, \( T_{cell} \) the cell temperature and \( q \) the elementary charge, the modified nonideality factor is:

\[
a = N_s \frac{k_B \cdot T_{cell}}{q} \cdot n
\]  

At standard test conditions, \( T_{cell} = 298K \), resulting in \( a = 0.025 \cdot n \cdot N_s \) [16].
Normally, values such as $I_{sc}$, $V_{oc}$, $I_{mp}$, and $V_{mp}$ can be found in the datasheet of the solar panel. These values depend on temperature ($T$) and irradiance ($G$), and can be found on the panel datasheet under Standard Test Conditions (STC) [16]. The test conditions of Irradiance, Cell Temperature, and Air Mass (AM), defined by this international industrial wide standard to indicate the performance of PV modules, are:

$$G = 1000 \, \text{W/m}^2$$

$$T_{cell} = 25^\circ \text{C or 298.25 K}$$

$$AM = 1.5$$

In order to accurately compute the $R_s$ and $R_{sh}$ parameters, reliable measurements of the $I$-$V$ curve under controlled irradiance and temperature conditions are necessary [16].

The National Renewable Energy Laboratory (NREL) developed a performance and financial model called the System Advisor Model (SAM) to facilitate decision making in PV systems designing and implementation. Inside this model, there is another model intitled California Energy Commission (CEC) Performance Model. This model is based on the 5-parameter solar cell model and uses parameters commonly found on PV modules datasheets to derive a set of coefficients that describe the $I$-$V$ curve shape of the module at STC conditions. Both the algorithms of the CEC model, as well as the database parameters, are available online in a Toolbox [17].

As mentioned, equation (21) depends on the temperature and irradiance, and the five parameters are valid in STC conditions. It is then necessary to also model the dependency of these parameters with temperature and irradiance changes. The CEC model takes into consideration these variations and adds a sixth parameter to the 5-parameter model, the Adjust parameter. The purpose of this new parameter is to adjust the Short-Circuit Current and Open-Circuit Voltage temperature coefficients ($\alpha_{sc}$ and $\beta_{oc}$) that are also in the solar panel datasheet. The idea is to adjust $\alpha_{sc}$ and $\beta_{oc}$ down and up, respectively, by the same percentage, so that the maximum power point temperature coefficient ($\gamma$), also in the datasheet, matches the one predicted by this new 6-parameter model. Below are the equations that translate the temperature coefficients adjustment and the variation of the MPP with temperature [17].

$$\alpha'_{sc} = \alpha_{sc} \left(1 - \frac{\text{Adjust}}{100}\right) \quad (23)$$

$$\beta'_{oc} = \beta_{oc} \left(1 + \frac{\text{Adjust}}{100}\right) \quad (24)$$
The current generated by the incident radiation (source current in the 5-parameter model) varies almost linearly with the irradiation available but also depends on the temperature as can be seen in expression (26).

\[
I_L = \frac{G}{G_{STC}} \cdot \frac{AM_{STC}}{AM} \left[ I_{LSTC} + \alpha_{sc} (T_{cell} - T_{cell,STC}) \right]
\]

Where \( G \) is the irradiance and \( AM \) is the air mass modifier [17].

On the other hand, the saturation current of the diode representing the p-n junction only depends on the temperature:

\[
I_0 = I_{0ref} \left( \frac{T_{cell}}{T_{STC}} \right)^3 \exp \left[ \frac{1}{k_B} \left( \frac{E_g}{T_{STC}} - \frac{E_g}{T_{cell}} \right) \right]
\]

The energy bandgap \( (E_g) \) depends on the semiconductor used (1.12 eV for silicon), and has also its dependency on the temperature:

\[
E_g = E_{gSTC} \left[ 1 - 0.0002677(T_{cell} - T_{cell,STC}) \right]
\]

Parameter \( Rsh \) depends only on the incident irradiation:

\[
R_{sh} = R_{sh} \frac{G_{STC}}{G}
\]

Parameter \( R_s \) is considered constant no matter the temperature and irradiance conditions [17].

The ideality factor will be contained inside the parameter called modified nonideality factor \( (a) \) that also encapsulates the diode thermal voltage and the number of cells in series \( (N_c) \) in the module. Its equation and temperature dependence are described in (30) and (31).
Given all these temperature dependencies and the datasheet parameters, it is possible to formulate constraints to solve the module I-V equation and determine the six parameters \(a, R_s, R_{sh}, I_L, I_0, \text{Adjust}\) [17].

The first constraint derives from the short circuit condition where \(V = 0\) and \(I = I_{sc}\):

\[
I_{sc} = I_L - I_0 \left[ \exp \left( \frac{I_{sc}R_s}{a} \right) - 1 \right] - \frac{I_{sc}R_s}{a}
\]

(32)

The second constraint derives from the open circuit condition where \(V = V_{oc}\) and \(I = 0\):

\[
0 = I_L - I_0 \left[ \exp \left( \frac{V_{oc}}{a} \right) - 1 \right] - \frac{V_{oc}}{R_{sh}}
\]

(33)

The third constraint derives from the maximum power point, where \(I = I_{mp}\) and \(V = V_{mp}\):

\[
I_{mp} = I_L - I_0 \left[ \exp \left( \frac{V_{mp} + I_{mp}R_s}{a} \right) - 1 \right] - \frac{V_{mp} + I_{mp}R_s}{R_{sh}}
\]

(34)

The fourth constraint requires that the slope of the P-V curve be zero around the MPP: Since \(P=I\cdot V\) [17].

\[
\left. \frac{d(I\cdot V)}{dV} \right|_{mp} = I_{mp} - V_{mp} \left. \frac{d(I)}{dV} \right|_{mp} = 0
\]

(35)

The fifth constraint ensures that the manufacturer specified \(\beta_{oc}\) matches the value determined by the six-parameter model. \(V_{oc}\) temperature dependence is as follows:

\[
V_{oc(T')} = \beta_{oc} \left( 1 + \frac{\text{Adjust}}{100} \right) \Delta T + V_{oc_{STC}}
\]

(36)

Where \(T' = \Delta T + T_{STC}\).

Substituting in the open circuit constraint equation (33) with \(a, I_L\) and \(I_0\) and their temperature adjustments, stays:
\[
0 = \left[ \alpha_{sc} \left( 1 - \frac{\text{Adjust}}{100} \right) \Delta T + I_L \right] - I_{th} \left[ \exp \left( \frac{V_{oc'}}{a_{th}} \right) - 1 \right] - \frac{V_{oc'}}{R_{sh}}
\]  

(37)

The sixth and final constraint forces the manufacturer maximum power point temperature coefficient \((\gamma_{spec})\) to equal the maximum power point temperature coefficient calculated by the six-parameter model \((\gamma_{model})\):

\[
\gamma_{spec} - \gamma_{model} = 0
\]

(38)

These six nonlinear constraint equations are solved simultaneously using a globally convergent variant of Newton’s method. Through this methodology, a database of already pre-calculated six parameters for several solar panels of different manufacturers is available online in the already mentioned Toolbox [17].

### 3.4.2. Simulation Model with CEC Parameters

After performing the previous experiments and learning each component’s influence in the behavior of the system and impact on the I-V curve, simulations of short-circuit and open circuit cells were made.

Using a graphical programming environment for modeling, simulating and analyzing multidomain dynamical systems, containing the CEC parameter values for STC conditions, a five-parameter model of the PV cell from the STP190S-24Ad+, which was the panel available for testing, was created, as it can be seen in Figure 3.14.

![Figure 3.14 - Five parameter and one diode PV cell block model](image)

According to the CEC model, the values for this solar panel cell are \(R_{sh}=258.20\,\Omega\), \(R_s=0.6\,\Omega\), and \(I_L=5.633\,A\). 

---

50
There is more than one diode model available in the block library. The diode that correctly models the PV cell p-n junction is the exponential diode model. This diode model has CEC model parameters that can be seen in equation (19).

By creating a block with this circuit, we have a PV cell; by connecting them in series a PV cell string is obtained.

![Figure 3.15 - 24 PV cells string](image)

By connecting a string of PV cells like the one seen in Figure 3.15 in parallel with a bypass diode and in series with other strings, a PV panel is obtained as can be seen in Figure 3.16.

![Figure 3.16 - 72 cells PV panel](image)

Creating a block out of this PV panel, connecting it with a load, an electrical ground, and sensors for voltage and current measurements, the PV monitoring system is obtained.
The load was defined as the MPP load, \( R_{mp} = \frac{V_{mp}}{I_{mp}} \), in order to set the operating point of the system in MPP conditions, since the input parameters for the model are the CEC parameters in STC conditions.

We can observe in Figure 3.17 that the voltage reading correctly corresponds to the expected maximum power voltage, \( V_{mp} = 36.69 \text{ V} \), for STC conditions, given in the datasheet of the panel.

Using this model, faults were induced in the system. As an example, ten short-circuited cells were introduced in Panel 1, as can be seen in the image below.
As it is possible to observe the voltage in Panel 1 (Figure 3.18) reduced from 36.69 V to 31.97 V this reduction of 4.99 V matches the expected since each cell has a voltage drop of around 0.5, i.e., 5 V for ten cells in short-circuit.

In figure 3.19, the I-V curve of the simulated panel can be seen, the voltage and current values from the datasheet of the panel approximately match the ones obtained.
4. Power Variations

In this chapter power loss induced by temperature variation along the year and its influence in fault
detection in PV systems will be presented.

4.1. Power Variation with Temperature

The voltage, current and consequently the power generated in a PV cell vary depending on irradiance
and cell temperature values which affect the short-circuit and open-circuit voltage temperature
coefficients, $\alpha_{sc}$ and $\beta_{oc}$, correspondently.

Through the NASA database, POWER DATA ACCESS VIEWER, sets of meteorological data were
obtained [18].

Firstly, a connection to the NASA Surface meteorology and Solar Energy database for a particular
location is needed. This is made by selecting the “Power single point solar access” for taking data for a
specific point on the map, Lisbon area was picked (Lat: 38.7207 | Lon: -9.1582) [18].

Following, keeping the default selection *SSE-Renewable energy selection, a temporal average had
to be chosen. The inter-annual option was picked since it presents the monthly average radiation for the
chosen years in this case 2018. The monthly option was picked since it presented a significant difference
in the values obtained between months, while in the daily average temperature sampling, the values did
not present a significant difference between them [18].

At last, the selection of the desired output file format and the selection of the desired meteorological
parameters to be presented are asked. The output format of ASCII and the following meteorological
parameters were selected, as shown in Figure 4.1.
The results for the chosen parameters of irradiance and temperature obtained are listed in Table 4.1.

**Table 4.1 - 2018 Average irradiance and maximum and minimum temperature [18]**

<table>
<thead>
<tr>
<th></th>
<th>JAN</th>
<th>FEB</th>
<th>MAR</th>
<th>APR</th>
<th>MAY</th>
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<th>AUG</th>
<th>SET</th>
<th>OCT</th>
<th>NOV</th>
<th>DEC</th>
<th>ANN</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tmax (°C)</td>
<td>15,0</td>
<td>14,5</td>
<td>14,93</td>
<td>17,0</td>
<td>19,5</td>
<td>21,8</td>
<td>23,3</td>
<td>26,94</td>
<td>25,9</td>
<td>21,8</td>
<td>16,9</td>
<td>16,2</td>
<td>19,5</td>
</tr>
<tr>
<td>Tmin (°C)</td>
<td>9,49</td>
<td>8,21</td>
<td>10,4</td>
<td>11,5</td>
<td>12,7</td>
<td>15,5</td>
<td>17,0</td>
<td>17,69</td>
<td>17,5</td>
<td>14,8</td>
<td>12,2</td>
<td>10,4</td>
<td>13,1</td>
</tr>
<tr>
<td>IRR(_{avg}) (W/m(^2))</td>
<td>230</td>
<td>326</td>
<td>400</td>
<td>517</td>
<td>640</td>
<td>637</td>
<td>682</td>
<td>664</td>
<td>508</td>
<td>389</td>
<td>225</td>
<td>208</td>
<td>451</td>
</tr>
</tbody>
</table>

Since \(\alpha_{sc}\) and \(\beta_{oc}\), change with irradiance and temperature thus affecting the power produced, the fault sensibility of any monitoring system needs to vary along the year in order to differentiate a fault, from a voltage deviation or a power loss originated by the temperature increase. A monthly temperature reference calibration is proposed.

As previously said, a significant difference in temperatures and irradiance between months is observed, e.g., even if the irradiance is much higher in August as it can be seen in Table 4.1, the temperature is also much higher, and this will have as a consequence an associated power loss and voltage deviation.
The smooth performance of a solar PV module is strongly geared to the factor temperature. Higher than standard conditions temperatures can mean losses in maximum output power which is why we would usually aim at optimally cooling the modules.

Each solar cell technology comes with a set of unique temperature coefficients. These temperature coefficients are crucial; the temperature of the solar cell has a direct influence on all electrical quantities being produced by it. Once the temperature at which a solar PV cell operates increases, its voltage and power output will decrease significantly, and its current will slightly increase.

Crystalline solar cells are the leading cell technology and usually come with a temperature coefficient of the maximum output power of -0.5%/°C. For the panel used this coefficient presents a value of -0.45%/°C which is better than the average value. The open-circuit voltage temperature coefficient ($\beta_{oc}$) for this panel is -0.34%/°C. The rated power as generally indicated on the module’s label is measured at 25°C, STC conditions, with any temperature increase above it; there is an associated maximum power loss of 0.9% and an open-circuit voltage decrease of 0.68%/2°C increase [19].

Most installed solar modules in sunny countries easily reach higher temperatures than 25°C. Cell temperatures of 50°C and above are easily reached [18].

There is a simplified module temperature model that consists of assuming that the module temperature concerning the ambient temperature is directly proportional to the incident irradiance multiplied by a constant [20-21].

\[ \theta_m = \theta_a + kG \] (39)

Where $\theta_m$ is the module temperature in (°C), $\theta_a$ is the ambient temperature in (°C), $G$ is the incident irradiance in (mW/cm²), and $k$ is the Ross constant with a value of 0.3 in (cm².°C.mW⁻¹) [21].

In order to obtain the incident solar irradiance, SOLCAST API Toolkit was used. It is a web user interface that makes it possible to obtain irradiance data from their solar radiation database. They have solar irradiance and weather data that extends up to 15 years. The data is highly accurate and near-zero bias [22]. The data obtained presents the GHI (Global Horizontal Irradiance) in (W/m²) at a sampling interval of 30 minutes, from 01/01/2018 until 03/06/2019, this time frame is defined by the user as well as the location. The location chosen was the North Tower of IST. The time the API (Application Programming Interface) takes to present the data depends on the chosen sampling interval.

Table 4.2 lists the averaging the maximum incident irradiances in (W/m²) for all the months of 2018, this can also be seen in Figure 4.2.
Using the maximum and minimum average temperatures obtained with the NASA database and averaging the maximum and minimum incident irradiances obtained through SOLCAST API Toolkit, the calculation of the average maximum power loss for each month is possible. This allowed the observation of the power and voltage variation with temperature and irradiance throughout the year at the chosen location.

The average module maximum temperature in °C, computed with (39) is:

Table 4.3 - Average module monthly temperature in °C

<table>
<thead>
<tr>
<th>JAN</th>
<th>FEB</th>
<th>MAR</th>
<th>APR</th>
<th>MAY</th>
<th>JUN</th>
<th>JUL</th>
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<th>SEP</th>
<th>OCT</th>
<th>NOV</th>
<th>DEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>28,66</td>
<td>32,22</td>
<td>35,10</td>
<td>42,32</td>
<td>48,48</td>
<td>49,56</td>
<td>51,81</td>
<td>54,30</td>
<td>49,14</td>
<td>40,07</td>
<td>30,23</td>
<td>29,26</td>
</tr>
</tbody>
</table>
The minimum irradiance is 0, and so for $G = 0 \text{ W/m}^2$, using (39), the equality (40) is obtained.

$$\theta_m = \theta_a$$

(40)

Since the lower temperature values correspond to the time of the day with small to non-existent radiation, these are not considered.

Having obtained the module average monthly temperatures for 2018, (Table 4.3 and Figure 4.3), and knowing the maximum output power and open-circuit voltage temperature coefficients, the computation of the associated average maximum power and open-circuit voltage decrease was carried out.

Firstly, it is needed to compute the difference in ($^\circ$C) between the module temperature $\Theta_m$ and the $25^\circ$C of the STC reference conditions:

$$\theta_m - \theta_{STC} = \Delta\theta$$

(41)

<table>
<thead>
<tr>
<th>JAN</th>
<th>FEB</th>
<th>MAR</th>
<th>APR</th>
<th>MAY</th>
<th>JUN</th>
<th>JUL</th>
<th>AUG</th>
<th>SEP</th>
<th>OCT</th>
<th>NOV</th>
<th>DEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>3.66</td>
<td>7.22</td>
<td>10.10</td>
<td>17.32</td>
<td>23.48</td>
<td>24.56</td>
<td>26.81</td>
<td><strong>29.30</strong></td>
<td>24.14</td>
<td>15.07</td>
<td>5.23</td>
<td>4.26</td>
</tr>
</tbody>
</table>

Table 4.4 - Monthly temperature variation $\Delta\Theta$ of the module with the STC condition of 25$^\circ$C in $^\circ$C
Multiplying the monthly temperature variation $\Delta \Theta$ by the maximum output power loss (42) and by the open-circuit voltage (43) temperature coefficients, the power and voltage decrease percentage due to the temperature factor is obtained, listed in Table 4.5, and Table 4.6.

\[
\Delta P(\%) = \Delta \Theta \cdot \gamma
\]  

(42)

Table 4.5 - Monthly power losses in (%) for the maximum irradiance hour ($\Delta P(\%)$)

<table>
<thead>
<tr>
<th></th>
<th>JAN</th>
<th>FEB</th>
<th>MAR</th>
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<th>OCT</th>
<th>NOV</th>
<th>DEC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>-1.65</td>
<td>-3.25</td>
<td>-4.55</td>
<td>-7.79</td>
<td>-10.57</td>
<td>-11.05</td>
<td>-12.06</td>
<td>-13.19</td>
<td>-10.86</td>
<td>-6.78</td>
<td>-2.36</td>
<td>-1.92</td>
</tr>
</tbody>
</table>
Figure 4.5 - Monthly power losses in (%) for the maximum irradiance hour ($\Delta P(\%)$)

\[ \Delta V(\%) = \Delta \theta \cdot \beta_{ac} \] (43)

Table 4.6 - Monthly voltage losses in (%) for the maximum irradiance hour ($\Delta V(\%)$)

<table>
<thead>
<tr>
<th>JAN</th>
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</thead>
</table>

Figure 4.6 - Monthly voltage losses in (%) for the maximum irradiance hour ($\Delta V(\%)$)
For the solar panel used in the lab, STP190S-24/Ad+ from SUNTECH with 72 cells, with a maximum power at STC of 190 W and an open-circuit voltage of 45.2 V the associated maximum average power loss in (W), (Table 4.7), and maximum open-circuit voltage decrease in (V), (Table 4.8), for each month of 2018 is given by (44) and (45).

\[ \Delta P(W) = \text{PowerLoss} \% \times P_{\text{max,STC}} \] (44)

Table 4.7 - Monthly power losses \(\Delta P\) in (W) for maximum irradiance hour in the STP190S-24/Ad+ PV panel

<table>
<thead>
<tr>
<th></th>
<th>JAN</th>
<th>FEB</th>
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<th>SEP</th>
<th>OCT</th>
<th>NOV</th>
<th>DEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta P)</td>
<td>-3,13</td>
<td>-6,17</td>
<td>-8,64</td>
<td>-14,81</td>
<td>-20,07</td>
<td>-21,00</td>
<td>-22,92</td>
<td>(-25,05)</td>
<td>-20,64</td>
<td>-12,88</td>
<td>-4,48</td>
<td>-3,64</td>
</tr>
</tbody>
</table>

Figure 4.7 - Monthly power losses \(\Delta P\) in (W) for maximum irradiance hour in the STP190S-24/Ad+ PV panel

\[ \Delta V(V) = \text{VoltageDecrease} \% \times V_{\text{o,c,STC}} \] (45)

Table 4.8 - Monthly voltage losses \(\Delta V\) in (V) for maximum irradiance hour in the STP190S-24/Ad+ PV panel

<table>
<thead>
<tr>
<th></th>
<th>JAN</th>
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<th>JUL</th>
<th>AUG</th>
<th>SEP</th>
<th>OCT</th>
<th>NOV</th>
<th>DEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>(\Delta V)</td>
<td>-0,56</td>
<td>-1,11</td>
<td>-1,55</td>
<td>-2,66</td>
<td>-3,61</td>
<td>-3,78</td>
<td>-4,12</td>
<td>(-4,50)</td>
<td>-3,71</td>
<td>-2,32</td>
<td>-0,80</td>
<td>-0,65</td>
</tr>
</tbody>
</table>
This means that the average maximum power ($MP$) produced (46) and open-circuit voltage ($OCV$) (47) in the hours of maximum solar irradiation are given by:

$$MP(W) = P_{max_{STC}} + \Delta P(W)$$

Table 4.9 - Monthly average maximum power produced in (W) at a maximum irradiance hour

<table>
<thead>
<tr>
<th>MONTH</th>
<th>JAN</th>
<th>FEB</th>
<th>MAR</th>
<th>APR</th>
<th>MAY</th>
<th>JUN</th>
<th>JUL</th>
<th>AUG</th>
<th>SEP</th>
<th>OCT</th>
<th>NOV</th>
<th>DEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>power</td>
<td>186.8</td>
<td>183.8</td>
<td>181.3</td>
<td>175.1</td>
<td>169.9</td>
<td>169.0</td>
<td>167.0</td>
<td><strong>164.9</strong></td>
<td>169.3</td>
<td>177.1</td>
<td>185.5</td>
<td>186.3</td>
</tr>
</tbody>
</table>
Figure 4.9 - Monthly average maximum power produced in (W) at a maximum irradiance hour

\[ OCV(V) = V_{ocSTC} + \Delta V(W) \]  \hspace{1cm} (47)

Table 4.10 - Monthly average open-circuit voltage in (V) at a maximum irradiance hour

<table>
<thead>
<tr>
<th>JAN</th>
<th>FEB</th>
<th>MAR</th>
<th>APR</th>
<th>MAY</th>
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<th>OCT</th>
<th>NOV</th>
<th>DEC</th>
</tr>
</thead>
<tbody>
<tr>
<td>44.64</td>
<td>44.09</td>
<td>43.65</td>
<td>42.54</td>
<td>41.59</td>
<td>41.08</td>
<td>40.70</td>
<td>41.49</td>
<td>42.88</td>
<td>44.40</td>
<td>44.55</td>
<td></td>
</tr>
</tbody>
</table>

Figure 4.10 - Monthly average open-circuit voltage in (V) at a maximum irradiance hour
When monitoring the PV system, these power and voltage losses need to be considered as these variations could be seen as a fault by the monitoring system. The system should be calibrated considering this variation so that the fault detection system differentiates a faulty panel from a power or voltage loss associated with temperature increase. For example, in the worst case in August 2018, the PV panel will be producing 164.95 W at the time of the highest solar irradiance due to the temperature increase of the cell. In case it is not calibrated, this creates a 25.5 W that could be indicated as a fault since the reference is 190 W.

If the detection method is calibrated monthly considering these new values as a reference, the uncertainty window will decrease. With the calibration, a new threshold for fault detection would be set, and faults could be detected more accurately.

4.2. Manufacturing Process Power Variation

In the datasheet of the PV panel STP190S-24Ad+, it is said by the manufacturer that a positive power deviation can exist and that it can vary from 0% to +5%. The monitoring system must be calibrated for the power deviation measured in each PV panel. This power deviation changes accordingly to the equipment used.

For this panel, there are 72 cells, and maximum power at STC conditions of 190 W, which using (48) corresponds to a power of 2.64 W per cell.

\[ P_{\text{cell}} = \frac{P_{\text{STC}}}{N_{\text{cell}}} \]  \hspace{1cm} (48)

Knowing that the maximum power deviation indicated by the manufacturer is +5%, the power produced by a cell can reach at least 2.772 W, which multiplied by the number of cells of the panel corresponds to a PV panel output power that varies between 190 W and 199.5 W, this corresponds according to (49) to a maximum power deviation of +9.5 W.

\[ \Delta P = P_{\text{max}} - P_{\text{STC}} \]  \hspace{1cm} (49)

There is the necessity of calibration; this power deviation should be considered. If the monitoring system is calibrated for the STC reference and there are faults in the PV system that correspond to that power value interval, the monitoring system will not be able to detect them.
5. Fault Detection Zone Evaluation

In this thesis, some recommendations for a fault detection method based on uncertainty induced by temperature variation are proposed, being uncertainty the threshold that separates a clear fault from a power loss of unknown origin. This could lead to a simple and comfortable method to implement because just voltage sensors and one current sensor are necessary per string.

The consequences at an electrical point of view of any defect in a PV panel will eventually lead to a short-circuited cell or an open-circuit. Taking this as a premise, these are faults being analyzed in this work specifically the short-circuit cell since open-circuit causes the activation of the bypass diode which corresponds to all the cells in the string being short-circuited and consequently losing all the power generated by the string.

Assuming that \( N_s \) is the number of panels in a string and that \( N_d \) is the number of panels monitored by a single voltage sensor, the power monitored by this sensor \( P_{sensor} \) is given by (50), and the total power in the string \( P_{string} \) is given by (51).

\[
P_{sensor} = N_d V_p I_d \\
P_{string} = N_s V_p I_d
\]

where \( V_p \) is the output voltage of the panel and \( I_d \) is the current in the string, the following relation is obtained:

\[
P_{weight} = \frac{P_{sensor}}{P_{string}} = \frac{N_d V_p I_d}{N_s V_p I_d} = \frac{N_d}{N_s}
\]

where \( P_{weight} \) is the weight of the power in (%) being monitored by the voltage sensor in the string. The value of \( P_{weight} \) will be defined after the operator decides the power loss uncertainty zone. The benefit of having a wider uncertainty zone is that fewer voltage sensors are necessary, which makes the monitoring system cheaper and less complex. The downside is that it increases the uncertainty of the monitoring system.

The accuracy of the decision made on whether the maintenance team should intervene or not will depend on the size of the uncertainty area. Allowing more uncertainty, the operator loses the accuracy of the monitoring system. Two different scenarios become possible inside the uncertainty area; the power loss could be caused by a temperature variation or by one or more faults. \( P_{weight} \) decreases with the reduction of the uncertainty zone.
Taking as an example the worst-case scenario for 2018, in the month of August an average voltage deviation for the maximum irradiance hour of -4.5 V (Table 4.8) can be expected per PV panel, if compared with the voltage drop loss associated with SC cells seen in Table 5.1, this corresponds to 9 SC cells and a power loss of 23.75 W. If two PV panels are covered by a voltage sensor these values will be doubled, and a voltage drop loss of 9 V with a power loss of 47.5 W become the new uncertainty zone range. The owner or operator of the installation should choose the number of panels in series being monitored by each voltage sensor, caring for this uncertain fault detection zone size caused by power variation induced by temperature increase.

Table 5.1 - SC cells associated power and voltage losses

<table>
<thead>
<tr>
<th>Short-Circuit Cells</th>
<th>Voltage Drop Loss (V)</th>
<th>Voltage Drop Loss (%)</th>
<th>Power Loss (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.50</td>
<td>1.4%</td>
<td>2.64</td>
</tr>
<tr>
<td>2</td>
<td>1.00</td>
<td>2.8%</td>
<td>5.28</td>
</tr>
<tr>
<td>3</td>
<td>1.50</td>
<td>4.2%</td>
<td>7.92</td>
</tr>
<tr>
<td>4</td>
<td>2.00</td>
<td>5.6%</td>
<td>10.56</td>
</tr>
<tr>
<td>5</td>
<td>2.50</td>
<td>6.9%</td>
<td>13.19</td>
</tr>
<tr>
<td>6</td>
<td>3.00</td>
<td>8.3%</td>
<td>15.83</td>
</tr>
<tr>
<td>7</td>
<td>3.50</td>
<td>9.7%</td>
<td>18.47</td>
</tr>
<tr>
<td>8</td>
<td>4.00</td>
<td>11.1%</td>
<td>21.11</td>
</tr>
<tr>
<td>9</td>
<td>4.50</td>
<td>12.5%</td>
<td>23.75</td>
</tr>
<tr>
<td>10</td>
<td>5.00</td>
<td>13.9%</td>
<td>26.39</td>
</tr>
<tr>
<td>11</td>
<td>5.50</td>
<td>15.3%</td>
<td>29.03</td>
</tr>
<tr>
<td>12</td>
<td>6.00</td>
<td>16.7%</td>
<td>31.67</td>
</tr>
</tbody>
</table>

The power and voltage loss uncertainty percentage remain the same with the increase of the number of panels covered by a voltage sensor, what will change is the power on which this percentage is applied which will have implications on the choice of the number of panels being monitored by each sensor. As an example, if 8 STP190S -24/Ad+ PV panels were to be connected in series a total power of 1520 W would be produced at STC conditions. Covering this group composed by 8 panels with a voltage sensor, would result in an uncertainty zone of 190 W (Table 5.2) resulting from the temperature variation in the month of August. This means that an uncertainty region with the range of power equivalent to a PV panel would be admitted therefore the owner of the plant would have to decide on how much power loss he can tolerate as an uncertainty window.

If the system is calibrated for power and voltage reference values that account for temperature variations (in this case monthly) the false alarm window diminishes.
Multiple arrangements for the position of the voltage sensors can be made as long as they measure voltage drops between nodes of the same string. The size of the uncertainty zone is a decision of the PV plant owner. The certainty of fault only exists when the maximum power loss due to temperature variation is overcome. If the power loss value falls inside the power variation due to temperature increase variation window, the outcome on whether a fault causes it or not will be inconclusive.

The no calibration leads to a power loss grey zone that increases with the number of panels in series being covered by a sensor, hence a fault or a false alarm can happen. In this case the deployment of a maintenance team to perform tests and substitute a faulty panel has a cost that has to be justified. Because of this the fault detection must have a significant level of certainty. Setting new monthly references, the uncertainty zone decreases and so the maintenance costs associated with false alarms on healthy panels.

In case of fault detection, in order to pinpoint the exact faulty panel, a team or technician is deployed on-site. The maintenance team has to carry measuring equipment to the field in order to pinpoint the faulty module inside the faulty zone. This method would require more time spent on the field by the maintenance team in comparison with other more immediate and precise methods, since tests need to be carried out on-site. The precision of this method is inversely proportional to the number of panels being monitored by the same voltage sensor.

Some problems may arise when using this approach. If there is a power variation in some of the panels in a given string and that the sum corresponds to the power deviation defined as a fault the system would still see it has a fault. The supposed detected fault might be the sum of the power loss due to the regular PV panel performance decrease with aging.

Table 5.2 - Uncertainty power and voltage range for the STP190S -24/Ad+

<table>
<thead>
<tr>
<th>PV Panels</th>
<th>Voltage Loss (V)</th>
<th>Power Loss (W)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>4,5</td>
<td>23,75</td>
</tr>
<tr>
<td>2</td>
<td>9</td>
<td>47,5</td>
</tr>
<tr>
<td>3</td>
<td>13,5</td>
<td>71,25</td>
</tr>
<tr>
<td>4</td>
<td>18</td>
<td>95</td>
</tr>
<tr>
<td>5</td>
<td>22,5</td>
<td>118,75</td>
</tr>
<tr>
<td>6</td>
<td>27</td>
<td>142,5</td>
</tr>
<tr>
<td>7</td>
<td>31,5</td>
<td>166,25</td>
</tr>
<tr>
<td>8</td>
<td>36</td>
<td>190</td>
</tr>
</tbody>
</table>
In case where the PV panels are covered by warranty and present an abnormal performance decrease that does not correspond to the expected specified by the manufacturers, the panels can be changed for new ones.

As explained before, the voltage and consequently the power produced varies with irradiance and temperature throughout the year. For this reason, for each month, the uncertainty zone can acquire different sizes, as shown in Figure 5.1.

![Figure 5.1 - Fault Decision Zones](image)

Observing Figure 5.1, if the power loss value corresponds to the orange zone a fault does or doesn’t exist, while if the power loss falls inside the yellow zone, a fault exists with certainty. If the power loss value falls into the orange zone it can be due to a fault or to the temperature increase and lead to a false fault alarm. If a new reference that starts in the yellow zone is set, the monitoring system will be able to detect faults much more accurately.

The problem of calibrating the system to new references values is that they are for the case of average maximum power loss of a given month. If the panel produces more power than the reference, then some fault might occur without notice. In this case, the power deviation is positive in relation to the reference if the fault power loss falls in that window the monitoring system will not detect it.

Applying this methodology with one panel per sensor and observing Table 5.3, the fault from SC fault simulated in (3.4.2) could be detected with certainty for all the months of the year. With less than ten
cells in short-circuit, fault detection could not be guaranteed, and its possible detection would depend on the corresponding month, e.g., nine short-circuited cells fault with a corresponding power loss of 23.75 W could not be guaranteed for the month of August since the uncertainty power loss window is 25.05 W.

For a power loss to fall inside the fault zone the following number of faults, listed in Table 5.3, must happen. If less than that number of faults occur the power loss will fall into the uncertainty zone. This case corresponds to one panel per sensor. The number of faults that can fall into the uncertainty zone increases with the number of panels being monitored by each voltage sensor.

<table>
<thead>
<tr>
<th>Months</th>
<th>Power Loss Uncertainty Zone (W)</th>
<th>SC</th>
<th>OC</th>
<th>BGHC</th>
<th>BGBC</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>n° of faults Ploss (W)</td>
<td>n° of faults Ploss (W)</td>
<td>n° of faults Ploss (W)</td>
<td>n° of faults Ploss (W)</td>
<td>n° of faults Ploss (W)</td>
</tr>
<tr>
<td>JAN</td>
<td>3.13</td>
<td>2</td>
<td>5.28</td>
<td>1</td>
<td>63,33</td>
</tr>
<tr>
<td>FEB</td>
<td>6.17</td>
<td>3</td>
<td>7.92</td>
<td>1</td>
<td>63,33</td>
</tr>
<tr>
<td>MAR</td>
<td>8.64</td>
<td>4</td>
<td>10.56</td>
<td>1</td>
<td>63,33</td>
</tr>
<tr>
<td>APR</td>
<td>14.81</td>
<td>6</td>
<td>15.83</td>
<td>1</td>
<td>63,33</td>
</tr>
<tr>
<td>MAY</td>
<td>20.07</td>
<td>8</td>
<td>21,11</td>
<td>1</td>
<td>63,33</td>
</tr>
<tr>
<td>JUN</td>
<td>21.00</td>
<td>8</td>
<td>21,11</td>
<td>1</td>
<td>63,33</td>
</tr>
<tr>
<td>JUL</td>
<td>22.92</td>
<td>9</td>
<td>23,75</td>
<td>1</td>
<td>63,33</td>
</tr>
<tr>
<td>AUG</td>
<td>25.05</td>
<td>10</td>
<td>26,39</td>
<td>1</td>
<td>63,33</td>
</tr>
<tr>
<td>SEP</td>
<td>20.64</td>
<td>8</td>
<td>21,11</td>
<td>1</td>
<td>63,33</td>
</tr>
<tr>
<td>OCT</td>
<td>12.88</td>
<td>5</td>
<td>13,19</td>
<td>1</td>
<td>63,33</td>
</tr>
<tr>
<td>NOV</td>
<td>4.48</td>
<td>2</td>
<td>5.28</td>
<td>1</td>
<td>63,33</td>
</tr>
<tr>
<td>DEC</td>
<td>3.64</td>
<td>2</td>
<td>5.28</td>
<td>1</td>
<td>63,33</td>
</tr>
</tbody>
</table>

As it can be observed in Table 5.3, the worst-case scenario happens in August where for fault detection to occur with certainty, 10 short-circuits, 1 open-circuit, 19 BGHC and 13 BGBG have to exist; otherwise the origin of the power loss cannot be accurately pinpointed.
6. Conclusions

In this thesis, a series of PV module failure detection methods were studied, and some possible fault detection method recommendations were made. Most of the existing fault detection methods can be complex and require expensive equipment and significant computational power. It was seen that the module temperature and solar irradiance have a significant impact on the power produced by a PV panel, hence the importance of developing a cheap and straightforward fault detection method that accounts for the variations of these physical quantities.

Solar panel efficiency is affected negatively as temperature increases. Photovoltaic modules are tested at a temperature of 25 degrees Celsius (STC) – about 77 degrees Fahrenheit, and depending on their installed location, heat can reduce its output efficiency by 10-25%. As the temperature of the solar panel increases, its output current increases marginally, while the voltage output is reduced linearly. The voltage reduction is so predictable that it can be used to measure temperature accurately.

The temperature coefficient of a SUNTECH STP190S -24/Ad+ is -0.45% per 1 degree Celsius. So, for every degree above 25 °C, the maximum power of the SUNTECH panel falls by 0.45%, for every degree below, it increases by 0.45%. What this means no matter where the panel is located, is that it will be affected by seasonal variations, hence the importance of a monthly reference calibration. However, the temperature coefficient also tells that the efficiency increases in temperatures below 25 °C. So, in most climates, the efficiency will balance out over the long run.

Three cells in different physical conditions were tested experimentally. The healthy cell, the healthy cell with a broken glass and a broken cell with broken front glass, presented the expected results as the there was a decrease of the output voltage from the healthy cell to the cells with the broken glass, regarding current the most significant loss was from the healthy cell to the broken cell.

Measuring systems include cabling, connectors and sensors, which have its own resistance, this means that a voltage drop will exist in these elements. In case the magnitude of this voltage drop is close to the one from the output of the cell or panel, the error in the voltage and current measurements will be significant and cannot be neglected. When making measurements the obtained values must be corrected as it was explained in this work.

Cells in open circuit revealed to be the most severe failure since it only takes one cell in open circuit to lose 1/3 of the module's power due to the activation of a bypass diode. On the other hand, short-circuited cells have a smaller impact on the module and the power loss is directly proportional to the number of short-circuited cells. Short-circuited cell location within the module is not relevant because it will not trigger a bypass diode, unlike a cell in open circuit. This said short-circuited cells are more
probable to fall on the uncertainty zone, while a few open circuits can easily overcome the uncertainty power loss zone since more power production is lost in each fault of this type.

After studying the negative impact of high temperature in PV cells, a possible future work would be to find a way on how to reduce the temperature of an operating PV system, by for example using the PV panel as a heat exchanger, absorbing the heat energy for some useful purposes.
7. References


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