FACULDADE DE ENGENHARIA DA UNIVERSIDADE DO PORTO

Aplicação de técnicas de aprendizagem profunda estruturada para diagnóstico de funcionamento de centrais fotovoltaicas.

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INICIAÇÃO À INVESTIGAÇÃO

MESTRADO EM ENGENHARIA ELETROTÉCNICA E COMPUTADORES

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Abstract

The increase in photovoltaic power plants has led to the need for effective methods for detecting and addressing component faults, which can have significant economic impacts. In this work, we will explore the current state of fault detection and state estimation tools in the field of PV systems, with a focus on understanding how these tools work and identifying their strengths and limitations. We will also propose improvements to existing approaches or develop a novel approach to address this issue. By examining the most successful tools to date and offering new solutions, we aim to help PV plant operators improve the reliability and efficiency of their systems.

Agradecimentos

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O Nome do Autor

“You should be glad that bridge fell down.
I was planning to build thirteen more to that same design”

Isambard Kingdom Brunel

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Abreviaturas e Símbolos

ADT	Abstract Data Type
ANDF	Architecture-Neutral Distribution Format
API	Application Programming Interface
CAD	Computer-Aided Design
CASE	Computer-Aided Software Engineering
CORBA	Common Object Request Broker Architecture
UNCOL	UNiversal COmpiler-oriented Language
Loren	Lorem ipsum dolor sit amet, consectetuer adipiscing elit. Sed vehicula lorem commodo dui
WWW	*World Wide Web*

Chapter 1

Introduction

The XIX century marked a significant shift in the world's perception of energy resources as the desire to invest in renewable energy sources to power modern societies grew. This transition was driven by the need to reduce dependency on fossil fuels, mitigate the effects of global warming, and slow climate change. Solar photovoltaic energy is a desirable renewable energy source due to its abundance, accessibility, and environmental benefits. Renewable energy sources offer a range of benefits, including reduced greenhouse gas emissions, improved air quality, and increased energy security. While solar photovoltaic energy has proven to be both cost-efficient and environmentally friendly, it also comes with unprecedented challenges, such as its intermittent nature, low electrical inertia, complex forecasting, and geographic-dependent operating conditions. Despite these challenges, recent reports **?** show that the economic benefits of investing in renewable energy outweigh the complications, as there is an increasing global investment trend in these sources.

The general construction of PV farms, particularly on the utility-scale, has led to a need for effective maintenance and monitoring to ensure maximum efficiency and operational reliability. To achieve this, various algorithms and routines are used to monitor the state of PV farms and identify any potential issues that may arise. Fault detection is a crucial aspect of this process, as it allows PV farm operators to identify and address any problems that may occur quickly. Given the importance of maintaining high levels of operation, knowing if action is needed to restore or fix components from an anomalous scenario is desirable. By detecting faults and identifying the necessary steps, PV farm operators can prevent or minimize downtime and ensure optimal performance.

Integrating intermittent energy resources into modern electric grids has led to stricter requirements for connecting such power systems to ensure safe grid operating conditions. As a result, companies that own or plan to build photovoltaic farms must comply with these requirements and have adequate power electronics and monitoring/control capabilities. Failure to meet these requirements can result in sanctions or fines for the responsible party, as well as potential impacts on system availability, asset value, and disturbance propagation to the grid. To minimize these risks and maximize the value of their assets, companies may opt to implement fault detection and state estimation tools. These tools allow for the early detection and resolution of potential issues and can prevent or minimize downtime. The need to create or improve existing fault detection and state estimation tools, and the search for the most effective methodologies for addressing these issues, drive research in this field.

Having laid the basis for why there must be system behavior assessment in utility-scale PV plants, it is necessary to understand what business concepts are crucial to this field. In the course of this work, the presented topics will go over the following questions:

- What components mostly fail in photovoltaic power systems?
- What is the average frequency of faults?
- What fault detection/state estimation tools exist for photovoltaic power systems?
- What are the most successful ones?
- What's their structure? Are they mostly centralized or decentralized?
- What are their computational costs/efficiency?
- What is the expected magnitude of precision and confidence?
- Which key performance indicators can evaluate the success of these tools?
- What are their implementation difficulties?

With these questions uncovered, the main objective is to adapt or design a novel algorithm/approach to fault detection based on modern artificial intelligence solutions. However, this can be split up into finer goals:

- Identify and study existing fault detection tools for photovoltaic power systems.
- Adapt or develop a new tool.
- Apply and test the new tool in real case study PV assets.
- Validate the developed methodologies by comparison to reference tools.

Before reviewing state-of-the-art fault detection tools, types of failures in photovoltaic systems need to be understood: find which components usually fail, which ones fail more often, and how often. For this, it is necessary to understand such components' physical and electrical properties and the modeling techniques used to characterize them. There will be an assessment of utility-scale power plants architecture through literature, alongside the detection objective of state-of-the-art fault detection tools applied in this field. Then, there shall be an extensive analysis and review of what tools have been designed and used in this field. In this step, critical evaluation of the literature is a must for understanding the tool's scope, ease of implementation, and understanding that the data sets available for this work are compatible. Having selected the most prominent ones, they're to be qualitatively and quantitatively compared to each other in their application context so that the results allow objective evaluations. This process requires implementing these tools, following the guidelines in the respective article/book/report, verifying their metrics, and checking if the achieved results resemble the same as the literature suggests. It will require gathering data sets, which can either be artificially generated through simulation or provided by an enterprise that services photovoltaic plant owners.

There's a desire that, in the end, the developed work helps achieve an improved method for fault detection and state estimation in photovoltaic power systems, resulting in a production-ready software application agile enough to deploy for any PV assets. Depending on the new algorithm's characteristics, it could result in an approach capable of generalization and application to other engineering systems, benefiting more than just PV systems. No matter the chosen methodology, fault detection will, in most cases, result in an economic benefit, catastrophe prevention, and safety increase. Those are a few positive contributions that are possible for this work's outcome.

Chapter 2

Fault detection in Utility Scale PV Plants

2.1 PV Plant's architecture and components

Utility-scale photovoltaic (PV) power plants are large-scale PV systems that are connected to the electrical grid and have installed capacities ranging from kilowatts peak (kWp) to megawatts peak (MWp). These systems typically consist of many PV panels interconnected through power electronics to aggregate and inject active power into the grid. The number and type of components in a PV power plant depend on the plant's scale and topology, with different configurations possible for large-scale applications, including central inverters, string inverters, and multi-string inverters **?**. Understanding the architecture and components of PV power plants is important for designing, operating, and maintaining these systems, as it helps optimize their performance and reliability.

In figure **??**, the fourth configuration presented (d) will not be considered for utility-scale plants due to its expensive nature. After DC/AC conversion, another voltage conversion step usually establishes the grid connection: an AC/AC transformer.

For completeness, the physical installation of PV modules can include solar tracking apparatuses, such as single and dual-axis trackers, which add to system complexity and change production behavior. Nonetheless, and turning the focus back toward the electrical components, the main ones are the following:

- Solar photovoltaic panels.
- Electric cabling.
- Inverter(s) (mostly with Max Power Point Trackers).
- AC Transformer(s).
- Protection components (circuit breakers, fuses, surge protectors, etc.)

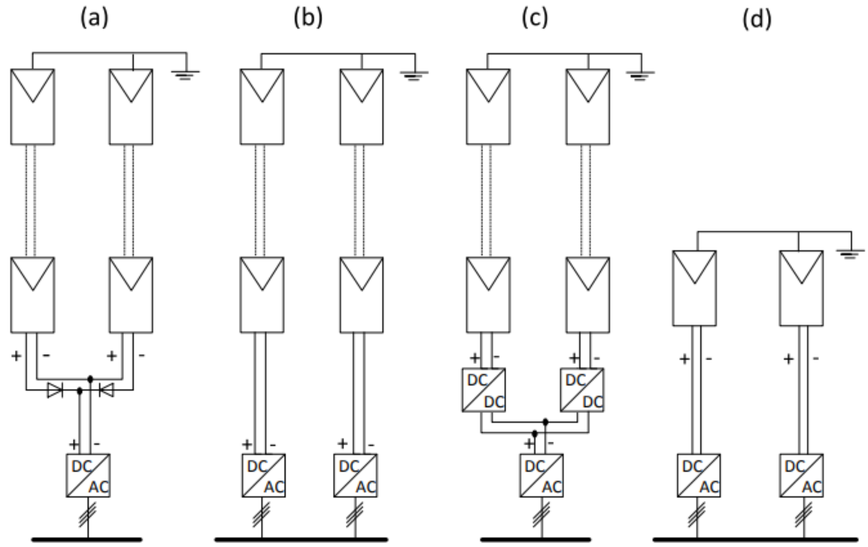

Figure 2.1: PV inverter topologies: (a) Central, (b) String, (c) Multi-string, (d) Module integrated **?**.

Most of these components have intrinsic variables, such as voltage and current values, that can help determine their operation states. Given that the utility grids (and the associated electricity market) integrate large-scale PV assets, some of the before-mentioned components require constant monitoring and control, achieved with adequate embedded systems and sensor infrastructure **?**. Thanks to the continuous advancements in communication technologies, namely in IoT (Internet Of Things), data acquisition is becoming faster, more reliable, and more precise. Not only is this fundamental for real-time asset assessment, but it also allows better training of prediction algorithms. However, on the industrial scale (in the order of MWp production), having sensors embedded in every PV module comes with a significant economical cost, and inverters are the components that usually possess monitoring capabilities.

2.2 Types of faults

Several types of faults can occur in utility-scale photovoltaic (PV) power plants, which can negatively impact the performance and reliability of the system, possibly causing safety hazards **?**. Some are challenging to detect and protect the electrical installation against, thus requiring more sophisticated detection algorithms **?**. According to **?**, these faults can mainly be classified into three categories: electrical, mechanical, and environmental. Electrical faults include issues such as short circuits, open circuits, and inverter failure, which can affect the PV panels' power output and the system's overall efficiency. Mechanical faults include issues such as broken panels, damaged cables, and defective inverters, which can lead to system downtime and reduced performance. Environmental faults include issues such as extreme weather events, such as hail or strong winds, which can damage the PV panels and other components **?**.

figures/chapter2/types_of_faults.pdf

Figure 2.2: Classification of faults in PV Systems, from **??**.

Throughout the literature **?**, some of the most studied faults in the context of fault detection are shading, module mismatch, soiling, short circuit (line to line and line to ground), open circuit, hot spot faults, and DC arc fault. Due to the difficulty of classifying some of these faults given their similarity (consequent effect in the system), it will be seen in further sections that most fault detection algorithms can only classify between two to five types of faults.

2.3 Modeling photovoltaic's physical behavior

Accurate modeling of photovoltaic (PV) modules is essential for characterizing their performance from the power converters' direct current (DC) side in a PV power plant. This information is critical for designing and optimizing PV power systems, as it allows for predicting the PV module's performance under different operating conditions, such as varying levels of solar irradiance and temperature. In addition, accurate PV module models are essential for state estimation and fault detection, as they can provide important information about the health and performance of the PV modules and allow for early identification of potential issues. Moreover, they can be used to optimize the control and operation of PV power systems, which can improve the overall efficiency and reliability of the system.

There are several state-of-the-art methods for modeling photovoltaic (PV) modules, which can be broadly categorized into two types: physical models and empirical models [1]. Physical models are based on the fundamental physical principles that govern the operation of PV modules and typically require detailed knowledge of the PV module's electrical and optical properties, such as its current-voltage (I-V) characteristics, spectral response, and temperature dependence [2]. These models can accurately predict the PV module's performance under a wide range of operating conditions, but they may be complex and computationally intensive to implement [3]. On the other hand, empirical models are based on experimental data and are typically simpler and easier to implement, but may not be as accurate as physical models, especially under conditions that differ significantly from those used to generate the experimental data [4]. Some examples of state-of-the-art physical models for PV modules include the single diode model [5], the two diode model [6], and the detailed balance model [7], while some examples of state-of-the-art empirical models include the P-V model [8] and the temperature correction model [9]. The choice of modeling method will depend on the specific application and the required level of accuracy and complexity; in some cases, a combination of physical and empirical models may be used [4].

If the need arises to model PV modules in this work, it is important to select a methodology that is simple enough that the module's datasheet characteristics are sufficient for accurate modeling. This is particularly important in the case of utility-scale PV systems, where detailed knowledge of the module's electrical and optical properties may not be readily available, and only datasheet data may be used for modeling. Using a complex model that requires more detailed information may not be feasible in such cases, and a simpler model that relies on fewer input parameters may be more appropriate. The single-diode model seems appropriate for this use case, given the good trade-off between complexity and accuracy.

2.3.1 Five parameter model

The five-parameter model, also known as the P-V model or the five coefficient model, is based on experimental data and relatively simple to implement, making it a popular choice for PV performance modeling.

The P-V model represents the PV module's current-voltage (I-V) characteristics as a function of solar irradiance and temperature. The model is based on the following equation:

I = $I_0 + I_pv - I_s - I_sh$

where I is the current generated by the PV module, $I_0 isthedarkcurrent, I_pvisthephotovoltaiccurrent, I_sistheseriesresis$

The five parameters in the model are $I_0, I_pv, I_s, I_sh, andV_oc, representingthedarkcurrent, photovoltaiccurrent, seriesre$
$circuitvoltageofthePVmodule, respectively. Theseparameterscanbedeterminedfromexperimentaldataormeasureddire$

Once the parameters have been determined, the P-V model can be used to predict the PV module's performance under a wide range of operating conditions, such as different levels of solar irradiance and temperature. However, it is worth noting that the accuracy of the P-V model may be limited, especially under conditions significantly different from those used to generate the experimental data.

2.4 Anomaly detection algorithms

The tools dedicated to fault detection and state estimation mostly come from mathematical/statistical methodologies, machine learning, and deep learning applications **?**. Parting from the three general problem-solving principles mentioned, machine learning and deep learning are the most popular and successful ones for recent applications that ought to solve complex problems. Such potential has led to an interest in their implementation for the renewable energy sector.

2.4.1 Statistical Methodologies

Statistical methodologies usually look into historical data to find the characteristics of how samples relate to the population (interpolation). These methodologies yield good results in case studies of PV farms that have been logging data for a considerable time, suffering in the cases that don't. Therefore, they are limited in that it's required to have curated data sets of historical significance for relevant features of the studied systems.

2.4.2 Machine Learning Methodologies

Machine learning came to solve some of the complications referred to in the two past subjects, as neural networks (or other learning structures) are easily capable of modeling complex, non-trivial, and nonlinear relations between data. Still, they are as good as the training data, with many structures requiring many representative learning examples to achieve good results. Their output can also be very obfuscated, meaning that many methods don't allow a direct interpretation of the relationship between inputs and outputs: this "black-box" characteristic, specifically of neural networks, is seen as a disadvantage. Besides, extrapolating data remains a challenge when classically using these structures. Still, they have immense applications for PV systems, from MPP (Max Power Point) estimation to power forecasting, soiling, and fault prediction.

2.4.3 Deep Learning Methodologies

The field of deep learning branches off from machine learning, with the term "deep" referring to amplified machine learning structures that ought to understand data patterns. A simple example would be the design of an artificial neural network with multiple hidden layers, with the intuition that each of these "extra" layers achieves feature/pattern recognition in a cascade. They have been explored alongside machine learning techniques for PV systems, although the known disadvantage is a usually high computational cost and relatively tricky implementation.

While classical fault detection lies in the synchronous and direct evaluation of state estimation variables, fault prediction requires the input of time-series features. Although relatively simple, some classical time-series forecasting and analysis tools can be of great support to help design a fault prediction algorithm, such as Box-Jenkins methods and the Partial Auto-correlation function. Still, the majority of modern prediction tools comprise neural networks and variations. With this in mind, recent developments in the intelligent composition of learner structures spark some interest in the application to this field, such as the new deep learning technique named Cell Complex Neural Networks **?**. Further investigation of such modern practices will unroll throughout the development of this work.

Chapter 3

Capítulo Exemplo

Neste capítulo apresentam-se exemplos de formatação de figuras e tabelas, equações e referências cruzadas.

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3.1 Introdução

Apresenta-se de seguida um exemplo de equação, completamente fora do contexto:

$$CIF_1: \quad F_0^j(a) = \frac{1}{2\pi\imath}\oint_\gamma \frac{F_0^j(z)}{z-a}dz \tag{3.1}$$

$$CIF_2: \quad F_1^j(a) = \frac{1}{2\pi\imath}\oint_\gamma \frac{F_0^j(x)}{x-a}dx \tag{3.2}$$

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3.2 Secção Exemplo

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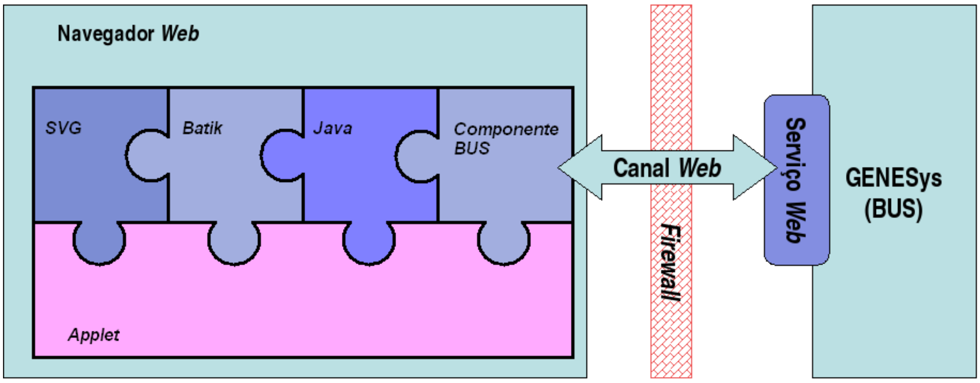

Figure 3.1: Arquitectura da Solução Proposta

- **Praesent** — Sit amet sem maecenas eleifend facilisis leo;
- **Pellentesque** — Habitant morbi tristique senectus et netus.

3.2.1 Exemplo de Figura

É apresentado na Figura **??** da página **??** um exemplo de figura flutuante que deverá ficar no topo da página.

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3.2.2 Exemplo de Tabela

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Table 3.1: Tabela Exemplo

Iteração k de $f(x_n)$				
k	x_1^k	x_2^k	x_3^k	comentários
0	-0.3	0.6	0.7	-
1	0.47102965	0.04883157	-0.53345964	$\delta < \varepsilon$
2	0.49988691	0.00228830	-0.52246185	$\delta < \varepsilon$
3	0.49999976	0.00005380	-0.523656	N
4	0.5	0.00000307	-0.52359743	
$\vdots$	$\vdots$	$\ddots$	$\vdots$	
7	0.5	0.0	**-0.52359878**	$\delta < 10^{-8}$

3.3 Secção Exemplo

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3.4 Resumo

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Chapter 4

Mais um Capítulo

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4.1 Secção Exemplo

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4.2 Mais uma Secção

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4.3 Resumo ou Conclusões

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Chapter 5

Conclusões e Trabalho Futuro

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5.1 Satisfação dos Objectivos

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5.2 Trabalho Futuro

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Appendix A

Loren Ipsum

Depois das conclusões e antes das referências bibliográficas, apresenta-se neste anexo numerado o texto usado para preencher a dissertação.

A.1 O que é o *Loren Ipsum*?

Lorem Ipsum is simply dummy text of the printing and typesetting industry. Lorem Ipsum has been the industry's standard dummy text ever since the 1500s, when an unknown printer took a galley of type and scrambled it to make a type specimen book. It has survived not only five centuries, but also the leap into electronic typesetting, remaining essentially unchanged. It was popularised in the 1960s with the release of Letraset sheets containing Lorem Ipsum passages, and more recently with desktop publishing software like Aldus PageMaker including versions of Lorem Ipsum (**?**).

A.2 De onde Vem o Loren?

Contrary to popular belief, Lorem Ipsum is not simply random text. It has roots in a piece of classical Latin literature from 45 BC, making it over 2000 years old. Richard McClintock, a Latin professor at Hampden-Sydney College in Virginia, looked up one of the more obscure Latin words, consectetur, from a Lorem Ipsum passage, and going through the cites of the word in classical literature, discovered the undoubtable source. Lorem Ipsum comes from sections 1.10.32 and 1.10.33 of "de Finibus Bonorum et Malorum" (The Extremes of Good and Evil) by Cicero, written in 45 BC. This book is a treatise on the theory of ethics, very popular during the Renaissance. The first line of Lorem Ipsum, "Lorem ipsum dolor sit amet...", comes from a line in section 1.10.32.

The standard chunk of Lorem Ipsum used since the 1500s is reproduced below for those interested. Sections 1.10.32 and 1.10.33 from "de Finibus Bonorum et Malorum" by Cicero are also reproduced in their exact original form, accompanied by English versions from the 1914 translation by H. Rackham.

A.3 Porque se usa o Loren?

It is a long established fact that a reader will be distracted by the readable content of a page when looking at its layout. The point of using Lorem Ipsum is that it has a more-or-less normal distribution of letters, as opposed to using “Content here, content here”, making it look like readable English. Many desktop publishing packages and web page editors now use Lorem Ipsum as their default model text, and a search for “lorem ipsum” will uncover many web sites still in their infancy. Various versions have evolved over the years, sometimes by accident, sometimes on purpose (injected humour and the like).

A.4 Onde se Podem Encontrar Exemplos?

There are many variations of passages of Lorem Ipsum available, but the majority have suffered alteration in some form, by injected humour, or randomised words which don’t look even slightly believable. If you are going to use a passage of Lorem Ipsum, you need to be sure there isn’t anything embarrassing hidden in the middle of text. All the Lorem Ipsum generators on the Internet tend to repeat predefined chunks as necessary, making this the first true generator on the Internet. It uses a dictionary of over 200 Latin words, combined with a handful of model sentence structures, to generate Lorem Ipsum which looks reasonable. The generated Lorem Ipsum is therefore always free from repetition, injected humour, or non-characteristic words etc.