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DOCTORAL THESIS:

The Impact of Renewable Energy Sources on the Quality of Electrical Power in Distribution Networks

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Content

List of abbreviations

ADN – Active Distribution Networks

aFRR – Automatic Frequency Restoration Reserve

AI – Artificial Intelligence

AID – Average Interruption Duration

AIF – Average Interruption Frequency

AIT – Average Interruption Time

AMI – Advanced Metering Infrastructure

ANOVA – Analysis of Variance

ANRE – National Energy Regulatory Authority

ANN – Artificial Neural Networks

ANSI – American National Standards Institute

AR – Autoregressive

ASAI – Average Service Availability Index

ASIDI – Average System Interruption Duration Index

ASIFI – Average System Interruption Frequency Index

ASUI – Average Service Unavailability Index

BAN – Body Area Network

BESS – Battery Energy Storage Systems

BPL – Processing and decision block

BPL – Broadband Power Lines

AC – Alternating Current

CAs – Operator Advisory CAs

CAIDI – Customer Average Interruption Duration Index

CAIFI – Indicele mediu de frecvență a întreruperilor pe client *(Customer Average Interruption Frequency Index)*

CEN –European standardization bodies

CENELEC – European standardization bodies

CCM – Current Control Module

CE – Continental Europe

CHE – Hydroelectric plant

CP1 – Principal Component 1

CP2 – Principal Component 2

CTE – Central European Time

CTE – Thermoelectric Power Plant

CDS – System Available Capacity

C-MSG – Current Message

CPD – Available Power Capacity

CPS – System Power Capacity

DC/AC – Direct Current to Alternating Current

DC – Direct Current

DER – Distributed Energy Resources

DFT – Discrete Fourier Transform

DG – Distributed Generation Integration

DMS – Distribution Management Systems

DR – Demand Response

DVR – Dynamic Voltage Restorer

DSP – Digital Signal Processing

EMC – Electromagnetic Compatibility

EMI – Electromagnetic Interference

EMS – Energy Management Systems

EMS-SCADA – Energy Management System — Supervisory Control and Data Acquisition

EN – European Norm

ENS – Energy Not Supplied

ENTSO-E – European Network of Transmission System Operators for Electricity

ESS – Energy Storage Systems

ETSI – European Telecommunications Standards Institute

EV – Electric Vehicles

FAN – Field Area Network

FCR – Frequency Containment Reserve

aFRR – Automatic Frequency Restoration Reserve

mFRR – Manual Frequency Restoration Reserve

FFT – Fast Fourier Transform

FACTS – Flexible AC Transmission Systems

FLISR – Fault Location, Isolation, and Service Restoration

FLC – Fuzzy Logic Controllers

FO – Fiber Optic

GIS – Geographic Information System

GL – Local Generation

GS – Synchronous Generator

HAN – Home Area Network

IAN – Industrial Area Network

ICS – Incident Classification Scale

IAS – Industry Applications Society

IEC – International Electrotechnical Commission

IED – Intelligent Electronic Devices

IEEE – Institute of Electrical and Electronics Engineers

IoT – Internet of Things

IPT – Instantaneous Power Theory

ISNS – ISNS Isolators for Network Stability

IT – High Voltage

JT – Low Voltage

λ**-droop** – λ-droop Control

LF – Fuzzy Logic

MAIFI – Momentary Average Interruption Frequency Index

MATLAB – Matrix Laboratory

MG – Microgrids

MLI – Multilevel Inverters

MPC – Model Predictive Control

MT – Medium Voltage

NAN – Neighborhood Area Network

NEMA – National Electrical Manufacturers Association

NFPA – National Fire Protection Association

NIST – National Institute of Standards and Technology

OD – Distribution Operator

OLTC – On-Load Tap Changer Control

OPCOM – Operator of the Electricity and Natural Gas Market

OTS – Transmission System Operator

PCA – Principal Component Analysis

PCC – Point of Common Coupling

PES – Power & Energy Society

PI – Proportional-Integral

PID – Proportional-Integral-Derivative

PMU – Phasor Measurement Units

PQ – Power Quality Standards

P&Q – Active and Reactive Power Control

QU-droop – QU-droop Control

PNS – Peak Not Supplied

PRAM – Protection, Relay, Automation, and Measurement

PU-droop – PU-droop Control

PV – Photovoltaic Systems

RNA – Artificial Neural Networks

RMS – Root Mean Square

RMSE – Root Mean Square Error

RTU – Remote Terminal Unit

SAIDI – System Average Interruption Duration Index

SAIFI – System Average Interruption Frequency Index

SCADA – Supervisory Control and Data Acquisition

SE – State Estimation

SEN – National Power System

SEE – Standard Error of the Estimate

SEM – Standard Error of the Mean

SEMI – Semiconductor Equipment and Materials International Standard

SI – Severity Index

SM – System Minutes

SOC – State of Charge

SRE – Renewable Energy Source

STLF – Short-Term Load Forecasting

SVC – Static Var Compensator

TCP/IP – Transmission Control Protocol/Internet Protocol

THD – Total Harmonic Distortion

TIF – Telephone Interference Factor

UL – Underwriters Laboratories

UPS – Uninterruptible Power Supply

V2G – Vehicle-to-Grid

VCM – Voltage Control Module

VVO – Volt/Var Optimization

VHD – High Voltage VHD-type Insulators

WAN – Wide Area Network

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Keywords

Distribution networks, renewable energy sources, energy storage system, power quality, voltage fluctuations, harmonics, optimization of power networks

Extended Summary

In the context of global climate change and the imperative need to reduce greenhouse gas emissions, the use of renewable energy sources has become a priority for most governments and the world's energy industry [1]. The sustainability of power systems, especially in distribution networks, is essential to ensure a successful and environmentally efficient energy transition [2, 3].

In recent years, the accelerated integration of SRE, such as solar and wind energy, into traditional power systems has increased significantly. However, this integration comes with significant challenges, especially related to the variability and intermittency of these sources, which can (negatively) influence the quality of electricity [4]. Problems such as voltage fluctuations, harmonics, *flicker* and power outages are more common and require innovative solutions to maintain power quality standards.

This thesis investigates the influence of the integration of renewable energy sources on the quality of electricity in distribution networks. The main goal is to identify the most effective methods of managing the associated challenges [5, 6]. The analysis focuses on the implementation of new technologies to improve and stabilize the quality of energy in distribution networks, ensuring a constant and high-quality energy flow for users. Also, the paper proposes improvements to the legislative framework regarding the integration of renewable energy sources in the distribution networks, with the objective of facilitating the transition to an energy system with a lower carbon footprint as well as a more reliable one.

Research problem

My professional interest and direct observations made as an engineer in the national energy system motivated me to address this topic of current and future interest. We have identified numerous systemic problems resulting from the increasing integration of SRE and their significant impact on the stability of power grids. These direct observations directed my attention to the need for a thorough analysis of these phenomena. Therefore, I decided to research these issues in my PhD thesis.

Thesis structure

The thesis is structured in six chapters presented in 199 pages:

1. Introduction, which presents the context of the research, the problem and its objectives;
2. The chapter on power quality, where the relevant standards and parameters for power quality analysis are described;
3. The chapter on the statistical analysis of electricity quality parameters, with an emphasis on renewable sources;
4. The chapter dedicated to the statistical characterization of modern electrical systems and the analysis of dynamic and economic components;
5. The chapter on technical proposals for improving the integration of electricity obtained from renewable sources and completing the legislative framework;

6. General conclusions, which summarize the major contributions of the thesis and provide recommendations for future research.

1. Context and importance of the topic

Currently, the integration of renewable energy sources (SRE), such as solar and wind energy, into traditional power systems has become a central objective in the context of reducing greenhouse gas emissions and the transition towards a more sustainable energy system. However, this integration brings significant challenges related to the variability and intermittency of renewable sources, which can negatively affect the quality of electricity, especially in distribution networks. Problems such as voltage fluctuations, harmonics, and power outages are becoming more frequent and require innovative solutions to maintain quality standards.

Globally, climate change and the need to reduce carbon emissions have accelerated the use of RES. However, the transition to a system based on renewable sources involves new technological challenges. The integration of renewable energy into electrical distribution networks has generated difficulties in maintaining power quality due to the variability of these sources. This raised the need for new network management solutions and the implementation of technologies to ensure the stability of the electricity flow.

The PhD thesis focuses on identifying effective methods to manage the challenges associated with RES, with the aim of optimizing the quality of electricity and ensuring the stability of distribution networks. In this context, technical solutions are proposed to improve the energy infrastructure and adjustments to the legislative framework to support the harmonious integration of these energy sources.

Thesis objectives and contributions

The main objective of the thesis is to analyze the impact of renewable sources on electricity quality parameters and to propose technical and legislative solutions for an efficient integration. The research aims to evaluate the effects of SRE on the stability and efficiency of electricity networks, to develop statistical models for the management of power quality fluctuations and to propose technical solutions for adapting the energy infrastructure to the new requirements.

The main contributions of the thesis include the development of advanced statistical models to allow the evaluation of energy quality parameters, as well as legislative proposals to improve the integration of renewable sources. The research results are relevant for energy policies and will be disseminated in specialized journals and presented at international conferences.

2. Power quality

The quality of electrical energy is essential for ensuring the efficiency and reliability of electrical energy systems, especially in the context of increasing integration of renewable energy sources. This chapter explores the various aspects of power quality, with a particular focus on the impact renewables have on distribution networks. Also discussed is the increasingly important role of active users or users in network dynamics and stability.

The operational efficiency of all sectors that use electricity depends critically on its quality. Power quality is defined and measured by a set of indicators that evaluate the constancy of the voltage, the frequency and the purity of the sinusoid. Deviations from these indicators can lead to equipment damage, frequent outages and decreased energy efficiency.

Variations in power quality parameters are classified according to the standard [7, 8] which presents different types of events, their spectral content, duration and magnitude of each event in terms of voltage.

These problems emphasize the need for continuous attention to limit disturbances and ensure an adequate level of power quality. Practical approaches to managing power quality problems can be classified into three main categories:

- Supply voltage quality;
- The quality of the supply service;
- Commercial quality.

Each category is essential to maintain adequate performance in the electricity distribution sector, which is an integral part of the energy system.

The evolution of the choice of voltages in electrical systems

The choice of operating voltages has been a major challenge in the development of electrical infrastructure. Safety initially mandated lower voltages to users to minimize the risk of electrocution, while higher voltages were preferred at the grid level to reduce energy losses.

The first voltages were 100-130 V, still maintained in the USA and Japan. As technology advanced, voltages increased, reaching 400/230 V in Europe. In Romania, the 400/230 V standard was adopted in the 1960s, after voltages of 208/120 V were initially used.

For industrial users and optimization of energy transport, voltages ranging from 690/400 V in the oil industry to 750 kV for long-distance transport have been adopted. In Romania, the standardized levels are 110 kV, 220 kV, 400 kV and 750 kV for high voltage, and 20 kV for medium voltage.

The impact of renewable sources and the role of active users

Integrating renewables into distribution networks brings challenges due to production variations. Active users, who produce energy and inject the surplus into the grid, contribute to stabilizing the system by storing energy and managing consumption [9].

To manage the disruptions caused by renewable sources, it is essential to develop technologies that enable predictability and control of production [10–12].

Management and regulatory strategies

Maintaining energy quality in the context of renewable sources requires the collaboration of all operators: producers, transporters, distributors and active users. Regulations must encourage investment in storage technologies and energy management systems that can reduce the impact of intermittency [13, 14].

Although modern networks are designed to minimize losses, energy transfer cannot guarantee perfect quality. Users must adopt improvement measures and balance the costs with the benefits of a higher level of quality [15, 16].

This chapter will detail the impact of renewables on energy quality and the measures needed for a sustainable transition.

Applicable power quality performance standards

Power quality assessment (PQ) requires a complex set of indicators, such as total harmonic distortion (THD), power factor, *flicker* factor and voltage imbalance. However, these indicators do not completely cover the complex situations of voltage and current curve distortions, affecting the calculation of energy losses and equipment evaluation [17].

International standards, developed by organizations such as IEEE, CENELEC and IEC, provide a necessary framework for assessing the severity of problems of hyperref[abbr:PQ]PQ. They support operators and users in determining the need to implement mitigation solutions [18].

Existing standards focus on periodic harmonics and include contributions from entities such as IEEE and IEC, providing guidance on harmonics control [19, 20] and management transient phenomena [21].

These standards are essential in assessing operational costs, equipment durability, system safety and overall power quality, and are vital for analyzing breakdowns and outages.

Interrupts - definition of interrupts

Power outages occur when users are temporarily or permanently disconnected from the main power source. They can be of short or long duration and sometimes require complex interventions to restore power.

Ideally, the voltage and frequency should remain constant and the voltage and current curves should be purely sinusoidal [22]. In practice, however, variations and distortions can occur, and sometimes the power supply is interrupted.

Networks are designed to minimize the number and duration of outages, but they are not infallible. Users with high reliability requirements must implement their own solutions.

The perception of outages differs between providers and users. For the supplier, the duration is the time when the voltage is zero, but for users it can also include the time to resume activity. For example, a one-minute outage can cause hours of production delay.

An interruption is considered long if it exceeds three minutes. Outages can be unplanned or planned, the latter being announced in advance to reduce impact [23]. Exceptional events, such as earthquakes, are excluded from standard assessments.

Phenomena that cause interruptions in electricity supply

Power outages are frequently caused by faults in the power grid. These faults are usually isolated from the action of circuit breakers, which are controlled by the network protection system, but there are other relevant causes. Among them are:

- Insulation damage as a result of overvoltages generated by lightning strikes, either directly in the power line or in its proximity.
- The natural aging of insulation, which reduces its ability to effectively insulate electrical components.
- Malfunctioning of equipment within the network, which may lead to unexpected power outages.
- Interference with wildlife, such as accidental contact of animals or birds with live equipment.
- Overloads in the elements of the electrical network that can activate the protection systems and lead to disconnections.
- Acts of vandalism leading to the destruction of insulation and other critical network components.
- Damage to equipment due to severe weather conditions, such as severe storms or extreme temperatures.
- Fires or explosions in electrical installations, which can seriously affect the operation of the network.

Outages can also be influenced by phenomena that occur in the electrical transmission network or the need for disconnections to perform maintenance or upgrade work on the electrical distribution network.

Performance indicators for evaluating the quality of electricity supply service

Performance indicators for energy supply are crucial for the management and development of transmission and distribution networks, with the main objectives of:

- Improvement of equipment reliability;
- Optimizing the quality of service for consumers.

Operators establish requirements to ensure continuity of supply, compliance with standards being essential for authorities and regulators. Power quality performances must be assessed separately for each entity: production, transmission, distribution and users. For example, an interruption at the transport level can be compensated by other operators, reducing the impact on the end user. Each operator must monitor its own events to assess performance.

Continuity indicators are used to measure performance and include:

- Adoption of system development measures;
- Identification of best practices;
- Inclusion in supply contracts;
- Evaluation by regulators;
- Monitoring the activity of operators.

These indicators must meet certain minimum conditions:

- Be clearly defined;
- To provide useful information;
- Be easy to understand;
- To allow evaluations over significant time intervals;
- To ensure comparability with other systems.

Indicators for electrical distribution networks

To ensure and evaluate the quality of power service in electric distribution networks, several critical indicators are used, which help to measure and continuously improve the performance of the network. These secondary indicators are fundamental in making strategic decisions for infrastructure management and development. The following secondary indicators are commonly used in annual network performance reviews:

System Average Interruption Duration Index *(SAIDI - System Average Interruption Duration Index)*

$$SAIDI = \frac{\sum_{s=1}^{n}(N_s \cdot D_s)}{N_t} \tag{1}$$

Where:

- N_s represents the number of users affected by the outage s lasting more than three minutes;
- D_s is the duration of the interruption s in minutes;
- n indicates the total number of interruptions recorded in the analyzed system during one year;
- N_t is the total number of users in the system.

System Average Interruption Frequency Index *(SAIFI - System Average Interruption Frequency Index)*

$$SAIFI = \frac{\sum_{s=1}^{n} N_s}{N_t} \tag{2}$$

Where:

- N_s is the number of users affected by a specific interruption s lasting more than three minutes;
- n indicates the total number of interruptions recorded in the system during the year;
- N_t is the total number of users served in the system.

Customer Average Interruption Duration Index *(CAIDI - Customer Average Interruption Duration Index)*

$$CAIDI = \frac{\sum_{s=1}^{n}(N_s \cdot D_s)}{\sum_{s=1}^{n} N_s} = \frac{SAIDI}{SAIFI} \tag{3}$$

Where:

- N_s is the number of users affected by the outage s lasting more than three minutes;
- D_s is the duration of the interruption s in minutes;
- n indicates the total number of outages recorded during a year.

Average system interruption duration index (ASIDI)

$$ASIDI = \frac{\sum_{s=1}^{n}(S_s \cdot D_s)}{S_t} \tag{4}$$

Where:

- S_s represents the power interrupted during the interruption s, whether contracted, installed or interrupted;
- D_s is the duration of the interruption s in minutes;
- n indicates the total number of interruptions in the system during a year;
- S_t is the total contracted, installed or disconnected power in the system.

Average System Interruption Frequency Index *(ASIFI - Average System Interruption Frequency Index)*

$$ASIFI = \frac{\sum_{s=1}^{n} S_s}{S_t} \tag{5}$$

Where:

- S_s represents the power interrupted during the interruption s;
- n indicates the total number of interruptions recorded in the system during a year;
- S_t is the total installed capacity in the system, including contracted and installed power.

Average outage frequency index per customer (CAIFI)

$$CAIFI = \frac{\sum_{s=1}^{n} N_s}{N_{ca}} \tag{6}$$

Where:

- N_s is the number of users interrupted in the interruption s;
- n represents the total number of interrupts, and;
- N_{ca} is the total number of unique customers affected by at least one outage during a year.

Energy not supplied *(ENS - Energy Not Supplied)*

$$ENS = \sum_{s=1}^{n} ENS_s \tag{7}$$

Where:

- ENS_s represents the amount of energy not delivered during the interruption s, and;
- n is the total number of outages during the year.

Peak not supplied *(PNS - Peak Not Supplied)*

$$PNS = \max_{s \in \text{interruption}} (PNS_s) \tag{8}$$

Where:

- PNS_s represents the power not supplied during the interruption s, and;
- the maximization is done over all the interruptions recorded in the system during a year.

Reliability analysis of distribution and transmission networks by means of PNS and ENS

indicators

Assessing the reliability of distribution and transmission networks is essential to ensure the continuity and security of electricity supply. The statistical or analytical methods used differ depending on the network configuration, with distinct evaluations for radial and interconnected networks. In this section, the essential principles of reliability assessment are discussed, with a focus on outage analysis and associated annual costs.

Dynamics of outages in interconnected and radial systems

The system's ability to support user load demand depends on several factors, including own capacity (CPS), local generation (GL), energy imports (IMP), storage (ESS) and participation in demand response (DR). The total available capacity (CPD) can be expressed as:

$$\text{CPD} = \text{CPS} + \text{GL} + \text{IMP} + \text{ESS} + \text{DR} \tag{9}$$

Where:

- **CPD** - The total capacity available at the power terminals;
- **CPS** - Own capacity of the system;
- **GL** - Local generation (renewable sources);
- **IMP** - Import of energy;
- **ESS** - Energy from storage systems;
- **DR** - Participation in demand response programs.

Unsupplied power and energy in the context of outages

An outage occurs when the available system capacity is insufficient to meet the load demand. A negative margin, illustrated in Figures 2.1 and 2.2, indicates the need to disconnect the load. The unsupplemented power PNS is thus determined by the available capacity deficit:

$$\text{PNS} = P - \text{CPD} = P - (\text{CPS} + \text{LG}) \tag{10}$$

Where:

– P is the total load, CPD is the total available capacity;

– CPS is the power system capacity;

– LG represents local generation.

Reliability modeling and outage cost estimation

The costs of outages at a distribution point are determined by the damage to users, and the frequency and duration of outages depend on system reliability. To estimate these costs, a reliability model is used that quantifies the frequency and duration of interruptions, applicable in various types of systems.

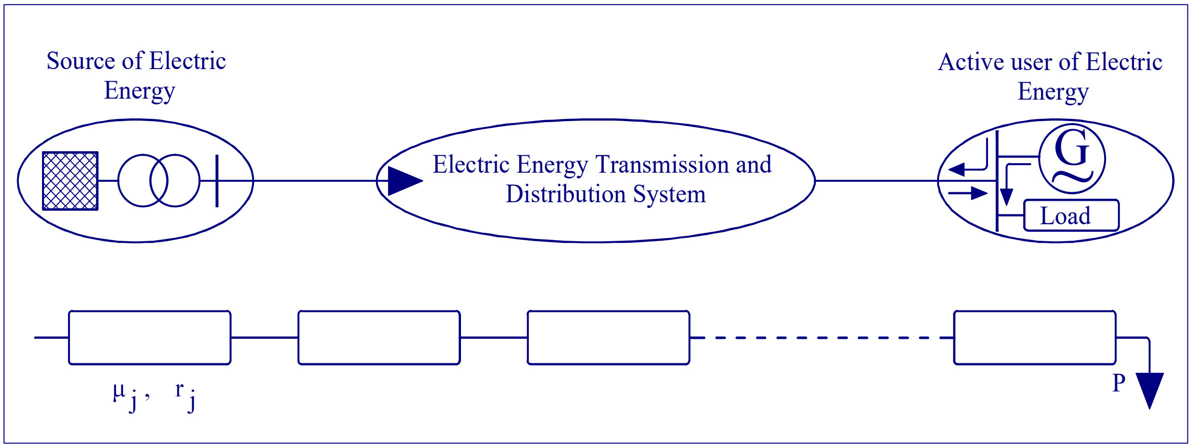

Figura 1: Reliability model: system component and influences on reliability

Reliability model used for annual cost analysis

Figure 2.7 illustrates the reliability model used to analyze annual outage costs. This model integrates all system components between the power supply and the load, modeling faults as interruption events. The calculation of annual reliability indices is based on the contributions of various outage events. For radial systems, the model used is detailed in reference [24], which evaluates each component of the network and its contribution to the overall reliability. This differs from the model in reference [25], which focuses on assessing the reliability of each feed point.

Calculation of reliability indicators

The basic reliability indicators for a supply point are calculated using the following formulas:

- Annual number of interruptions:

$$\mu = \sum_j \mu_j \quad [\textit{interruptions/year}] \tag{11}$$

- Annual total downtime:

$$U = \sum_j \mu_j \cdot r_j \quad [\textit{hours/year}] \tag{12}$$

- Average downtime per incident:

$$r = \frac{U}{\mu} = \frac{\sum_j \mu_j \cdot r_j}{\sum_j \mu_j} \quad [\textit{hours/break}] \tag{13}$$

Where:

- μ_j represents the failure rate (in events per year) associated with the interruption event j;
- r_j is the estimated duration of repair or restoration of service for event j.

Estimation of Unsupplied Power and Energy (PNS, ENS)

These traditional analytical calculation methods are specific for radial systems, but for looped systems they require detailed adjustments. Unsupplemented power and energy are calculated based on the mentioned equations and adjusted according to the load actually interrupted during the interruptions, not just based on the total load:

Expected undelivered power:

$$EPNS = \mu \cdot P \quad [\textit{kW/year}] \tag{14}$$

Expected undelivered energy:

$$EENS = U \cdot P = \mu \cdot r \cdot P \quad [\textit{kWh/year}] \tag{15}$$

Where:

- P represents the anticipated nominal load at the delivery point.

Quantifying the impact of interruptions

The effects of interruptions on industrial production can be modeled by the loss function L, defined as:

$$L = C_d \cdot \left(1 - e^{-\beta \cdot t}\right) \tag{16}$$

Where:

- C_d represents the direct cost of stopping production per time unit [lei/hour];
- β is a coefficient that reflects the speed of loss growth [1/hour];
- t is the duration of the interruption in hours [h].

The function L describes the total loss of industrial production as a function of the duration of the interruption. As the disruption persists, the cost of production loss increases rapidly, and this increase is determined by the coefficient β, which reflects the sensitivity of the industrial process to disruptions. For very short interruptions, the losses are low, but as t increases, the losses L approach the maximum value given by C_d.

Economic impact

Economic losses due to power outages can be quantified in terms of lost production and additional costs to resume business. One way to express these losses is through an economic loss index L_e, calculated as:

$$L_e = \int_0^T P(t)\, dt \tag{17}$$

Where:

- L_e is the economic loss index, measured in MWh;
- $P(t)$ is the power lost during production shutdown, measured in MW;
- T represents the total period of production interruption, measured in hours.

This index measures the total energy that would have been consumed during the outage period, providing an estimate of the economic loss in terms of lost production.

Harmonics and their impact on power quality

Harmonics are multiples of the fundamental frequency of a sinusoidal voltage or current signal and are generated by electronic equipment that uses power converters, such as rectifiers, inverters, frequency converters, and other modern devices. In an electrical network, the presence of harmonics can distort the sinusoidal waveform and lead to a number of negative effects on equipment and systems [26].

Harmonics have multiple adverse effects on distribution networks and equipment, including:

- **Overheating of equipment:** Additional harmonic current increases ohmic losses in transformers, motors and cables, which can cause overheating and premature damage to these components.
- **Electromagnetic interference:** Harmonics contribute to interference with communications and control equipment, affecting the proper operation of digital monitoring and protection systems.
- **Reduced system efficiency:** Additional losses caused by harmonics reduce the efficiency of the power grid, which can lead to higher operational costs and lower utilization of transmission capacities.

Modeling harmonics in the electrical network

To analyze the behavior of harmonics in an electrical system, it is essential to use Fourier analysis, which decomposes a distorted signal into a sum of sinusoidal components. The general Fourier series formula describing a distorted waveform is:

$$f(t) = A_0 + \sum_{n=1}^{\infty} A_n \cos(n\omega t + \phi_n) \tag{18}$$

Where:

- A_0 represents the constant component (signal average);
- A_n is the amplitude of harmonics of order n;
- ω is the fundamental angular velocity ($2\pi f$, where f is the fundamental frequency);
- ϕ_n is the phase of harmonics of order n.

The fundamental frequency component has $n = 1$, and the values $n > 1$ represent higher-order harmonics. This analysis allows for the quantification and identification of dominant harmonics in an electrical network.

Figure 2.9 provides a graphical representation of harmonic distortion in a current signal, demonstrating how different harmonics affect the shape of the fundamental curve in an electrical distribution system. The graph shows five harmonics, each contributing to the total distortion of the signal.

On the horizontal axis (t), time is measured in radians, from 0 to 2π, and on the vertical axis ($f(t)$), the amplitude of the signal is represented. Each harmonic component is colored distinctly for clarity.

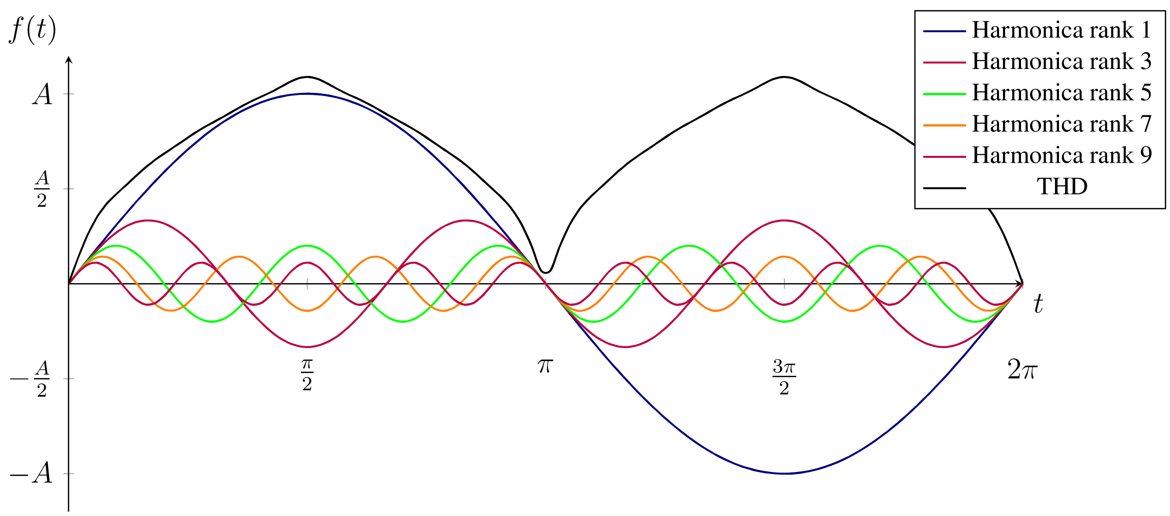

Figura 2: Example of current curve affected by harmonic distortion in an electrical distribution system

The superposition of these harmonics is highlighted by the black curve, labeled THD, which shows how the individual contributions combine to form a complex wave profile. This graph is essential to understanding how harmonic distortions can influence power system performance and distribution system integrity, providing a visual basis for evaluating the impact of each harmonic on the fundamental signal.

Mathematical modeling of disturbances in energy systems with SRE

The integration of renewable energy sources (SRE) into electricity networks can generate various types of power quality disturbances. These include voltage dips and spikes, rapid voltage variations (*flicker*) and harmonics, all of which are influenced by the intermittent nature of sources such as wind and solar power [27].

To model these disturbances, we can describe the voltage and current variations using the following components:

$$V_{\text{perturbation}}(t) = V_{\text{nominal}} + V_{\text{sag}}(t) + V_{\text{swell}}(t) + V_{\text{flicker}}(t) + V_{\text{harmonics}}(t) \tag{19}$$

Where:

- $V_{\text{perturbation}}(t)$ represents the total perturbed voltage as a function of time;
- V_{nominal} is the nominal network voltage;
- $V_{\text{sag}}(t)$ describes the momentary voltage drops (below the nominal voltage) over a short period;
- $V_{\text{swell}}(t)$ describes momentary voltage increases (above the nominal voltage);
- $V_{\text{flicker}}(t)$ represents the rapid and repeated voltage variations, which can affect the visual quality of the lighting;
- $V_{\text{harmonics}}(t)$ is the voltage component associated with harmonic distortions, which can be multiple frequencies of the fundamental frequency.

The harmonic current produced by renewable sources can be expressed as:

$$I_{\text{harmonics}}(t) = \sum_{n=1}^{\infty} I_n \sin(n\omega t + \phi_n) \tag{20}$$

Where:

- I_n represents the amplitude of the harmonic current of order n;
- n is the harmonic order (multiple of the fundamental frequency ω);
- ϕ_n is the phase of the harmonic current of order n.

This modeling allows a detailed analysis of the various disturbances that may occur in distribution networks integrated with renewable energy sources and provides a basis for the development of compensation and power quality control strategies.

Harmonic Modeling and Separation

Harmonics in the load current can significantly influence the performance and stability of electrical distribution systems. The load current, with its harmonic composition, can be efficiently expressed by a Fourier series, which decomposes the waveform into its fundamental and harmonic components [28,29]. This decomposition is essential for power quality analysis and the design of efficient filtering solutions.

The modeling of the electric load current in the three phases, using the Fourier series, is given by the following equations:

$$i_{L,\text{phase a}}(t) = A_{0,\text{phase a}} + \sum_{h=1}^{N} \left(A_{h,\text{phase a}} \cos(h\omega_0 t) + B_{h,\text{phase a}} \sin(h\omega_0 t)\right) \tag{21}$$

$$i_{L,\text{phase b}}(t) = A_{0,\text{phase b}} + \sum_{h=1}^{N} \left(A_{h,\text{phase b}} \cos\left(h\omega_0 t - \frac{2\pi}{3}\right) + B_{h,\text{phase b}} \sin\left(h\omega_0 t - \frac{2\pi}{3}\right)\right) \tag{22}$$

$$i_{L,\text{phase c}}(t) = A_{0,\text{phase c}} + \sum_{h=1}^{N} \left(A_{h,\text{phase c}} \cos\left(h\omega_0 t + \frac{2\pi}{3}\right) + B_{h,\text{phase c}} \sin\left(h\omega_0 t + \frac{2\pi}{3}\right)\right) \tag{23}$$

Where:

- $i_{L,\text{phase x}}(t)$ represents the instantaneous current in phase x at time t;
- $A_{0,\text{phase x}}$ is the continuous component of the electric current in phase x;
- $A_{h,\text{phase x}}$ and $B_{h,\text{phase x}}$ are the Fourier coefficients for harmonics of order h of electric current in phase x,
- ω_0 is the fundamental angular velocity;
- N is the number of harmonic terms considered in the model.

3. Statistical analysis of power quality parameters in distribution networks

This analysis allows the assessment of the contribution of harmonics to the behavior of the electric current and constitutes the basis for solutions to reduce their impact on the network.

The chapter presents a detailed statistical analysis of the parameters influencing power quality in distribution networks, identifying trends and problems as well as opportunities for improvement.

The challenges of renewable energy integration

Integrating renewables into existing grids brings significant challenges, including managing the intermittency of solar and wind sources, which cause unpredictable fluctuations in the grid and affect power quality [30–32]. In addition, the inverters of these sources introduce harmonics and distortion. Measurement techniques, such as harmonic analysis, are crucial to maintaining good power quality. Energy generated by renewable sources and active users can be injected into the grid, requiring continuous monitoring and flow management to ensure grid stability, as illustrated in Figure 3.1.

Figure 3.1 shows the flow of energy from renewable and conventional sources, highlighting the essential role of power quality monitoring to ensure grid stability and reliability.

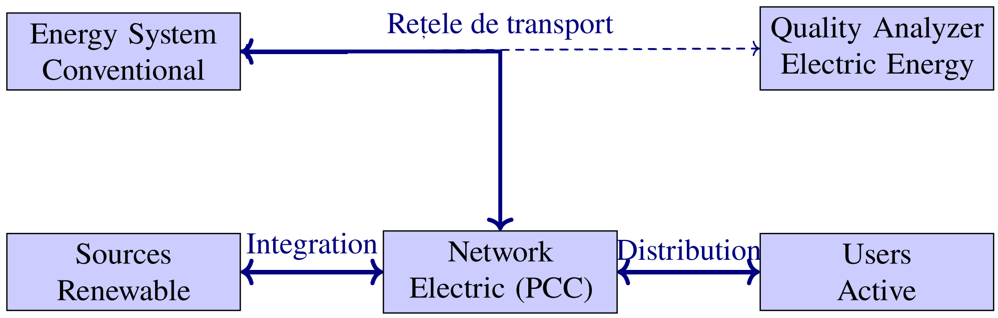

Figura 3: Scheme of the renewable energy integration process in the electricity grid

Data collection methodology

In this section, the paper describes the methods and tools for measuring and collecting power quality data. Collecting accurate and consistent data is essential for valid statistical analysis and for identifying problems and opportunities in need.

Power quality data was collected using a variety of methods, including:

- **Direct measurements** - Using specialized equipment to measure power quality parameters, such as network analyzers and power quality monitors.
- **Data SCADA** - SCADA systems use for real-time monitoring and control of power grid parameters.
- **Surveys and Reports** - Collection of data from surveys and reports provided by network operators and end users.

Measuring Instruments

Tools used to measure power quality include:

- **Mains Analyzers** - Equipment that measures and records power quality parameters, including voltage, current, frequency, and harmonics.
- **Power Quality Monitors** - Devices that monitor voltage variations and short-term interruptions.
- **Systems SCADA** - Integrated platforms that allow real-time monitoring and control of electrical networks.

Disruption Analysis

Outages are analyzed to determine their frequency and duration. The information presented in Figure 3.3 comes from the archive of a national electricity distributor, Year 2023, from a 20 kV line from a local substation. The graph shows the number of outages per month and their total duration.

The graph indicates that the duration of outages does not always follow the number of outages. With a small number of interruptions, the total duration can be very high and vice versa, due to the type of faults that occur. Most outages are recorded during the summer period, having a transient character, while other faults have a longer time to fix, affecting the supply to users. This can be related to the overloads and extreme weather conditions of the summer period. At other times of the year, faults are more difficult to fix, leading to increased downtime.

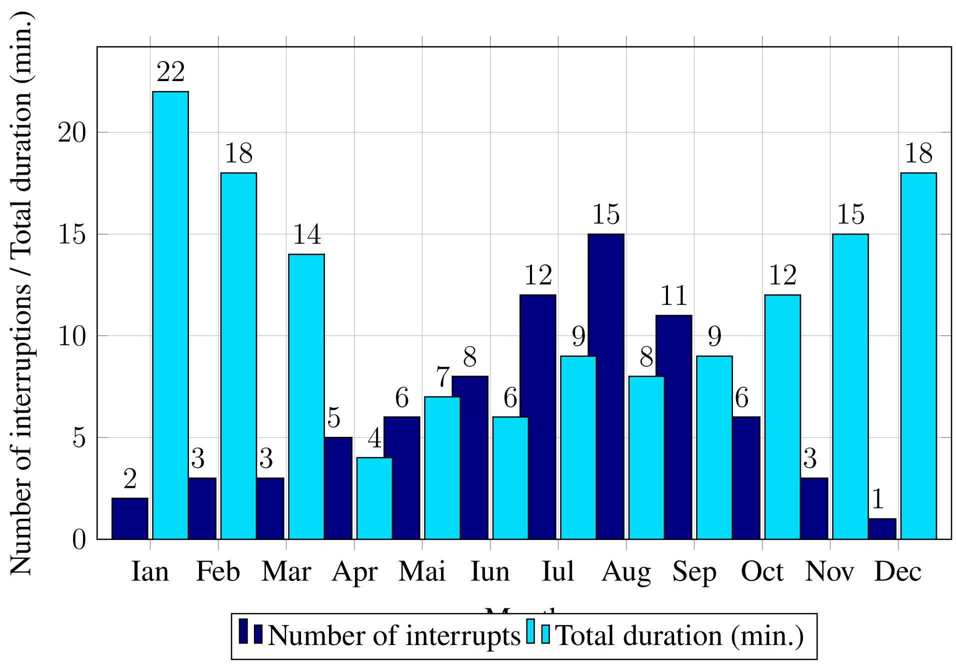

Figura 4: Number of outages per month and total duration

The results of the statistical analysis show general stability of the voltage, but also problems with frequent interruptions in certain periods. These data are essential for formulating measures to improve power quality, which will be discussed in the next section.

Impact of voltage harmonics on power quality

Harmonics are components of electric current or voltage with multiple frequencies of the fundamental frequency. Their presence can cause distortions in the voltage waveform, generating excessive heating of the equipment and additional losses in the network.

In this study, we measured the Total Harmonic Distortion (THD) to assess the impact of harmonics on power quality. The THD values ranged between 2.0% and 3.0%, indicating the presence of moderate harmonics. Although these values are generally acceptable, they require constant monitoring to prevent long-term power quality issues.

Analysis of load fluctuations over the full 24-hour interval - case I, and during sunny periods - case II

Context: One of the biggest challenges in power grid management is load fluctuation, which can affect power quality.

Methodology: A statistical approach was used to model load fluctuations throughout a day. Load data

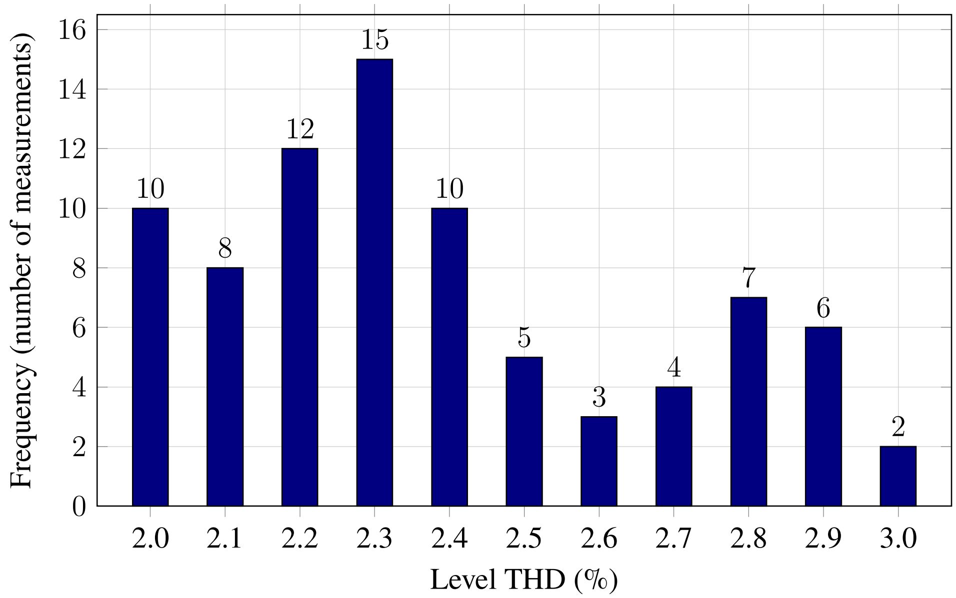

Figura 5: Distribution of THD levels measured in the 20 kV network

was collected from the Photovoltaic Park and analyzed using Gaussian distribution [33]. The formula used is:

$$f(x) = \frac{1}{\sigma\sqrt{2\pi}} e^{-\frac{1}{2}\left(\frac{x-\mu}{\sigma}\right)^2} \tag{24}$$

Where, μ and σ represent the mean and standard deviation of energy production for that day.

The resulting graphs 3.15, 3.17 give us an insight into the distribution of energy production and highlight the peak and minimum moments of production. This approach helps us to better understand the behavior of the energy production in the photovoltaic park and to identify possible trends or anomalies.

The analysis of confidence intervals, presented in Figures 3.16, 3.19, highlights the error margins associated with the estimate of the average energy production for different confidence levels.

Case 1 highlighted peak times and general fluctuations throughout the day, allowing operators to plan resources for efficient load management. On the other hand, **Case 2** focused on sunny periods, providing a specific understanding of the load under optimal sunlight conditions, thus facilitating a more precise adjustment of resources in these intervals. These findings contribute to more efficient management and better adaptation to load fluctuations depending on lighting and sunshine conditions.

Modern Electrical Systems: Statistical Characterization

This chapter analyzes the performance of modern electrical systems, with an emphasis on the dynamic and economic evaluation of innovative solutions to improve power quality. The goal is to statistically characterize these systems and discuss the impact of emerging technologies.

Statistical characterization allows optimizing the performance of electrical networks by analyzing the

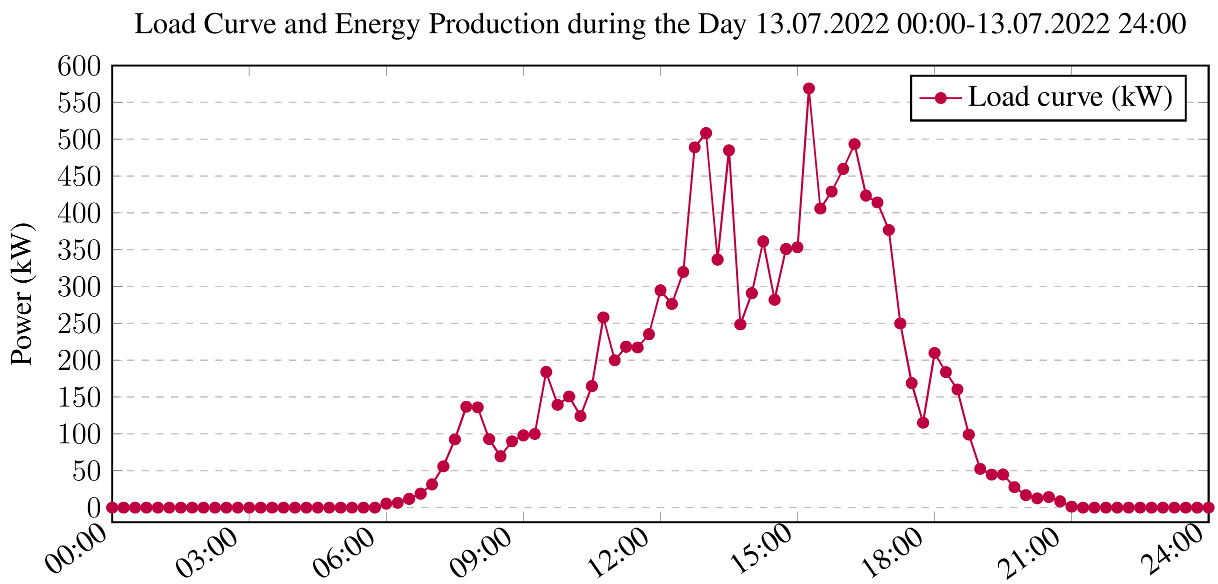

Figura 6: Analysis of Load Fluctuations over the Full 24-Hour Interval at 15-Minute Intervals

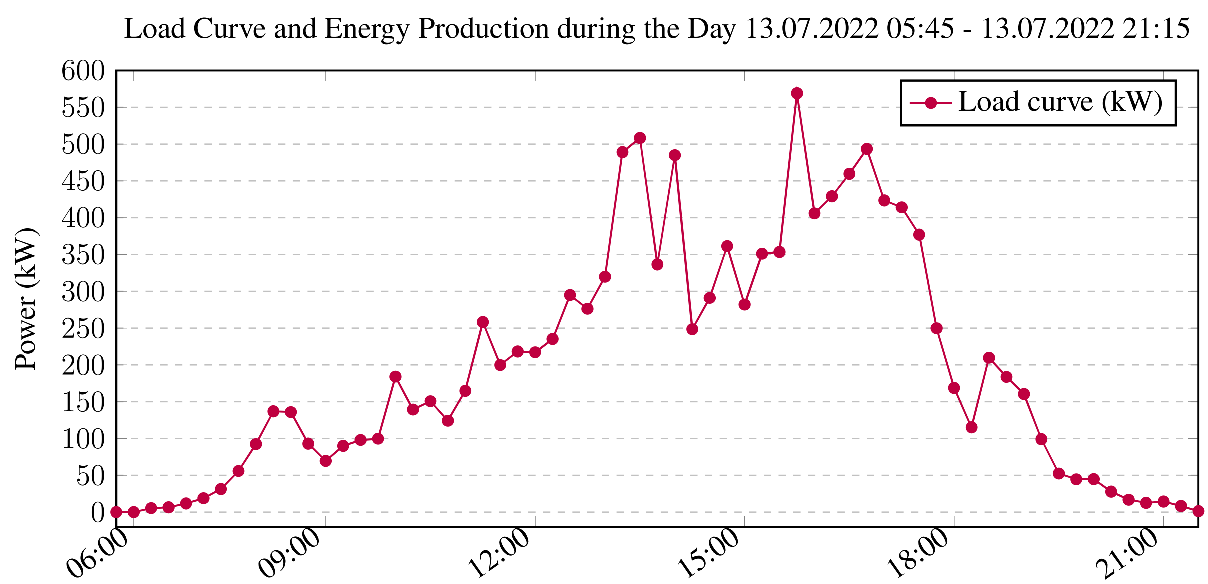

Figura 7: Hourly Load Fluctuation Analysis with sunlight at 15 minute intervals

relationships between critical parameters. The use of linear regression identifies correlations between voltage, frequency and power factor, providing a solid framework for improving networks.

PCA simplifies the analysis by reducing the dimensionality, highlighting the main factors influencing the electrical networks, and the hypothesis tests statistically validate the results obtained, ensuring a correct interpretation of the data.

Through these techniques, effective management strategies are developed, contributing to the creation of more reliable and sustainable networks.

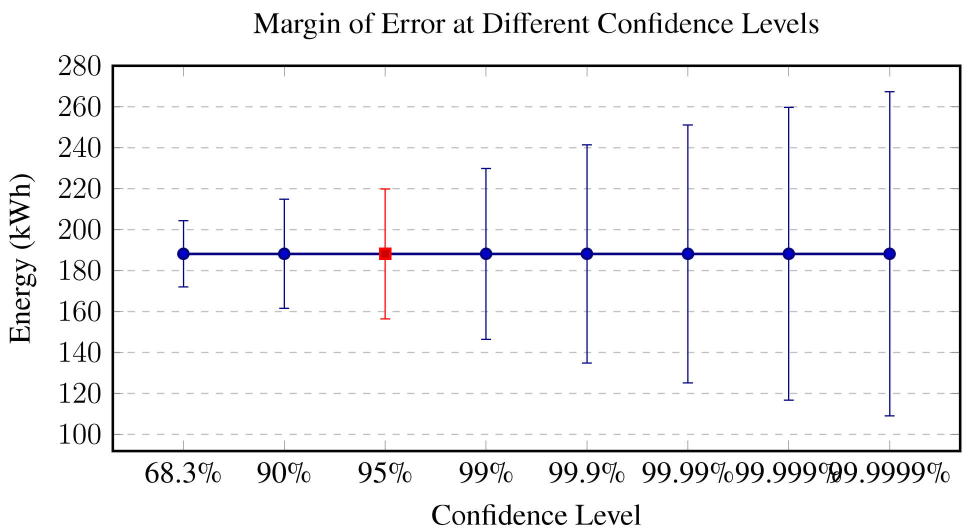

Figura 8: Graphical representation of margin of error for different confidence levels

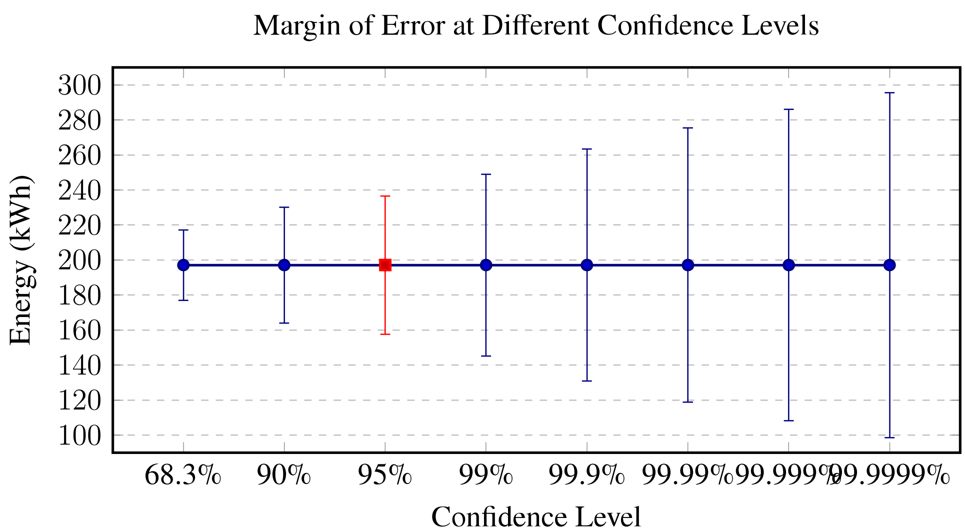

Figura 9: Graphical representation of margin of error for different confidence levels

Linear regression estimation

Linear regression is used to determine relationships between parameters that influence power quality. This method quantifies the impact of independent variables such as voltage, frequency and power factor on a dependent variable such as the number of interruptions or voltage variations [34–37]. The analysis performed on the dataset shown in Table **??** demonstrates the application of these indicators and highlights how they can influence network performance.

Linear Regression Model

The linear regression model can be expressed by the following mathematical equation:

$$y = \beta_0 + \beta_1 x_1 + \beta_2 x_2 + \cdots + \beta_n x_n + \epsilon \tag{25}$$

The table 1: Data used for linear regression analysis

No. crt.	**Voltage (kV)**	**Frequency (Hz)**	**Power Factor**	**Number of Breaks**
1	20.58	50.012	0.743	0
2	20.65	50.007	0.597	1
3	20.59	50.017	0.722	1
4	20.87	49.994	0.685	2
5	20.65	50.008	0.03	0
⋮	⋮	⋮	⋮	⋮
334	20.69	50.013	0.557	2

Where:

- y represents the dependent variable (eg, number of interruptions),
- β_0 is the intercept term,
- $\beta_1, \beta_2, \ldots, \beta_n$ are the regression coefficients,
- $x_1, x_2, \ldots, x_n$ represent the independent variables (such as voltage, power factor or frequency),
- ϵ is the model error.

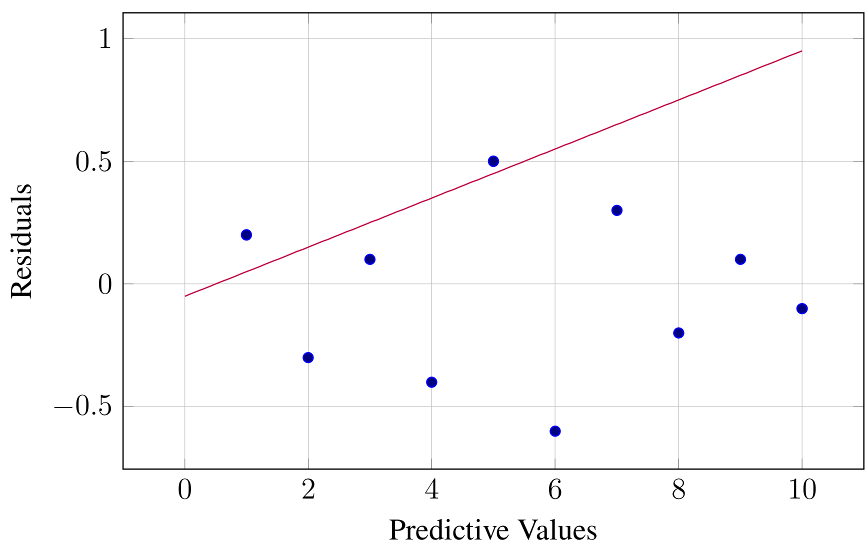

Figura 10: Graph of residuals with regression line

The residuals plot in Figure 10 provides a visual assessment of model errors and helps identify potential model fit problems. In addition, to assess the error distribution of the linear regression model, the plot in Figure 11 is presented.

PCA analysis - in identifying the dominant harmonic rank and amplitude

To extend the analysis, a real harmonic data set is examined. These data include harmonic rank and harmonic amplitude, which are essential for understanding harmonic behavior in electrical systems.

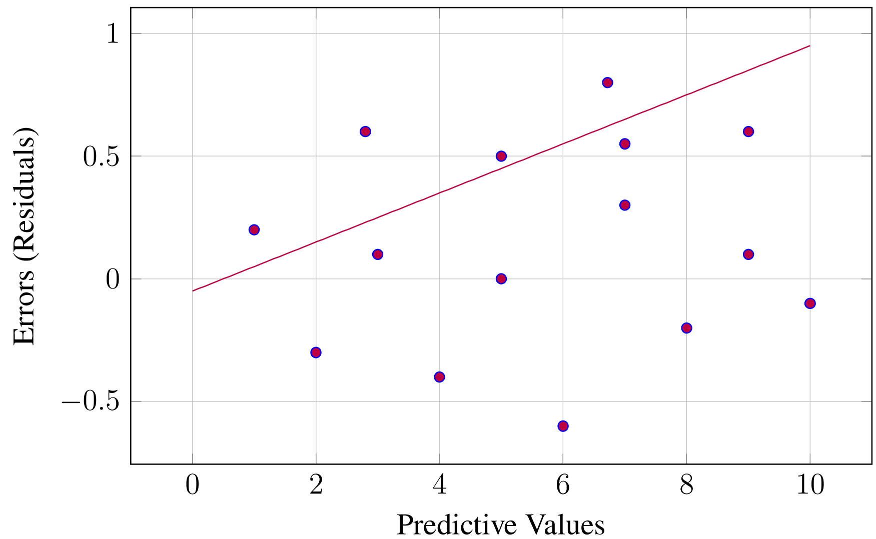

Figura 11: Linear regression model error plot

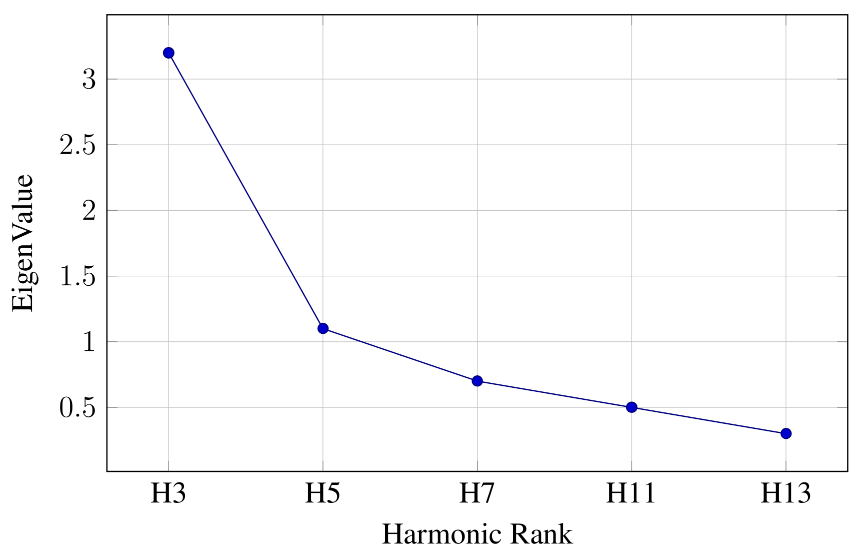

Figura 12: Graficul Scree pentru valorile proprii asociate matricei de covarianță a datelor armonice

The Scree plot shown in Figure 4.4 illustrates the eigenvalues associated with the covariance matrix of harmonic data. These eigenvalues help determine the relative importance of each principal component in explaining the total variability of the data. Each point on the plot represents an eigenvalue associated with a principal component, and the descending slope of the plot indicates the contribution of each principal component to the total variability of the dataset. Analyzing the Scree plot helps identify the most significant principal components that contribute to the variability in harmonic data.

This analysis confirms that most of the variance is explained by the first two harmonics, highlighting their importance in the behavior of the electrical system. The Scree plot for the obtained harmonic values clearly highlights the principal components influencing the total variability of the data.

Hypothesis Testing

Hypothesis testing is an essential statistical tool used to validate the significance of observations and conclusions from an analysis. In the context of modern electrical systems, these tests allow the verification of significant relationships identified between variables of interest, such as voltage, frequency, and power factor, and system performance [38, 39].

The **t-test** is used to compare the mean of a population with a specific value or to compare the means of two populations. The formula for the t-test statistic for a single sample is:

$$t = \frac{\bar{x} - \mu}{\frac{s}{\sqrt{n}}} \tag{26}$$

Where:

- $\bar{x}$ is the sample mean.
- μ is the population mean under the null hypothesis.
- s is the sample standard deviation.
- n is the sample size.

Figure 4.5 illustrates the t-test distribution for two independent samples, Group 1 and Group 2. The horizontal axis represents the t-values, while the vertical axis represents the probability density.

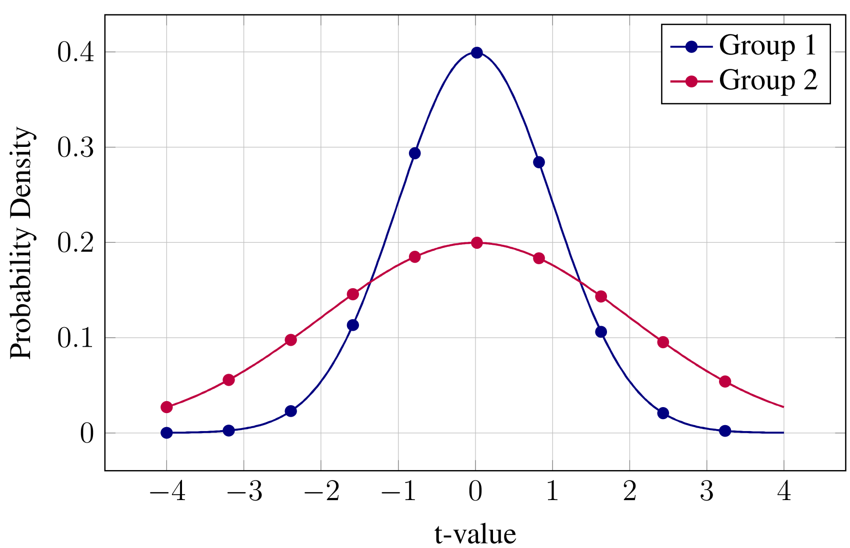

Figura 13: Test distribution of **t** for two independent samples

In this graph, the blue and red curves represent the theoretical distributions of **t** values for the two independent samples. The distributions are Gaussian (normal), each having specific mean and standard deviation values. The blue curve corresponds to Group 1, while the red curve corresponds to Group 2.

The ANOVA Test

The ANOVA test was used to compare the means of three or more groups of data obtained from measurements on the electrical network. In this case, the test was applied to determine whether there are significant differences between the mean values of the voltage harmonics measured in three operating conditions: daytime, evening, and nighttime.

The p-value and Decision

The **p**-value represents the probability of observing an effect at least as extreme as the one in our data, under the null hypothesis. If the p-value is less than the significance level (α), we reject the null hypothesis and accept the alternative hypothesis.

$$\text{p-value} = P(T \geq t \mid H_0) \tag{27}$$

Where:

- $P(T \geq t \mid H_0)$ indicates the probability that the test statistic T is at least as extreme as the observed value t, assuming the null hypothesis H_0 is true.
- T represents the random variable for the test statistic.
- t is the observed value of the test statistic from our data.
- H_0 is the null hypothesis, which states that there is no significant difference or effect.

Figure 4.6 illustrates the normal distribution and the concept of the **p**-value in the context of hypothesis testing. The horizontal axis represents the test values, while the vertical axis represents the probability density.

The blue curve illustrates the standard normal distribution, with a mean of zero and a standard deviation of one. This represents the theoretical distribution of test values under the null hypothesis (H_0), which states that there is no significant difference or effect.

The shaded red area represents the p-value, which is the probability of observing an effect at least as extreme as the one present in our data, assuming the null hypothesis is true. The p-value is calculated as the area under the normal distribution curve, starting from the observed test value to the extremes of the distribution.

In hypothesis testing, when the p-value is less than the significance level (α), usually set at 0.05 or 0.01, the null hypothesis is rejected in favor of the alternative hypothesis (H_1). This indicates that the observed results are unlikely under the null hypothesis, suggesting the presence of a significant effect.

Active Distribution Management Systems

EMS are vital for balancing energy sources and consumption while minimizing costs [40, 41]. Proper monitoring ensures reliable and safe energy supply. EMS is used by the OTS to maintain the safety and

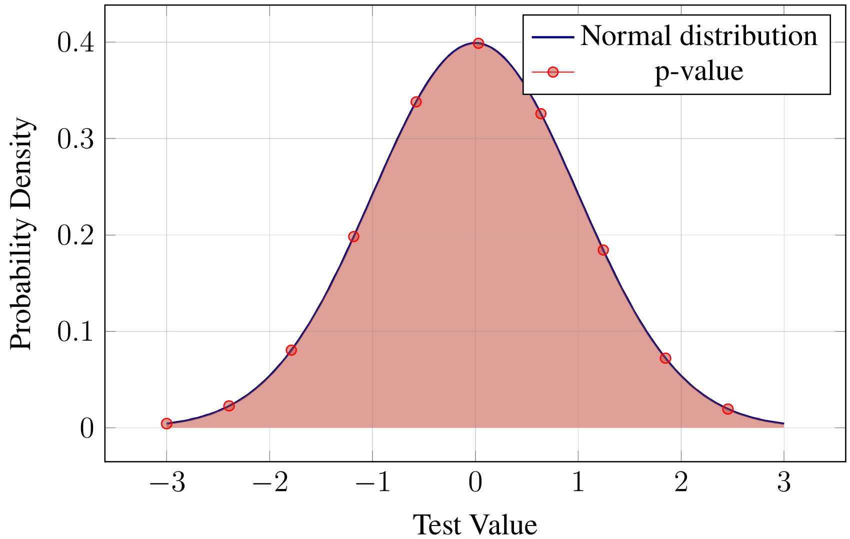

Figura 14: Normal distribution and **p** value

stability of the energy transmission system.

DMS, developed in the 1970s, adapts EMS functions to manage distribution networks, providing specific functionalities for this segment [42].

Mathematical Model for Optimizing the Operation of a Distribution Network

The mathematical model for optimizing the operation of a distribution network through EMS can be expressed by the following extended formula:

$$\min\left(\sum_{i=1}^{n} C_i P_i + \sum_{j=1}^{m} S_j \sqrt{P_j^2 + Q_j^2} + \alpha \sum_{i=1}^{n} \text{Loss}_i + \beta \sum_{j=1}^{m} \text{Penalty}_j\right) \tag{28}$$

Under constraints:

$$\sum_{i=1}^{n} P_i + \sum_{j=1}^{m} Q_j = D, \quad \text{(Balance of Power)} \tag{29}$$

$$P_i^{\min} \leq P_i \leq P_i^{\max}, \quad Q_j^{\min} \leq Q_j \leq Q_j^{\max}, \quad \text{(Operating Limits)} \tag{30}$$

$$\text{Loss}_i \leq \text{Allowable limit}, \quad \text{(Acceptable losses)} \tag{31}$$

$$\text{Penalty}_j \geq 0, \quad \text{(Non-negative penalties)} \tag{32}$$

Where:

- P_i is the active power supplied by source i;

- Q_j is the reactive power managed by device j;
- C_i and S_j are the costs associated with supplying active and reactive power;
- D represents the total power demand;
- $P_i^{\min}$, $P_i^{\max}$, $Q_j^{\min}$, and $Q_j^{\max}$ are the minimum and maximum limits of active and reactive power;
- Loss_i represents the power losses in the network for each source i;
- Penalty_j represents penalties for exceeding operational limits;
- α and β are adjustment coefficients for losses and penalties.

This extended formulation considers not only operating costs but also power losses and penalties associated with network operating conditions. The coefficients α and β adjust the contribution of these factors to the total cost function, allowing for a more comprehensive optimization of network performance.

Introduction to the Optimization Model

In this section, we implemented a mathematical model to optimize the operation of an energy distribution network. The model applies optimization principles with constraints using Lagrange multipliers, a well-established method in mathematical optimization, to find optimal solutions under specified constraints.

The proposed model aims to minimize the total cost of active and reactive energy generated and distributed, expressed by the function (4.15).

The constraints of the model are:

- The total power balance must match the consumption demand:

$$\sum_{i=1}^{n} P_i + \sum_{j=1}^{m} Q_j = D \tag{33}$$

- Respecting the operational limits for each energy source:

$$P_i^{\min} \le P_i \le P_i^{\max}, \quad Q_j^{\min} \le Q_j \le Q_j^{\max} \tag{34}$$

Application of Lagrange Multipliers

Using Lagrange multipliers allows the integration of constraints into the optimization of the objective function. The multipliers, λ_1 and λ_2, reflect the sensitivity of the objective function to the relaxation of constraints. The Lagrangian function associated with the model is:

$$\mathcal{L}(P_i, Q_j, \lambda_1, \lambda_2) = \sum_{i=1}^{n} C_i P_i + \sum_{j=1}^{m} S_j Q_j + \lambda \left(\sum_{i=1}^{n} P_i + \sum_{j=1}^{m} Q_j - D \right) \tag{35}$$

The partial derivatives of this Lagrangian function, taken with respect to each variable, including λ, must be zero to satisfy the optimization conditions. These conditions ensure the minimization of the total cost while respecting the network capacity and consumption demand constraints.

This optimization model plays a crucial role in efficient network operations planning, with the potential to improve network performance and reduce costs associated with energy production and distribution.

Data and Results for PCA Analysis

The mathematical model presented in equation (4.21) optimizes the operation of the distribution network through DMS, reducing the costs of active and reactive power supply while meeting the energy demand.

The analysis was based on real data from April 2022, containing average values of active and reactive power, collected at 10-minute intervals over two distinct time periods.

Evolution of Power Factor (λ_1) for the First Studied Interval

Figure 4.7 illustrates the evolution of the power factor (λ_1) over the determined period. This graph highlights the temporal variations of the power factor, showing how fluctuations in active and reactive power influence the system's energy efficiency.

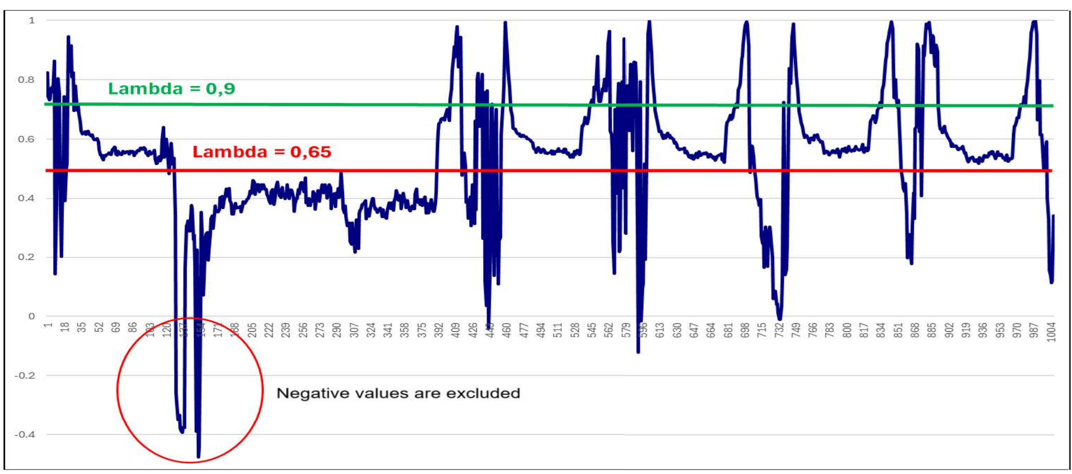

Figura 15: Evolution of Power Factor During Measurements

Note: The power factor (λ) is an indicator of how efficiently electrical energy is converted into useful mechanical work in electrical systems. Its value ranges between -1 and 1, where:

- $\lambda > 0$: The system consumes active power.
- $\lambda < 0$: The system supplies energy (for consumers injecting energy into the grid).
- $\lambda = 0$: All energy is reactive (no active power).

In Figure 4.7, negative power factor (λ) values were observed under specific conditions and are excluded from the main analysis. The measurements were taken at the point of common coupling (PCC) of a photovoltaic park with an installed capacity of 3.2 MW, which injects energy into the grid during the day, but at night, when there is no solar energy production, the park draws electricity from the grid for its own consumption.

These negative values do not indicate a malfunction of the system but rather reflect the operational reality of the photovoltaic park during non-production periods when it draws energy from the grid for internal consumption. However, to avoid misleading conclusions regarding the park's energy performance during periods of energy injection into the grid, the negative values were excluded from the main analysis.

Active Power Evolution for the First Interval Studied

Figure 4.8 presents the evolution of active power at the PCC. The graph shows how the total active power varies over time, highlighting daily fluctuations and consumption patterns.

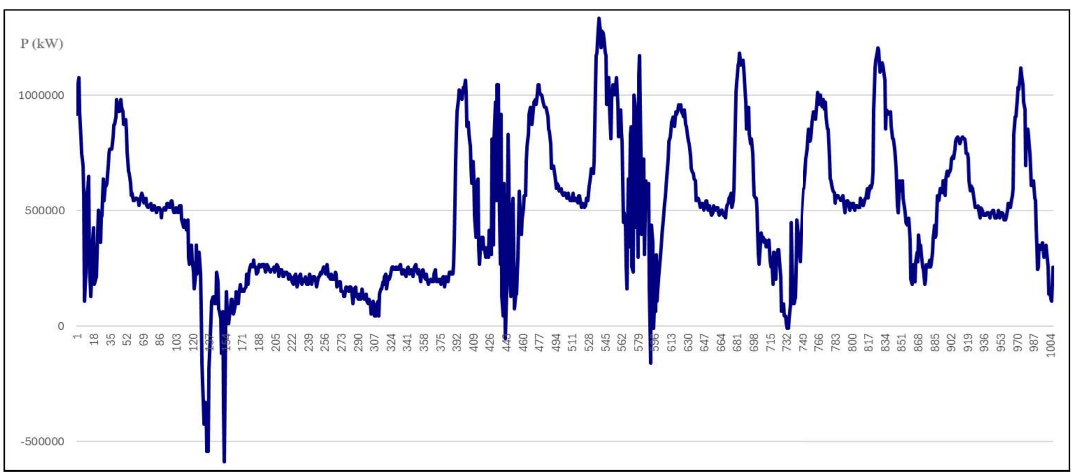

Figura 16: Active Power Evolution at the PCC

Power Factor Evolution (λ_2) for the Second Interval Studied

Figure 4.12 illustrates the evolution of the power factor (λ_2) over the duration of the measurements for the second studied interval. This graph highlights how the power factor varies over time, emphasizing the influence of active and reactive power fluctuations on the system's energy efficiency.

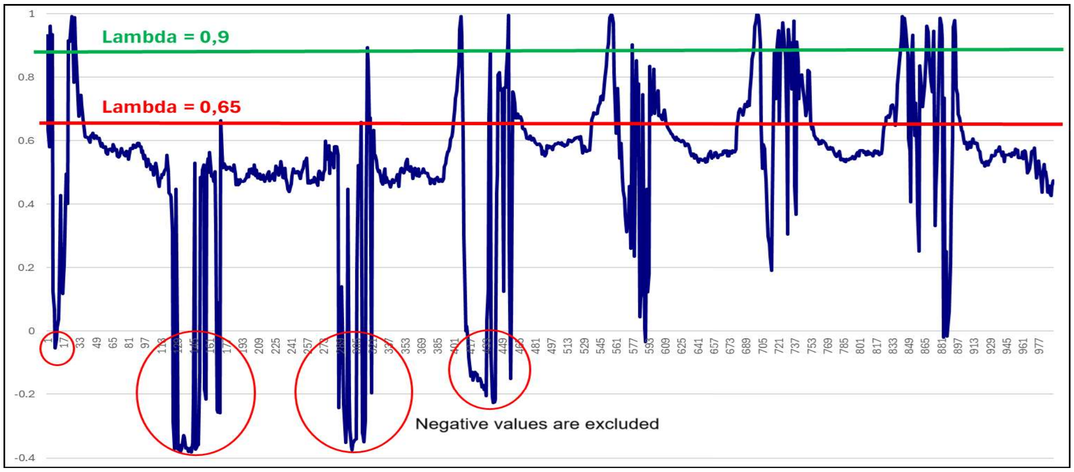

Figura 17: Power Factor Evolution over the Measurement Period - Interval 2

Active Power Evolution for the Second Interval Studied

Figure 4.13 presents the active power evolution for the second interval studied at the PCC. The graph illustrates the time variations of the total active power, highlighting the daily fluctuations and consumption patterns specific to this interval.

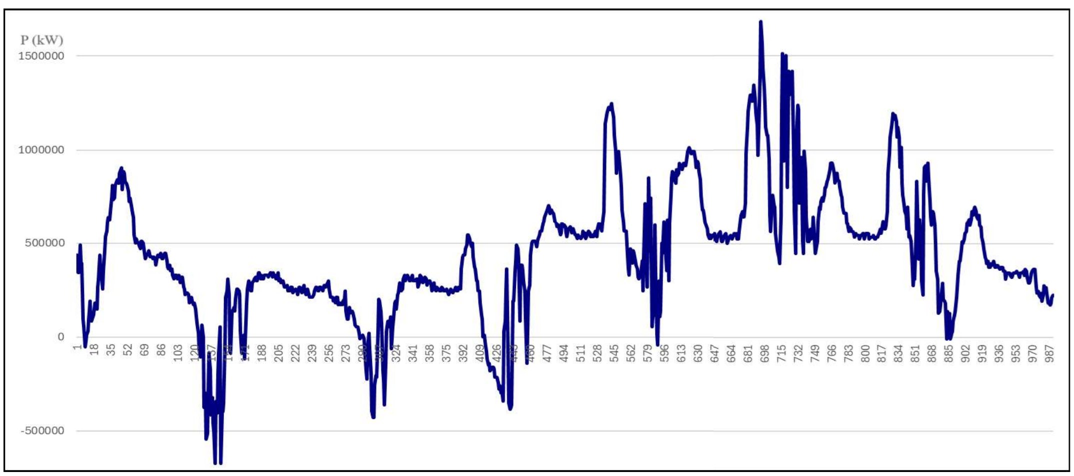

Figura 18: Active Power Evolution at PCC

Conclusions Regarding Costs Based on the Graphs Presented in Figures 4.7, 4.12

1. Costs for Power Factor Between 0.9 and 1:
   - In this range, no reactive power charges apply;
   - The graph shows that during certain periods, the power factor (λ) falls within this range, thereby avoiding additional costs for reactive power.
2. Costs for Power Factor Between 0.65 and 0.9:
   - Reactive power is billed at a regulated rate by ANRE [43];

- The graph indicates that in many periods, the power factor (λ_1) falls within this range, leading to additional costs.

3. Costs for Power Factor Below 0.65:

   - Reactive power is billed at three times the regular rate;
   - The graph shows periods where the power factor (λ_2) drops below 0.65, resulting in significant costs for the user.

4. Efficiency Zones:

   - A power factor (λ) above 0.9 indicates efficient energy usage, without incurring additional costs for reactive power.

Comparative Analysis of Prices and Network Operation Optimization Using the Lagrange Method

This section presents a detailed analysis of price evolution and the operational performance of the electrical network over two distinct weeks, using the Lagrange Multipliers method. The comparative price analysis, shown in Figure 4.17, and the identification of the network's optimal operation, illustrated in Figure 4.18, offer valuable insights into how energy constraints and market factors influence price dynamics and network performance. The application of the Lagrange function in this context allows for the optimization of operating parameters, contributing to the efficient management of energy resources and the reduction of operational costs.

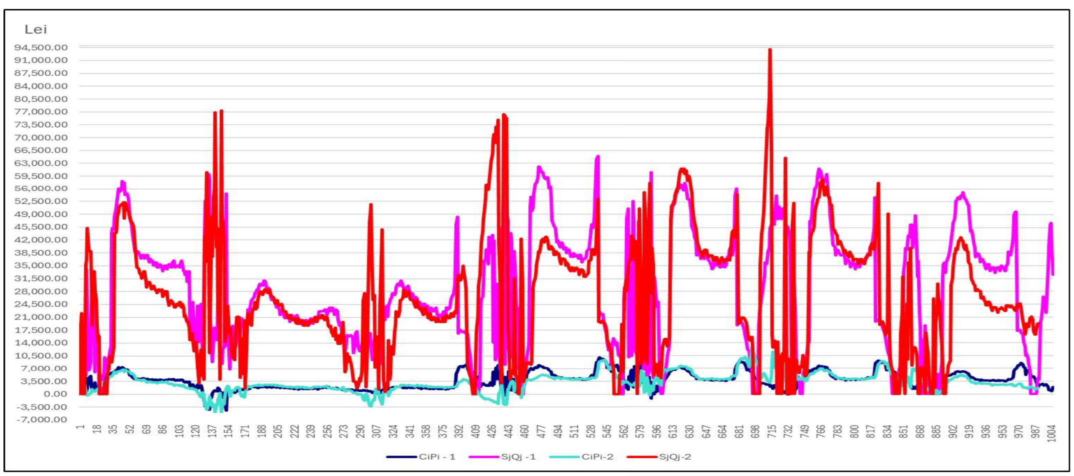

Figura 19: Comparative analysis of price evolution for the two weeks considered

Figure 4.17 presents the comparative analysis of price evolution for the two weeks, applying Lagrange Multipliers. It highlights the differences and similarities in price evolution, providing insights into the market factors and energy conditions influencing price variations. The analysis helps identify trends and anomalies that may affect energy resource management.

Figure 4.18 shows the network's optimal operation using the Lagrange function. The application of this method optimizes the network's operational parameters, such as voltage and frequency, ensuring energy efficiency and stability. The graph emphasizes the benefits of a rigorous approach to network management, underlining the importance of optimization in the energy sector.

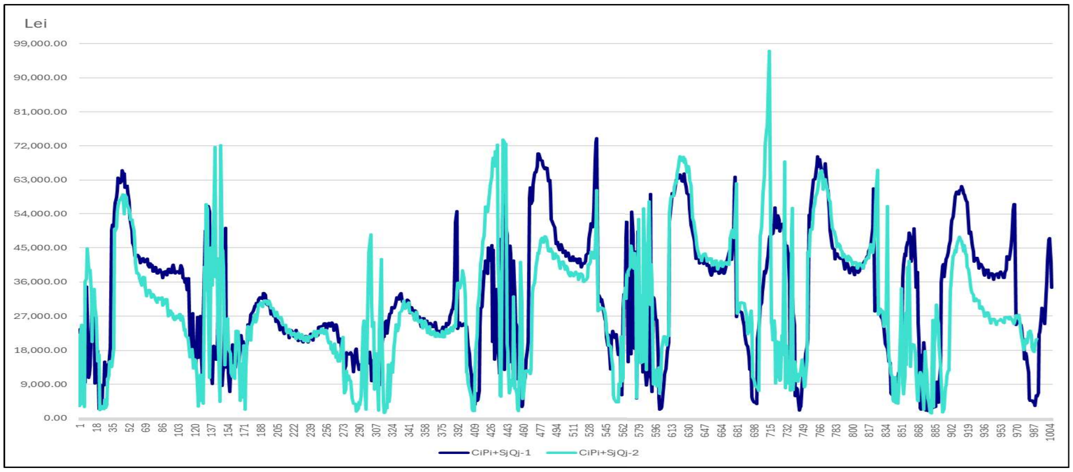

Figura 20: Identification of the optimal operation of the considered network using the distribution management system

Functions of Active Distribution Management Systems

The functions of applications that provide network model analysis and capability constitute the core of the DMS. As shown in Figure 4.19, the DMS functions can be divided into three categories: system monitoring, decision support, and control actions [**?**].

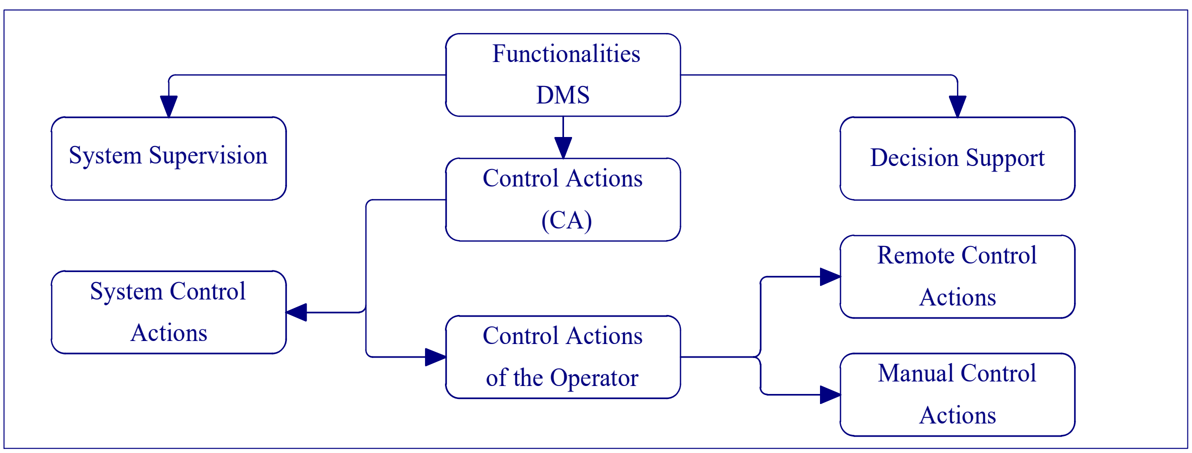

Figura 21: Main categories of DMS functions: system monitoring, decision support, and control actions

The DMS environments can be presented in the following areas:

- **Distribution operating environment**: Provides operators with system visibility, decision support, and control for managing distribution operations.
- **Engineering study environment**: Develops historical system performance indices.
- **Operations planning environment**: Facilitates operations planning, such as analyzing the impact of an outage.

- **Training simulation system**: Provides scenarios for training system operators.

- **Quality assurance system**: Examines new applications and updates before integrating them into the production system.

Control Actions of DMS

In distribution networks, various power devices, both in substations and in the field, such as circuit breakers, reclosers, disconnect switches, on-load tap changers, capacitor banks, shunt reactors, and voltage regulators, are managed by DMS.

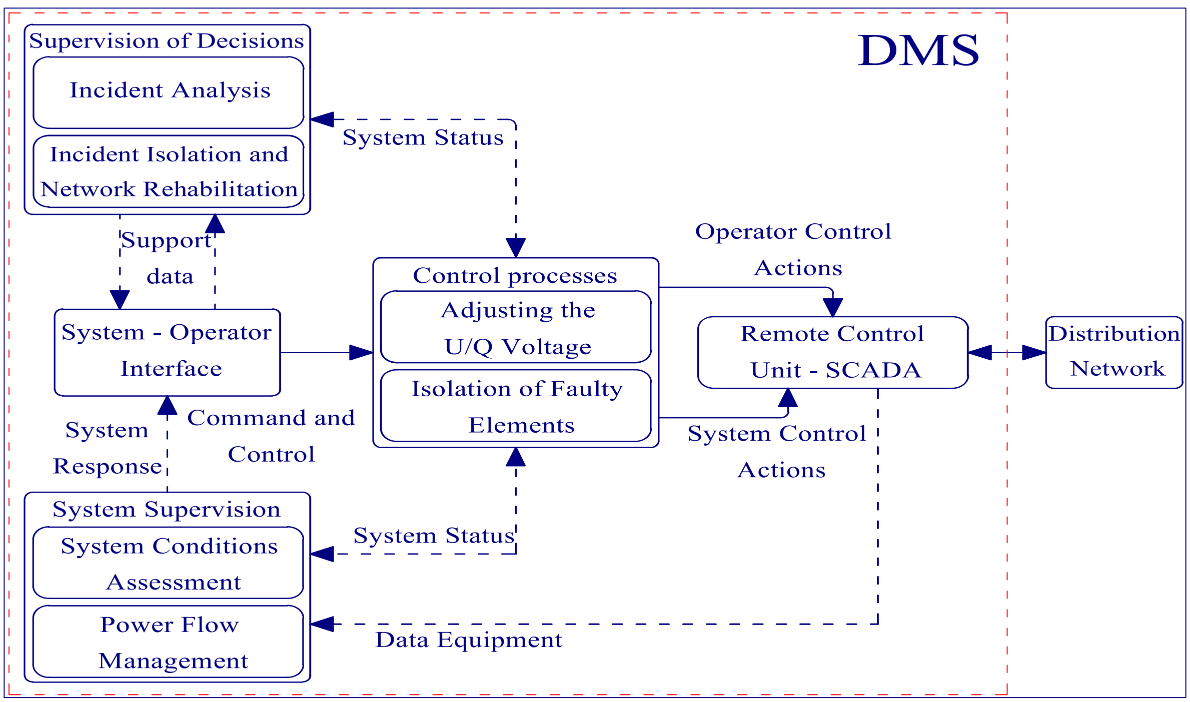

Figura 22: Interactions between system monitoring, decision support, and control actions within DMS

Software Overview

The architecture of DMS is designed modularly to enhance system reliability, flexibility, and maintenance. Each module operates independently but communicates through common links, ensuring redundancy and flexibility.

Figure 23 illustrates the conceptual design of DMS, highlighting the interaction between modules such as the Monitoring System, Data Management, State Estimation, and Volt/VAr Control, all contributing to the network's stability and efficiency.

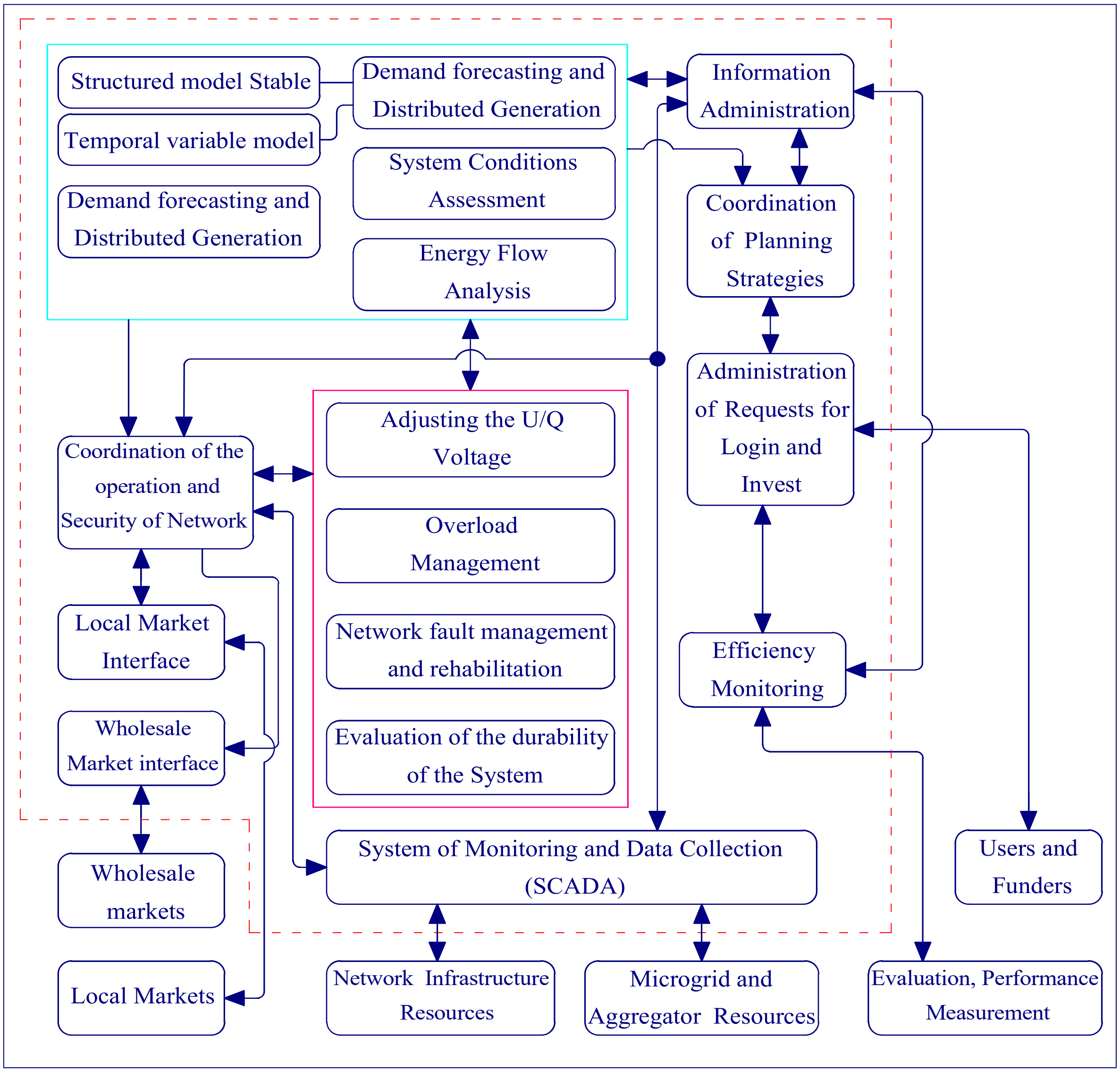

Figura 23: Conceptual Design of the Distribution Management System

Figure 24 shows the importance of each module and their impact on system performance. This evaluation is crucial for resource prioritization and ensuring efficient management of distribution networks.

Integration of Energy Storage in Proactive Network Management

Active Energy Management

The integration of ESS with wind turbines and PV systems can efficiently smooth out the intermittent production of these renewable sources, thus reducing system-wide frequency deviations caused by the high penetration of SRE into distribution networks.

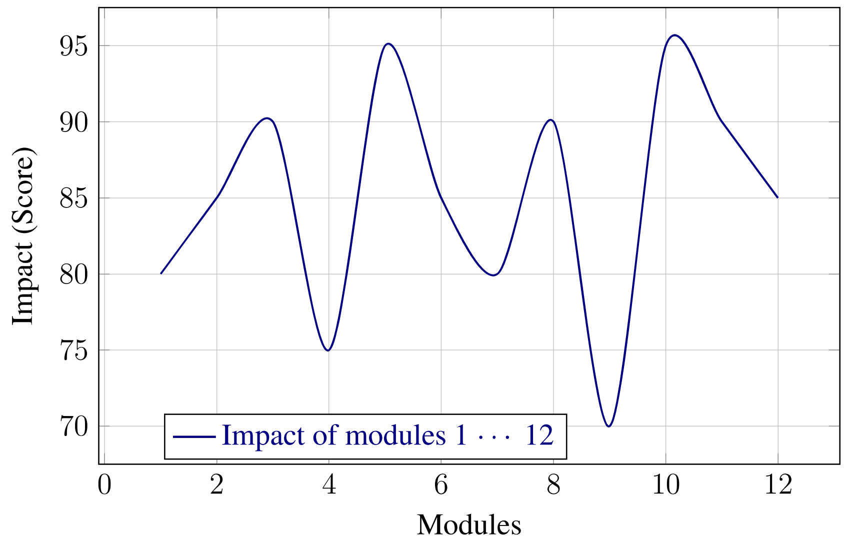

Figura 24: Modular Structure of DMS and the Impact of Each Module

$$P_{ESS}(t) = \begin{cases} P_{gen}(t) - P_{load}(t), & \text{if } P_{gen}(t) > P_{load}(t) \text{ (storage)} \\ P_{load}(t) - P_{gen}(t), & \text{if } P_{gen}(t) < P_{load}(t) \text{ (discharge)} \end{cases} \tag{36}$$

Where:

- $P_{ESS}(t)$ represents the power stored or delivered by the ESS at time t;
- $P_{gen}(t)$ is the power generated by the renewable sources at time t;
- $P_{load}(t)$ is the energy demand of the load at time t.

Studies show that the use of BESS is a more practical and economical method due to the high cost of other types of energy storage systems and the recent technological developments in BESS. A simplified scheme of BESS integration into the network is presented in Figure 25.

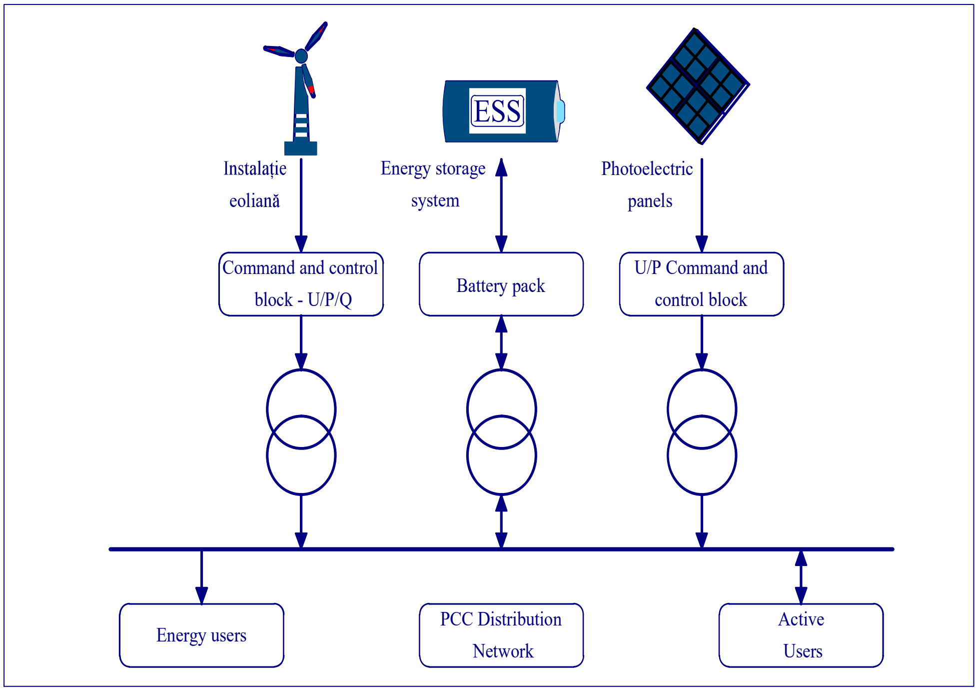

Figura 25: Diagram of BESS Integration in the Distribution Network

These categories and applications of ESS are essential for optimizing the operation of distribution networks and ensuring superior power quality in the context of increasing penetration of renewable energy sources.

5. Technical Proposals for Improving the Integration of Renewable Energy and Enhancing the Legislative Framework

This chapter presents technical proposals structured into five key areas, ranging from the mandatory installation of storage capacities for active users and large producers to the introduction of smart meters and strategies for flattening the load curve. These proposals are backed by detailed analyses and specific examples highlighting the benefits and impact of legislative changes.

1. **Technical Proposals for Improving Renewable Energy Storage and Integration**

    - The technical proposal for improving renewable energy integration and the legislative framework focuses on integrating storage solutions for electrical installations from SRE under 100 kW, owned by active users. This addresses the current challenges of frequent overvoltage caused by the large number of active users and reduced consumption during peak hours.

2. **Social Equity in Grant Allocation**

    - It is essential to consider social equity in the allocation of grants for production capacities from SRE, aiming to cover self-consumption without supplying surplus to the grid. Proposed changes to eligibility criteria are based on the historical consumption of active users over the past five years, with data provided by the local OD.

3. **Mandatory Storage Installation for Large Renewable Energy Producers**

   - The paper proposes that all energy producers from SRE with an installed capacity of over 1 MW be required to install storage capacities. This measure is crucial for managing intermittency and ensuring grid stability, regardless of voltage level (MT or IT).

4. **Mandatory Storage Installation at Network Interfaces**

   - The implementation of storage capacities at distribution and transmission station buses connected to renewable sources is crucial for managing load fluctuations. These measures ensure a rapid response to production variations and help prevent network instabilities.

5. **Legislative Proposal for Demand Response Management in Distribution Networks**

   - Integrating SRE into distribution networks requires efficient *demand response* mechanisms to maintain energy stability and quality. These mechanisms adjust demand according to SRE availability, optimizing energy resource use and balancing the grid.

Scientific Contributions

This study includes original contributions regarding the maintenance and improvement of power quality.

1. Extensive literature review on:

   – Theoretical aspects concerning the influence of renewable energy sources on the power quality in distribution networks.

   – Short and long-term impact assessment of SRE on the stability and efficiency of electrical networks.

   – Development and validation of statistical models to manage power quality fluctuations caused by SRE.

   – Proposal of technical solutions and infrastructure adaptations to improve the integration of SRE without compromising power quality.

   – Formulation of proposals for efficient integration of SRE into distribution networks, with a legislative framework adapted to new energy requirements.

2. Collection and analysis of multiple datasets from renewable energy sources provided practical insights into managing power quality issues, which can be classified into three main categories:

   – Supply voltage quality;
   – Power service quality;
   – Commercial quality.

3. Conducting case studies on how harmonic distortions propagate in an electrical network that integrates renewable energy sources with variable production.

4. Using Matlab-Simulink, Python, and PSCAD software for various types of analyses:
   - ANOVA analysis for linear regression models;
   - PCA analysis and Scree plot for the eigenvalues associated with the harmonic data covariance matrix;
   - Hypothesis testing analysis:
     - **t**-test and **p**-test for independent samples;
     - ANOVA test to compare the means of three or more groups of data obtained from measurements.
5. Applying Lagrange Multipliers to optimize the objective function, allowing for the integration of constraints. The multipliers, λ_1 and λ_2, reflect the sensitivity of the objective function to the relaxation of these constraints.
6. Testing the mathematical model for optimizing the operation of a distribution network using DMS, with Lagrange Multipliers, is essential for minimizing costs associated with the supply of active and reactive power, while ensuring total energy demand is met.
7. Comparative analysis of prices and identification of the network's operational optimum using the Lagrange method, providing insights into how energy constraints and market factors influence price dynamics and network performance.
8. Evaluating the feasibility of using battery energy storage systems ESS to flatten the load curve in distribution networks with a high integration of renewable energy sources with variable production.
9. Technical proposals to improve the integration of renewable energy and update the legislative framework.
10. Presentation and dissemination of research results at international conferences such as UPEC 2022, EPE 2022, SIER 2022, MPS 2023, CIEM 2023, Inter-Eng 2023, and publication in the EMERG journal.

The theoretical and practical contributions of this thesis are relevant not only for the energy sector but also for public policies regarding the transition to a sustainable energy system. The research results will continue to be published in scientific journals and presented at international conferences, supporting the development of new research directions in the field of renewable energy.

This thesis contributes to the development of a more sustainable and reliable energy system, supporting the transition to a *green* economy by proposing appropriate technical and legislative solutions. It addresses both researchers and policymakers in the relevant ministries, providing a solid foundation for optimizing electrical networks in the context of large-scale integration of renewable energy sources.

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