Power Quality Issues with Modern Appliances

Master's thesis in
Sustainable Electric Power Engineering and Electromobility Program

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DEPARTMENT OF ELECTRICAL ENGINEERING

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Cover: Experience the electric chaos of modern appliances as they struggle to maintain power quality

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Abstract

This master thesis investigates and analyzes the topic "Power quality problems with modern appliances." The investigation examines the power consumption patterns, power factor, and harmonic distortions found in a wide range of modern household lighting and devices, utilizing two power quality analyzers: Entes MPR-47SE and Unipower Unilyzer 900. Significant variations in power quality measures were observed in the experimental data, with an emphasis on the disruptive effect of harmonic distortions emitted by modern appliances such as LED bulbs and electronics; while the impact of a single appliance is marginal, the large-scale aggregation of these modern loads injects substantial cumulative harmonic distortions into the network. This collective behavior compromises the power quality and dependability of low-voltage distribution systems by overloading neutral conductors and causing premature thermal aging of distribution transformers. As a result, the study underlines the necessity to develop solutions for reducing harmonic distortions and improving power quality in residential settings. The findings reveal that while the widespread adoption of energy efficient appliances like LEDs and small electronics reduces overall consumption, it introduces severe current Total Harmonic Distortion (THD), particularly third and fifth odd harmonics, which can trigger neutral overloads, accelerate transformer degradation, and increase distribution network losses. Future research should focus on designing integrated, real-time adaptive filtering strategies through collaborative efforts among academia, industry, and regulatory bodies, with the goal of standardizing harmonic signatures and protecting grid reliability while aligning consumer device efficiency with network stability.

Key words: Power Quality, Harmonic Distortion, Modern Appliances, Electrical Engineering.

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Lastly, I want to thank myself for believing in me, for putting in the hard work, and never giving up.

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis listed in alphabetical order

AC	Alternating Current
ASDs	Adjustable Speed-Drives
CENELEC	European Committee for Electrotechnical Standardization
CFLs	Compact Fluorescent Lamps
CTs	Current Transformers
DC	Direct Current
DERs	Distributed Energy Resources
EIFS	Energimarknadsinspektionen föreskriver
EMC	Electromagnetic Compatibility
EMI	Electromagnetic Interference
EU	European Union
HID	High Intensity Discharge
Hz	Hertz
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IHD	Individual Harmonic Distortion
LED	Light Emitting Diode
LV	Low Voltage
MOVs	Metal-Oxide Varistors
MV	Medium Voltage
ORC	Organic Rankine Cycle
Plt	Long term flicker severity
POC	Point of Connection
Pst	Short term flicker severity
PTs	Potential Transformers
PV	Photovoltaic
RMSquare	Root Mean Square
RPF	Reverse Power Flow
SMPS	Switch Mode Power Supplies
THD	Total Harmonic Distortion
THDI	Total Harmonic Distortion of Current
THDU	Total Harmonic Distortion of Voltage
TRMS	True Root Mean Square

Contents

List of Figures

List of Tables

1 Introduction

1.1 Brief Overview of Power Quality

1.1.1 Definition of Power Quality

Power quality refers to the characteristics of electrical power that allow electrical systems and equipment to operate properly and efficiently without interference or disruption. It involves supplying electric power that meets the specifications and needs of the connected devices and systems. As stated in the IEC 61000-1-2 [1] Standard, power quality is defined as "*the degree to which the power system meets the requirements of the loads connected to it in terms of continuity of service, voltage and frequency characteristics, and the level of disturbances."* Similarly, IEEE Standard 1100-1992 [2] defines power quality as "*the compatibility between the characteristics of the electrical power supplied and the electrical power requirements of the end-use equipment.*

Note that the IEC definition emphasizes the importance of power quality in meeting the requirements of the loads connected to the power system, and how it focuses on key power quality parameters such as service continuity, voltage and frequency characteristics, and disturbance levels. This definition shares similarities with the IEEE definition. Still, it includes the concept of continuity of service, which is critical for ensuring that electrical systems provide reliable and uninterrupted power to their loads.

In addition, power quality also describes the characteristics of electrical power that determine its ability to meet the needs of the equipment and devices it powers. It defines voltage level, frequency, waveform, and the level of disturbances and fluctuations.

The following factors are characteristic of power quality:

Voltage: "The Root Mean Square (RMS) value of the voltage should be within a specified range, typically between 90 and 240 volts for residential and commercial applications" [3].

Frequency: "The frequency of the voltage should be 50 or 60 Hertz (Hz), depending on the region" [3].

Waveform: "The voltage waveform should be a sine wave, with no significant deviations from the ideal shape" [4].

Harmonics: Harmonics are non-fundamental frequencies that are added to the fundamental frequency of the voltage waveform. Harmonics can be caused by various factors, such as electronic devices, motor drives, and power converters [5].

Transients: "Transients are sudden spikes or dips in voltage that can last for a very short time. Transients can be caused by lightning strikes, switching operations, and other events." [4].

Unbalance: "Unbalance is a condition where the three phases of the voltage waveform do not have equal voltage magnitudes or the phase angle between two phase vectors is not equal to 120 degrees. Unbalance can be caused by faulty wiring or unbalanced loads" [6].

1.2 Research Goal

This study investigates the impact of modern residential appliances on power quality at the point of common coupling. The research focuses primarily on contemporary lighting systems, specifically comparing modern energy-efficient LED and halogen lamps against traditional incandescent bulbs. Through a combination of an extensive literature review and controlled laboratory measurements, this thesis aims to characterize the harmonic profiles of these modern loads and evaluate their cumulative effects on the local distribution grid.

1.3 Objectives

To achieve the comprehensive research goal, the following specific objectives will be addressed:

Characterize the electrical signatures and current waveforms of common residential non-linear loads and widespread LED luminaires.

Quantify the harmonic and supraharmonic distortions introduced by these devices under controlled operating scenarios.

Evaluate voltage fluctuations and the resulting flicker effect caused by the simultaneous and intensive operation of these loads.

Analyze the occurrence of electrical transients, undervoltages, and overvoltages linked to the dynamic behavior of a household installation.

Propose technical recommendations and mitigation guidelines to optimize power quality from the end-user side.

1.4 Scope and Limitations

Scope:

This study focuses exclusively on low-voltage residential electrical installations, evaluating power quality from the load side. The technical analysis encompasses specific power quality phenomena defined in the initial Planning Report: harmonic and supraharmonic distortion, voltage fluctuations (flicker), high-frequency transients, and temporary undervoltage/overvoltage variations. The evaluations are based on representative models of commercial LED luminaires and standard domestic non-linear appliances.

Limitations:

This research does not extend to the distribution network or utility grid level (supply side). Effects on medium- or high-voltage transformers, utility substation automation, or wide-area stability are outside the scope of this work. Furthermore, environmental factors affecting grid supply stability are not considered, as the grid input is assumed to be an ideal voltage source for the purposes of isolating load-side behavior.

1.5 Report Structure

The thesis is organized into twelve chapters to provide clear and logical progression of the research:

- **Chapter 1: Introduction:** Presents the background of power quality in modern residential systems, defines the research goal, specific objectives, scope, and limitations of the project.

- **Chapter 2: Background:** Examines the fundamental importance of power quality, differentiates between supply-side and load-side disturbances, and details key parameters such as harmonic distortion, supraharmonics, voltage fluctuations, transients, and flicker.

- **Chapter 3: Significance of Modern Appliances:** Explores the technical characteristics of contemporary residential loads, focusing on modern illumination devices, rooftop photovoltaic installations, and adjustable speed control systems.

- **Chapter 4: European Context: Standards and Regulations:** Reviews the European regulatory framework, analyzing relevant EN/IEC standards, comparing them with North American regulations, and highlighting the implications of the EIFS 2023 regulations in Sweden.

- **Chapter 5: Power Quality Issues with Lamps:** Conducts a comprehensive literature review on how different lighting systems interact with the grid and induce harmonic distortions.

- **Chapter 6: Power Quality Issues with Rooftop PV:** Analyzes the theoretical impact of solar inverters on residential power quality parameters based on international grid standards.

- **Chapter 7: Laboratory Procedures and Data Acquisition:** Details the experimental methodology, circuit topologies, and specifications of the instrumentation used (Entes MPR-47SE and Unipower Unilyzer 900) to measure house devices loads.

- **Chapter 8: Laboratory Test Results:** Presents empirical data and waveforms for the tested devices, analyzing their individual harmonic profiles and evaluating compliance with regulatory limits.

- **Chapter 9: Discussion:** Synthesizes the experimental findings, offering an in-depth evaluation of cumulative power factor degradation and harmonic spectrum behaviors.

- **Chapter 10: Ethical and Sustainability Implications of Power Quality Issues:** Evaluates the broader environmental, economic, and social consequences of residential power quality degradation from a sustainability standpoint.

- **Chapter 11: Conclusions and Future Work:** Summarizes the core outcomes of the research in alignment with the initial objectives and proposes practical recommendations and future technical paths.

- **Chapter 12: Bibliography:** Lists all academic references, standards, and literature cited throughout the research.

2 Background

2.1.1 Importance of power quality

The world is already in the age of modern technology and with our ever-increasing reliance on electronic devices, power quality has become more important than ever. The rise in sophisticated appliances, ranging from smart home devices to intricate industrial machinery, necessitates a reliable and consistent supply of electricity. These modern appliances are extremely sensitive to voltage, frequency, and waveform variations, so power quality is critical to ensuring their optimal functionality and longevity. The microprocessors and electronic components found in these appliances are vulnerable to disruptions such as voltage sags, surges, and harmonic distortions, which can cause not only malfunctions but also permanent damage.

Power quality significantly impacts the performance and reliability of electrical power systems and electronic devices. Amid the widespread adoption of smart grid technologies and interconnected devices, maintaining power quality is critical to ensuring the operational efficiency and resilience of modern electrified infrastructure. Poor power quality can create a variety of difficulties, including voltage fluctuations, harmonic distortions, sags, surges, and outages. These disturbances can harm the performance and lifespan of electronic equipment, resulting in increased downtime, equipment damage, and higher maintenance costs. Additionally, these electrical disturbances introduce systematic inefficiencies in energy consumption, driving up operational costs for both commercial enterprises and end consumers.

2.1.2 Power quality supplied, and power quality affected by the load.

Modern appliances often incorporate complex electronic control systems, making them unbalanced and non-linear loads. The operation of such loads can cause power quality problems in low-voltage networks [7]. Therefore, it is essential to differentiate between the power quality delivered by the electrical network and the power quality affected by the connected loads.

Differentiating power quality at the supply side vs load side

The power quality at the supply side refers to the power and voltage characteristics provided by the utility company at the point of connection, usually, this is the transformer, before reaching the customer's property. This quality is regulated by standards such as IEC 60038 (nominal voltages) and EN 50160 (voltages characteristics of public distribution systems). The utility company oversees maintaining stable voltage and frequency levels, as well as minimizing fluctuations and interruptions. This kind of power quality could be influenced by different factors like the operation of power generation, transmission, distribution systems, and other loads.

Evaluating the performance of these external networks and assessing the overarching grid power quality fall beyond the defined scope of this investigation.

On the other hand, the power quality at the load side describes the impact of connected equipment on the power quality experienced at the point of connection to the grid, once more this would be the transformer. This power quality is primarily influenced by the current drawn by the equipment, specifically its harmonic content, fluctuations, and transients. In this point, the customer is responsible for selecting equipment with low harmonic emissions and implementing mitigation strategies like power factor correction to minimize their impact on the grid, because the different types of loads, such as motors, electronic devices, lighting systems, and voltage inverters while drawing power, can inadvertently inject disturbances into the electrical system through harmonic currents. These disturbances, if not controlled, might disrupt the operation of other devices that are interconnected and reduce overall power performance. To handle this kind of disturbance the standard EN 61000-2-2 provides emission limits for conducted disturbances, with a focus on harmonics (EN 6100-2-2:2022). Manufacturers seek to develop devices that adhere to these restrictions, using techniques such as power factor correction and harmonic filtering. This combined effort guarantees that each piece of equipment contributes minimally to the overall disturbance level on the grid, reducing the influence on other connected equipment and ensuring a reliable power supply.

Equipment must not only restrict its emission of harmonic currents but also shows enough immunity to existing grid disturbances. The EN 61000-2-2:2022 standard defines the mandatory immunity thresholds regarding low-frequency conducted phenomena for devices operating on public low-voltage distribution networks. This ensures that devices can withstand anticipated voltage fluctuations, harmonics, and other disturbances without malfunctioning. Adherence to electromagnetic compatibility principles ensures equipment immunity, which adds to overall system stability and prevents disruptions caused by grid disturbances. [8]

Figure 1[1] shows the relationship between EMC levels and limitations. The relative positions of the two curves demonstrate that overlap is possible but should not be an accurate indication of the size of the overlap.

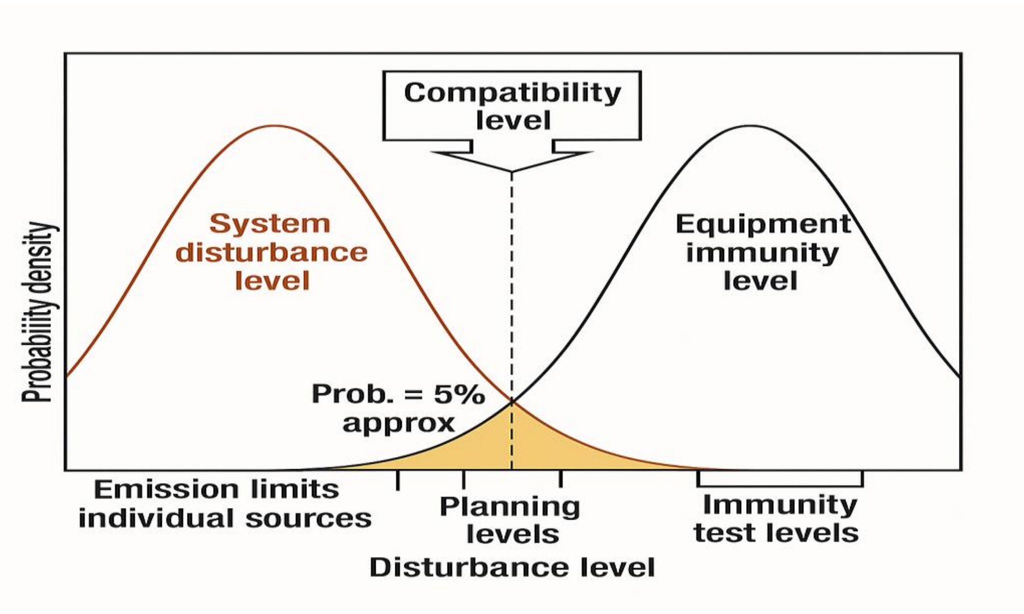


Figure 1 Consideration of the limits for emissions of interference and immunity as defined in IEC Standard 61000-3-2

[1] *Note*. Adapted from *Electromagnetic compatibility (EMC) - Part 2-2: Environment - Compatibility levels for low-frequency conducted disturbances and signaling in public low-voltage power supply systems* (EN 61000-2-2, Annex A), by European Committee for Electrotechnical Standardization (CENELEC), 2002. Copyright 2002 by CENELEC.

Key Differences:

Table 1.Key Power Quality Criteria: Utility vs. Customer Perspective

Aspect	*Supply Side (Utility)*	*Load Side (Customer)*
Location	Point of connection (POC)	Equipment connection point
Responsibility	Utility company	Customer
Regulated by	Standards (e.g., IEC 60038, EN 50160)	Equipment characteristics
Main concerns	Voltage level, frequency, stability	Harmonic distortion, fluctuations, transients

To exemplify this more clearly, consider it analogous to water quality: you want it to be clear and constant. The utility company provides electricity to your building on the supply side. They oversee keeping voltage levels consistent, frequency steady, and fluctuation-free, much like a water company makes sure your tap water is pure and at the proper pressure, as shown in Figure 2 below.

The load side is the specific point where your equipment connects to the power grid. The quality of the power is influenced by how your equipment draws current. Some devices cause distortions or fluctuations in the system, such as a misshapen valve that disrupts the smooth water flow. Choosing equipment designed to reduce these distortions and implementing mitigation techniques is critical for maintaining good power quality at the load side that is, ensuring your devices "drink" the electrical power cleanly and do not cause problems for the rest of the system.

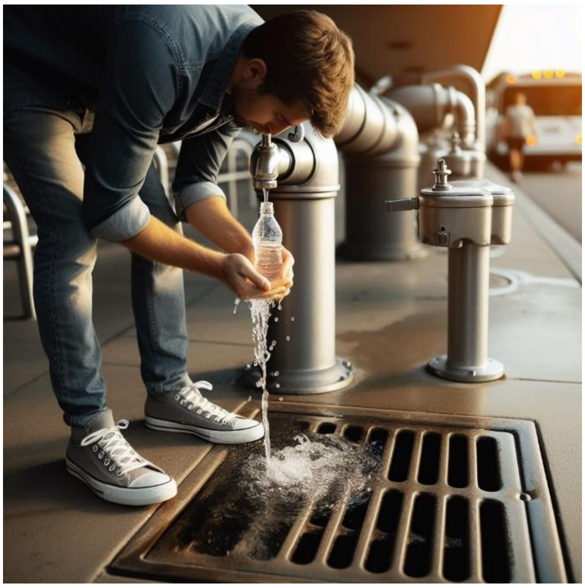


Figure 2 Analogy between water quality and power quality.
Illustration produced using artificial intelligence. Created by Herold Fuentes, 2024

2.1.3 Key parameters: harmonic and super harmonics distortion, voltage fluctuations, transients, and flicker effect.

Understanding and mitigating various parameters in energy quality is critical for ensuring electrical system reliability and efficiency. This section looks at key parameters like harmonic distortion, supra-harmonic distortion, voltage fluctuations, transients, and the flicker effect.

Harmonic distortion: Harmonic distortion occurs when a voltage or current waveform deviates from its ideal sinusoidal shape. Such deviations typically arise from the operation of non-linear loads, including power electronics equipment and adjustable-speed motor drives. This type of distortion is distinguished by the presence of harmonics, which are non-fundamental frequencies that are added to the fundamental frequency of a voltage or current waveform [5]. This leads to power quality issues and potential equipment damage, including overheating, reduced efficiency, and noise. Harmonic distortion can be measured using a variety of methods, including total harmonic distortion (THD) and individual harmonic distortion (IHD).

When talking about harmonics we must know that harmonics always originate as current harmonics that are produced by the load (customer side). When these distorted current waveforms flow across the grid's impedance, which includes both source and power lines elements, they cause a corresponding harmonic voltage drop across them. This will cause distortion in the supply voltage waveform. Thus, voltage harmonics are formed. An elevated source impedance, often driven by factors such as extensive cable lengths and high-impedance transformers, directly amplifies these voltage harmonics. Consequently, the relationship can be understood as the electrical network generating voltage harmonics as a direct response to the injected current harmonics.

Current Harmonics

In an ideal world, the current drawn from the power grid perfectly mirrors the voltage waveform, both following a smooth sine wave. However, this perfect balance is compromised by the presence of current harmonics. These phenomena are variations in the sinusoidal profile of the current, originating from spectral components whose frequencies are multiples of the fundamental frequency of the grid (generally 50 Hz in most parts of the world or 60 Hz in the Americas). In **Figure 3**[2] it shows a pure sine wave representing the ideal current (number 1). Current harmonics introduce additional "ripples" on top of this fundamental wave, altering the overall waveform. Harmonics come in an infinite number of orders or harmonic numbers. While higher harmonics may not significantly impact in most cases, lower order harmonics such as the first 5, 7, and even up to the 25th harmonic can affect and distort the waveform. In Figure 3, two different orders of harmonics are shown with the numbers 2 and 3, and the distorted sine wave at the end is represented by the number 4.

[2] *Note*. Adapted from *Armónicos 2.png* [Image], by Wikipedia User "Pólux", 2011, Wikimedia Commons (https://es.wikipedia.org/wiki/Archivo:Arm%C3%B3nicos_2.png). CC BY-SA 3.0.

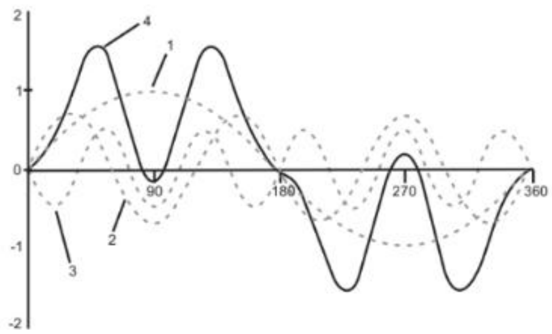


Figure 3. (1) Ideal current profile is defined by a pure sinusoidal wave. (2 & 3) Distinct spectral orders of current harmonics. (4) Resultant current waveform.

As stated, before current harmonics are mostly the responsibility of consumers or end users who operate non-linear loads linked to the electrical grid. Unlike linear loads (e.g., incandescent bulbs) which maintain a direct proportionality between the applied voltage and the resulting current, non-linear equipment draws distorted, non-sinusoidal waveforms. This operating behavior injects harmonic frequency components directly back into the electrical network.

The main contributors to current harmonics include:

- Power electronics: Devices such as rectifiers in chargers, variable speed drives in motors, and switch-mode power supplies (SMPS) used in computers and electronics distort the current waveform as they convert AC to DC or vice versa, drawing current in abrupt pulses rather than smoothly.
- Industrial equipment: Various industrial equipment, such as arc furnaces, welding machines, and rolling mills, can introduce non-linear behavior and generate harmonic currents.
- Residential and commercial loads: Modern electronic equipment, including computers, televisions, LED lighting, and other consumer electronics, can contribute to the generation of current harmonics due to their non-linear characteristics.

Current harmonics introduce several adverse effects across the electrical grid and its associated loads

- Thermal stress in transformers and motors: Harmonic currents accelerate both hysteresis and eddy current losses within the magnetic cores of motors and transformers. This mechanism drives up operational temperatures and degrades efficiency, ultimately accelerating insulation aging, shortening equipment lifespan, and elevating the probability of premature failure.
- Neutral conductor overloading: Within three-phase configurations, triplen harmonics (specifically the 3rd, 9th, and 15th orders) align in phase and accumulate directly in the neutral path. This summation can trigger severe conductor overheating, introducing structural damage risks, fire hazards, and broader operational safety concerns.
- Resonance: Harmonic currents can stimulate the capacitive and inductive elements found in the power network. This interaction can cause resonance phenomena, which greatly increase existing harmonic distortion levels.

- Power Factor Reduction: Current harmonics can cause a reduction in power factor, which can lead to inefficiencies in power transmission and distribution. Utilities may impose penalties on customers with low power factors, which can increase operating costs.
- Interference: Harmonic currents can interfere with sensitive electronic equipment and communication systems, potentially causing malfunctions or disruptions in the electrical grid.
- Metering errors: Harmonic currents can cause errors in energy meters, leading to inaccurate billing and revenue losses for utilities.
- Voltage distortion: Current harmonics flowing through the system impedances create voltage drops across these impedances, resulting in voltage distortion or voltage harmonics.

The (IEC) standard IEC 61000-3-2 establishes the acceptable limitations for introducing current harmonics into the electrical system in Europe. This standard establishes limitations on the amount of harmonic current that electrical devices linked to Europe's public low-voltage supply system may emit.

The equipment type and input power determine the permissible limitations. This regulatory system categorizes devices into four distinct classes (marked A, B, C, and D) according to its features and intended usage. The limits are given for the first 39 harmonics, and the standard sets different limits for each class:

- Class A: This class includes balanced three-phase equipment and all single-phase equipment not included in the other categories (e.g., household appliances, power tools, general-purpose lighting). For Class A devices, the permissible harmonic current thresholds are defined relative to the fundamental current component, encompassing harmonic orders up to the 40th.
- Class B: This class includes portable tools. The harmonic limits for Class B equipment are the same as those for Class A equipment.
- Class C: This class includes lighting equipment, which often contributes significantly to harmonic emissions. Class C equipment must meet specific limits for individual harmonics up to the 40th.
- Class D: This class includes equipment with a rated power greater than 75 W and input current up to 16 A per phase (e.g., computers, monitors, and televisions). Class D equipment must meet specific limits for individual harmonics up to the 39th.

The limits for current harmonics are expressed either as a percentage of the fundamental current (for Class A and B) or as absolute values of current (for Class C and D), depending on the equipment category and harmonic order. These limits have been set to ensure that the equipment does not inject excessive current harmonics into the power system. Such high-frequency components jeopardize grid power quality, triggering systemic inefficiencies and equipment degradation.

For detailed information regarding the specific values and allowable limits for each harmonic order and class of equipment, please refer to the complete text of IEC 61000-3-2.

Voltage harmonics

Voltage harmonics manifest as deformations in the sinusoidal voltage profile, stemming from the interaction of current harmonics with the system's impedances. From a spectral perspective, these distortions are defined by the occurrence of supplementary sinusoidal waves at frequencies that exist as integer multiples of the fundamental. This degradation is driven by harmonic current components traversing the combined line and source impedances, which induces localized voltage drops and ultimately shapes a distorted voltage waveform.

While current harmonics originate from non-linear loads, voltage harmonics are primarily the responsibility of the utility or power provider. The utility is responsible for maintaining a clean voltage supply, but the presence of current harmonics from customers' non-linear loads can lead to voltage harmonics on the grid.

Voltage harmonics are not created by a single entity, but rather by the combined impact of multiple sources and loads connected to the electrical grid. The primary originators of voltage waveform distortion are classified as:

- Non-linear loads: These are loads that draw non-sinusoidal currents from the supply, such as rectifiers, switched-mode power supplies, and variable-speed drives. The non-sinusoidal currents interact with the system impedance, creating voltage harmonics.
- Power electronic devices: Devices like static power converters, inverters, and active front-end drives can generate harmonic currents and contribute to voltage distortion.
- Distributed generation sources: Renewable energy sources, such as solar photovoltaic systems and wind turbines, often employ power electronic converters that can introduce harmonic currents and contribute to voltage harmonics.

Voltage harmonics are mostly caused by harmonic current sources, although grid operators and utilities also play a role in manage, control and reduce these distortions by using harmonic filters, designing systems correctly, load balancing and adhering to power quality guidelines.

Harmonic distortions in the voltage waveform can have several adverse effects on the electrical network components, leading to decreased efficiency, increased maintenance costs, and potential safety hazards. Here's an overview of the impact of voltage harmonics on the electrical grid's main components:

Transformers are particularly susceptible to the detrimental effects of voltage harmonics.

- Increased Losses: larger peak voltages brought on by the distorted voltage waveform result in larger iron losses from hysteresis and eddy currents. Moreover, the windings' resistive losses rise as a result of the increasing current harmonics. The cumulative effect of these losses directly compromises transformer efficiency, thereby driving up operating costs.
- Degraded Insulation: The transformer's insulation system may be put under stress by the voltage harmonics' higher peak voltages. Transformer failure risk may increase due to accelerated aging and possible insulation collapse brought on by this ongoing stress.

- Derated Capacity: Transformers working under high harmonic distortion may need to be derated, or run at a lower power level, in order to assure safe and dependable operation due to increased losses and thermal stress.
- Noise and Vibration: Voltage harmonics can cause transformers to produce excessive noise and vibrations due to magnetic forces acting on the transformer core and windings.

Power lines also feel the impact of voltage harmonics:

- Increased Heating: The distorted voltage waveform results in higher effective currents flowing through the conductors. This translates to increased resistive heating in power lines, potentially exceeding their thermal design limits and leading to premature aging or conductor sag.
- Skin effect: At higher frequencies, the skin effect causes uneven current distribution in conductors, leading to increased resistance and losses.
- Corona losses: Harmonics can increase the electric field stress on conductors, potentially leading to corona discharge and associated power losses.
- Voltage Regulation Issues: The additional voltage drops caused by harmonic currents flowing through the line impedance can exacerbate voltage regulation problems. This can lead to voltage fluctuations at the customer end, impacting sensitive equipment.

Voltage harmonics can also impact other components of the electrical network, such as:

Capacitor banks: Harmonics can cause resonance conditions with capacitor banks, leading to amplified voltage distortion and potential failure of capacitors.

Motors and generators: Harmonics can induce additional losses, torque pulsations, and vibrations in rotating machines, reducing efficiency and potentially causing mechanical stress.

Switchgear and relays: Voltage harmonics increase heating and losses in switchgear, reducing their current-carrying capacity and shortening their lifespan due to voltage stress. Voltage harmonics can also cause malfunctions in protective relays and control systems.

Comparative of Current vs. Voltage Waveform Distortion

Table 2. Voltage & Current Harmonics Contrast

Aspect	Current Harmonics	Voltage Harmonics
Primary Source	Non-linear loads (e.g., rectifiers, variable speed drives, power electronic devices)	Interaction between current harmonics and system impedance, non-linear power sources
Cause	Draw non-sinusoidal currents from the supply	Caused by non-linear currents and system impedance
Main Effects	Increased heating and losses in conductors and equipment, voltage distortion, transformer overheating, neutral conductor overloading	Increased heating and losses in equipment, interference with communication systems, resonance effects with capacitor banks
Propagation	Propagate through the system impedance, contributing to voltage harmonics	Propagate through the system, affecting connected equipment

Measurement Point	Measured at the point where the non-linear load connects to the system	Measured at any point in the system, as they propagate through the network.
Responsibility	End-users operating non-linear loads	Utilities responsible for maintaining clean voltage supply.

Supra-harmonic distortion: Supraharmonics are waveform distortions in voltage and current with frequencies ranging from 2 to 150 kHz. Supraharmonics are electromagnetic disturbances that travel through cables and electrical equipment and occasionally radiate into the atmosphere. The use of modern power electronics-based devices and protocols to maximize energy efficiency has increased from supraharmonic sources.

Supraharmonics might cause problems like insulation material aging, failure of medium-voltage (MV) cable terminations, aging of capacitors in electronic devices, audible noise, LED lamp light flicker, EV charging interruption, and energy meters reporting inaccurate measurements. Problems with supraharmonics exist in both low-voltage (LV) and medium-voltage networks [9].

Voltage fluctuations: Voltage fluctuations are variations in the voltage level of an AC power supply from its nominal value. These variations can be caused by a variety of factors, including changes in electrical installations' power demand, the operation of fluctuating loads, and the switching of electrical equipment such as capacitor banks, transformers, and motors.

Voltage fluctuations can appear as sudden changes in voltage levels over short periods, as well as longer-term variations that may affect the stability and performance of electrical and electronic equipment connected to the power supply. These fluctuations can have an impact on the proper functioning of sensitive equipment as well as the quality of lighting provided by lamps and other illumination sources [10].

Voltage fluctuation is an important feature of power quality. These fluctuations can be either increases (overvoltages) or reductions (undervoltages) in amplitude. Several factors contribute to voltage variation:

- Grid Instability: Voltage fluctuations are frequently triggered by an unstable electrical grid operating under inadequate supply conditions. This phenomenon typically arises from a deficit in generation capacity, transmission bottlenecks, or peak demand periods that outstrip the available supply headroom.
- Faults and Short Circuits: Electrical faults, such as short circuits or equipment malfunction, can cause sudden voltage fluctuations. Such anomalous events induce abrupt variations in the network's impedance profile and current pathways, consequently degrading transient voltage stability.
- Reactive Power Imbalance: The regulation of voltage levels is intrinsically linked to reactive power dynamics, which support the operation of electromagnetic and electrostatic loads. Consequently, any equilibrium mismatch between the network's inductive and capacitive components directly drives fluctuations in the voltage profile.
- Voltage Regulation Issues: Non-optimal voltage control on the utility side or misconfigured transformer tap changers can lead to instability in the voltage profile.

These fluctuations are often exacerbated by deficient control loops and inaccurate adjustments to the nominal voltage thresholds.

- Weather and Environmental Factors: Severe meteorological phenomena and atmospheric discharges, such as lightning strikes, can introduce rapid voltage transients into the transmission grid. These environmental disturbances ultimately compromise the stability and quality of the supply voltage delivered to downstream electrical systems.

Voltage fluctuations can lead to various issues:

- Equipment Damage: Both electrical machinery and solid-state electronic devices possess limited tolerance thresholds regarding voltage variations. Prolonged or transient overvoltages and undervoltages can degrade or permanently damage these sensitive components.
- Process Anomalies: Voltage variations may cause shutdowns or anomalies in industrial processes.
- Aging: System components age faster due to irregular voltage levels.
- Electronics Malfunctions: Sensitive electronic devices may malfunction.

Figure 4[3] illustrates the difference between voltage waveforms affected by variation problems.

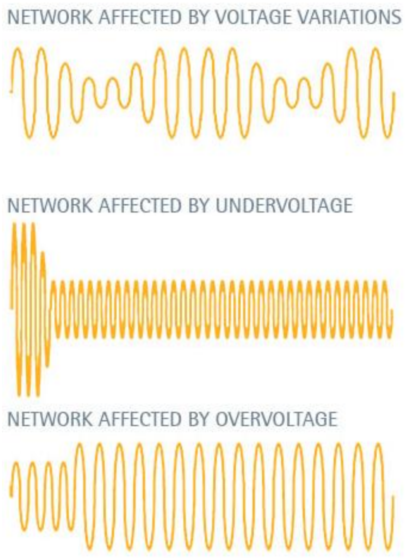


Figure 4. Voltage waveform that can be present on an electrical system affected by voltage variation problems.

Undervoltage

In accordance with the IEEE 1159 standard, an undervoltage condition is characterized by a reduction in the root-mean-square (RMS) AC voltage: typically fluctuating between 80% and 90% of the nominal rating: sustained at the power frequency for a duration exceeding one minute, as illustrated in **figure 5**[3].* Undervoltage is typically caused by low distribution voltage as a result of heavily loaded circuits that create significant voltage drop, switching on a big load or group of loads, or turning off a capacitor bank.

[3] *Note*. Adapted from *Power quality problem: voltage variation*, by IREM, n.d., (https://www.irem.it/en/power-quality-problem-voltage-variation/). Copyright by IREM. Reprinted with permission.

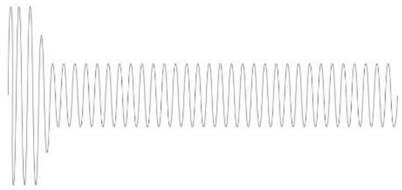


Figure 5. Undervoltage Waveform.

Under-voltage conditions pose a significant risk to heavy household appliances; such as refrigeration units, dryers, and air conditioning systems; often leading to thermal overload, operational malfunctions, unexpected shutdowns, and premature equipment degradation.

The undervoltage problems may be mitigated by:

- Reduce System Impedance
    - Increases transformer size to handle loads better.
    - Shorten line lengths to minimize voltage drop.
    - Add series capacitors to improve voltage stability.
- Improve Voltage Profile
    - Adjust transformer's tap settings to maintain optimal voltage.
    - Install voltage regulators or automatic on-load tap changers.
- Reduce Line Current
    - Transfer loads to other substations to balance the system.
    - Add shunt capacitors to compensate for reactive power.
    - Consider upgrading to a higher voltage level.

Undervoltage poses risks to equipment performance and reliability. Implementing the right mitigation measures ensures a stable and efficient electrical system.

Overvoltage

Overvoltage, as defined by the IEEE, is the increase in AC voltage (RMS) at the power frequency for more than one minute, usually ranging from 110% to 120% of nominal, as is shown in **figure 6**[4]. It usually occurs due to high distribution voltage caused by mismatched transformer tap settings, turning off a large load, or overcompensating for voltage loss on the transmission and distribution networks by powering several capacitor banks.

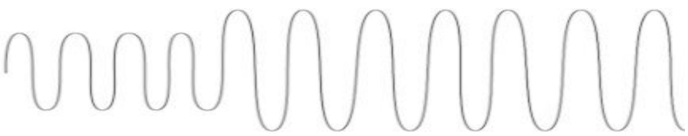


Figure 6. Overvoltage waveform.

[4] Adapted from *The Seven Types of Power Problems*, by Power Quality Blog, 2021 (https://powerquality.blog/2021/09/02/the-seven-types-of-power-problems/). Copyright 2021 by Power Quality Blog.

Overvoltage can cause extensive damage to electrical systems, disrupt operations, and result in costly repairs. Proper protection measures and voltage regulation are essential to mitigate these risks.

The Overvoltage problems may be mitigated by:

- Surge arresters and metal-oxide varistors (MOVs): These devices are designed to divert and dissipate transient overvoltages, protecting sensitive equipment.
- Overvoltage protection relays: These relays monitor the system voltage and initiate protective actions, such as tripping circuit breakers or isolating affected sections, when overvoltages are detected.
- Voltage regulators and tap changers: These devices can regulate the voltage to prevent sustained overvoltages by adjusting the tap positions or controlling reactive power flow.
- Proper system design and grounding: Appropriate system design, including adequate insulation levels, proper grounding, and adherence to safety standards, can help mitigate overvoltage risks.

Transients: are short-duration voltage, current, or electromagnetic disturbances in an electrical circuit. They can be caused by lightning strikes, switching operations, or faults in the power system. Transients can cause equipment damage, malfunction, and failure, and can also lead to electromagnetic interference (EMI).

The flicker phenomenon refers to rapid and repetitive variations in the voltage profile over a brief timeframe. It can be caused by heavy loads like welding machines, elevators, and cranes, or by loose connections in the power system. The flicker effect can result in fatigue, lack of concentration, migraines, and, in some cases, epileptic shock. It can also reduce employee productivity and cause equipment tripping [11].

The flicker perception threshold is shown graphically in **Figure 7**[5]. The area below the curve denotes an unnoticeable zone, whereas the region above the displayed curve suggests a disruption zone where the flicker effect is probably noticeable and could irritate human viewers. Furthermore, the graph's dotted lines show how well tungsten bulbs operate at different nominal voltage ratings.

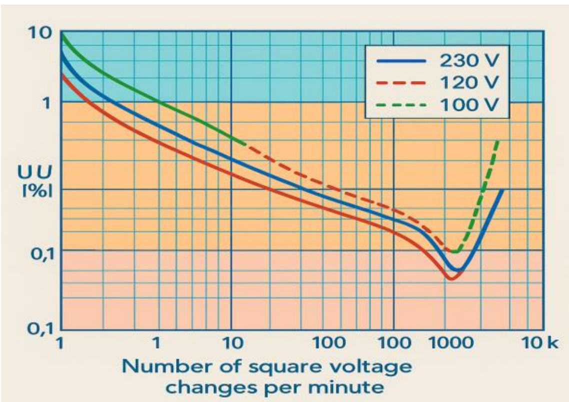


Figure 7. Flicker perception characteristic for square-shaped voltage changes applied to 60 W bulbs

[5] *Note.* Figure 7 was plotted by the author based on curve parameters from [32]

Flickering lights can be both irksome and potentially hazardous in any home or workplace. Not only do they create an unpleasant environment, but they can also indicate underlying electrical problems that require prompt attention.

There are two main types of Flickering:

- Occasional Flickering: If flickering occurs sporadically in specific fixtures or rooms, it may be due to a loose bulb, a faulty socket, or a loose wire connection.
- Constant Flickering: If flickering persists across various fixtures and rooms, there may be a more serious issue with the electrical system, such as overloaded circuits, a loose service wire, or a faulty electrical panel.

While occasional flickering may not always be cause for alarm, constant or persistent flickering should prompt investigation and addressed to prevent accidents, protect health and maintain safety of the workplace or home.

The potential dangers this phenomenon carries are:

Electrical Hazards:

- Fire Risk: Continuous voltage fluctuations often serve as an indicator of degraded wiring, compromised connections, or circuit overloads. These issues can lead to electrical sparks, which in turn can cause fires.
- Short Circuits: Flickering lights could be a sign of short circuits. A short circuit occurs when electrical current flows along an unintended path due to damaged wires or faulty components. This can result in overheating, melting insulation, and fire.

Health and Safety Concerns:

- Eye Strain and Discomfort: Frequent flickering can strain your eyes, leading to discomfort, headaches, and difficulty concentrating.
- Seizure Risk: In patients diagnosed with photosensitive epilepsy, rapid luminous transitions possess the clinical potential to induce epileptiform seizures. While this is relatively rare, it’s essential to address flickering lights promptly.

Premature Wear and Damage to Connected End-Use Equipment:

- Voltage Fluctuations: Luminous intensity variations typically manifest concurrently with voltage fluctuations. These fluctuations can harm sensitive electronic devices, such as computers, TVs, and appliances. Over time, inconsistent voltage can shorten the lifespan of these devices.

Reduced Energy Efficiency:

- Diminished Bulb Lifespan: Frequent flickering can cause incandescent and fluorescent bulbs to burn out faster. The constant on-off cycles stress the filaments and electrodes, reducing their longevity.
- Increased Energy Consumption: Flickering lights consume more energy due to the repeated start-up process. This operational inefficiency directly translates into elevated electricity expenditures.

Indication of Underlying Electrical Issues:

- Loose Connections: Flickering lights often result from loose bulb connections, faulty switches, or loose wiring. Ignoring these issues can lead to more significant problems down the line.
- Aging Infrastructure: If your home's electrical system is outdated, flickering lights may signal the need for an upgrade. Old wiring, outdated panels, and worn-out components can compromise safety.

Main differences between these phenomena

Table 3. Voltage Events: Fluctuation, Flicker, Transient Contrast.

Aspect	***Voltage Fluctuation***	***Flicker***	***Transients***
Definition	Variations in the amplitude of the voltage waveform across the power network.	Visual perception of instability in luminous flux induced by rapid variations in voltage magnitude.	Temporary unwanted voltage spikes caused by various incidents.
Cause	Load variations, grid instability, faults, reactive power imbalance, weather conditions.	Transient variations in network voltage compounded by source impedance, have a direct impact on luminaire output.	Sudden release of stored energy (e.g., lightning strikes, contact bounce, arcing)
Effects	Equipment damage, unstable power supply.	Health impact (fatigue, migraines, lack of concentration). Annoyance.	Can cause equipment malfunction, tripping, and other issues.
Sensitivity	Affects overall power system.	Primarily affects incandescent lighting. LED lighting is less sensitive.	Varies based on equipment susceptibility
Human Perception	Not directly perceived by humans.	Directly perceived as flickering lights.	Not directly perceived but can impact equipment performance.

3 Significance of Modern Appliances

Modern appliances can significantly affect power quality. According to studies, modern appliances can cause power quality issues in residential networks, particularly harmonic-related problems when used excessively. The power characteristics of modern appliances have also been studied, indicating a significant shift in the electrical properties of household appliances and devices [12].

3.1.1 Illumination Devices

Analyzing the significance of various types of lamps for power quality entails considering their impact on factors such as harmonic distortion, voltage fluctuations, and overall electrical system stability.

Incandescent Lamps: Incandescent lamps are well-known for their high-power consumption and inefficiency. They are resistive loads, causing minimal harmonic distortion in the electric system, and their simple design results in fewer power quality issues. However, their high starting current can cause voltage sags and flickering.

Compact Fluorescent Lamps (CFLs): CFLs are more energy-efficient than incandescent lamps, but due to their electronic ballast, can contribute more to power quality issues such as voltage fluctuations and harmonic distortion. These issues can lead to shorter lifespans and lower light output.

Light Emitting Diode (LED) Lamps: LED lamps are highly energy efficient and have grown in popularity due to their long lifespan and low power consumption. LEDs are typically less sensitive to power quality issues than CFLs. However, LED lamps typically use power electronic drivers, and their switching nature can cause harmonic distortion; still, some high-quality LED drivers may include power factor correction to mitigate power quality issues.

High-Intensity Discharge (HID) Lamps: HID lamps require a stable power supply and are susceptible to power quality issues. HID lamps use magnetic ballasts, which can introduce harmonic distortion into the system or lower power factors, resulting in less efficient use of electrical power, and HID may cause voltage fluctuations during the starting process.

3.1.2 Rooftop PV

Rooftop Photovoltaic (PV) systems have emerged as a popular distributed energy resource, allowing people and businesses to generate electricity locally using solar panels installed on rooftops. Rooftop PV has a significant impact on power quality because of its ability to generate clean energy and because of its potential drawbacks, including system integration and intermittency.

The significance of rooftop PV for power quality lies in a variety of factors, including:

Clean energy generation: The use of rooftop PV contributes to a cleaner energy mix by reducing reliance on fossil fuels and minimizing environmental impacts.

Grid support and stability: Rooftop PV systems can help stabilize the grid by injecting energy into it during the day, reducing demand for traditional energy sources.

Intermittency Challenges: The irregularity of solar energy can lead to variations in power generation and affect the stability of the grid, necessitating sophisticated grid management techniques.

Harmonic distortion: The quality of the voltage waveform can be impacted by harmonics introduced into the electrical system by inverters used in rooftop photovoltaic systems.

Protection and regulation of voltage: Rooftop photovoltaic systems have the potential to affect the local distribution network's voltage levels. As a result, suitable voltage regulation devices, like smart inverters, are needed to keep the voltage within allowable bounds and safeguard connected loads.

3.1.3 Adjustable Speed Control Mechanisms

Speed control mechanisms for rotating machines are essential for maintaining good power quality. They help to regulate the speed of motors and other rotating equipment, which can significantly reduce the generation of harmonics, voltage fluctuations, and other power quality disturbances.

Adjustable speed drives (ASDs) can both influence and be impacted by power quality. Some common power quality issues caused by the speed control mechanisms are:

Harmonic Distortion: ASDs can produce harmonic distortion. They can produce high-frequency harmonic currents, increasing total harmonic distortion (THD) in the power system.

Voltage Sags and Swells: Speed control mechanisms can cause voltage sags and swells, which can be harmful to equipment operation and disrupt the power supply.

Transient Over-Voltages: The switching of speed control mechanisms can result in transient over-voltages, which can cause power quality problems and impair the performance of electrical equipment.

Capacitor Switching Transients: Capacitor switching transients related to speed control mechanisms can cause high-energy transients that affect power quality. [13].

Next, it is shown how ASDs can affect power quality [14]:

Frequency Regulation: Speed control mechanisms are critical for controlling the frequency of generated electrical power, particularly in grid-connected systems. This is critical for the stability and dependability of the power system.

Harmonic Mitigation: By controlling the speed of rotating machines, speed control mechanisms can help reduce the generation of harmonics, which are bad for power quality. This is especially important in applications like Organic Rankine Cycle (ORC) power generation systems.

Voltage Regulation: Speed control has a direct influence on generator voltage output. Proper voltage regulation is critical to keeping power quality within acceptable limits.

Efficiency and Energy Conservation: Effective speed control helps rotating machines operate more efficiently, lowering energy losses and improving overall system performance. This in turn improves power quality.

Flicker Reduction: Speed control mechanisms can help reduce flicker from motor starting or pulsating loads, improving power quality.

4 European Context: Standards and Regulations.

4.1 Overview of European Standards

In Europe, a comprehensive framework of standards has been established to govern power quality, which includes parameters such as voltage stability and harmonic limits. This section provides an overview of European standards related to power quality, with a specific focus on the exploration of these standards and their alignment with IEC standards.

4.1.1 Exploration of European standards related to power quality.

Exploring European power quality standards reveals a comprehensive framework for ensuring electrical power reliability and quality. The primary European standard for power quality is:

EN 50160: Voltage characteristics of electricity supplied by public distribution systems. This standard defines the nominal voltage levels, acceptable voltage ranges, and flicker limitations for the public electricity supply in Europe. It applies to low-voltage and medium-voltage networks, covering residential, commercial, and industrial applications. Importantly, EN 50160 complements and aligns with the international standard IEC 60038: Standard voltages.

Additional European standards address specific aspects of power quality:

EN 61000-3-2: Harmonics and interharmonics in public low-voltage supply systems complement EN 50160 by setting limits for harmonic distortion in the LV network. It is consistent with IEC 61000-3-2 on the same topic.

EN 61000-3-11: Voltage fluctuations caused by switching on public low-voltage distribution systems set limits for voltage fluctuations caused by switching operations in the LV network. This standard is consistent with IEC 61000-3-11.

EN 61000-4-7: *General test methods for harmonics and interharmonics measurements and instrumentation details measurement methods and equipment for harmonics and interharmonics, aligning with IEC 61000-4-7.*

These standards establish a comprehensive framework for power quality management in Europe. They ensure compatibility between equipment and power grids in different member states, promoting trade and efficient energy markets.

4.1.2 Alignment with IEC standards

Harmonization of European and international standards is critical for maintaining consistency and interoperability in the global context. The IEC, a leading international standards organization, works with a variety of stakeholders to develop and maintain standards that address various aspects of power quality; as a result, one of the key strengths of European standards is their close alignment with IEC standards. This alignment is critical for promoting consistency in the application of power quality requirements and specifications across different regions and markets, and it also provides several benefits:

International Harmonization: Aligning with IEC standards facilitates global trade and equipment interchangeability. Manufacturers can design products that comply with both European and international standards, simplifying market access and reducing costs.

Technical Expertise: The IEC brings together technical experts from around the world, ensuring that standards are based on the latest scientific advancements and industry best practices. By aligning with IEC standards, Europe benefits from this shared expertise and international cooperation.

Consistency and Transparency: Aligned standards foster clear and consistent communication between stakeholders in the power industry, including utilities, manufacturers, and regulators. This reduces misunderstandings and facilitates efficient problem-solving.

However, there are some differences between European and IEC standards due to regional variations and regulatory requirements. For example, EN 50160 specifies additional flicker limitations that IEC 60038 does not.

It is important to note that IEC standards are not mandatory but are frequently used as the foundation for national and regional regulations. Many European countries have either directly adopted or incorporated EN standards into national regulations. This reinforces the alignment of European and international practices.

4.1.3 EIFS 2023 and Its Implications for Power Quality in Sweden

The Swedish Energy Markets Inspectorate's regulations and general advice on network development plans (*Energimarknadsinspektionens föreskrifter och allmänna råd om nätutvecklingsplaner,* EIFS 2023:3) [15], establish the criteria for structural adaptation. This regulatory framework ensures that long-term distribution grid planning directly contributes to the capacity, flexibility, and overall quality of electricity transmission. Based on this regulation, the key requirements for ensuring high-quality power transmission within grid development frameworks are as follows:

Voltage Characteristics: The regulations establish parameters for voltage changes, stability, and fluctuations to ensure a consistent and reliable energy supply. It defines permissible voltage changes to prevent disruptions in power transmission.

Interruptions: Network operators are required to limit the duration and frequency of power outages. The document describes interruptions as situations in which the connecting point is electrically severed, resulting in a near-zero voltage condition. Effective management of disruptions is critical for providing uninterrupted power supply to users.

Voltage Disturbances: The standards for detecting voltage harmonics and the allowed degrees of distortion in the electrical supply are refined. Network operators are required to reduce the effects of harmonics and maintain a steady power supply by enhanced monitoring and regulating voltage disturbances.

Compliance with Standards: The text underlines the continued importance of adhering to international standards for measuring voltage characteristics, such as SS-EN 61000-4-30. Following defined techniques for assessing power quality guarantees that voltage parameters are evaluated consistently and accurately.

Short-Term Voltage Drops: Network owners are responsible for correcting short-term voltage drops within specified ranges to minimize disruption to electricity customers. The energy grid's reliability can be improved by putting in place appropriate mechanisms to prevent and regulate voltage variations.

Regulations and recommendations: The document outlines detailed regulations and recommendations for maintaining high power quality requirements in electricity transmission. It establishes clear standards for network operators to maintain a dependable and efficient energy supply, therefore contributing to a sustainable and resilient electricity infrastructure.

4.2 Compliance and Regulatory Framework

4.2.1 How modern appliances comply with European power quality standards and regulations.

Modern appliances play an important role in today's society, providing convenience and efficiency in a variety of daily activities. These appliances must comply with European power quality standards and regulations to ensure their safe and efficient operation. The European Committee for Electrotechnical Standardization (CENELEC) oversees developing and maintaining power quality standards in Europe.

In Europe, the regulatory framework that governs the design and performance of modern appliances is extensive and strict. The European Union (EU) has enacted directives and regulations to increase energy efficiency and environmental sustainability while maintaining power quality standards. A primary mechanism within this regulatory suite is the Eco-design Directive (2009/125/EC), which mandates specific environmental criteria for energy-related products, thereby directly dictating the design baselines of contemporary appliances [16]. The comprehensive framework that includes both Eco-design and Energy labeling regulations for various product groups aims to improve the energy efficiency and overall performance of household appliances.

Another critical aspect of ensuring power quality compliance is dealing with electromagnetic compatibility (EMC) issues. The EMC Directive (2014/30/EU) requires that appliances do not emit electromagnetic interference that could disrupt the operation of other devices in the electrical system. Modern appliances comply with the EMC Directive to reduce the risk of introducing disturbances that could compromise power quality. These directives are critical in ensuring that modern appliances meet essential safety, health, and environmental requirements, ultimately contributing to the stability and reliability of the electrical supply system.

European power quality standards, such as the EN 50160 and EN 61000 series, outline specific guidelines for manufacturers to follow when designing and manufacturing appliances. Manufacturers of modern appliances can use a variety of strategies to ensure compliance with European power quality standards and regulations. These strategies include designing appliances with low harmonic distortion, implementing active power filters, and ensuring that appliances are designed to withstand the detrimental effects of power quality disturbances, such as voltage sags and swells.

4.2.2 Comparison between North American and European Power Quality Standards

There are significant differences in power quality standards between North America and Europe [17],[[18]]. In North America, the most common standards are IEEE 519-2014, CSA C22.2 No. 0.9, and various ANSI standards such as C84.1. These include recommended practices for harmonic control, EMC requirements, and voltage regulation. In Europe, EN 50160 is the primary standard for regulating voltage and power quality at the user interface point. IEC standards such as IEC 61000 are also used to assess electromagnetic compatibility.

In contrast, North America tends to adopt more stringent standards, particularly in terms of harmonics. IEEE 519 limits total harmonic distortion to 5%, which is stricter than the 8% limit in EN 50160. IEEE 519 also recommends lower THD limits of 3% for dedicated systems and 5% for general systems under certain conditions. In terms of voltage regulation, EN 50160 allows for a 10% voltage deviation, whereas ANSI C84.1 specifies +/- 5%. For flicker, Short-term flicker severity (Pst) = 1 and Long-term flicker severity (Plt) = 0.65 according to EN 50160, compared to Pst=0.8 in IEEE 519. IEC EMC standards also generally specify more stringent immunity requirements than corresponding CISPR standards in North America.

However, European standards have improved over time and are now becoming more comparable to North American levels. The wider adoption of international IEC standards, such as IEC 61000, is also contributing to increased consistency. However, North America still lacks comprehensive supply-side regulations like EN 50160. Overall, North America maintains higher standards, whereas Europe relies more on regulated standards.

Table 4. US vs. EU Standards

STANDARD	NORTH AMERICA	EUROPE
Harmonic Distortion	IEC 61000-3-2 (baseline), IEEE 519 (additional)	IEC 61000-3-2
Harmonics Limits	THD < 5% (IEEE 519)	THD < 8% (EN 50160)
Nominal Voltage	120/240 V (Single-phase), 208Y/120 V, 480Y/277 V (Three-phase)	230/400 V (Three-phase) (common), variations exist
Voltage Regulation	+/- 5% (ANSI C84.1)	+10%/-10% (EN 50160)
Flicker	Pst < 0.8 (IEEE 519)	Pst < 1, Plt < 0.65 (EN 50160)
EMC Requirements	CISPR standards	IEC 61000 standards
Scope	Voluntary guidelines	Mandatory standards

5 Power Quality Issues with Lamps

5.1 Review of studies on harmonic distortion, voltage fluctuations, and flicker effect caused by different types of lamps.

Power quality is a critical aspect of lighting systems, as power quality issues can affect the performance and durability of lamps, as well as cause disturbances in the electrical grid. Among these issues, harmonic distortion, voltage fluctuations, and flicker effect are prevalent.

Harmonic distortion is a major concern with non-linear loads like electronic ballasts used in compact fluorescent lamps and light-emitting diode lamps. A study by R. Carbone et al. [19] analyzed the harmonic emission characteristics of different lamp types, including incandescent, fluorescent, and LED lamps. The results showed that LED lamps had the highest harmonic content, with THD values ranging from 105% to 148%, followed by CFLs with THD values between 70% and 120%. These high THD levels can cause overheating, increased losses, and premature aging of electrical equipment.

Another study by M. S. Ganjavi et al. [20] examined the harmonic distortion of LED street lighting systems. The authors found that the harmonic currents injected by LED drivers could exceed the limits set by standards like IEC 61000-3-2, necessitating the use of passive or active harmonic filters to mitigate the harmonic pollution.

Voltage fluctuations can occur when lamps with high inrush currents are switched on or off, causing rapid changes in the load current drawn from the power system. These sudden changes can result in inadequate lighting and a reduction in lamp lifespan. Various types of lamps have the potential to induce voltage fluctuations within the power network. LED lamps, compact fluorescent lamps, and incandescent lamps are examples of lighting sources that can introduce harmonic distortion into the distribution system, consequently causing fluctuations in voltage levels. Specifically, LED lamps are recognized for generating highly distorted harmonic currents that surpass standard thresholds, thereby influencing the overall power quality [21]. Similarly, CFLs, functioning as nonlinear loads, are capable of producing harmonic distortions that result in voltage fluctuations and an escalation in current along the neutral wire of low-voltage networks [22].

The utilization of diverse lamp types, particularly in significant quantities, has the capacity to contribute to voltage fluctuations and influence the stability and quality of the utility grid. It is imperative for professionals in the field to acknowledge the harmonic characteristics of lighting systems when designing and managing power networks to address and alleviate potential voltage fluctuations. By comprehending the effects of different lamp varieties on power quality, engineers can implement appropriate strategies to minimize voltage fluctuations and uphold a reliable and stable power supply system.

Lastly, the **flicker effect,** a rapid and repetitive fluctuation in light output caused by lamps, poses a significant concern in lighting applications. LED lamps, CFLs, and incandescent lamps are known to contribute to flicker due to various factors such as their operating characteristics, power supply fluctuations, and harmonic distortions [21]. LED lamps, with their rapid on-off switching behavior, can exhibit noticeable flicker effects, particularly at lower dimming levels. CFLs may also introduce flicker, especially as they age or when used with incompatible dimmer switches. While incandescent lamps are generally less prone to flicker compared to LED and CFL lamps, they can still produce flicker under specific conditions.

The presence of flicker in lighting systems can have detrimental effects on visual comfort, productivity, and health, potentially leading to eye strain, headaches, and discomfort for occupants exposed to flickering light sources. Therefore, it is imperative for professional engineers to consider flicker characteristics when designing and selecting lighting systems to ensure optimal visual conditions and mitigate the negative impacts of flicker on individuals [22]. By addressing flicker issues in lighting design, engineers can enhance lighting quality and create environments that promote well-being and productivity.

In this segment of the thesis, various studies related to these power quality issues in lamps will be reviewed, focusing on their effects on lamp performance and durability, as well as on lighting quality and visual comfort.

5.2 Impact of Lighting Systems on Power Quality

The utilization of various types of lamps can lead to different power quality problems in the electrical power system, as mentioned earlier. These problems can differ depending on the lamp technology, including incandescent, fluorescent, LED, and HID lamps.

Most incandescent lighting systems have sinusoidal current waveforms that are synchronized with the voltage waveform, which means that they do not typically affect the power quality of a distribution system.

Current waveforms in fluorescent, high-intensity discharge, and low-voltage incandescent lighting systems that rely on transformers or ballasts may be distorted, as shown in **Figure 8[6].**

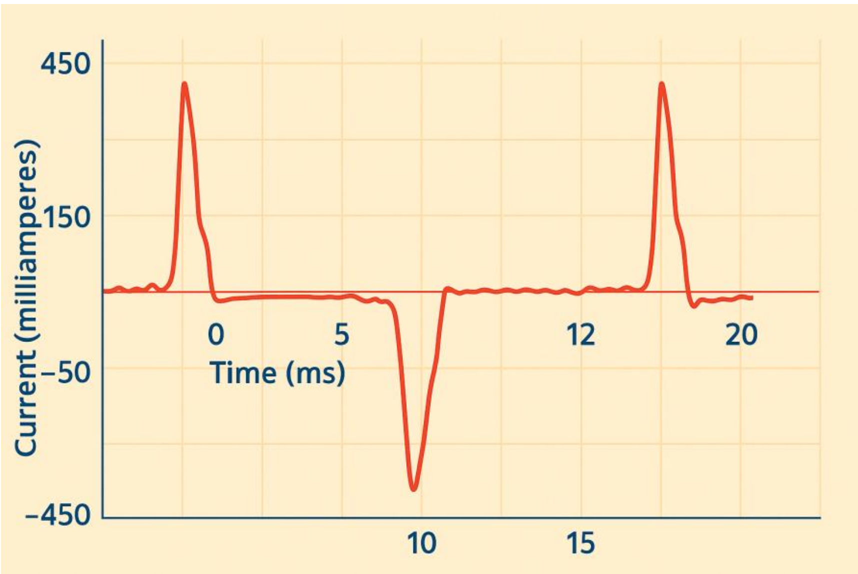


Figure 8. The current waveform shows a high level of distortion.

[6] Note. Figure 8 & 9 prepared by the author base on the conceptual framework from [33].

Devices with these kinds of distorted current waveforms pull current abruptly rather than gradually, which distorts the voltage. The voltage and current waveforms of these devices may also be out of phase. The alternating current circuit's efficiency may be lowered by such a phase shift. During intervals where a phase displacement exists between the voltage and current waveforms, the load temporarily stores and returns reactive power. This energy exchange is illustrated by the shaded regions of **Figure 9**[6], where the voltage and current polarities are opposed. Consequently, useful work is only derived during the unshaded segments of the cycle, which correspond to the active power delivered to the device.

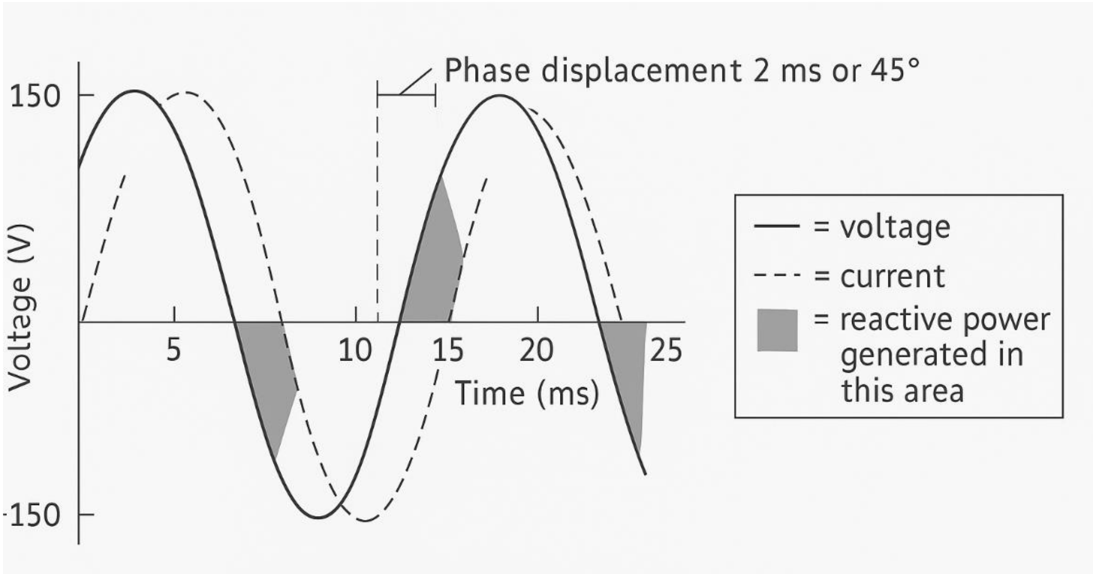


Figure 9. Phase shift between voltage and current.

Reactive power does not cause voltage distortion. Even if reactive power doesn't do any good, utilities' distribution networks still need to be able to handle it, which makes it a significant power quality issue.

Here is a summary of different types of lamps and the potential power quality issues they may cause when installed in large numbers on an electrical network.

Incandescent Lamps

Description: Incandescent light sources operate by passing current through a resistive filament, heating it to extreme temperatures until it glows and radiates visible electromagnetic energy. They are inefficient and have low luminous efficacy**.**

Power Quality Issues: Incandescent lamps generally have fewer power quality issues compared to other lamp types. However, they can still contribute to:

- High energy consumption is due to low efficiency.
- High thermal inrush currents during startup, which can cause minor localized voltage dips if a massive quantity of lamps is switched on simultaneously [23].

Impact: Although their impact on the power system is minimal, using large numbers of incandescent lamps may affect system efficiency.

Fluorescent Lamps
Description: Gas discharge and phosphorescent coatings are used by fluorescent lights to generate light. They are more energy-efficient than incandescent lamps.

Power Quality Issues: Fluorescent lamps, particularly older ones with magnetic ballasts, can generate problems such as:

- Harmonic Distortion: Introduction of harmonics due to the magnetic ballasts.
- Voltage Fluctuations: Susceptibility to supply voltage variations.
- Flicker: Visible changes in light output due to voltage changes or frequency modulation.

Impact: These issues can lead to inefficiency in the power system, discomfort for users, and interference with communication lines.

LED Lamps
Description: These electronic components produce light whenever an electric current flows through them.

Power Quality Issues: LED lamps, while energy-efficient, can generate power quality issues such as:

- Harmonic Distortion: Switching power supplies in LED drivers can introduce significant levels of harmonics.
- Flicker: Low-quality drivers may not provide stable output, resulting in flickering.
- Voltage Fluctuations: Sensitivity to changes in input voltage can cause unstable output.

Impact: These issues can lead to reduced equipment life, visual discomfort for users, and potential interference with other devices.

HID Lamps
Power Quality Issues: High-intensity discharge lamps can introduce problems such as:

- Harmonic Distortion: Electronic ballasts can produce harmonics, though generally to a lesser extent than LED lamps.
- Voltage Fluctuations: Sensitivity to changes in input voltage, causing potential instability in light output.
- Flicker: Visible flickering can occur due to instability in the power supply or ballast operation.

Impact: Such disruptions often reduce illumination quality and can interfere with the operation of nearby electrical devices.

Mercury Vapor Lamps
Description: Mercury vapor lamps generate light by establishing an electrical arc through a pressurized gaseous mercury environment.

Power Quality Issues: Mercury Vapor lamps can introduce problems such as:

- Harmonics: Mercury vapor lamps contribute to harmonic distortion.
- Low Power Factor: Their power factor is usually low.

Metal Halide Lamps

Description: Metal halide lamps use a mixture of metal halides and mercury vapor.

Power Quality Issues:

- Harmonics: Metal halide lamps can produce harmonics.
- Voltage Fluctuations: Sensitive to voltage variations.

Table 5. Differences Among Lamp Types

Lamp Type	Working principle	Harmonic Distortion	Voltage Fluctuations / Flicker	Power Factor
Incandescent	Heating filament to emit light	Low	Low	Good
Fluorescent (with magnetic ballast)	Mercury vapor excited by UV, phosphor coating converts to visible light	Moderate	Moderate	Moderate
Fluorescent (with electronic ballast)		High (low order harmonics & interharmonics)	Low (local) / High (induced grid flicker)	Poor
LED	Semiconductor light-emitting diodes	High (high order harmonics)	Moderate	Moderate to poor
HID Lamps	Electric arc through ionized gas	Moderate	Moderate	Moderate
Mercury Vapor	Electric arc in mercury vapor	Moderate	Moderate	Moderate
Metal Halide	Electric arc in metal halide mixture	Moderate	Moderate	Moderate

6 Power Quality Issues with Rooftop PV

6.1 Analysis of the impact of rooftop PV systems on harmonic distortion, voltage fluctuations and transients.

Rooftop photovoltaic systems, which provide a sustainable and eco-friendly source of electricity, are essential to the changing energy landscape. Their production of renewable energy helps to lessen reliance on fossil fuels, supporting international initiatives to slow down climate change. In addition to supplying electricity throughout the day, rooftop PV systems also improve grid stability and help regulate voltage.

Besides being sustainable, cost-effective and environmentally friendly, PV systems also have some negative effects. These include voltage fluctuations, voltage increases, reverse power flow (RPF), harmonics, frequency distortions, system stability issues, and problems with system faults and protection. These factors can affect the voltage and power quality of the electricity system, as shown in Figure 10. [24]

- *Voltage unbalance due to change between generation and consumption*
- *Reverse power flow due to voltage rise*
- *Voltage rise due to net generation bigger than net consumption*
- *Power losses due to shady or dusty*
- *Harmonics due to no-linear load*
- *Voltage sag due to starting motor, lightning, short circuit, etc.*

Figure 10. Challenges of photovoltaic systems. Image created by artificial intelligence. Created by Herold Fuentes, 2024.

Power quality is challenged by solar energy's sporadic nature, though. Grid stability may be impacted by variations in power output brought on by shifting weather patterns and the time of day. Mitigating possible concerns like harmonic distortion and ensuring adequate voltage regulation requires the use of smart inverters, advanced grid management tactics, and compliance with standards like IEEE Std 1547-2018.

To optimize distributed solar energy benefits and preserve a high-quality power supply, it is imperative to strike a balance between the advantages of rooftop photovoltaic systems and practical methods for managing intermittent power outages.

Key areas of impact include harmonic distortion, voltage fluctuations, and transients.

- Harmonic Distortion:
  Rooftop photovoltaic systems have the potential to cause harmonic distortion in the electrical network. This is mainly because of the inverters utilized in PV systems to convert direct current (DC) from solar panels to AC for use in the electrical grid. These inverters can introduce non-linear loads, which can lead to harmonic distortions in the grid.

  - Impact: These waveform distortions frequently degrade power quality, leading to excessive thermal stress, electromagnetic interference in telecommunication networks, and accelerated aging of system components.
  - Mitigation: To avoid these issues, it is important to use high-quality inverters that have proper filtering and harmonic reduction capabilities. Standards like IEEE 1547 provide limits on harmonic emissions from inverters which can help to minimize the risk of harmonic distortions.

- Voltage Fluctuations:
  Photovoltaic systems can potentially cause voltage fluctuations in the electrical network due to the intermittent nature of solar energy production. When there is a sudden change in solar irradiance, such as clouds passing over the panels, the output of the PV system can vary rapidly.

  - Impact: Voltage fluctuations can cause issues like voltage sags, swells, or flicker. These issues can negatively impact on sensitive equipment and result in customer complaints.
  - Mitigation: Advanced inverters with fast control systems can help mitigate these issues. Through the dynamic regulation of active and reactive power injection, these units effectively stabilize the local voltage profile and isolate downstream equipment from transient fluctuations.

- Transients:
  Transients in electrical networks can occur due to switching operations, such as starting or stopping a PV system or due to weather events like lightning strikes.

  - Impact: Transient incidents can cause damage to electrical equipment and interrupt grid operations.
  - Mitigation: Using suitable surge protection devices, as well as fast-acting switches and protective relays, can assist safeguarding the grid and its associated equipment against transients.

- Transformer Overloading:
  High penetration of solar PV systems in a distribution network can lead to reverse power flow from the low-voltage side to the transformer during periods of high solar generation and low load demand.

  - Impact: Overloading the distribution transformer may result in increased heating and accelerated insulation aging.
  - Mitigation: The proper sizing and design of solar PV systems, coordination of protection devices and proper grounding is recommended to mitigate this issue.

6.2 Discussion of relevant IEC and IEEE standards for rooftop PV.

IEC and IEEE standards are crucial in ensuring the safe and reliable integration of PV systems with the electrical grid. Technical requirements for various aspects of PV systems are established by these standards to help maintain power quality, reduce harmonic distortion, voltage fluctuations, and transients.

IEEE 1547 and IEC 61727 are particularly important for proper interconnection of PV systems, ensuring that voltage and frequency parameters remain within acceptable limits. Additionally, IEC 62109 and IEEE 519 standards address safety and harmonic control, respectively, which are essential for the proper functioning and longevity of PV systems.

It is essential for manufacturers, installers, and system operators to adhere to these standards to maintain the stability and reliability of the electrical network. As PV penetration continues to increase, ongoing updates and revisions to these standards are necessary to keep up with evolving technologies and grid conditions.

IEC Standards

The IEC has created a comprehensive set of standards that address all elements of photovoltaic systems. The most relevant IEC standards for PV systems in terms of power quality are listed below:

- IEC 61727: This standard establishes recommendations for integrating PV systems with the grid, with a focus on connecting inverters to the electricity network. It establishes limits for voltage fluctuations, frequency deviations, and voltage balance, all of which are crucial to network power quality [25].

- IEC 62109: This standard is a collection of papers that specify the safety needs for PV system controllers, converters, and inverters. IEC 62109 assists in preventing electrical faults and disturbances that could jeopardize power quality by making sure this equipment adheres to strict safety standards.

- IEC 61000-3-2: This standard describes the maximum levels of harmonic emissions from grid-connected electrical equipment; however, it does not specifically address PV systems. IEC 61000-3-2 assures that inverters conform to the harmonic limits to maintain power quality, since PV inverters have the potential to create harmonic distortions.

- IEC 61000-3-3: This publication establishes constraints on voltage fluctuations and flicker produced by equipment intended for connection to public low-voltage supply networks.

IEEE Standards

A few PV-specific standards have been produced by the IEEE, with an emphasis on the systems' interaction with the grid and power quality effects. Among these standards, the following stand out:

- The IEEE 1547 framework, titled "Standard for Interconnection and Interoperability of Distributed Energy Resources with Associated Electric Power Systems Interfaces," delineates the comprehensive technical requirements governing the integration of distributed energy resources (DERs) to the grid in a way that is both secure and efficient. This standard covers PV systems and covers topics including protection, frequency regulation, and voltage regulation [26].

- IEEE 929: The requirements for connecting small-scale and residential photovoltaic systems to the electric utility grid are the main subject of this standard. It addresses topics including isolation, grounding, and synchronization—all crucial for preserving steady power quality [27].

- IEEE 519: This standard offers recommendations for power systems harmonic distortion mitigation and control. Because of the non-linear nature of their inverters, PV systems might create harmonics; therefore, it is essential to follow IEEE 519 to minimize the influence of these systems on power quality.

Key Differences between IEC and IEEE Standards for power quality in PV Systems.

A detailed comparison in table 6 reveals that IEEE standards concentrate on interconnection requirements, harmonic control, and recommended practices for power systems with PV integration. In contrast, IEC standards encompass equipment testing, measurement methods, and characterization of power quality phenomena specific to PV systems. The combination of these standards fosters consistent and robust practices across the PV industry, promoting the effective implementation of power quality measures.

While these standards play a pivotal role in managing power quality issues associated with PV systems, ongoing research and development efforts are crucial to further enhance the integration of these systems into the electrical grid. Key areas of focus include advanced inverter technologies, energy storage solutions, and grid management strategies to mitigate the intermittent nature of solar energy generation. These initiatives will pave the way for seamless PV system integration and ensure optimal power quality in the grid of the future.

Table 6. Differences between IEC and IEEE Standards

Aspect	**IEEE Standards**	**IEC Standards**
Focus	Interconnection requirements, harmonic control, and recommended practices for power systems with PV integration	Broader scope covering equipment testing, measurement methods, and characterization of power quality phenomena specific to PV systems
Harmonic Limits	IEEE 519 provides recommended practices and limits for current and voltage harmonic distortion levels in power systems with PV integration.	IEC 61000-3-2 specifies limits for harmonic current emissions from equipment like PV inverters with input currents up to 16A per phase
Voltage Fluctuations and Flicker	IEEE 1453 addresses measurement and limits of voltage flicker on AC power systems, relevant for PV systems.	IEC 61000-3-3 specifically addresses limitation of voltage fluctuations and flicker caused by equipment connected to public low-voltage distribution systems, including PV systems.
Measurement and Testing	Does not cover detailed measurement and testing procedures specific to PV systems	IEC 61000-4-30 and IEC 61000-4-15 provide guidelines for power quality measurement methods and flicker meter specifications, applicable to PV systems.
Equipment Characterization	Does not typically address equipment characterization and certification specific to PV systems	IEC 61400-21 and IEC 61400-22 focus on measurement, assessment, conformity testing, and certification of power quality characteristics of grid-connected wind turbines, which can also be relevant for PV systems

7 Laboratory Procedures and Data Acquisition

The research incorporated a dual method approach to acquire empirical data from light bulbs. This multifaceted strategy allowed a comparison of the different types of comprehensive analysis carried out by the different equipment available on the market. Both methods act by capturing a wide range of information that is shown in the general results of the study. Utilizing two distinct data acquisition methodologies enhanced the reliability of the findings, thereby reinforcing the overall validity of the study.

In the experimental setup, A standard power outlet (230 V, 50 Hz) is used along with the ENTES MPR-47SE Power Quality and Energy Network Analyzer [28], and a digital oscilloscope to form the circuit shown in figure 11. To ensure measurement traceability and experimental reproducibility, the core technical specifications, operating ranges, and international standard compliances of the MPR-47SE analyzer are detailed in Table 7.

Table 7. Technical specifications and compliance standards of the ENTES MPR-47SE analyzer.

Parameter	Technical Specification / Value
Voltage Measurement Range	5 to 300 V AC (L-N) / 10 to 500 V AC (L-L)
Current Measurement Range	Nominal: 1 A / 5 A (Configurable via external CTs) Minimum measurable current: 5 mA
Auxiliary Supply Voltage	85 to 300 V AC/DC, 50/60 Hz
Sampling Rate / Harmonics	64 samples per cycle (Measures individual harmonics up to the 51st order for both Voltage and Current)
Measured Parameters	Phase/Line Voltages, Currents, Active Power (P), Reactive Power (Q), Apparent Power (S), Power Factor (PF), Cos phi, Frequency, THD-V, THD-I, Total Active/Reactive Energy (Import/Export).
Measurement Accuracy	• Active Energy: Class 0.5S (IEC 62053-22) • Reactive Energy: Class 2 (IEC 62053-23) • Voltage & Current: ±0.2% • Power Factor: ±0.1%
Data Logging & Outputs	16 MB internal flash memory, RS-485 communication port (Modbus RTU protocol), 2 Digital Inputs, 2 Digital Outputs.
International Standards & Certifications	• **IEC 62053-22:** Static meters for active energy (classes 0.2S and 0.5S). • **IEC 62053-23:** Static meters for reactive energy (classes 2 and 3). • **IEC 61010-1:** Safety requirements for electrical equipment for measurement, control, and laboratory use. • **CE Certified:** Compliant with European EMC and Low Voltage Directives.

Figure 11. Testing circuit diagram

The electrical diagram for this setup is shown in Figure 12.

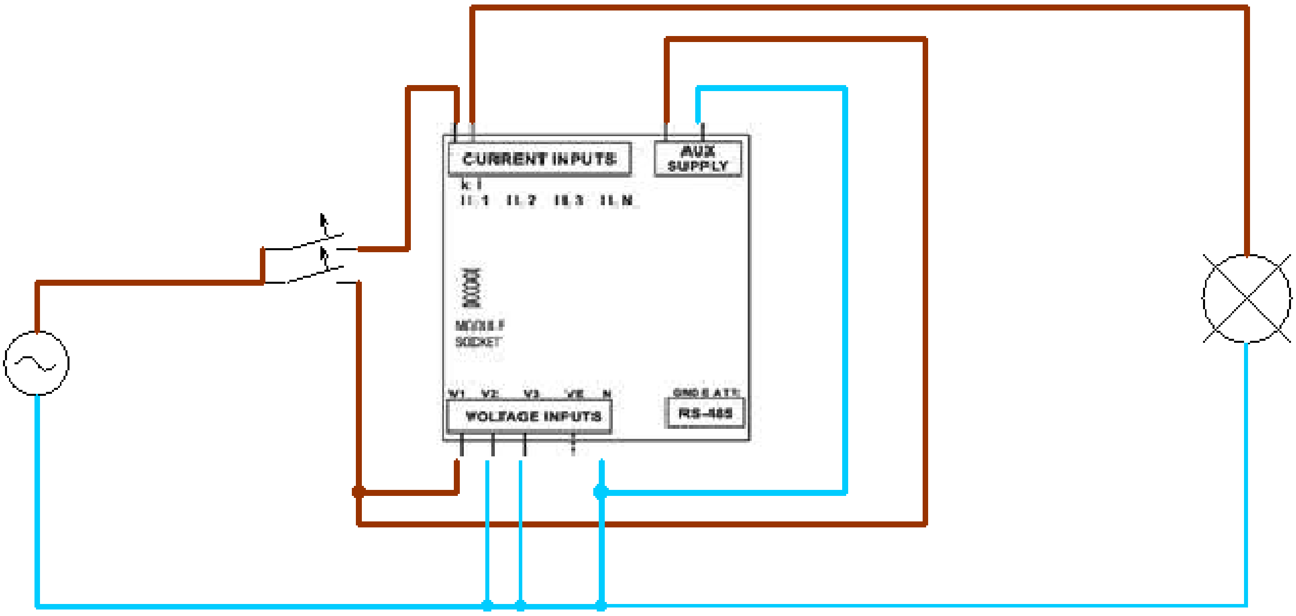
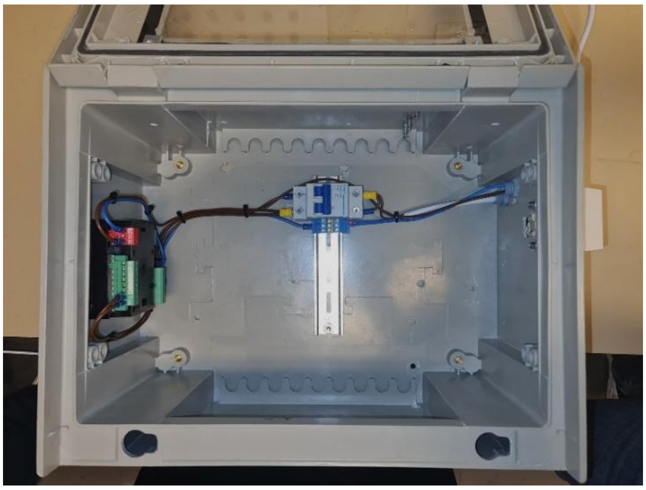


Figure 12. Electrical connection of Entes Energy Network Analyzer

Modern devices come with a triplex power cord and an external insulator that prevents them from coming apart. Therefore, Figure 13.a shows a panel that was built to separate the power cables (line and neutral) of each device for measurement purposes. This was done to be able to connect the CT that is integrated into the Entes measurement equipment as shown in Figure 13.b.



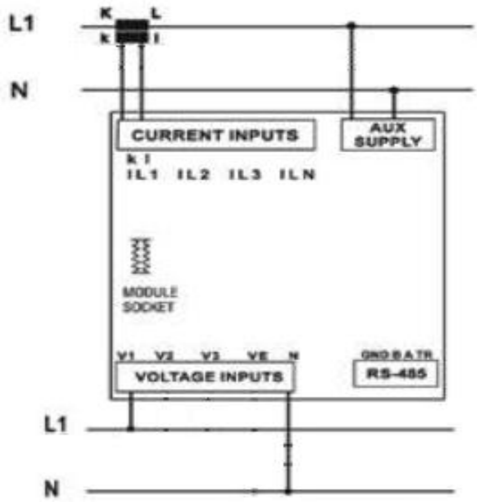


Figure 13a. Panel showing electrical connections. *Figure 13b. Connection diagram for Entes equipment.*

To improve the accuracy and reliability of the data collecting process and establish measurement redundancy, the Unipower Unilyzer 900 Power Quality Analyzer was added as a secondary measuring instrument. This device was chosen for its ability to provide precise measurements and perform a wide range of power quality tests. To ensure measurement traceability, the comprehensive technical specifications, operative ranges, and standard compliances for the Unilyzer 900 [29] are detailed in Table 8. As a result, incorporating the Unilyzer 900 into the experimental configuration not only improved overall understanding of the system's behavior under a variety of conditions, but also provided strong validation of the primary measurement equipment's readings, ensuring a comprehensive and reliable data set for future analysis. The diagram connection of this equipment is shown in Figure 14.

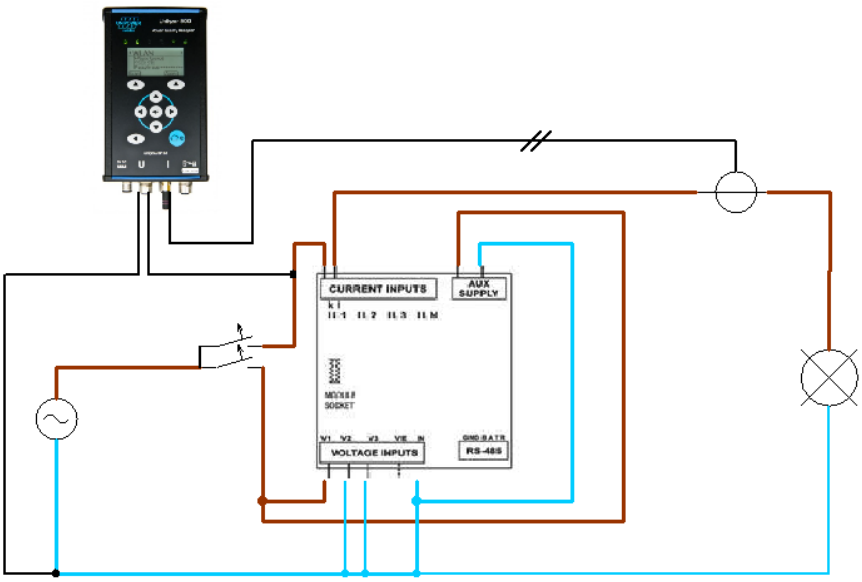


Figure 14. Electrical connection of Unilyzer 900.

Table 8. Technical specifications and compliance standards of the Unipower Unilyzer 900 analyzer.

Parameter	Technical Specification / Value
Voltage Inputs	4 channels: 0 to 600 V AC/DC (L-N) / Continuous overvoltage up to 1000 V
Current Inputs	4 channels: 0 to 1.5 V RMS (Designed for external clamp-on CTs / Rogowski coils)
A/D Conversion & Sampling	16-bit resolution, 512 samples per cycle (Simultaneous sampling on all channels)
Memory Capacity	32 MB internal RAM (Non-volatile, flash memory backup)
Measured Parameters & Harmonics	Voltage/Current magnitudes, Active/Reactive/Apparent Power, Power Factor, Unbalance, Flicker (P_{st}, L_{st}), Signalling, Sags/Swells, Transient capture. Measures individual harmonics up to the 63rd order (including interharmonics)
Measurement Accuracy	• **Class A** compliance for all major parameters. • Voltage: ±0.1% of reading. • Current: Dependent on external sensor (±0.1% internal processing).
Interfaces & Connectivity	USB, RS-232, and optional Ethernet / Wi-Fi / GPRS modem interfaces.
International Standards & Certifications	• **IEC 61000-4-30 Class A:** Power quality measurement methods (highest standard for regulatory compliance). • **IEC 61000-4-15:** Flicker meter functional and design specifications. • **IEC 61000-4-7:** Harmonics and interharmonics instrumentation. • **EN 50160:** Fully integrated automatic evaluation module. • **IP65 Rated:** Robust enclosure for field measurements.

The Unilyzer 900 is a compact device with an IP65 protection rating, making it suitable for conducting power quality measurements in the field. This equipment complies with the IEC 61000-4-30 Class A standard for power quality measurements, guaranteeing precise and reliable outcomes. Lacking any moving components, the Unilyzer 900 operates using connected Current Transformers (CTs) and Potential Transformers (PTs) to capture measurements, which are subsequently transmitted to a centralized database for storage and analysis. Remote access to the database is facilitated via an Internet connection, enabling convenient data retrieval and processing. Moreover, the device features an integrated real-time oscilloscope, which served as an essential diagnostic tool to visually represent, analyze, and compare the voltage waveforms obtained from the mains under two distinct conditions: without load and with the influence of the load. By analyzing these waveforms, one can gain insights into the behavior of the system and identify potential discrepancies or power quality issues. The oscilloscope offered a visual representation of the voltage signals over time and enabling accurate assessment of their relative shapes and characteristics. All the devices used for measurements are True Root Mean Square (TRMS) meters, suitable for non-sinusoidal loads. The standard grid voltage in Sweden is 230 V, with a frequency of 50 Hz. The Swedish grid permits voltage variations within a range of ±10% of the nominal voltage, which means that the voltage can be between 207 V and 253 V.

Test subjects.

A sample of 6 different lamps and 2 small appliances was utilized to conduct an analysis of their impact on the power quality in the electrical grid. The lamps were selected based on their adherence to EU standards, as indicated by the presence of a CE label, ensuring their compliance with relevant safety and performance regulations. The two small appliances were a laptop and a cellphone. The selected lamps exhibit variations in certain attributes, offering a comprehensive representation of the category of lamps most used in homes today. Detailed information regarding the electrical measurements and manufacturer-specified parameters of the tested equipment is provided in the subsequent table 9, facilitating a rigorous comparison and analysis of their individual characteristics and overall performance.

Table 9. Testing subjects.

Lamps	Nominal Power (W)	Life Span (Hours)
Detalco LED	5.5	15,000
Philips LED	7	15,000
Detalco Smart LED Strip	24	25,000
SHOT Incandescent infrared	150	1,500
Unilite Incandescent	100	1500
LEDVANCE Linear compact	8	50,000
Samsung Galaxy Note 20	25	
ASUS Laptop ROG Strix G17	240	

The chosen lamps for the power quality and harmonic analysis operate within the standard voltage range of 220–240 V and at a frequency of 50 Hz, ensuring their compatibility with typical electrical systems. The first column of the table lists the brands of equipment used in the study, while the types of lamps/devices are denoted beside the brand names.

To standardize the data collection methodology, the process was initiated one minute prior to the ignition of each bulb. This allowed for the establishment of a baseline for comparison. Subsequently, the equipment ran for a period of 10 minutes to ensure the attainment of a steady-state regime, which is crucial for the accurate assessment of the equipment's performance. During this stable phase, all parameters were recorded, enabling a thorough and comprehensive analysis of the data.

During the experimental trials, the electrical network of the laboratory was chosen as the power source, in contrast to an isolated system. This decision was made to incorporate the inherent harmonic distortions that are typically encountered in real-world grid-connected environments. To accurately characterize these distortions and create a reliable reference point for the network's performance, a comprehensive set of measurements was performed over a duration of 10 minutes. This established baseline for the harmonics present in the system.

Figure 15 shows the grid supply voltage waveform, it shows the total RMS voltage value ($U_{rms)}$ = 231.1 V and peak value ($U_{p)}$ = 329.4 V. The waveform presents a slight distortion from a pure sinusoidal shape. This means that there are voltage harmonics present in this signal (Figure 16). The total harmonic distortion value in voltage THD_U was 3.2%. These values are within permissible regulatory limits.

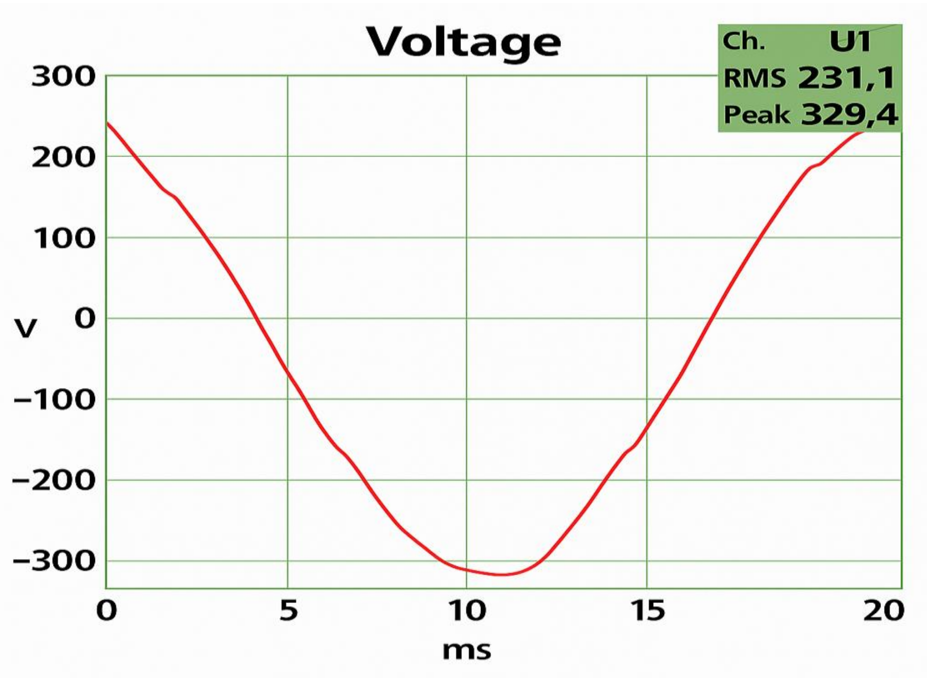


Figure 15. Voltage waveform used to power the gadgets under test.

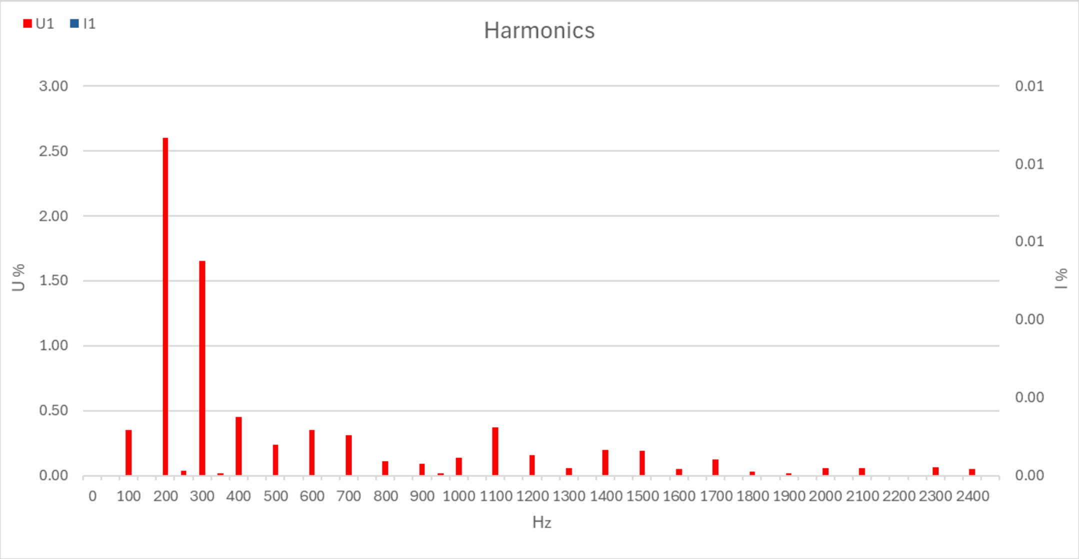


Figure 16. Characteristic of voltage harmonics in % of the fundamental

Figure 16 illustrates the existence of voltage-associated harmonics (indicated by red columns) under no-load conditions within the POC. The system presents a combination of both odd and even harmonics, with odd harmonics prevailing. Notably, harmonics of orders 5 and 7 exhibit the most substantial impact on the system. These findings align with the research conducted by the Institute of Electrical and Electronics Engineers (IEEE), which reported that the 5th and 7th harmonic orders contribute to nearly 60% of total harmonic distortion in modern electrical systems.

8 Laboratory Test Results

8.1 Overview of Findings

This section presents the results of the power quality challenges related to modern appliances. The findings are organized to show the most notable differences derived from empirical data obtained by using the Entes MPR-47SE and Unipower Unilyzer 900 power quality analyzers. The research focuses on energy consumption, power factor and harmonic distortions in a range of lamps and compact home devices.

The data gathered from six different types of lamps and two small appliances revealed considerable differences in power consumption, power factor, and harmonic distortion. LED lighting, while energy efficient, caused significant harmonic distortions. In contrast, incandescent bulbs have modest harmonic distortions but lower energy efficiency. Small gadgets, such as laptops and cellphones, also showed significant harmonic distortions, affecting overall power quality.

The measured parameters are shown in Table 10, and these parameters are total active power (W), total reactive power (Var), true power factor (PF), Voltage THD% (%), Current THD (%).

Table 10. Results of measurements of electrical parameters

Lamp	Nominal Power (W)	Measured Active Power (W)	Q (VAr)[7]	Power factor	Voltage THD (%)	Current THD (%)
Detalco LED	5.5	5.01	-2.7	0.525	2.03	129.65
Philips LED	7	6.4	-1.364	0.65	2.25	120.06
Detalco Smart LED	24	10.68	-0.684	0.524	-	-
LEDVANCE Linear compact	8	7.94	-4.927	0.591	2.40	100.72
SHOT Incandescent infrared	150	149.2	-0.08	1.000	1.97	1.91
Unilite Incandescent	100	98.04	-0.04	1.000	1.95	1.90
Samsung Galaxy Note 20	25	21.35	-4.113	0.512	2.59	174.83
ASUS Laptop ROG Strix	240	41.7	-21.74	0.769	2.96	33.50

A comparison of the nominal and experimental power data presented in Table 10 reveals a close correspondence between the manufacturer's specifications and the actual power

[7] Note: Negative values in the reactive power (Q) column indicate a capacitive power factor. In accordance with the passive sign convention, a negative sign implies that the electronic drivers of these lighting systems inject (supply) leading reactive power back into the grid, rather than absorbing it.

consumption of each lamp, indicating a high degree of accuracy in the reported values and a well-controlled experimental setup. The Detalco Smart LED lamp consumes the most active power compared to the other types of LED lamps because of wireless infrastructure network which allows the bulb to change the color of the light emitted as well as being dimmable.

The most notable difference between the nominal power and the measured power is in the laptop's power consumption and this difference may be because the manufacturer's nominal specification reflects a maximum design threshold calculated for the worst-case scenario, which includes peak hardware stress as well as active battery fast-charging. During the steady-state measurements, the computer was run in a typical processing mode with no severe graphics card usage, and the battery was kept at a full charge. As a result, the internal charging circuit required no power from the network, yielding an experimental figure that represents only a fraction of the nominal capacity.

Incandescent bulbs have a power factor of 1 as they are purely resistive loads, conversely LED bulbs present an average capacitive power factor of 0.5725, because of their non-linear characteristics. The lower power factor of LED lamps compared to incandescent lamps indicates that LEDs, despite their higher energy efficiency in terms of lumens per watt, introduce inefficiencies related to the phase difference between current and voltage.

8.2 Analysis of the harmonics of each device.

8.2.1 Lamps

Detalco LED

In figure 17 we can see the waveforms of the voltage and current that is generated with the Detalco LED lamp. The voltage rms is U_{rms} = 233.2 V and U_{pp}=330.3 V and the current rms is I_{rms} = 40.72 mA and the I_{pp}= 166.1 mA.

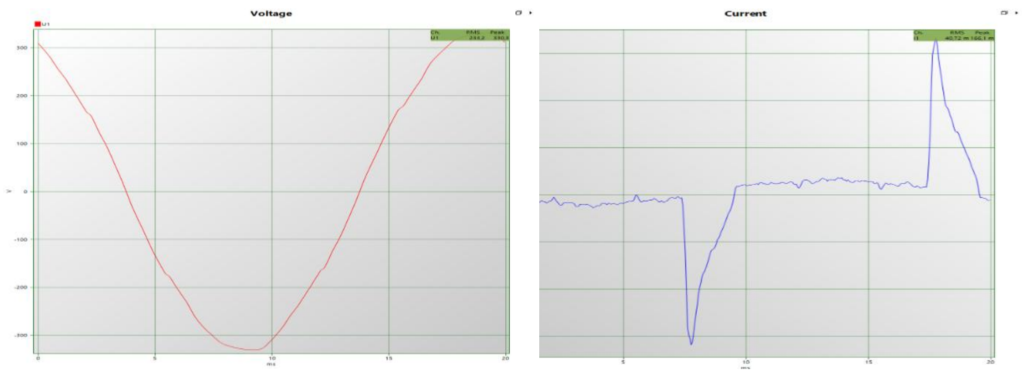


Figure 17a. Voltage wave form. *17b. Current wave form.*

The harmonics in % of the fundamental are shown in Figure 18, where the THD_U = 2.03 % and THD_I = 129.65 %. It is important to note that the THD_U represents the baseline background distortion that existed in the local power grid previous the experiment. Due to the single LED lamp's low power rating, its connection has a small impact on the grid's voltage waveform, with no measured difference in THD_U before or after the device is activated. In contrast, the high THD_I value is essentially a localized impact generated by the nonlinear switching characteristics of the lamp's internal electrical driver. Furthermore, this effect also explains why Figure 18's voltage harmonic spectrum (red columns) differs just little from Figure 16.

These disparities, rather than being caused by the test devices' performance, reflect the time-varying, stochastic character of background voltage distortion in the public distribution network. Because the experimental trials were not carried out sequentially, the baseline grid voltage harmonics varied significantly between measurements due to the fluctuating behavior of external non-linear loads in the larger electrical sector. The current harmonics, represented in blue, exclusively exhibit odd harmonics, with the 3rd order harmonic being the most prominent. In addition, the voltage harmonics, depicted in red, encompass both even and odd harmonics, with the 5th and 7th order harmonics being the most significant.

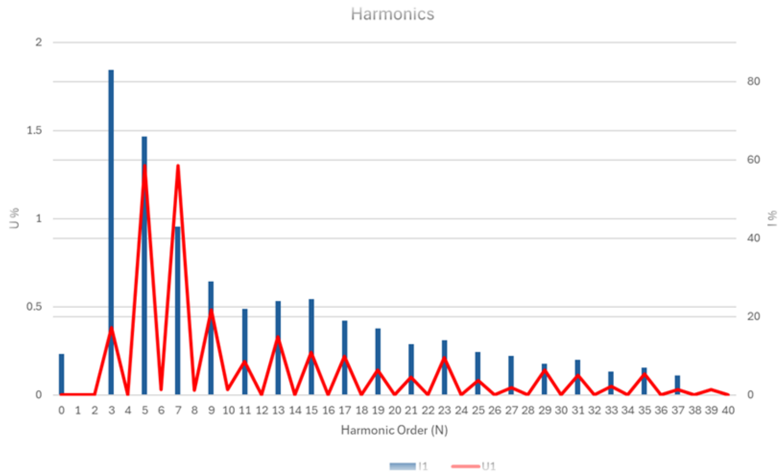


Figure 18. Harmonics % of the fundamental. Red columns are the voltage harmonics and blue columns are current harmonics.

Phillips LED

In figure 19 we can see the waveforms of the voltage and current for a cycle that is generated with the Phillips LED lamp. The voltage rms is U_{rms} = 231.4 V and U_{pp}=327.9 V and the current rms are I_{rms} = 44.26 mA and the I_{pp}= 166.1 mA.

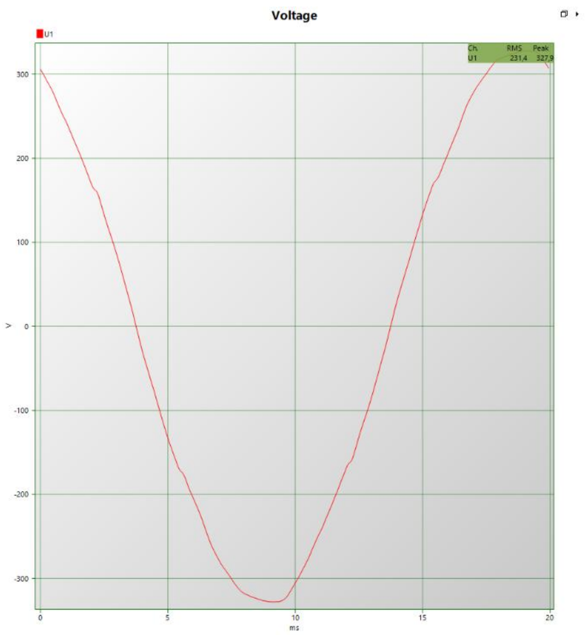


Figure 19a. Voltage wave form Phillips LED Bulb

Figure 19b. Current wave form Phillips LED bulb

The values for the harmonics in % of the fundamental are shown in Figure 20, where the THD_U = 2.25% and THD_I = 120.06%. It is evident that in the current harmonics only the odd harmonics that are in blue are present, the 3rd order harmonic being the largest. The harmonics in red correspond to the voltage harmonics and only the odd harmonics also appear, one of the main differences that can be seen is that for these harmonics the highest one corresponds to the 5^{th} order.

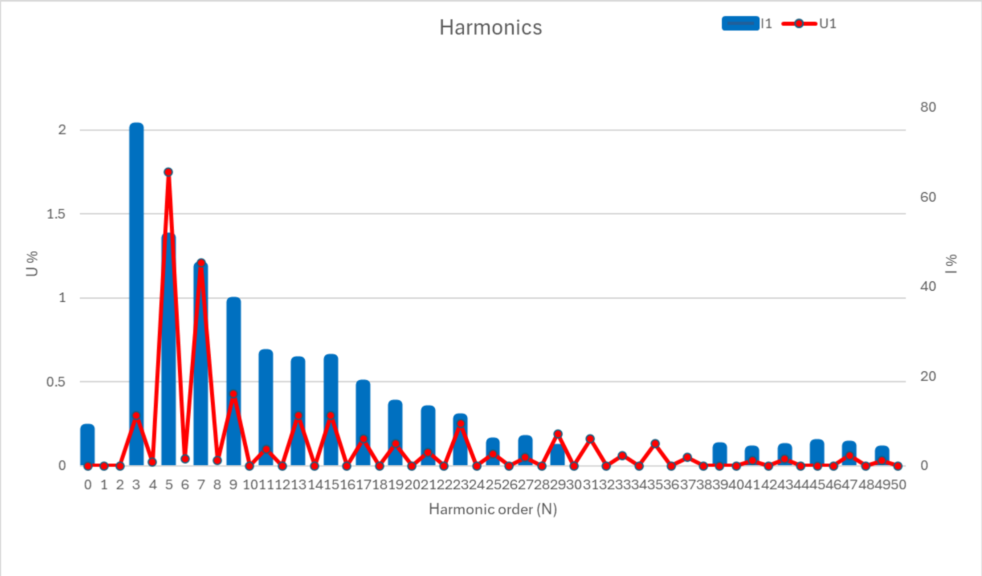


Figure 20. Harmonics in % of fundamental for the Phillips LED bulb, the columns in blue are the current harmonics and columns in red are the voltage harmonics

Detalco Smart LED

This bulb can be dimmable and change color, so the necessary tests were done to see how these two conditions affect the current and harmonics produced by this bulb.

Because the load is very small for the electrical system to which we are connected, the changes in color and opacity of the light in this bulb will not generate visible changes in the voltage waveform. Figure 21 shows the voltage waveform, where the voltage rms is U_{rms} = 235.8 V and U_{pp}=323.3 V. The slightly higher RMS value and increased visual distortion compared to prior trials are solely due to the time-varying, unpredictable nature of the public low-voltage grid. Because the experimental measurements were taken sequentially at different times, typical background grid fluctuations and changing non-linear workloads in the area account for the differences. The voltage profile remains constant whether the LED bulb is connected or unplugged, indicating that the load does not distort or increase the supply voltage.

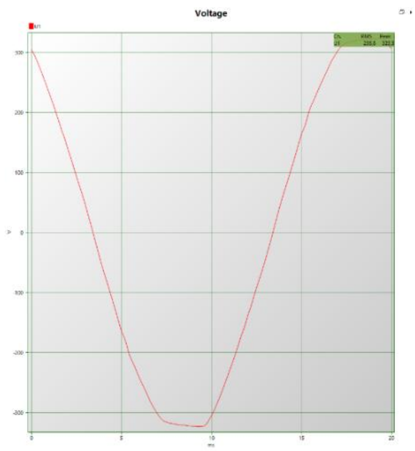


Figure 21. Voltage wave form Detalco Smart LED

The current waveform during a cycle has little variation in terms of color temperature, where the variation is most noticeable is in the amount of current used in the different stages as we can see in table 11.

Table 11. Detalco LED's Current used by different color temperatures

Color temperature	I_{RMS} (mA)	I_{pp} (mA)
6500 K (Daylight)	103.9	487.0
5550 K (Cool white)	92.38	398.2
4600 K (Neutral white)	86.13	375.6
3650 K (Warm white)	78.99	317.1
2700 K (Soft/warm white)	73.67	250.4

Figure 22 shows the most extreme cases of the waveform corresponding to the current provided by the Detalco Smart LED lamp.

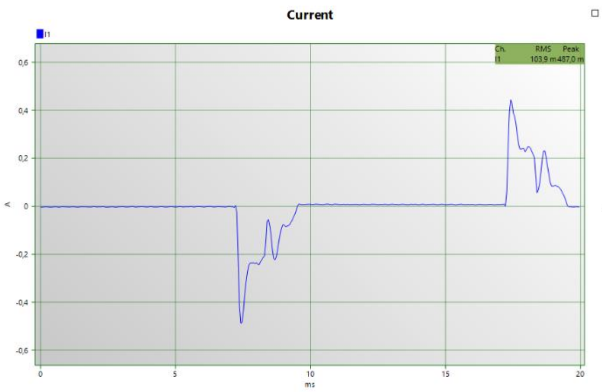


Figure 22a. Current wave form for color temperature 6500 K.

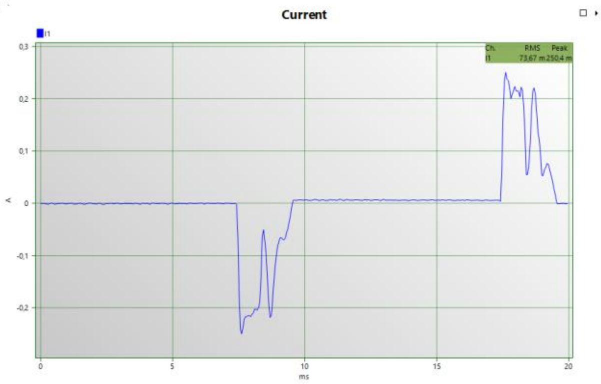


Figure 22b. Current wave form for color temperature 2700 K.

Figures 22a and 22b reveal that the current waveform exhibits greater distortion when using a color temperature of 2700 K, compared to using a color temperature of 6500 K. This higher distortion is due to an increase of 1.8 % in the current harmonics. The TDH_I is 148.45% for the 6500 K, whereas it rises to 150.25% for the 2700 K configuration (figure 22b).

When evaluating the relationship between lamp color change and current variations, Table 12 shows that there is an inverse correlation between current harmonics and consumption. This finding implies that fluctuations in the color temperature and spectrum output of the lamps are accompanied by changes in the harmonic content of the drawn current.

Table 12. Correlation of Current Harmonics and Consumption with Variations in Lamp Color

Color change	I_{RMS} (mA)	Voltage THD (%)	Current THD %
Green	43.36	2.37	189.87
Blue	46.63	2.44	182.95
Red	57.45	2.45	168.81
Purple	61.12	2.39	164.46
Orange	72.71	2.41	152.25
White	85.95	2.42	148.45

Upon examining Figures 23 and 24, which depict the current and voltage harmonics corresponding to the green and white light colors, it becomes evident that although the white color exhibits a higher-order number of harmonics, reaching up to the 83rd order, only a small fraction of these harmonics surpasses 20% of the fundamental component. In contrast, the green color, while showcasing a lower-order harmonic spectrum limited to the 55th order, presents a majority of harmonics that exceed 20% of the fundamental component's value.

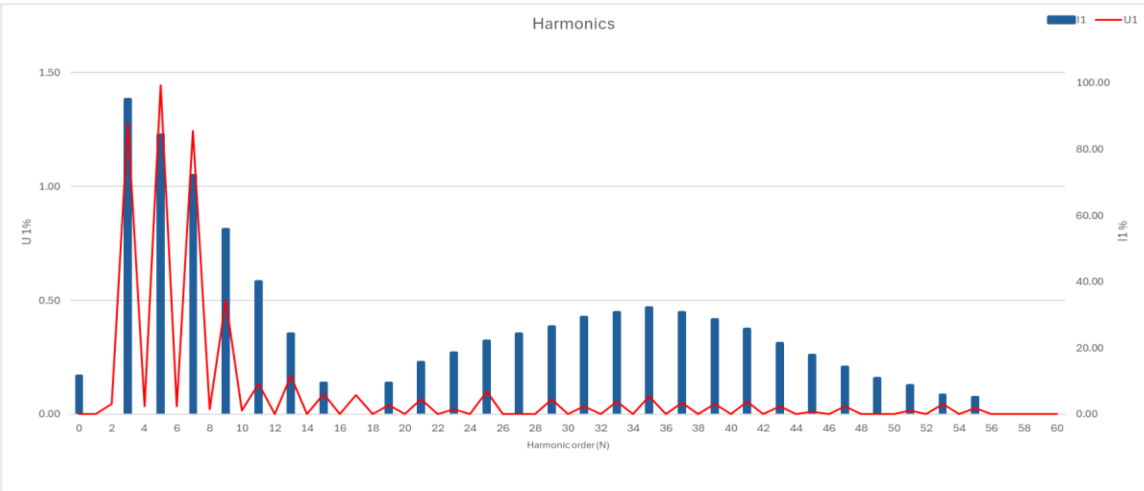


Figure 23. Green light's voltage and current harmonics.

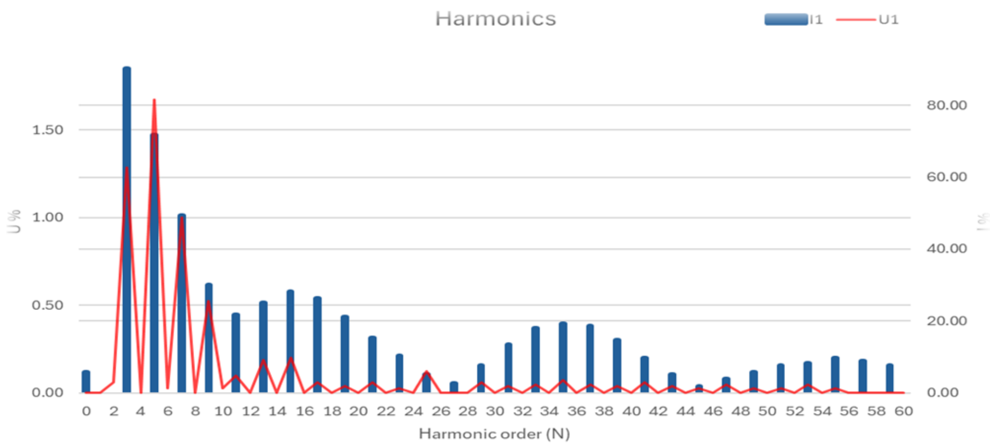


Figure 24. White light's voltage and current harmonics.

LEDVANCE Linear compact

In Figures 25a and 25b it shows the waveforms of the voltage and current for a cycle that is generated with the LEDVANCE Linear compact lamp. The voltage rms is U_{rms} = 232.2 V and U_{pp}=329.2 V and the current rms is I_{rms} = 57.41 mA and the I_{pp}= 203.8 mA.

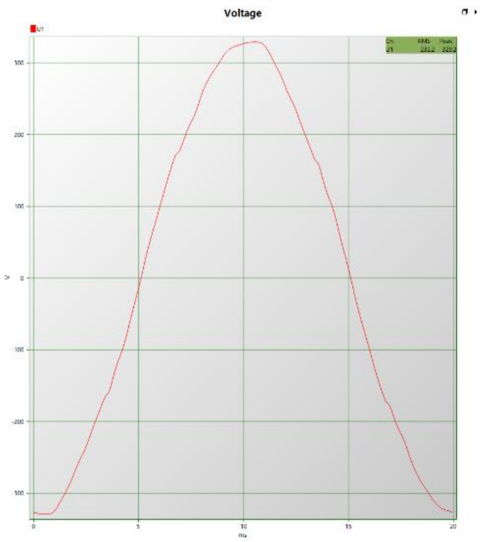


Figure 25a. Voltage wave form LEDVANCE bulb.

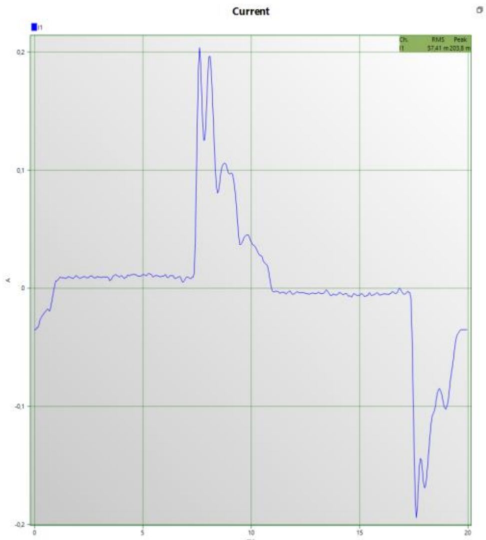


Figure 25b. Current wave form LEDVANCE bulb

The harmonics in % of the fundamental are shown in Figure 26, where the THD_U = 2.40 % and THD_I = 100.72 %. The current harmonics, represented in blue, exclusively exhibit odd harmonics, with the 3rd order harmonic being the most prominent. In addition, the voltage harmonics, depicted in red, encompass both even and odd harmonics.

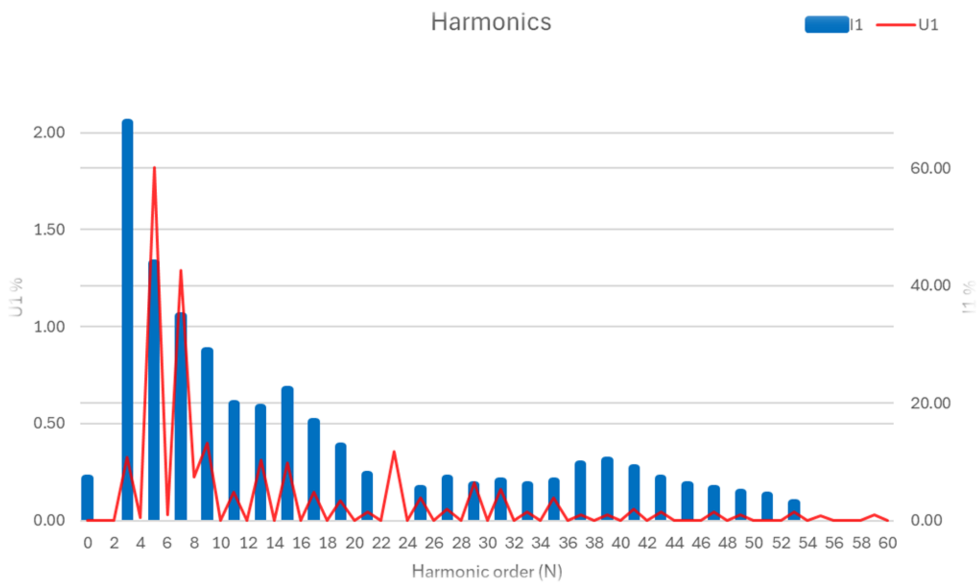


Figure 26. Ledvance Linear compact's harmonics in % of fundamental, the columns in blue are the current harmonics and columns in red are the voltage harmonics

SHOT Incandescent infrared

In the context of the incandescent lamps examined, notably the Unilite Incandescent bulbs and SHOT infrared, the voltage, current, and harmonic waveforms show negligible fluctuation. Given the minor changes discovered, it was deemed appropriate to exclude the graphical representations of the Unilite Incandescent bulb from the results reported in this thesis. This decision was made to retain conciseness and emphasis on the study's most noteworthy findings. However, it is critical to recognize that the consistent waveform features of incandescent lamps highlight their reliable performance and contribute to their long-term presence in a variety of lighting applications.

In Figures 27a and 27b it shows the waveforms of the voltage and current for a cycle that is generated with the SHOT incandescent infrared lamp. The voltage rms is U_{rms} = 231.3 V and U_{pp}=328.6 V and the current rms is I_{rms} = 647.1 mA and the I_{pp}= 915.4 mA.

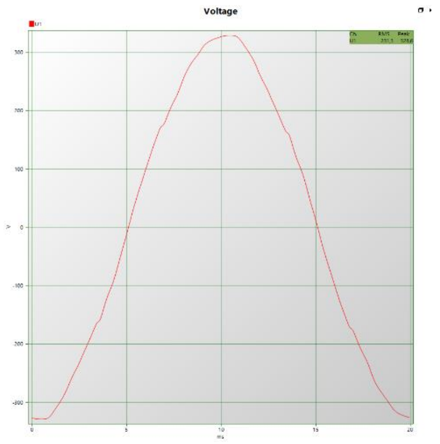


Figure 27a. Voltage wave form incandescent bulb. bulb

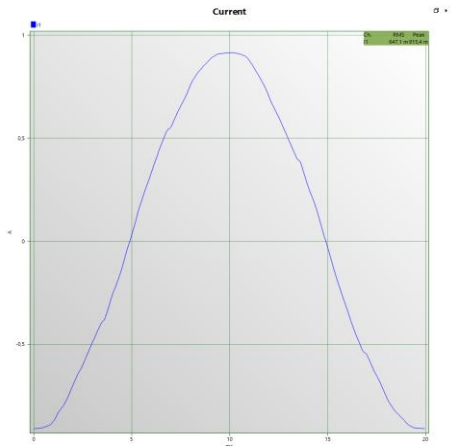


Figure 27b. Current wave form Incandescent

The harmonics as a percentage of the fundamental component are shown in Figure 28, where the THD_U = 1.95 % and THD_I = 1.90 %. An observation about the current harmonics, which are displayed in blue, is that they only occur in the odd harmonics. Among these, the fifth harmonic is the bigger one. Notably, the current harmonics closely match the relative amplitudes of their voltage counterparts (shown in red). This tight correlation confirms the purely resistive behavior of the incandescent filament, where current is directly proportional to the applied voltage.

However, slight instrumental artifacts can be seen throughout the spectrum. A negligible DC component is detected; this is due to residual instrumentation DC offset and internal channel calibration drift inside the power analyzer, not a physical feature of the bulb. Furthermore, when some higher-order harmonics contain a voltage component, the associated current registers as zero. This might happen because the absolute magnitudes of those pre-existing grid voltage harmonics are so small that when applied across the lamp's resistance, the resulting current values are less than the quantization noise floor and the sensitivity resolution threshold of the instrument's current channel. The experiments were carried out with a Unipower Unilyzer 900 power quality analyzer. This instrument complies with the stringent IEC 61000-4-30 Class A requirements for power quality measurement instrumentation. It uses a 24-bit resolution architecture and has a certified voltage/current measurement uncertainty of less than 0.1% (<0.1% U_{din}), establishing the baseline resolution limits for these trace measurements.

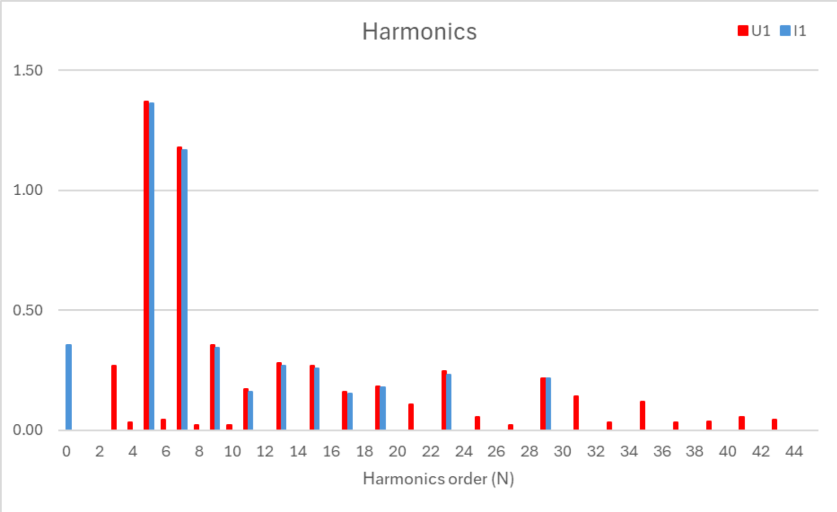


Figure 28. Incandescent lamp's harmonics in % of fundamental, the columns in blue are the current harmonics and columns in red are the voltage harmonics

8.2.2 Small appliances

Samsung Galaxy Note 20

Figure 29 shows us the waveform, voltage and current generated using a Samsung Galaxy Note 20 cell phone. The voltage rms is U_{rms} = 231.4 V and U_{pp}=315.8 V and the current rms is I_{rms} = 180.3 mA and the I_{pp}= 965.7 mA.

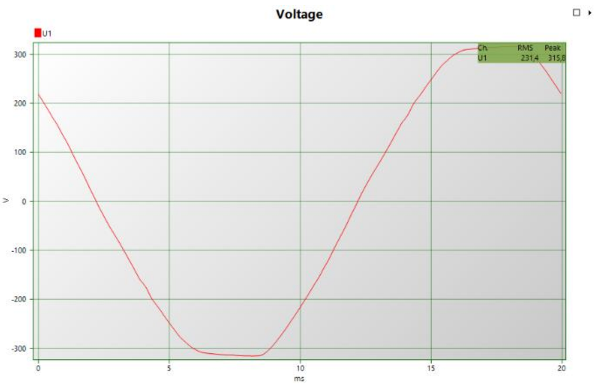


Figure 29a. Voltage wave form Samsung Galaxy Note 20.

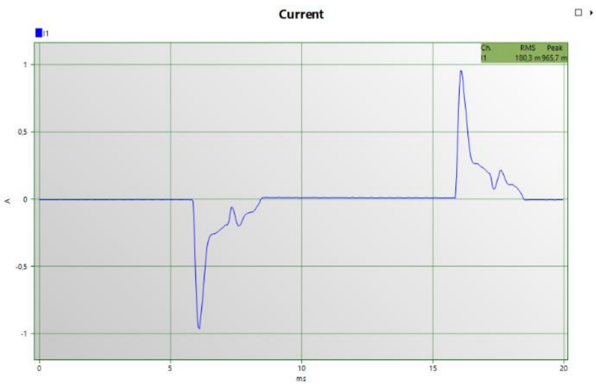


Figure 29b. Current wave form Samsung Galaxy Note 20.

As illustrated in Figure 30, the cellular phone under examination exhibits a wide range of harmonics generation, these occur up to the 99th order. Notably, this device exhibits the highest level of current harmonic distortion among all measured devices. Despite the high percentage of distortion, the device completely meets EMC requirements, notably IEC 61000-3-2 (and EN 61000-3-2). There are two main elements that determine this compliance. The charger's modest active power requirement (≤ 25 W) results in very small (milliampere) fundamental and harmonic currents. The IEC 61000-3-2 standard exempts Class A and Class D equipment with rated power less than 75 W from strict harmonic current limits. As a result, while the relative harmonic profile appears extremely distorted, the absolute harmonic current injected into the low-voltage network is well below safe regulatory limits and poses no hazard to the electromagnetic environment.

The sole instance in which the observed current harmonic distortion is surpassed is the case of the Detalco Smart LED lamp when emitting either green or blue light. This finding highlights the significant impact of certain color configurations on the harmonic behavior of LED lighting systems The harmonics in % of the fundamental are shown in Figure 30, where the THD_U = 2.59 % and THD_I = 174.83 %.

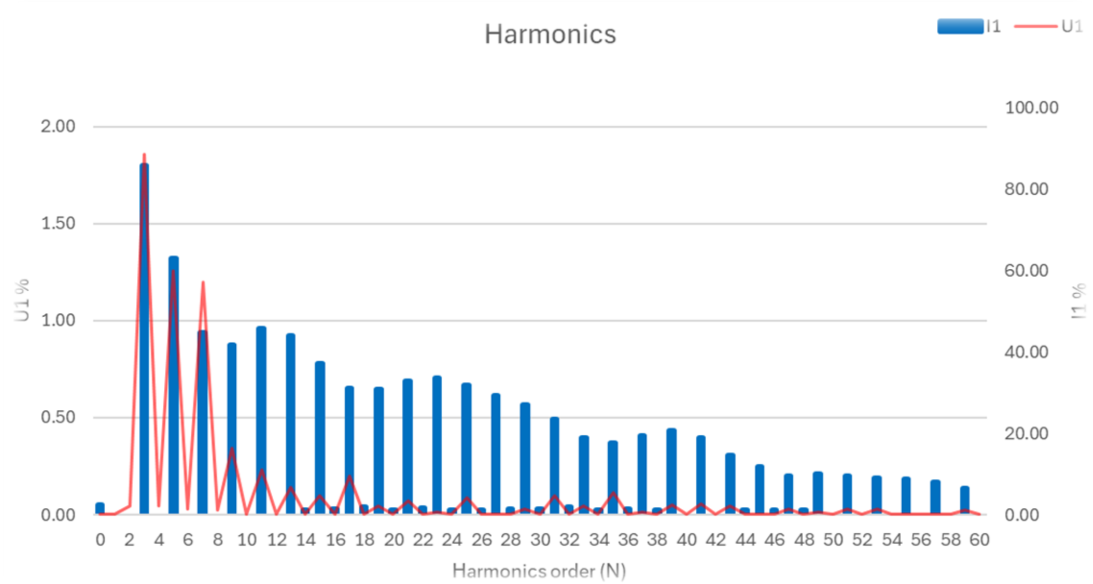


Figure 30. Samsung Galaxy Note 20's harmonics in % of fundamental, the columns in blue are the current harmonics and columns in red are the voltage harmonics

ASUS Laptop ROG Strix

The supply voltage waveform shown in Figure 31a has a flat-topping appearance, in which the peak and bottom parts of the sinusoids appear significantly clipped or chopped. This evident geometric distortion is a common occurrence in modern low-voltage distribution grids, caused by the cumulative influence of residential and commercial non-linear electronic loads in the vicinity that only draw current pulses at voltage peaks. Because the power consumption of the ASUS ROG Strix laptop under test is quite small (I_{rms} = 623.5 mA), its connection has no impact on this profile; the observed voltage distortion remains unchanged whether the laptop is connected to the grid or unplugged. The current waveform in Figure 31b, on the other hand, shows a discernible and considerably more severe nonlinear distortion caused by the device's internal switched-mode power supply. During this operational state, the measured

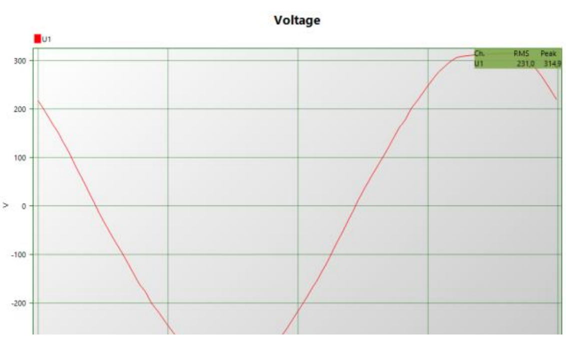


Figure 31a. Voltage wave form Asus Laptop.

Figure 31b. Current wave form ASUS Laptop.

electrical parameters are U_{rms} = 231.0 V and U_{pp}=314.9 V, alongside a I_{rms} = 623.5 mA and the I_{pp} = 1060 mA.

Upon analyzing the Asus ROG Strix computer's operation, it is found that the harmonics that are produced are similar to those of a cell phone and reach up to the 99th order, but a significant difference becomes apparent since in this instance, the harmonic magnitudes are much smaller than those generated by the mobile device. The third harmonic is the only one that exceeds 15% of the value of the fundamental component, as Figure 32 makes clear. The harmonics in % of the fundamental are shown in Figure 32, where the THD_U = 2.96 % and THD_I = 33.5 %.

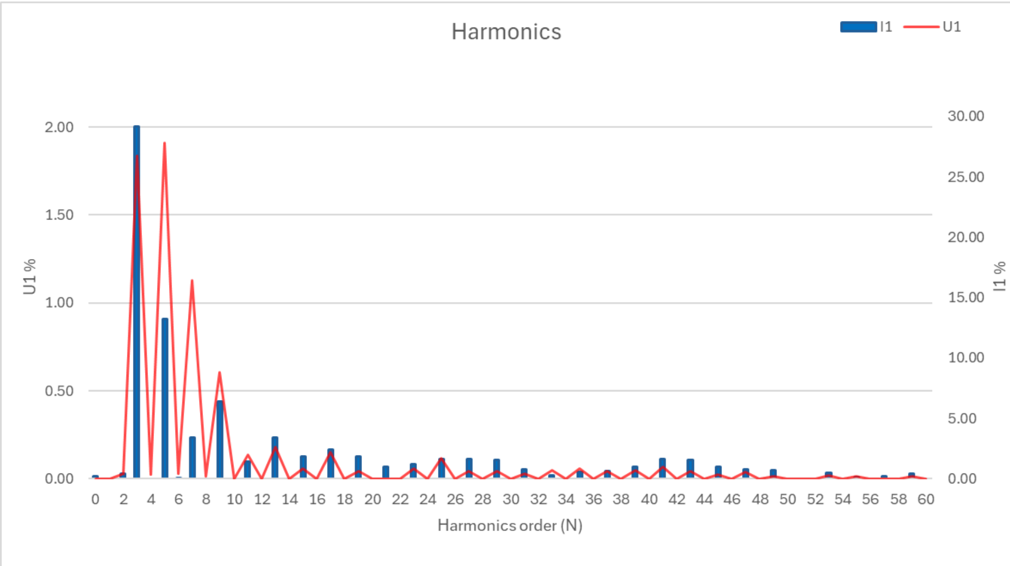


Figure 32. Asus ROG Strix's harmonics in % of fundamental, the columns in blue are the current harmonics and columns in red are the voltage harmonics

A dual y-axis format is utilized to accommodate the variation in scale between voltage and current distortion. The primary (left) axis shows voltage harmonics (red histogram) as a small part of the fundamental voltage ($U1$) on a compressed 0-2% scale, highlighting low-level ground distortion. The secondary (right) axis visualizes the non-linear behavior of the laptop's power supply by displaying current harmonics (blue columns) as a percentage of the fundamental current ($I1$) on a 0-30% scale.

8.2.3 Compliance with Power Quality Standards

To assess the grid-side impact of the tested loads from a regulatory perspective, the experimental harmonic emission profiles reported in Sections 8.2.1 and 8.2.2 were compared to the international standard IEC 61000-3-2 (and its European counterpart EN 61000-3-2). This framework enforces harmonic current limits for equipment with a rated input current not exceeding 16 A per phase, thereby securing electromagnetic compatibility (EMC) in low-voltage distribution systems. Within this regulatory framework, the commercial lighting loads studied in Section 8.2.1 are subject to Class C regulations, but the laptop power supply reviewed in Section 8.2.2 meets Class D requirements for personal computing devices. As CE-marked mass-market consumer goods, all tested devices are factory-certified to meet these standards.

9 Discussion

The findings of this study stress the significant impact of modern appliances on power quality, notably harmonic distortion and power factors. Using the Entes MPR-47SE and Unipower Unilyzer 900 power quality monitors, specific patterns and issues associated with various lighting systems and tiny household devices were recognized and investigated. These discoveries add to our understanding of the complicated interaction between modern electrical devices and power system performance, giving useful insights for the creation of tailored measures to improve power quality in home and commercial settings.

9.1 Power Consumption and Power Factor

The comparison of power consumption and efficiency between LED and incandescent bulbs demonstrates a significant difference. Energy-efficient LED lights use much less active power than incandescent lighting. For example, consider the Detalco LED bulb, which has a nominal power of 5.5 W but a measured active power of 5.01 W. In contrast, the SHOT infrared incandescent bulb, which has a nominal output of 150 W, consumes nearly that power at 149.2 W. This noticeable disparity highlights the energy-saving benefits of LED technology, which is an important aspect in sustainable power management.

The power factor of the devices tested also varied considerably. LED lamps generally showed lower power factors, with values such as 0.525 for the Detalco LED and 0.65 for the Philips LED. This low power factor correlates with a negative reactive power value in the experimental data, indicating a leading (capacitive) property. Rather than drawing reactive power from the grid, the electronic driver circuits in these LED lamps return capacitive reactive electricity to the network. Regardless of the sign or direction of this reactive component, any variation from a unity power factor raises the total RMS current needed to produce the same amount of active power. Inflation of RMS current causes increased ohmic losses in distribution infrastructure, reducing overall system efficiency. This highlights the importance of monitoring power factor trends as low-power non-linear electronics loads increase.

Incandescent lamps, on the other hand, maintained a near-unity power factor of 1, indicating optimal power usage with negligible reactive power. This efficiency in power usage, however, comes at the cost of higher energy consumption and lower lifespan compared to LED lamps.

The study revealed a striking finding: the predominance of negative reactive power (Q) across all examined devices, showing that modern electrical appliances and LED lighting systems are largely capacitive, contributing to a leading true power factor. This capacitive behavior is caused by the input electromagnetic interference filters and smoothing capacitors included in modern switched-mode power supplies and LED drivers. Regulatory standards such as IEC 61000-3-2 (and its equivalent Swedish SS-EN 61000-3-2) govern these devices. For instance, lighting equipment rated above 25 W must maintain a fundamental displacement power factor ($\cos \Phi \geq 0.9$), while smaller residential loads between 5 W and 25 W must maintain a $\cos \Phi \geq 0.5$.

The widespread use of capacitive elements can be traced to their importance in power management and power factor correction. According to research conducted by the US Department of Energy [30], capacitive devices lead to a 25% average power factor improvement in current electrical systems. Furthermore, the optimization of capacitive filtering topologies and topology designs in modern electronic drivers has successfully eliminated internal thermal power losses while increasing overall end-device efficiency, achieving peak efficiency of up to 92%, as reported by the IEEE [31].

However, the widespread, uncontrolled expansion of these low-power capacitive loads poses a significant systemic risk to the distribution network. A high density of devices injecting capacitive reactive power into the grid particularly during low-load periods such as nighttime, might induce localized voltage rise (overvoltage) along low-voltage feeders. This forces distribution transformers to operate under an unfavorable leading power factor regime, increases ohmic line losses due to unnecessary reactive current circulation.

As a result, the consistent observation of negative reactive power among the tested devices emphasizes the need to know how capacitive elements affect power quality in the design and operation of current appliances. This insight serves as the foundation for designing solutions to optimize power management and reduce potential power quality issues in an era marked by widespread integration of modern electronics and lighting systems.

9.2 Harmonic Distortion

When compared to incandescent lamps, the use of LED bulbs creates significant harmonic distortion into the electrical system. Total harmonic distortion (THD) readings for LED lamps are significantly higher: the Detalco LED lamp has a current THD of 129.65%, while the Philips LED lamp has 120.06%. These figures are in direct opposition to the present THD produced by incandescent lamps, such as the SHOT infrared lamp (1.91%) and the Unilite incandescent lamp (1.90%). Figure 33 provides visual comparisons of current waveforms for extreme cases.

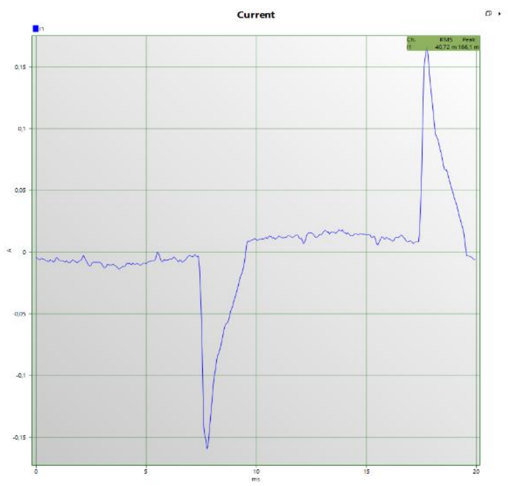


Figure 33a. Current wave form with THDI =129.65%

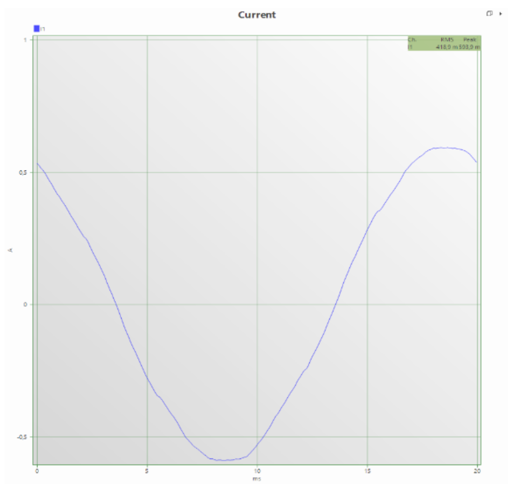


Figure 33b. Current wave form with THDI = 1.90%

The significant levels of harmonic distortion attributable to LED lamps may cause various power quality issues, as previously discussed, highlighting the importance of addressing these implications in the context of modern power systems. This strong contrast underscores a key trade-off: *while LEDs are more energy-efficient, they contribute significantly more to harmonic pollution in the power system.*

The findings of this research also indicate that the color of light substantially impacts the distortion of the current waveform. This is evidenced by the discernible difference in current wave distortion when comparing white light and green light, as illustrated in Figure 34. The implications of this observation on power quality necessitate further exploration, given the increasing prevalence of multi-color LED lighting systems and the potential for varying distortion levels based on the selected color configuration.

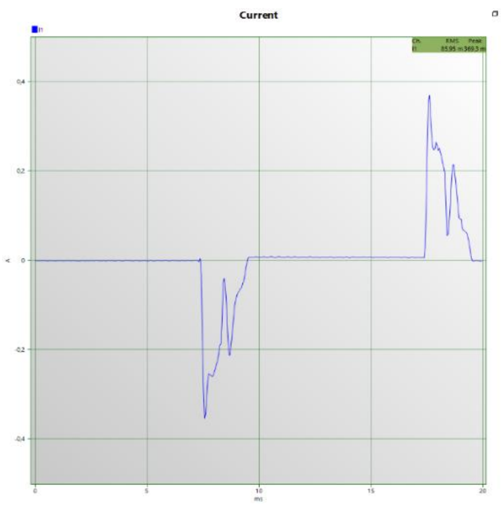


Figure 34a. White light's current wave with THDI =148.45%

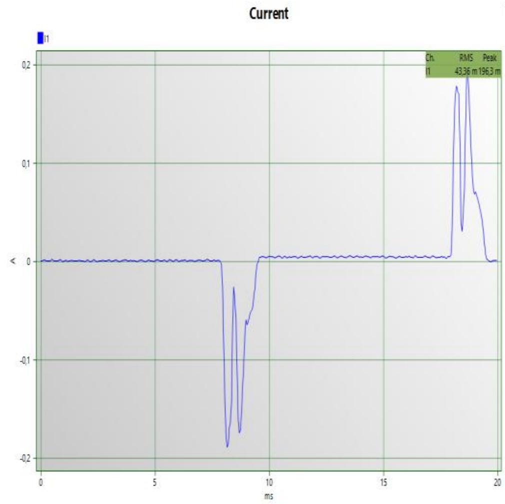


Figure 34b. green light's current wave form with THDI = 189.87%

Another finding from this analysis is the distinct harmonic signatures displayed by various classes of electronic equipment, as well as predictable spectral similarities between categories, while individual appliances within the same category, particularly the various LED lamps evaluated, display highly matching harmonic envelopes due to the industry-standardized topologies of their solid-state driver circuits, individual assessments remain crucial. These intra-category devices continue to exhibit significant differences in absolute harmonic magnitudes and current total harmonic distortion profiles as a consequence of component quality and internal filtering architecture. When comparing behavior across categories, such as the Asus ROG Strix laptop's advanced switch-mode power supply to the Samsung Galaxy Note 20's low-power electronics architecture, the harmonic footprints and spectral spans differ dramatically. Each device's particular profile is ultimately determined by its internal structure, component selection, loading characteristics, and current operating conditions. As a result, these differences highlight the importance of complete, case-by-case harmonic characterizations in accurately assessing the cumulative degradation that various nonlinear load categories inflict on power quality.

The interaction between the distinct harmonic signatures of various electronic devices contributes to the overall harmonic profile of the electrical system. Consequently, this interaction will lead to non-linear effects and amplified harmonic distortion within the network, negatively impacting the quality of power supply.

Understanding these harmonic signatures is crucial for identifying the principal sources of harmonic distortion and designing effective reduction measures. The unique interaction between the harmonic signatures of different devices can lead to non-linear effects and amplified harmonic distortion within the electrical network. These interactions are adversely affecting the overall power quality, leading to issues such as equipment overheating, reduced efficiency, and potential damage to sensitive electronic components.

10 Ethical and Sustainability Implications of Power Quality Issues

Modern appliances have undeniably transformed daily life, offering unprecedented levels of convenience, comfort, and productivity. However, this widespread adoption of advanced electronic devices has introduced significant power quality challenges to the electrical grid. While the preceding chapters of this thesis meticulously investigate the technical aspects of these issues – such as harmonic distortion, reactive power consumption, and flicker – it is crucial to recognize that these technical problems extend beyond mere electrical inefficiencies. They carry profound ethical and sustainability implications that affect consumers, manufacturers, grid operators, and the broader societal and environmental landscape.

This chapter explores the sustainability elements, including the effects on the environment, the financial costs, and the social repercussions, with an emphasis on how these problems limit the use of renewable energy sources.

10.1 Ethical Implications

The proliferation of modern appliances, while beneficial, presents several ethical considerations that demand attention from all stakeholders in the electrical ecosystem.

10.1.1 Consumer Responsibility and Protection

The effects of power quality are most noticeable to consumers. Even if they benefit from contemporary equipment, they could unintentionally cause and experience power quality decrease. It is ethically required of consumers to be aware of the power quality and energy consumption features of the electronic devices they buy. Manufacturers and regulatory agencies, however, also have a responsibility to give clear and intelligible information.

When power quality issues, such as high harmonic distortion or low power factor, cause early equipment failure and higher energy costs due to inefficiencies (e.g., overheating components or flickering lights), consumers suffer direct financial losses and annoyance. The ethical question here is whether customers are effectively safeguarded from these hidden costs and potential risks, particularly given the technical complexities of power quality events.

10.1.2 Manufacturer Responsibility

Modern appliance manufacturers have a big ethical responsibility in the power quality scenario. As the designers and manufacturers of these devices, they are uniquely positioned to address many of the fundamental power quality issues at the source. This responsibility involves the following:

- Ecodesign and Power Quality Standards. Ethically, producers should prioritize "ecodesign" for their goods, incorporating power quality considerations from the start. This includes using efficient power conversion circuits, optimizing harmonic distortion levels to meet or exceed applicable standards (for example, IEC 61000-3-2 for harmonic current emissions), and implementing flicker reduction techniques. The ethical imperative here is to create devices that are both practical and "grid-friendly."

- Transparency and information. Manufacturers have an ethical commitment to offer clear, accurate, and transparent information regarding their goods' power quality. This could include labeling and technical requirements that explicitly define harmonic current emissions, power factor, and other pertinent factors. This transparency enables customers to make informed decisions and leads to a more responsible market.
- Research and development. Ethical commitment to continual improvement requires investing in research and development to create novel solutions for power quality mitigation within appliances, rather than relying on external grid operators.

10.1.3 Grid Operator Responsibility

Power utility companies and grid operators also have an ethical responsibility to provide a dependable and high-quality power supply to all customers. While they cannot influence the internal design of consumer appliances, they are accountable for:

- Maintain grid stability and reliability, grid operators should invest in infrastructure and technologies (e.g., filters) to address increasing harmonic distortion and reactive power demands from modern loads.
- Fairness in Service Provision. All consumers, regardless of socio-economic level or geographical location, should have access to a reliable power supply. Ethical concerns occur when specific locations or consumer groups are disproportionately affected by power quality issues as a result of neglected infrastructure or inadequate mitigating attempts.
- Collaboration and Data Sharing: Grid operators have an ethical role in working with manufacturers, regulators, and research institutes to better understand and manage the evolving difficulties faced by modern appliances. Sharing data on grid-side power quality issues can help improve appliance design and policy decisions.

10.2 Sustainability Aspects

Beyond moral considerations, problems with electricity quality have a significant effect on sustainability's more general environmental, economic, and social facets.

10.2.1 Environmental Impact

The environmental impact of power quality decline is enormous, mostly due to increasing energy use and resource depletion.

- **Higher energy use and greenhouse gas emissions**: Poor power quality, namely low power factor and excessive harmonic distortion, causes inefficiencies in the power delivery system. This causes more current to flow through lines and transformers than is required to produce the same usable power, resulting in larger losses. These losses directly translate into increased demand for electrical generation, which for traditional power sources means increased consumption of fossil fuels and, as a result, higher greenhouse gas emissions.
- **Resource Consumption**: The inefficient use of electricity caused by power quality degradation, such as harmonic-induced thermal losses, requires additional active power generation to compensate for system inefficiencies. This indirectly accelerates the consumption of non-renewable resources within fossil-fuel-dependent energy mixes. Furthermore, if electrical equipment's lifespan is shortened by poor power quality, the additional replacement parts and devices increases raw material

extraction, intensifies production energy demands, and escalates electronic waste accumulation.

- **Challenges for Renewable Energy Integration:** As society moves toward a more sustainable energy future, the integration of renewable energy sources such as solar PV and wind power is critical. However, power quality issues present considerable barriers to this integration. Renewable energies frequently link to the grid using power electronic converters, which can generate harmonics. Furthermore, the intermittent and changeable nature of this generation requires a steady and durable grid for optimal integration. The existing power quality issues produced by modern appliances increase these concerns, making it more difficult to maintain grid stability and voltage quality when substantial volumes of renewable energies are added. Addressing power quality on the load side is therefore critical for a smooth and rapid transition to a clean energy mix.

10.2.2 Economic Impact

Poor power quality has significant economic effects across the entire electrical supply chain.

- **Higher operating costs for consumers and businesses**. Consumers may pay higher electricity costs because of inefficient energy usage caused by poor power factor and harmonic losses. For enterprises and industries, power quality issues can cause considerable economic losses by:
- **Damage to Sensitive Equipment.** Electronic equipment is vulnerable to voltage sags, swells, transients, and harmonic distortion, resulting in premature failure, increased maintenance expenses, and capital investment for replacements.
- **Reduced Equipment Lifespan**. Continuous operation under distorted voltage or current waveforms can damage electrical components, resulting in accelerated aging and shorter operating lifespan for motors, transformers, and electronics.
- **Increased Investment and Maintenance Costs.** Grid operators suffer higher investment and maintenance expenses due to network losses, resulting in inefficient electricity delivery.
- **Equipment Overheating and Reduced Lifespan.** Distorted currents can cause equipment to overheat and shorten its lifespan, resulting in diminished capacity, premature degradation, and early replacement.
- **Investment in mitigation equipment**, such as harmonic filters, reactive power compensators, and active power quality conditioners, is necessary to preserve grid stability and quality.
-

10.2.3 Social Impact

The social consequences of electricity quality issues, while sometimes less obvious, are as critical for a sustainable society.

- Reliable and trustworthy power supply is crucial in modern society. Power quality concerns can appear as flickering lights, faulty appliances, or even complete blackouts in specific locations, causing annoyance, discomfort, and aggravation for residents.

- Power quality disturbances, such as overvoltages or harmonic resonance, can cause equipment overheating or fires. However, these are less prevalent in residential settings under normal conditions.

- Ensuring a stable power supply is crucial for equal access to education, healthcare, and economic opportunities that rely on technology. If electricity quality issues disproportionately affect specific communities or populations, they exacerbate preexisting social inequities.

The technical analyses presented in the previous sections of this thesis, particularly those involving the measurement and characterization of harmonic distortion and power factor in various modern appliances, highlight the importance of the ethical and sustainability concerns discussed in this chapter.

The ethical and environmental implications of power quality issues caused by modern appliances are key considerations for the future of power systems. It is obvious that technical solutions alone are insufficient; a holistic approach necessitates incorporating ethical values and ecological goals into the design, operation, and regulation of the electrical grid.

11 Conclusions and Future Work

11.1 Conclusions

The Extensive characterization of the power quality of selected appliances indicates that modern solid-state lighting solutions, specifically LED luminaires, introduce a non-negligible degree of localized harmonic distortion. Empirical findings reveal a wide prevalence of lower-order odd harmonics, with a marked concentration in the third and fifth spectral orders. Evaluated against current regulatory frameworks, experimental data confirms that all monitored non-linear electronic loads strictly comply with the harmonic current emission thresholds prescribed by IEC 61000-3-2 and SS-EN 61000-3-2 standards for low-power residential equipment.

To confirm the empirical validity and reproducibility of these findings, a data cross-verification methodology was carried out with two independent power quality analyzers of varying technical characteristics. Despite architectural differences between the instruments, particularly in terms of reference sampling rates and inherent measurement accuracy tolerances, steady-state spectral measurements showed excellent correlation and minimal mathematical variation, confirming the structural integrity of the acquisition setup [2]. As a result, these findings highlight a critical power quality paradox: while individual mass-market electronic loads fall within standard compliance limits, their aggregate deployment creates a distinct and cumulative harmonic footprint that fundamentally distorts current waveforms in comparison to legacy linear assets.

11.2 Future work

Based on the empirical findings and methodological constraints presented in this thesis, three essential routes for future research are offered to increase the understanding of the impact of modern nonlinear loads on power quality:

- **Large-Scale Network Simulations of Aggregate Non-Linear Loads:** While this study characterized individual domestic appliances and small-scale devices, future work should focus on scaling these empirical harmonic and capacitive profiles into network wide simulation environments. Modeling a realistic low-voltage distribution feeder—such as a typical Swedish residential neighborhood—would allow for the quantification of aggregate harmonic cancellation or amplification effects and the precise mapping of localized voltage inflation under high-penetration scenarios.
- **Dynamic and Transient Power Quality Analysis:** This research primarily evaluated power quality parameters under steady-state operating conditions. Future investigations should incorporate dynamic load variations, transient behaviors during device start-up sequences, and long-term statistical monitoring. Capturing seasonal load profiles and time-varying harmonic distortion would provide a more comprehensive framework for grid-level risk assessment.
- **Mitigation Strategies for Distributed Capacitive Injection:** Given the identified trend of cumulative capacitive reactive power injection from modern electronic drivers during light-load hours, research is needed into adaptive mitigation strategies. Future studies could explore the coordination of smart inverters (e.g., from residential photovoltaic systems or electric vehicle chargers) to actively absorb excess capacitive reactive power and regulate voltage profiles along low-voltage feeders.

12 Bibliography

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