

Article

Power Quality and Service Continuity in a Low-Voltage Urban Network in the Municipality of Kamalondo in Lubumbashi, DR Congo

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Abstract

Power quality degradation in low-voltage (LV) distribution networks remains insufficiently documented in many rapidly urbanizing African cities despite its significant impact on electrical equipment, service reliability, and network operation. This study investigates the following research question: To what extent does the power quality of an urban low-voltage distribution network comply with international standards, and which network characteristics are most strongly associated with the observed disturbances? To address this question, an extensive field measurement campaign was conducted from October 2024 to February 2025 on five radial feeders supplied by the Babemba medium-voltage/low-voltage (MV/LV) substation in Lubumbashi, Democratic Republic of the Congo. Electrical parameters were monitored using a Class B Chauvin Arnoux Qualistar C.A. 8331 power quality analyzer and evaluated against internationally recognized power quality standards. The measurements revealed persistent power quality degradation characterized by chronic under-voltage, with prolonged voltage levels below 207 V, typical deviations ranging from −20% to −30%, and voltage dips reaching 70–80% of the nominal voltage during peak loading conditions. Power supply continuity was also severely affected, with a System Average Interruption Frequency Index (SAIFI) of 7.85 interruptions/year and a System Average Interruption Duration Index (SAIDI) of 491 min/year, while a medium voltage outage lasting approximately 48 h highlighted the limited resilience of the distribution system. Additional disturbances included phase voltage imbalance reaching 18%, neutral currents up to 327 A, and short-term flicker values (Pst) approaching 1.5, exceeding the recommended comfort threshold. Overall, the observed disturbances were associated with heterogeneous feeder loading conditions, network configuration, non-standard electrical connections, and documented physical deterioration of the infrastructure. This study provides a comprehensive field-based assessment of power quality and service continuity in an urban LV distribution network in the Democratic Republic of the Congo and offers a quantitative basis for prioritizing feeder

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reinforcement, phase balancing, infrastructure rehabilitation, and the establishment of continuous local power quality monitoring.

Keywords: power quality; low-voltage distribution networks; voltage stability; power system reliability; developing urban networks

1. Introduction

The quality of electricity supply has become a major challenge for the sustainable development of modern societies because it directly affects the reliability of electrical systems, the operational performance of industrial and commercial activities, and the lifespan of electrical equipment [1]. This challenge is particularly critical in low- and middle-income countries, where electricity distribution networks are frequently characterized by ageing infrastructure, insufficient investment, rapid urbanization, and continuously increasing electricity demand [2–4]. In the Democratic Republic of the Congo (DRC), and particularly in the city of Lubumbashi, the combined effects of unplanned urban expansion, inadequate maintenance, and limited reinforcement of distribution infrastructure have resulted in electricity services that are not only insufficient in quantity but also highly variable in quality [5]. Consequently, beyond the issue of electricity access itself, increasing attention is now being directed toward the technical quality and reliability of the electricity effectively delivered to end users.

According to internationally recognized standards, power quality refers to the ability of an electrical network to deliver electricity with stable voltage and frequency levels while maintaining a sinusoidal waveform within prescribed operating limits [6,7]. Compliance with these requirements is essential for ensuring the safe operation of electrical equipment, reducing technical losses, improving energy efficiency, and maintaining the overall reliability of electrical systems [8,9].

Power quality is commonly assessed through a set of standardized electrical indicators that characterize both the operating condition of the distribution network and the quality of electricity supplied to consumers. These indicators include frequency stability, voltage magnitude, slow voltage variations, voltage sags and swells, short- and long-duration interruptions, voltage fluctuations and flicker, phase voltage imbalance, total harmonic distortion (THD), inter-harmonics, carrier signals, and transient disturbances [10–12]. Together, these parameters provide a comprehensive framework for assessing the technical performance and reliability of low-voltage distribution systems. Recent studies have further highlighted that continuous monitoring of voltage profiles, voltage imbalance, reverse power flow, and other power quality indicators is becoming increasingly important in modern low-voltage distribution networks with high penetration of distributed renewable energy resources, enabling improved network observability, voltage regulation, and operational reliability [9,13]. Figure 1 summarizes the principal power quality indicators commonly considered in international standards for evaluating electrical distribution networks.

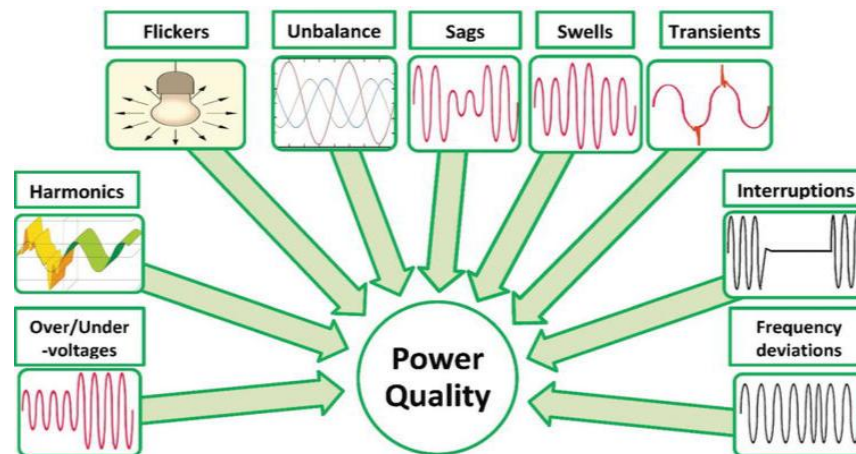


Figure 1. Key parameters of electrical power quality.

Power quality degradation originates from a combination of network-related and load-related factors. On the demand side, the widespread use of electronic and non-linear loads including information technology equipment, switched-mode power supplies, variable speed drives, LED lighting systems, air conditioners, battery chargers, and household appliances has become one of the principal sources of harmonic distortion, voltage imbalance, and waveform distortion, even in residential distribution networks [14,15]. These loads inject non-sinusoidal currents that interact with the impedance of low-voltage distribution feeders, resulting in voltage distortion, increased technical losses, and reduced network efficiency [16,17]. On the supply side, the rapid integration of distributed energy resources (DERs), continuous load growth, and limited network reinforcement further aggravate feeder congestion, voltage regulation problems, and transformer overloading [5]. In many developing urban networks, these technical challenges are compounded by ageing infrastructure, inadequate maintenance practices, conductor undersizing, transformer overloading, and the widespread presence of non-standard or illegal electrical connections, all of which are associated with increased voltage deviations and reduced service continuity [5,18].

Despite these well-established causes of power quality degradation, important knowledge gaps remain regarding their combined effects under real operating conditions in rapidly growing African urban distribution networks. This observation leads to the following research question addressed in this study: To what extent does the Babemba low-voltage distribution network comply with internationally accepted power quality and service continuity standards, and which technical factors are most strongly associated with the observed electrical disturbances? Addressing this question requires not only quantifying the principal power quality indicators but also analysing their relationships with feeder characteristics and network operating conditions.

Recent studies have considerably improved the understanding of power quality in low-voltage distribution networks, particularly in developing countries where ageing infrastructure, rapid urbanization, and continuously increasing electricity demand place significant stress on electrical systems. For example, Ref. [6] demonstrated that combining continuous field measurements with simulation tools enables the identification of harmonic distortion, voltage deviations, and transformer overloading in low-voltage distribution networks. Likewise, Refs. [7,15] emphasized that systematic monitoring of power quality and reliability provides essential evidence for identifying inequalities in electricity service and supports more equitable energy planning across African cities. In addition, Ref. [9] highlighted that advanced monitoring, intelligent control, and artificial intelligence-based techniques have become essential for enhancing power quality, improving

renewable energy hosting capacity, and increasing the operational observability of modern distribution networks. Similarly, Ref. [13] reported that the growing penetration of distributed renewable energy sources in low-voltage networks requires continuous monitoring of voltage profiles, voltage imbalance, and reverse power flows to ensure voltage regulation and reliable network operation. Other studies have shown that low-cost monitoring architectures can effectively provide real-time information on voltage profiles, voltage imbalance, and reverse power flow, thereby improving network observability while reducing implementation costs.

Although these studies have significantly advanced power quality assessment, most focus on specific disturbances, particular network configurations, or isolated monitoring approaches. Comprehensive field-based investigations simultaneously integrating standardized power quality measurements, continuity of service indicators, and detailed feeder characteristics under real operating conditions remain scarce in sub-Saharan African urban distribution networks, particularly in the Democratic Republic of the Congo. This limitation constitutes the principal scientific gap addressed by the present study.

To better position the contribution of the present work within the existing body of knowledge, Table 1 compares representative studies on power quality assessment in low-voltage distribution networks with respect to their study context, investigated power quality indicators, principal findings, identified limitations, and the specific contribution of the present study.

Table 1. Comparative review of representative studies on power quality assessment in low-voltage distribution networks and the scientific contribution of the present study.

Reference	Study Area/Network	Power Quality Indicators Investigated	Main Findings	Research Gap
[6]	Covenant University distribution network (Nigeria)	Voltage profile, voltage sag, harmonics	Proposed corrective measures to improve distribution network power quality.	Limited to a university campus; no assessment of service continuity indices or customer-level supply reliability.
[7]	African electricity systems	Power quality and reliability measurements	Highlighted the importance of systematic measurements to improve electricity reliability and energy justice across Africa.	Provides a continental perspective but no detailed field assessment of a real low-voltage urban feeder.
[15]	Low-voltage distribution network	Harmonic currents generated by nonlinear household loads	Demonstrated that nonlinear loads significantly deteriorate voltage quality and increase harmonic distortion.	Focused mainly on harmonics without evaluating overall power quality and continuity of service.
[17]	Lubumbashi (DR Congo)	Household electrical service quality	Identified major causes of poor electrical service quality experienced by consumers.	Did not perform standardized instrumental measurements of power quality or evaluate compliance with IEC/EN standards.
[19]	Residential low-voltage network with household PV systems	Voltage deviation, additional losses, power quality	Showed that increasing residential PV penetration may deteriorate	Restricted to photovoltaic integration; service continuity and infrastructure

			voltage quality and increase network losses.	condition were not considered.
[20]	Academic electrical distribution system	Voltage quality, harmonics, disturbances	Identified several power quality disturbances affecting institutional electrical installations.	Results are site-specific and do not include interruption indices (SAIFI, SAIDI) or urban public distribution networks.
Present study	Babemba low-voltage distribution network, Lubumbashi (DR Congo)	Voltage variation, frequency, harmonics, flicker, interruptions, SAIFI, SAIDI, feeder characteristics and field measurements	Provides a comprehensive instrumental assessment of power quality and service continuity according to international standards under real operating conditions.	First integrated study combining standardized measurements, power quality indices, continuity-of-service assessment and feeder characterization for an urban low-voltage network in the Democratic Republic of the Congo.

In Lubumbashi, the second largest city in the Democratic Republic of the Congo, previous studies have shown that although a substantial proportion of households are connected to the public electricity network, the quality and continuity of the supplied electricity remain highly variable. Consumers frequently experience prolonged and unpredictable outages resulting from both generation shortages and distribution network constraints [5]. In addition, socio-economic investigations conducted in several municipalities have reported extremely high rates of non-standard and illegal electrical connections, reaching more than 75% in some informal settlements [5,18]. These conditions are further aggravated by the widespread use of high-power domestic appliances, ageing electrical infrastructure, and inadequate maintenance practices, all of which are associated with increased feeder loading, voltage fluctuations, transformer overloading, and prolonged service interruptions [21].

Although these previous investigations have considerably improved the understanding of electricity access, customer perceptions, electricity theft, and socio-economic constraints in Lubumbashi, they do not provide a comprehensive technical assessment of power quality in real low-voltage distribution networks. Existing local studies generally examine isolated indicators, such as harmonic distortion or current imbalance, within limited geographical areas, without simultaneously evaluating voltage quality, service continuity, harmonic distortion, flicker, phase imbalance, infrastructure condition, and feeder characteristics under standardized measurement conditions. Consequently, the actual technical performance of urban low-voltage distribution networks in Lubumbashi remains insufficiently documented.

To address this knowledge gap, the present study aims to evaluate the quality of electrical energy and service continuity in the low-voltage distribution network supplied by the Babemba MV/LV substation in the municipality of Kamalondo, Lubumbashi. The assessment is performed using internationally recognized standards, including EN 50160, IEEE 519-2014, IEC 61000-4-15, and IEEE 1159, together with recent methodological approaches for low-voltage power quality assessment [22].

More specifically, this study pursues four complementary objectives: (i) to quantify the principal power quality indicators, including voltage deviations, interruptions, harmonic distortion, flicker, and phase imbalance; (ii) to evaluate the compliance of the investigated feeders with internationally accepted power quality standards; (iii) to analyse the relationships between feeder characteristics and the observed electrical disturbances;

and (iv) to identify the technical factors most strongly associated with power quality degradation within the investigated distribution network.

Based on the identified research gap and the existing literature, the study is founded on three research hypotheses. First, the low-voltage feeders supplied by the Babemba MV/LV substation are expected to exhibit significant deviations from internationally accepted power quality and service continuity standards. Second, the observed voltage degradation and continuity disturbances are hypothesized to be significantly associated with feeder loading conditions, phase imbalance, neutral current levels, and the prevalence of non-standard electrical connections. Third, it is hypothesized that the combined effects of infrastructure ageing, feeder overloading, and unbalanced loading constitute the dominant factors associated with the observed deterioration of power quality within the investigated network.

The originality of this study lies in its integrated field-based assessment of voltage quality, service continuity, harmonic distortion, flicker, infrastructure condition, and feeder characteristics within a poorly documented African urban low-voltage distribution network. Beyond providing one of the first comprehensive instrumental datasets on power quality in Lubumbashi, this work establishes quantitative relationships among measured network operating conditions and electrical disturbances at the investigated site. The findings provide context-specific evidence from the Babemba distribution network and may serve as a methodological and comparative reference for future investigations of similar urban low-voltage networks in sub-Saharan Africa.

2. Materials and Methods

2.1. Study Site and Electrical Network

The study was conducted in Lubumbashi, the second largest city in the Democratic Republic of the Congo (DRC), located in the Haut-Katanga Province between latitudes 11°20'–12°00' S and longitude approximately 27°10' E. Lubumbashi comprises seven administrative municipalities, including three planned municipalities (Lubumbashi, Kenya, and Kamalondo) and four predominantly self-developed municipalities (Katuba, Kampemba, Ruashi, and Annexe). Among these, the municipality of Kamalondo was selected as the study area because it combines a relatively high electrification rate with a substantial prevalence of non-standard and illegal electrical connections, making it one of the most representative urban areas for investigating power quality issues in the city [18,23]. In addition, Kamalondo accommodates a wide variety of residential, commercial, and small industrial activities including restaurants, bars, hotels, welding workshops, carpentry shops, dry cleaners, and schools which generate highly diversified and variable load profiles representative of many rapidly growing urban distribution networks in the DRC [18].

2.2. Description of the Babemba MV/LV Substation

The investigated electrical network is supplied by the Babemba medium-voltage/low-voltage (MV/LV) distribution substation. The substation receives electrical power from the 15 kV medium-voltage network through two incoming feeders, namely Amato and Synteskin, and is equipped with a 630 kVA, 15/0.4 kV Dyn11 distribution transformer protected by a 1250 A circuit breaker. The transformer has a nominal secondary current of 907 A and supplies five outgoing low-voltage feeders. Four feeders supply residential, commercial, and small industrial consumers, whereas the fifth feeder is dedicated to a private customer.

The Babemba low-voltage distribution network is characterized by progressive and largely uncontrolled network extensions associated with sustained load growth. The

distribution system mainly consists of overhead copper and aluminium conductors exhibiting heterogeneous and, in some locations, undersized cross-sectional areas. Long feeder lengths, together with the extensive use of fused connections, contribute to significant voltage drops toward the remote ends of the feeders, particularly during peak loading periods.

Power quality degradation within the investigated network is further associated with several structural characteristics observed during the field survey, including frequent transformer overloading, non-standard electrical connections, phase sharing between neighboring installations, inappropriate neutral conductor arrangements, and ageing distribution infrastructure. These characteristics make the Babemba substation a representative case study for investigating power quality and service continuity in urban low-voltage distribution networks in Lubumbashi. In addition to these technical considerations, the substation was selected because it provided suitable accessibility, operational safety, and sufficient energy availability throughout the five-month measurement campaign.

2.3. International Standards for Power Quality Assessment

Because no national power quality standard is currently implemented or systematically enforced by the National Electricity Company (*Société Nationale d'Électricité*, SNEL, DRC), the present study adopts internationally recognized standards as the reference framework for evaluating power quality and service continuity. This approach ensures that the measured electrical parameters can be assessed using internationally accepted performance criteria and facilitates comparison with similar studies reported in the scientific literature.

The assessment framework is based on the following international standards:

- EN 50160, which defines the principal voltage characteristics expected in public low-voltage distribution networks, including voltage magnitude, frequency, voltage variations, and continuity of supply;
- IEC 61000-4-15 [24], which specifies standardized procedures for measuring and evaluating short-term and long-term voltage flicker;
- IEEE Std 519-2014 [25], which establishes the recommended limits for voltage and current harmonic distortion in low-voltage electrical networks;
- IEEE Std 1159 [26], which provides standardized definitions and classifications of power quality disturbances, including voltage sags, swells, interruptions, and transient events;
- IEEE Std 1100 [27], which presents recommendations concerning electrical compatibility, power disturbances, and the protection of sensitive electrical equipment;
- IEC 61009, which provides requirements related to overcurrent protection and the safe operation of low-voltage electrical installations.

Throughout this study, the measured electrical quantities and calculated power quality indicators were systematically compared with the threshold values specified by these international standards in order to assess the technical performance of the investigated low-voltage distribution network.

2.4. Electrical Network Modeling

2.4.1. Network Reconstruction

To provide a rigorous representation of the investigated electrical system and to support the interpretation of the field measurements, the Babemba low-voltage distribution network was reconstructed using the technical information collected during the field survey. The reconstruction relied on the actual network topology, conductor characteristics,

feeder lengths, transformer specifications, and network configuration observed during the measurement campaign.

As illustrated in Figure 2a, the Babemba MV/LV substation is supplied through a 630 kVA, 15/0.4 kV Dyn11 distribution transformer feeding five outgoing low-voltage feeders connected to a common secondary busbar. Each feeder supplies a different sector of the study area and exhibits distinct electrical characteristics in terms of feeder length, customer density, connected loads, and operating conditions.

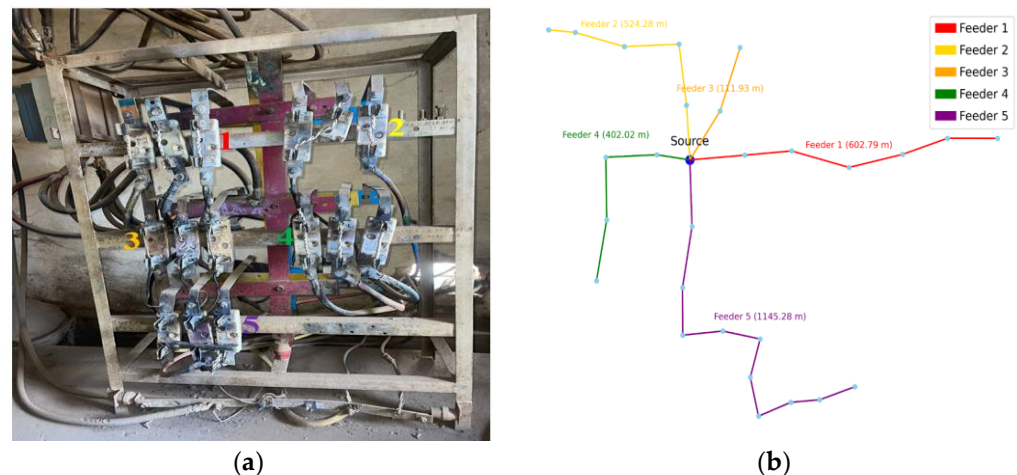


Figure 2. (a) Layout of the LV main switchboard of the Babemba substation. (b) electrical characteristics of the investigated distribution network. The reconstructed network topology is presented in (b). The network was represented as a radial distribution system comprising five outgoing feeders originating from the transformer secondary bus. Each feeder was modelled as a succession of electrical buses interconnected by distribution lines whose characteristics were obtained from utility technical records and verified during field inspections.

2.4.2. Electrical Parameters of the Network

The reconstructed electrical model incorporates the principal physical characteristics of the investigated distribution network measured during the field survey. Each line section is defined by its feeder identification, upstream and downstream buses, conductor length, conductor cross-sectional area, electrical resistance, and reactance.

The investigated network comprises five radial feeders with lengths of 602.79 m, 524.28 m, 111.93 m, 402.02 m, and 1145.28 m for Feeders 1 to 5, respectively. These parameters were incorporated into the reconstructed model to ensure an accurate representation of the electrical impedance of each distribution path.

The impedance of each line section is expressed as:

$$Z_{ij} = R_{ij} + jX_{ij} \quad (1)$$

where R_{ij} and X_{ij} denote the resistance and reactance of line section ij , respectively.

2.4.3. Transformer Representation

The upstream electrical source was represented by the Babemba distribution transformer supplying the investigated low-voltage network. The transformer is rated at 630 kVA with a nominal voltage ratio of 15/0.4 kV, a Dyn11 vector group, a rated secondary current of 907 A, and upstream protection provided by a 1250 A circuit breaker. Within the reconstructed network, the transformer secondary bus was selected as the reference node from which all five outgoing feeders originate. This representation accurately reflects the actual operating configuration observed during the field investigation.

2.4.4. Load Representation

The electrical demand connected to each feeder was represented using the active and reactive power measurements recorded during the five-month monitoring campaign. Individual customer nodes were modelled as constant-power (PQ) loads, a modelling approach widely adopted for steady-state analysis of low-voltage distribution systems. The measured three-phase active and reactive powers were assigned to the corresponding electrical buses according to their actual geographical location within the reconstructed network. Consequently, the model preserves the loading conditions observed during the experimental campaign while maintaining consistency with the field measurements.

2.4.5. Modeling Assumptions

The Babemba MV/LV substation was selected because it combines high electricity demand, diverse consumer categories, substantial levels of non-standard electrical connections, and recurrent power quality disturbances. The measurement campaign covered all five outgoing feeders and therefore encompassed a wide range of feeder lengths, conductor characteristics, customer densities, load compositions, and operating conditions within the investigated network. Nevertheless, the results should be considered representative of the Babemba distribution network and should not be interpreted as statistically representative of all low-voltage distribution networks in Lubumbashi or Sub-Saharan Africa.

Power quality measurements were performed using the Chauvin Arnoux Qualistar C.A. 8331 (France), which complies with IEC 61000-4-30 Class B requirements. The use of a Class B instrument is appropriate for field-based power quality surveys, disturbance identification, network diagnostics, and comparative assessment of operating conditions. However, Class B measurements have greater methodological flexibility than Class A measurements and are not intended to provide the same level of metrological traceability required for contractual or regulatory compliance testing. Consequently, comparisons with EN 50160, IEEE 519, and IEC 61000 reference limits in this study are interpreted as an engineering assessment of network performance rather than as formal certification of regulatory compliance.

Measurement uncertainty was evaluated from the manufacturer's specifications together with the conditions encountered during field installation. According to the manufacturer's specifications, the Qualistar C.A. 8331 provides a TRMS voltage accuracy of $\pm(0.5\% \text{ of the reading} + 0.2 \text{ V})$, while current measurement accuracy depends on both the analyser and the flexible AmpFlex current sensors used during the monitoring campaign. Harmonic measurements are also subject to instrument-specific accuracy limits, with the uncertainty in THD reflecting the combined effect of RMS and harmonic-component measurements. Similarly, active, reactive, and apparent power measurements depend on the simultaneous acquisition of voltage and current and therefore incorporate the uncertainties associated with both measurement channels. Flicker measurements are additionally influenced by the measurement class and the implementation of the flicker meter specified in IEC 61000-4-15.

Under field conditions, additional sources of uncertainty may arise from the positioning of flexible current sensors, conductor geometry, selection of the measurement range, phase identification, electrical connection quality, and variations in network operating conditions during installation. These factors were minimized through systematic verification of phase sequence, sensor identification, network configuration, measurement ranges, and channel operation before each monitoring period. The accuracy specifications reported by the manufacturer should therefore be regarded as baseline instrumental uncertainties, while the actual field measurements may include additional installation-related contributions that cannot be quantified independently from the available dataset.

Despite these limitations, the magnitude of the principal disturbances observed during the monitoring campaign was substantially greater than the expected measurement uncertainty. Voltage deviations frequently reached 20–30% of the nominal value, voltage imbalance reached approximately 18%, and neutral conductor current approached 327 A. Consequently, these major deviations cannot reasonably be attributed to instrumental uncertainty alone. Greater caution is nevertheless required when interpreting measurements located close to the adopted standard thresholds, particularly THD and flicker values. Accordingly, the present study distinguishes clear power quality disturbances from marginal threshold exceedances and interprets the results within the measurement capabilities and limitations of the Class B monitoring system.

2.5. Measuring Equipment and Experimental Protocol

A comprehensive field measurement campaign was conducted to characterize the power quality and service continuity of the investigated low-voltage distribution network. Measurements were performed using a Chauvin Arnoux Qualistar C.A. 8331 power quality analyzer installed directly on the investigated feeders, as illustrated in Figure 3 [28,29]. The monitoring campaign extended over five months, from October 2024 to February 2025, covering both the dry and rainy seasons in order to capture representative variations in network operating conditions. Each of the five outgoing feeders supplied by the Babemba MV/LV substation was monitored continuously for seven consecutive days, in accordance with the recommendations of EN 50160 for power quality assessment in public distribution networks [6].

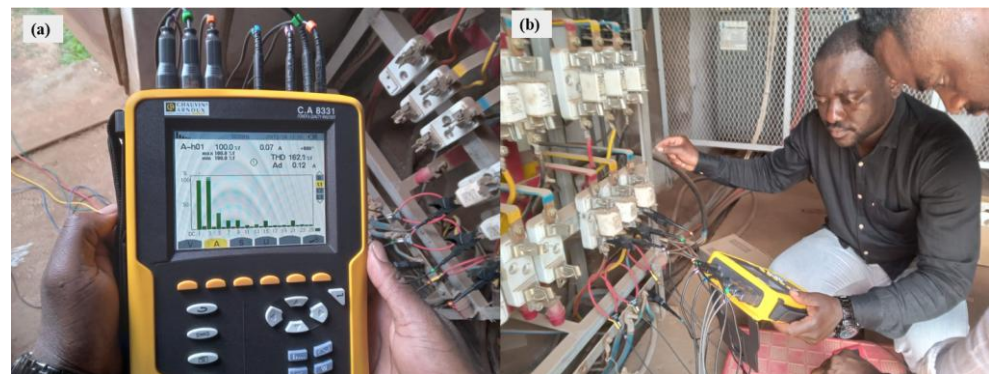


Figure 3. Chauvin Arnoux Qualistar C.A. 8331 power quality analyzer (a) and installation on the investigated low-voltage feeder (b).

2.5.1. Measuring Instrument

Power quality measurements were performed using a Chauvin Arnoux Qualistar C.A. 8331 power quality analyzer compliant with IEC 61000-4-30 Class B, IEC 61010 safety requirements, and supporting automatic reporting according to EN 50160. The analyzer is equipped with four voltage channels and three current channels, enabling the simultaneous recording of RMS voltages and currents, active, reactive and apparent power, frequency, harmonic distortion up to the 50th order, voltage and current unbalance, short-term and long-term flicker (Pst and Plt), transient events, inrush currents, and energy parameters. Current measurements were carried out using flexible AmpFlex sensors adapted to the expected current ranges within the investigated feeders. Prior to each monitoring campaign, the analyzer configuration was verified by checking the network topology, phase sequence, current sensor identification, transformer ratios when applicable, and recording parameters according to the manufacturer's operating procedures [30,31].

2.5.2. Recorded Electrical Variables

The monitored electrical variables included phase-to-phase and phase-to-neutral RMS voltages, phase currents, active and reactive power, active and reactive energy, frequency, phase and total power factors, voltage and current total harmonic distortion (THD), and short-term flicker (Pst). To complement the feeder-level assessment, additional measurements were performed at selected customer connection points in order to evaluate the quality of electricity directly supplied to representative low-voltage consumers.

The principal feeder measurements reported in this study were performed at the outgoing terminals of the low-voltage main switchboard (LVMSB) inside the Babemba MV/LV substation. Therefore, the feeder-level voltage and current distributions represent the electrical conditions at the sending end of each feeder. Complementary voltage measurements were also performed at selected downstream customer connection points to assess voltage conditions experienced farther from the substation.

2.5.3. Data Quality Control

Particular attention was devoted to ensuring the quality and reliability of the acquired measurements. Before each monitoring campaign, the analyzer underwent functional verification, including phase identification and validation of voltage and current measurement channels. During data processing, the recorded datasets were systematically screened for abnormal values, communication interruptions, analyzer disconnections, and incomplete records. Invalid observations were excluded whenever necessary, and only validated measurements were retained for the subsequent calculation of power quality indicators.

2.5.4. Measurement Representativeness and Uncertainty

The Babemba MV/LV substation was selected because it constitutes one of the most representative urban distribution systems in Kamalondo, combining high electricity demand, a wide diversity of consumer categories, significant levels of non-standard electrical connections, and recurrent power quality complaints. The measurement campaign covered all five outgoing feeders, thereby encompassing a broad range of feeder lengths, customer densities, load compositions, and operating conditions representative of the investigated urban distribution network.

The measurement uncertainty associated with the monitoring equipment remained significantly smaller than the magnitude of the observed disturbances. According to the manufacturer's specifications, the Qualistar C.A. 8331 provides a TRMS voltage accuracy of $\pm(0.5\%$ of reading $+ 0.2$ V), a current accuracy of $\pm(0.5\%$ of reading $+ 2$ counts), harmonic measurement accuracies of $\pm(0.1\%$ of reading $+ 0.1$ V) for voltage and $\pm(0.1\%$ of reading $+ 2$ counts) for current, and a THD accuracy of $\pm(1\%$ of reading $+ 2$ counts). Considering that the principal observed disturbances were substantially larger than the manufacturer-specified instrumental uncertainties, these disturbances are unlikely to be attributable to measurement uncertainty alone. Greater caution is nevertheless required for measurements close to the adopted reference thresholds. Accordingly, the dataset is considered suitable for characterising the operating conditions observed during the monitoring campaign within the investigated Babemba low-voltage network.

2.6. Household Sampling and Supplementary Data Collection

To complement the electrical measurements, supplementary qualitative and quantitative information was collected through household surveys, semi-structured interviews, and direct field observations. Because the exact number of customers supplied by the Babemba MV/LV substation was not available, households were randomly selected among

plots connected to the investigated low-voltage feeders. Only consumers effectively supplied by the SNEL distribution network were included in the survey. For each selected household, the questionnaire was administered preferentially to the household head or, when unavailable, to another adult household member (18 years or older) [31–33].

Semi-structured interviews were conducted with managers, engineers, and technical staff from the SNEL Customer Service Centre. The interviews addressed four principal topics: (i) load-shedding practices and operational procedures, (ii) recurrent voltage quality problems and supply interruptions, (iii) electricity billing and consumption practices, and (iv) the operation and maintenance of MV/LV substations and distribution feeders.

The household questionnaire comprised three sections covering user characteristics, MV/LV substation information, and feeder-specific electrical conditions. During the field survey, the geographical coordinates of substations and distribution lines were recorded using GPS, while detailed information concerning household electrical appliances, installed capacities, load types, and usage patterns was collected. These complementary data facilitated the interpretation of the measured electrical load profiles and the identification of factors potentially influencing power quality.

2.7. Data Preparation and Power Quality Indicators

Raw measurement files generated by the Qualistar C.A. 8331 analyzer were first exported using Power Analyzer Transfer software and subsequently transferred to Microsoft Excel for preliminary data organization and verification.[34,35] Statistical processing was then performed in the R programming environment using the packages tidyverse, readxl and ggplot2 [31], lubridate [34].

A unified DateTime variable was created by combining the recorded date and time fields, allowing temporal analyses at hourly, daily, and weekly resolutions. The day of the week was also extracted to distinguish weekday and weekend operating conditions. Voltage and current measurements were retained in their original form, whereas derived indicators including total harmonic distortion (THD), power factor (PF), and short-term flicker (Pst) were calculated from the three-phase measurements according to the recommendations of IEEE Std 519-2014.

Voltage harmonic distortion (THD-V), line-voltage harmonic distortion (THD-U), and current harmonic distortion (THD-I) were selected as the principal harmonic indicators. Compliance with international recommendations was evaluated by comparing the measured voltage THD values with the 5% limit specified by IEEE Std 519-2014. Similarly, flicker severity was assessed using the IEC 61000-4-15 reference threshold of Pst = 1 [27,36]

Service Continuity Assessment

Service continuity was evaluated using the internationally recognized reliability indices SAIFI (System Average Interruption Frequency Index) and SAIDI (System Average Interruption Duration Index), following the methodology recommended by IEEE Std 1366. Supply interruptions were automatically identified from the voltage recordings acquired by the Qualistar C.A. 8331 analyzer. An interruption event was registered whenever the three line-to-line voltages simultaneously fell below the threshold specified by EN 50160. For each validated event, the interruption start time, restoration time, and interruption duration were automatically extracted from the measurement database. Following data validation, incomplete or erroneous events were removed before calculating the reliability indices.

The SAIFI index represents the average number of sustained interruptions experienced by a customer during the observation period, whereas SAIDI represents the corresponding average interruption duration. Both indices were calculated for the five

investigated feeders and subsequently annualized to facilitate comparison with internationally reported service continuity indicators.

The SAIFI represents the average number of interruptions experienced by a user during the observation period and is determined by:

$$SAIFI = \frac{\sum_{i=1}^n N_i}{N_T} \quad (2)$$

where:

- N_i : number of users affected by interruption;
- N_T : total number of users served by the studied network.

The SAIDI represents the average duration of interruptions experienced by a user. It is calculated as:

$$SAIDI = \frac{\sum_{i=1}^n N_i U_i}{N_T} \quad (3)$$

where:

- U_i : duration of interruption i (in minutes).

The approximately 48 h interruption recorded during the monitoring campaign was associated with an exceptional outage of the upstream medium-voltage supply rather than with a failure originating within the investigated low-voltage feeders. This event was therefore excluded from the calculation of the feeder-level SAIFI and SAIDI indices, which were intended to characterize recurrent service interruptions affecting the investigated low-voltage distribution network. Nevertheless, the event was retained and reported separately because it provides relevant information on the vulnerability of the overall electricity supply system to upstream disturbances. Including this exceptional MV event in the feeder-level reliability indices would have disproportionately increased the interruption-duration indicator and would not have reflected the recurrent interruption behaviour specifically associated with the investigated LV network.

2.8. Power Quality Event Detection and Statistical Analysis

Power quality events were identified using threshold values established by the selected international standards. Voltage dips were detected whenever phase-to-neutral voltages decreased below 90% of the nominal voltage (230 V), whereas three-phase voltage sags were identified when line-to-line voltages fell below 95% of the nominal voltage (400 V). Supply interruptions corresponded to simultaneous line-to-line voltages below 10 V. Harmonic events and flicker disturbances were identified whenever THD exceeded 5% or the short-term flicker index exceeded $P_{st} = 1$, respectively.

For each feeder, daily frequencies of voltage disturbances, interruptions, harmonic events, and flicker exceedances were calculated. Temporal trends were analysed using locally weighted regression (LOESS), while feeder-to-feeder comparisons were performed using box-and-whisker plots summarizing medians, interquartile ranges, and extreme observations.

Descriptive statistical analyses included the calculation of the mean, standard deviation, minimum, maximum, and coefficient of variation for all principal power quality indicators. Comparative analyses among feeders were conducted to investigate the influence of feeder length, customer density, load composition, and the prevalence of legal and non-standard electrical connections on the observed network performance. The interpretation of the results combined electrical measurements, feeder characteristics, field observations, and infrastructure condition assessments to provide a comprehensive evaluation of power quality within the investigated distribution system. Finally, seasonal load profiles corresponding to the dry and rainy seasons were constructed from hourly active power measurements using spline interpolation to facilitate comparisons of seasonal

demand patterns and their potential influence on voltage quality, service continuity, and feeder loading conditions.

To further investigate the relationships among the measured power quality variables, pairwise correlation analysis was performed using Spearman's rank correlation coefficient (ρ). This non-parametric approach was selected because several electrical variables exhibited asymmetric distributions and extreme observations. Statistical significance was evaluated using two-sided tests at a significance level of $\alpha = 0.05$. Correlations with $p < 0.05$ were considered statistically significant. The analysis was considered exploratory, and statistically significant associations were not interpreted as evidence of causal relationships.

3. Results

3.1. Characteristics of the Investigated Low-Voltage Network

The principal physical and operational characteristics of the five investigated low-voltage feeders are summarised in Table 2. The feeders exhibit substantial differences in length, conductor cross-section, customer density, consumer categories, and connection status, reflecting the heterogeneous operating conditions of the Babemba distribution network.

Table 2. Physical and operational characteristics of the investigated low-voltage feeders.

Feeders	Length (m)	Section (mm ²)	Number of Households	User Type				Connection	
				Residential (%)	Hotels (%)	Schools (%)	Commercial or Craft Activities (%)	Legal (N)	Illegal (N)
Feeder 1	602.79	110	126	49.21	6.35	0	44.44	50	76
Feeder 2	524.28	110	160	54.37	0	0.62	45	91	69
Feeder 3	111.93	35	15	6.67	6.67	0	86.67	15	0
Feeder 4	420.02	110	187	48.13	2.14	1.07	48.66	101	86
Feeder 5	1145.28	110	144	63.89	3.47	0.69	31.94	103	41

No grid-connected distributed generation was identified on the investigated feeders during the field survey and monitoring campaign. Nevertheless, supplementary field observations indicated the use of privately owned diesel generators by some consumers as backup electricity sources during grid outages. Since these units are generally operated independently from the public distribution network rather than in parallel with it, they were not classified as grid-connected distributed energy resources in the present study. Consequently, the power quality measurements reported here primarily characterize the operating conditions of the public low-voltage distribution network.

Feeder lengths range from 111.93 m (Feeder 3) to 1145.28 m (Feeder 5). Four feeders are equipped with 110 mm² conductors, whereas Feeder 3 has a smaller conductor cross-section of 35 mm². The number of connected households varies considerably, from only 15 customers on Feeder 3 to 187 customers on Feeder 4, indicating marked differences in loading conditions among the investigated feeders.

Residential customers constitute the predominant consumer category on Feeders 1, 2, 4, and 5, accounting for approximately 48–64% of connected users, while commercial and artisanal activities represent between 32% and 49% of customers. In contrast, Feeder 3 is characterised by a clear predominance of commercial and artisanal activities (86.67%), with only a limited residential presence. Hotels and educational facilities represent a relatively small proportion of customers across all feeders.

The distribution of legal and non-standard connections also differs substantially among feeders. Feeders 1 and 4 exhibit the highest numbers of non-standard connections, with 76 and 86 illegal connections, respectively, whereas no illegal connection was identified on Feeder 3. These observations illustrate the heterogeneous structural characteristics of the investigated distribution network and provide the basis for analysing the variations in power quality and service continuity presented in the following sections.

3.2. Daily Load Profiles and Temporal Power Variations

Figure 4 illustrates the daily active power profiles recorded during the dry and rainy seasons. In both seasons, the network exhibits a similar daily operating pattern characterised by a progressive increase in demand during the early morning, a pronounced morning peak, a period of relatively stable demand around midday, and a second peak during the evening. These recurrent patterns indicate a consistent daily load cycle throughout the measurement campaign.

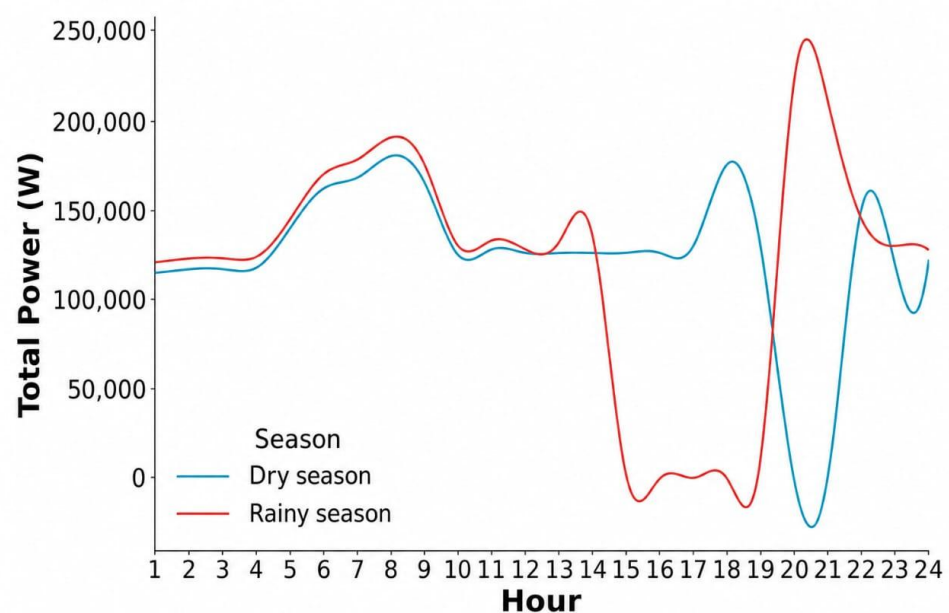


Figure 4. Daily active power profiles recorded during the dry and rainy seasons.

Although the overall shape of the load profiles remains comparable between seasons, noticeable differences are observed in demand magnitude. Morning peak demand reaches approximately 180–190 kW in both seasons, whereas the evening peak is considerably higher during the rainy season, attaining approximately 230–240 kW. During the middle of the day, demand decreases and remains relatively stable at approximately 120–140 kW before increasing again during the evening period.

Distinct reductions in measured power are also observed during specific periods of the day. These reductions are more pronounced during the rainy season, particularly during the late afternoon, while the dry-season profile exhibits a marked decrease during the evening before partially recovering. During these periods, the recorded active power approaches zero, indicating the occurrence of extended supply interruptions or load-shedding events within the investigated distribution network.

Overall, the measured load profiles demonstrate substantial temporal variability in electricity demand throughout the day and reveal clear seasonal differences in network loading conditions. These observations provide the operational context for the subsequent

analysis of voltage quality, service continuity, harmonic distortion, and other power quality indicators.

3.3. Condition of the Electrical Distribution Infrastructure

The field inspections revealed numerous signs of physical deterioration affecting the electrical infrastructure of the investigated low-voltage distribution network. Representative observations are presented in Figure 5, illustrating the condition of the principal components of the Babemba distribution system.

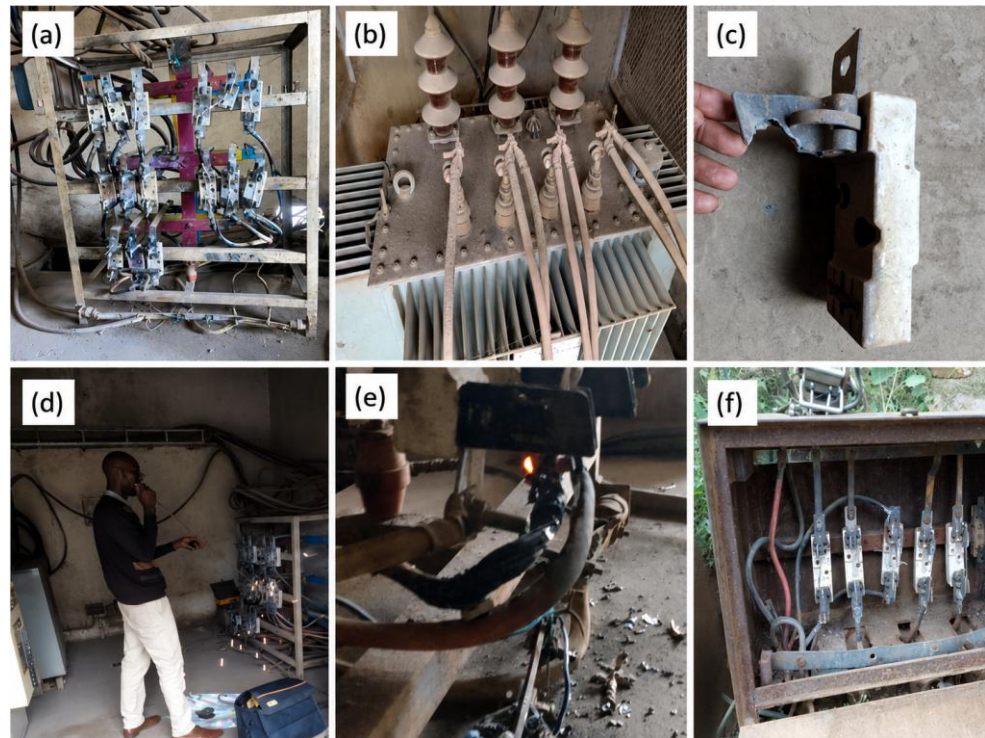


Figure 5. Representative observations of the electrical infrastructure in the investigated Babemba low-voltage distribution network: (a) low-voltage distribution panel, (b) distribution transformer, (c) mechanical support structure, (d) cable routing and electrical connections, (e) overheated electrical joints, and (f) outdoor distribution cabinet.

The low-voltage distribution panel (Figure 5a) exhibits extensive surface oxidation, dust accumulation, and visible ageing of electrical components. Similarly, the distribution transformer shown in Figure 5b is installed in an environment exposed to dust and moisture, with visible signs of limited maintenance. Mechanical support structures also exhibit deterioration, including damaged structural elements and degraded fastening components (Figure 5c).

The inspection further revealed disorganised cable routing, degraded insulation materials, and numerous non-standard electrical connections (Figure 5d). Localised overheating marks and severely carbonised electrical joints are visible at several connection points (Figure 5e), while the outdoor distribution cabinets exhibit advanced corrosion and weathering, accompanied by partially exposed conductors (Figure 5f).

Overall, the field observations indicate widespread ageing of electrical equipment and the presence of multiple visible defects affecting several components of the investigated distribution infrastructure. These observations complement the electrical measurements presented in the following sections and provide additional evidence of the operating condition of the investigated network.

3.4. Voltage and Current Characteristics of the Investigated Feeders

The distributions of line-to-line RMS voltages and phase RMS currents measured on the five investigated low-voltage feeders are presented in Figure 6. The boxplots provide a comparative representation of the electrical operating conditions observed throughout the measurement campaign, highlighting both temporal variability and differences among feeders.

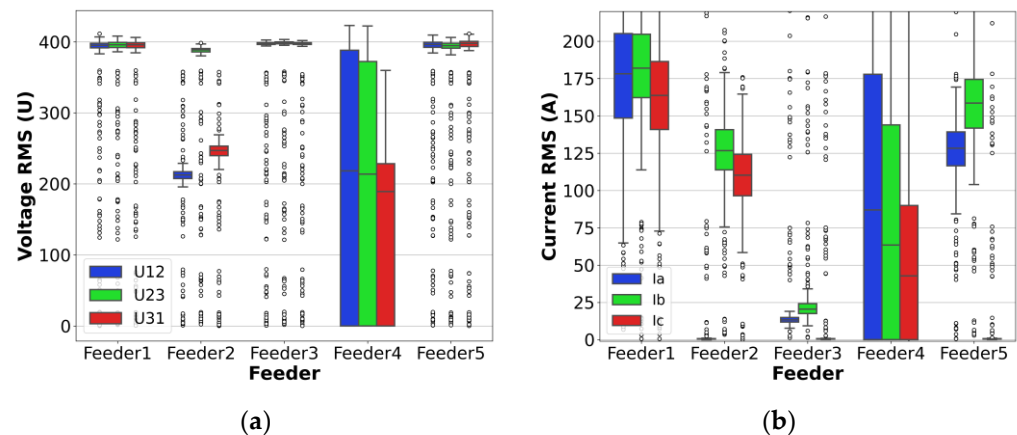


Figure 6. Distribution of electrical operating conditions across the five investigated low-voltage feeders: (a) RMS line-to-line voltage and (b) RMS phase current. Boxplots represent the distributions recorded during the monitoring periods for each feeder.

The voltage distributions shown in Figure 6a reveal marked differences among the investigated feeders. Feeders 1, 3, and 5 maintain median line-to-line voltages close to the nominal value of 400 V, with relatively narrow interquartile ranges, indicating stable voltage conditions during most of the monitoring period. Nevertheless, all three feeders exhibit numerous lower outliers, demonstrating the occurrence of intermittent voltage reductions.

In contrast, Feeders 2 and 4 exhibit substantially greater voltage variability. Feeder 2 shows pronounced differences among the three measured line voltages, with U12 and U31 presenting considerably lower median values than U23, indicating unequal voltage conditions between phases. Feeder 4 exhibits the widest voltage distributions, characterised by broad interquartile ranges and median values substantially below the nominal voltage, reflecting significant temporal fluctuations throughout the observation period.

The current distributions presented in Figure 6b also demonstrate considerable differences among feeders. Feeders 1 and 5 carry the highest current levels, with median phase currents generally exceeding 120 A and maximum values approaching 200 A. Conversely, Feeder 3 exhibits consistently low current levels on all three phases, with measurements remaining below approximately 25 A for most of the monitoring period. Feeder 2 presents intermediate loading conditions with moderate dispersion among phases.

Among all investigated feeders, Feeder 4 displays the greatest variability in phase currents. The exceptionally wide current distributions, extending from values close to zero to peaks exceeding 200 A, indicate highly variable operating conditions during the monitoring campaign. Such variability contrasts with the relatively stable distributions observed on Feeders 3 and 5 and highlights the heterogeneous electrical behaviour of the investigated distribution network.

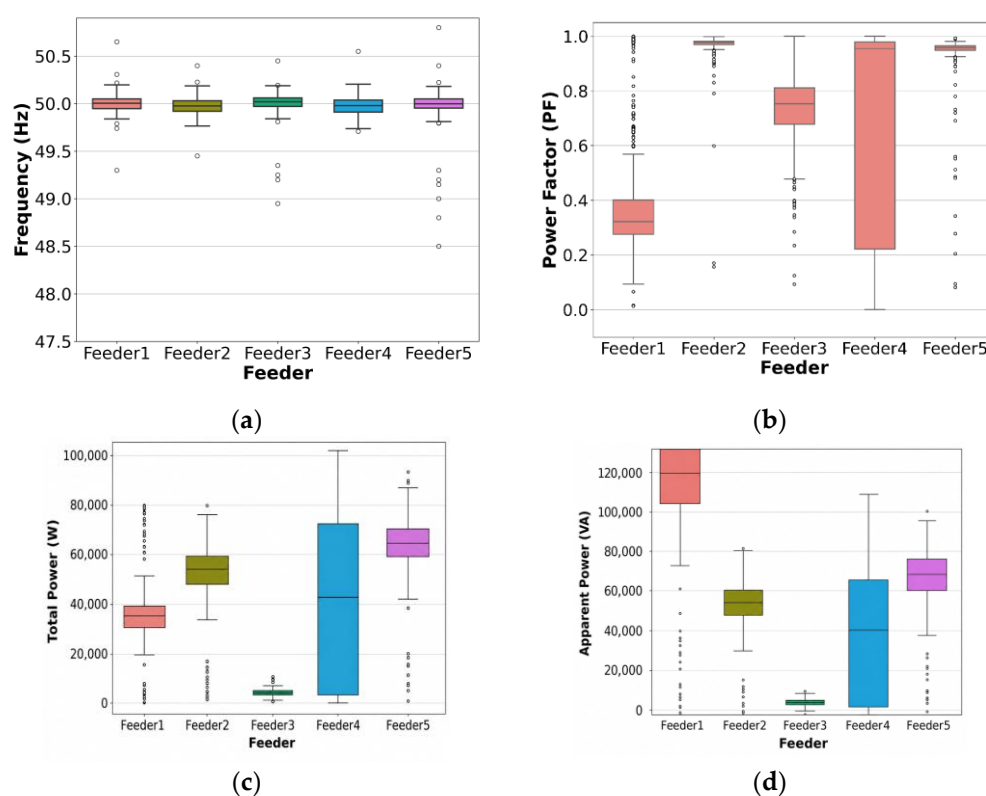
Overall, the voltage and current distributions demonstrate substantial spatial variability among the five feeders, with pronounced differences in voltage stability and electrical loading. These observations provide the basis for the subsequent assessment of power

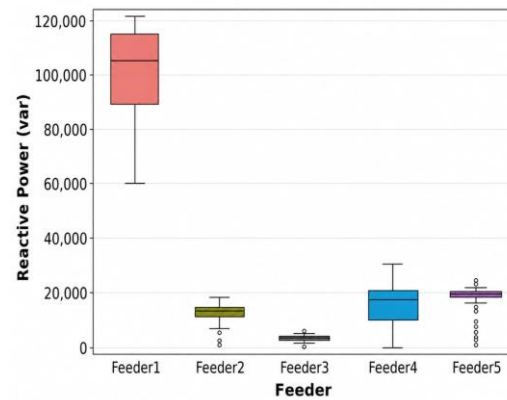
quality indicators, voltage disturbances, harmonic distortion, and service continuity presented in the following sections.

It should be noted that current imbalance does not necessarily result in a proportional voltage imbalance at the feeder sending end. The voltage response depends not only on the magnitude of phase-current imbalance but also on feeder impedance, conductor characteristics, feeder length, load distribution, and the location of the unbalanced loads along the feeder. Consequently, feeders exhibiting comparable current imbalance may present different voltage responses. In the present network, these effects are particularly relevant because the five feeders differ substantially in length, conductor cross-section, customer density, and load composition. Moreover, the voltage distributions presented in Figure 6a correspond to measurements at the feeder outgoing terminals of the LVMSB; therefore, voltage imbalance developing progressively along a radial feeder, particularly toward remote customer connection points, may not be fully reflected by the sending-end measurements.

3.5. Power Quality Indicators of the Investigated Feeders

The principal electrical operating indicators measured on the investigated feeders are presented in Figure 7, including frequency, power factor, active power, apparent power, and reactive power. These parameters provide a comprehensive overview of the electrical operating conditions of the distribution network during the monitoring campaign.





(e)

Figure 7. Distribution of the principal electrical operating indicators across the five investigated low-voltage feeders: (a) frequency, (b) power factor, (c) active power, (d) apparent power, and (e) reactive power.

As shown in Figure 7a, the system frequency remains tightly distributed around the nominal value of 50 Hz for all feeders, exhibiting only minor temporal variations throughout the monitoring period. The limited dispersion observed confirms the stability of the upstream power system frequency during the measurement campaign.

The power factor distributions presented in Figure 7b exhibit greater variability among feeders. While several measurements remain close to unity, lower values are also observed on some feeders, resulting in broader distributions and indicating differences in the electrical operating characteristics among the investigated circuits.

Figure 7c–e show pronounced differences in active, apparent, and reactive power among the five feeders. The box-plots reveal substantial variability in power demand, with some feeders exhibiting broad interquartile ranges and elevated maximum values, whereas others remain characterised by comparatively stable power levels. The distributions of apparent and reactive power generally follow the same trend as active power, reflecting the heterogeneous loading conditions observed across the investigated distribution network.

Overall, the results indicate relatively stable frequency conditions throughout the monitoring campaign, whereas power factor and power demand exhibit appreciable spatial variability among feeders. These differences provide additional evidence of the heterogeneous operating conditions characterising the investigated low-voltage distribution network and constitute the basis for the subsequent analysis of service continuity and voltage disturbances.

3.6. Voltage Disturbances and Service Continuity

Figure 8 presents the spatial and temporal distributions of the principal service continuity disturbances recorded on the five investigated feeders, including short-duration interruptions, their temporal evolution, long-duration interruptions, and voltage sags. These indicators provide a comprehensive overview of the continuity of electricity supply during the monitoring campaign.

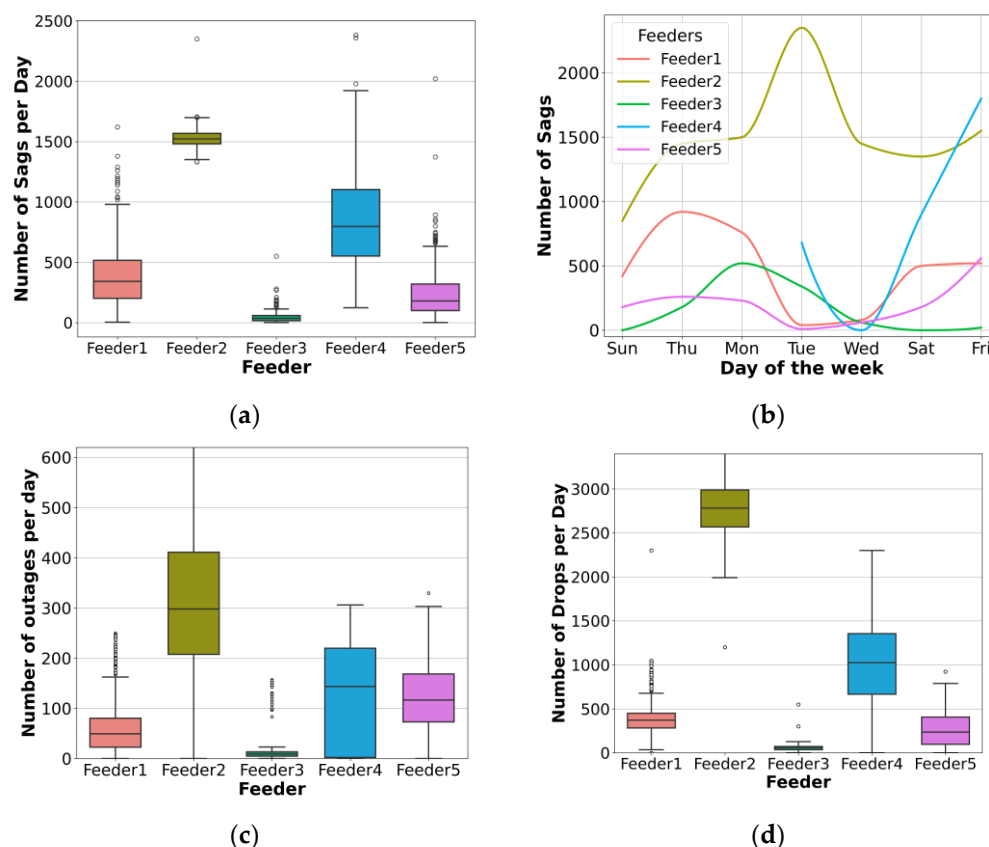


Figure 8. Distribution of service continuity disturbances recorded on the investigated feeders: (a) number of sags per day, (b) number of sags, (c) number of outages per day, and (d) number of drops per day.

The distributions of short-duration interruptions shown in Figure 8a reveal noticeable differences among the investigated feeders, indicating that interruption frequency is not uniformly distributed throughout the network. These differences are further illustrated by the weekly evolution presented in Figure 8b, which demonstrates considerable day-to-day variability in the occurrence of interruption events.

Figure 8c shows that long-duration interruptions were also recorded during the monitoring campaign. Their occurrence varies among feeders, confirming differences in service continuity across the investigated distribution network. In addition to interruption events, the voltage sag distributions presented in Figure 8d indicate that voltage depressions occurred repeatedly throughout the observation period, with marked differences in occurrence among feeders.

Among the investigated feeders, Feeder 2 exhibits the highest occurrence of voltage sags and interruption events, whereas lower frequencies are observed on the remaining feeders. Overall, the results demonstrate significant spatial and temporal variability in service continuity throughout the investigated low-voltage distribution network. These observations provide the basis for the comparative assessment of compliance with international continuity standards presented later in this study.

3.7. Harmonic Distortion and Flicker

Figure 9 presents the distributions of total harmonic distortion (THD) and short-term flicker (Pst) measured on the five investigated feeders during the monitoring campaign. These two indicators provide complementary information on waveform distortion and voltage fluctuations and therefore contribute to the overall assessment of power quality within the investigated low-voltage distribution network.

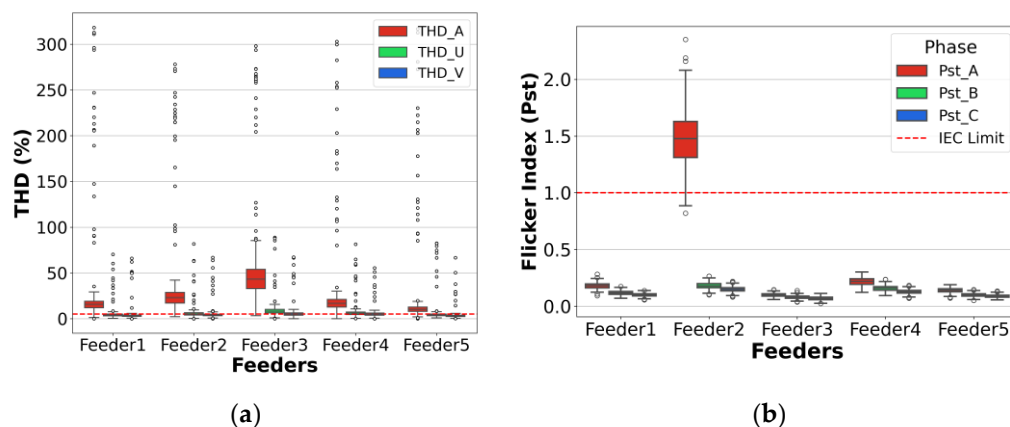


Figure 9. Distribution of power quality disturbance indicators across the five investigated low-voltage feeders: (a) total harmonic distortion (THD) and (b) short-term flicker severity (Pst). Dashed reference lines indicate the corresponding threshold values adopted in this study for power quality assessment.

The distributions of total harmonic distortion presented in Figure 9a reveal noticeable variability among the investigated feeders. Current harmonic distortion exhibits consistently higher values and greater dispersion than voltage harmonic distortion, whereas voltage THD remains comparatively more concentrated around lower values. The box-plots further indicate that harmonic conditions differ from one feeder to another, with several observations approaching or exceeding the reference limits adopted for power quality assessment.

The short-term flicker distributions shown in Figure 9b also exhibit marked spatial variability across the investigated feeders. While several feeders maintain relatively limited Pst variations, others present broader distributions and higher maximum values, indicating more pronounced voltage fluctuation events during the monitoring period. A number of observations are close to or exceed the reference threshold of $Pst = 1$, highlighting the occurrence of perceptible voltage fluctuations within parts of the investigated distribution network.

Taken together, the harmonic distortion and flicker measurements demonstrate that power quality disturbances are not uniformly distributed throughout the investigated network. The observed differences among feeders complement the voltage, current, and service continuity results presented in the previous sections and provide a comprehensive description of the electrical performance of the investigated low-voltage distribution system.

To complement the graphical distributions presented in Figure 9a, the principal descriptive statistics of voltage and current total harmonic distortion are summarised in Table 3 for each investigated feeder. The table reports the mean THD values together with their 95% confidence intervals, thereby facilitating a quantitative comparison of harmonic distortion levels across the investigated network.

Table 3. Summary statistics of harmonic distortion measured across the five investigated feeders. (Values are expressed as mean and 95% confidence interval.)

Feeder	THD-I (%)	THD-U (%)	THD-V (%)
Feeder 1	15.51 (11.85–18.95)	3.95 (2.94–5.00)	3.21 (2.48–3.88)
Feeder 2	22.94 (17.08–28.57)	5.11 (3.92–6.39)	4.00 (3.16–4.92)
Feeder 3	43.12 (32.75–53.95)	8.04 (6.30–10.07)	5.07 (3.68–6.29)
Feeder 4	16.74 (12.60–21.01)	5.91 (4.47–7.25)	5.01 (3.75–6.06)
Feeder 5	10.12 (7.91–12.59)	4.06 (3.20–5.02)	2.94 (2.31–3.73)

Table 3 provides a quantitative summary of the harmonic distortion levels presented in Figure 9. Marked differences are observed among the five feeders, with current harmonic distortion being substantially higher than voltage harmonic distortion. Feeder 3 exhibits the highest harmonic distortion, with mean THD-I, THD-U, and THD-V values of 43.12%, 8.04%, and 5.07%, respectively. Feeder 4 also shows relatively high voltage distortion, with mean THD-U and THD-V values of 5.91% and 5.01%, respectively. In contrast, Feeder 5 presents the lowest overall harmonic distortion, particularly for THD-I (10.12%) and THD-V (2.94%). These results confirm the feeder-to-feeder variability observed in Figure 9 and indicate that harmonic distortion is particularly pronounced on Feeder 3.

3.8. Neutral Conductor Current Distribution

Figure 10 presents the distribution of neutral conductor current recorded during the monitoring campaign, providing an overview of the magnitude and variability of neutral loading in the investigated low-voltage network.

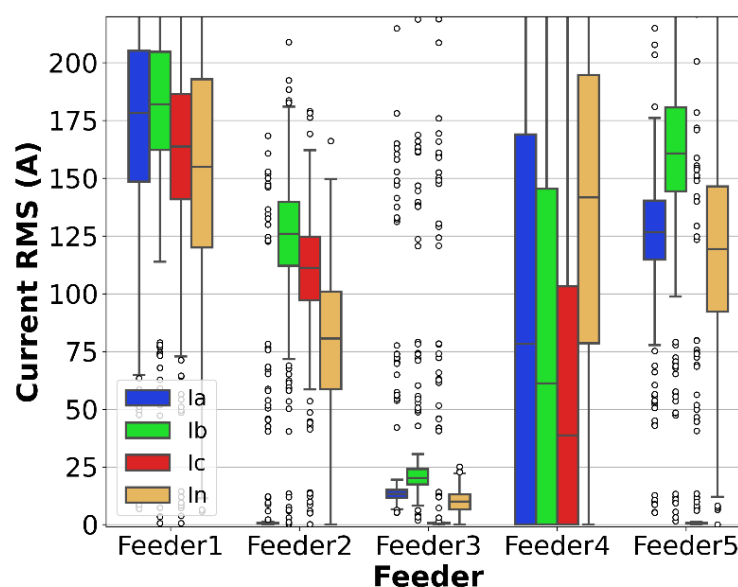


Figure 10. Distribution of neutral conductor current recorded in the investigated low-voltage distribution network during the monitoring campaign.

The measurements reveal elevated neutral current levels, with maximum values reaching approximately 327 A. The broad distribution and frequent high-current observations indicate that elevated neutral conductor loading was recurrent rather than limited to isolated events. These results are consistent with the phase-current imbalance reported previously in Figure 6b, suggesting that neutral conductor loading constitutes an important operating constraint in the investigated network. However, the respective contributions of phase imbalance and harmonic currents to the measured neutral current cannot be quantified separately from the available measurements. The observed neutral current levels therefore provide complementary evidence of the network operating conditions and form the basis for discussing the possible influence of phase imbalance and harmonic components in Section 4.

3.9. Customer Perception of Electricity Supply Quality

Figure 11 presents the distribution of the main power quality disturbances reported by customers connected to the investigated low-voltage distribution network in the

municipality of Kamalondo, Lubumbashi. The survey provides complementary information to the electrical measurements by highlighting the disturbances that are most frequently perceived by end users during the monitoring period.

The survey results indicate that power outages and service interruptions constitute the most frequently reported disturbance, accounting for 35.5% of all responses. Voltage dips represent the second most frequently perceived disturbance, corresponding to 30.4% of the reported events. Disturbances associated with voltage sags and interruptions account for 20.8%, while voltage flicker represents 9.9% of the reported power quality problems. Harmonic distortion is the least frequently perceived disturbance, representing only 3.4% of the total responses.

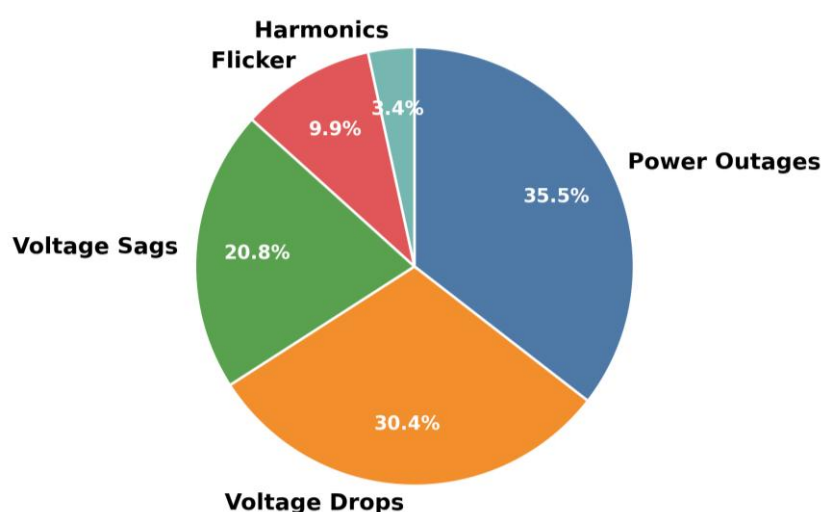


Figure 11. Comparison between instrumentally measured power quality disturbances and electricity-service problems reported by surveyed customers in the Babemba distribution area. Instrumental and survey data are presented as complementary sources of evidence and should not be interpreted as directly equivalent measurements.

The results clearly show that disturbances directly affecting the continuity of electricity supply and voltage stability dominate customers' perception of power quality. Collectively, outages, interruptions, voltage dips, and voltage sags account for more than 85% of all reported disturbances, indicating that these phenomena constitute the principal concerns experienced by consumers connected to the investigated low-voltage network. In contrast, flicker and harmonic distortion account for a comparatively small proportion of the reported events.

Overall, the customer survey confirms that the most frequently perceived power quality disturbances are those related to supply continuity and voltage variations. These findings complement the electrical measurements presented in the previous sections and provide an end-user perspective on the overall performance of the investigated low-voltage distribution network.

3.10. Compliance with International Power Quality Standards

Table 4 summarizes the assessment of selected power quality and service continuity indicators measured during the monitoring campaign against the reference values adopted in this study. The assessment focuses on interruption indices (SAIFI and SAIDI), voltage magnitude, voltage dips, and short-term flicker (Pst).

Table 4. Assessment of selected power quality and service continuity indicators against the reference values adopted in this study.

Power Quality Indicator	Regulatory Limits	Observations in Kamalondo Lubumbashi
Interruptions SAIFI	0.5 to 2.0 interruptions/year (IEEE 1366)	7.85 interruptions/year. 4 to 15 times > standards
SAIDI interruptions	100 to 180 min per year (IEEE 1366)	491 min/year. 2.7 to 4.9 times > thresholds
Voltage dip	>90% of nominal voltage during 95% of the time (EN 50160)	70 to 80% dip during peak loads over several days
Voltage (RMS)	$\pm 10\%$ of 230V (EN 50160)	Frequent variation of -20 to -30% . Voltage < 207V over long periods every day.
Flicker	≤ 1 (CEI 61000-4-15)	Maximum Pst of 1.5 observed in the evening (visual flickering)

The comparison presented in Table 4 shows that several measured indicators deviate substantially from the reference values adopted for the present assessment. System frequency remained within the adopted acceptable range throughout the monitoring campaign, indicating stable frequency conditions during the observation period. In contrast, several indicators associated with voltage quality and service continuity showed substantial deviations from their corresponding reference values.

The observed deviations include sustained voltage variations, voltage sag events, harmonic distortion, elevated flicker levels, and service interruption indices. The measured voltage unbalance and neutral conductor current also indicate constrained operating conditions within the investigated low-voltage network. Taken together, these results demonstrate that the network experienced multiple and concurrent power quality and service continuity disturbances during the monitoring period.

Overall, the compliance assessment indicates that, although frequency remained relatively stable, several measured power quality and service continuity indicators deviated substantially from the reference values adopted in this study. These findings provide the quantitative basis for the subsequent discussion of the operating conditions and factors associated with the observed network performance.

3.11. Correlation Analysis of Power Quality Indicators

Figure 12 presents the correlation matrix of the main electrical power quality indicators derived from the monitoring campaign. Spearman's rank correlation analysis was used to quantify the strength and direction of the associations among the selected variables.

Spearman's rank correlation analysis revealed statistically significant relationships among several power quality indicators. The three line voltages were strongly positively correlated, with coefficients ranging from $\rho = 0.664$ to 0.948 ($p < 0.001$), indicating a consistent evolution of voltage conditions across the three phases. Positive correlations were also observed among the phase currents, although their magnitude varied considerably: A1–A2 exhibited a strong association ($\rho = 0.651$, $p < 0.001$), A2–A3 a moderate association ($\rho = 0.374$, $p < 0.001$), and A1–A3 only a weak association ($\rho = 0.175$, $p < 0.001$). Voltage harmonic distortion was negatively associated with the corresponding RMS line voltage, with ρ values of -0.703 for U12, -0.469 for U23, and -0.753 for U31 (all $p < 0.001$). Similarly, current harmonic distortion was negatively associated with RMS current for phases A1 ($\rho = -0.669$, $p < 0.001$) and A2 ($\rho = -0.401$, $p < 0.001$), whereas the association for A3 was very weak despite being statistically significant ($\rho = 0.078$, $p < 0.001$). These results demonstrate statistically significant associations among several measured power quality variables; however, the correlations should not be interpreted as evidence of direct causal relationships.

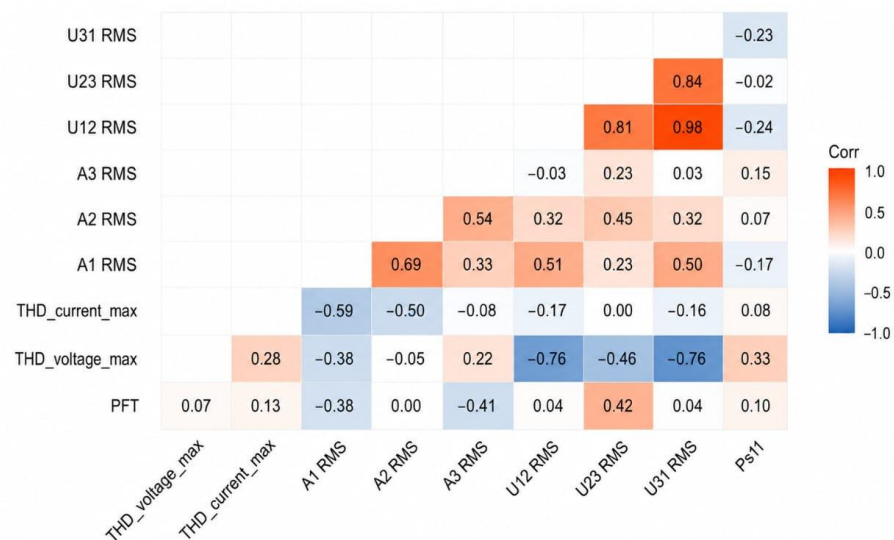


Figure 12. Correlation matrix of the main electrical power quality indicators. The statistical significance and strength of selected relationships were further evaluated using Spearman's rank correlation analysis, as reported in the accompanying text.

4. Discussion

4.1. Voltage Quality and Network Operating Conditions

The monitoring campaign revealed significant spatial and temporal variations in the electrical operating conditions of the investigated low-voltage distribution network. Pronounced voltage fluctuations were observed on Feeders 2 and 4, while Feeders 1 and 5 exhibited comparatively high current loading, demonstrating substantial heterogeneity in network operating conditions. The daily load profiles further revealed two distinct demand peaks, with the highest evening demand occurring during the rainy season. Taken together, these measured results indicate that the network experiences markedly different operating conditions across feeders and periods of increased loading during peak demand.

These findings can be interpreted in relation to the physical and operational characteristics of the investigated feeders. Feeder lengths range from 111.93 m to 1145.28 m, while the number of connected customers varies from 15 on Feeder 3 to 187 on Feeder 4. Four feeders are equipped with 110 mm² conductors, whereas Feeder 3 uses a substantially smaller cross-section of 35 mm². In radial low-voltage networks, voltage drops are influenced by feeder impedance and load current; consequently, long and/or heavily loaded feeders may be more susceptible to sustained voltage deviations, particularly at downstream connection points. Similar behaviour has been reported by [36] and [6], who showed that uneven loading and increasing electricity demand can significantly deteriorate voltage regulation in low-voltage distribution systems. Moreover, unevenly distributed single-phase loads can contribute to phase imbalance, elevated neutral current and increased network losses, as reported by [25,36].

Within the present study, some of the measured power quality patterns are consistent with these structural characteristics, although the observed relationships should not be interpreted as direct evidence of causality. Feeder 4, for example, supplies the largest number of customers (187) and exhibited particularly broad voltage and current distributions. Feeder 5, with a length of 1145.28 m, is the longest investigated feeder and was also among the feeders carrying the highest current levels. These observations suggest an association between feeder configuration, loading conditions and voltage performance. However, because several network characteristics vary simultaneously among the

feeders, the individual contributions of feeder length, loading level and conductor characteristics cannot be isolated conclusively from the present measurements.

The quantitative feeder characteristics are complemented by direct field observations of the physical condition of the distribution infrastructure. Field inspections revealed corroded electrical equipment, deteriorated insulation, overheated and carbonised electrical joints, weathered distribution cabinets, disorganised cable routing and partially exposed conductors. These observations document the physical deterioration of parts of the investigated infrastructure but do not, by themselves, establish a quantitative causal relationship with the measured power quality disturbances. From an engineering perspective, such defects can increase contact resistance and thermal stress and may increase the likelihood of electrical faults, thereby contributing to voltage degradation and reduced service reliability. Similar effects of deteriorated distribution infrastructure and inadequate maintenance on voltage stability and network reliability have been reported by [5,37,38]. However, reliable installation dates and service-age records were not available for several components of the investigated network. Therefore, the present study characterises infrastructure condition on the basis of documented physical deterioration rather than chronological equipment age.

Another important characteristic of the investigated network is the prevalence of illegal and non-standard electricity connections. Quantitatively, 76 non-standard connections were identified on Feeder 1 and 86 on Feeder 4, corresponding to the highest numbers among the investigated feeders. Feeder 4, which has the highest number of such connections, also exhibited substantial voltage and current variability. This correspondence represents an observed association within the present dataset rather than evidence of a direct causal relationship. From an engineering perspective, uncontrolled customer connections may increase feeder loading beyond the conditions considered in the original network design and can contribute to additional voltage drops and increased losses. Previous studies conducted in Lubumbashi and other African urban networks have similarly associated electricity theft and non-standard connections with increased network loading, voltage instability, technical and non-technical losses, and reduced electricity service quality [5,15,18,23,39]. Nevertheless, the present results do not allow the contribution of non-standard connections to be isolated from other simultaneously acting network factors.

Overall, the findings indicate that voltage-quality degradation in the Babemba low-voltage network is associated with interacting structural and operational constraints, including heterogeneous feeder characteristics, high loading conditions, uneven phase loading, non-standard customer connections and physical deterioration of the distribution infrastructure. The quantitative electrical measurements establish the magnitude and variability of the observed power quality disturbances, while feeder characteristics and field inspections provide complementary evidence for interpreting the conditions under which these disturbances occur. However, their individual causal contributions cannot be separated conclusively within the present observational study. These findings support the need for coordinated measures including feeder reinforcement, phase-load balancing, rehabilitation of deteriorated infrastructure, preventive maintenance and improved management of non-standard customer connections. Since voltage quality and service reliability are closely related, the following section examines the continuity of electricity supply through the analysis of interruption and voltage-sag events.

4.2. Service Continuity Performance

The results demonstrate that service continuity represents one of the most critical weaknesses of the investigated low-voltage distribution network. The high occurrence of short- and long-duration interruptions, together with frequent voltage sag events, indicates substantial reliability limitations within the Babemba distribution network. In

particular, Feeder 2 exhibited the highest frequency of interruption events and voltage sags, revealing greater operational vulnerability than the remaining feeders. This poor continuity performance is further reflected in the calculated reliability indices, with a SAIFI of 7.85 interruptions/year and a SAIDI of 491 min/year, both exceeding the reference values adopted from IEEE 1366 in this study. An exceptional outage lasting approximately 48 h was also recorded during the monitoring campaign. However, because this event originated from the upstream medium-voltage supply rather than from the investigated low-voltage feeders, it was analysed separately and excluded from the feeder-level SAIFI and SAIDI calculations.

The measured reliability performance should be interpreted alongside the physical condition and operating characteristics of the investigated network. Field inspections revealed corroded distribution cabinets, overheated electrical joints, degraded insulation and other signs of physical infrastructure deterioration. These observations do not establish a direct quantitative relationship between infrastructure condition and interruption frequency, but they provide relevant contextual evidence regarding the operating environment of the network. From an engineering perspective, deteriorated electrical components may increase the likelihood of permanent and transient faults and contribute to increased maintenance requirements. Similar observations were reported by [5,37], who demonstrated that ageing distribution infrastructure significantly reduces system reliability by increasing equipment failures and maintenance requirements. Likewise, heavily loaded feeders may experience increased thermal and electrical stress, potentially contributing to equipment deterioration and protection operations.

The poor continuity of supply must also be considered in the context of increasing electricity demand and the prevalence of non-standard customer connections. The present study identified substantial numbers of such connections, particularly on Feeders 1 and 4. Although the available data do not allow their individual contribution to interruption frequency or duration to be quantified, uncontrolled connections may increase feeder loading without corresponding reinforcement of conductors and protection devices. Previous studies conducted in Lubumbashi and other African urban networks similarly identified electricity theft and insufficient infrastructure investment as major causes of poor service continuity [5,15]. These comparisons suggest that the reliability problems observed in Babemba occur within a broader context in which technical constraints and non-technical factors can interact to affect electricity service continuity.

To place the measured reliability performance in a broader regional context, the results were compared with findings reported for other African distribution networks. Service continuity problems have been documented across rapidly urbanising regions, although their severity varies according to network characteristics, infrastructure condition and maintenance practices [18]. Ref. [40] reported frequent voltage disturbances in the Windhoek distribution network, but with a substantially better continuity performance than that observed in the present study. Likewise, measurements performed in Accra, Ghana, within the GridWatch project revealed chronic undervoltage and recurrent service interruptions in densely populated urban districts [15,41]. These comparisons indicate that the disturbances recorded in Babemba are consistent with broader power quality and reliability challenges reported in African urban distribution networks. However, direct quantitative comparisons should be interpreted cautiously because monitoring periods, network configurations, reliability definitions and data-collection methodologies may differ among studies.

From an operational perspective, poor service continuity has significant technical, economic and social implications. Frequent interruptions can reduce customer confidence in the public electricity supply, increase reliance on alternative electricity sources and generate additional costs for consumers. Repeated switching operations and prolonged

overload conditions may also contribute to accelerated equipment deterioration and increased maintenance requirements, thereby reinforcing a cycle of declining network performance [20,36,42]. These consequences highlight that service continuity is not only a reliability issue but also an important consideration for network operation and infrastructure planning.

Overall, the present findings establish that service continuity is a major operational concern in the investigated network, as demonstrated quantitatively by the measured interruption events and the calculated SAIFI and SAIDI indices. Field observations and feeder characteristics provide complementary contextual evidence for interpreting these reliability problems, but their individual causal contributions cannot be determined conclusively from the present observational dataset. Improving service continuity therefore requires a coordinated strategy combining infrastructure rehabilitation, reinforcement of heavily loaded feeders, optimisation of protection coordination, preventive maintenance and improved management of non-standard connections. While service continuity characterises the reliability of electricity supply, it does not fully describe the electrical conditions experienced by end users. Therefore, the following section examines harmonic distortion and voltage fluctuations as additional dimensions of power quality degradation.

4.3. Harmonic Distortion and Voltage Fluctuations

The monitoring campaign identified harmonic distortion and voltage fluctuations as recurrent power quality issues in the investigated low-voltage distribution network. Their severity varied substantially among the investigated feeders, indicating heterogeneous waveform quality across the network. In particular, the measured THD and short-term flicker (Pst) values demonstrate that harmonic distortion and voltage fluctuations constitute relevant operational concerns. These disturbances may affect the performance and service life of sensitive electrical equipment even in the absence of complete supply interruptions.

The harmonic measurements revealed substantial feeder-to-feeder differences. Current harmonic distortion was particularly pronounced on Feeder 3, which exhibited a mean THD-I of 43.12%, compared with 22.94% on Feeder 2, 16.74% on Feeder 4, 15.51% on Feeder 1 and 10.12% on Feeder 5. Voltage harmonic distortion followed a less pronounced but still heterogeneous pattern, with Feeder 3 also exhibiting the highest mean THD-U (8.04%) and THD-V (5.07%). These results demonstrate that harmonic distortion is not uniformly distributed across the investigated network and suggest that local load characteristics and feeder operating conditions may influence the observed harmonic levels.

Although the individual harmonic sources were not directly identified during the monitoring campaign, the measured distortion is consistent with the presence of non-linear loads, including electronic appliances, LED lighting and power electronic devices. Such loads can inject harmonic currents into low-voltage networks, which interact with feeder impedance and may result in voltage waveform distortion. Similar mechanisms have been reported by [27,43], who identified non-linear loads as major contributors to harmonic pollution in low-voltage distribution systems. Therefore, the contribution of non-linear loads to the harmonic distortion observed in Babemba should be regarded as a plausible engineering interpretation supported by previous studies rather than as a directly quantified causal relationship.

The measured flicker levels provide complementary evidence of voltage fluctuations within the investigated network. Short-term flicker severity occasionally exceeded the adopted reference threshold of $P_{st} = 1$, with maximum values reaching approximately 1.5. These measurements establish the occurrence of perceptible short-term voltage fluctuations but do not independently identify their sources. From an engineering perspective,

such fluctuations may be associated with rapid variations in residential and commercial loads and with insufficient voltage regulation under highly variable loading conditions. According to [6], insufficient voltage regulation and fluctuating loads increase the risk of flicker, particularly in overloaded urban networks. The observed Pst exceedances therefore indicate periods of increased voltage fluctuation severity within the Babemba network.

The combined THD and flicker results should be interpreted within the broader operating conditions documented in the investigated network. High feeder loading, heterogeneous load characteristics, physical infrastructure deterioration and increasing electricity demand may create conditions that favour waveform distortion and voltage fluctuations; however, their individual contributions were not quantified in the present study. Similar power quality challenges have been reported in African distribution networks facing rapid urbanisation and limited infrastructure investment [6,15]. From an operational perspective, excessive harmonic distortion can increase electrical losses and thermal stress, while flicker can reduce visual comfort and affect the operation of sensitive electrical equipment [44,45].

Overall, the results demonstrate that harmonic distortion and voltage fluctuations constitute important components of power quality degradation in the investigated network. The measurements quantify the magnitude and variability of these disturbances, whereas their potential origins are interpreted using the observed network characteristics and mechanisms reported in previous studies. Improving waveform quality therefore requires not only the mitigation of harmonic emissions but also improved load management, reinforcement of highly loaded feeders, rehabilitation of deteriorated infrastructure and continuous power quality monitoring. Since harmonic currents may also contribute to neutral conductor loading and interact with phase imbalance, the following section examines these phenomena and their implications for the operation of the investigated network.

4.4. Neutral Conductor Current and Phase Imbalance

The measured neutral conductor current and phase imbalance provide further evidence of the constrained operating conditions of the investigated distribution network. Neutral current remained elevated during substantial portions of the monitoring period, with maximum values reaching approximately 327 A. These measurements are consistent with the considerable phase-current imbalance observed across the investigated feeders and indicate that the three phases are not uniformly loaded. Such operating conditions are commonly encountered in urban low-voltage networks characterised by a predominance of single-phase customers that may be unevenly distributed among the available phases [5,18,36,46,47].

The correlation analysis provides additional quantitative evidence of relationships among the measured power quality indicators. The three line voltages were strongly positively correlated, while the phase-current correlations varied in strength. Negative associations were observed between RMS voltage and the corresponding voltage THD, as well as between RMS current and current THD for two of the three phases. These statistical relationships indicate that several power quality parameters vary concurrently under changing network operating conditions; however, they should not be interpreted as evidence of direct causal relationships. The individual mechanisms underlying these associations cannot be isolated from the correlation analysis alone.

The observed phase imbalance can be interpreted in the context of the network characteristics documented during the field investigation. Uneven allocation of single-phase loads, heterogeneous electricity demand and non-standard customer connections represent plausible contributors to unequal phase loading. Under unbalanced operating

conditions, the neutral conductor carries the vector sum of the phase currents, potentially increasing conductor losses, thermal stress and voltage unbalance. Similar findings have been reported in low-voltage distribution systems where phase imbalance reduces network efficiency and increases electrical stress on network components [27,36]. In addition, harmonic currents generated by non-linear loads, particularly triple harmonic components, may contribute to neutral conductor loading and further increase thermal stress [40,48]. However, the respective contributions of fundamental-frequency phase imbalance and harmonic currents to the measured neutral current were not separately quantified in the present study.

From an operational perspective, these findings highlight phase-load balancing as a relevant strategy for improving the operating conditions of the investigated network. A more balanced allocation of single-phase customers among the three phases, improved management of non-standard connections and periodic monitoring of neutral conductor current could contribute to reducing phase imbalance, technical losses and excessive conductor loading. These measures should be considered alongside feeder reinforcement and infrastructure rehabilitation, particularly in sections of the network exhibiting high loading and substantial voltage variability.

Overall, the combined assessment of neutral current, phase imbalance and correlations among power quality indicators demonstrates that several electrical disturbances coexist within the Babemba network. The instrumental measurements establish the magnitude of these disturbances, while the network characteristics and field observations provide complementary evidence for interpreting the conditions under which they occur. Nevertheless, the present measurements do not allow the individual contribution of each mechanism to be isolated conclusively. This distinction between measured relationships and engineering interpretation provides a more robust basis for the corrective actions discussed in the following section, together with the study limitations and future research perspectives.

4.5. Practical Implications, Study Limitations and Future Perspectives

The present findings have important implications for both the distribution utility and electricity consumers. The coexistence of voltage instability, harmonic distortion, phase imbalance and poor service continuity indicates that improving power quality in the Babemba distribution network requires an integrated approach rather than isolated corrective actions. Priority should be given to infrastructure rehabilitation, reinforcement of highly loaded feeders, phase-load balancing, preventive maintenance and improved management of non-standard customer connections. These measures could contribute to improved voltage regulation, reduced technical losses and enhanced reliability of electricity supply. Similar recommendations have been proposed for urban distribution systems facing rapid demand growth and deteriorating infrastructure [6,7,18,20,36].

The customer survey provides a complementary perspective on the electrical conditions documented during the monitoring campaign. Respondents frequently reported voltage fluctuations, prolonged outages and electricity-related equipment damage, indicating that the power quality and service continuity problems identified instrumentally are also reflected in users' reported experiences. These disturbances may have broader socioeconomic consequences, including expenditure on appliance repair or replacement, increased reliance on alternative electricity sources and reduced confidence in the public electricity supply [5,42,49]. The convergence between instrumental measurements and customer-reported experiences provides complementary evidence of the severity of electricity service problems in the investigated area. However, the survey responses represent users' perceptions and reported experiences and should not be interpreted as independent instrumental validation of the measured power quality indicators.

Several limitations should nevertheless be acknowledged. First, the monitoring campaign was limited to five feeders supplied by a single MV/LV substation and therefore cannot be considered statistically representative of the entire Lubumbashi distribution network. Second, although the measurement campaign covered both dry- and rainy-season conditions, each feeder was monitored for a limited observation period; longer-term continuous monitoring would provide a more comprehensive assessment of seasonal and interannual variability. Third, reliable installation dates and service-age records were unavailable for several network components, preventing a quantitative assessment of chronological infrastructure ageing. The study therefore assessed infrastructure condition primarily through documented physical deterioration observed during field inspections. Fourth, although associations were identified among electrical variables, feeder characteristics and field observations, the observational design does not allow the individual causal contribution of feeder loading, phase imbalance, infrastructure deterioration or non-standard connections to be isolated. Finally, the individual sources of harmonic distortion and the respective contributions of phase imbalance and harmonic currents to neutral conductor loading were not separately quantified.

Future research should therefore extend the monitoring programme to additional MV/LV substations and longer observation periods to assess the spatial and temporal representativeness of the present findings. More detailed load characterisation and harmonic-source identification would help quantify the contribution of specific consumer loads to waveform distortion and neutral conductor loading. Future studies should also investigate the contribution of distributed energy resources and evaluate corrective measures, including feeder reinforcement, phase-load redistribution and infrastructure rehabilitation, using power-flow simulations and optimisation techniques. Such analyses would allow the effectiveness of alternative network improvement strategies to be quantified before their practical implementation.

Overall, the combined analysis of electrical measurements, infrastructure condition and customer perceptions demonstrates substantial power quality and service continuity limitations within the investigated network. Several measured indicators exceeded the reference limits adopted from international standards, while field observations revealed important structural and physical constraints within the distribution infrastructure. Rather than establishing a single causal mechanism, the findings indicate that feeder loading, phase imbalance, non-standard customer connections and physical infrastructure deterioration are plausible and interacting factors associated with the observed network performance. These results provide a technical basis for prioritising network rehabilitation and operational improvements in the Babemba distribution network and offer methodological insights that may be relevant to other rapidly growing urban distribution systems facing similar challenges.

5. Conclusions

This study evaluated power quality and service continuity in the low-voltage distribution network supplied by the Babemba MV/LV substation in Kamalondo Municipality, Lubumbashi (DR Congo). The monitoring campaign revealed substantial degradation of electrical service quality, characterised by recurrent supply interruptions, chronic undervoltage, phase imbalance, excessive neutral conductor currents, voltage fluctuations and occasional harmonic distortion exceeding internationally accepted limits. The comparison with EN 50160, IEEE 519-2014, IEC 61000-4-15 and IEEE 1159 confirmed that several monitored indicators do not comply with current power quality and reliability requirements, demonstrating that the investigated network operates under challenging technical conditions.

The results further demonstrate that these disturbances are not isolated phenomena but arise from the interaction of several structural and operational factors. Feeder overloading, uneven distribution of single-phase loads, ageing electrical infrastructure, excessive neutral currents and non-standard customer connections collectively contribute to voltage degradation and poor service continuity. The correlation analysis identified significant associations among several voltage, current, and harmonic distortion indicators, while the consistency between instrumental measurements, infrastructure inspections, and customer surveys provided complementary contextual evidence for interpreting the observed power quality problems.

Beyond the assessment of compliance with international standards, this work provides a comprehensive framework for diagnosing power quality in urban low-voltage distribution systems. Unlike previous studies that focused on individual indicators, the proposed approach combines long-term electrical measurements, field inspection of network infrastructure, customer perception surveys, reliability assessment and statistical correlation analysis to provide an integrated understanding of the mechanisms responsible for power quality degradation. This multidisciplinary approach responds directly to the need identified in the literature for more comprehensive assessments of distribution network performance in rapidly growing urban environments.

From an operational perspective, the findings highlight that improving electricity service quality requires an integrated network management strategy rather than isolated corrective actions. Priority should be given to feeder reinforcement, phase-load balancing, rehabilitation of ageing infrastructure, regularisation of illegal connections, preventive maintenance and the deployment of continuous power quality monitoring systems. Such measures would improve voltage regulation, reduce technical losses, enhance service continuity and support more reliable operation of urban distribution networks under increasing electricity demand.

Although the present study focused on a single MV/LV substation, the proposed methodology can readily be applied to other urban low-voltage networks operating under similar technical and socioeconomic conditions. Future research should extend the monitoring programme to additional substations, integrate power-flow simulations and network modelling to evaluate the electrical impact of corrective actions, and investigate the contribution of distributed energy resources, including photovoltaic systems, battery energy storage systems and microgrids, to improving power quality and network resilience. Furthermore, assessing the long-term economic consequences of poor power quality and infrastructure deterioration would provide valuable support for investment planning and asset management.

Overall, this study demonstrates that the combination of field measurements, infrastructure assessment, customer feedback and statistical analysis provides a robust and transferable methodology for diagnosing power quality problems in urban low-voltage distribution networks. The findings not only establish a technical baseline for the rehabilitation of the Lubumbashi distribution network but also offer practical guidance for utilities and decision-makers seeking to improve the reliability, efficiency and sustainability of electricity supply in rapidly urbanising regions of Sub-Saharan Africa.

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Abbreviations

The following abbreviations are used in this manuscript:

DRC	Democratic Republic of the Congo
LV	Low Voltage
MV	Medium Voltage
V	Voltage
SAIFI	System Average Interruption Frequency Index
SAIDI	System Average Interruption Duration Index
A	Ampere
Pst	Short-term Flicker Severity
IEA	International Energy Agency
THD	Total Harmonic Distortion
CENELEC	European Committee for Electrotechnical Standardization
IEC	International Electrotechnical Commission
IEEE	Institute of Electrical and Electronics Engineers
IT	Information Technology
LED	Light Emitting Diode
DER	Distributed Energy Resources
EN	European Norm
km	Kilometer
kV	Kilovolt
kVA	Kilovolt-ampere
SNEL	National Electricity Company
mA	Milliampere
Hz	Hertz
U	Voltage
RMS	Root Mean Square
P	Active Power
Q	Reactive Power
EP	Active Energy
EQ	Reactive Energy
fc	Load factor
PF	Power Factor
CVS	Sales and Service Center
GPS	Global Positioning System
AC	Alternating current
mm²	Square Millimetre
m	Metre
am	Ante meridiem
pm	Post meridiem
kW	Kilowatt
PV	Photovoltaic

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