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

The quality of low-voltage power affects the lifespan of equipment and the quality of service, but it is still poorly quantified in many African urban networks. In Lubumbashi, Democratic Republic of Congo (DRC), we conducted an instrumented campaign on five feeders supplied by the Babemba medium/low voltage (MV/LV) substation to assess the continuity and voltage stability of LV consumption systems in relation to international standards. Here, we show that the deviations are dominated by a combination of frequent interruptions and chronic undervoltage. The recordings (October 2024–February 2025) indicate prolonged periods below 207 V, with typical variations of −20 to −30%, and dips reaching 70–80% of the nominal voltage during peaks. Reliability is degraded system average interruption frequency index (SAIFI 7.85 interruptions/year; and system average interruption duration index (SAIDI 491 min/year) and a medium-voltage event lasting approximately 48 hours highlights low resilience. Phase imbalances (up to 18%) and high neutral currents (up to 327 A), as well as flicker exceeding the comfort threshold (P_{st} max ≈ 1.5), complete the diagnosis. These results provide a quantitative basis for prioritizing rehabilitation (reinforcement of feeders, phase balancing, regularization of connections) and establishing regular local monitoring.

Keywords: Power Quality, Low-Voltage Distribution Networks, Voltage Stability, Power System Reliability, Developing Urban Networks

1. Introduction

The quality of the electricity supply has become a key issue for economic and social development (Dora et al., 2025), particularly in low- and middle-income countries where networks are often outdated, undersized, and subject to strong growth in demand (IEA, 2019; Shi et al., 2025; World Bank, 2025). In the Democratic Republic of Congo (DRC), and more specifically in Lubumbashi, rapid urbanization, unplanned neighborhood expansion, and low investment in infrastructure have led to an electricity supply that is both limited in quantity and highly heterogeneous in quality (Wa Banza Bonaventure et al., 2018; Bonaventure, 2019a). In this context, the question is no longer simply whether households are connected or not, but also what type of electricity they actually receive at their outlets.

Power quality is defined as the ability of the grid to provide stable voltage and frequency, with a sinusoidal waveform that complies with standards (Samuel et al., 2025; Osunmuyiwa et al., 2025), thus ensuring the reliability of the power supply and the proper functioning of equipment (Naderi et al., 2018; Pannila & Edirisinghe, 2021; Kutubuddin & Liyakat, n.d.; Antyufeyeva, 2019; Stanko et al., 2025).

In terms of standards, the key parameters of power quality include frequency, voltage magnitude, slow voltage variations, voltage sags/dips and temporary surges (swells), short and long interruptions, voltage fluctuations and flicker, voltage imbalance in three-phase networks, total harmonic distortion (THD), interharmonics, carrier signals, and certain fast transients as illustrated in Figure 1 (CENELEC, 2010; IEC, 2015; Stanko et al., 2025; IEEE, 2019; Taghvaie et al., 2023; Zhang et al., 2024).

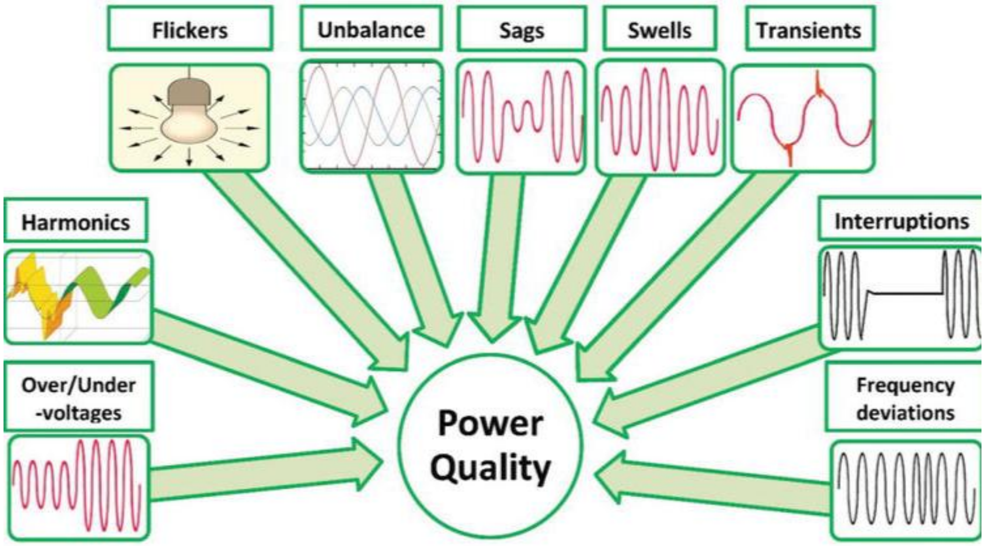

Figure 1: key parameters of electrical power quality

There are many causes of power quality degradation, relating to both the characteristics of the networks and the nature of the connected loads. In modern distribution systems, the rise of electronic and non-linear loads (IT equipment, switching power supplies, variable speed drives, LED lamps, air conditioners, phone chargers, household appliances) is one of the main sources of harmonic distortion and imbalance, including at the residential level (Caicedo et al., 2023; Guerrero-Rodríguez et al., 2024). These loads inject non-sinusoidal currents into the grid which, when interacting with the impedance of (LV) distribution networks, cause voltage distortions and increased losses (Michalec et al., 2021). In the distribution network, the development of distributed energy resources (DERs) and new loads intensifies congestion and voltage problems, resulting in frequent overloads and deviations from permissible thresholds (Benzerga et al., 2025). In urban networks in developing countries, these technical factors are compounded by structural issues such as chronic transformer overload, lack of maintenance, illegal connections, aging conductors, ross-sections, which exacerbate voltage drops and the frequency of outages (Bonaventure, 2019b; Wa Banza Bonaventure et al., 2018; David & Bonaventure, 2019a).

In Lubumbashi, the second largest city in the DRC, studies indicate that a significant proportion of households are connected to the grid but receive poor quality service, characterized by long and unpredictable outages due to both production shortages and distribution overload (Bonaventure, 2019b). Socio-economic surveys conducted in various municipalities have revealed very high rates of illegal connections, sometimes reaching 80% to 100% of households in informal settlements...

(David & Bonaventure, 2019a; Mbungu et al., 2023a; Kasumba et al., 2025), the non-compliance of a significant proportion of domestic installations, and the growing use of energy-intensive appliances and equipment on an already fragile network (Bonaventure, 2019a). In particular, a recent study on electricity theft in Lubumbashi shows that outlying municipalities such as Katuba and Kampemba have illegal connection rates exceeding 75%, correlated with frequent voltage fluctuations, transformer overloads, and prolonged outages (Kasumba et al., 2025a).

To date, most existing studies have focused either on access to electricity and socio-economic aspects, or on perceptions of service quality. However, few studies offer a detailed instrumental characterisation of electrical energy quality parameters at the level of the city's LV consumption systems. Nevertheless, a few local technical contributions have looked at harmonic distortion and current imbalances in certain parts of Lubumbashi's low-voltage network (Bonaventure, 2019b). However, these studies remain limited and do not allow for a comprehensive and representative diagnosis of the quality of electrical energy within low-voltage consumption systems.

The overall objective of this study is to characterise the quality of electrical energy in LV consumption systems supplied by the Babemba MV/LV substation located in the Kamalondo district of Lubumbashi. This analysis will be based on international standards (EN 50160, IEEE 519-2014, IEC 61000-4-15, IEEE 1159) and recent methodological approaches to LV power quality analysis (Rustemli et al., 2023; Hajjej & Sbita, 2024a; Landolfi et al., 2024a).

2. Materials and methods

2.1. Study site and electrical network

The study was conducted in the city of Lubumbashi, located in the province of Haut-Katanga, in the south-east of the DRC, between 11°20'–12°00' S and 27°10'–27°10' E. The city has seven administrative communes: three planned communes (Lubumbashi, Kenya, Kamalondo) and four mainly self-built communes (Katuba, Kampemba, Ruashi, Annexe). The commune of Kamalondo is made up of two neighbourhoods, Kitumaini and Njanja, covering an area of approximately 1.35 km². The municipality of Kamalondo was selected as the main study area because it has both a high electrification rate and a significant proportion of households with illegal access to electricity, making it a particularly critical area in terms of power supply quality (Mbungu et al., 2023a; Kasumba et al., 2025). This municipality also has many energy-intensive activities (bars, restaurants, hotels, welding shops, dry cleaners, carpentry shops, schools), which generate load profiles that are particularly demanding on the grid (Kasumba et al., 2025a).

2.2. Description of the Babemba cabin and scheduled departures

The Babemba substation is supplied with MV (15 kV) by two feeders, Amato and Synteskin. It is equipped with a 630 kVA transformer, protected upstream by a 1250 A circuit breaker. The substation has five LV outputs, four of which are dedicated to supplying residential and industrial users, and one of which is reserved for a private individual for his activities.

The associated network is characterised by uncontrolled extensions and a high rate of illegal connections, in a context of growing loads. The distribution lines are mainly overhead, made of copper or aluminum, with sections that are sometimes heterogeneous and undersized, built over long distances, with extensive use of fuse links. These characteristics, combined with 630-400 kVA transformers that are frequently overloaded at peak times, contribute to significant voltage drops at the end of the line. In addition, non-compliant connection practices, such as sharing phases and neutral conductors between substations or using non-standardised internal cabling, exacerbate phase imbalances and neutral voltage variations. The Babemba substation was ultimately selected due to a combination of these technical factors, but also for reasons of accessibility, safety and energy availability during the observation period.

2.3. Standardised framework for assessing energy quality

In the absence of strictly enforced national standards on power quality and regular compliance reports produced by the National Electricity Company (SNEL), the assessment is based entirely on international standards. The study draws on the following in particular:

- EN 50160, for low-voltage distribution characteristics;
- The IEC 61000 series, in particular IEC 61000-4-15 for flicker measurement;
- The IEEE 519-2014 standard for harmonic distortion limits (THD $\leq 5\%$ in LV);
- The IEEE 1159 standard for the classification of power quality disturbances;
- The IEEE 1100 standard for power faults and compatibility recommendations;
- The IEC 61009 standard for aspects related to overcurrents (Oubrahim et al., 2023; IEEE, 2014; CENELEC, 2010).

2.4. Measuring device and experimental protocol

Power quality measurements were performed using as shown in Fig. 1a network analyser, a portable device specifically designed for low-voltage power quality studies (Pedro Correia Freire de Almeida et al., n.d.; Rüstemli et al., 2025; Saidani et al., 2025 Gençay et al., 2025; Bedoui et al., 2025). The campaign took place over a five-month period, from October 2024 to February 2025, following to a continuous monitoring protocol of one week per departure, in accordance with the recommendations of standard EN 50160 (Samuel et al., 2025).

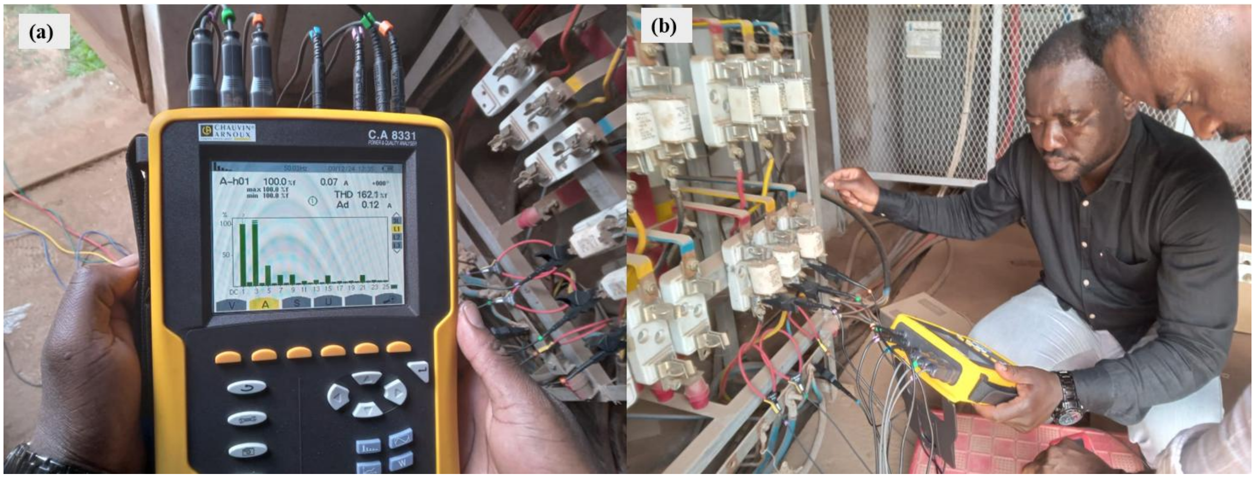

Figure 2. Illustration of the measuring device (a) and its installation (b)

The Line currents were measured using three AmpFlex A 193 flexible loops, while voltages were recorded via four crocodile clips connected to the three phases and neutral. The range of the current sensors was set between 100 mA and 100 A, with a one-minute acquisition interval, allowing for the precise detection of load variations and disturbance events (Garabitos Lara et al., 2023; Landolfi et al., 2024; Hajjej & Sbita, 2024b). The device was continuously powered by the mains (100–240 V, 50/60 Hz) to ensure sufficient autonomy for long-term recordings.

The following parameters were recorded for each circuit: phase-to-phase and phase-to-neutral effective voltages (U12 RMS, U23 RMS, U31 RMS), phase effective currents (A1 RMS, A2 RMS, A3 RMS), active power (P), reactive power (Q), active energy (EP), reactive energy (EQ), fundamental frequency (fc), phase power factors (PF1, PF2, PF3) and total (PFT), total harmonic distortion of voltage and current (THD) and the short-term flicker index P_{st}. For certain representative users connected to the selected feeders, the device was installed at the delivery points in order to document the quality of the energy directly at the input of the low-voltage consumption systems.

2.5. Household sampling plan and collection of supplementary data

As the total number of SNEL network subscribers in the Babemba substation service area is not precisely known, a random sample of households was taken from plots located downstream of the various branches. Only households actually connected to the SNEL network were included. In each selected plot, the questionnaire was administered primarily to the head of the household (male or female); in their absence, another member of the household aged 18 or over responded to the survey.

Data collection was based on a mixed methodology inspired by (Rustemli et al., 2023b), (Hajjej & Sbita, 2024b) and (Landolfi et al., 2024b), combining literature review, semi-structured interviews and direct observations. Interviews were conducted with agency managers, technical agents and operational staff at SNEL's Sales and Service Centre (CVS). They focused on four themes: i) load shedding schedules and procedures, ii) the quality of the voltage supplied and recurring disruptions, iii) billing and consumption practices, iv) the operational management of MV/LV substations and network interventions.

A questionnaire divided into three sections (information about the user, characteristics of the MV/LV substation, parameters specific to each departure) was administered to households and accredited SNEL staff. The geographical coordinates of the distribution lines and substations were recorded by GPS, while the surveyors collected detailed information on the electrical equipment present in households, their technical specifications (power ratings, types of loads) and their modes of use (schedules, seasonality, frequency of use). This dual instrumental and declarative approach makes it possible to link observed consumption profiles to usage behaviours and installation characteristics.

2.6. Preparation of energy quality data and indicators

The raw files from Qualistar C.A 8331 were retrieved using Power Analyzer Transfer software and then exported to Excel format for initial pre-processing. All statistical analyses were then performed in R (version 4.x; R Core Team, 2024) using mainly the tidy verse (Wickham et al., 2019), lubridate (Grolemund & Wickham, 2011), readxl (Wickham & Bryan, 2019) and ggplot2 (Wickham, 2016) packages.

A single Datetime variable was constructed by merging the date and time fields, and the day of the week was extracted to facilitate temporal analyses (weekly profile, weekday/weekend differences). The effective voltages (U12, U23, U31) and currents (A1, A2, A3) were used as is, while the derived indicators – total harmonic distortion (THD), power factor (PF) and flicker indices Pst1–Pst3 – were calculated as arithmetic means of the three phases, in accordance with IEEE recommendations (2014).

Three harmonic distortion indicators were selected: THD_V (phase-to-neutral voltage), THD_U (compound voltage) and THD_A (current). The overall THD was calculated by averaging the THD values for each phase. Regulatory compliance was assessed by comparing the voltage THD values to the 5% threshold recommended by the IEEE 519-2014 standard for low-voltage networks (IEEE, 2014). Short-term flicker indices (Pst1, Pst2, Pst3) were analysed on a fine time scale (time series) and summarised by departure using distributions (box plots), taking the value Pst = 1 as the reference threshold according to IEC 61000-4-15 (CENELEC, 2010).

2.7. Power quality event detection and statistical analysis

Detection of power quality events was carried out systematically using standardised thresholds. Voltage dips were identified when single voltages fell below 90% of the nominal voltage of 230 V; voltage dips on the three-phase network were detected when the composite voltages fell below 95% of the nominal voltage of 400 V; interruptions were defined as cases where the three composite voltages simultaneously fell below 10 V, in accordance with the definitions in standard EN 50160 (CENELEC, 2010). Flicker events were counted as soon as a P_{st} index exceeded 1, and harmonic events as soon as the voltage or current THD exceeded 5% (Rezapour et al., 2024).

For each feeder, the number of daily events was calculated by type of disturbance (voltage dips, voltage sags, interruptions, flicker, harmonic distortions). Temporal trends were explored using LOESS smoothing (Cleveland et al., 1992) applied to daily counts in order to highlight variations according to the days of the week and observation periods. The distribution of the number of events between departures was studied using box-and-whisker plots, allowing for comparison of median values, interquartile ranges and extreme values.

The statistical aggregation of event types was performed by calculating the average daily frequency for each disruption category over the entire study period. These frequencies were then normalised to obtain the relative contributions (as a percentage) of each type of disruption in relation to the total number of events, represented in a ring chart. Finally, seasonal load profiles (dry season vs. rainy season) were constructed from the total active power recorded hourly over a 24-hour cycle. Spline interpolation (de Boor, 2001) was applied to generate continuous smoothed curves, allowing for detailed comparison of diurnal load variations between seasons and discussion of their potential impact on energy quality in the study area.

3. Results

3.1. Characteristics of the network studied

Table 1 summarises the main characteristics of the five LV feeders studied, which vary greatly in terms of length, size and load composition. Lengths range from 111.93 m (Branch 3) to 1,145.28 m (Branch 5), with a conductor cross-section of mainly 110 mm² (Branches 1, 2, 4 and 5), compared to 35 mm² for Branch 3. The number of households connected varies greatly (15 to 187 households), with Departures 4 and 2 being the densest (187 and 160 households). In terms of usage, the load is dominated overall by residential (~ 48–64% on branches 1, 2, 4 and 5) and/or commercial and craft activities (~ 32–49%), while Branch 3 stands out with a clear predominance of commercial/craft activities (86.67%). Hotels remain in the minority (0 to 6.35%) and schools are marginal (0 to 1.07%). Finally, the distribution of connections highlights a significant number of illegal connections, particularly on Branches 1 (76 illegal for 50 legal) and 4 (86 illegal for 101 legal), while Branch 3 appears to be entirely legal (15 legal, 0 illegal).

Table 1 - *Summary of the characteristics of the departures studied*

Branches	Length (m)	Section (mm²)	Number of households	User type				Connection	
				Residential (%)	Hotels (%)	Schools (%)	Commercial or craft activities (%)	Legal (N)	Illegal (N)
Branch 1	602,79	110	126	49,21	6,35	0	44,44	50	76
Branch 2	524,28	110	160	54,37	0	0,62	45	91	69
Branch 3	111,93	35	15	6,67	6,67	0	86,67	15	0
Branch 4	420,02	110	187	48,13	2,14	1,07	48,66	101	86
Branch 5	1145,28	110	144	63,89	3,47	0,69	31,94	103	41

3.2. Load profiles and power behaviour over time

Figure 2 highlights marked daily variability in total power, with broadly comparable dynamics between seasons but different amplitudes. In both cases, the load increases gradually from night-time (~1–4 a.m.), then rises sharply in the morning to reach a first maximum around 7–9 a.m. (~ 180–190 kW), before falling and stabilising relatively in the middle of the day (~ 10–2 p.m., around 120–140 kW). In the rainy season, there is then a very sharp drop in power between around 3 pm and 7 pm, followed by a sudden recovery and an evening peak higher than the dry season (maximum around 8–9 pm, ~ 230–240 kW), before a decline at the end of the evening. In the dry season, the profile retains an evening peak (~ 6–7 p.m.) but also shows a very significant dip around 8–9 p.m. (power close to zero), followed by a partial recovery at the end of the day. These periods when the measured power becomes almost zero suggest interruptions or load shedding occurring at specific times of day, with a more pronounced effect in the rainy season in the late afternoon.

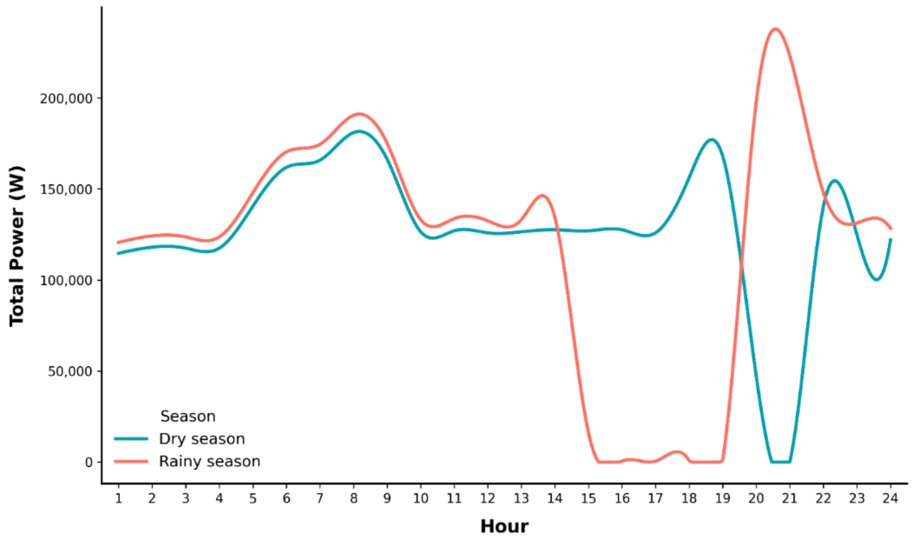

Figure 3. Daily load profiles for both seasons

3.3. Condition of the observed electrical infrastructure

Figure 4 highlights the advanced deterioration of SNEL's low-voltage distribution network infrastructure in Lubumbashi. Observations reveal a generally heavily oxidised and dirty low-voltage panel, reflecting significant ageing of the equipment and a clear lack of maintenance (Figure 4(a)). The distribution transformer is installed in an unsuitable environment, with no protection against dust and humidity and without proper maintenance, which increases the risk of overheating and thermal failure (Figure 4(b)). Structural mechanical components show visible breaks and damage, compromising the mechanical integrity of the connections (Figure 4(c)). The presence of degraded insulation, disorganised cabling and non-standard connections is evidence of uncontrolled interventions, repeated overloads and a lack of preventive maintenance (Figure 4(d)). Severely charred connections, combined with signs of localised overheating, indicate prolonged electrical arcing and poor contacts (Figure 4(e)). Finally, heavily corroded outdoor cabinets and partially stripped conductors indicate prolonged exposure to the elements and advanced ageing of outdoor equipment (Figure 4(f)).

Taken together, these findings highlight an infrastructure that is particularly vulnerable to breakdowns, electric arcs and frequent power outages, while revealing non-compliance with current international standards. This situation significantly compromises the reliability of the distribution network and the safety of users and operating personnel.

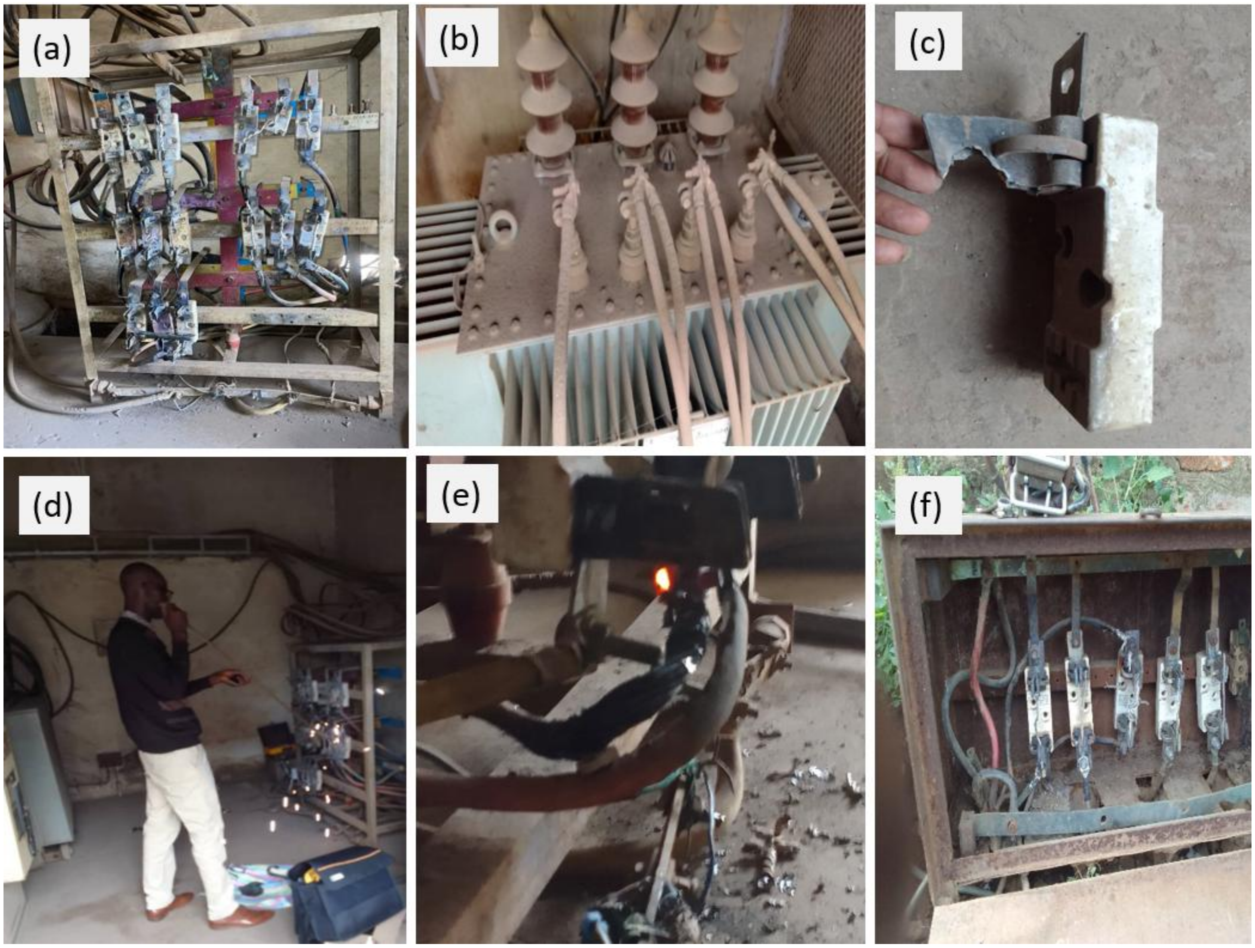

Figure 4. Observations on the quality of SNEL electrical infrastructure in the Kamalondo city of Lubumbashi.

3.4. Summary of disruptions observed in the SNEL/Lubumbashi distribution network

The results presented in Figure 5 highlight significant deterioration in the quality of the electrical waveform in the low-voltage distribution network in Lubumbashi. The box plots in Figure 5(a) reveal significant spatial and temporal variability in phase-neutral effective voltages across all feeders. The nominal value of 230 V is rarely maintained over the measurement period; voltage levels below 207 V (i.e. < 90% of the nominal value) are frequently observed, particularly on the most heavily loaded feeders and during evening peak periods. These recurring voltage dips exceed both the duration and frequency tolerances defined by the EN 50160 standard, which only allows occasional deviations limited to ± 10% of the nominal voltage (Samuel et al., 2025a).

Furthermore, no overvoltage exceeding the regulatory range of ± 10% was recorded on the various feeders, indicating an absence of constraints related to voltage excesses. However, the current distributions shown in Figure 5(b) reveal high and highly dispersed levels on certain phases, reflecting significant loads and marked phase imbalance, which directly contributed to the observed voltage drops. Taken together, these results indicate that the SNEL distribution network in Kamalondo is mainly affected by chronic voltage deficiency linked to overloads and imbalance.

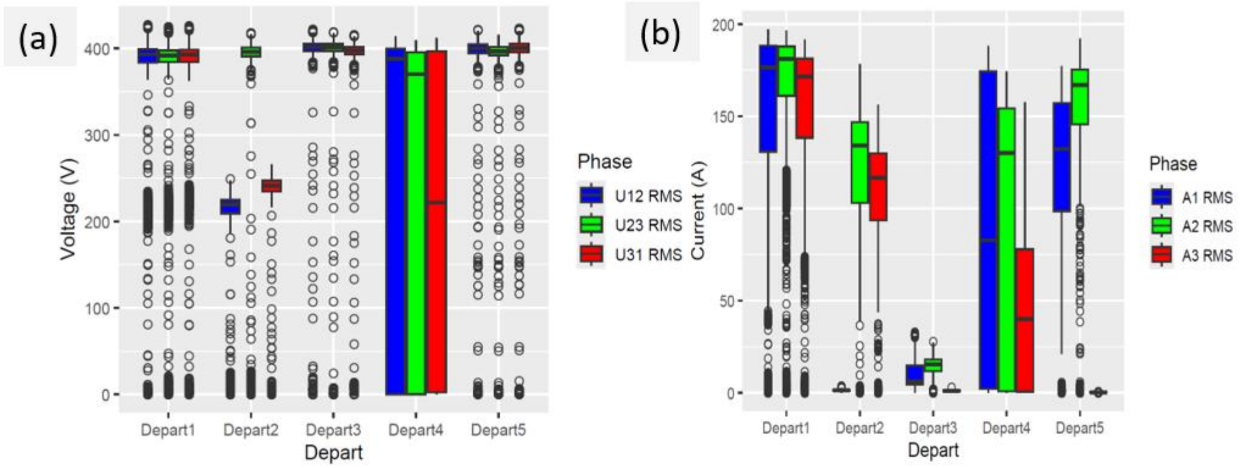

Figure 5. Characterization of voltage and current imbalances per phase in the feeders3.5 Power quality indicators by departure

The comparative analysis of the main electrical energy quality indicators by feeder in Figure 6(a) shows an overall stable frequency close to the nominal value of 50 Hz across all feeders, indicating good regulation of the upstream system. However, the power factor distributions shown in Figure 6(b) reveal values frequently below 0.9 on certain feeders, reflecting significant reactive power consumption and operation that does not comply with standard distribution network recommendations (Hannagan et al., 2023a). The box plots in Figure 6(c) show a high degree of heterogeneity in active power, reflecting contrasting load profiles between feeders. This variability is also found in apparent power (Figure 6(d)) and reactive power (Figure 6(e)), highlighting load imbalances and increased demand on certain feeders. Overall, these results highlight the coexistence of controlled frequency with degraded performance in terms of power factor and load distribution, which may impact the efficiency and reliability of the distribution network.

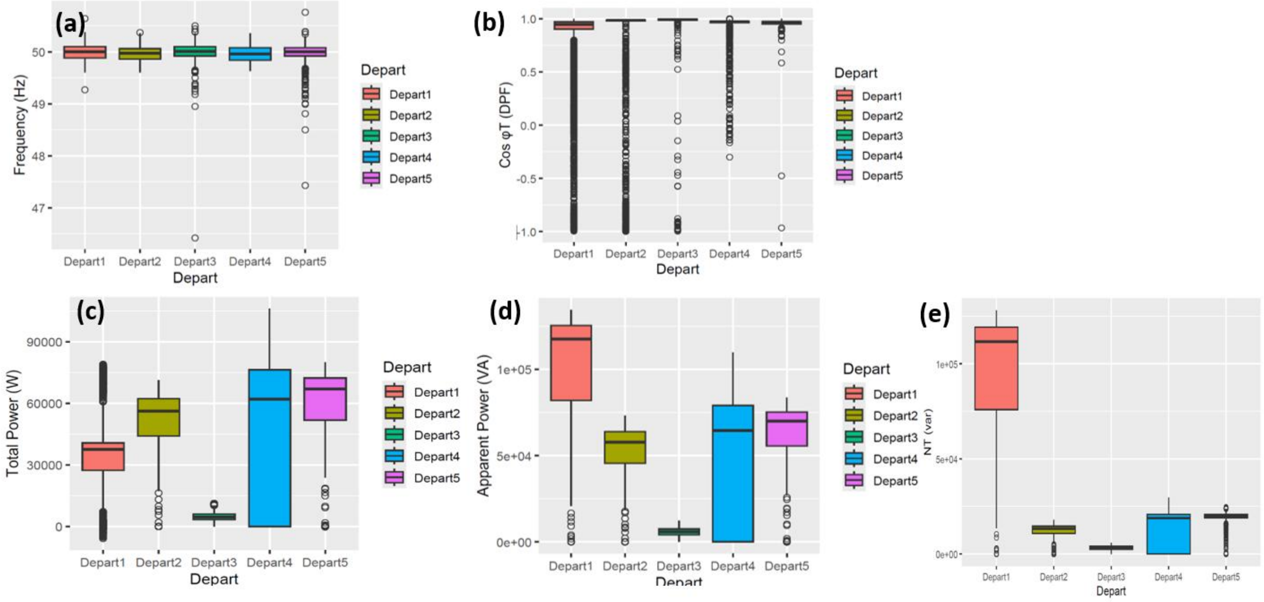

Figure 6. Analysis of electrical energy quality indicators per circuit. (Frequency, power factor, active, apparent and reactive power) per low-voltage network circuit.

The main disruptions to continuity and voltage quality by departure are summarised in Figure 7. Short outages, comparable to voltage dips, are shown in Figure 7(a), while their weekly evolution is illustrated in Figure 7(b), highlighting contrasting daily profiles. The longer outages observed in Figure 7(c) confirm a significant deterioration in service continuity on certain feeders. The voltage dips shown in Figure 7(d) reflect severe constraints on the low-voltage network. The comparative analysis indicates that feeder 2 is the most critical, with significantly higher occurrences of voltage dips and sags, mainly due to a high density of unregulated connections and the proximity of households, which accentuate local overloads and network imbalances.

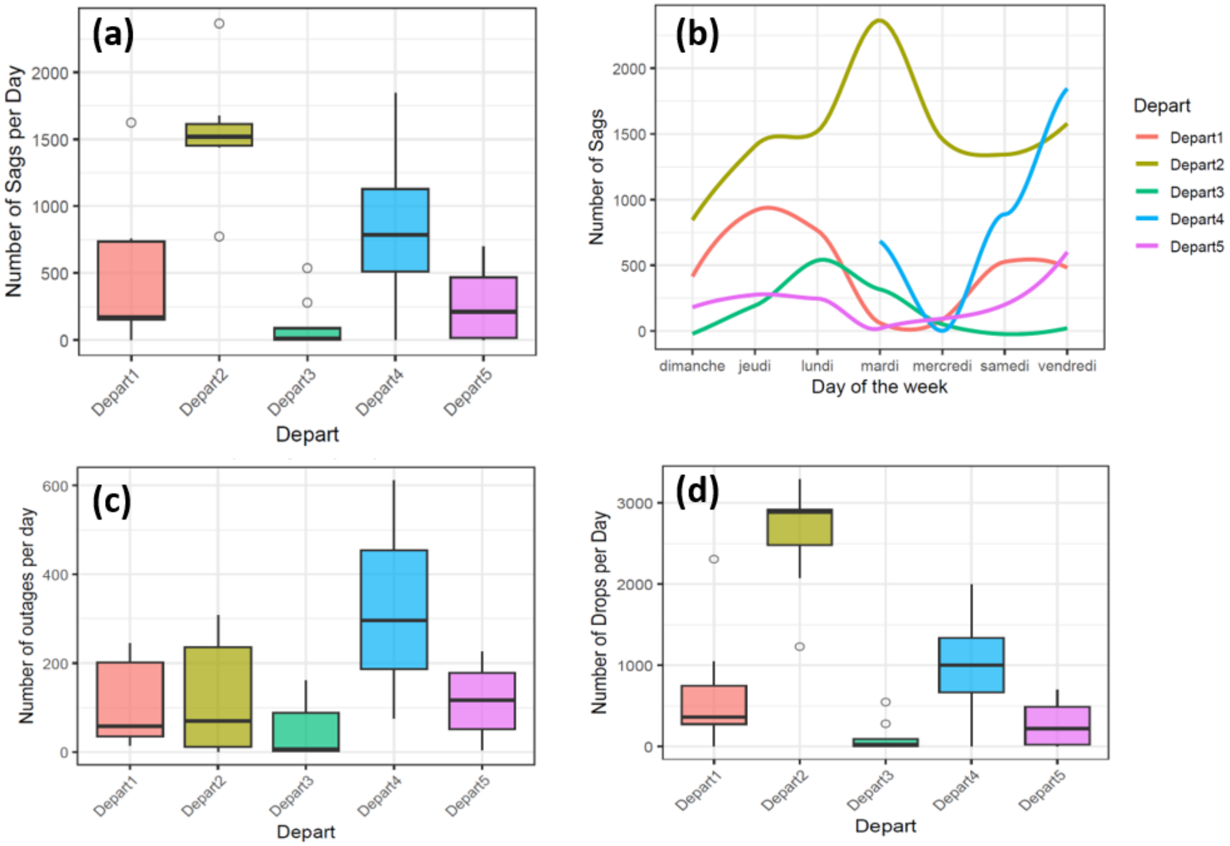

Figure 7. Spatial and temporal distribution of voltage dips, interruptions and voltage drops by departure

Figure 8 shows the distribution of harmonic distortion and voltage fluctuation indicators by branch. The results in Figure 8(a) show the levels of total harmonic distortion measured in current, single voltage and composite voltage. It shows that harmonic distortion in current is dominant across all circuits, with values frequently higher than those observed in voltage, indicating the presence of highly disruptive non-linear loads. Furthermore, Figure 8(b) highlights a significant occurrence of flickers (Pst), with levels varying between circuits, reflecting rapid load fluctuations and repeated voltage variations.

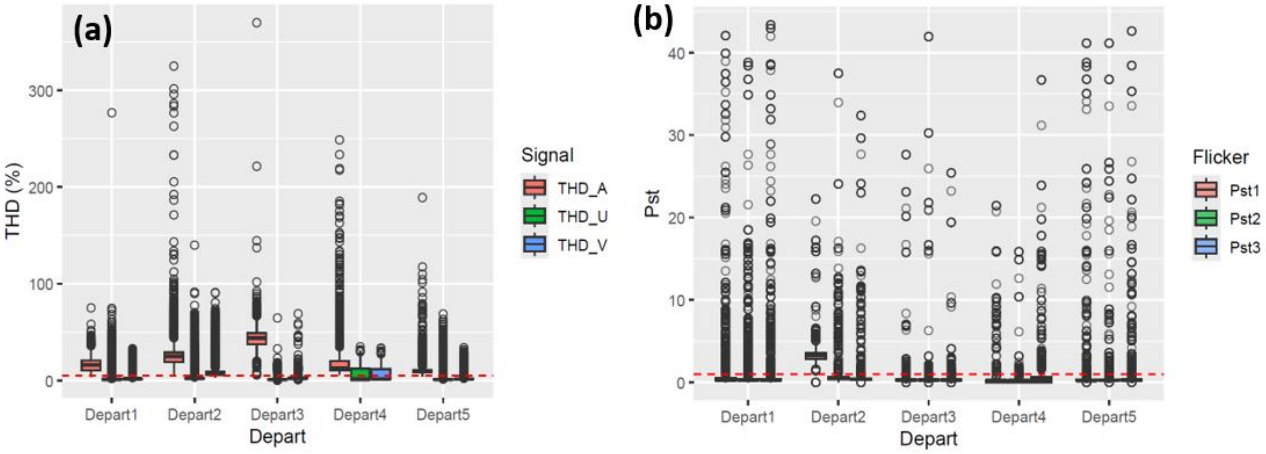

Figure 8. Distribution of THD and flicker levels per feeder in relation to standard power quality thresholds

3.5. Technical causes of excessive current in the neutral conductor

The current in the neutral conductor, shown in red in the figure 9, illustrates the abnormally high neutral current reaching up to 327 A at output 1 (Figure 9(a)), systematically exceeding the reference threshold of 160 A, indicating a more severe phase imbalance. This neutral overload, which is particularly pronounced in feeders 1 (Figure A), feeder 2 (Figure B) and feeder 5 (Figure E), reflects an asymmetrical distribution of dominant single-phase loads (Al-Jaafreh & Mokryani, 2019; Al Dahmi & Al Ahmad, 2008). In cases where the neutral remains low at feeder 3 (Figure C), the phases are better balanced. Combined with the imbalance rate reaching 18% on some feeders (Figure F),

The excessive rise in current in the neutral conductor can be explained by a combination of major technical failures, including: advanced degradation of the conductors, which affects current distribution, and the strong predominance of single-phase connections, which accentuate load asymmetries. Repeated fuse blowouts leading to single- or two-phase power supplies, these imbalances are exacerbated by abnormal connections between phases and neutrals from different substations, irregular load redistribution during load shedding, and long lines with heterogeneous sections responsible for voltage drops. Together, these factors contribute to neutral conductor overload and deterioration in the quality of the distributed energy.

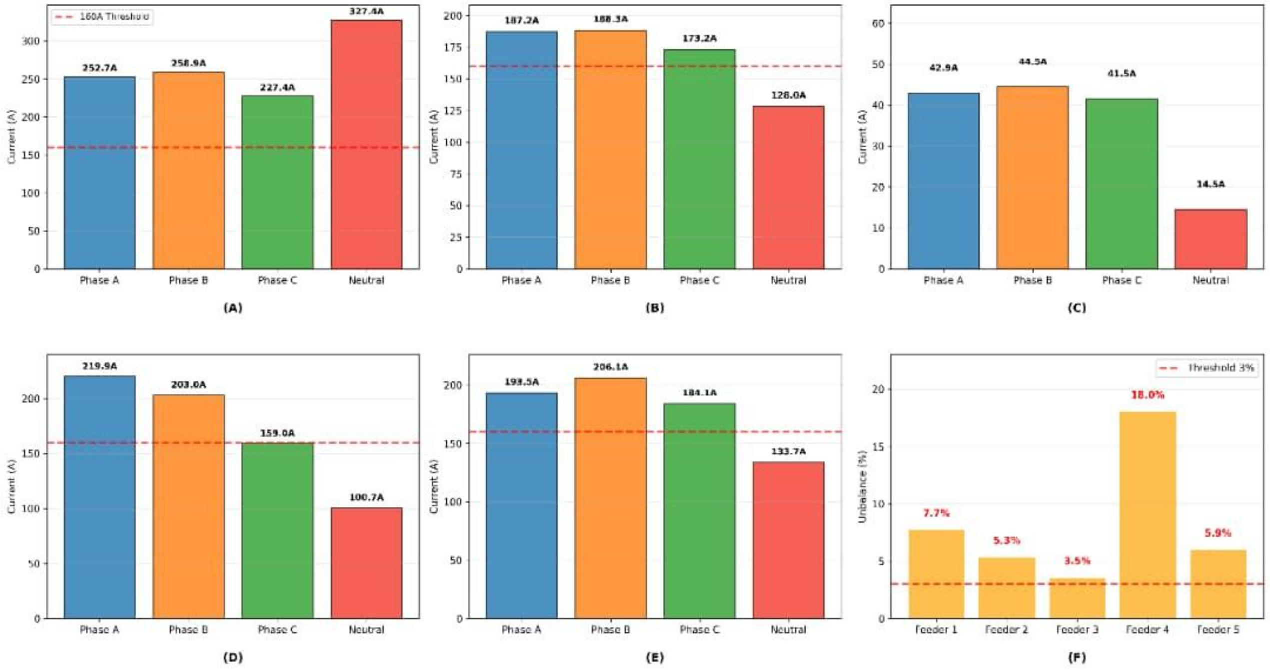

Figure 9. Distribution of phase currents and neutral current by branch circuit, Feeder current 1 (A), Feeder current 2 (B), Feeder current 3 (C), Feeder current 4 (D), Feeder current 5 (E), Neutral current (F)

Surveys conducted among customers of the LV network in the municipality of Kamalondo in Lubumbashi reveal that power cuts (outages), voltage dips and voltage sags are the main power quality disturbances that cause significant inconvenience and have considerable financial repercussions on various household appliances (Bhattacharyya & Cobbe, 2011; Hannagan et al., 2023b; Blazek et al., 2020). The figure 10 shows the percentage distribution of electrical power quality problems. It shows that 35.5% of disturbances are caused by outages and interruptions, 30.4% are due to voltage dips, 20.8% are due to voltage sags and interruptions, while 9.9% are attributable to flicker. The remaining 3.4% are related to harmonics.

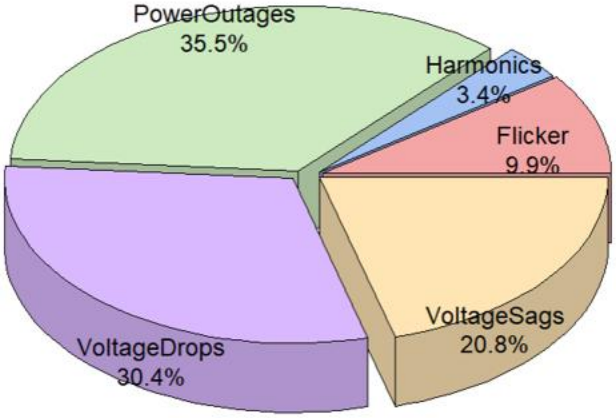

Figure 10. The main disruptions to power quality in the SNEL/Kamalondo low-voltage network

3.6. Assessment of Power Quality and Service Continuity Compliance

Table 2 presents a summary comparison between the power quality indicators measured on the distribution network studied in Lubumbashi and the reference values from international standards (EN 50160, IEEE 1366, IEC 61000-4-15). The results highlight a severe deterioration in service continuity. The SAIFI reached 7.85 interruptions/year, which is approximately 4 to 15 times higher than the generally accepted range (0.5–2 interruptions/year), while the SAIDI stands at 491 minutes/year, exceeding best practice thresholds (100–180 minutes/year) by 2.7 to 4.9 times.

In terms of voltage quality, measurements reveal recurring dips reaching 70–80% of the nominal voltage during peak loads, as well as chronic undervoltage characterised by frequent variations of −20 to −30%. The phase-to-neutral effective voltage thus remains consistently below 207 V (lower limit of ±10% around 230 V) for long periods each day. In addition, flicker exceeds standard criteria, with a maximum P_{st} close to 1.5, mainly observed in the evening, indicating a high probability of noticeable discomfort for users.

Overall, this comparative analysis highlights simultaneous non-compliance in key areas of power quality, continuity, voltage level and flicker, confirming the structural nature of the disturbances affecting the study area.

The total number of power interruptions recorded during the measurement period is also a cause for concern. The campaign highlighted both repeated brief outages and long-term interruptions. In particular, a major failure on the medium-voltage network, which occurred from Saturday 28 to

Monday 30 December 2024, deprived the study area of electricity for approximately 48 hours, as documented by SNEL. Cumulatively, the inclusion of this outage leads to a loss of power for more than 15% of the weekly time for the households studied, a level that is largely incompatible with the requirements of modern urban networks. Even excluding this extreme event, the daily frequency of outages and brief interruptions remains well above internationally acceptable thresholds.

Table 2 - *Comparison of energy quality indicators measured in Lubumbashi with standards and best practices*

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 minutes per year (IEEE 1366)	491 minutes/year. 2.7 to 4.9 times > thresholds
Voltage dip	> 90% of (One) during 95% of the time (EN 50160)	70 to 80% dip during peak loads over several days
Tension (RMS)	±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 P_{st} of 1.5 observed in the evening (visual flickering)

4. Discussion

Observations made on various electrical power quality events highlight/show a picture of a residential distribution network experiencing significant difficulties in terms of power supply quality. The underlying causes of these malfunctions must be analysed and their potential consequences assessed in order to compare them with other contexts and identify general trends.

4.1. Causes and contributing factors to electrical power quality disturbances

Several factors explain the poor quality of electricity in the SNEL Lubumbashi distribution network (David & Bonaventure, 2019b). On the one hand, overloads and increased current in the neutral conductor, and on the other hand, the rapidly growing demand for electricity from households, both in terms of consumption and power demand per household, which has reached or exceeded the capacity of the existing infrastructure (Banza et al., 2022). The predominance of single-phase power supplies, often unbalanced between the three available phases (Popa, 2022). This configuration is a major cause of increased neutral current, deterioration of the power factor and additional energy losses (Kumar Panda et al., 2021).

The low power factor, often below 0.9 in the evening according to our measurements, further exacerbates this situation by increasing the current flowing for a given active power, which causes increased voltage drops on the lines due to series impedance. This overload is exacerbated by illegal connections (Kasumba et al., 2025a). Studies have shown that around one fifth of users in Lubumbashi are connected informally (Mbungu et al., 2023b). This creates a financial shortfall for SNEL, but also inevitably introduces uncontrolled tapping points, often at the end of the lines, leading to significant localised voltage drops. This phenomenon of energy theft is known to deteriorate service quality wherever it is widespread (David & Bonaventure, 2019c; Kasumba et al., 2025). A direct correlation has been noted between the rate of fraud and the extent of voltage fluctuations observed in the peri-urban neighbourhoods of Lagos, Nigeria (Osunmuyiwa et al., 2025). This assertion is well documented in the work of (Kasumba et al., 2025a), explaining the double burden of energy theft and ageing electrical infrastructure, which exacerbate disruptions to the quality of electrical energy in Lubumbashi is therefore likely that local constraints, in particular the dilapidated state of equipment, the loss of infrastructure performance, electricity theft and overloads, are the main causes of disruptions to the quality of electricity within the SNEL distribution network in Lubumbashi.

4.2. Consequences for usage and the network

The impacts of poor electricity quality on the SNEL Lubumbashi distribution network are manifold and are shared between suppliers and consumers connected to the network (Chen et al., 2024; Alawasa & Al-Badi, 2024; Samuel et al., 2025b).

On the electricity supplier side (SNEL), poor quality results in technical losses, increased costs, reduced distribution efficiency, and more customer complaints (Bhattacharyya & Cobbe, 2011; Yu et al., 2024). Some customers are switching to alternative solutions such as PV and generators. The dilapidated state of the network's equipment is also a major risk. During our investigations, we observed advanced obsolescence of the electrical infrastructure, severe material degradation and obvious non-compliance with international distribution standards, which explains the recurring problems with the quality of electrical energy in the study area. In short, a vicious circle can develop where poor quality fuels the operational inefficiency of the grid, which reduces the lifespan of the transformer and can cause premature failures and disrupt the behaviour of circuit breakers and fuses, which in turn can misdetect certain overcurrents and overloads (Ulinuha & Sari, 2021; Seddik et al., 2024; Costa et al., 2025; Roldán-Porta et al., 2014; Gebreslassie et al., 2024). The supplier is responsible for the quality of the 'product' supplied and the quality of the associated 'service' (Popa, 2022b). They must guarantee defined technical parameters, such as the symmetry of three-phase systems, voltage and frequency. They must also monitor the level of magnetic pollution and ensure continuity of supply, which refers to short or long interruptions and the security of supply, the condition of equipment; in short, they must maintain a clean network.

On the low-voltage consumer side, there is a negative impact on the performance and lifespan of household appliances (Zuch, 2025; Gnaciński et al., 2024; Gnacinski et al., 2024). Appliances such as refrigerators and freezers overheat when voltages fall to between 20 and 30% of the nominal value. Sudden fluctuations, such as voltage dips followed by a return to normal, place much greater stress on appliances such as televisions, computers and radios, which are often sensitive to voltage variations (Zhang et al., 2024). Thus, the work of (Samuel et al., 2025a) reported that when the quality of the power supply deviates from the nominal voltage, sensitive equipment suffers malfunctions and damage. We can also expect dissatisfaction among users in the city of Lubumbashi, who are faced not only with frequent and prolonged power cuts, sometimes requiring the use of generators or emergency UPS systems, but also with an unreliable service that damages their valuable property (Banza et al., n.d.; David & Bonaventure, 2019d; Kasumba et al., 2025a). This has socio-economic consequences such as the cost of backup energy, increased expenditure on appliance repairs, and obstacles to certain local economic activities requiring a stable power supply. Users also have an obligation to ensure that their own equipment does not pollute the system beyond certain limits. This limitation is essential because the rapid increase in non-linear and unbalanced equipment is a major source of disruption (Popa, 2022a; Oubrahim et al., 2023).

Comparing the results of our research with those in the literature, we find that electrical power quality problems are widespread in many developing countries. Their severity in the municipality of Kamalondo in Lubumbashi seems particularly acute. The work carried out by Aldrin Mubiana et al. (2016) in Windhoek (Namibia), a city with a more robust infrastructure, over several years (2007-2014) revealed a total of 2,295 voltage dips and 6,954 voltage surges. Although these figures show a significant amount of disruption, the cumulative duration of interruptions was dominated by outages of around 275 hours, indicating a more reliable network than in Lubumbashi, where we had 48 hours of outages in a single week.

Various initiatives in Ghana, such as the GridWatch project in Accra, have made it possible to measure the quality of service in urban neighbourhoods (Osunmuyiwa et al., 2025). The results of these measurements showed chronic undervoltage in poor peri-urban neighbourhoods, where the average voltage was around 210 to 220 V, as well as periods of undervoltage lasting several hours a day. These values are comparable to those in Lubumbashi and Kamalondo, confirming that undervoltage is a widespread regional problem. On the other hand, in some modern networks, flicker management seems to be better controlled. Local companies in South Africa have adopted codes of good practice to maintain flicker (pst< 0.8) at all times through stricter control of large fluctuating loads such as mining pumps, arc furnaces, etc. (Samuel et al., 2025). The Lubumbashi distribution network, operated by SNEL, does not have such control measures in place and is more severely affected by flicker when several low-voltage loads vary simultaneously.

It would also be instructive to look at international standards and see how far the SNEL Kamalondo distribution network deviates from them. For low voltage, standard EN50160 stipulates that 95% of the effective voltage values (RMS) measured over a week must remain within ± 10% of the nominal voltage (Samuel et al., 2025), and that all instantaneous values must also remain within approximately ± 15%. However, the SNEL Lubumbashi distribution network has at least one phase permanently below – 10%, and even – 20%, 100% of the time. Similarly, 61000-4-15 and the IEC 61000-3-3 standard, which sets flicker emission limits for equipment, aim for $P_{st} < 1$, and even $P_{st} < 0.8$ on average per week (Oubrahim et al., 2023). The SNEL Kamalondo distribution network occasionally exceeds the flicker limit ($P_{st}=1$), which, while not catastrophic, indicates a level of user comfort that falls below modern standards.

it is important to note that the measurement campaign only covered a period of a few months and a limited area, corresponding to a single municipality out of the seven that make up the city of Lubumbashi. The analyses carried out should therefore be generalised with caution. Disruption levels may differ in other neighbourhoods, particularly those with lower access rates, where reduced loads may limit voltage drops, or, conversely, where a less dilapidated network may result in fewer outages. Despite these limitations, the trends observed remain consistent with user testimonials and the orders of magnitude reported in similar contexts, thus reinforcing the robustness and credibility of the conclusions drawn.

5. Conclusion

This study highlights a significant deterioration in the quality of electrical energy in the neighbourhoods of Lubumbashi, illustrating similar challenges faced by many distribution networks in sub-Saharan Africa. Measurements reveal prolonged and frequent outages, voltage dips and sags, flicker and harmonic distortions, reflecting a marked non-compliance with international standards (IEEE, IEC, CENELEC). These results highlight the urgent need to integrate power quality into network expansion and rehabilitation strategies, beyond the sole objective of access to electricity. Future investigations could examine the contribution of domestic PV microgrids and the economic impacts associated with technical losses and material damage, as well as assessing the influence of the deterioration in electrical power quality on performance losses, ageing and the reliability of low-voltage distribution network conductors. Nevertheless, the results provided constitute a robust scientific basis for recommending priority actions to improve the Lubumbashi network and encourage the implementation of systematic power quality monitoring program in urban networks in developing countries. This level of investment is necessary to ensure a power supply that is not only universal, but also reliable, safe, and compliant with modern electrical engineering standards

Abbreviations

The following abbreviations are used in this manuscript:

Symbol	Description
DRC	Democratic Republic of Congo
LV	Low Voltage
MV	Medium Voltage
V	Voltage
SAFI	System Average Interruption Frequency Index
SADI	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	Kilometre
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
CA	Alternating current
$\boldsymbol{mm^2}$	Square Millimetre
m	Metre
am	Ante meridiem
pm	Post meridiem
kW	Kilowatt
PV	Photovoltaic

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