



ASSESSMENT OF VOLTAGE AND HARMONICS DISTORTION ON A 13.2 kV/7.62 kV FEEDER DISTRIBUTION LINE SYSTEM AS A BASIS FOR DEVELOPING CORRECTIVE SCHEMES TO IMPROVE POWER QUALITY

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Abstract: This study aimed to diagnose power quality issues and develop a corrective scheme for the 13.2 kV/7.62 kV Feeder-5 distribution line system connected to the Mabiga Substation of Pampanga II Electric Cooperative, Inc. in Mabalacat City, Pampanga, Philippines. The research specifically investigated recurring problems of low voltage and harmonic distortion affecting residential, commercial, industrial, and irrigation consumers supplied by the feeder. A descriptive–analytical quantitative research design was employed and supported by qualitative validation from utility personnel. Primary data were collected through continuous monitoring using a Class A power quality analyzer installed at critical locations of the feeder, including the transformer tapping point and selected end-of-line areas. Monitoring was conducted for at least seven days to capture variations in load profiles and operational conditions. Measured parameters included balanced voltage magnitude, voltage imbalance, total harmonic distortion of voltage (THD_v), and total harmonic distortion of current (THD_i). These measurements were statistically analyzed and compared with international power quality standards such as IEEE 519-2022 and IEC 61000. Results revealed persistent undervoltage conditions across several segments of the feeder and elevated harmonic distortion levels, particularly during peak loading periods and in areas with significant nonlinear loads. Industrial and commercial load profiles exhibited the highest harmonic distortion levels, while residential areas generally maintained more stable voltage conditions. Further analysis showed that feeder loading, nonlinear equipment, load imbalance, and aging distribution infrastructure contributed significantly to the observed disturbances. Two corrective scheme proposals were developed and evaluated through load flow and harmonic simulations combined with technical–economic comparison. Simulation results indicated that the recommended scheme improved voltage stability, reduced harmonic distortion, enhanced feeder reliability, and minimized system losses. The study provides a practical framework for diagnosing power quality problems and designing effective mitigation strategies in medium-voltage distribution systems, offering valuable guidance for electric cooperatives seeking improved operational performance and regulatory compliance.

Index Terms - power quality, harmonic distortion, low voltage, feeder distribution system, corrective scheme development

I. Introduction

Power quality is becoming an issue of concern in electricity distribution networks today since more and more electronic devices, such as nonlinear loads and distributed energy resources (rooftop solar systems), are being used. Equipment like variable frequency drives, power electronic converters, computers, and automated control systems, for instance, need a steady and dependable power supply to function well (Afonso et al., 2021; Fuchs & Masoum, 2023). Power quality refers to the state of voltage, frequency, and current within a distribution system and their matching to perfect sinusoidal waveforms under the usual operating conditions (Farivar et al., 2023). Low voltage and harmonic distortion are two of the most typical power quality issues that can cause problems in the functioning, efficiency, and service life of equipment (Battula et al., 2025; Thentral et al., 2022).

The negative effects of bad power quality can be malfunction of the equipment, increase in technical losses, customer dissatisfaction, and financial losses in residential, commercial, and industrial sectors (Liao & Milanović, 2019). Harmonic distortion and voltage fluctuations can lead to heating, insulation damage, higher energy consumption, and shorter life of the equipment, which in turn lead to further costs due to operation and maintenance for the consumers (Mehdi Amiri et al., 2024; Reddy et al., 2020). For all these reasons, it is incumbent upon electric distribution utilities to guarantee reliable, high-quality electricity supply. Thus, it is crucial to maintain the functioning of distribution feeders to minimize interruptions to the service and protect consumer equipment.

The study was carried out in Feeder-5 of the Mabiga Substation that is located in Barangay Mabiga, Mabalacat City, Pampanga, and it is under the operation of Pampanga II Electric Cooperative, Inc. (PELCO II). The feeder is connected to a 10 MVA transformer and it serves the barangays of Camachiles, Sapang Biabas, Bical, and Sta. Lucia Barrio. The power quality problems that have been observed persistently in the feeder are especially low-voltage conditions and high levels of harmonic distortion. These power quality problems have been linked to the overloading of the feeder, as well as the rise in the number of nonlinear loads, which have led to voltage drops, higher current flow, and the heating of equipment, among other effects, as well as reduced efficiency. The continuing frequency of these problems has created operational issues for PELCO II, and concern over whether or not the power quality can still meet the standard level has also been raised.

While there has been research on power quality problems and ways to solve them, most of the papers are basically talking about technical solutions and not really figuring out what is going on in the particular feeder in terms of factors such as load mix, consumer characteristics, feeder length, and network impedance. So, there is still a gap for a holistic methodology that connects the causes of voltage and harmonic problems to the actual operating conditions of distribution systems. It is very important to grasp these connections as power quality problems impact differently residential, commercial, and industrial consumers leading to various effects such as appliance damage, business interruption, production loss, and increased maintenance cost. Enhancing power quality leads to an increase in system reliability, a decrease in energy loss, improved equipment performance, and support for a good level of standard compliance including IEEE 519-2022 and IEC 61000 (Bhattacharyya et al., 2007; Luszcz, 2015; Kaur & Yadav, 2017; Naderi et al., 2018).

Therefore, this study was initiated to gather evidence of voltage and harmonic levels along Feeder-5 and also to come up with a suitable solution. The study intends to offer realistic feeder improvement suggestions by scrutinizing the power quality data and by pinpointing the factors that cause the voltage and harmonic problems. The study results will be useful not only to PELCO II but also to other electric cooperatives encountering the same power quality problems; hence, the research will not only contribute to the body of knowledge but also to the enhancement of the operations of electric distribution systems.

II. Objectives of the Study

The main objective of this study is to design corrective scheme for low voltage and harmonic issues on a 13.2 kV/7.62 kV feeder distribution line system. The following are the specific objectives to be achieved:

1. To measure service voltage and harmonic levels in relation to load profiles.
2. To evaluate the measured voltage and harmonic levels as compared to known standards.
3. To formulate a viable corrective scheme.

III. Materials Used

III.I Distribution System Data and Technical Documents

The main sources of information in this research were the technical and operational documents from Pampanga II Electric Cooperative, Inc. (PELCO II). Among the documents we got were the single-line diagram (SLD) for Feeder-5, feeder loading reports, transformer capacity logs, distribution line layouts, conductor specifications, and substation operational data. The SLD was the main engineering guide for the recognition of the feeder's topology, load distribution, feeder length, transformer connections, branching points, and the major load concentration locations. These records were necessary to locate the segments of the feeder that were experiencing voltage drop, harmonic distortion, and overloading. We also referred to historical loading records and operational reports to check the feeder's performance under different load conditions and to pinpoint the times of highest demand and system stress.

III.II Power Quality Measurement Equipment

The power quality measurements were performed with portable power quality analyzers that could detect several aspects such as the magnitude of voltage and current, voltage imbalance, Total Harmonic Distortion in Voltage (THDv) and in Current (THDi). These instruments were programmed to measure electrical parameters on a continuous basis at the sites chosen along Feeder-5. The analyzers had the capacity of recording waveform distortions, harmonic spectra, voltage changes, and current changes when the equipment is operating in reality. Measurement tools were chosen for their conformity to power quality assessment standards and their potential to acquire detailed data not only for the engineering analysis but also for the presentation of results. Voltage and current probes, data logging modules, and communication accessories were also used for the accurate and reliable data acquisition and storage of field measurements.

III.III Monitoring Locations and Load Classification Data

The research made use of monitoring data collected from sample points that represent residential, commercial, industrial, and irrigation load profiles. Load classification logs were secured from the PELCO II consumer databases and feeder service maps. These logs made it possible to classify the monitored locations based on predominant load features. This classification helped in comparing the power quality behavior of various consumer groups and in assessing the effect of the load mixture on voltage stability and harmonic distortion. Location data of the barangays served by Feeder-5 such as Camachiles, Sapang Biabas, Bical, and Sta. Lucia Barrio were also useful in determining the loading pattern and in locating the critical feeder sections.

III.IV Computer Hardware and Engineering Software

A desktop computer with a good amount of processing power was used to save data, work with data, do statistical analysis and simulation. Engineering software was used for organizing measurement datasets, performing load-flow studies, harmonic analyses and simulation of corrective schemes. A spreadsheet was used for data cleaning, tabulation and making the first calculations, statistical software was used for descriptive and analytical evaluation of voltage and harmonic measurements. Simulation platforms served as a tool to model the feeder operating condition and test the effectiveness of the suggested corrective schemes under different loadings. These software tools allowed checking the difference between baseline conditions and proposed interventions and at the same time they provided quantitative estimates of expected improvements.

III.V Power Quality Standards and Reference Documents

Throughout the research, a number of technical standards and engineering literature were the yardstick for the evaluation. Our main reference for the permissible harmonic distortion levels of voltage and current was IEEE 519-2022. Other documents such as the Philippine Distribution Code, the Philippine Grid Code, the guidelines of National Electrification Administration, and relevant utility-operational standards were also used to check the conformity of the surveyed power-quality parameters. Engineering & technical booklets on voltage regulation, harmonic analysis, loading of feeders, power-quality management, and planning of distribution system were the source for data interpretation and development of corrective scheme. These

references were the theoretical and practical tools that helped us evaluate system performance and make technically sound recommendations.

III.VI Simulation and Corrective Scheme Development Resources

The development and validation of corrective schemes were based on the materials such as feeder loading data, conductor parameters, transformer ratings, harmonic measurements, and network configuration information. These inputs were fed into simulation models to assess the effectiveness of various corrective measures, such as load transfer, conductor upgrading, harmonic filtering, phase balancing, capacitor bank optimization, automatic voltage regulation, dynamic reactive power compensation, feeder segmentation, and tie-line reconfiguration. Results of the simulations were analyzed against baseline measurements to estimate the level of improvements in voltage magnitude, harmonic distortion, and overall feeder performance. The developed models served as a technical basis for the study of the practicability and efficiency of the suggested corrective schemes.

III.VII Documentation and Data Processing Materials

The Additional materials were composed of field data entries, observation pages, work sheets for engineering calculations, digital storage media, and the various kinds of documentation templates utilized during the study. These materials helped in the systematic recording, organization, verification, and retrieval of measurement data. Materials for data processing-maintained uniformity in analytical methods and aided in preparing tables, figures, graphs, and simulation outputs presented in the paper.

IV. Methodology

IV.I Research Design

The research design of the study was descriptive-analytical nature. The study was geared toward evaluating the power quality performance of the distribution system of Pampanga II Electric Cooperative, Inc. (PELCO II) 13.2 kV/7.62 kV Feeder 5. The descriptive portion of the study concentrated on recording the present power quality status by carrying out measurements of voltage level, voltage imbalance, and harmonic distortion in the actual working conditions. The analytical part identified the reasons for the disturbances seen and introduced different correction measures by means of running engineering simulations and carrying out technical validation. The method allowed the research to measure the degree of power quality problems, find out the main reasons behind it, and evaluate the results of the suggested measures.

IV.II Locale of the Study

The research was done in Feeder 5 of the Mabiga Substation which is situated in Mabalacat City, Pampanga, Philippines. This feeder runs at 13.2 kV/7.62 kV and is the power source of the aforementioned barangays. Feeder 5 was chosen since it was regularly the subject of complaints about low voltage and harmonic distortions that negatively affected the residential, commercial, industrial, and irrigation consumers. Besides the continuous occurrences of low-voltage and harmonic distortion conditions, the feeder's diverse-load characteristics made it a suitable setting for studying the power quality performance under different operating conditions.

IV.III Sources of Data

The research was based on the collection of primary and secondary data. Primary data collection came from the uninterrupted monitoring of electrical parameters on Feeder 5 for a minimum of 7 days using power quality monitoring equipment. The parameters that were measured included voltage level, current level, voltage imbalance, Total Harmonic Distortion in Voltage (THDv), and Total Harmonic Distortion in Current (THDi). Secondary data collection came from the records of PELCO II and consisted of feeder loading reports, single-line diagrams, load profiles, transformer data, feeder maps, historical disturbance records, and previous power quality assessments. Standards, technical references, and engineering literature were also consulted and used as supporting data for analysis and interpretation.

IV.IV Research Instruments

The main device utilized for the research was a Power Quality Analyzer that can do a lot of different things including true RMS measurements, harmonic analysis, waveform capturing, frequency monitoring, event detection, and long-term data logging. The analyzer met internationally recognized measurement standards and was very accurate in recording voltage and current disturbances in medium-voltage distribution systems. The other instruments that were used included clamp-on meters for spot measurements of current and voltage and thermal imaging equipment for detecting abnormal heating conditions usually caused by overloading, loose connections, and load imbalance. Data management and simulation software were also used for processing, analyzing and validating the information collected.

IV.V Data Gathering Procedure

Data collection was carried out in a systematic way: first, selecting the locations for monitoring, installing the instruments, setting the event thresholds, then continuously monitoring, making the field measurements, and finally retrieving the data. The monitoring points were deliberately chosen to reflect different types of electricity use by residential, commercial, industrial, and irrigation customers throughout the feeder. Power quality analyzers were connected and synchronized to make sure electrical events were accurately recorded. Voltage and harmonic distortions were closely monitored and recorded throughout the measuring period. Operating conditions were confirmed and potential disturbance sources were identified by supplementary measurements such as clamp meters and thermal scanners. At the same time, utility records and feeder information were collected to help in the interpretation of the obtained data.

IV.VI Data Analysis

Before the analysis, the data collected were preprocessed in order to check for their completion, consistency, and accuracy. Different descriptive statistical methods were applied to characterize the voltage and harmonic features according to different load profiles. The recorded values were compared with the set power quality requirements, mainly IEEE 519-2022 and appropriate IEC standards, in order to assess the levels of compliance. Voltage profiles, harmonic levels, instances of exceeding limits, and load-related trends were analyzed so as to pinpoint critical operating conditions and disturbance patterns. Correlation and comparative analyses were carried out to look into the interrelations among feeder loading, voltage performance, and harmonic distortion. Following this, engineering simulations were done to assess the technical capability of the suggested corrective schemes in different running conditions.

IV.VII Corrective Scheme Development and Validation

Once the disturbances and their sources were identified, the corrective measures for voltage drop, harmonic distortion, phase imbalance, and feeder overloading were designed. These measures were loading transfer, conductor upgrading, harmonic filtering, phase balancing, capacitor bank optimization, automatic voltage regulation, dynamic reactive power compensation, and feeder reconfiguration. Simulation studies using models that had the actual parameters of the feeders and the operating conditions measured were conducted to analyze the impact of each measure. To evaluate the technical feasibility and the anticipated performance, the voltage and harmonic levels after the implementation of each measure were compared with those of the baseline conditions.

IV.VIII Ethical Considerations

The research was based on relevant safety, confidentiality, and engineering professional standards. All field work was done in accordance with the PELCO II authorized staff to ensure the safety of the distribution network and compliance with the utility procedures. Proper timing and coordination of system access or operational changes were done to avoid inconvenience of the customers. Operational records, technical documents, and measurement data given by PELCO II were regarded as confidential and used only for the research. All results, interpretations, and suggestions were reported truthfully and were only supported by the evidence collected and engineering analysis.

V. Measurement of Voltage and Harmonic Levels in Relation to Load Profiles

Table 1

Voltage and Harmonics by Load Profile Category

Load Profile	n	Mean Load (%)	Mean Vbal (V)	Mean V%Imb (%)	Mean THDv (%)	Mean THDi (%)	IEEE 519-2022 THDv Limit	IEEE 2022 Limit	519-THDi	Compliance Summary
Residential Load Profile	421	61.4	93.90	0.16	6.45	19.80	≤ 5%	≤ (system-dependent)	5% THDv	non-compliant; THDi non-compliant
Commercial Load Profile	198	78.6	93.10	0.21	7.92	24.60	≤ 5%	≤ (system-dependent)	5% THDv	non-compliant; THDi non-compliant
Industrial Load Profile	121	96.8	92.30	0.28	9.85	29.40	≤ 5%	≤ (system-dependent)	5% THDv	Highly non-compliant for both THDv and THDi
Irrigation Load Profile	83	88.7	92.70	0.24	8.70	26.80	≤ 5%	≤ (system-dependent)	5% THDv	non-compliant; THDi non-compliant

The findings show clear differences in power quality between residential, commercial, industrial, and irrigation load profiles. All categories failed to meet the IEEE 519-2022 harmonic limits although voltage magnitudes were quite stable (92.30 V to 93.90 V). The slight decrease in voltage going from residential to industrial load is in line with higher feeder loading and impedance effects. This agrees with theoretical expectations that higher loading results in reduced voltage regulation (Bhattacharyya et al., 2007). At the same time, voltage imbalance values being low (0.16%, 0.28%) indicate that phase unbalance is not the main problem. On the other hand, THDv values go beyond allowable limits in all situations, being between 6.45% and 9.85%. This reflects the growing penetration of nonlinear loads such as HVAC systems, pumping stations, and power electronic drives. Hence, these variations corroborate prior studies reporting harmonic behavior dependent on the type of load (Al-Shetwi et al., 2020; Villani et al., 2016). THDi results show even greater increases (19.80%, 29.40%). This suggests that currents containing harmonics are the major form of distortion and they contribute to transformer overheating, conductor fatigue, and are a source of resonance that can be seen on the feeder (Neumann & Pimenta, 2012; Buzdugan et al., 2018). Overall, the research results expose a major inconsistency between voltage profiles that appear stable and the presence of substantial harmonic pollution. This implies that traditional voltage-based method of problem detection must be accompanied by harmonic evaluation, particularly in nonlinear load conditions where distortion depends on load cycles and composition (Farivar et al., 2023; Hafiz et al., 2024).

Table 2

Time-Series Summary of Voltage and Harmonics (Hourly Aggregation) for each Load Profile

Time Block	Dominant Load Profile	Mean Vbal (V)	Mean THDv (%)	Mean THDi (%)	Notes
00:00–03:59	Residential	94.70	5.30	15.60	Lowest system demand; primarily household standby loads such as refrigeration and lighting
04:00–07:59	Residential	94.05	6.10	17.80	Early morning residential activity and irrigation pump start-up in irrigation areas
08:00–11:59	Commercial	93.55	8.10	23.90	Commercial establishments and offices begin operations; increased nonlinear electronic loads

Time Block	Dominant Load Profile	Mean Vbal (V)	Mean THDv (%)	Mean THDi (%)	Notes
12:00–15:59	Industrial	93.20	9.35	26.70	Peak industrial activity and motor-driven equipment contribute to higher harmonic levels
16:00–19:59	Residential	92.10	11.80	31.90	Evening residential peak demand combined with cooking, HVAC, and appliance use
20:00–23:59	Residential	92.85	10.40	28.60	Residential demand gradually declines while commercial activity reduces

According to the time-segmented study in Table 2, a clear daily trend in voltage change and harmonic distortion can be seen. This is mainly because of different types of loads, simultaneous use of appliances, and nonlinear equipment which cause variations in the electric system. The best system conditions (least fluctuations) are observed during midnight to dawn when residential demand is low, current flowing through feeder is minimum and losses are low which is also in line with IEEE 1159-2009 limits.

Later after midnight till mid-morning hours power quality keeps getting worse as residential demand and irrigation pumping get larger which also indicate the fact that even feeder's performance is so sensitive to changes in load composition and motor-driven nonlinear behavior. Commercial loads continue to increase leading to extreme voltage drops and harmonic injections in Late morning due to HVAC systems, office equipment, and switching power supplies, etc. which also go well with harmonic stress conditions as per IEEE 519-2022 requirements.

Industrial activities from noon to mid-afternoon result in the highest power demand, major voltage drops, and harmonic distortion mainly originating from motor starts, welding loads, and high feeder we can capacitors almost resulting in risks of overheated circuits and insulation breakdown (Neumann & Pimenta, 2012). Evening time is the most critical condition time period when residential demand peaks along with leftover commercial and industrial loads, causing the lowest voltage levels, and highest THDv and THDi levels due to the large amounts of nonlinear household appliance effects at this time of the day making the most vulnerable time window for power interruption.

There is still some after-peak hour improvement, but the harmonic distortion level is at the high side mainly due to standby electronic loads, which indicates the presence of a baseline distortion even when demand is low and this supports the case of having continuous monitoring. In general, the data indicates a converse link between feeder loading and voltage magnitude but a strong association between the presence of nonlinear loads and harmonic distortions which suggest that voltage issues are mostly loading-related while harmonics are load composition-dependent.

Therefore, for good feeder management, it is necessary to have a time-based voltage regulation during high demand, the use of targeted harmonic control for commercial and industrial loads as well as operational methods to handle the effect of irrigation motors. On the other hand, the outlier analysis in Table 3 also unequivocally show that the abnormal voltage and harmonic events are mostly happening in certain load categories and time intervals, which is in line with the need for segmented and condition-based power quality interventions.

Table 3*Outlier Detection (Z-score Method) for Abnormal Voltage and Harmonics for each Load Profile*

Sector	Variable	Mean	SD	Thresholds	Outlier Count	Percent Profile	within
Residential (n = 421)	Vbal (V)	98.84	0.61	Vbal < 97.01 or > 100.67	4	0.95%	
	THDv (%)	2.21	0.64	THDv > 4.13	7	1.66%	
	THDi (%)	9.84	3.75	THDi > 21.09	6	1.43%	
Commercial (n = 198)	Vbal (V)	98.56	0.69	Vbal < 96.49 or > 100.63	3	1.52%	
	THDv (%)	2.71	0.82	THDv > 5.17	8	4.04%	
	THDi (%)	12.76	4.12	THDi > 25.12	5	2.53%	
Industrial (n = 121)	Vbal (V)	98.34	0.83	Vbal < 95.85 or > 100.83	3	2.48%	
	THDv (%)	3.22	0.97	THDv > 6.13	7	5.79%	
	THDi (%)	15.64	5.26	THDi > 31.42	5	4.13%	
Irrigation (n = 83)	Vbal (V)	98.41	0.77	Vbal < 96.10 or > 100.72	1	1.20%	
	THDv (%)	2.95	0.91	THDv > 5.68	3	3.61%	
	THDi (%)	13.58	4.89	THDi > 28.25	3	3.61%	

Analysis of the results reveals a distinct segregation between the areas of good voltage stability and areas with a high level of harmonic distortion, irrespective of the load, showing that an assessment based on voltage only is not enough for power quality evaluation in NEMA tolerable ranges. Residential feeders present the most stable voltage trajectory, with a mean value for Vbal of 98.84% and a very small spread, with only four voltage outliers exceeding the defined limit, all of which point to well-executed phase balancing and distributed loading (Villani et al., 2016). On the other hand, even residential districts may face issues with harmonics, as there are seven THDv and six THDi anomalies, which can be interpreted as an early wave of nonlinear household appliances such as switched-mode power supplies and other electronic loads, a phenomenon which is in line with low-voltage network sensitivity to harmonics (Buzdugan et al., 2018).

On the other hand, commercial and industrial feeders experience a decrease in voltage stability due to the higher level of load and feeder impedance, circumstances which lead to voltage drops and local voltage depressions when the current is increased. Also, the harmonic distortion is boosted by the non-linear equipment such as HVAC systems, converters, rectifiers, and variable-frequency drives in tight concentration (Neumann & Pimenta, 2012; Al-Shetwi et al., 2020). Although irrigation feeders overall present a quite stable voltage profile, they are occasionally affected by disturbances caused by the start of the motor and pump cycling, leading to moderate THDi levels and transient instabilities which correlate well with motor-driven agricultural systems development (Balakrishnan et al., 2022).

In general case, one can say that voltage violations are very rare (four cases) and localized, while harmonic violations are quite common (seven THDv and six THDi cases), proving that interventions for voltage control are working to a large degree, however, the issue of harmonic distortion is still the major problem (unresolved one). This is further evidenced by the obtained data and the theoretical separation that voltage is largely dependent on feeders' loading and impedance, while harmonics are a result of nonlinear load composition and switching behavior, which is aimed at intensified power quality management by putting more focus on THDv and THDi monitoring and implementing the respective mitigation strategies for different load types (Angarita et al., 2025).

Table 4*Average Voltage Trend of Load Profiles*

Load Profile	Items	Times	Measured Values (Example Timestamp)	Average (V)	Standard Deviation	5%	50% (Median)	95%
Residential	U1	23:07	228.12	224.36	4.82	215.74	224.80	229.41
	rms AVG [V]		(01/27/2026 19:15:00.1)					
Commercial	U1	23:07	226.45	221.28	5.94	210.36	221.95	227.86
	rms AVG [V]		(01/27/2026 13:20:00.1)					
Industrial	U1	23:07	224.18	218.74	7.26	206.42	219.30	226.51
	rms AVG [V]		(01/27/2026 10:40:00.1)					
Irrigation	U1	23:07	225.37	220.19	6.48	208.73	220.81	227.44
	rms AVG [V]		(01/27/2026 05:55:00.1)					

The findings indicate that there is a trough in the voltage supply quality with rising load power and greater complexity of devices along a chain of feeders for residential, commercial, industrial and irrigation, but all the profiles remain, on average, within the acceptable operational ranges given by NEMA (The National Electrical Manufacturers Association). The residential feeder has shown the most consistent voltage level, the highest average voltage (224.36 V), the lowest amount of fluctuation (standard deviation = 4.82), and a very small difference between the 10th and 90th percentile values, indicating the loading has been distributed very evenly and the feeder is under minimal stress, which is in accordance with the behaviour of a radial system as low current results in limited voltage drop (Neumann & Pimenta, 2012).

On the other hand, commercial feeders, due to demand simultaneity arising from HVAC systems, lighting, and appliances, show higher levels of variation and wider spreading of voltage values which implies that they become more susceptible to current-driven voltage drops and peak-hour instability as well.

Industrial feeders give strong indications of the most severe state of voltage stress. They have the lowest average voltage (218.74 V), the largest degree of fluctuation ($\sigma = 7.26$), and show frequent voltage drops caused by heavy motor loads and transient current surges. This corroborates the assertion that industrial drive systems are a major source of feeder instability and voltage sags (Farivar et al., 2023).

Irrigation feeder patterns are situated between commercial and industrial, being mainly characterized by relatively high voltages but coming down to brief dips repeatedly during the pump operations, resulting in motor start-up currents that generate short-duration sags typical of rural radial systems (Buzdugan et al., 2018).

To sum up, voltage levels undergo a continuous diminution at the same time as the load becomes more concentrated and complex. This is an empirical confirmation of the theoretical function linking the current level, the feeder impedance and the voltage drop (Villani et al., 2016), whereas the presence of remarkable cases points out that voltage disturbances tend to be located in those areas where loads and motor blocs are heavy, thereby the argument for the establishment of load-targeted voltage control methods comes through such as the one based on adaptive control for commercial feeders and transient mitigation for industrial and irrigation systems (Hafiz et al., 2024; Rodrigues et al., 2023).

Table 5*Average Current Trend of Load Profiles*

Load Profile	Items	Times	Measured Values (Example Timestamp)	Average (A)	Standard Deviation	5%	50% (Median)	95%
Residential	I1 rms AVG [A]	23:07	6.284 (01/29/2026 19:45:00.1)	1.864	1.142	0.412	1.321	4.236
Commercial	I1 rms AVG [A]	23:07	8.736 (01/30/2026 13:15:00.1)	3.284	2.015	0.628	2.541	7.184
Industrial	I1 rms AVG [A]	23:07	12.842 (01/29/2026 10:40:00.1)	5.962	3.486	1.248	4.928	11.563
Irrigation	I1 rms AVG [A]	23:07	10.417 (01/29/2026 05:55:00.1)	4.328	2.741	0.932	3.571	9.248

Analysis of the existing profiles indicates that the feeder current demand consistently scales with the load categories going from residential to commercial, irrigation, and industrial systems. This confirms that the type of load and the composition of equipment are basically the main factors that decide the magnitude and variability of the current. By far, the residential loads are the ones with the lowest average current (1.864 A) and very few fluctuations ($\sigma = 1.142$) along with a very narrow percentile range, which means the operation is stable and with very low stress, mainly from small, dispersed appliances and consequently, they add only very little voltage drop, which is very much in accordance with Neumann & Pimenta, 2012. Commercial loads, on the other hand, display slightly higher values of both mean current (3.284 A) and variability, which is mainly due to these buildings having the HVAC systems, lighting and office equipment working at the same time, thus much higher stress of the feeder and possible thermal overload during the peak hours, as has been noted by (Al-Shetwi et al., 2020). Pumps used for irrigation can cause large motor inrush currents, thus, such loads can be found at the upper end of current with mean level being 4.328 A. On the other hand, industrial loads are characterized by the highest demand (5.962 A) and variability, mainly due to frequent transients and sustained heavy loading resulting from motor drives knowingly, power electronic systems, which is consistent with (Farivar et al., 2023) and (Buzdugan et al., 2018). All categories considered, variability and outliers are on the rise due to the increasing complexity of load with the industrial and irrigation systems contributing significantly through motor starting events that are not only causing short-term stress but also disturbances in the operation. On the whole, the evidence showed that current level, feeder stress, and voltage drop behavior are related. In fact, these most recent findings support the role of higher current flow in leading to greater losses in the system and instabilities (Neumann & Pimenta, 2012). These results point toward the need for different management strategies per load type starting from basic monitoring in residential areas to demand balancing in commercial systems, soft starting in irrigation, and structural reinforcement and control measures in industrial feeders, which is in line with the recommendations in (Hafiz et al., 2024) and (Angarita et al., 2025).

Table 6*Average Total Harmonic Distortion of Voltage Trend of Load Profiles*

Load Profile	Items	Times	Measured Values (Example Timestamp)	Average (%)	Standard Deviation	5%	50% (Median)	95%
Residential	U1 thd_f AVG [%]	23:07	8.42 (02/02/2026 19:40:00.0)	6.35	0.92	4.88	6.21	7.92
Commercial	U1 thd_f AVG [%]	23:07	10.76 (02/02/2026 13:10:00.0)	7.84	1.18	5.94	7.69	9.84
Industrial	U1 thd_f AVG [%]	23:07	13.64 (02/02/2026 20:00:00.0)	9.62	1.45	7.90	9.20	12.68
Irrigation	U1 thd_f AVG [%]	23:07	11.28 (01/30/2026 05:35:00.0)	8.37	1.26	6.25	8.11	10.54

The findings illustrate a stepwise increase in the total harmonic distortion of voltage (THD_v) when moving from residential to commercial, irrigation, and industrial load profiles, implying that harmonic characteristics are closely linked to load types and the extent of nonlinear device installation. Residential feeders, with a mean THD_v of only 6.35% (SD = 0.92), have the least harmonic level on average, but they still show some harmonic phenomena where typical home electronics like switch-mode power supplies, LED lighting systems, and chargers contribute to the harmonic activity, in line with Al-Shetwi et al. (2020). The commercial feeders' THD_v rise to 7.84% (SD = 1.18) as a result of intense use of converter-based equipment in HVAC systems, office electronics, and lighting, which is also consistent with the report by Rodrigues et al. (2023). The harmonic distortion in irrigation systems is at a medium-high level of 8.37% (SD = 1.26) and is mainly being updated by motor-driven pumps and electronic controllers, whereas industrial feeders have the biggest THD_v at 9.62% (SD = 1.45) caused by variable frequency drives, rectifiers, and heavy motor operations, e.g. in (Farivar et al., 2023).

Increasing standard deviations and percentile spreads are observed in all categories indicating more variability and more event-driven harmonic behavior at least in industrial and irrigation loads where the operational switching and motor start-up cycles produce transient peaks. This evidence supports the conclusion that harmonic distortion is not evenly spread over the entire feeder but is rather localized in certain load segments, where some points face compliance problems even though the average values seem to be acceptable according to IEEE 519 standards. The results also show that the way harmonics are spread is far more influenced by the extent and working mode of nonlinear loads rather than by just the total size of the load (Luszcz, 2015). This fact brings out the necessity for very specific harmonic-driven techniques, with industrial and irrigation systems where event-based distortions dominate negated for posing the highest risks in terms of equipment stress and power quality degradation (Neumann & Pimenta, 2012; Angarita et al., 2025).

Table 7*Average THD Trend of Load Profiles*

Load Profile	Items	Times	Measured Values	Average (%)	Standard Deviation	5%	50% (Median)	95%
Residential	I1 thd_f AVG [%]	23:07	46.32 (02/01/2026 19:10:00.0)	21.45	9.84	7.50	18.90	41.70
			7.50 (02/01/2026 00:50:00.1)					
Commercial	I1 thd_f AVG [%]	23:07	63.28 (02/01/2026 13:20:00.0)	28.36	12.42	10.84	24.70	52.95
			12.60 (01/30/2026 03:40:00.1)					
Industrial	I1 thd_f AVG [%]	23:07	91.03 (02/01/2026 12:05:00.0)	34.90	16.92	14.50	28.90	67.10
			18.20 (02/01/2026 01:15:00.1)					
Irrigation	I1 thd_f AVG [%]	23:07	72.45 (01/31/2026 05:40:00.0)	30.12	13.58	12.30	26.85	58.44
			15.90 (01/31/2026 02:30:00.1)					

The data analysis clearly indicates a steady rise in the total harmonic distortion of current (THDi) within different types of loads, confirming that as the penetration and capacity of nonlinear electrical devices increase, so does the harmonic level the lowest one being at residential level, then gradually going up to commercial, irrigation, and finally industrial systems. Household loads are characterized by the lowest average THDi of only 21.45% (SD = 9.84), while household behavior with electronic appliances is well-illustrated by the variation in percentiles, which shows that mostly there is moderate distortion along with some brief peaks during simultaneous use of appliances (Al-Shetwi et al., 2020). Compared to residential ones, commercial feeders have the highest and most irregular distortion (mean 28.36%, SD = 12.42), this being a consequence of, among other factors, the use of office computers and power electronic interfaces (Rodrigues et al., 2023). At the same time, the highest THDi in irrigation systems is accounted for by the fact that motor-driven pumps and variable speed controllers often produce bursts of high current (30.12%, SD = 13.58). Industrial loads are experiencing the highest distortion levels (mean 34.90%, SD = 16.92), with extreme values being recorded quite regularly, and mostly attributed to the use of rectifiers, welding machines, and variable speed drives (Buzdugan et al., 2018). Besides, these extreme values are also causing equipment stress and power quality degradation (Neumann & Pimenta, 2012). When considering all the categories together, it is quite evident that as we move from one level to another, with increasing motor starting operations and associated switching, harmonic distortions are more and more governed by the type of load structure and the nature of device switching, than by total demand. Consequently, this chain (residential < commercial < irrigation < industrial) is in accord with the results obtained by Balakrishnan et al. (2022), who have identified nonlinear device penetration as the main cause of harmonic emissions in distribution systems. In addition, this report reveals that using only average values for compliance assessment is very much a limitation due to the fact that intermittent peaks are capable of exceeding IEEE 519 limits. Overall, findings underline the importance of implementing harmonic mitigation methods tailored to the type of load, which can be as mild as passive filtering in residential feeders and as complex as active and hybrid filtering with continuous monitoring in commercial, irrigation, and industrial systems, which is also in line with the proposals for enhancing feeder reliability and decreasing equipment degradation (Angarita et al., 2025; Hafiz et al., 2024).

VI. Evaluation of the Measured Voltage and Harmonic Levels in Comparison to Known Standards

Table 8

Comparison and Evaluation of the Measured Voltage and Harmonic Levels

Load Profile	Power Quality Metric	Observed Range	Mean Median	Compliance Summary	Remarks
Residential	Voltage Magnitude (V)	205–229 V	224.4 V	Within acceptable range; minor fluctuations during evening peak	Compliant
	Current (A)	0.41–6.28 A	1.86 A	Within operational limits	Compliant
	THDv (%)	4.88–8.42	6.35	Slightly above recommended levels in some intervals	Non-Compliant
	THDi (%)	7.50–46.32	21.45	Moderate distortion from household nonlinear loads	Non-Compliant
Commercial	Voltage Magnitude (V)	198–227 V	221.3 V	Generally compliant; minor voltage drop during peak business hours	Compliant
	Current (A)	0.63–8.74 A	3.28 A	Within operational limits	Compliant
	THDv (%)	5.94–10.76	7.84	Frequently approaching upper recommended limits	Non-Compliant
	THDi (%)	10.84–63.28	28.36	Moderate to high distortion due to electronic equipment	Non-Compliant
Industrial	Voltage Magnitude (V)	192–224 V	218.7 V	Partial compliance; load-driven voltage drops observed	Non-Compliant
	Current (A)	1.25–12.84 A	5.96 A	Within operational capacity but higher feeder loading	Compliant
	THDv (%)	7.90–13.64	9.62	Exceeds recommended harmonic limits	Non-Compliant
	THDi (%)	14.50–91.03	34.90	Significant non-compliance due to nonlinear industrial equipment	Non-Compliant
Irrigation	Voltage Magnitude (V)	195–226 V	220.2 V	Generally compliant with occasional drops during pump startup	Compliant
	Current (A)	0.93–10.42 A	4.33 A	Within operational limits	Compliant
	THDv (%)	6.25–11.28	8.37	Slightly elevated due to motor-driven loads	Non-Compliant
	THDi (%)	12.30–72.45	30.12	Moderate to high distortion during pump operation	Non-Compliant

**Note: IEEE 519 current distortion limits vary by I_{sc}/I_L . Since utility fault level data is not provided, a conservative feeder-level limit was used for comparative analysis (consistent with applied field studies).*

Voltage levels remain within acceptable operating limits under all load conditions, pointing to generally stable feeder performance at standard distribution situations; at the same time, harmonic distortion is the major power quality concern that is being highlighted.

Voltages on residential feeders are generally stable, with only minor evening fluctuations; however, the existence of THDi is indicative of the initial introduction of nonlinear household devices like electronics and switch-mode power supplies. This finding is in agreement with (Al-Shetwi et al., 2020) and points to mild but cumulative degradation effects.

Compared to residential loads, commercial loads are much more variable in both THDv and THDi levels and their load clustering and simultaneous operation of office equipment, HVAC systems, and electronic devices is causing them to reach the planning thresholds leading to the harmonic accumulation as described by (Rodrigues et al., 2023).

Industrial feeders mark the worst scenario as far as power quality is concerned. Apart from the noticeable voltage drop during peak demand, they also record the highest level of harmonic distortions mainly due to the use of rectifiers, converters, and motor-driven systems, thus equipment gets stressed, and the asset life is reduced as corroborated by the results of Buzdugan et al., 2018.

Irrigation loads, although slightly, are also affected by voltage stability in that they get transitory disturbances and moderately harmonics due to motor start-up and pump cycling, this is further complicated by the feeder impedance effect present in the remote locations as mentioned by (Al-Shetwi et al., 2020). Looking at the big picture, the results reveal that voltage level on its own is not an adequate indicator of system performance as both THDv and THDi point to hidden degradation risks, especially for commercial and industrial feeders where occasional exceedances of IEEE 519 limits have been detected. In other words, harmonic indices better uncover hidden systemic degradation and ongoing operational stresses.

Table 9*Analysis Summary (Numerical Equivalent)*

Voltage and THDv Boxplot Summary by Load Profile								
Load Profile	Metric	Min	Q1	Median	Q3	Max	Standard Limit	Compliance Interpretation
Residential	Vbal (V)	97.85	98.46	98.92	99.34	100.12	90–110	Entire distribution comfortably within limit
	THDv (%)	1.2	1.9	2.3	2.8	5.6	≤5.0	Few upper outliers slightly exceed limit
Commercial	Vbal (V)	97.22	98.14	98.63	99.05	99.88	90–110	All observations within standard range
	THDv (%)	1.4	2.4	2.9	3.6	7.4	≤5.0	Upper whisker exceeds limit due to nonlinear loads
Industrial	Vbal (V)	96.92	98.18	98.68	99.20	100.02	90–110	Entire distribution inside limit
	THDv (%)	0.9	2.0	2.5	3.1	6.8	≤5.0	Upper whisker exceeds limit (few outliers)
Irrigation	Vbal (V)	97.04	98.09	98.54	98.97	99.76	90–110	Within allowable voltage limits
	THDv (%)	1.3	2.2	2.7	3.4	6.1	≤5.0	Some outliers associated with pump operation

THDi Boxplot Summary (n = 823) by Load Profile								
Load Profile	Metric	Min	Q1	Median	Q3	Max	Standard Limit	Visual Compliance Interpretation
Residential	THDi (%)	2.4	7.1	9.8	12.6	26.4	≤20	Majority within limit; few household electronic load outliers
Commercial	THDi (%)	3.2	9.6	12.4	16.8	41.5	≤20	Several upper outliers due to electronic office equipment
Industrial	THDi (%)	4.5	12.8	17.3	22.6	91.0	≤20	Significant outliers linked to motor drives and nonlinear loads
Irrigation	THDi (%)	3.8	10.5	14.2	19.3	72.4	≤20	Outliers occur during pump

startup and heavy
motor operation

All load profiles meet the standard voltage range of 90, 110 V, with the median values closely packed (98.5, 98.9 V) for residential, commercial, industrial, and irrigation feeders. This suggests that there has been good voltage regulation and only small, temporary deviations in voltage at times of heavy loading, such as when residential demand is high in the evenings, commercial activities during the day, and industrial and irrigation operations of motor-driven machines. This shows that voltage levels are not the main issue when it comes to power quality in the system under examination. On the other hand, harmonic distortion, especially THV and even more importantly THDi, exhibit significant changes between different types of loads and indicate a reaction to the increasing share of nonlinear loads, which is in accordance with (Al-Shetwi et al., 2020; Rodrigues et al., 2023).

Residential feeders keep distortion to a relatively low level, whereas commercial and irrigation loads account for most of the higher levels due to the presence of a number of electronic devices and motors. At the same time the industrial feeders have the highest THDi due to an extensive use of rectifiers, variable speed drives, and other power electronic devices. Besides, it has been noticed that the irrigation systems although showing very short but very high distortions which are pump motor start-up events that although short in duration, still are the thermal stress and increased losses creators of the network components. In general, the findings reveal that there is a considerable gap between voltage meeting standards and harmonic non-meeting standards, which is a clear indication that relying on voltage for assessment is no longer sufficient since it is the event driven nonlinear loads which are dominating the distribution systems of today. This is in fact kin to the argument for the provision of power quality management for different types of loads that will be able to focus on the reduction of harmonics through operational controls that are well coordinated, including reactive power compensation and load sequencing.

Furthermore, the temporal analysis illustrated in Table 10 indicates that the instances of harmonics levels above limits are mainly during peak demand times, which in turn strengthens the link between stress of the system and load simultaneity, and at the same time it provides a rationale for the planning of interventions targeted at the low-voltage networks.

Table 10
Exceedance Concentration (Peak-Hour Harmonic Events)

Time Block	Typical Load Condition	THD _v Exceedance %	THD _i Exceedance %	Interpretation	Load Profile Type	Compliance Summary
00:00–05:59	Light	0.0%	0.0%	Minimal activity	Residential / Commercial	Compliant
06:00–11:59	Moderate–High	2.1%	3.0%	Morning lighting, small machinery	Commercial / Industrial	Compliant
12:00–15:59	High	4.5%	6.2%	Midday process and service loads	Commercial / Industrial	Near limit (THD _v)
16:00–19:59	Overloaded	14.3%	18.5%	Evening HVAC, + irrigation pumps	Residential / Irrigation	Non-compliant
20:00–23:59	High	6.8%	8.7%	Residual demand	Residential / Commercial	Non-compliant (THD _v)
00:00–05:59	Light	0.5%	0.7%	Minimal night operation	Industrial	Compliant
06:00–11:59	Moderate	1.8%	2.5%	Irrigation start, residential use	Irrigation / Residential	Compliant
12:00–15:59	High	5.0%	7.0%	Peak irrigation commercial overlap	Irrigation / Commercial	Borderline (THD _v)

Time Block	Typical Load Condition	THDv Exceedance %	THDi Exceedance %	Interpretation	Load Profile Type	Compliance Summary
16:00–19:59	Overloaded	13.5%	17.0%	Combined residential industrial stress	+ Residential / Non-peak Industrial	compliant
20:00–23:59	Moderate–High	4.0%	5.5%	Night commercial operations	Commercial	Borderline

The temporal assessment in Table 10 taken alongside the IEEE 519 (THDv planning reference of ~5% at the PCC) and NEMA MG 1 voltage quality standards reveals that harmonic distortions are highly dependent on the time factor and the simultaneous operation of loads and nonlinear devices. From 00:00 to 05:59, the system demonstrates full compliance with no violations at all, underscoring minimal nonlinear load activity and stable feeder conditions.

In the next phase of the day, 06:00, 11:59, there are only very small exceedances in THDv (1.8, 2.1%) and THDi (2.5, 3.0%), which are linked to system energization such as office startup, HVAC, irrigation, and early industrial operations, in line with the gradual increase of nonlinear load penetration (Balakrishnan et al., 2022).

From 12:00 to 15:59, the level of distortion increases with THDv reaching planning limits (4.5, 5.0%) and THDi going over 6% primarily due to simultaneous operation of commercial, HVAC, irrigation, and industrial loads which, in combination, create harmonic stress even though the voltage is within acceptable limits.

The situation becomes most critical in the period 16:00, 19:59, when THDv (13.5, 14.3%) and THDi (17.0, 18.5%) greatly go beyond limits as a result of the overlap between residential peak demand, watering cycling, and industrial activity, which is producing time-clustered harmonic events contributing to transformer thermal stress and losses in the system (Hafiz et al., 2024).

At last, from 20:00 to 23:59, distortion levels slightly drop (THDv 4.0, 6.8%, THDi 5.5, 8.7%) given that industrial and irrigation loads are decreasing, nevertheless, residential and commercial nonlinear loads still cause some exceedances from time to time. These results triangulate that harmonic distortion is more influenced by the type and simultaneity of load rather than the volume of demand alone, thus implying that harmonic mitigation should be time-targeted rather than using uniform voltage-based control approaches.

VII. Proposal of a Viable Corrective Scheme

Table 11

Corrective Scheme and Simulation Validation for Proposal A

Disturbance Pattern	Evidence from Results	Recommended Corrective Scheme	Target Sections (SLD-Based Location with Barangay Coverage)	Expected Improvement	Simulation Results – Vbal	Simulation Results – THDv	Simulation Results – THDi	Notes
Overloading-related voltage depression	$\rho = -0.62$; $\beta = -0.018$	Load transfer + conductor upgrading >110% loading segments	Feeder F3: Downstream radial covering Brgy. Lucia (outer	+0.4 to +0.7 Vbal	98.93 V	2.62%	12.7%	Voltage recovery dominant; end-line undervoltage reduced

Disturbance Pattern	Evidence from Results	Recommended Corrective Scheme	Target Sections (SLD-Based Location with Barangay Coverage)	Expected Improvement	Simulation Results - Vbal	Simulation Results - THDv	Simulation Results - THDi	Notes
Harmonic-dominant pockets	Cluster C4; $\beta = 0.084$	Tuned passive active filters at PCC nodes	zone), Brgy. Sapang Biabas (edge feeders), and peripheral residential-irrigation laterals Feeder F4: Industrial-commercial cluster covering Brgy. Sta. Lucia industrial zone and Magalang boundary commercial terminals (VFD, rectifier-heavy nodes)	THDv -0.8% -1.6%	to 98.67 V	1.94%	9.2%	Strong localized harmonic suppression
Phase imbalance	$\rho = +0.41$	Phase balancing + service drop reassignment	Feeder F2: Mid-feeder mixed residential zones covering Brgy. Camachile interior residential blocks and Sapang Biabas residential taps	Imbalance -0.05% -0.15%	to 98.76 V	2.55%	12.2%	Improves phase symmetry in mixed residential load area
Peak-hour harmonic rise	$\beta = +0.22$	Capacitor switching + feeder monitoring	Whole Feeder F1-F4 with critical nodes at	THDv -0.2%	99.21 V	1.72%	8.4%	Best system-wide performance during

Disturbance Pattern	Evidence from Results	Recommended Corrective Scheme	Target Sections (SLD-Based Location with Barangay Coverage)	Expected Improvement	Simulation Results – Vbal	Simulation Results – THDv	Simulation Results – THDi	Notes
Persistent high THDi	$\rho = +0.66$	Customer-level harmonic enforcement + audits	Feeder F4: Large industrial and irrigation customers in Brgy. Sta. Lucia industrial belt and irrigation pump clusters near downstream agricultural boundary zones	THDi to -8%	99.21 V	1.72%	8.4%	Requires enforcement at PCC level

Mitigation of harmonic and voltage quality issues in Feeder F4 (Cluster C4, Bus B6–B8) was achieved through a combination of tuned 5th and 7th harmonic filters and selective active filtering at the point of common coupling, resulting in significant reductions in THDv to 1.94% and THDi to 9.2%, while maintaining stable voltage at 98.67 V and lowering THDv exceedances beyond 5% to 1.8%, consistent with NEMA MG-1 guidelines and reinforcing findings that nonlinear industrial and commercial devices are primary harmonic sources (Luszcz, 2015). Phase imbalance in Feeder F2–F3 (Bus B2–B4), identified via PCA ($\rho = +0.41$), was addressed through phase load balancing and service drop redistribution, reducing THDv to 2.55% and THDi to 12.2%, improving thermal performance despite limited harmonic reduction, consistent with the role of imbalance in amplifying feeder stress (Neumann & Pimenta, 2012). System-wide peak-hour mitigation (16:00–19:59) using capacitor switching, dynamic monitoring, and operational planning improved stability (Vbal 99.21 V, THDv 1.72%, THDi 8.4%), demonstrating the effectiveness of time-based control strategies in reducing transient harmonic accumulation during overlapping demand peaks. Persistent high THDi in industrial and commercial loads ($\rho = +0.66$) was further reduced through client-level harmonic audits and nonlinear load management, achieving 4–8% reductions and supporting IEEE 519 principles on shared harmonic responsibility at the point of common coupling. Overall, Proposal B produced measurable system-wide improvements, including reduced low-voltage occurrences (from 14.2% to 6.2%) and THDv exceedances (to 0.6%), while also confirming that voltage depressions are

strongly linked to overloading ($\rho = -0.62$) and can be effectively mitigated through OLTC optimization and automatic voltage regulation, improving average Vbal to 99.08%.

Table 12
Corrective Scheme and Simulation Validation for Proposal B

Disturbance Pattern	Evidence from Results	Recommended Corrective Scheme	Target Sections (SLD-Based Location with Barangay Coverage)	Expected Improvement	Simulation Results – Vbal	Simulation Results – THDv	Simulation Results – THDi	Simulation Notes
System-wide voltage depression under high loading	$\rho = -0.62$; high-load segments $\geq 100\%$ show $V_{bal} < 98.5\text{ V}$	AVR deployment at mid-feeder + OLTC optimization	Mid-feeder zones covering Brgy. Camachile central distribution area and Sapang Biabas mixed residential-commercial laterals	+0.5 to +0.9 Vbal	99.08 V	2.63%	12.6%	Strong voltage recovery; reduced low-voltage violations
Harmonic amplification due to nonlinear clusters	$\beta = 0.084$; Cluster C4 dominant	Hybrid harmonic filters at feeder head and nonlinear nodes	Feeder head (Camachile substation Brgy. Sta. Lucia industrial-commercial boundary (VFD, rectifier-heavy nodes) Brgy. Camachile residential interior blocks Brgy. Sapang Biabas mixed residential-commercial taps	+ THDv -1.0% to -1.8%; THDi -5% to -9%	98.72 V	1.68%	8.7%	Highest harmonic reduction efficiency in industrial zones
Uneven phase loading in mixed zones	$\rho = +0.41$; PCA imbalance pattern	Automated phase switching and dynamic rebalancing		+ Imbalance -0.08% to -0.18%	98.95 V	2.21%	11.4%	Stabilizes phase voltage symmetry

Disturbance Pattern	Evidence from Results	Recommended Corrective Scheme	Target Sections (SLD-Based Location with Barangay Coverage)	Expected Improvement	Simulation Results – Vbal	Simulation Results – THDv	Simulation Results – THDi	Notes
Peak-hour reactive power stress	β +0.22; THDv spike 16:00–19:59	Dynamic = VAR compensation with harmonic-blocking capacitor banks	Whole Feeder 5 with priority at Brgy. Camachile s (Bus B3 peak zone) and Brgy. Sta. Lucia (Bus B6 load center)	THDv -0.3% to -0.6%; Vbal +0.2 V	98.95 V	2.21%	11.4%	Strong evening peak stabilization
High feeder impedance harmonic propagation	Harmonic spread increase with feeder length	Feeder segmentation + tie-line reconfiguration	Long laterals in Brgy. Sapang Biabas–Sta. Lucia corridor (downstream radial extension zones)	THDv -0.4% to -0.9%	98.88 V	2.05%	10.9%	Reduces harmonic propagation pathways

Mitigation of harmonic and voltage issues in Feeder F4 (Cluster C4, Bus B6–B8) was achieved through coordinated use of passive tuned filters and active power filters at both feeder head and nonlinear load points, targeting harmonic sources such as VFDs and rectifiers in line with NEMA MG-1 guidelines, resulting in reduced THDv to 1.68% and THDi to 8.7%, with THDv exceedances above 5% decreasing to 1.2%, confirming the effectiveness of multi-point harmonic mitigation in power-electronics-dominated networks (Luszcz, 2015). In mixed residential-commercial clusters (C2–C3, Bus B2–B4), automated phase balancing based on PCA correlation ($\rho = +0.41$) improved voltage stability to Vbal = 98.95 V while maintaining THDv at 2.21% and THDi at 11.4%, indicating that load balancing primarily reduces neutral currents and voltage fluctuation rather than significantly lowering harmonics, consistent with (Neumann & Pimenta, 2012). During peak stress hours (16:00–19:59), smart capacitor bank-based VAR control provided time-coordinated mitigation of harmonic peaks, maintaining stable distortion levels and demonstrating the effectiveness of dynamic reactive power management under simultaneous residential, commercial, and irrigation demand. Additionally, feeder segmentation and impedance optimization in Clusters C3–C4 reduced THDv to 2.05% and THDi to 10.9%, highlighting the role of feeder topology in harmonic propagation, as noted by (Angarita et al., 2025). Overall, Proposal B integrates filtering, phase balancing, VAR control, and structural feeder improvements, producing the most comprehensive reduction in low-voltage events and harmonic exceedances, while Table 13 confirms its superior technical and operational viability compared to alternative corrective schemes.

Table 13 Viability Ranking (Cost–Impact–Feasibility) for Mabiga Feeder 5 Corrective Scheme

Corrective Action	Technical Impact	Cost Level (PH context)	Implementation Difficulty	Observed Improvement (Simulation)	Overall Viability	Technical–Economic Verdict	Notes / Justification
Proposal A – Combined Scheme (Load Transfer + Harmonic Filters + Phase Balancing + Operational Switching + Customer Mitigation)	High. Voltage raised from 98.64 V → 99.21 V; THDv reduced to 1.72%; THDi reduced to 8.4%	Moderate. Cost of conductor upgrades, tuned filters, and operational monitoring moderate but manageable	Medium. Requires coordination across feeder clusters and some customer-level interventions	Strong. Low-voltage entries reduced from 14.2% → 3.1%; THD near target levels	Very High. Combines multiple interventions with clear improvements	Recommended. High technical impact justifies moderate costs and manageable implementation	Delivers the best overall outcome with comprehensive mitigation; operational plus technical measures work synergistically; feasible with current utility resources.
Proposal B – Combined Scheme (AVR + OLTC Optimization + Hybrid Harmonic Filters + Phase Switching + Dynamic VAR Feeder Reconfiguration)	Very High. Voltage raised from 98.64 V → 99.08–98.95 V across scenarios; THDv reduced to 1.68–2.05%; THDi reduced to 8.7–10.9%	High. AVRs, OLTC adjustments, hybrid filters, dynamic VARs, and feeder reconfiguration increase capital expenditure	High. Requires sophisticated control devices, smart capacitor banks, feeder reconfiguration, and staff training	Very Strong. Voltage recovery and harmonic mitigation achieved, though more complex interventions	High. Superior technical outcome but high cost and implementation difficulty may limit feasibility	Recommended with caveat. Technically superior but economically more demanding	Provides robust voltage and harmonic control; ideal for long-term reliability; best for high-demand feeders but may be cost-prohibitive in Philippine context compared to Proposal A

Two coordinated mitigation schemes were evaluated for Feeder F5, incorporating load transfer, filtering, phase balancing, switching operations, and customer-level interventions in Proposal A, alongside more advanced controls such as AVR deployment, OLTC optimization, hybrid filtering, automatic phase shifting, dynamic VAR compensation, and feeder reconfiguration in Proposal B. Simulation results show that Proposal A improves system performance by increasing V_{bal} to 99.21 V, reducing THDv from 11.3% to 1.72%, and lowering THDi to 8.4%, while significantly decreasing low-voltage occurrences from 14.2% to

3.1%, consistent with NEMA MG-1 compliance requirements and reflecting the effectiveness of distributed mitigation at nonlinear load nodes, particularly in commercial and industrial sectors. Proposal B achieves comparable but more technically advanced outcomes, with V_{bal} ranging from 98.95 V to 99.08 V, THD_v reduced to 1.68%–2.05%, and THD_i lowered to 8.7%–10.9%, though residual harmonic peaks persist during high nonlinear loading conditions such as motor drives and irrigation pumps. Overall, while Proposal B offers superior technical sophistication and integrated control, Proposal A is assessed as more practical and cost-effective for utility implementation due to simpler operational requirements and lower investment demands, whereas Proposal B requires complex coordination and advanced infrastructure despite its marginal performance gains.

VIII. Conclusion

This research analyzed the power quality of Feeder 5 at Mabiga Substation PELCO II by looking at voltage conditions, harmonic distortion levels, feeder loading characteristics, and network configuration. The results indicated that Feeder 5 was at 104.07% loading with the highest demand of 8,972 kVA, which reflects a stress condition. Examination of the feeder design has shown that long radial sections, concentrated downstream loads, and high feeder impedance are the factors causing low voltage and increased harmonic susceptibility.

Investigations of voltage magnitude, voltage balance, THD_v, and THD_i at various load profiles such as residential, commercial, industrial, and irrigation have revealed that even if voltage levels were mostly within permitted limits, harmonic distortions were often above the levels set, especially for the industrial and irrigation sectors.

Evidence supported that power quality performance is primarily influenced by the type of load, load magnitude, feeder configuration, and time of operation. Harmonic distortions were highest in industrial and irrigation because these sectors depend heavily on motor-driven equipment, variable frequency drives, and other nonlinear devices. Commercial loads also depicted increased levels of harmonics due to the concentration of electronic and switching loads, while residential loads showed the most stable voltage performance in spite of the rising harmonic components. Analysis of the peak-hour identified 16:00–19:59 as the most critical period when joint operation of residential, commercial, and irrigation loads caused maximum voltage and harmonic disturbances.

The research additionally showed that the causes that lead to voltage drops and harmonics propagation are feeder overloading, long-distance radial extensions, and concentrated downstream load centers. Mapping of the feeder highlighted critical points where system stress was maximum and it was verified that power quality issues not only depend on the load magnitude but also on feeder geography and network topology. Perfective methods simulation based on the cases stood those combined solutions linking voltage regulation, harmonic mitigation, load redistribution, and operational improvements can significantly upgrade feeder functionality. Both corrective schemes proposed managed to decrease voltage deviations and harmonic distortion but Proposal A, on the other hand, met almost the same technical results as Proposal B with lower investment costs and less operational complexity.

Given these findings, it can be inferred that implementation of utility-level and customer-level interventions combined is the solution to effective power quality improvement. Load transfer, conductor upgrading, harmonic filtering, phase balancing, operational switching, real-time monitoring, and customer harmonic compliance programs for large nonlinear loads are part of the recommended plan. The highest priority should be implementation of the Proposal A, as it provides the most practical balance between technical effectiveness, economic feasibility, and ease of implementation within Philippine distribution systems. Continued monitoring, targeted infrastructure upgrades, and shared responsibility for harmonic mitigation between utilities and customers are keys to maintaining voltage quality, reducing harmonic distortion, improving system reliability, and ensuring long-term compliance with power quality standards.

IX. References

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