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Original Article

Optimization of Electric Service Quality in Distribution Substations in Urban-Rural Areas of Central Peru: An Approach Based on the Technical Standard for Electric Service Quality

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Abstract - *Electric power supply in urban and rural Peru is loaded with issues, especially in the quality of service offered at distribution substations. Voltage fluctuations compromise power quality, leading to equipment breakdowns and inadequate service delivery. This research tackles the problem of power quality optimization based on the analysis of accurate data and corrective measures using simulation techniques. The effect of setting the transformer tap changer and voltage control device on supply stability was examined using the PandaPower library in Python. Through the strict implementation of the Technical Standard for the Quality of Electric Services (NTCSE) and the Technical Standard for the Quality of Rural Electric Services (NTCSER), the performance of the secondary circuits powered by a transformer of 100 kVA in urban areas and 25kVA in rural areas was evaluated. A threshold of 2.6 V was set to detect borderline cases where corrective actions could be intelligently modified. The findings proved that adjustments of tap changer positions are a viable low-cost option to enhance power quality in networks with small capacity while achieving compliance with the regulations and improving the overall services. This helps improve the power supply quality in rural areas while offering an adaptable approach for power infrastructure optimization in the region. Further studies should aim to fusion real-time monitoring systems and machine learning to improve predictive maintenance and adaptive control strategies, particularly concerning energy policy and sustainable development.*

Keywords - *Quality of electrical, Voltage variations, Electrical simulations, PandaPower, Simulation, Electric service, Single-phase transformer.*

1. Introduction

The distribution of electrical energy plays a crucial role in ensuring a stable and efficient power supply from transmission substations to end users through distribution lines and transformers [1]. Maintaining a reliable electricity supply in Peru is particularly challenging in urban and rural areas, especially in central regions where infrastructure limitations often lead to service instability. Compliance with national regulations, such as the NTCSE and NTCSER, is essential to avoid regulatory penalties and ensure customer satisfaction [2, 3].

One of the primary challenges in electric distribution networks is voltage variation, which directly affects power quality, leading to equipment failures, inefficiencies, and an overall decline in service reliability. Although technological advancements have enabled real-time monitoring and analysis of electrical networks, deficiencies persist, particularly in low-voltage networks of developing countries, where infrastructure limitations and fluctuating demand contribute to service instability [4, 5]. While these monitoring systems provide valuable insights, they cannot implement adaptive corrective mechanisms for stabilizing voltage fluctuations in dynamically changing conditions. Simulation-based optimization is widely accepted for improving power quality, enabling predictive modeling, risk assessment, and efficient resource allocation before real-world implementation [6].

However, the variability of operating conditions and the unique characteristics of each service area complicate the adoption of standardized solutions. In distribution systems, factors such as user density, transformer capacity, and grid topology play a critical role, requiring the development of customized corrective strategies tailored to specific grid conditions [7]. Despite existing regulatory frameworks, voltage fluctuations remain a recurrent issue in central Peru's secondary circuits of urban and rural networks. To address this gap, this study utilizes real-world service quality data and advanced simulation techniques with the PandaPower library in Python to optimize voltage stability in low-voltage networks powered by 100 kVA and 25 kVA transformers. Specifically, this research seeks to answer the following research question: Can corrective procedures based on simulations effectively mitigate voltage instability in low-voltage networks with 100 kVA and 25 kVA transformers?

To answer this question, this study assesses corrective actions and analyzes the power quality metrics measured before and after implementation. The findings demonstrate the effectiveness of optimizations performed through simulation in enhancing voltage regulation in the low-voltage network, which provides the basis for reliability improvement of services in areas with infrastructural limitations.

2. Literature Review

Low-voltage power distribution networks have been intensively studied to ensure power quality due to their direct relevance to system reliability, service efficiency, and regulatory compliance. Various methodologies have been developed to address voltage variation and power disturbances using advanced modeling, monitoring, and adaptive control techniques. However, their effectiveness depends on region-specific infrastructure conditions, making context-specific adaptations imperative. In this segment, the focus is on analyzing the existing research on the challenges posed by voltage regulation and how simulation-based techniques have contributed to improving the service quality of electric power supply.

2.1. Techniques for Analysing and Detecting Voltage Variations

The research [9] created a practical approach to determining the causes of voltage variation employing the Bi-LSTM with an attention mechanism. It achieved an impressive accuracy of 99.7% for noise-free data, highlighting its robustness against noise and variability while examining 3508 events of simulated and actual ID measurement voltage drop data. This method surpasses conventional approaches to voltage sensing, making it extremely useful for diagnosing and alleviating service instability in real-time.

Another study [10] proposed a simplified unit vector control scheme for a Dynamic Voltage Restorer (DVR). It was possible to use this technique to keep the load voltage stable during drops and surges. At the same time, the more straightforward calculations facilitated a more straightforward design and implementation of the DVR. This is useful for power distribution companies seeking lower-cost solutions to voltage control problems.

This research [11] designed a method for the real-time detection and classification of voltage sags and swells employing Independent Component Analysis (ICA) for detection and neural networks with Support Vector Machine (SVM) classifiers for the classification. This method resulted in a detection failure rate of 0.86 percent inaccurate signals, which is outstanding and demonstrates an excellent tolerance to network disturbances, such as harmonics and flickering.

2.2. Simulation-Based Optimization for Power Quality Improvement

A deep-depth simulation-based approach has been used to analyze and optimize power quality in distribution networks. A particular study [12] pointed out the effectiveness of power flow simulations in assessing the voltage stability of secondary circuits. It showed that adjusting the transformer tap changer significantly reduces voltage swings. Another study [13] investigated the application of adaptive corrective measures in low-voltage networks. It showed that combining the settings with real-time monitoring and simulation-based control allows for better regulation of voltage levels than simulation alone. The study also showed that developing countries' infrastructures need simple, cost-effective solutions that can be easily integrated with existing systems.

The PandaPower simulation library has emerged as an essential component for modeling and simulating low-voltage power systems. Research [14, 15] demonstrated that PandaPower-based simulations that comply with IEC 60909 standards effectively model voltage variation scenarios and enable utilities to respond and implement corrective actions proactively and efficiently.

2.3. Need for Adaptive Voltage Regulation in Developing Regions

Studies [16, 17] suggest that these regions have implemented stringent power quality standards leveraging real-time monitoring and smart grid technologies when comparing voltage control strategies in Europe, Asia, and North America. However, power distribution networks in South America, especially in rural areas, frequently lack the infrastructure for real-time corrective actions, making flexible and affordable approaches vital.

Even with advances focused on simulation-based optimizations, voltage control strategies are not well suited to rural low-voltage grids in developing countries. Being able to identify regionally specialized corrective actions remains a gap in the literature that this research seeks to fill. By incorporating historical power quality data with simulations in PandaPower, this research aims to design a tailored corrective framework that optimizes voltage control in the secondary circuits of urban-rural low-voltage power distribution networks.

3. Materials and Methods

3.1. Analysis Procedures

This study focuses on improving power quality in low-voltage distribution networks by analyzing real-world data and implementing simulation-based corrective procedures.

Power quality data from secondary circuits with a voltage deviation time series was simulated using the PandaPower library in Python. Developed by IEC 60909 standards, PandaPower provides a specialized modeling and simulation environment that enables power flow analysis using the Newton-Raphson method [13, 14]. This software was chosen because of its real-time modeling capabilities, which help determine practical corrective actions.

A decision flowchart was designed to systematically evaluate supply quality and determine the required corrective actions based on voltage variability. As shown in Figure 1, the analysis begins with assessing power quality parameters. Corrective actions are applied if voltage variations exceed the predefined 2.6 V standard deviation threshold. If the variability exceeds acceptable limits, the most significant contributions to the fluctuations are identified and corrected. In cases where the variability remains within acceptable limits, tap changer adjustments in the transformer are implemented to optimize voltage stability further.

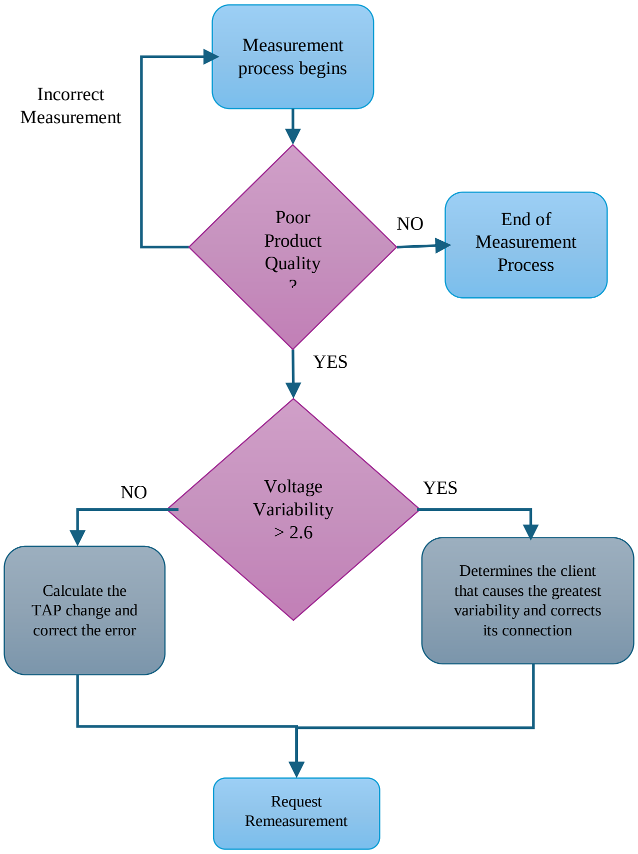

Fig. 1 Diagram of the analysis and correction process of product quality in the electricity supply

3.2. NTCSE Supreme Decree N° 020-97-EM

The NTCSE, published in 1999, states that variations in nominal voltage should not exceed a margin of ±5.0% in urban areas. In rural [urban-rural], this margin is widened to ±7.5%, according to the NTCSER [16]. Electrical service is considered low quality if the voltage is outside these limits for more than 5% of the measurement period, seven continuous days in urban areas, and 3 days in rural areas.

3.3. International Comparison of Voltage Variation Ranges

The study of voltage variation ranges in distribution networks reveals significant regional differences. In Europe, the EN 50160 standard allows a range of ±10% over the nominal value, while in North America, the ANSI C84.1 standard enables a variation of ±5% under normal conditions, extending to ±8% in extreme situations. In South America, tolerance margins range from ±5% to ±10%, depending on local infrastructure and conditions [17]. Table 1 compares the voltage variations allowed in different countries in Peru.

Table 1. Voltage variation in different countries

Country	Nominal Voltage	Mandatory Regulation	Voluntary Regulation
Australia	230	-6.1% + 10.0%	-6.1% + 10.0%
Canada	120	-8.3% + 4.2%	-8.3% + 4.2%
Germany	230	±10.0%	±10.0%
Japan	100	±6.0%	Not existed
Korea	220	±5.9%	±10.0%
U.K	230	-6.1% + 10.0%	±10.0%
U.S.A	120	±5%	±5%

3.4. Technical Data for Transformers

Two commonly used distribution transformer capacities, 25 kVA and 100 kVA, were considered for the simulation and analysis of power supply quality. These transformers were selected based on technical specifications obtained from regulatory documents used by concessionaire companies in Peru for transformer acquisition [18]. The specifications include key electrical parameters such as rated power, no-load losses, short-circuit voltage, no-load current (as a percentage of rated current), number of taps, and the percentage of adjustment between taps.

The 100 kVA focal transformer case study has 90 W no-load losses, 374 W total losses at 75°C, and a short-circuit impedance of 4%. In addition, this transformer has five voltage regulation sockets, with each socket allowing for a 2.5% voltage jump between sockets.

From the specifications of the power consumed by the 25kVA transformer, it is known that the no-load loss is 120W, and the no-load current is 2.1% of the current at full load. These values are shown in Table 2; they are important to accurately configure a PandaPower simulation model to ensure that the simulated network behaves like the actual operating environment.

Table 2. Technical specifications of the distribution transformers used in the simulation

Potency	Empty Losses	Short-Circuit Voltage	No-Load Current in % of Rated Current		Taps Numbers	Percentage of Passage between Taps
25 kVA	120	4%	2.1		5	2.5
100 kVA	374	4%	2.99		5	2.5

3.5. Distribution Network Configuration

The model for the low-voltage distribution network was created from 0.6/1 kV Aluminum-Steel (CAAI) conductors, which were chosen considering the standard parameters of an overhead distribution network in Peru. This model modeled three different types of conductors used in practice with a fixed resistance value for each. This allowed us to realistically model voltage drop and power losses in distribution lines. The resistance power of the conductors shaped the PandaPower model, which is quite different from the actual situation in the distribution network. Table 3 describes the parameters of the chosen conductors and their resistance values per kilometer, which were used to model the voltage drop in the distribution system for the model presented.

Table 3. Resistance specifications of the distribution conductors used in the simulation

Conductor	Ohm - Km
3x35 + 1x25 mm	0.868
3x25 + 1x25 mm	1.2
3x16 + 1x16 mm	1.91

Mapbox-OpenStreetMap was used to establish the spatial configuration of the distribution network, which facilitated the design of a georeferenced model of the electric power distribution system in the district of El Tambo in central Peru [19]. This model included a 100 kVA, 3-phase substation with a 220 V low-voltage secondary output and a 10 kV primary voltage, which fed three distinct low-voltage secondary output circuits. As shown in Figure 2, the light poles and substation locations within the distribution network are illustrated, and the grid configuration and coverage in the region of interest are clearly understood [20].

Fig. 2 Secondary distribution network with 100 kVA transformer, 80 users, and 20 luminaires in El tambo district, peru

Additionally, in the Cochas Chico Annex of the same district, an urban-rural area, an electrical distribution network equipped with a 25 kVA transformer was implemented. Figure 3 shows the poles' spatial distribution and the substation's strategic location in this network.

Fig. 3 Secondary distribution network with 25 kVA transformer, 30 users, and five luminaires, located at Jr. Miguel Grau 510, in El tambo, peru cochas chico annex district

3.6. User Consumption and Load Modelling

For the simulation of the 100 kV substation, a database was created with consumption profiles of 80 users, each with up to 10 appliances, including televisions (150 W), lamps (80 W, 40 W, 30 W), electric showers (4500 W), microwaves (1100 W), computers (200 W), and refrigerators (400 W). Demand was configured with temporal variability, reflecting peak consumption during morning and evening hours.

Following the NTCSE standards, the simulation ran over 15-minute intervals over 7 days, enabling voltage variation assessment based on real-time demand. For the 25 kVA substation, a database was generated with profiles of 30 users, each with up to 5 appliances: televisions (150 W), lamps (40 W, 30 W), computers (150 W), and refrigerators (250 W). By NTCSER standards, the simulation ran in 15-minute intervals over 3 days.

3.7. Simulation Modelling in PandaPower

The simulation model in PandaPower was designed to replicate the operating conditions of the secondary circuit under study, integrating parameters such as system load, transformer technical specifications, and environmental factors such as temperature and humidity, which affect transformer performance and voltage stability. Initial supply data, measured according to the NTCSE, showed a voltage variability of 3.52 V and an average voltage of 220.45 V, as shown in Figure 4. These results indicate acceptable supply quality. However, variations were observed, especially at night hours.

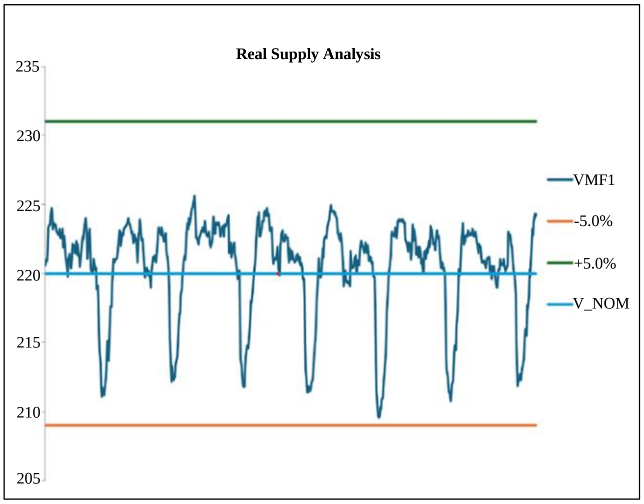

Fig. 4 Analysis of the actual supply in a simulated substation circuit, showing voltage variability and average voltage

The modeled network incorporated 20 public lighting poles equipped with 135 W luminaires each, operating from 18:00 to 06:00 hours. The voltage regulator was initially set to position 2 for power flow simulations, replicating existing field configurations. Simulation results were evaluated according to NTCSE parameters to assess supply quality compliance across network points.

Circuit 2 of the secondary distribution network, shown in Figure 5, was analyzed to evaluate demand impact on voltage stability and identify voltage profile improvement opportunities. This diagram illustrates the circuit's specific structure and behavior under varying load conditions.

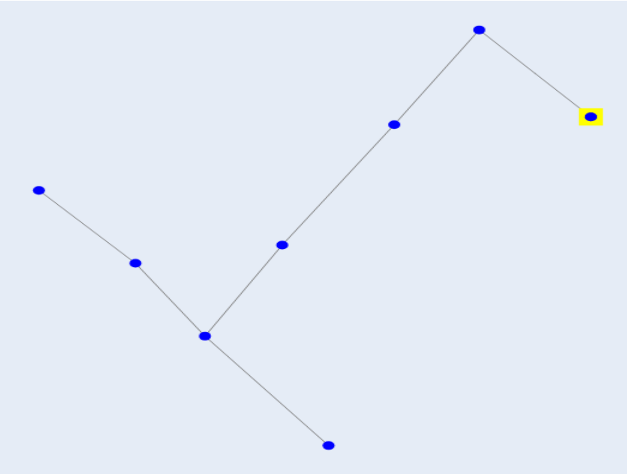

Fig. 5 Circuit 2 diagram of the secondary electrical distribution network

In Circuit 2, measurements at pole 12, the network's furthest point, revealed a standard deviation of 2.151 V with an average voltage of 217.08 V, as illustrated in Figure 6. These values indicate operation within acceptable quality parameters.

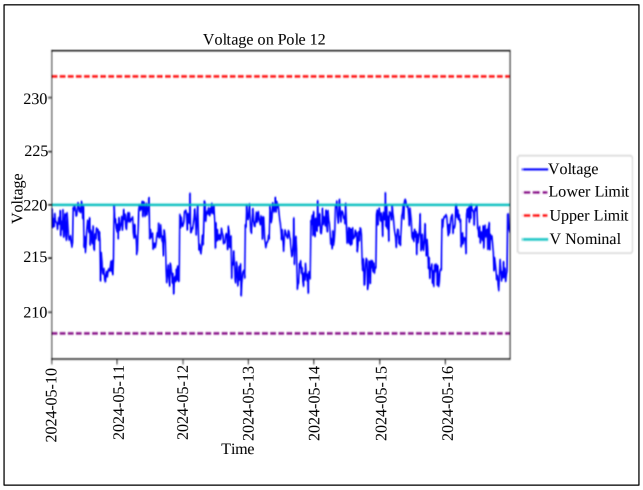

Fig. 6 100 kVA substation with good product quality with a standard deviation of 2.151 V and average voltage of 217.08 V

Figure 7 presents initial results for the 25 kVA substation in the urban-rural area. These results show a standard deviation of 0.77 V and an average voltage of 215.16 V, demonstrating notable stability in electrical supply.

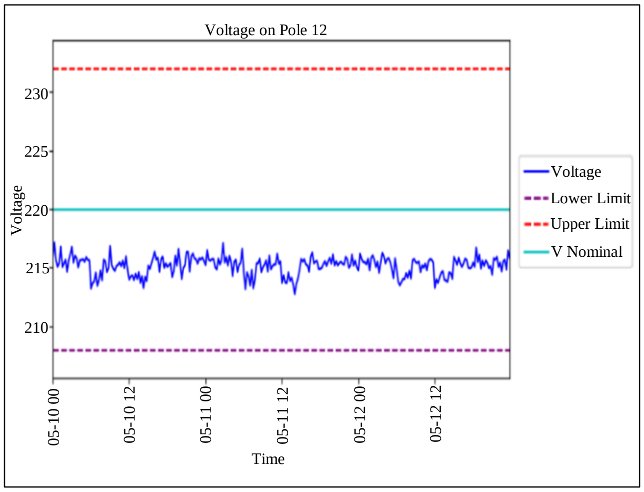

Fig. 7 25 kVA substation with good product quality with a standard deviation of 0.77 V and average voltage of 215.16 V

These circuits served as the basis for analyzing two critical scenarios:

- Poor product quality when standard deviation exceeds 2.6 V, typically caused by special loads requiring detailed analysis. In these cases, the recommended solution is implementing a dedicated service line for users with special loads.

- Poor product quality is caused by over/under voltage with a standard deviation below 2.6 V. The solution focuses on voltage regulator adjustment to optimize network voltage levels in these situations.

3.8. Implementation of Corrective Procedures

Based on the results obtained from the simulation, different corrective procedures were applied to improve the quality of the electricity supply in the low-voltage network. These procedures included:

Change of the tap changer in the Transformer: Changes in the position of the transformer tap changer were evaluated to regulate the output voltage and adjust the drop or overvoltage at the furthest points of the substation. This adjustment was performed using Equation (1), which determines the voltage correction based on the percentage variation of the tap changers, as expressed in the following equation:

$$V_{N_m} = \frac{V_m \cdot \left(1+cp \cdot (p_p-3)\right)}{(1+cp \cdot (p_n-3))} \qquad (1)$$

V_{N_m} is represents the resulting mean voltage, while cp represents the rate of change between regulation positions. The parameters p_n and p_p correspond to a new and an old position, respectively. V_m depicts the mean voltage for the actual situation. This adjustment enabled the simulation of changes in the tap changer and allowed for the analysing of its influence on voltage control along the distribution line. The improvement of this parameter positively impacted the quality of the supplied power, enhancing the stability and regulation of voltage throughout the entire network.

Load redistribution strategies in the low-voltage network were explored to reduce demand peaks and their impact on voltage profiles. Optimization algorithms were employed to identify load configurations that maximize supply efficiency, reduce voltage drop risks, and improve overall network stability [21]. This approach proved effective for special loads, which are primary contributors when voltage standard deviation exceeds 2.6 V.

4. Results

The results of this study demonstrate the effectiveness of corrective procedures applied to improve voltage stability in low-voltage distribution circuits. PandaPower analyzed accurate data and simulations to identify critical points in the network and evaluate the improvements achieved through different interventions in the network configuration and the transformer.

4.1. Evaluation of the Case of 100 kVA Transformers

Based on Figure 6, we simulated a poor regulator configuration at position 3 with a 10 kW special load at pole 8, Circuit 2. Measurements showed an average voltage of 210.91 V with a standard deviation of 2.76 V (Figure 8), exceeding NTCSE limits 36 times.

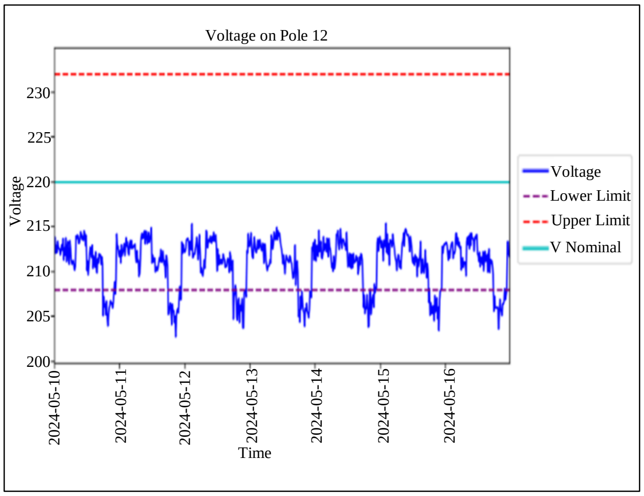

Fig. 8 100 kVA substation with poor product quality, standard deviation of 2.76 V, and average voltage of 210.91 V

Implemented the correction of the voltage regulation by applying Equation (1):

$$V_{N_m} = \frac{210.96 \cdot (1+0.05 \cdot (3-3))}{(1+0.025 \cdot (2-3))}$$

$$V_{N_m} = 216.34\,V$$

Figure 9 demonstrates improved voltage quality post-adjustment, reaching values near calculated predictions. However, the standard deviation (2.68 V) remained above the recommended 2.6 V threshold.

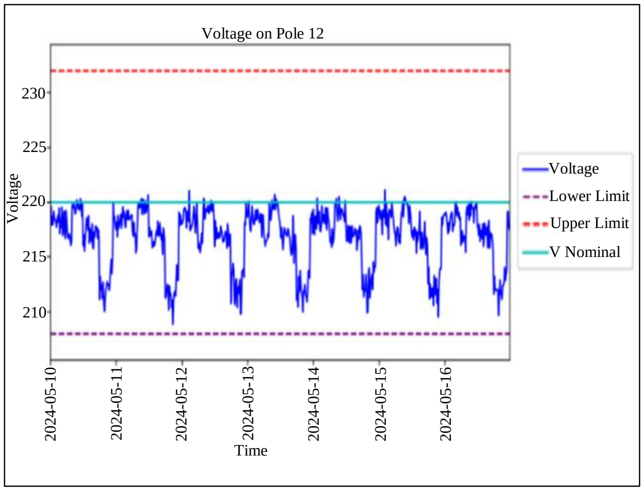

Fig. 9 100 kVA substation with good product quality, standard deviation of 2.68 V, and average voltage of 216.792 V

Contrary to common distribution company practice, which concludes after voltage correction, we implemented a dedicated service line for the special load. This intervention resulted in an average voltage of 217.29 V and a standard deviation of 2.16 V (Figure 10), demonstrating significant stability improvement.

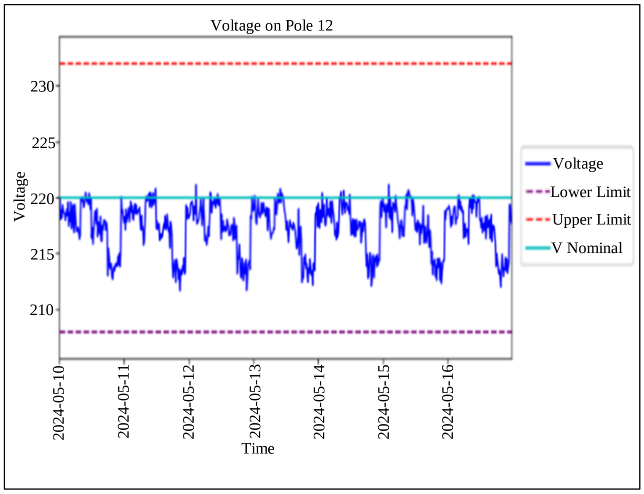

Fig. 10 100 kVA substation with good product quality, standard deviation of 2.16 V, and average voltage of 217.29 V

4.2. Evaluation of the Case of a 25 kVA Transformer

Initial assessment from Figure 7 with regulator position 5 showed an average voltage of 204.36 V and a standard deviation of 0.89 V (Figure 11).

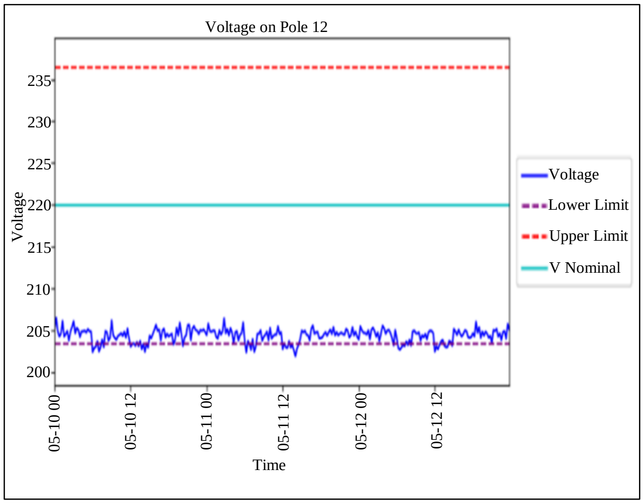

Fig. 11 25 kVA substation with poor product quality, standard deviation of 0.89 V, and average voltage of 204.36 V

Given the low standard deviation, the correction focused solely on adjusting the voltage regulator from position 5 to 2. The target stress was calculated using Equation (1):

$$V_{N_m} = \frac{204.36\cdot(1+0.025\cdot(5-3))}{(1+0.025\cdot(2-3))}$$

$$V_{N_m} = 220.08\,V$$

Post-intervention results Figure 12 demonstrated improved product quality with an average voltage of 220.85 V, closely matching calculated predictions, while maintaining a low standard deviation of 0.76 V.

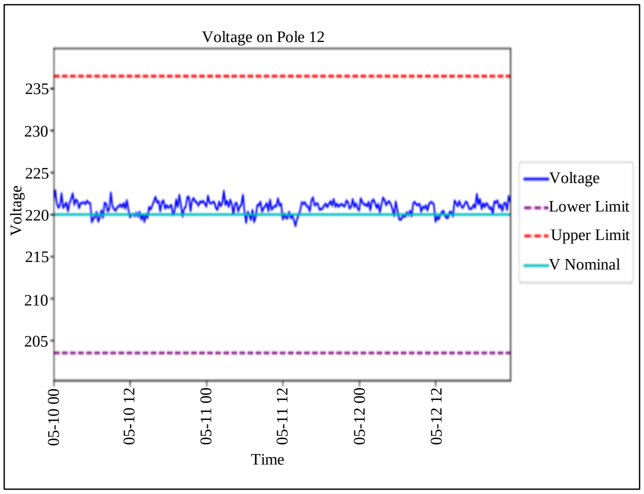

Fig. 12 25 kVA substation with good product quality, standard deviation of 0.76 V, and average voltage of 220.85 V

4.3. Load Distribution Optimization

An optimized load redistribution strategy was implemented to mitigate voltage drops during peak demand hours. Using advanced optimization algorithms, the system was adjusted to minimize peak consumption impact, improve voltage profiles at circuit endpoints, and enhance supply efficiency while reducing voltage drop risks. The simulation findings verified that the voltage drop was significantly reduced while maintaining a standard deviation of less than 2.6 V, which is by NTCSE standards.

4.4. Quality Improvement Procedure for Secondary Distribution Networks

Based on the results, a structured quality improvement framework was implemented. The first step was to review the standard deviation analysis. When the deviation exceeded 2.6 V, attempts were made to identify special loads and service lines installed. For deviations less than or equal to 2.6V, the required changes to the voltage control were implemented as outlined. Having set the corrective actions, they were incorporated into the network. Specifically, the changes to the transformer connections, voltage regulation, and load balance were implemented. The outcomes of the interventions were assessed to determine if the NTCSE quality of service complied with the defined limits, and this was compared with the prior and post-evaluations.

4.5. Pre- and Post-Intervention Voltage Quality Comparison

The last evaluation witnessed a marked enhancement in voltage quality in both test cases. The average voltage for the 100 kVA transformer improved from 210.91 V to 217.29 V, while the standard deviation decreased from 2.76 V to 2.16 V.

Also, the average voltage for the 25 kVA transformer improved from 204.36 V to 220.85 V, while the standard deviation decreased from 0.89 V to 0.76 V. The findings prove that the corrective actions have been implemented successfully, allowing for improved supply quality in urban and rural settings while ensuring low-voltage distribution networks meet regulatory standards. The results also highlight the impact adaptive corrective strategies, for example, changes to the load tap changer and load redistribution, have on voltage stability.

5. Discussion

This research demonstrates that the corrections services implemented via advanced simulations can be effectively used in southern Peru's rural areas with low-voltage electricity networks. The voltage fluctuations and power supply stabilization issues were solved by applying transformer tap changes and voltage-controlled regulators. Such configurations guarantee compliance with the quality standards of NTCSE and enhance service reliability in poorly infrastructure regions.

Comparative analysis with studies conducted in other [22, 23], most developed areas indicates that the strategies of voltage regulation need to be modified to fit the unique circumstances of each distribution network. Compared to Europe, Asia, and North America, where the power quality of service regulation is very rigid, there is a lack of real-time regulatory and monitoring sources like smart grids in rural areas of South America. These economically depressed regions require many more financially viable solutions. In this scenario, transformer outlet changes form a practical and reasonable solution. Reducing fluctuation of the voltage supply eliminates interruptions in the electric power supply, causing an improved quality of service. Also, installing voltage control devices at specific critical locations supports system stability during high-demand periods, such as nightly peak consumption. The outcomes emphasize the necessity for constant and flexible modernization of the power distribution system tailored to the conditions of each region. Such research is instrumental in designing corrective measures for areas with inadequate infrastructure, improving electric service reliability, and fostering sustainable rural community development.

6. Conclusion

This research develops a practical approach to enhance voltage quality in low-voltage distribution networks using corrective measures based on sophisticated simulations. The 2.6 standard deviation value enabled problem zones to be pinpointed precisely while also separating situations that need unique transformer connection configurations from those that can be fixed with tap changes. This approach guarantees compliance with the NTCSE legal framework and improves the quality of service in poorly developed infrastructure areas. The output from the experiments and simulations confirms that this methodology offers economically rational and technologically sound answers to the problem of voltage quality in rural distribution networks.

These findings form a solid basis for power quality management in low-voltage grids, especially in developing regions where resource optimization is critical. In addition, this methodological approach drives technological progress in electricity distribution. It encourages the implementation of sustainable and flexible energy solutions to improve the stability and reliability of the electricity supply in the long term.

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