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# THE EFFECT OF VOLTAGE QUALITY VARIATIONS ON THE PERFORMANCE AND OPERATIONAL LIFESPAN OF ELECTRONIC EQUIPMENT IN THE ELECTRICAL SYSTEM OF EDUCATIONAL BUILDINGS

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***Abstract.*** This study aims to analyze the effect of voltage quality variations on the performance and estimated operational lifespan of electronic equipment. The study uses a quantitative explanatory approach with a field measurement design (in-situ) through the use of a power quality analyzer and supporting instruments. Data were analyzed using descriptive statistics, correlation analysis, and multiple linear regression. The results show that voltage quality variations occur unevenly, with the highest level of disturbances in areas with high electronic load density. Total harmonic distortion (THDv), voltage sag, and voltage unbalance are the most dominant factors influencing performance degradation and accelerating equipment operational degradation. The regression model shows a significant effect with strong explanatory power. This study confirms that voltage quality variations directly impact short-term performance and contribute to equipment operational lifespan reduction through the accumulation of electrical and thermal stress, making power quality management a crucial aspect in improving system reliability and efficiency of educational building facility management.

**Keywords:** Voltage Quality Variation, Electronic Equipment Performance, Operational Lifespan, Educational Buildings

***Abstrak.*** Penelitian ini bertujuan untuk menganalisis pengaruh variasi kualitas tegangan terhadap kinerja serta estimasi umur operasional peralatan elektronik. Penelitian menggunakan pendekatan kuantitatif eksplanatori dengan desain pengukuran lapangan (*in-situ*) melalui penggunaan *power quality analyzer* dan instrumen pendukung. Data dianalisis menggunakan statistik deskriptif, analisis korelasi, dan regresi linear berganda. Hasil penelitian menunjukkan bahwa variasi kualitas tegangan tidak terjadi secara merata, dengan tingkat gangguan tertinggi pada area yang memiliki kepadatan beban elektronik tinggi. Total harmonic distortion tegangan (THDv), *voltage sag*, dan *voltage unbalance* menjadi faktor paling dominan yang memengaruhi penurunan kinerja serta mempercepat degradasi operasional peralatan. Model regresi menunjukkan pengaruh yang signifikan dengan daya jelaskan yang kuat. Penelitian ini menegaskan bahwa variasi kualitas tegangan berdampak langsung terhadap kinerja jangka pendek dan berkontribusi terhadap penurunan umur operasional peralatan melalui akumulasi stres listrik dan termal, sehingga pengelolaan kualitas daya menjadi aspek penting dalam meningkatkan keandalan sistem dan efisiensi pengelolaan fasilitas bangunan pendidikan.

**Kata Kunci:** Variasi Kualitas Tegangan, Kinerja Peralatan Elektronik, Umur Operasional, Bangunan Pendidikan

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## INTRODUCTION

The rapid digital transformation of educational environments has substantially increased the concentration of sensitive electronic loads within building electrical systems, including computers, servers, networking devices, UPS units, inverter-based air-conditioning systems, and laboratory equipment. While investments in digital infrastructure continue to expand, improvements in internal power quality management often lag behind, creating a structural imbalance between load characteristics and voltage supply conditions. As a result, facility managers face growing difficulty in making informed operational and maintenance decisions due to limited understanding of how voltage quality issues affect equipment reliability in real conditions. Consequently, educational buildings are increasingly exposed to voltage disturbances that undermine equipment performance, despite appearing technologically advanced (Alawasa & Al-Badi, 2024).

Voltage quality disturbances such as harmonics, voltage sag, and voltage unbalance do not always cause immediate equipment failure, but instead impose cumulative electrical and thermal stress that gradually degrades performance and shortens operational lifespan. In educational settings where electronic devices operate continuously and simultaneously, even minor voltage deviations can propagate system-wide inefficiencies, disrupt learning activities, and increase maintenance costs. This positions voltage quality not merely as a technical issue, but as a key consideration in operational planning and facility management (Samuel et al., 2025).

Previous studies have documented the sources and characteristics of power quality disturbances in educational and institutional buildings. Alawasa and Al-Badi (2024) identified interactions between UPS systems and fluctuating loads as major contributors to voltage instability, while Samuel et al. (2025) reported elevated harmonic distortion and poor power factor in campus networks. From an equipment perspective, Tabora et al. (2024) and Stanko et al. (2025) showed that voltage variations reduce efficiency and increase thermal stress, while Iqbal et al. (2020) and Kumar et al. (2022) demonstrated that modern electronic devices themselves can be dominant sources of harmonics.

Despite these contributions, existing research largely examines power quality either at the system level or at the level of individual equipment, with limited integration of multiple voltage disturbance effects on both performance degradation and equipment lifespan. This fragmentation constrains the usefulness of prior findings for facility managers responsible for reliability planning and asset management. Addressing this gap, the present study provides an integrated, in-situ analysis of how multiple voltage quality disturbances jointly influence equipment performance and estimated operational lifespan in educational buildings, offering a more practical evidence base to support operational decision-making and power quality management in digitally intensive facilities.

## METHOD

This study used a quantitative explanatory approach with an in-situ field measurement design to capture voltage quality under real operating conditions in an educational building. Measurements were conducted at the main panel, sub-panels, and selected end-use locations to represent the electrical distribution path and daily operational variations. The research setting involved buildings with intensive use of sensitive electronic equipment, including computers, projectors, networking devices, UPS units, inverter-based air-conditioning systems, and laboratory instruments. Samples were selected purposively based on usage intensity, electrical sensitivity, and operational importance.

The independent variable was voltage quality variation, measured through steady-state voltage deviation, voltage sag, voltage swell, voltage unbalance, and total harmonic distortion of voltage (THDv). The dependent variables were equipment performance and estimated operational lifespan, assessed through indicators of operational stability, abnormal events, temperature rise, and cumulative operational degradation. Data were collected using a power quality analyzer supported by electrical and thermal measurement instruments. Data analysis included descriptive statistics, assumption testing, and multiple linear regression to examine partial and simultaneous effects, with model significance evaluated at a 0.05 level using t-tests, F-tests, and the coefficient of determination ($R^2$). The main instrument was a portable power quality analyzer capable of in-situ monitoring of voltage quality parameters in low-voltage AC systems. The analyzer should support RMS voltage measurement, event logging, voltage unbalance measurement, harmonic analysis, and timestamped disturbance recording.

**Table 2.** Standards and Methodological References Supporting Field Measurement

| Reference | Methodological role | Application in the study |
|---|---|---|
| IEC 61000-4-30:2025 | Power-quality measurement methods | Guides in-situ measurement of voltage magnitude, dips, swells, interruptions, unbalance, harmonics, and related parameters. |
| IEC 61000-4-7 | Harmonics and interharmonics measurement guidance | Supports harmonic-measurement procedure and interpretation of waveform distortion. |
| IEEE 1159-2019 | Recommended practice for monitoring electric power quality | Provides standardized terminology and event interpretation for power-quality disturbances. |
| Alawasa & Al-Badi (2024) | Recent campus case study | Supports the use of field monitoring at multiple nodes in an academic building. |

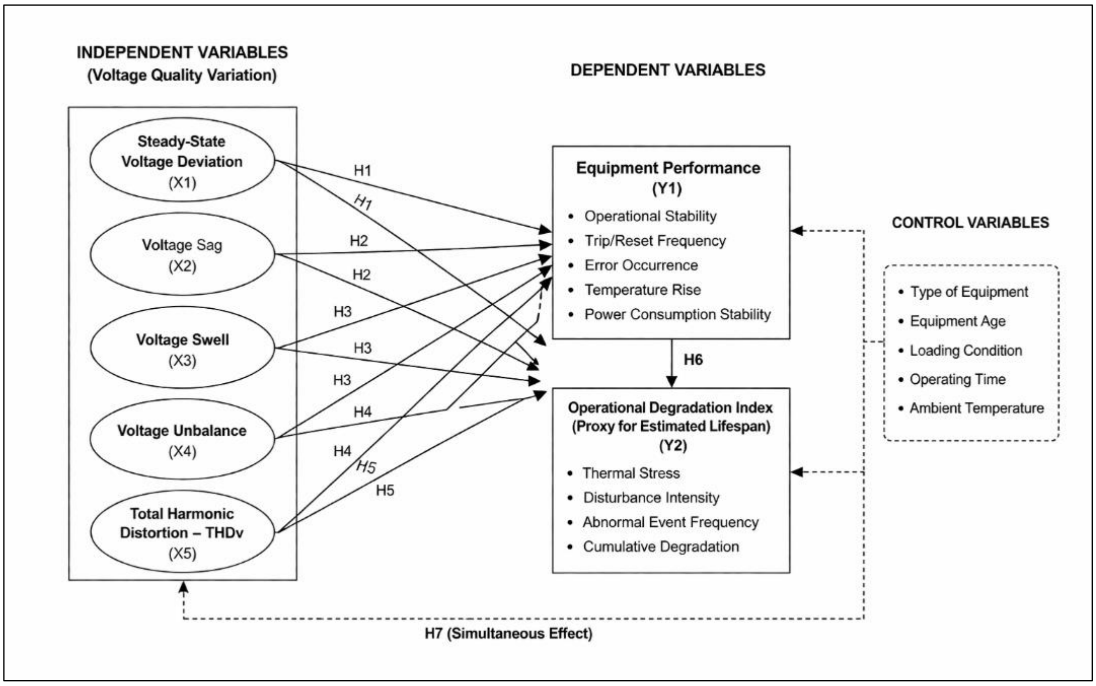

**Figure 1.** Conseptual Framework

This study conceptualizes voltage quality variation as the independent variable influencing both electronic equipment performance and equipment operational lifespan within educational building electrical systems. Voltage quality variation is represented by five key indicators: steady-state voltage deviation (X1), voltage sag (X2), voltage swell (X3), voltage unbalance (X4), and total harmonic distortion of voltage (THDv) (X5). These indicators were selected because they reflect the most frequent power quality disturbances in buildings dominated by electronic and nonlinear loads. Variations in these parameters are expected to directly affect how electronic equipment operates under normal and stressed electrical conditions.

Equipment performance (Y1) serves as the first dependent variable and refers to the ability of electronic devices to operate stably and reliably. It is measured through indicators such as operational stability, frequency of trips or resets, occurrence of operational errors, temperature rise, and power consumption stability. Increased voltage quality disturbances are expected to reduce operating stability, increase malfunction frequency, and intensify thermal stress. The second dependent variable is the operational degradation index (Y2), which represents the estimated operational lifespan of equipment. Rather than measuring lifespan in years, this index reflects cumulative degradation resulting from repeated electrical and thermal stress, assessed through disturbance intensity, abnormal event frequency, thermal stress, and accumulated degradation effects. The framework assumes a direct relationship between equipment performance and operational degradation, where declining performance signals increasing degradation that may shorten lifespan. Control variables, including equipment type, age, loading condition, operating duration, and ambient temperature, are incorporated to account for technical and environmental influences. Overall, the framework illustrates that voltage quality variation affects equipment lifespan both directly and indirectly through its impact on equipment performance.

## RESULTS AND DISCUSSION

### Voltage Quality Variation Profile

his section describes the profile of voltage quality variation measured at several strategic points in the electrical system of the educational building. Measurements were conducted at the main distribution panel, sub-distribution panels, and selected end-use equipment locations supplying electronic devices in classrooms, laboratories, and administrative areas. The observed parameters included steady-state voltage deviation, voltage sag, voltage swell, voltage unbalance, and total harmonic distortion of voltage (THDv). The objective of this analysis was to identify the distribution pattern of voltage disturbances and to determine areas with the highest exposure to power quality issues.

Overall, voltage quality conditions varied noticeably across the electrical system. The main distribution panel showed relatively stable conditions, indicating that the incoming supply was generally reliable. In contrast, disturbance levels increased at downstream panels and end-use locations, particularly in areas with dense electronic loads and long daily operating hours. Computer laboratories and administrative spaces exhibited more frequent voltage sag events, higher voltage deviation, and increased harmonic distortion, reflecting the influence of nonlinear loads and simultaneous equipment operation.

The detailed measurement results for each observation point are summarized in Table 3. The most critical condition was observed at End-Use Equipment Point 1, which recorded the highest values for nearly all voltage quality indicators, including steady-state voltage deviation, voltage sag frequency, voltage unbalance, and THDv. Other locations, such as the computer laboratory and administration room panels, also showed high disturbance levels, while classroom-related points tended to fall within a moderate category. These results confirm that voltage quality variation was not uniformly distributed and tended to intensify closer to sensitive electronic equipment, providing an important basis for explaining differences in equipment performance and operational degradation in subsequent analyses.

**Table 3.** Profile of voltage quality variation at each measurement point

| **Measurement Point** | **Steady-State Voltage Deviation (%)** | **Voltage Sag (events)** | **Voltage Swell (events)** | **Voltage Unbalance (%)** | **THDv (%)** | **Condition Category** |
|---|---|---|---|---|---|---|
| Main Distribution Panel | 1.8 | 2 | 1 | 0.9 | 2.4 | Normal |
| Computer Laboratory Panel | 4.6 | 7 | 2 | 1.8 | 5.8 | High |
| Classroom Panel | 3.2 | 4 | 1 | 1.3 | 4.1 | Moderate |
| Administration Room Panel | 4.1 | 6 | 2 | 1.6 | 5.0 | High |
| End-Use Equipment Point 1 | 4.9 | 8 | 3 | 2.0 | 6.3 | High |
| End-Use Equipment Point 2 | 3.8 | 5 | 2 | 1.4 | 4.7 | Moderate |

### Performance Condition of Electronic Equipment

This section describes the performance condition of electronic equipment operating in the educational building under the observed voltage quality profile. Equipment performance was evaluated using five indicators: operational stability, trip or reset frequency, error occurrence, temperature rise, and power consumption stability. This analysis aimed to identify patterns of vulnerability across different equipment groups and to examine how operating conditions changed in response to varying levels of voltage disturbance. In general, equipment located in areas with moderate voltage disturbance, such as classrooms and administrative offices, demonstrated relatively better performance. Classroom projectors and office devices maintained high operational stability, experienced fewer trip or reset events, and showed limited temperature rise. These results suggest that under moderate voltage variation, electronic equipment can still operate within acceptable performance limits, although minor instability remains evident through occasional resets and fluctuating power consumption.

A detailed summary of equipment performance indicators is presented in Table 4. The table shows that equipment positioned closer to end-use points with higher THDv, more frequent voltage sag events, and greater voltage unbalance exhibited lower operational stability, higher trip or reset frequency, and increased thermal response. In particular, UPS-supported end-use PCs and inverter-based air-conditioning units recorded the weakest performance profiles. Overall, these findings confirm that deterioration in voltage quality is directly reflected in measurable declines in equipment performance, reinforcing the practical impact of voltage disturbances in educational building environments.

**Table 4.** Performance Condition of Electronic Equipment

| Equipment Group | Operational Stability (%) | Trip/Reset Frequency (events) | Error Occurrence (incidents) | Temperature Rise (°C) | Power Consumption Stability |
|---|---|---|---|---|---|
| Computer Laboratory PCs | 86 | 6 | 5 | 11.8 | Moderate |
| Classroom Projectors | 90 | 3 | 3 | 8.6 | Moderate |
| Routers and Network Switches | 88 | 5 | 4 | 9.7 | Moderate |
| UPS-Supported End-Use PCs | 82 | 8 | 6 | 13.2 | Low |
| Inverter Air-Conditioning Units | 85 | 4 | 3 | 12.4 | Low-Moderate |
| Office Printers and Admin Devices | 91 | 3 | 2 | 7.9 | Stable |

### Operational Degradation Index as a Proxy for Estimated Lifespan

This section describes the operational degradation index as a proxy for the estimated operational lifespan of electronic equipment. The index was constructed from four components, namely thermal stress, disturbance intensity, abnormal event frequency, and cumulative degradation, which were normalized on a scale from 0 to 1. Higher index values indicate a stronger tendency toward operational degradation and an increased risk of reduced equipment durability. This approach allows lifespan risk to be assessed not by chronological age, but by accumulated electrical and thermal stress experienced during operation.

Overall, the results indicate that equipment exposed to more severe and frequent voltage disturbances tends to exhibit higher degradation tendencies. UPS-supported end-use devices recorded the highest operational degradation index, reflecting intense thermal stress, repeated abnormal events, and strong exposure to voltage instability. Computer laboratory PCs followed with similarly elevated degradation levels, driven by frequent resets, increased temperature rise, and sustained harmonic distortion. In contrast, administrative electronics, network devices, and classroom projectors showed moderate degradation tendencies, suggesting that while stress accumulation was present, it was less severe than in high-risk end-use equipment.

A detailed comparison of degradation components across equipment groups is presented in Table 5. The table shows clear differentiation between high, moderate, and low degradation categories, with LED lighting-support devices consistently exhibiting the lowest index values. These findings confirm that operational lifespan risk emerges primarily through repeated electrical disturbances and cumulative thermal effects rather than equipment age alone. Consequently, voltage quality variation contributes not only to short-term performance degradation, but also to the gradual weakening of equipment durability in educational building environments.

**Table 5.** Operational degradation index by equipment group

| Equipment Group | Thermal Stress | Disturbance Intensity | Abnormal Event Frequency | Operational Degradation Index | Category |
|---|---|---|---|---|---|
| Computer Laboratory PCs | 0.68 | 0.74 | 0.70 | 0.71 | High |
| UPS-Supported End-Use Devices | 0.79 | 0.82 | 0.81 | 0.81 | High |
| Classroom Projectors | 0.52 | 0.49 | 0.46 | 0.49 | Moderate |
| Administrative Electronics | 0.61 | 0.66 | 0.58 | 0.62 | Moderate |
| Routers and Network Devices | 0.57 | 0.63 | 0.60 | 0.60 | Moderate |
| LED Lighting-Support Devices | 0.38 | 0.42 | 0.35 | 0.39 | Low |

*Note. Index categories were interpreted as low (<0.45), moderate (0.45–0.69), and high (≥0.70).*

## The Effect of Voltage Quality Variation on Equipment Performance and Estimated Lifespan

The final stage of the analysis evaluated the effect of voltage quality variation on equipment performance and the operational degradation index using correlation analysis and multiple linear regression. This analysis aimed to determine the direction and strength of the relationship between each voltage quality parameter and the two dependent variables, as well as to identify the most influential electrical stressors affecting equipment condition.

The correlation analysis shows a clear and consistent pattern. Voltage sag, voltage unbalance, and total harmonic distortion of voltage (THDv) exhibited strong correlations with both equipment performance and the operational degradation index. Negative correlation coefficients with equipment performance indicate that increasing disturbance severity was associated with declining operational stability, while positive correlations with the degradation index suggest a higher tendency toward long-term deterioration. In contrast, voltage swell and steady-state voltage deviation showed weaker and less consistent relationships, indicating a comparatively smaller role in influencing equipment condition. A detailed overview of these relationships is presented in Table 6.

**Table 6.** Correlation between Voltage Quality Indicators and the Dependent Variables

| **Independent Variable** | **r with Y1 (Equipment Performance)** | **p-value** | **r with Y2 (Operational Degradation Index)** | **p-value** |
|---|---|---|---|---|
| Steady-State Voltage Deviation (X1) | -0.71 | 0.003 | 0.68 | 0.005 |
| Voltage Sag (X2) | -0.82 | <0.001 | 0.79 | <0.001 |
| Voltage Swell (X3) | -0.49 | 0.042 | 0.45 | 0.058 |
| Voltage Unbalance (X4) | -0.76 | 0.002 | 0.73 | 0.003 |
| THDv (X5) | -0.85 | <0.001 | 0.83 | <0.001 |

The regression analysis further strengthened these findings. For equipment performance, the regression model produced an R² value of 0.832, indicating that 83.2% of performance variation could be explained by the voltage quality parameters. THDv emerged as the most dominant predictor, followed by voltage sag and voltage unbalance, all of which had significant negative coefficients. A similar pattern was observed in the second model for the operational degradation index, which yielded an R² value of 0.816. In this model, THDv again showed the strongest positive influence, followed by voltage sag and voltage unbalance, confirming their role as the main contributors to cumulative degradation. The detailed regression results for both dependent variables are summarized in Table 7.

**Table 7.** Multiple linear regression results for equipment performance (Y1) and operational degradation index (Y2)

| **Variable** | **β for Y1** | **Sig.** | **Interpretation for Y1** | **β for Y2** | **Sig.** | **Interpretation for Y2** |
|---|---|---|---|---|---|---|
| Steady-State Voltage Deviation (X1) | -0.214 | 0.067 | Not significant | 0.229 | 0.058 | Not significant |
| Voltage Sag (X2) | -0.331 | 0.011 | Significant | 0.317 | 0.015 | Significant |
| Voltage Swell (X3) | -0.118 | 0.184 | Not significant | 0.102 | 0.211 | Not significant |
| Voltage Unbalance (X4) | -0.274 | 0.028 | Significant | 0.248 | 0.039 | Significant |
| THDv (X5) | -0.389 | 0.004 | Significant | 0.402 | 0.003 | Significant |
| Model Fit | $R^2 = 0.832$ | $F = 26.71$; $p < 0.001$ | Strong model | $R^2 = 0.816$ | $F = 23.84$; $p < 0.001$ | Strong model |

Overall, these results confirm that voltage quality variation has both statistically significant and practically meaningful effects on electronic equipment in educational buildings. THDv represents the most critical factor, consistently influencing short-term performance decline and long-term operational degradation, while voltage sag and voltage unbalance act as major complementary stressors. These findings indicate that improving equipment reliability and extending operational lifespan requires focused power quality management, particularly through harmonic mitigation, reduction of voltage sag events, and improved phase load balancing within building electrical systems.

## Discussion

### Uneven Distribution of Voltage Quality Variation in Educational Building Electrical Systems

The results indicate that voltage quality variation in the educational building was not distributed evenly across the electrical network. The main distribution panel remained relatively stable, while the computer laboratory panel, the administration room panel, and the end-use equipment points showed noticeably higher values of steady-state voltage deviation, voltage sag frequency, voltage unbalance, and THDv. This pattern suggests that the deterioration of voltage quality became more visible as the measurement point moved closer to concentrated electronic loads. Such a result is consistent with the study of Alawasa and Al-Badi, who found that power quality disturbances in an academic institution did not emerge uniformly, but were associated with particular nodes where nonlinear loads, variable-speed systems, and electronic conversion devices were concentrated (Alawasa & Al-badi, 2024). The present findings therefore confirm that, in educational buildings, disturbance intensity is shaped more by local load composition than by the upstream condition of the network alone.

Another implication of the non-uniform disturbance pattern is that it reflects the heterogeneity of usage cycles in educational buildings. The electrical profile of a classroom, a computer laboratory, and an administration room cannot be treated as equivalent because their occupancy schedules, intensity of device use, and load combinations differ substantially. Alawasa and Al-Badi emphasized that time-varying loads and interacting equipment types contribute to the emergence of complex power quality signatures in academic settings (Alawasa & Al-badi, 2024). Samuel et al. likewise showed that local operational conditions affect the severity of disturbance at different campus supply points (Samuel et al., 2025). Therefore, the present study suggests that the observed differences among panels were not simply technical anomalies, but rather a structural consequence of how the building is used. In this sense, voltage quality variation becomes a functional issue linked to room activities and equipment clustering.

Taken together, these results provide an important foundation for the interpretation of the next analytical stages. Because the distribution of disturbance was spatially uneven, any decline in equipment performance or increase in operational degradation should also be expected to vary by location. The findings therefore strengthen the argument that educational building power quality analysis should move beyond a single-node diagnostic approach and instead adopt a location-sensitive perspective that links disturbance intensity with load sensitivity and room function. This conclusion is strongly supported by the campus-based evidence of Alawasa and Al-Badi, the multi-point distribution findings of Samuel et al., and the load-identification framework of Yi et al. (Alawasa & Al-badi, 2024; Samuel et al., 2025; Yi et al., 2024). In practical terms, the present study shows that the most relevant intervention points are not necessarily at the main supply, but at the downstream zones where sensitive loads are concentrated.

## Harmonic Distortion and Nonlinear Loads as the Main Sources of Voltage Quality Degradation

Among all measured parameters, THDv emerged as the most persistent indicator of disturbance, particularly at the computer laboratory panel, the administration room panel, and end-use equipment points. This pattern indicates that harmonic distortion is not incidental, but structurally embedded in the electrical environment of the educational building. Previous studies provide a clear explanation for this condition. Iqbal et al. (2020) demonstrated that switch-mode power supplies generate time-varying current harmonics, a characteristic shared by most computers, monitors, chargers, and networking devices commonly used in educational facilities. As a result, the building’s digital infrastructure functions not only as a major electricity consumer, but also as a continuous source of waveform distortion.

In addition to IT equipment, lighting systems contribute to the observed harmonic environment. Wantuch and Olesiak (2023) showed that LED lighting behaves as a nonlinear load and affects voltage quality parameters. Given the extensive use of LED lighting across classrooms, laboratories, offices, and corridors, harmonic distortion in educational buildings should be understood as the cumulative effect of multiple electronic subsystems operating simultaneously. This explains why elevated THDv values were consistently recorded in occupied zones, reflecting an integrated disturbance mechanism rather than isolated equipment-related issues.

Compared to short-duration voltage swell events, harmonic distortion appears more deeply embedded in daily building operation. Harmonic-producing loads such as switch-mode power supplies, UPS units, and LED drivers operate continuously or semi-continuously, whereas swell events are typically episodic. This interpretation is consistent with the findings of Iqbal et al. (2020) and Kumar et al. (2022), which highlight the persistent nature of harmonics generated by modern electronic equipment. Overall, the findings indicate that voltage quality degradation in educational buildings is primarily driven by the nonlinear characteristics of contemporary digital and administrative technologies. Consequently, harmonic distortion should be treated as a primary power quality concern in educational facility management, requiring targeted mitigation strategies rather than being regarded as a secondary technical issue.

## The Effect of Voltage Quality Variation on Electronic Equipment Performance

The results indicate that locations exposed to higher voltage quality variation also tended to show weaker equipment performance, particularly in terms of operational instability, more frequent trip or reset events, higher error occurrence, and increased temperature rise. This pattern suggests that equipment performance in educational buildings is highly responsive to the local electrical environment. The significance of this result is supported by Tabora et al., who demonstrated that voltage variation can alter electrical and thermal performance by changing operating efficiency, power factor, and temperature behavior (Júnior et al., 2024). Although their study focused on permanent-magnet synchronous motors, the core implication remains relevant: deviation from nominal voltage conditions changes how equipment consumes and converts electrical energy, which can destabilize its operation. In the current study, such a mechanism helps explain why panels with poorer voltage quality were associated with weaker performance indicators at the end-use level.

The link between voltage quality degradation and temperature rise is especially important because temperature was one of the clearest performance indicators in the present results. Stanko et al. found that degraded power quality in office devices increased both energy consumption and device temperature (Stanko et al., 2025). This is directly relevant to educational buildings, where computers, displays, routers, printers, and related administrative devices operate for long periods in densely occupied rooms. The current findings show that the highest disturbance zones also corresponded to the highest temperature rise and lower operational stability, which implies that poor voltage quality imposes not only electrical stress but also thermal stress on sensitive equipment. From a performance perspective, this is critical because rising temperature often precedes more visible symptoms such as malfunction, unexpected shutdown, or reduced operating reliability.

Therefore, the findings of this study support the argument that voltage quality variation has a direct and operationally meaningful effect on the day-to-day performance of electronic equipment in educational buildings. The decline in operational stability, the increase in trip or reset frequency, and the rise in temperature should be understood as interconnected responses to supply quality deterioration. This interpretation goes beyond a purely descriptive reading of the results because it identifies a mechanism linking local power conditions to device behavior. Consistent with Tabora et al., Stanko et al., and Rodrigues et al., the present evidence indicates that equipment performance cannot be evaluated in isolation from the surrounding electrical environment (Júnior et al., 2024; Rodrigues et al., 2022; Stanko et al., 2025). In educational buildings, where continuity and reliability are essential for academic activities, this relationship is particularly consequential.

## Operational Degradation as an Early Indicator of Reduced Equipment Lifespan

One of the main contributions of this study lies in positioning the operational degradation index as a practical proxy for estimating equipment lifespan under real operating conditions. Rather than treating power quality impacts as immediate failure events, this study aligns with existing technical literature in viewing equipment deterioration as a cumulative process driven by repeated electrical and thermal stress. The finding that areas with higher levels of voltage disturbance also exhibit higher operational degradation index values confirms earlier evidence that long-term reliability loss is more closely associated with sustained exposure to abnormal conditions than with isolated extreme events. In this sense, the present study confirms and operationalizes established degradation concepts within the specific context of educational buildings.

At the same time, the results extend prior work by shifting the focus from upstream components to end-use equipment commonly found in educational facilities. While Seddik et al. (2024) demonstrated that harmonic-rich environments accelerate transformer aging through increased losses and elevated temperatures, this study shows that a comparable degradation mechanism is already observable at downstream equipment points. Similarly, the thermal and loss-related effects of harmonic currents reported by Radwan-Pragłowska et al. (2024) provide a theoretical foundation for interpreting the higher degradation index values recorded in zones with persistent distortion. By applying these principles to classrooms, laboratories, and administrative spaces, the study expands the empirical scope of power quality degradation research beyond traditional infrastructure-focused analyses.

Furthermore, this study complements disturbance tolerance frameworks such as those proposed by Yao et al. (2025) by emphasizing repeated exposure rather than single-event severity. The operational degradation index integrates disturbance intensity and abnormal event frequency, allowing cumulative stress to be assessed in relation to typical operating limits. This approach does not claim to predict exact remaining service life, but it offers an early-warning perspective that bridges measured voltage quality issues and long-term reliability risks. As such, the study both confirms established degradation mechanisms and extends them by providing a building-level, application-oriented framework tailored to the operational realities of educational institutions.

## Technical and Managerial Implications for Educational Building Electrical System Management

The findings of this study have important technical and managerial implications because they demonstrate that voltage quality deterioration in educational buildings is strongly linked to routine infrastructure and operational choices, not merely to external grid disturbances. This interpretation is reinforced by the work of Gutierrez-Ballesteros et al. (2022), who showed that commonly used devices, particularly LED lighting systems, can induce voltage fluctuations and quality problems such as flicker. The consistency between their findings and the present results strengthens the conclusion that everyday electrical loads play a significant role in shaping voltage quality conditions in educational buildings. Given the extensive use of LED luminaires alongside sensitive electronic equipment, effective power quality management must therefore consider load interaction at the building level, rather than focusing solely on upstream supply components.

This conclusion is further supported by Putz et al. (2019), who demonstrated that disturbances generated by LED lighting systems can be mitigated through appropriate technical measures. Their findings reinforce the interpretation of the present study that the observed disturbance profile is not an unavoidable consequence of digitalization, but a manageable condition. The alignment between prior evidence and the current results underscores that design choices, load placement, filtering strategies, and maintenance practices can significantly reduce waveform distortion and voltage instability. As a result, areas such as computer laboratories and administrative zones, which showed higher disturbance levels in this study, can be systematically improved through targeted interventions.

The energy-management implications are also strengthened by previous research. Phannil et al. (2018) found that harmonic distortion in lighting systems is closely linked to energy consumption behavior, indicating that power quality and energy efficiency are interrelated rather than independent concerns. This finding directly supports the results of the present study, where zones with poorer voltage quality also exhibited reduced performance stability and higher thermal stress. The convergence of these findings emphasizes that improving voltage quality can simultaneously enhance equipment efficiency and durability, reinforcing the need for integrated electrical management strategies in educational buildings.

Finally, the consistency between this study and earlier work by Gutierrez-Ballesteros et al. (2022) and Putz et al. (2019) strengthens the argument for predictive and preventive maintenance. These studies indicate that disturbances caused by distributed electronic devices often accumulate gradually and may not be immediately visible at upstream supply points. The present findings confirm this pattern, as the most severe disturbances were observed at local end-use zones rather than at the main distribution panel. Together, these results provide strong empirical support for shifting maintenance strategies toward routine monitoring of disturbance-prone areas, allowing early detection of rising THDv, sag sensitivity, and operational instability.

In conclusion, supported by consistent evidence from previous studies, the present findings confirm that effective electrical management in educational buildings requires attention to nonlinear load composition, local device interaction, and harmonics-aware design. The convergence between this study and earlier research strengthens the conclusion that improving reliability and equipment longevity depends not only on increasing supply capacity, but also on systematic monitoring, load segregation, and targeted mitigation at the local level.

## CONCLUSION

This study concludes that variations in voltage quality significantly affect both the performance and the expected operational lifespan of electronic equipment in educational buildings. Voltage disturbances tend to concentrate in areas with dense and continuously operating electronic loads, leading to reduced operational stability, higher error rates, increased thermal stress, and a greater risk of long-term degradation. These findings confirm that repeated electrical and thermal stress plays an important role in accelerating equipment deterioration, not just chronological usage.

Overall, the results strengthen existing evidence on the impact of poor power quality while offering a more integrated view by linking multiple voltage parameters to short-term performance and long-term degradation. The study highlights the need for improved power quality management through harmonic mitigation, voltage stabilization, and load balancing, especially in high-load zones. Although limited to a single building and based on estimated lifespan indicators, the findings provide a useful basis for future studies involving broader settings and longer observation periods.

## REFERENCES

Alawasa, K. M., & Al-badi, A. H. (2024). Investigation and Analysis of the Power Quality in an Academic Institution’s Electrical Distribution System. *Energies*, *17*(16), 3998. https://doi.org/10.3390/en17163998

Gutierrez-ballesteros, E., Rönnberg, S., & Gil-de-Castro, A. (2022). Characteristics of voltage fluctuations induced by household devices and the impact on LED lamps. *International Journal of Electrical Power & Energy Systems*, *141*, 108158. https://doi.org/10.1016/j.ijepes.2022.108158

Iqbal, M. N., Kütt, L., Asad, B., Vaimann, T., Rassõlkin, A., & Demidova, G. L. (2020). Time Dependency of Current Harmonics for Switch-Mode Power Supplies. *Applied Sciences*, *10*(21), 7806. https://doi.org/10.3390/app10217806

Júnior, J. M. T., Junior, L. C. dos S., Matos, E. O. de, Soares, T. M., Manito, A. R. A., Tostes, M. E. de L., & Bezerra, U. H. (2024). Exploring the Effects of Voltage Variation and Load on the Electrical and Thermal Performance of Permanent-Magnet. *Energies*, *17*(1), 8. https://doi.org/10.3390/en17010008

Kumar, M., Uqaili, M. A., Memon, Z. A., & Das, B. (2022). Experimental Harmonics Analysis of UPS (Uninterrupted Power Supply) System and Mitigation Using Single-Phase Half-Bridge HAPF (Hybrid Active Power Filter) Based on Novel Fuzzy Logic Current Controller (FLCC) for Reference Current Extraction (RCE). *Advances in Fuzzy Systems*, 5466268. https://doi.org/10.1155/2022/5466268

Phannil, N., Jettanasen, C., & Ngaopitakkul, A. (2018). Harmonics and Reduction of Energy Consumption in Lighting Systems by Using LED Lamps. *Energies*, *11*(11), 3169. https://doi.org/10.3390/en11113169

Putz, Ł., Bednarek, K., & Nawrowski, R. (2019). Disturbances Generated by Lighting Systems with LED Lamps and the Reduction in Their Impacts. *Applied Sciences*, *9*(22), 4894. https://doi.org/10.3390/app9224894

Radwan-Pragłowska, N., Mamcarz, D., Albrechtowicz, P., & Rozegnał, B. (2024). The Current Harmonic Impact on Active Power Losses and Temperature Distribution in Power Cables. *Energies*, *17*(16), 4170. https://doi.org/10.3390/en17164170

Rodrigues, L. M. ., Jr., J. R. M., Gondim, I. N., Rezende, P. H. ., & Xavier, G. L. (2022). Analysis of the sensitivity of electronic active energy meters to voltage sags. *Electric Power Systems Research*, *206*, 107787. https://doi.org/10.1016/j.epsr.2022.107787

Samuel, I. A., Toyin, D. A., Somefun, T. E., Awelewa, A. A., & Abba-Aliyu, S. (2025). Evaluation and improvement of power quality of distribution network : a case study of Covenant University , Ota. *Frontiers in Energy Efficiency*, *2*, 1389622. https://doi.org/10.3389/fenef.2024.1389622

Seddik, M. S., Eteiba, M. B., & Shazly, J. (2024). Evaluating the Harmonic Effects on the Thermal Performance of a Power Transformer. *Energies*, *17*(19), 4871. https://doi.org/10.3390/en17194871

Stanko, P., Regula, M., & Otcenasova, A. (2025). Impact of power quality degradation on energy consumption and temperature rise of office devices. *Electrical Engineering*, *107*(10), 13387–13400. https://doi.org/10.1007/s00202-025-03214-4

Wantuch, A., & Olesiak, M. (2023). Effect of LED Lighting on Selected Quality Parameters of Electricity. *Sensors*, *23*(3), 1582. https://doi.org/10.3390/s23031582

Yao, J., Lv, W., Li, N., & Jiang, T. (2025). Optimized method for testing equipment sensitivity to voltage sags and interruptions based on DC link voltage prediction. *Electric Power Systems Research*, *241*, 111337. https://doi.org/10.1016/j.epsr.2024.111337

Yi, Z., Liangyu, Z., Bijie, L., Jintao, C., & Wenxu, Y. (2024). Voltage sag sensitive load type identification based on power quality monitoring data. *International Journal of Electrical Power and Energy Systems*, *158*(July 2023), 109936. https://doi.org/10.1016/j.ijepes.2024.109936