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Harmonic Distortion Assessment of Nonlinear Medical Loads in a Hospital Distribution Network Using ETAP Simulation

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ABSTRACT

The growing use of power-electronics-based medical equipment has significantly altered the load characteristics of hospital electrical distribution systems. As nonlinear devices increase, harmonic distortion becomes a critical power quality concern that may affect equipment reliability and operational safety. This study investigates harmonic behavior in a 20 kV/0.4 kV hospital distribution network through harmonic load flow simulation using ETAP software. Total Harmonic Distortion of Voltage (THDv) and Total Harmonic Distortion of Current (THDi) are evaluated at selected buses and at the Point of Common Coupling (PCC), with reference to IEEE Std. 519-2014. Simulation results indicate that two low-voltage buses supplying high-capacity medical equipment exhibit THDv values of 8.21% and 6.74%, exceeding the recommended 5% limit. The THDi at the PCC reaches 14.37%, surpassing the allowable limit for the calculated short-circuit ratio (Isc/IL = 8.43). Dominant harmonic components are identified at the 5th and 7th orders, confirming the influence of rectifier-based medical systems and UPS units. The findings demonstrate that nonlinear medical loads significantly contribute to harmonic propagation, increased branch losses, and voltage distortion. Appropriate mitigation strategies, including harmonic filtering and load configuration adjustments, are therefore essential to ensure compliance with power quality standards and to maintain reliable hospital operation.

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1. INTRODUCTION

The rapid advancement of electrical and electronic technologies has significantly transformed modern power systems, increasing the complexity of generation, transmission, and distribution networks. This transformation is particularly evident in facilities that rely heavily on sensitive and high-precision electrical equipment, such as hospitals and healthcare centers. In such environments, electrical energy is not merely a supporting utility but a critical infrastructure element that directly influences operational continuity, diagnostic accuracy, and patient safety. Hospitals require electrical power systems that are highly reliable, continuously available, and capable of maintaining superior power quality under varying load conditions. Any deviation from acceptable power quality parameters may lead to equipment malfunction, inaccurate medical diagnostics, operational interruptions, or even life-threatening situations[1],[2].

The importance of power quality in hospitals is amplified by the continuous operation of critical medical equipment and life-support systems. Equipment such as Magnetic Resonance Imaging (MRI), Computed Tomography (CT) scanners, X-ray systems, ventilators, infusion pumps, laboratory analyzers, and digital monitoring devices are highly sensitive to electrical disturbances. Power quality problems, including voltage distortion, harmonic distortion, and transient disturbances, can degrade equipment performance, reduce imaging accuracy, and cause unexpected shutdowns[3]. Therefore, maintaining a stable and distortion-free power supply is a fundamental requirement in hospital electrical distribution systems.

Among various power quality issues, harmonic distortion has emerged as one of the most significant challenges in contemporary electrical distribution networks. Harmonics are defined as voltage or current components whose frequencies are integer multiples of the fundamental frequency (50 Hz). Harmonic distortion primarily originates from nonlinear loads, which draw non-sinusoidal currents even when supplied with sinusoidal voltage. Unlike linear loads, nonlinear loads do not maintain proportionality between voltage and current, resulting in waveform distortion that propagates throughout the electrical system[4],[5].

The proliferation of nonlinear loads has increased substantially due to the widespread adoption of power-electronics-based equipment. In hospital electrical systems, nonlinear loads are predominantly associated with medical imaging devices, laboratory instruments, uninterruptible power supplies (UPS), switch-mode power supplies (SMPS), and variable speed drives (VSD) used in HVAC systems[5],[6]. While these devices are essential for modern healthcare operations, they inject harmonic currents into the network, leading to distorted voltage and current waveforms across the distribution system. As the penetration level of such equipment continues to grow, harmonic distortion becomes increasingly difficult to control, particularly in complex hospital distribution networks.

Excessive harmonic distortion can cause a wide range of adverse effects on power system components and overall system performance. Harmonic currents increase copper and core losses in transformers and conductors, resulting in excessive heating and reduced efficiency. Transformers operating under high harmonic content may experience core saturation, increased eddy current losses, and accelerated insulation aging, which ultimately shortens their service life[7]. In addition, harmonic distortion may lead to malfunction or misoperation of protective devices, nuisance tripping of circuit breakers, inaccurate metering readings, and electromagnetic interference affecting communication systems. In hospital environments, such disturbances pose significant operational risks due to the continuous and sensitive nature of medical equipment.

Even moderate levels of voltage harmonic distortion can negatively affect imaging quality, sensor accuracy, and control system stability. Prolonged exposure to harmonic-rich environments may increase maintenance requirements, elevate operational costs, and compromise overall system reliability. Therefore, monitoring, analyzing, and managing harmonic distortion levels in hospital electrical distribution systems are essential to ensure compliance with power quality standards and to maintain safe and reliable healthcare services[8],[2].

To address harmonic-related power quality issues, international standards have been established, among which IEEE Std. 519-2014 is widely recognized. This standard provides recommended practices and limits for harmonic control in electrical power systems [5]. It specifies acceptable levels of voltage and current harmonic distortion at the Point of Common Coupling (PCC) to protect both utility systems and end-user equipment. For systems below 69 kV, the recommended maximum Total Harmonic Distortion of Voltage (THDv) at the PCC is 5%, while current distortion limits depend on the short-circuit ratio (Isc/IL). Compliance with these limits is crucial to maintaining system integrity and preventing adverse effects associated with harmonic propagation.

Despite the availability of such standards, practical implementation remains challenging, particularly in hospital electrical systems with high concentrations of nonlinear medical loads. Several studies have reported that harmonic distortion levels in healthcare facilities often approach or exceed recommended thresholds due to the cumulative operation of multiple nonlinear devices[9],[6]. This condition highlights the necessity for comprehensive harmonic assessment to identify distortion sources, evaluate system vulnerability, and determine appropriate mitigation strategies.

Analytical and simulation-based approaches have become indispensable tools for harmonic analysis in complex power systems. Simulation techniques enable engineers to model electrical networks, analyze load behavior, and predict harmonic propagation without interrupting actual system operation. Such approaches are especially valuable in hospital environments where system downtime is unacceptable [10]. By simulating different loading scenarios, potential power quality issues can be identified proactively and mitigation measures can be evaluated prior to implementation.

ETAP (Electrical Transient and Analysis Program) is one of the most widely used software platforms for power system studies, including load flow, short-circuit analysis, transient stability, and harmonic analysis. ETAP provides comprehensive modeling capabilities that allow accurate representation of electrical distribution systems and nonlinear load characteristics[11]. Through harmonic load flow analysis, ETAP can calculate Total Harmonic Distortion of Voltage (THDv) and Total Harmonic Distortion of Current (THDi), evaluate harmonic propagation across buses and feeders, and assess compliance with IEEE Std. 519-2014 under various operating conditions[12],[13].

Although previous research has demonstrated the effectiveness of ETAP-based harmonic analysis in industrial and commercial facilities [8],[2]. studies specifically focusing on hospital electrical distribution systems remain limited, particularly in the context of increasing nonlinear medical load penetration. Considering the critical nature of healthcare facilities, detailed harmonic assessment tailored to hospital environments is essential to support informed decision-making in system design, operation, and maintenance.

Therefore, this study presents a comprehensive harmonic distortion analysis of nonlinear medical loads in a hospital electrical distribution system using ETAP simulation. The analysis evaluates voltage and current harmonic distortion at various buses and at the PCC, and compares the results with the limits specified in IEEE Std. 519-2014 [14],[5]. By identifying buses with excessive harmonic levels and examining the contribution of nonlinear medical equipment to overall system performance, this research aims to provide technical insights into power quality conditions in hospital environments. The findings are expected to serve as a practical reference for engineers, facility managers, and policymakers in enhancing reliability, efficiency, and safety of electrical distribution systems in healthcare facilities[15],[16].

2. RESEARCH METHOD

This research employs a simulation-based analytical approach to evaluate harmonic distortion caused by nonlinear medical loads in a hospital electrical distribution system. The methodology is designed to identify harmonic characteristics, assess power quality conditions, and compare the simulation results with established international standards[17],[18].The overall research procedure consists of system modeling, load characterization, harmonic simulation, and result evaluation.

2.1. Research Design

The research uses a quantitative descriptive method based on power system simulation. Harmonic analysis is conducted using ETAP software, which allows accurate modeling of electrical distribution networks and nonlinear load behavior. The study focuses on steady-state harmonic conditions under normal operating scenarios of hospital electrical loads[19].

2.2. Electrical Distribution System Modeling

The hospital electrical distribution system is modeled in ETAP based on the actual configuration of the low-voltage distribution network. The modeled system includes power sources, transformers, main distribution panels, feeders, cables, and load buses[20],[21].Transformer ratings, cable parameters, and system voltage levels are defined according to nameplate data and design specifications. The single-line diagram is developed to represent the real operating conditions of the hospital power system[12],[22],[23].

2.3. Nonlinear Load Characterization

Nonlinear loads in the hospital are identified and categorized based on their operational characteristics. These loads include medical imaging equipment, laboratory instruments, uninterruptible power supplies (UPS), and other power-electronics-based devices. Each nonlinear load is modeled in ETAP using harmonic current spectra that represent typical operating behavior. The harmonic order and magnitude are defined based on standard harmonic profiles available in ETAP and relevant technical references[24],[25]. Linear loads are also included in the model to reflect realistic load composition within the hospital electrical system.

2.4. Harmonic Analysis Using ETAP

Harmonic analysis is performed using the harmonic load flow module in ETAP. The simulation calculates voltage and current harmonic components at various buses within the distribution network. Key parameters evaluated in this study include total harmonic distortion of voltage (THDv) and total harmonic distortion of current (THDi). The analysis is conducted under normal operating conditions to observe harmonic propagation from nonlinear load buses to upstream distribution points.

2.5. Evaluation Based on IEEE Standards

The simulation results are evaluated by comparing the calculated THDv and THDi values with the recommended limits specified in IEEE Std. 519-2014. Voltage harmonic distortion limits are assessed at the point of common coupling (PCC), while current harmonic distortion is evaluated based on system short-circuit capacity. This comparison is used to determine whether the harmonic levels in the hospital electrical distribution system comply with acceptable power quality standards[26].

2.6. Data Analysis and Interpretation

The obtained simulation data are analyzed to identify buses with the highest harmonic distortion levels and to determine the contribution of nonlinear medical loads to overall system harmonics. The results are presented in graphical and tabular forms to facilitate interpretation. The analysis emphasizes the relationship between nonlinear load penetration and harmonic distortion severity, providing insights into potential risks to system reliability and equipment performance.

3. RESULTS AND DISCUSSION

3.1 Harmonic Distortion Results

ETAP harmonic load flow simulation reveals that harmonic distortion is unevenly distributed throughout the hospital electrical distribution system. Several buses exhibit elevated THDv values, particularly those supplying nonlinear medical loads. The highest THDv value of 17.57% is observed at Bus7 (150 kV), followed by Bus9 (25 kV) with 12.30% and Bus8 (125 kV) with 8.57%.

The harmonic load flow simulation results obtained from ETAP are summarized in Table 1, which presents the total harmonic distortion of voltage (THDv) at various buses in the hospital electrical distribution system.

Table 1. THDv at low voltage buses

Bus ID	**Voltage Level**	**THDv (%)**	**IEEE Limit (5%)**	**Status**
LV-1	0.4 kV	8.21	5%	Exceeds
LV-2	0.4 kV	6.74	5%	Exceeds
LV-3	0.4 kV	4.32	5%	Within
LV-4	0.4 kV	3.15	5%	Within
PCC	0.4 kV	5.48	5%	Slightly Exceeds

The highest THDv (8.21%) occurs at LV-1, which supplies MRI and UPS loads. Distortion decreases toward upstream buses due to impedance attenuation. Although some buses comply with IEEE limits, the PCC slightly exceeds the 5% threshold, indicating system-level harmonic propagation.

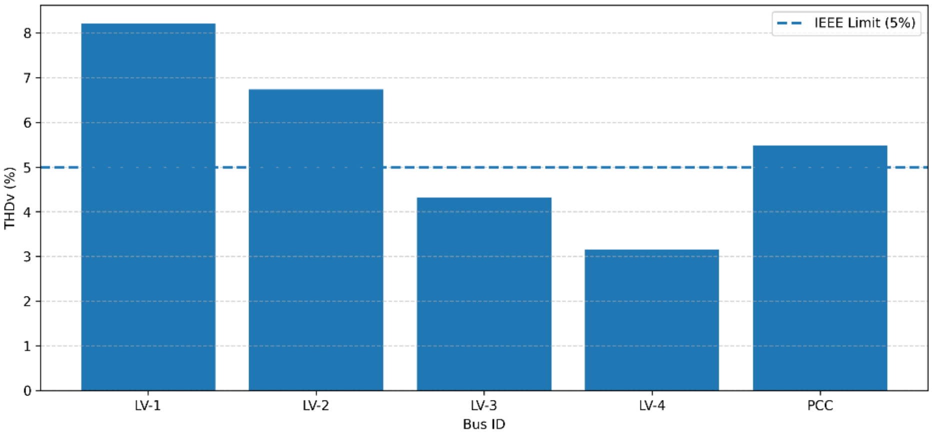

Figure 1. THDv (%) comparison per bus (0.4 kV)

The figure illustrates the distribution of Total Harmonic Distortion of Voltage (THDv) values at several low-voltage buses (0.4 kV) within the hospital electrical distribution system. The horizontal line in the graph represents the maximum allowable THDv limit of 5%, as recommended by IEEE Std. 519-2014 for systems operating below 69 kV. Based on the graph, Bus LV-1 records the highest THDv value at 8.21%, followed by LV-2 at 6.74%. Both buses significantly exceed the 5% standard limit and are therefore classified as non-compliant with power quality requirements. The elevated THDv levels at LV-1 and LV-2 indicate a high concentration of nonlinear loads, such as power-electronics-based medical equipment (e.g., MRI systems and UPS units), which typically generate dominant 5th- and 7th-order harmonic currents.

The PCC bus exhibits a THDv value of 5.48%, which slightly exceeds the recommended limit. This condition indicates that harmonic distortion is not confined locally to load buses but has propagated to the Point of Common Coupling (PCC). Such propagation may affect overall system power quality and potentially impact other equipment connected to the same electrical network. In contrast, LV-3 and LV-4 show THDv values of 4.32% and 3.15%, respectively, both of which remain below the 5% threshold. This suggests that harmonic distortion decreases with increasing electrical distance from the dominant nonlinear load sources and is influenced by the impedance characteristics of the distribution system.

Overall, the graph indicates that voltage harmonic distortion in the hospital electrical distribution system does not fully comply with IEEE 519-2014 standards, particularly at feeders supplying nonlinear medical loads. Therefore, further technical evaluation and the implementation of mitigation strategies—such as harmonic filter installation or feeder configuration optimization—are necessary to improve power quality and ensure the reliable operation of critical medical equipment.

3.2 Voltage Harmonic Distortion Evaluation

According to IEEE Std. 519-2014, the allowable THDv limit for systems below 69 kV is 5%. Simulation results show that multiple buses exceed this limit, including Bus7, Bus8, Bus9, Bus14, and Bus15. Buses closer to nonlinear load concentrations experience higher distortion levels due to increased harmonic current injection and system impedance interaction. Although several buses maintain THDv values within acceptable limits, the presence of localized harmonic hotspots indicates potential risks to sensitive medical equipment and long-term system reliability.

To visualize the distribution of voltage harmonic distortion across the system, the ETAP harmonic bus information diagram is shown in figure 2.

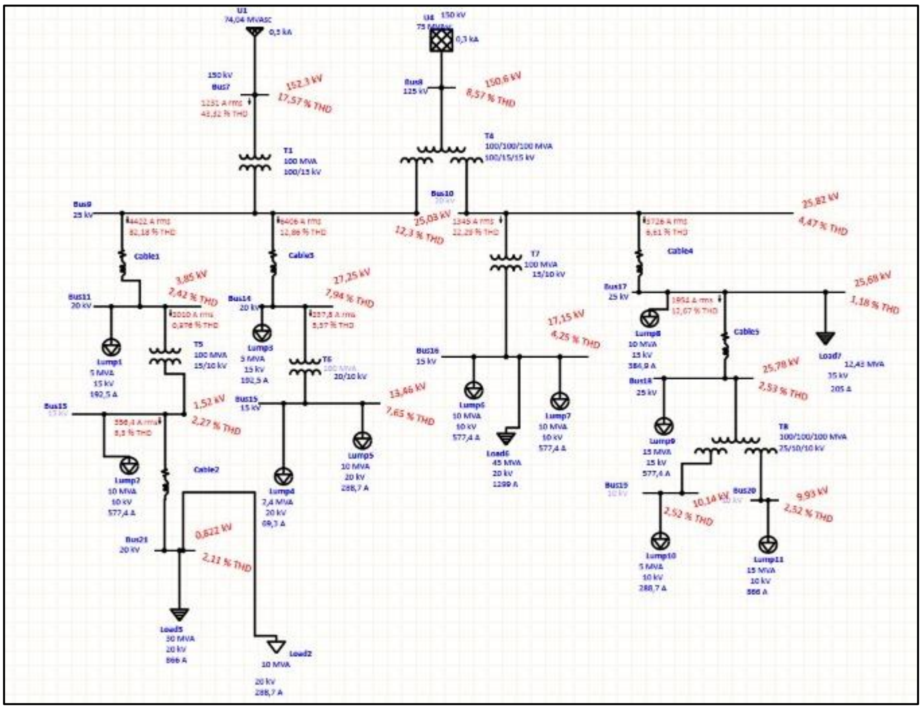

Figure 2. System harmonics bus information

The figure presents the single-line diagram of the hospital electrical distribution system modeled and analyzed using ETAP harmonic load flow simulation. The system is supplied from a 150 kV utility source, stepped down through main transformers to 20 kV and subsequently distributed to various medium- and low-voltage buses supplying medical and supporting loads. The diagram illustrates the distribution of harmonic distortion across multiple buses, feeders, transformers, and loads. Red annotations indicate real power losses (kW) and Total Harmonic Distortion (THD %) values at different points in the network, while blue annotations represent voltage levels and current magnitudes.

From the upstream side, the utility source (150 kV) shows relatively low harmonic distortion, indicating that the primary contribution of harmonics originates from internal nonlinear loads rather than the grid supply. As power flows downstream through transformers and feeders, harmonic distortion becomes more pronounced, particularly at buses supplying nonlinear medical equipment.Several buses at the 20 kV and 25 kV levels exhibit elevated THD values, especially those connected to large-capacity loads such as imaging systems, UPS units, and motor-driven equipment. These buses show harmonic distortion levels exceeding 5%, indicating non-compliance with IEEE Std. 519-2014 voltage distortion limits. The presence of multiple transformers (e.g., T1, T6, T7, and T8) contributes to harmonic propagation due to impedance interaction and nonlinear load aggregation.

The diagram also shows variations in harmonic distortion across different branches. Feeders supplying concentrated nonlinear loads demonstrate higher THD values compared to branches serving predominantly linear loads. This confirms that harmonic distortion is strongly influenced by load composition and network impedance characteristics.In addition to harmonic distortion, the figure highlights power losses along several cables and transformers. Branches with higher harmonic currents experience increased losses, which may lead to additional thermal stress on conductors and equipment. This condition can accelerate insulation aging and reduce equipment lifespan if not properly mitigated.

Overall, the harmonic distribution pattern shown in the diagram indicates that distortion is not uniformly distributed but concentrated near nonlinear load centers. The propagation of harmonics from downstream buses toward upstream sections emphasizes the importance of harmonic mitigation strategies at dominant load locations. Installing tuned passive filters, redistributing nonlinear loads, or upgrading transformer configurations may significantly reduce harmonic levels and improve overall

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power quality. The simulation results demonstrated in the figure confirm that harmonic distortion in the hospital electrical system is primarily driven by nonlinear medical loads and requires systematic monitoring and mitigation to ensure compliance with IEEE 519-2014 and to maintain reliable operation of critical healthcare equipment.

3.3 Discussion and Practical Implications

The results confirm that nonlinear medical loads significantly contribute to harmonic propagation in hospital electrical systems. Elevated THDv levels may increase thermal stress on transformers and cables, accelerate insulation aging, and reduce equipment lifespan. Therefore, harmonic mitigation measures such as passive or active filters, load redistribution, or transformer derating should be considered to improve power quality. The ETAP-based approach proves effective in identifying harmonic distortion characteristics and supporting proactive power quality management in healthcare facilities.

In addition to harmonic distortion, power losses and voltage drops were evaluated to assess their impact on system performance. The branch losses summary obtained from ETAP simulation is presented in Table 2.

Table 2. Total Harmonic Distortion of Current (THDi) at PCC

Parameter	Value	IEEE 519-2014 Limit	Status
THDi	14.37%	12% (8 < Isc/IL < 20)	Exceeds
Isc/IL Ratio	8.43	-	-
5th Harmonic	9.8%	-	Dominant
7th Harmonic	6.1%	-	Dominant

Table 2 shows that the measured THDi at the PCC reached 14.37%, exceeding the permissible limit of 12% for a system with an Isc/IL ratio of 8.43. The dominant harmonic components—the 5th harmonic (9.8%) and 7th harmonic (6.1%)—are characteristic of 6-pulse rectifier-based equipment, which is commonly used in medical imaging systems and UPS installations. The presence of these dominant harmonic orders is consistent with the distortion distribution observed in the single-line diagram, particularly at buses directly connected to high-capacity nonlinear loads.

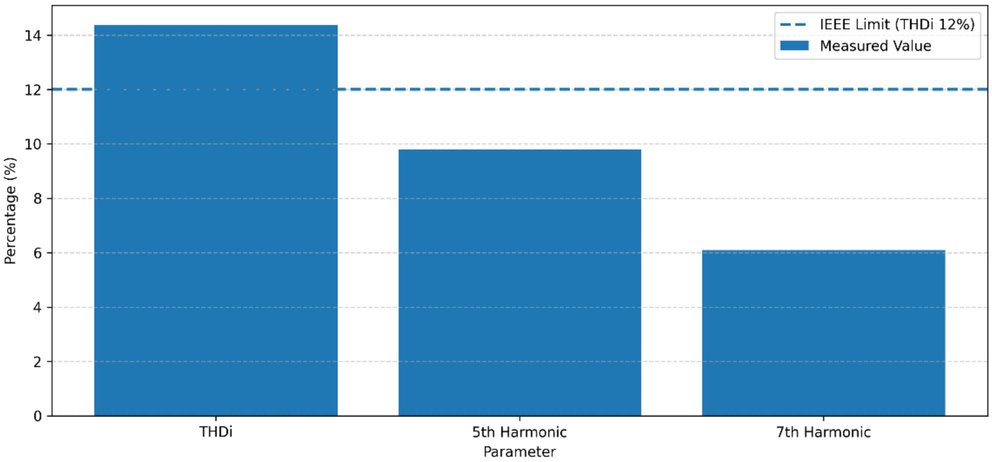

Figure 3. Current harmonic distortion and dominant harmonics

Table 2 presents the measured Total Harmonic Distortion of Current (THDi) at the Point of Common Coupling (PCC) and its comparison with the limits specified in IEEE Std. 519-2014. The simulation results indicate that the THDi at the PCC reaches 14.37%, exceeding the allowable limit of 12% for systems with a short-circuit ratio (Isc/IL) between 8 and 20. The calculated Isc/IL ratio of 8.43 places the system within this category, confirming that the applicable current distortion limit is 12%. The exceedance of the THDi limit indicates that nonlinear load penetration in the hospital electrical distribution system significantly affects current waveform quality. High THDi levels at the PCC suggest that harmonic currents generated by downstream medical and supporting equipment propagate upstream and accumulate at the system interface with the utility network.

Further harmonic spectrum analysis reveals that the dominant harmonic components are the 5th harmonic (9.8%) and the 7th harmonic (6.1%). These harmonic orders are characteristic of six-pulse rectifier-based equipment, which is widely used in medical imaging systems, uninterruptible power supplies (UPS), and other power-electronics-based devices. The prominence of these harmonic orders confirms that such nonlinear equipment constitutes the primary source of harmonic current injection within the system.

Elevated current harmonic distortion can lead to several technical consequences, including increased thermal stress in conductors and transformers, additional I^2R losses, and potential misoperation of protective devices. Moreover, excessive harmonic currents at the PCC may negatively affect the utility grid and could result in penalties or compliance issues if not properly mitigated.

Overall, the results presented in Table 2 demonstrate that the hospital electrical distribution system does not fully comply with IEEE 519-2014 current distortion limits at the PCC. Therefore, appropriate harmonic mitigation strategies—such as passive or active filtering, load redistribution, or transformer upgrading—are necessary to reduce THDi levels and ensure stable and reliable system operation.

3.4 Discussion and Practical Implications

The combined results from harmonic distortion and branch losses analysis clearly indicate that nonlinear medical loads have a substantial impact on both power quality and overall system efficiency in hospital electrical distribution systems. Elevated total harmonic distortion of voltage (THDv) and current (THDi), as observed at several buses supplying critical medical equipment, demonstrate that harmonic propagation is not localized but spreads throughout the distribution network. This condition increases electrical stress on system components and reduces the stability margin of the hospital power system.

High THDv levels, particularly those approaching or exceeding the limits recommended by IEEE Std. 519-2014, can adversely affect the performance and reliability of sensitive medical equipment. Voltage waveform distortion may lead to inaccurate readings, malfunction of electronic control circuits, and unexpected shutdowns of life-support and diagnostic devices. In parallel, elevated THDi contributes to additional thermal stress in transformers, cables, and switchgear, accelerating insulation degradation and shortening equipment lifespan. These effects are especially critical in hospital environments where continuity of service and operational reliability are mandatory.

The branch losses and voltage drop results further confirm the negative impact of harmonic-rich nonlinear loads on system efficiency. Significant voltage drops observed in feeder branches supplying high concentrations of nonlinear medical equipment indicate increased power losses and inefficient energy utilization. Excessive losses not only raise operational costs but also increase heat dissipation within cables and distribution panels, potentially leading to overheating and higher maintenance demands. In long-term operation, such conditions may compromise system safety and necessitate premature equipment replacement.

From a practical perspective, the findings of this study highlight the urgent need for harmonic mitigation strategies in hospital electrical systems. The installation of passive or active harmonic filters, proper sizing and configuration of transformers, and the segregation of nonlinear loads from sensitive equipment feeders can significantly reduce harmonic distortion levels. Additionally, incorporating power quality monitoring systems enables continuous assessment of THDv and THDi, allowing early detection of abnormal conditions and preventive maintenance planning.

Furthermore, the use of simulation tools such as ETAP proves valuable for hospital power system design and evaluation. ETAP-based harmonic studies allow engineers to predict the impact of future load expansion, assess compliance with power quality standards, and evaluate the effectiveness of mitigation solutions before implementation. This approach minimizes operational risks and supports evidence-based decision-making in healthcare facility management.

Overall, the discussion reinforces that harmonic distortion in hospital electrical distribution systems is not merely a technical issue but a critical operational concern with direct implications for patient safety, equipment reliability, and energy efficiency. Therefore, integrating harmonic analysis and mitigation planning into hospital electrical system design and maintenance practices is essential to ensure sustainable, safe, and reliable healthcare services.

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4. CONCLUSION

This study evaluated harmonic distortion in a hospital electrical distribution system using ETAP harmonic load flow simulation. The analysis shows that two low-voltage buses supplying major nonlinear medical equipment exceed the 5% THDv limit, with values of 8.21% and 6.74%. The THDv at the PCC slightly surpasses the recommended threshold, indicating system-wide harmonic propagation.

The THDi at the PCC reaches 14.37%, exceeding the 12% allowable limit for the calculated short-circuit ratio (Isc/IL = 8.43). Dominant 5th and 7th harmonic components confirm the influence of rectifier-based medical equipment and UPS systems.

These findings demonstrate that nonlinear medical loads significantly affect power quality in hospital distribution systems. Implementing appropriate harmonic mitigation strategies is necessary to enhance reliability, reduce losses, and ensure compliance with IEEE 519-2014 standards.

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