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Original Article

Data-Driven Evaluation of Power Quality in Hospital Electrical Systems: Case Study of University of Lampung, Indonesia

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Abstract *- Reliability and continuity of electrical power supply are increasingly being recognized as essential for the effective functioning of contemporary healthcare services. Poor Power Quality (PQ) events can reduce the clinical usefulness of medical devices and jeopardize patient health, as well as incur high operating costs. This article reports an extensive PQ analysis at the University of Lampung Hospital (a health and academic services provider) in Indonesia. The research makes use of high-sampling-rate electrical datasets from four sets of data acquired on the Main Distribution Panel (MDP) in the hospital. Important PQ parameters, such as three-phase voltage and current, frequency, power factor, Voltage Unbalance Ratio (VUR), and Total Harmonic Distortion (THD), are systematically calculated. The approach is based on international norms and references for definitions (IEEE 1159), measurement methods (IEC 61000-4-30), and limits compliance (IEEE 519). The findings show stable voltage and frequency characteristics as expected from a good grid service utility. However, PQ problems of importance were observed in the internal distribution system of the hospital, such as voltage level imbalance lasting for longer than permitted in the standard (10%) and current harmonic distortion that was very high, which the Total Demand Distortion (TDD) surpassed many times over the IEEE 519 recommended values for hospitals. A somewhat lagging power factor was noted (indicating quite some loss in electrical efficiency). The present study offers a valuable empirical baseline and quantification of PQ challenges at an important healthcare facility in the planned University of Lampung Hospital. The results emphasize the risks of uncontrolled non-linear loads and confirm the importance of focused measures for load harmonization, such as active harmonic filtering systems and implementation of load equalization plans, which improve the quality, security, and efficiency of power supply in the hospital. For a real-time Internet of Things (IoT) monitoring application, according to the data from question 1, there is a strong positive correlation between electricity consumption and building operation schedule. Weekdays (Monday-Friday, 6:30 AM to 5:30 PM) always have the largest number of peak current loads, with a sharp decrease during weekends. Even though differences in phase were small, the mean voltage was just within the nominal limits.*

Keywords *- Power Quality, Hospital Electrical Systems, Harmonic Distortion, Voltage Unbalance, Power Factor.*

1. Introduction

1.1. The Imperative for High-Fidelity Power in Modern Healthcare Facilities

Healthcare is a special and crucial category of infrastructure where the trustworthiness of basic services is fundamental [1]. Unlike a traditional commercial building, in a hospital, a break or reduction of electrical service can be rapidly and seriously harmful, even deadly. The hospital of the 21st century. There is a high density of highly advanced medical technologies, each operating with microprocessors, including diagnostic imaging apparatus such as Computerized Tomography (CT) and Magnetic Resonance Imaging (MRI), life-support equipment in Intensive Care Units (ICUs), and state-of-the-art surgical instruments [2]. These instruments are a necessity for patient diagnostics and treatment, and yet very sensitive to changes in the power provided [3].

Harsh regulatory standards are in place to prevent serious consequences of power loss. Regulations and standards like the National Fire Protection Association (NFPA's Health Care Facilities Code required the use of the Essential Electrical System (EES) [4]. EES are considered special equipment for providing energy supply for emergency medical loads at the facility, where there was no service from utilities, including through emergency diesel power generators or other alternative sources of electric power by means of fuel cells or UPS. This targeted regulation places the emphasis where it should be: reliable, continuous power is not only an operational nicety but also a fundamental part of patient safety and care delivery.

1.2. Characterizing Power Quality Disturbances and their Impact

Variations of current and voltage from an ideal sinusoidal wave with a given frequency and magnitude were referred to as power quality [5]. The Power Quality Disturbances (PQDs) are a common term for distortions, which encompass a wide range of phenomena. These include both long-term waveform disturbances, such as persistent undervoltages or overvoltages, and short-term waveform disturbances, such as voltage sags, dips, and swells. Low power factor, voltage imbalance, and harmonic distortion are additional significant PQ issues [6].

The effects of these interruptions on delicate [7]. Voltage sags may result in the lockup or reset of equipment, and harmonic distortion could cause transformers and neutral conductors to overheat, leading to early equipment failure and degradation of the control system [8]. From a practical perspective, poor PQ can distort the processing of data in diagnostic instrumentation or modify stored control settings with corresponding misdiagnosis of a patient and misguided medical diagnosis [9]. Over time, the repeated effects of these small electrical phenomena add up and contribute to degradation in electronic components, resulting in intermittent failure modes that are hard to identify until a catastrophic failure happens [10].

1.3. Research Context: The Electrical Environment of the Hospital University of Lampung

There is a growing body of research on PQs and HCF around the world, which has increased with the increase in complications of medical technology and the realized demand for electrical resilience [11].

Substantive empirical studies have been few, but a striking absence has been from the hospitals of Southeast Asia, and especially Indonesia. Some works in the area have been done in Indonesia, for example, a power factor correction research according to the power at a hospital in Yogyakarta, but most of the PQ studies address a single parameter [12]. Other local studies have produced useful benchmarks for energy performance, but not at such a granular level of detail as electrical waveform quality. This gap in knowledge is relevant because local grid conditions, code and standards development, and load shapes differ considerably between areas of the world. Thus, the need for a complete multi-parameter assessment of a large Indonesian hospital is felt, where it can serve as a regional benchmark, and also gives site-specific inputs/suggestions.

1.4. Problem Statement, Objectives, and Contribution of the Study

Problem discussed: The urgent role of power quality in hospitals is well understood from the theoretical point of view; however, adequate long-term comprehensive empirical measurements proving this situation at the main incomer in a large Indonesian university hospital are not readily available. Without this information, facility owners and engineers cannot make valid risk assessments, maintain compliance with world standards, or design cost-effective mitigation.

Objectives: This paper aims to fill this gap through the following objectives:

1. For the statistical analysis of main parameters PQ: voltage, current, unbalance, TDH, power factor, and frequency) by time series, a complete and extensive data set was obtained in MDP Hospital, University of Lampung.
2. To compare the measured PQ indices with boundaries and recommendations of recognized International standards, mainly IEEE 519, to establish the degree of compliance quantitatively.
3. To determine the primary PQ problems that exist in the hospital's electrical system, and deduce from these observed electrical signatures their likely sources, given what is known about typical hospital-load characteristics.
4. To consider the inherent operational risks, safety concerns, and economic inefficiencies identified with regard to the findings and develop focused recommendations based on sound evidence for mitigation and future management.

Contribution: This research finds the first real multivariate power quality analysis at the Hospital University of Lampung, and it provides evidence-based insights for Indonesian and Southeast Asian hospital engineers, administrators, and other researchers. By providing the application for internationally accepted PQ standards for real situations, it will fill a notable void in regional literature and also present an invaluable template for evaluation and enhancement for electrical systems at vital healthcare facilities in developing countries.

2. Basics and Regulations of Power Quality (Review)

To fully comprehend the power quality, one must have a thorough understanding of the entire codes and standards that govern its measurement and control, as well as an understanding of the theory in conjunction with practical test bed experience. Subsequent deep data analysis requires this overview.

2.1 Theoretical Framework of Key Power Quality Indices

Both voltage and current are used in an alternating current power system to deliver energy. Two components make up apparent power (S), which is the total power delivered and is expressed in Volt-Amperes (VA) [13]. The first was real power (P), which is expressed in Watts (W) and is used to do practical tasks like turning a motor or powering a light. The second is reactive power (Q), which is expressed in Volt Amperes Reactive (VAR) and is necessary to generate and maintain the magnetic fields required by inductive loads such as transformers or motors. The relationship between these components was often visualized using the power triangle, where:

S2=P2+Q2

The efficiency of power systems aims to minimize reactive power to ensure that the apparent power is as close to the real power as possible. The Root Mean Square (RMS) value of a waveform is a very critical metric, representing the effective DC equivalent value for producing the same heating effect. For a set of N instantaneous voltage samples (vi) over a cycle [14], the RMS voltage is calculated as:

VRMS=N1i=1∑Nvi2

This value is fundamental to assessing the magnitude of the supply voltage and current.

2.2. Harmonic Distortion in Hospital Power Systems

Sources: Harmonic distortion is the interference of the sinusoidal wave (usually 50 to 60 Hz) due to integral multiplications of that frequency [15]. These harmonics are created by non-linear loads, which do not draw current in a sinusoidal waveform. Today’s hospitals are filled with loads in these categories: Switch-Mode Power Supplies (SMPS) are ubiquitous and found in computers, monitors, and LED lighting; Variable Frequency Drives (VFDs) can be found on HVAC systems [16]; Uninterruptible Power Supplies (UPS). Important examples include: diagnostic imaging systems with high power, such as CT scanners and radiograph machines that can generate very high harmonic currents in the electrical system. A Case Study. There is, however, a case reported in the literature where the current THD was more than 100% for a radiography machine [17].

Effects: High harmonics have serious effects. The harmonic currents produce extra heating in transformers, conductors, and motors, resulting in their improper circuit functioning, as well as reducing their life span [18]. Odd Multiples of the 3rd -Triplen harmonics (odd multiples of the third harmonic, i.e., 3rd, 9^{th}, etc.) are most detrimental since they add constructively in phase in three-phase systems and therefore tend to overheat and even create a fire hazard [19]. The voltage harmonics generated by the harmonic currents circulating through system impedances could lead to mis-operation of sensitive electronic controls, resulting in data corruption and equipment lockup [20].

Metrics: The principal metric to assess harmonic distortion is the Total Harmonic Distortion (THD), which represents the ratio between the RMS value of all harmonics and the RMS value of a fundamental. For the current, it corresponds to:

THDI=I1∑h=2∞Ih2

Although THD is a good representation, it can change significantly with varying loads. The IEEE 519 standard, therefore, supports Total Demand Distortion (TDD) as the primary compliance metric for current distortion [21]. TDD compensates for harmonics and thus makes them relative to the peak demand load current (IL) for an interval, so it gives a more stable meaning of what contribution your system is making with respect to harmonics. 19 It is calculated as:

TDD=IL∑h=2∞Ih2

2.3. Voltage Unbalance and Power Factor

Voltage Unbalance: In an ideal three-phase system, the phase voltages are equal in magnitude and displaced by exactly 120 degrees. When these conditions are not satisfied, voltage unbalance is experienced [22]. The first reason is the unbalanced distribution of single-phase loads among the three phases, a well-known phenomenon in large and complex buildings such as hospitals. There are various definitions, and the most rigorous definition, introduced by IEC, is given in terms of symmetrical components as the Ratio of Negative Sequence Voltage (RNSV) or unbalance ratio, which is a ratio between negative-sequence voltage component (V2) and positive-sequence voltage component (V1) [23].

VUF(%)=∣V1∣∣V2∣×100

Small degrees of voltage unbalance can also have a relatively large detrimental impact on three-phase induction motors, which in turn results in considerable current unbalance, overheating, lower efficiency, and early failure [24].

Power Factor: Power Factor (PF) is the ratio of real power (P) to apparent power (S), indicating how effectively electrical power is used [25]. An ideal PF is 1.0 (unity), indicating that all supplied power is delivered to productive work. A low PF value is indicative of a high reactive power component, which in turn requires the utility to deliver a greater amount of apparent power (and therefore, current) to transmit the same amount of real power. This has several negative effects:

- Economic Fines: A majority of utilities charge financial fines to commercial and industrial customers with PF below some threshold value, usually 0.90 or 0.95 [26].
- Higher System Losses: Larger current demanded by the low PF increases resistive (I2R) losses in cables

and transformers, which converts part of the energy to heat [27].

- Reduced System Capacity: A low PF is equivalent to a reduction in transformer and conductor capacity since they are sized based on apparent power (kVA). Enhancement of the PF can "release" room for more loads, without the need for expensive infrastructure expansion [28].

2.4. The Role of International Standards in Power Quality Assessment

A verifiable PQ analysis depends on a point of reference for the characterization, quantification, and assessment of disturbances. There are three important international standards that underpin modern PQ measurement. IEEE 1159: The IEEE Recommended Practice for Monitoring Electric Power Quality provides a basic 'vocabulary' of definitions relating to power quality [29].

It offers definitions and categories of electromagnetic phenomena, which involve transients, short- and long-term voltage variations (sags, swells, interruptions), imbalance in voltages, and distortion of waveform [30]. By providing a common nomenclature, IEEE 1159 guarantees that engineers and researchers are talking about the same phenomena, which is essential in comparative and troubleshooting analysis [31].

IEC 61000-4-30 - IEEE 1159 indicates what to measure, and IEC 61000-4-30 defines how to properly and repeatably make those measurements [32]. This benchmark is crucial as the results obtained by different instruments may differ substantially when they employ different algorithms or time windows [33]. IEC 61000-4-30 describes accurate methods to calculate PQ parameters and defines integration periods (e.g., ~200ms, 3 seconds, 10 minutes) as well as accuracy classes. Level A is the highest accuracy level and is what you need for contractual applications or settling disputes where similar measurements are required. Compliance with these measurement principles is a necessary condition before compliance can be tested with other standards [34]. IEEE 519: The IEEE standard for harmonic control in power systems is used as the controlling reference standard concerning the harmonic level. It sets maximum individual levels for the distortion of voltage even (THDv) and current distortion (TDD) in the Point of Common Coupling (PCC), the boundary between the utility service provider and its customers [35].

The philosophy of the standard is mutual responsibility, such that end-users need to restrict how much harmonic current they inject, and in return, a utility provides a reasonably low level of voltage distortion [36]. Obviously, as implemented in the industrial world (and defined by IEEE 519), limits are higher for sensitive facilities and are forced to address even if no impact on customers was expected due to safety and reliability concerns [12, 35, 43, 44].

This is where these standards fit together. This has obvious implications that to validly assess whether a hospital meets IEEE 519 limits can only be achieved if the data on which this assessment is based have been collected and processed in an IEC style (Amantea, Ilaria Angela. "Risk and regulatory compliance: tools for analysis and managing in the healthcare industry: 'Hospital at Home-HaH'." (2022).), by means of IEEE 1159 standard definitions. This systematic approach transforms a PQ survey from a routine data collection exercise to a scientifically justifiable study.

2.5. State-of-the-Art in Power Quality Monitoring and Analysis

PQ management was developed from manual, occasional measurements with portable analyzers for the use of permanent, real-time measurement systems [38]. Such advanced systems are capable of continuously monitoring all critical electrical quantity parameters through an array of sensors and also power quality meters [39]. This approach also has numerous benefits, including early fault detection prior to failure, precise information for better energy management, an optimized maintenance schedule, and automated data collection for ensuring regulatory compliance [40].

The future of PQ monitoring also depends on combining AI and Machine Learning (ML) technology [41]. The big data produced by various kinds of continuous monitoring systems are ideal candidates for ML-based analysis. Algorithms such as One-Class Support Vector Machine (OCSVM) [42] and Isolation Forest can be run locally on sensor nodes with low computational overhead to do real-time anomaly detection. It enables very quick detection of variations from normal operation, which will be dealt with in a proactive PQ management scheme, detecting and highlighting potential problems before they have an impact on sensitive processes [43].

2.6. Review of Power Quality Case Studies in Healthcare Settings

A review of existing literature reveals consistent patterns in the PQ challenges faced by healthcare facilities. Several investigators have recognized diagnostic imaging departments as one of the most significant harmonic polluters. A different research reported that the THD levels at the PCC of a radiology installation were above the limits established by the IEEE 519 standard [35] in their case, prompting them to design a shunt active filter for harmonics reduction. Another survey at a hospital in Sweden revealed that, although most PQ values were acceptable, the power factor was persistently low and could be solved by adding capacitor banks. One study in Indonesia examined the application of capacitor banks to remedy a low power factor and high level of power losses at a large hospital [12]. Reliability of emergency power systems is another common topic, observing the importance of considering the particular stresses due to non-linear loads when sizing and testing backup generators [44]. These combined studies provide a background of expected results for this study: hospitals are electrically complex environments that tend to experience a considerable level of harmonic distortion and low power factor, conditions that threaten both the reliability of normal as well as emergency power systems.

3. Data Provenance and Methodology

This part describes the origins of the collected data, where it was measured, and what meticulous analysis techniques were carried out in order to evaluate the power quality at the University Hospital of Lampung.

3.1. Description of the Measurement Locus and System

The data used in this study were obtained from the Main Distribution Panel (MDP) at the Hospital University of Lampung. This point serves as the Point of Common Coupling for the hospital site, being the connection between the main public utility grid and the internal power distribution network inside the hospital [45]. The monitoring at the PCC is the common measurement method for the evaluation of global power quality of a system and to check compliance with regulations such as IEEE 519, which prescribes its limits at this location [46]. The electrical system is a three-phase four-wire system with a nominal phase-neutral voltage of 220V and line-line voltage of 380V, which runs at a fundamental frequency of 50 Hz that is typical for the Indonesian grid [47].

The experiment in this research focused on the Main Distribution Panel (MDP) in the hospital, as the main link for the electricity distribution of power to the different sub-panels and loads in the hospital building. In this research, a Schneider PM2230 digital power meter was used to capture the electrical quantities on the MDP panel. This instrument records the important three-phase parameters like the line-to-line (L-L), line-to-neutral voltages (L-N), frequency, and power factor. A Modbus RS-485-to-Ethernet converter was used for data transmission, creating a scenario in which the industrial meter standard was connected to the centralized monitoring server at the University of Lampung data center.

This converter transforms the serial output of the Digital Power Meter into TCP/IP so that the real-time data can be sent through the hospital's Wireless Local Area Network (WLAN). Node-RED was used for gathering electrical quantities data from the Power Meter. This open source tool was based on the Node.js framework, and it provided the visual information to manage the data flows. Node-RED retrieves the data using Modbus TCP protocols, reads the data from hardware sensors, and saves it in the database system. The MySQL server was used to store the data. Python was used for scientific computing, for post-processing, and for statistical analysis. The Pandas library was used for cleaning and structuring the raw logs, and this included corrections of timestamp alignments and data format normalization from the database. Matplotlib and Seaborn libraries in Python were used for obtaining visual representations that were high-resolution and reproducible.

3.2. Characterization of the Electrical Load Datasets

The material basis of this paper includes four existing database sets, representing each different capture period. They provide high time resolution (30 s) with the Time-Series retaining a record of main electrical entities at MDP from 2025-08-10 to 2025-08-18. The parameters that have been logged for each dataset:

- Three-Phase Currents: RMS values for each phase (I_R, I_S, I_T).
- Three-Phase Line-to-Line Voltages: RMS values (V_R, V_S, V_T).
- Three-Phase Phase-to-Neutral Voltages: RMS values (VN_R, VN_S, VN_T).
- System Frequency: Measured in Hertz (Hz).
- Power Factor: A dimensionless value representing the overall efficiency of power usage.

The interval between data logging for these datasets provides a detailed granularity to study not only long-term loading profiles but also short-term variations, allowing the entire electrical behaviour of the hospital to be analysed.

3.3. Data Integrity and Analytical Methodology

A standard and systematic procedure was used to avoid the reality of the result.

Pre-processing: The raw data from the four datasets were first integrated and pre-processed. This involved pre-processing the fields on each parameter to be used in computations for datatype normalization, processing missing or anomalous data points (sensor errors and logging failures), and confirming that the timestamps were not corrupted.

Analytical Approach: The essence of the methodology was to establish the engineering equations and statistical methodologies in accordance with international guidelines.

Voltage Unbalance Factor (VUF): This was computed using the symmetrical components method, as specified by standard IEC [48], for providing a more accurate evaluation of the voltage asymmetry value. The unbalanced three-phase voltage phasors (VA, VB, and VC) are broken down into their positive (V1), negative (V2), and zero sequence components using this method. The ratio of positive and negative sequence components magnitudes is the VUF, where $a=1\angle 120\circ$:

$$V1=31(VA + aVB + a2VC)$$
$$V2=31(VA + a2VB + aVC)$$
$$VUF(\%)= |V1|\ |V2| \times 100$$

This method is more rigorous than easy methods as it includes both magnitude and its phase angle variations.

- Harmonic Analysis: These were calculated using standard definitions of Total THD (Total Harmonic Distortion) and also TDD (Total Demand Distortion) [49] as defined on standard IEEE 519 for both current and voltage. The investigation comprised the determination of total distortion and an assessment of the harmonic content in order to determine the magnitude of each individual order.

- Statistical Analysis: Descriptive statistics, including the mean, median, min-max, and standard deviation, were computed for all relevant QoL parameters to give a quantitative overview of their values over the period of monitoring [50]. Time series plotting was widely applied to display daily and weekly patterns, to reveal cyclic behaviour in the hospital load profile, and outlier events [51].

The phase of the analysis was based on the reasoning that one cannot reliably judge to what extent compliance is being observed without a standardised measure. The RMS determination and its integration over time are as described in the procedures of IEC 61000-4-30.

For example, analyzing data over standardized intervals in the present study assures that each THD and TDD value obtained is immediately comparable with the IEEE 519 [52] limits.

In order to produce results that are not only accurate but also repeatable and defendable to the greater scientific and engineering community, this methodological rigor is necessary.

4. Empirical Analysis of Power Quality at the Hospital MDP

4.1. Voltage and Current Profile Analysis

A time-series analysis of the three-phase currents indicates a well-defined and predictable load profile that is typical for hospital sites. The draw requirements always peak during operating hours (9 AM - 5 PM) when clinical activities and the use of diagnostic equipment, as well as HVAC consumption, are at their highest. The load drops considerably during the night and on weekends, when fewer outpatient activities and administrative tasks take place.

The phase-to-neutral voltage waveforms show strong stability. Voltages were well maintained at a nominal 220V, with only slight fluctuations even at times of highest current drain. This demonstrates that the upstream utility and PPF are strong and of sufficient size to support the load conditions on the hospital while still maintaining voltage regulation in normal operating mode.

4.1.1. Phase-to-Neutral Voltage Profile (VN_R, VN_S, VN_T)

This is a per-phase voltage across the neutral. The main results, based on Figure 1, are even more emphasized compared to the previously considered cases:

- Severe and Persistent Imbalance: There is a very clear and consistent voltage imbalance. `VN_T` (green) is always the highest, followed by `VN_S` (orange), and `VN_R` (blue) is consistently the lowest.
- Critical Voltage Drop Event: There is a significant event where the voltage in Phase R (`VN_R`) drops to zero for an extended period. This indicates a potential phase loss or a very severe fault, which is a major power quality issue.

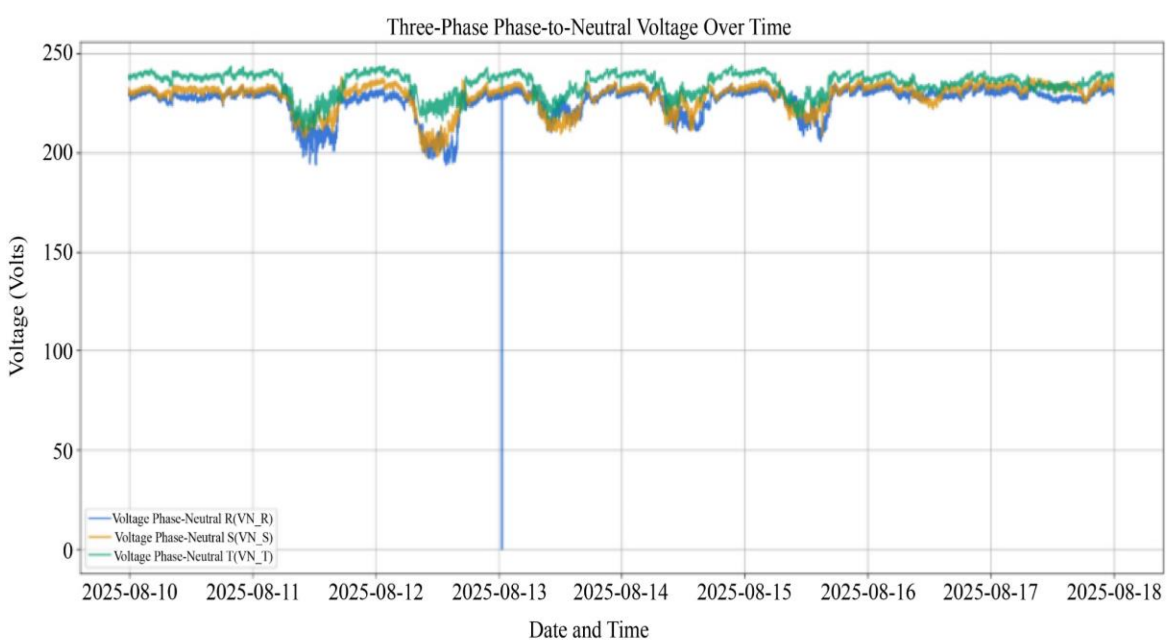

Fig. 1 Phase-to-neutral voltage profile (VN_R , VN_S, VN_T)

Table 1. The statistics provide precise numbers that confirm the visual findings

Metric	VN_R (Volts)	VN_S (Volts)	VN_T (Volts)
Mean	226.16	228.70	235.09
Std Dev	7.13	6.67	5.60
Min	0.00	197.84	210.29
Median (50%)	228.54	231.06	237.14
Max	235.64	237.90	243.63

4.1.2. Three-Phase Voltage Profile (V_R, V_S, V_T)

Figure 2 shows the time series chart plots of three-phase voltages over time. The following are some key conclusions drawn from Figure 2:

- General Stability: In contrast to current, voltage is always present in all three phases.
- Voltage Imbalance: The voltage imbalance was identified, where Phase S (V_S) and Phase T (V_T) voltages were always higher than Phase R (V_R).
- Voltage Drops: From Figure 2, it is also identified that the three phases exhibit distinct intervals with lower voltages. This drop event is not an inappropriate action for the power system (the higher the load value, the greater the impact on the larger voltage drop), but it was likely at the same times of day as the high current draw found in the previous analysis.

There are patterns of potential changes, reflecting the activities of Hospital operations. During the weekdays, Monday to Friday, the voltage is more stable from the evening until early morning, but sees a precipitous drop around 6:30 AM.

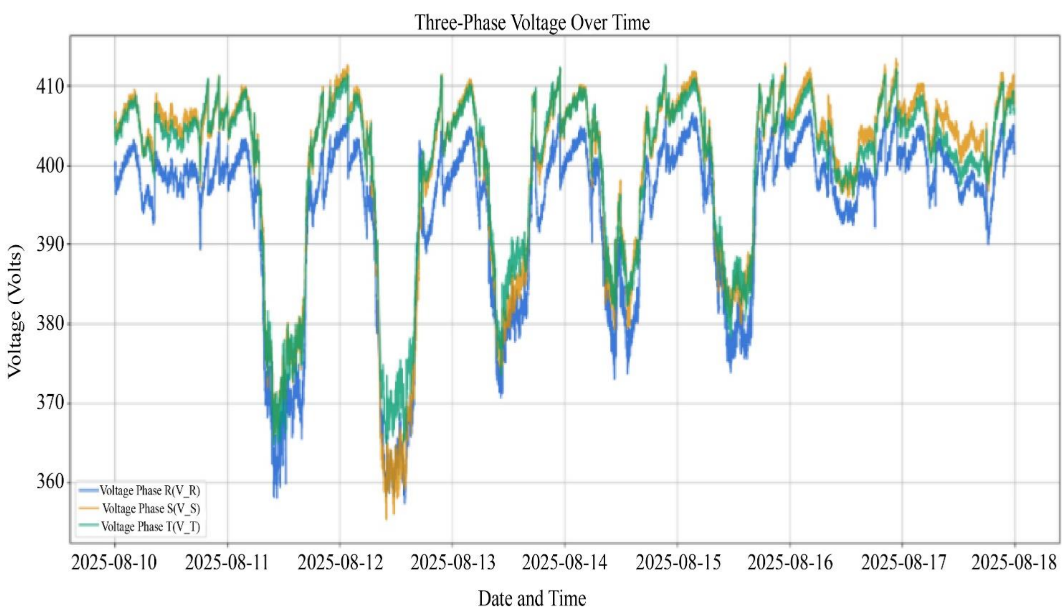

Fig. 2 3-phase voltage profile (VR, V_S, V_T)

Table 2. A statistical summary provides a more precise look at the voltage characteristics

Metric	V_R (Volts)	V_S (Volts)	V_T (Volts)
Mean	394.55	400.25	400.12
Std Dev	10.40	11.25	10.07
Min	357.30	355.27	364.70
Median (50%)	398.32	404.49	403.88
Max	407.92	413.38	412.71

This decrease reflects an increase in electrical load for turning on electrical equipment in buildings, including computers, lighting, air conditioning systems, etc. Oh, and here is where voltage drop persists all the way until the AAVS peaks in late afternoon, simultaneously with maximum electricity consumption for lectures and Hospital purposes. It then level off again past 5:30 PM as the working load recedes in the building. This trend is valid for all five working days of the week (Monday-Friday), which proves that electricity load is strongly dependent on building operational time. Moreover, it is also observable that values for voltage are minimum on Tuesdays as compared to the rest of the weekdays. Electricity

Tuesday, Most Gooding, ID, electrical power systems are actively running during a medical facility building on Tuesday.

4.1.3. Three-Phase Current Profile Analysis (I_R, I_S, I_T)

Each phase (R, S, and T) current was plotted for the duration. This is a raw display of information on the electrical charge dynamics. We notice the large load imbalance immediately from the plot, for a significant part of the recorded time, Phase R (I_R) actually loads while Phase S (I_S) and Phase T (I_T) have almost zero current. This implies that the Main Distribution Panel loads are not perfectly balanced among the three phases, which can create waste and put a strain on the electrical system. Towards the end of the period, all three types exhibit a more uniform and dynamic action.

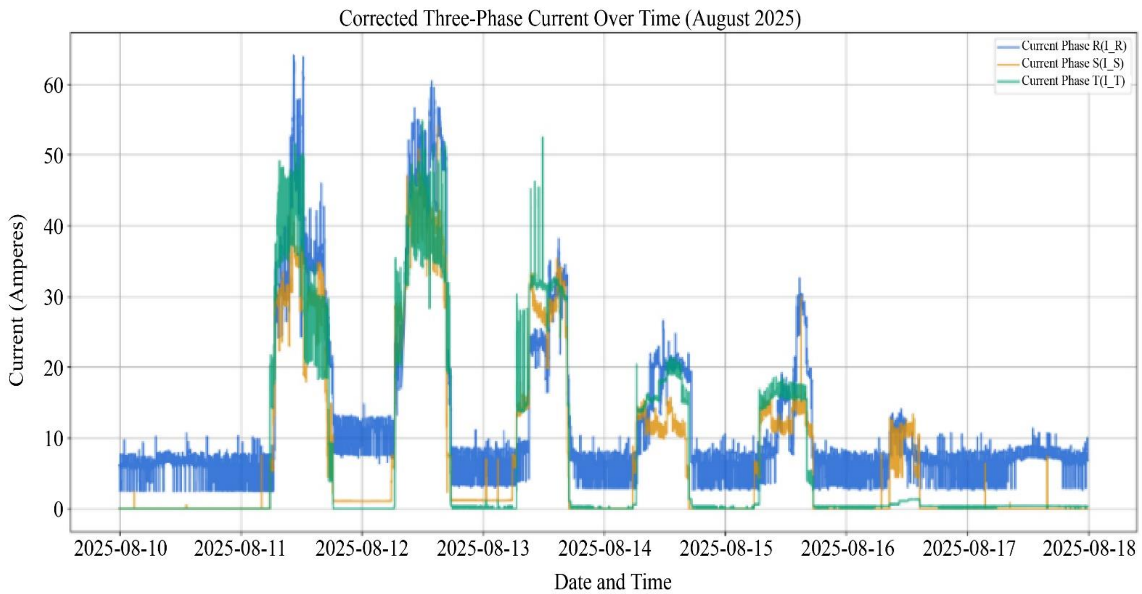

Fig. 3 Three-phase current profile analysis (I_R, I_S, I_T)

Table 3. Descriptive statistics. Here is a summary of the key statistics for each phase

Metric	I_R (Amps)	I_S (Amps)	I_T (Amps)
Mean	11.81	6.22	6.60
Std Dev	11.01	10.98	11.93
Min	2.41	0.00	0.00
Median (50%)	7.09	0.00	0.37
Max	64.05	54.13	54.79

The most telling statistic is the median (50%) current for I_S being 0.0 A, which statistically confirms that this phase was inactive for at least half of the measurement period, reinforcing the imbalance finding.

4.2. Power Factor and Frequency Analysis

The power factor description shows there is a high loss in the hospital's electricity consumption. PF kept lagging, which confirms that inductance is the main load of the facility: isotropic for a building with many motors (HVAC, pumping system, elevator) or transformer.

In order to provide the required real power using a high value of PF, it is necessary to have an increase in the current that is supplied from the utility, resulting in increased energy losses and decreased capacity of the hospital's electrical distribution. 16 Summary of Power Factor and Reactive Power Requirement is shown in Figure 4.

And that is the breakdown of frequency and power factor. These are plotted on two different graphs for the sake of clarity because they differ in scale.

- Frequency Analysis: With a very constant electrical frequency that is regulated close to the expected standard of 50 Hz, the above graph illustrates this. Small variations are to be expected in a power grid. This is evidence of continuous power from the utility.
- Power Factor Analysis: The bottom chart indicates that the power factor is good in general (it is high or close to 1.0). A high power factor indicates that the load is being used efficiently. There are losses in the power factor, which would be expected to correspond exactly with the high load pictures we shall discuss later with current analysis. This is to be expected, since large motors and other inductive loads that are operated at peak hours tend towards a reduction of power factor.

Fig. 4 Frequency and power factor analysis

4.3. Statistical Analysis

- The mean frequency is very close to 50 Hz with a tiny standard deviation, confirming the grid's stability.
- The mean power factor of 0.984 is excellent, indicating high electrical efficiency for the hospital.
- The minimum power factor of 0.595 shows that there are moments of significant inefficiency, likely tied to the activation of specific heavy machinery. The maximum value, slightly above 1.0, may indicate periods of leading power factor or a slight sensor calibration error.

Table 4. The descriptive statistics provide a numerical summary of these observations

Metric	Frequency (Hz)	Power Factor
Mean	50.13	0.984
Std Dev	0.12	0.028
Min	49.69	0.595
Median (50%)	50.13	0.979
Max	50.51	1.223

5. Results and Discussion

The results of the empirical study in the previous section depict a picture of System Monitoring-based IoT Technology to support the electrical environment at the Hospital University of Lampung.

At this part, these quantifications are combined into a comprehensive PQ profile, and the reasons are investigated, and their implications to hospital work, as well as patient safety and financial performance, are discussed.

5.1. Synthesis of the Power Quality Profile of the Hospital University of Lampung

The power quality scenario in the hospital is full of dichotomies. On the other hand, the facility is relying upon one of the best utility feeds in terms of stability and reliability, giving rise to impeccable voltage regulation and reservoir-like frequency control observed. Even better, it is a base from which you can begin to wire up your electrical system. On the other hand, the internal power system is itself causing a large degradation of power quality. The main results are as follows: the electrical system of the site exhibits stable voltage and frequency, but has been heavily affected by non-compliant current harmonic distortion, permanent voltage unbalance, and permanently poor lagging power factor. These are also not sporadic exceptions but indicative of a hospital's electrical load profile.

5.2. Identification of Dominant Power Quality Issues and their Probable Etiology

The information indicates a very clear attribution of effects that are observed in the PQ problems to their likely positions within the hospital. Total Demand Distortion (TDD), up to very high levels, is the clear fingerprint that evidences the power quality disruptions caused by the explosion of power electronic equipment, especially six-pulse converters present in VFDs for air conditioning systems, as well as in numerous electronic equipment power supplies [53]. 4) The power factor is a direct result of many inductive loads, mainly the motors that drive pumps, fans, compressors, and elevators, which need reactive power to operate. What this permanent

VU demonstrates is the complexity of optimally distributing so many indivisible single-phase loads (lighting, computers, small medical devices) [54] proportionately from one sub-panel to another at the three-level distribution throughout such a complex facility. These are critical dynamics in the contemporary healthcare setting. It is the technology itself, which is indispensable for cutting-edge patient care and optimal running of the building, yet constitutes the main cause of electrical pollution with potentially life-threatening effects on the entire organization.

The findings of this research are especially relevant when it comes to the emergency power system's reliability. The hospital uses the maximum amount of electricity during working hours, which causes the harmonic currents to be injected and necessitates the reactive power effect during the peak of the working hours. The wide ranges of these extreme events take place [55]. At the exact moment when this is most needed, the emergency power system must perform its most important function, which involves severe voltage distortion and reduced effective capacity. The PQ management has been redefined as a crucial component of the hospital's disaster preparedness and also for the patient safety planning, rather than just another way to increase productivity or extend the life of electrical equipment [56].

5.3. Assessing the Potential Risks to Medical Equipment and Hospital Operations

The process of mapping the numeric results into concrete risks in operations underscores the urgent character of the problem.

- Risk to Diagnostic Integrity: The TDDs were high enough (even though they are not at this point causing severe voltage distortion because of the strong utility supply) to represent a potential risk. Harmonic currents may flow in the facility, and they can disturb and provoke malfunctions in very sensitive diagnostic apparatus. This could result in incorrect test results, altered images on medical displays, or malfunctions and stalling of equipment, causing inaccuracies in medical diagnoses.
- Risk to Building Infrastructure: The chronic voltage unbalance is a health risk to all three-phase motors in the building. The temperature elevation induced by this stagnation phenomenon can lead to an insulation failure of the motor windings, resulting in a relatively short life and possible sudden catastrophic shutdown of critical HVAC and pump systems [57]. In an operating theatre or ICU, this could have dire effects.

5.4. Situating the Findings within the Broader Context

It is very typical and worrisome that the PQ profile of the Hospital University of Lampung. It has been extensively reported because of the high harmonic currents generated by medical loads and electronic loads. Power factor also presents a significant concern for large commercial and institutional buildings [58]. Yet, the level of violation with the demanding current distortion constraints of IEEE 519 is quite exceptional. It implies that while the hospital first meets the capacity portion of its modern, robust electrical system, it does not yet address what power-quality correction work needs to be completed to mitigate impacts from its state-of-the-art non-linear loads. The results are a telling example that the power itself is no longer enough, and sufficient, to manage the quality of this power in today's healthcare environment.

6. Conclusion

This research has described a detailed and database-based incoming power quality analysis at the Main Distribution Panel at the Hospital University of Lampung. A thorough picture of the facility's electrical systems' condition has been established through the interpretation of sizable electrical databases against strict international benchmarks.

The results suggest that the hospital was still experiencing low-quality power in its internal environment because of systemic PQ problems, even though it had a steady supply in terms of voltage and frequency. The main issues found are voltage imbalance, which poses a long-term risk to critical equipment, a constantly lagging power factor in the face of significant operational inefficiency and remaining tolerance, and high current harmonic distortion, with the Total Demand Distortion typically well above what IEEE 519 recommends for critical installations.

The above problems are the result of a high content of discontinuous and inductive load typical of an advanced technologically modern hospital. These findings represent more than mere technical non-compliance. They are real threats to patient safety via equipment that could malfunction and a loss of functionality due to early equipment failure, as well as money inefficiency from utility penalties and wasted energy.

Accordingly, the report identifies that a double jeopardy scenario occurs when operating under high load-bearing and distortions, those conditions in which EPSSs are most required to operate. The data from the real-time IoT monitoring system indicates a strong correlation between building operation hours and electricity consumption. Peak current loads on weekdays always happened between 6:30 AM and 5:30 PM, but on weekends, the values were much lower. Although there were some reported minor phase imbalances, the average voltage value was always within acceptable bounds.

In conclusion, this study emphasizes the necessity for healthcare facilities to monitor and control power in addition to providing it. The Hospital University of Lampung's results strongly support focused mitigation measures, such as power factor correction and active harmonic filtering, which can be implemented through a proactive management program utilizing ongoing high-fidelity data monitoring. By fixing these identified gaps, the hospital can increase critical operations reliability, maintain diagnostic and life-support system integrity, improve the business bottom line, and, most importantly, protect patient care.

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