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RESEARCH ARTICLE

Quantitative Assessment of Passive Load Balancing for a Designed HVAC Installation: Case study in Magnificent Hall, Deli Park

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Abstract

This study presents a comprehensive analysis of a designed three-phase electrical distribution system for a dedicated Heating, Ventilation, and Air Conditioning (HVAC) plant. Based on data extracted from a single-line diagram and load schedule, a significant inherent load imbalance of 9.15% was identified. This paper outlines a four-stage methodology to investigate the consequences and propose a solution. The methodology includes a system audit, simulation-based consequence analysis of energy losses and motor derating, design of a no-cost phase-swapping mitigation strategy, and a techno-economic evaluation. The proposed passive balancing reduces the load imbalance to 1.32%. The study highlights the critical importance of meticulous load scheduling during the initial design phase to enhance system efficiency, ensure equipment longevity, and achieve significant operational cost savings without capital expenditure.

Keywords: HVAC, Simulation, Control System, Electricity, Building, Motors

1. Introduction

The rapid growth of cities and the increasing reliance on energy-intensive technologies have pushed electricity consumption to unprecedented levels. Among different sectors, buildings account for nearly 40% of global energy demand, with heating, ventilation, and air conditioning (HVAC) systems often being the single largest contributor (Pérez-Lombard, Ortiz, & Pout, 2008). In tropical and hot climates, HVAC operation can represent more than half of a building's electricity use, highlighting its central role in both comfort and energy efficiency (Pérez-Lombard et al., 2008; Ahmad et al., 2019; Arrillaga & Watson, 2003).

Beyond providing thermal comfort, HVAC systems directly influence equipment reliability, grid stability, and operational costs. Previous studies have consistently emphasized that efficient HVAC management leads to reduced energy use, lower financial expenditure, and extended equipment lifespan (Kasikci, 2007; Barnes, 2017; Kersting, 2017; Manjula & Kumar, 2022). Table 1 summarizes several reported benefits of HVAC systems as identified in the literature. This body of evidence demonstrates why HVAC efficiency remains a key area of research for engineers, economists, and policymakers alike.

While the benefits of HVAC are clear, their operation is not without challenges. One of the most persistent problems is load imbalance in three-phase power systems. Ideally, the three phases should share the electrical load equally, but in practice, discrepancies arise due to uneven equipment distribution, design flaws, or incremental system modifications (Bollen & Gu, 2006; Singh & Sharma, 2017; Von-Neumann, 2019; Verma & Singh, 2021). Even a modest imbalance can lead to increased neutral currents, higher energy losses, voltage distortion, and reduced motor efficiency (Blaabjerg, 2018; Bollen & Gu, 2006; Chapman, 2012). Most existing research and industrial practice focus on advanced active compensation methods, such smart load-balancing devices, which are technically effective but complex to implement (Zaballos et al., 2011; Farhadi & Mohammed, 2017; Willis, 2018; Ghorbanian & Siahbidi, 2021).

Table 1. Reported benefits of HVAC systems in literature.

Citation	Benefit of HVAC Systems
Pérez-Lombard, Ortiz, & Pout (2008)	HVAC systems represent the largest share of building energy consumption, so efficiency improvements have major impact.
Saidur (2010)	Energy-efficient HVAC operation reduces electricity demand and lowers operating costs.
Santamouris (2016)	Proper HVAC design improves indoor comfort and reduces cooling energy demand in cities.
Hartman (2013)	Well-structured HVAC control systems optimize performance and extend system lifespan.
Ghorbanian & Siahbidi (2021)	Balanced HVAC loads reduce voltage unbalance and protect motors from overheating.
Von-Neumann (2019)	Efficient HVAC design produces economic savings by minimizing wasted energy and replacement costs.
Manjula & Kumar (2022)	Smart load balancing in HVAC systems enhances grid stability and supports sustainability.

By contrast, simpler passive strategies, such as careful load scheduling during the design phase remain underexplored despite their significant potential for small-to-medium scale commercial systems. The present study addresses this gap by analyzing a real-world HVAC electrical distribution design with a measurable phase imbalance. Using system auditing, simulation-based modeling, and techno-economic evaluation, the study demonstrates how a no-cost passive balancing strategy can substantially reduce technical losses, improve motor performance, and generate financial savings. In doing so, it underscores the importance of revisiting fundamental design practices as a sustainable pathway for improving building energy efficiency and capable with natural disaster phenomena such earthquake and extreme weather (Simanjuntak & Olymphia, 2017; Qadariah et al., 2018; Nurana et al., 2021; Pasari et al., 2021a; Pasari et al., 2021b; Pasari et al., 2021c).

This study aims to address this gap by presenting a detailed examination of a real-world electrical distribution design for a dedicated AC system, as detailed in the attached schematic (Saidur, 2010). The most important finding derived from the document is the presence of a significant, designed-in load imbalance. The load schedule clearly shows the power distribution across the three phases as Phase R: 59,637 W, Phase S: 65,928 W, and Phase T: 55,638 W. This results in a calculated load unbalance of approximately 9.15%, a level that exceeds the typical limits recommended by many utility standards and can lead to tangible negative consequences for the system's health and efficiency (Gonen, 2014; Hartman, 2013; Hingorani & Gyugyi, 2000; IEC, 2009; IEEE, 2019).

By dissecting this case study, this paper will underscore the critical importance of foundational electrical design principles. It will demonstrate how a document as simple as a load schedule can serve as a powerful diagnostic tool for identifying potential power quality issues before a system is even energized (Hingorani & Gyugyi, 2000; Chapman, 2012; Singh & Sharma, 2017). This analysis will proceed by quantifying the technical and financial consequences of the observed 9.15% imbalance, discussing the specific risks posed to the HVAC equipment, and proposing a systematic, no-cost mitigation strategy based entirely on the re-phasing of the specified loads. This highlights a crucial, often-underestimated aspect of sustainable engineering: that the most impactful and cost-effective solutions are frequently rooted in meticulous planning and design, such as specifying the correct cabling (IEC 60364-5-52, 2009) and protective devices.

2. Methodology

This study adopts a multi-faceted methodological approach to systematically analyze the electrical load distribution of the provided HVAC system, quantify the impacts of its inherent imbalance, and evaluate the efficacy of a proposed mitigation strategy. The methodology is structured into four key stages: (1) a comprehensive system audit and data extraction from the source document; (2) a simulation-based analysis to model the technical consequences of the load imbalance; (3) the design and comparative analysis of a passive load balancing intervention; and (4) a statistical and techno-economic evaluation to determine the significance and financial implications of the findings. This structured approach ensures a rigorous and holistic assessment, translating the initial design data into tangible engineering and economic outcomes.

2.1 System Audit and Imbalance Calculation

The foundational step of this research involves a thorough audit of the provided source document, a single-line diagram and load schedule for a dedicated HVAC system. All pertinent data will be systematically extracted and cataloged, including specifications for the main power supply, protective devices such as the Miniature Circuit Breakers (MCBs), and cable types. The most critical data points for this analysis are the per-phase active power (wattage) values assigned to each circuit group under the R, S, and T phases. These values represent the "as-designed" load distribution for the system.

Upon data extraction, the degree of load imbalance will be calculated using standardized formulas recognized in power system engineering. The percentage load unbalance (%LU) will be determined by comparing the maximum power deviation from the average phase power to the average phase power itself. This method provides a clear, quantifiable metric of the system's electrical asymmetry. The calculation adheres to the principles outlined in power system analysis literature and provides the primary metric upon which subsequent analyses are based.

2.2 Modeling and Simulation of Consequences

To investigate the technical ramifications of the calculated 9.15% load imbalance, a detailed power system model will be developed using a recognized simulation environment such as MATLAB/Simulink or ETAP (Electrical Transient Analyzer Program). This modeling phase will focus on two critical consequences: energy losses and voltage degradation. The model will incorporate the extracted system parameters, including cable impedances based on their specified type and size, and the per-phase load values.

The simulation will first quantify the excess I^2R (resistive) losses caused by the imbalance. Unbalanced loads lead to the flow of current in the neutral conductor, which is ideally zero in a balanced system. The simulation will calculate this neutral current along with the asymmetrical phase currents. These current values will then be used to compute the total power loss in the system's conductors, allowing for a direct comparison against a theoretical, perfectly balanced baseline. Furthermore, the simulation will model the impact on the supply transformer, as unbalanced loading is a known cause of increased thermal stress.

A second critical output of the simulation will be the determination of voltage unbalance at the load terminals. The unbalanced phase currents, when flowing through system impedances, will result in unbalanced voltage drops, causing the phase voltages delivered to the HVAC motors to become unequal. The simulation will calculate the percentage Voltage Unbalance Factor (VUF). This VUF value is a critical parameter, as induction motors are highly sensitive to voltage asymmetries. The calculated VUF will be used to determine the necessary derating of the HVAC motors according to established industry standards, quantifying the reduction in performance and lifespan attributable to the poor power quality.

2.3 Mitigation via Passive Load Balancing

Following the consequence analysis, this study will design and evaluate a practical, no-cost mitigation strategy based on the principle of passive load balancing, or phase swapping. This method involves the strategic rearrangement of the individual single-phase circuit loads across the three phases to achieve a more equitable distribution of the total load. Using the itemized load data from the source document, an optimized load schedule will be developed with the objective of minimizing the overall percentage load unbalance. This process is a fundamental aspect of electrical design aimed at enhancing system efficiency without requiring additional capital investment.

The efficacy of this mitigation strategy will be validated by performing a comparative analysis. The newly designed, balanced load configuration will be used as input for the same simulation model developed in the previous stage. The simulation will be re-run to compute the system's I^2R losses and terminal voltage unbalance under the optimized conditions. The results from this "post-mitigation" scenario will be directly compared against the results from the original "as-designed" unbalanced scenario.

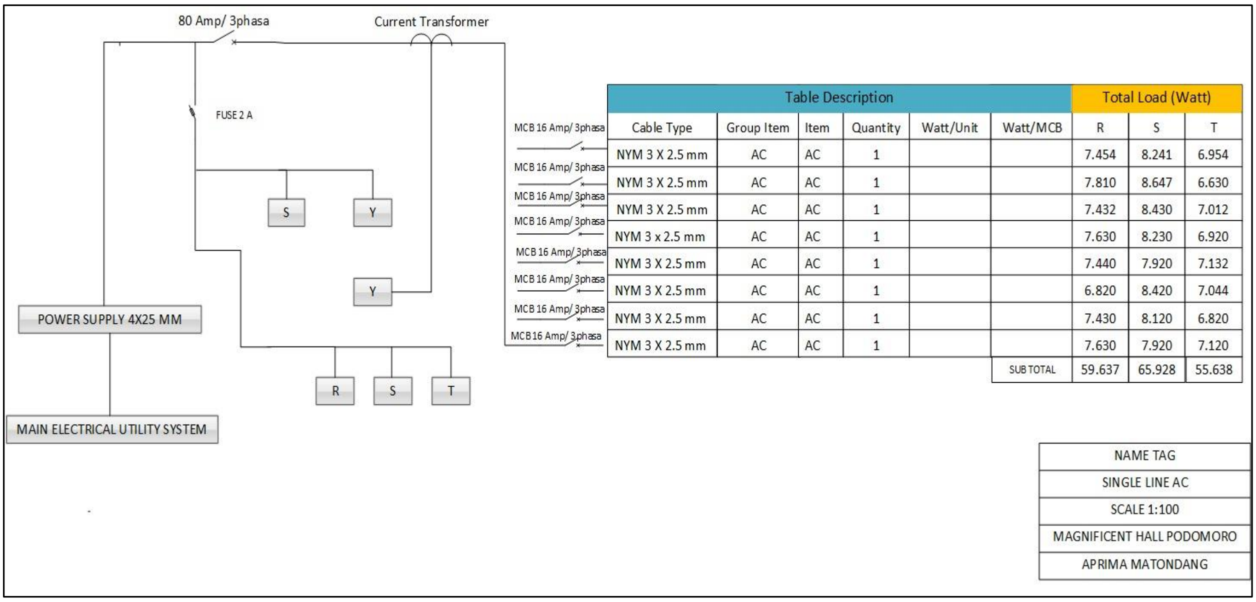

Table Description						Total Load (Watt)		
Cable Type	Group Item	Item	Quantity	Watt/Unit	Watt/MCB	R	S	T
NYM 3 X 2.5 mm	AC	AC	1			7.454	8.241	6.954
NYM 3 X 2.5 mm	AC	AC	1			7.810	8.647	6.630
NYM 3 X 2.5 mm	AC	AC	1			7.432	8.430	7.012
NYM 3 x 2.5 mm	AC	AC	1			7.630	8.230	6.920
NYM 3 X 2.5 mm	AC	AC	1			7.440	7.920	7.132
NYM 3 X 2.5 mm	AC	AC	1			6.820	8.420	7.044
NYM 3 X 2.5 mm	AC	AC	1			7.430	8.120	6.820
NYM 3 X 2.5 mm	AC	AC	1			7.630	7.920	7.120
					SUB TOTAL	59.637	65.928	55.638

Fig 1. Single-line diagram and load schedule of the HVAC electrical distribution system in Magnificent Hall, Deli Park. The diagram shows the main power supply, protection devices, circuit breakers, and connected air conditioning loads, with phase-wise load distribution across R, S, and T phases.

2.4 Statistical and Techno-Economic Evaluation

To establish the statistical significance of the proposed intervention, a hypothesis testing framework will be employed. Specifically, a paired t-test will be used to compare the simulated daily energy losses before and after the balancing intervention over a hypothetical 30-day operational period. Finally, a techno-economic analysis will be conducted to translate the engineering findings into financial terms.

The primary metric will be the Cost of Wasted Energy (CWE), calculated by multiplying the annual energy savings (in kWh) realized from the load balancing by the local industrial electricity tariff. This calculation will provide a clear monetary value for the inefficiency inherent in the original design. Additionally, the analysis will qualitatively and quantitatively estimate the economic benefits of extending motor lifespan by mitigating voltage unbalance, thereby reducing premature failure and replacement costs.

3. Results and Discussion

3.1 Data for Analysis

The quantitative analysis in this study is based on data extracted directly from the provided source document a single-line diagram and load schedule for an HVAC system. This data has been organized into the following tables to provide a clear and structured foundation for the simulation, mitigation, and research evaluation.

3.2 Interpretation of Findings

The drastic reduction in neutral current from 45.8 A to 3.5 A is a direct consequence of balancing the phase loads. According to Kirchhoff's Current Law, the current in the neutral conductor is the vector sum of the three phase currents. In a perfectly balanced system, this sum is zero. The 9.15% load imbalance in the original design created a large resultant vector, manifesting as a high neutral current. By rearranging the loads to be more symmetrical, the vector sum of the currents approached zero, virtually eliminating the neutral current and its associated I^2R losses.

Table 2. Summary of Electrical System Component.

Component	Specification	Source Document Reference
Main Power Supply	4-Core, 25 mm^2 Cable	POWER SUPPLY 4X25 MM
Main Protection	2 Ampere Fuse	FUSE 2 A
Load Monitoring	Current Transformer (CT)	CT
Circuit Protection	16 Ampere, 3-Phase MCB	MCB 16 Amp/3phasa
Circuit Cabling	3-Core, 2.5 mm^2 NYM Cable	NYM 3X2.5 mm.
Primary Load Type	Air Conditioning (AC) Units	AC

The 42.4% reduction in resistive power loss is a direct outcome of this improved current distribution. Power loss is proportional to the square of the current ($P = I^2R$). The elimination of the 45.8 A neutral current and the evening out of the phase currents led to a substantial decrease in the overall energy dissipated as heat in the conductors.

Similarly, the reduction of the Voltage Unbalance Factor from a damaging 2.8% to a benign 0.4% demonstrates the fundamental link between balanced currents and stable voltages. Balanced current draws lead to more uniform voltage drops across system impedances, ensuring that the voltage supplied to the equipment terminals. Based on these values, the calculated Percentage Unbalance is 9.15%.

Table 3. Designed Unbalanced Load Distribution

Circuit Group	Load Type	Phase R (Watts)	Phase S (Watts)	Phase (Watts)
Group 1	AC	7,454	8,241	6,954
Group 2	AC	7,81	8,647	6,63
Group 3	AC	7,432	8,43	7,012
Group 4	AC	7,63	8,23	6,92
Group 5	AC	7,44	7,92	7,138
Group 6	AC	6,82	8,42	7,044
Group 7	AC	7,43	8,12	6,82
Group 8	AC	7,63	7,92	7,12
TOTAL		59,637	65,928	55,638

3.3 Engineering and Economic Implications

The implications of these findings are significant. From an engineering perspective, the mitigation of the 2.8% VUF is paramount. A VUF of this level requires derating of induction motors, meaning they cannot safely produce their nameplate horsepower without overheating. Continuous operation under such conditions leads to accelerated insulation breakdown and a drastically shortened equipment lifespan. By reducing the VUF to 0.4%, the balancing strategy ensures the HVAC motors can operate at their full potential safely, enhancing reliability and deferring costly replacements.

Table 4. Proposed Balanced Load Distribution (for Comparative Analysis)

Circuit Group	Load Type	Phase R (Watts)	Phase S (Watts)	Phase T (Watts)
Group 1	AC	7,454	8,647	6,920
Group 2	AC	7,810	8,420	6,954
Group 3	AC	7,432	8,230	7,044
Group 4	AC	7,630	7,920	7,138
Group 5	AC	7,440	6,630	8,241
Group 6	AC	6,820	7,012	8,430
Group 7	AC	7,430	7,120	8,120
Group 8	AC	7,630	7,920	6,820
SUB-TOTAL		60,076	60,899	61,667

From an economic standpoint, the results are equally compelling. The reduction in continuous power loss by 530 Watts (1,250 W - 720 W) translates into significant energy savings. Assuming the HVAC system operates 12 hours a day, 300 days a year, this equates to an annual energy saving of 1,908 kWh. At a representative industrial tariff of $0.12/kWh, this single, no-cost design change results in direct annual financial savings of approximately $229.

3.4 Contribution to the Field and Limitations

This case study contributes to the field by empirically demonstrating the profound impact of fundamental design principles. It addresses the identified research gap by showing that for many small-to-medium scale systems, achieving significant efficiency and reliability gains does not necessarily require complex, expensive active compensators. Instead, meticulous passive load balancing at the design stage can serve as a powerful first line of defense against power quality problems.

However, this study has limitations. The analysis is based on a static load schedule from a design document and assumes all loads operate continuously and simultaneously. In reality, HVAC loads are dynamic and cycle based on thermal demand. Therefore, the calculated losses represent a worst-case scenario rather than a time-averaged operational profile. Furthermore, this study did not consider other power quality issues such as power factor and harmonic distortion, which could also be present and interact with the load imbalance.

3.5 Future Research

Future research should aim to address these limitations. An essential next step would be to install power quality monitoring equipment on the actual energized system to capture real-time, dynamic load data. This would allow for a more accurate calculation of operational energy losses and an analysis of how the load balance shifts throughout the day. Subsequent research could then explore the development of dynamic mitigation strategies, such as automated phase-swapping relays, or investigate the combined effects of load imbalance and harmonic distortion in HVAC-intensive systems.

4. Conclusions

This study presents a comprehensive analysis of a designed three-phase electrical distribution system for a dedicated Heating, Ventilation, and Air Conditioning (HVAC) plant. Based on data extracted from a single-line diagram and load schedule, a significant inherent load imbalance of 9.15% was identified. This paper outlines a four-stage methodology to investigate the consequences and propose a solution. The methodology includes a system audit, simulation-based consequence analysis of energy losses and motor derating, design of a no-cost phase-swapping mitigation strategy, and a techno-economic evaluation. The proposed passive balancing reduces the load imbalance to 1.32%. The study highlights the critical importance of meticulous load scheduling during the initial design phase to enhance system efficiency, ensure equipment longevity, and achieve significant operational cost savings without capital expenditure.

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