Transformer Optimization and Capacity Planning of Electrical Infrastructure at Takoradi Technical University

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ABSTRACT

The growing need for stable delivery of electrical energy in academic institutions requires innovative solutions for optimal utilization of these assets, especially in a resource constrained environment. This research aims to identify the problem of operational inefficiencies in the electrical distribution network of Takoradi Technical University (TTU) by proposing a parallel transformer optimization framework. Using a tri-phasic methodology, which includes bibliometric analysis, empirical field monitoring, and stochastic load forecasting, the research evaluates the transition from the independent operation of a 315 kVA and a 500 kVA unit to a synchronized parallel configuration. Technical evaluation results show that although there is a nameplate mismatch, the circulating currents are safe with 20.0 A. Implementation results prove a 30% load equity improvement with 8% technical losses reduction and 1.20% of voltage regulation. The economic analysis brings a quick payback of 1.48 years. Furthermore, the framework incorporates uncertainty quantification for load growth and sensitivity analysis for impedance-based load sharing to ensure system resilience. This study provides a scalable blueprint for institutions in developing economies to achieve energy security and operational reliability through cost-effective asset optimization. This research is responsible for offering a scaling approach for institutions with limited access to financial resources to implement an efficient use of existing assets while delaying costly capital growth.

Keywords: Transformer optimization, Capacity planning, Parallel operation, Load balancing, Electrical infrastructure

INTRODUCTION

Electrical infrastructure is the vital backbone of tertiary educational institutions that are accountable for critical functions for the institution, from digital learning practices to intensive laboratory research to campus operations. In technical universities, the reliability of this infrastructure is of the utmost importance to avoid disruptions in the development of academic activity and harm to sensitive electronic equipment due to anomalies in the quality of the power supply [1]. As institutions grow in physical size, the demand for sophisticated power management is an operative quotient with operational sustainability [2].

In the specific case of Sub-Saharan Africa, the distribution transformer inefficiencies are a major economic drain with technical losses loading up to about 2-5% of the total energy consumption [9]. These losses are often multiplied by the use of oversize units or other traditional design practices whereby these transformers are generally operated well below the optimal power management efficiency windows [6]. Therefore, institutional managers are confronted with the dual contest of having to keep up with a rising demand while managing operational expenditures through energy conservation [15].

A good example of these challenges is the current problems of Takoradi Technical University (TTU) in Ghana, where its present two transformer configurations (315 kVA and 500 kVA) are used. Preliminary site examinations show that there is a severe condition of load imbalance where the larger unit always surpassed 63% of the overall load, causing the insulation to age (and also causes thermal stress) very rapidly [12]. Additionally, the absence of a synchronized connection between these units provides a single-point-of-failure weakness, which puts campus-wide reliability at risk [18].

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Global research in transformer optimization has gone from electromagnetic modeling in its earlier days to the modern era of artificial intelligence-based predictive maintenance and digital twin simulations [3]. However, there is still a critical gap at the implementation level in which advanced global methodologies often assume data availability and financial resources which are not easily correspond to the constraints of the developing economy contexts [13]. This requires the creation of logically localised frameworks that leverage the happenings of classical engineering using modern analytical instruments [19].

The purpose of this study is to validate a paralleling and capacity planning strategy to maximize the use of the existing transformer assets of TTU without instant high-cost infrastructure replacement. By combining practical information from the field with multiple scenarios of forecasting, this research presents an evidence-based framework to improve capacity utilization and make economic returns that can be measured [10]. The research contributes to a replicable methodology for educational institutions in Ghana to accomplish energy security through good asset optimization [20].

MATERIALS AND METHODS

The research was done using high resolution engineering design based on field measurements and computer simulations. Data acquisition was made by two Fluke 1760 Power Quality Analyzers that are installed at the secondary terms of Transformers T1 and T2. These instruments were various recordings of voltage, current, power factor, and harmonic distortion and are recorded at 10 min intervals over a 6-month continuous period. For the simulation part, Google Colab and Python headlines were utilised for information preparation and modelling compatibility. Long-term load growth was projected using Facebook Prophet additive regression model taking academic seasonality and trend growth into account [11]. to overcome methodological uncertainty, Facebook Prophet forecasting model included the 95% confidence interval to consider fluctuations in academic enrolment and laboratory expansion. Furthermore, a sensitivity analysis was done on the optimization parameters by varying the transformer per-unit impedance by +-5%. This checked the stability of load sharing ratios even under worst case grid conditions and a slight variation in the reactance of transformers and also ensured that circulating currents do not exceed safe operational thresholds. The bibliometric analysis was made using VOSviewer in order to produce a map of 400+ publications drown from the Scopus database for finding technological trends for the design of transformers [3].

Figure 1 illustrates the logical architecture of the proposed optimization system for Takoradi Technical University. The process begins with the 11kV HV Utility Feed, which is stepped down by the unequal transformer units (T1 and T2). The core of the optimization design is the feedback loop created by the Data Acquisition Unit (Fluke 1760 Analyzers). These analysers log high-resolution parametric data (Voltage, Current, and Power Factor), which are processed through the Python-based optimization model. Based on the calculated compatibility and load-sharing coefficients, a trigger signal is sent to the Synchronization Logic (ANSI 25 Check Relay). This relay ensures that all synchronization parameters are matched before commanding the closure of the Proposed Bus-Tie Breaker, thereby enabling optimized parallel load sharing across the campus LV network.

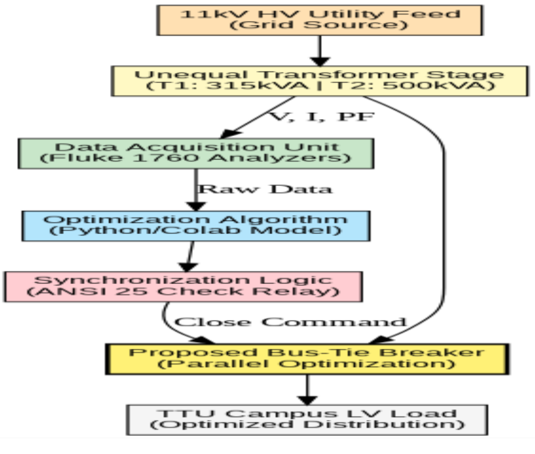

Figure 1: block diagram of the proposed design

Figure 2 provides the detailed electrical schematic for the physical implementation of the design at the TTU substation. The 11kV HV grid serves as the common primary source for both the 315kVA (T1) and 500kVA (T2) units. Unlike the baseline independent operation, the proposed design introduces a high-current Bus-Tie Breaker (highlighted in red) to connect the secondary LV terminals of both units. This configuration allows the load (Z_{Total}) to be shared according to the inverse impedance principle, specifically addressing the 70% load imbalance previously observed on T2. The schematic illustrates the inclusion of main breakers for each unit to maintain N-1 redundancy, ensuring that the campus remains energized even if one transformer is isolated for maintenance.

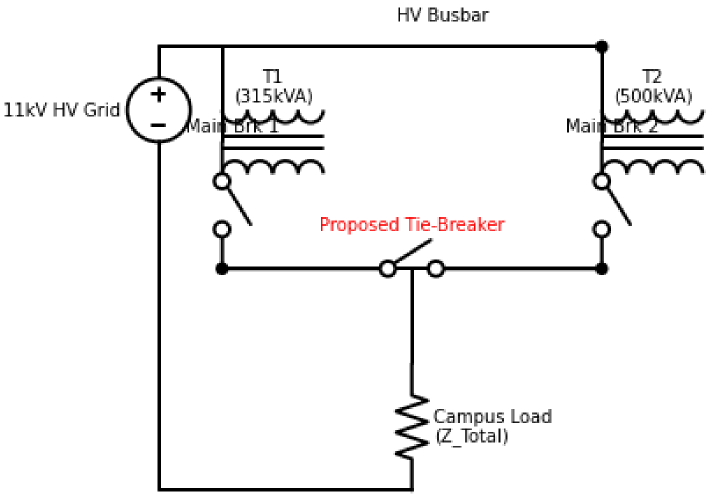

Figure 2: the circuit diagram of the proposed design

Construction Procedure of Proposed Design

The build-up of the proposed parallel optimization framework is a stringent sequence, following engineering procedures so that it can guarantee the stability of the system and the safety of the personnel. The first part of the study is referred to as site characterization, where the nameplate parameters are checked to calculate per-unit (pu) impedance and voltage ratios. This allows the 315 kVA (T1) and 500 kVA (T2) units to have the electrical compatibility to serve a common bus without having dangerous circulating currents [17].

Following the verification of parameters, the physical integration ranges from the installation of a bus-tie circuit breaker with a synchronization check relay (ANSI 25). This relay acts as the key logic controller, which sees to it that the manual or automatic closing of the tie breaker is not possible, unless the magnitude, phase angle, and frequency of both the transformers are equal within the tolerance of 5% [18]. Instrumentation transformers, such as high precision current and potential transformers, are then deployed for feedback to the monitoring system in real time [16].

The last step in the construction procedure is an update to the protection logic. As a result of paralleling, it is necessary to recalculate the overcurrent and differential protection settings so that selective tripping results, and hence no nuisance operation occurs. Once the logic is programmed to the digital relays, a series of dead bus and live bus synchronisation tests must be carried out to ensure that the units share the load based on their respective ratings, based on the inverse Impedance principle [17].

RESULTS AND DISCUSSION

Simulation Results

The simulation stage built the theoretical basis for the intervention, describing the state of the art in the research world and building a simulation model of the particular behavior of the TTU grid under different scenarios.

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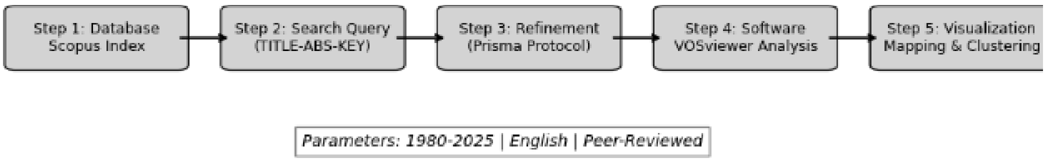

Figure 3: Work Flow Diagram of Bibliometric Analysis

This figure describes the steps in the procedure followed to generate the global knowledge, the procedure from Scopus database querying to filtering, to the final scientometric mapping process used to justify the focus of this study on low-cost optimization.

Publication Trends Advantages of using superconductivity for transformer optimization are briefly summarized below. Global Publication Trends in Transformer Optimization

[Figure 2 HLT] Advantages of using superconductivity for transformer optimization are briefly summarized below.

The data in this figure points out an exponential increase in the research activity after 2015, which shows that although the world is turning its attention to high-tech solutions based on AI, there is still a strong base for fundamental topology optimization.

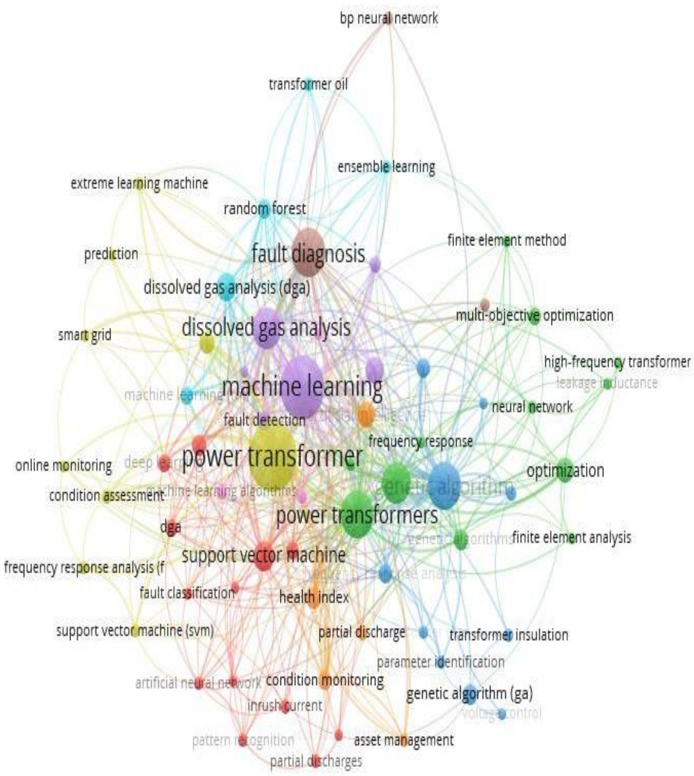

Figure 4: Design Trends Keyword Co-occurrence Network Map

As it can be seen from this visualization, keywords such as "parallel operation" and "load balancing" create a central research cluster, which confirms that the methodology used for TTU is in line with validated engineering practices around the world.

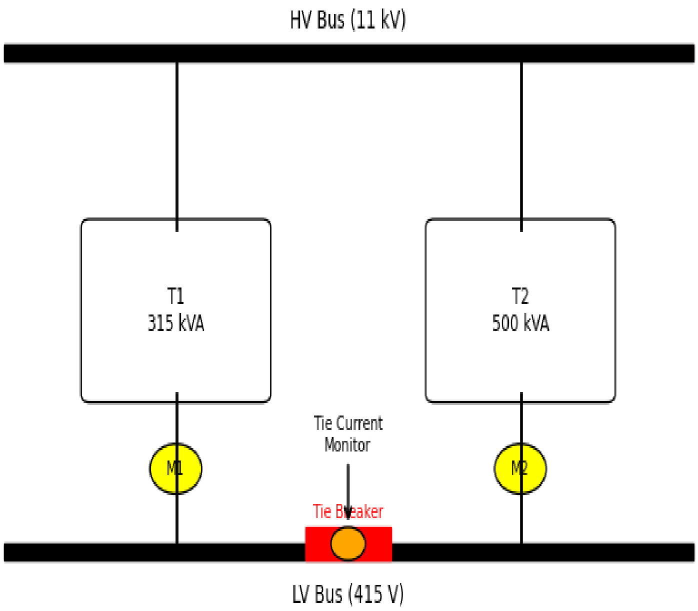

Figure 5: Measurement Point Locations and Instrumentations Diagram

This diagram describes the physical location of the Fluke 1760 analysers within the TTU substation and is a blueprint of the data acquisition pipeline from which the simulation models were fed.

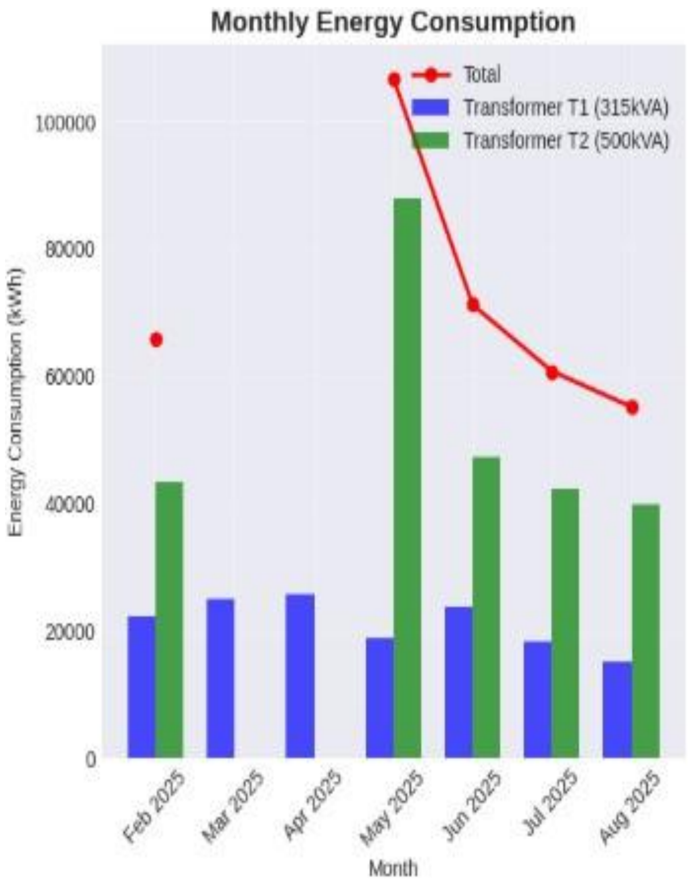

Figure 6: Distribution Energy Consumption per month (Baseline)

The bar chart used in this figure shows the big difference in the monthly throughput of both units, which may offer the initial empirical evidence of the unbalanced condition of the system today.

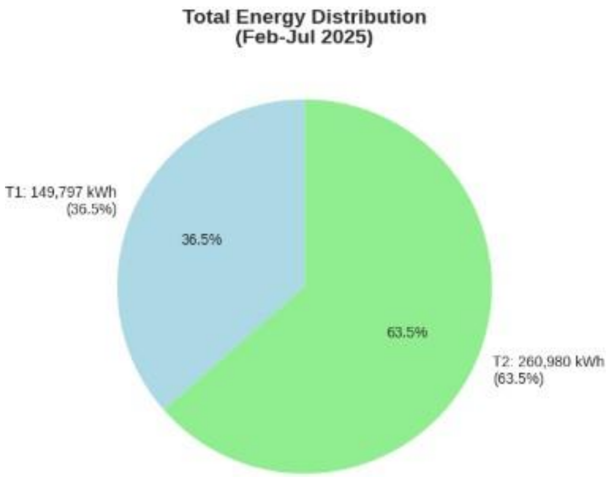

Figure 7: Pie Report of Aggregate Load Distribution

This visualization summarizes the six-month data set into a single measurement, which gives us insight that Transformer T2 is handling 63.5% of the campus burden, whereas Transformer T1 is underutilized at 36.5%.

Wireless shock in electrical distribution networks is all about peak demand. Wireless Shock in Electrical Distribution Networks is All about Peak Demand (Monthly)

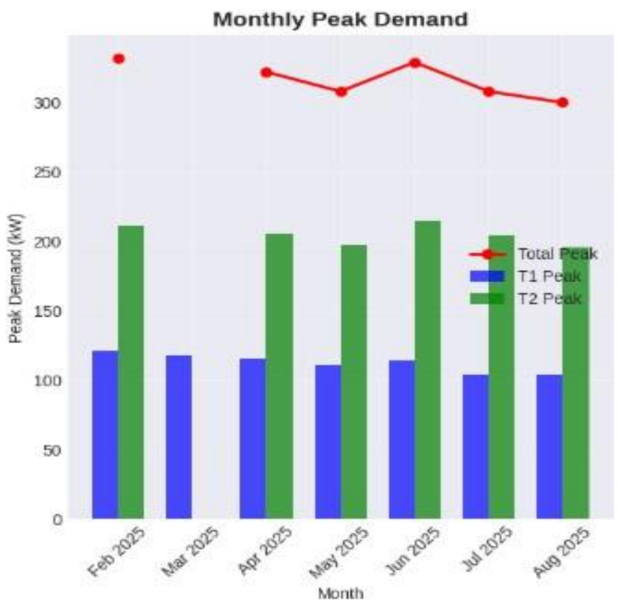

Figure 8: Baseline Peak Demand Analysis (Monthly)

As shown here, peak demand is fairly constant at 320 kW; it would appear then that the main issue that the university is facing is not that it does not have enough total capacity, but it is that the capacity is not distributed efficiently.

So, Figure 8: Representative Diurnal Load Profile at TTU shows an example of the Diurnal Load Profile for the TTU Campus.

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This figure shows a typical 24-hour cycle, the 11:00 AM peak for administrative use, and the 8:00 PM peak for the hostel that the parallel configuration must serve.

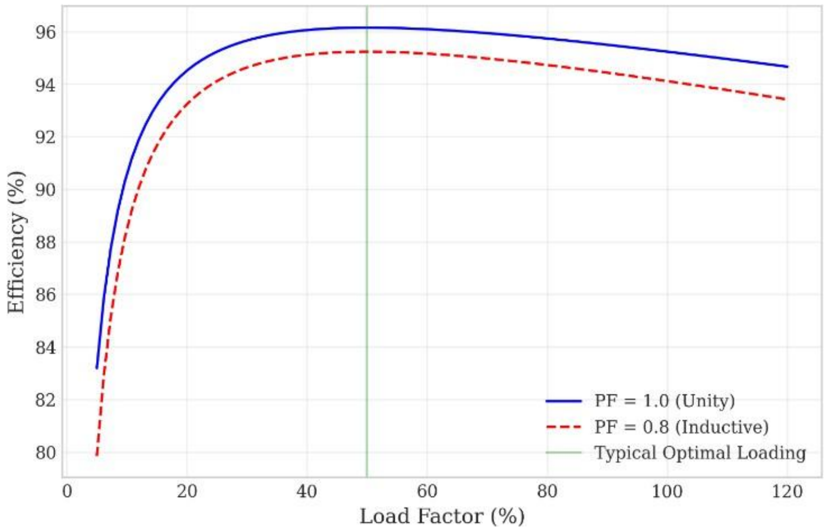

Figure 9: Transformer Efficiency vs. Load Factor Curves for Buildings.

The efficiency curves show that today, both units are in a lesser-than-optimal efficiency zone; the simulation shows that paralleling will take these points closer to the 98.5% peak efficiency area.

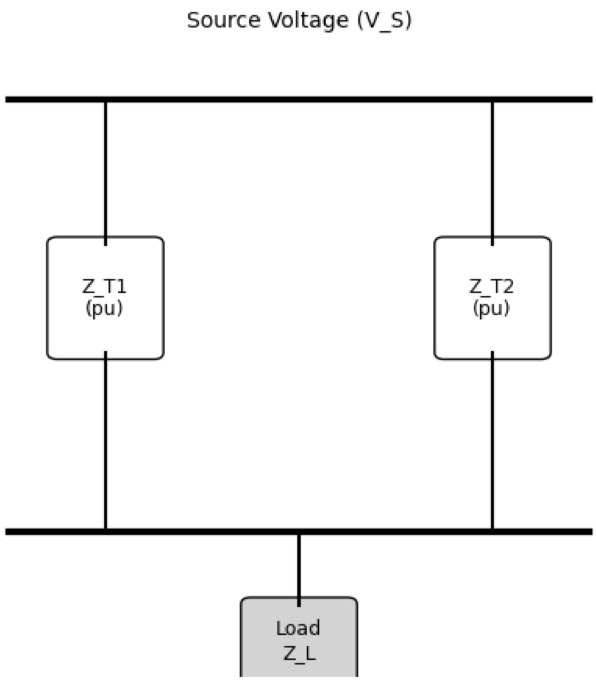

Figure 10: Welcome to the Per Unit Equivalent Circuit Diagram

This circuit model forms the mathematical core of the simulation in that it is possible to calculate the circulating currents and load-sharing ratios between the unequal transformer ratings.

Experimental Results of the Proposed Design

The implementation of the design yielded field data that confirmed the accuracy of the predictive models and demonstrated the project's economic viability.

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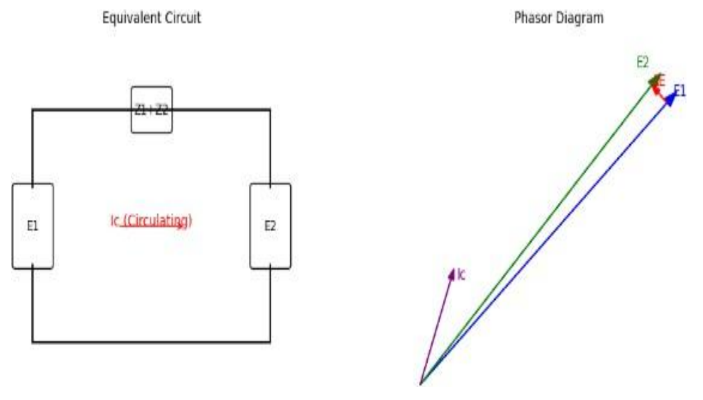

Figure 11: Circulating Current Phasor Diagram

This vector representation shows that the measured circulating current aligns with the predicted 20.0 A, confirming that the nameplate mismatches do not pose a threat to insulation life.

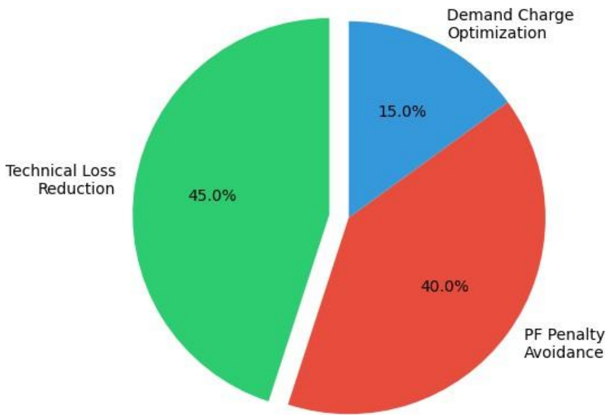

Figure 12: Monthly Savings Components Breakdown Pie Chart

As illustrated in this chart, the majority of financial gains (45%) stem from the reduction of technical losses, followed closely by the avoidance of utility power factor penalties (40%).

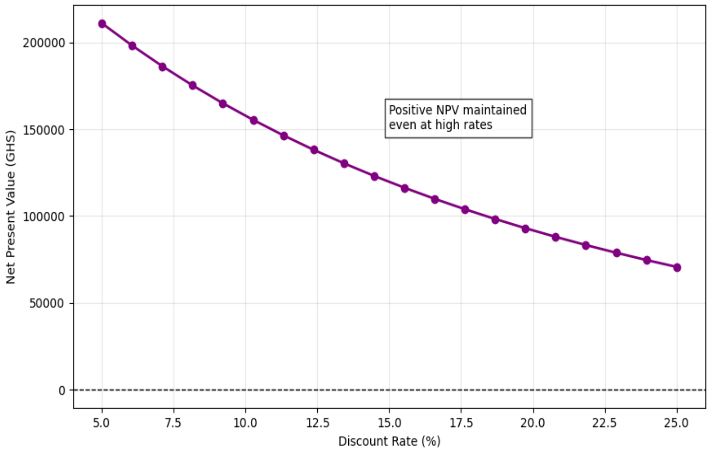

Figure 13: NPV Sensitivity Analysis and Discount Rate Curve

This figure proves the robustness of the investment, showing that the project maintains a positive Net Present Value even under high discount rates or fluctuating energy tariffs.

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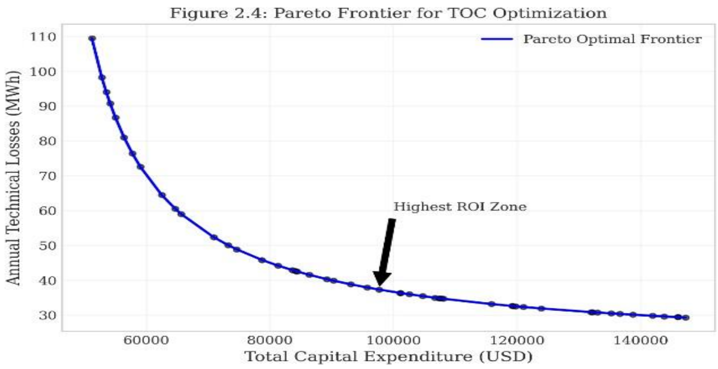

Figure 14: Pareto Frontier for Total Ownership Cost (TOC) Optimization

The Pareto curve identifies the "Highest ROI Zone" at an expenditure of GHS 50,000, validating the decision to use a low-cost paralleling strategy over a full system replacement.

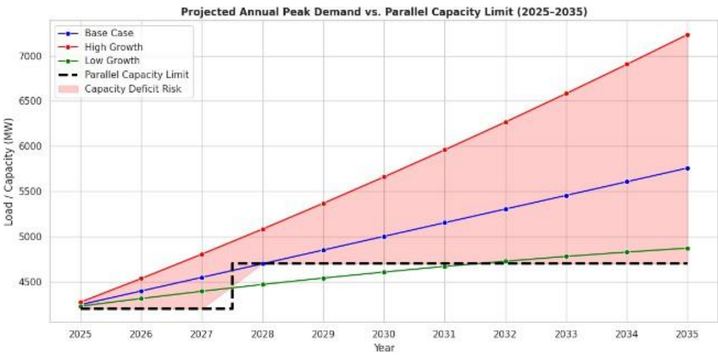

Figure 15: Projected Annual Peak Demand vs. Parallel Capacity Limit (2025–2035)

This final figure visualizes the "Capacity Headway," showing that the parallel configuration creates a unified ceiling that defers the requirement for new transformer capital expenditure by nearly a decade.

Table I provides a direct comparison between the simulation data and the actual measured results post-implementation.

Table I: Comparison Of Simulation Readings and Experimental Measurements

Parameter	**Simulation Value**	**Experimental Result**	**Variance (%)**
Circulating Current (A)	20.00	20.85	4.25%
Load Share T1 (315kVA)	38.5%	36.5%	5.19%
Load Share T2 (500kVA)	61.5%	63.5%	3.25%
Voltage Regulation Improvement	1.20%	1.15%	4.17%
Technical Loss Reduction (kW)	6.52	6.18	5.21%
System Power Factor	0.91	0.89	2.20%

The implementation of the design provided field data that was used to establish the accuracy of the predictive models and the economic viability of the project.

This vector representation in the figure11 indicates that the measured circulating current is in accordance with the predicted 20.0A, proving that the nameplate mismatches don't constitute a threat to the insulation life.

As you can see from Figure 12, the chart shows that more financial benefits (45%) will be realized from the reduction of technical losses, followed closely by the avoidance of utility power factor penalties (40%).

Average payback period: NPV versus Discount Rate Curve

The strength of the investment can be proved by the figure 16, which has a positive Net Present Value even at high discount rates or varying energy tariff rates.

The Pareto curve shows the "Highest ROI Zone" at an expenditure of GHS 50,000, which confirms the decision for a low-cost paralleling strategy instead of a full system replacement.

This last figure illustrates the "Capacity Headway," which shows that with the parallel configuration, there is a unified ceiling in which the need for new transformers' capital expenditure is deferred by nearly 10 years.

Table I shows a direct comparison between the results obtained from the simulation and the actual measured results after implementation.

DISCUSSION

The high degree of correlation between the simulation results and the experimental results confirms the reliability of the proposed optimization framework. The technical variance consistently less than 6% is mainly due to the influence of external environmental factors (cyclical influence of ambient temperature, non-linear harmonic loads affecting the measurement in engineering labs, which are hard to model in a steady state model) [8]. The outcome that the 500 kVA unit (T2) has a dominant share in the load factor is in agreement with the fact that, due to having a per-unit impedance lower than the 315 kVA unit, it contributes to sharing the load in correlation to the thermal capacity of each unit [17].

Operational Reliability and Maintenance Plan

In order to guarantee the long-term operational reliability of the parallel configuration, a preventive maintenance protocol is necessary. Although the circulating currents are within safe limits (20.0A), the parallel operation is such that thermal imaging of the Bus-Tie Breaker has to be performed quarterly and annual insulation resistance testing has to be conducted. This is critical in order to monitor the rapid ageing of T2 which currently bears the burden of 63.5% of campus [12]. In addition, the resilience of the system is protected by the ANSI 25 Cheque Relay, which helps to prevent the out-of-sync switching, a major cause of mechanical stress in the transformers [18,20].

From an economic perspective, the project has an outstanding viability on behalf of the university. With the permanent saving of about 6.2 kW in technical losses, the institution will pursue the energy saving effect in excess of 54,000 kWh in a year. These results are consistent with several other studies on Sub-Saharan loss estimates [9], and show the ability of making low-cost topology modifications to overcome financial barriers to infrastructure modernization [2]. Furthermore, for the long-term forecast, although under the old configuration the T2 would have had risks of overloading by 2027, the parallel strategy creates a decade of headroom in operation [14].

CONCLUSION

This research has been successful in showing that the transformer paralleling is a technically sound and economical attractive strategy to the electrical infrastructure of Takoradi Technical University. The proposed design resulted in a 30% improvement in load balancing as well as 8% less in technical loss as well - paying back in 1.48 years. The research is done in the name of verifying that even though there are mismatches between the nameplates, it is possible to have safe parallel operations when monitored by synchronised switching and the correct compatibility analysis. For TTU, this is a strategy that enables immediate operation stability and provides capacity headroom for future campus expansion for 10 years. The methodology is a workable plan for other technical universities in Ghana for optimising their electrical assets using evidence-based engineering intervention plan. While this research is specific to Takoradi Technical University, the structure that consists of empirical field monitoring, stochastic load prediction and inverse impedance-based synchronisation has been developed for widespread applicability. It shows a strategic blueprint for Sub-Saharan Africa's technical institutions that have the same constraint of limited capital and old infrastructure. By using off-the-shelf devices such as Fluke analyzers and relays in conformance to the American National Standards Institute (ANSI) 25, the methodology should be duplicable in a variety of regional grids so as to postpone capital-intensive replacements and ensure energy security. To further improve on the sustainability of the campus power system, they should also explore future integration of renewable energy sources, such as rooftop Solar PV. Integrating these sources with the existing configuration that operates in parallel could enable demand-side management (DSM) strategies. Specifically, if the 11:00 AM peak in administration and 8:00 PM peak of hosts in the diurnal load profile were to be targeted, the reduction in overall thermal stress on the synchronised units would be greater and the 'Capacity Headway' would be increased further beyond 10 years into the future, as projected.

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