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Load-Dependent Copper Loss Analysis in Educational-Scale Transformers: An Experimental Approach

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Abstract

This study aims to experimentally investigate the effect of load resistance variation on copper loss and transformer efficiency at the laboratory scale. Two transformer configurations—step-up and step-down—were tested with load resistances ranging from 10 to 500 Ohms. Measurements of voltage, current, and power were taken on both the primary and secondary sides to calculate copper loss and efficiency. The experimental results demonstrate a nonlinear inverse relationship between load resistance and copper loss, consistent with theoretical predictions. The step-up configuration exhibited higher copper loss under low-load conditions, whereas the step-down transformer showed a more stable efficiency profile across varying loads. Statistical validation, as indicated by the coefficient of determination ($R^2 > 0.98$) and Root Mean Square Error (RMSE < 0.08 W), demonstrates a strong agreement between the theoretical models and experimental data, confirming the model's accuracy and the reliability of the experimental setup. These findings have practical implications for optimizing transformer loading strategies to reduce long-term energy losses and improve operational efficiency. Moreover, the results support the development of vocational education laboratory modules that link Theory with hands-on learning, enhancing students' understanding of real-world transformer performance and energy efficiency concepts. This study contributes to the field by validating a theoretical model with experimental data, highlighting critical load-loss relationships in transformer operation, and providing a practical framework for both industry applications and technical education.

INTRODUCTION

Transformers are essential components in electric power systems, functioning to transfer energy between two circuits through the process of electromagnetic induction. During operation, transformers experience power losses, primarily categorized into core losses and copper losses [1]. Copper loss occurs due to the flow of electric current through the copper windings and is influenced by both the magnitude of the current and the resistance of the circuit [2]. Consequently, variations in load resistance directly affect the current flow and, in turn, the magnitude of copper losses. Under certain conditions, an increase in load resistance can reduce current and thus decrease copper loss. However, this relationship is not always linear, particularly when considering operational variables and the physical characteristics of the transformer [3]. Therefore, an experimental investigation is needed to observe directly the behavior of copper loss under varying load resistances.

Copper loss significantly contributes to the reduction of transformer efficiency, especially under high-load conditions [4]. As the current in the windings increases, copper losses rise, resulting in lower power conversion efficiency and elevated transformer temperatures, which can shorten lifespan and increase operational costs [5]. Transformer efficiency declines sharply when the load exceeds 80% of its rated capacity due to increased copper losses [6], a trend particularly evident in large-capacity transformers operating under heavy loads [7].

Proper selection and management of the load are crucial to minimizing copper losses and maintaining system efficiency. A mismatch between the load and the transformer's rated capacity can lead to higher energy consumption [8], reduced system reliability [9], and elevated operational costs [10]. Thus, a clear understanding of how load resistance affects copper losses is vital, not only for industrial electrical system design but also for vocational education at polytechnic institutions.

Most studies on transformers rely on numerical simulations or theoretical models [11, 12, 13]. Simulations using tools like MATLAB/Simulink have been employed to model copper losses under various load configurations; however, these emphasize the importance of experimental validation through laboratory studies [14]. Although numerous studies have investigated copper loss using theoretical models or numerical simulations, such approaches may not fully capture the practical complexities encountered in real transformer operation, particularly under varying load conditions. The absence of experimental validation limits the applicability of those findings in educational and useful settings. This study addresses this gap by providing empirical data to test theoretical predictions and evaluate model accuracy.

In vocational polytechnic education, hands-on learning is crucial for strengthening students' understanding of physical principles and their applications in industry. While the relevance of copper loss has been introduced in textbooks and lecture settings, direct student exposure to real transformer behavior under load is still rare. Therefore, this experimental study supports the development of practical lab modules that integrate real-world data with foundational Theory. Practical modules based on real-world phenomena have been shown to enhance students' conceptual understanding and the relevance of their learning to industry needs [15,16].

This study aims to conduct an experimental investigation into the effect of load resistance variation on transformer copper loss and to analyze the relationship between copper loss and transformer efficiency. The research is conducted on a laboratory scale as part of developing practical modules to support learning in vocational education, particularly in introductory physics lab courses. The outcomes are expected to contribute to the design of useful, measurable, and industry-relevant educational experiments.

RESEARCH METHODS

This study employed an experimental method to investigate the relationship between copper loss and load resistance in a small-scale laboratory power transformer. The experimental setup consisted of a 10 VA transformer with a primary winding of 500 turns and a resistance of 2.5 Ω and a secondary winding of 1000 turns with a resistance of 9.5 Ω. The transformer could operate as either a step-up or step-down unit by interchanging the primary and secondary windings. It was connected to a 26 V AC power supply with a frequency of 50 Hz. Voltage, current, and power were measured on both the primary and secondary sides using digital voltmeters, ammeters, and wattmeters.

The transformer employed a solid iron U-core with an iron yoke (LD Systeme model 562 115). The U-core was made of solid iron, with dimensions of 17 cm in height and 15 cm in width and a cross-sectional area of 4 cm × 4 cm. The iron yoke measured 4 cm × 4 cm × 15 cm. The measurement instruments used were digital meters with TRUE RMS capability to ensure accurate readings under AC conditions. Voltage measurements ranged from 0.1 to 260.0 V with a resolution of 0.1 V and an accuracy of (0.3% + 0.3 V). Current measurements were divided into two ranges: up to 1 A with a resolution of 0.1 mA and an accuracy of (0.3% + 0.3 mA) and up to 2 A with a resolution of 1 mA and an accuracy of (0.3% + 3 mA). Power was measured using a precision wattmeter capable of low-power detection, featuring two auto-ranging scales: 0.00 to 99.99 W with a resolution of 0.01 W and 100.0 to 520.0 W with a resolution of 0.1 W, with an overall accuracy of (1% + 0.5 W).

The load resistance was varied using fixed resistors with the following values: 10, 20, 30, 40, 50, 60, 70, 80, 90, 100, 110, 120, 130, 140, 200, 300, 400, and 500 ohm. These discrete values allowed for systematic observation of the transformer's performance and copper loss across a wide range of load conditions. Each measurement was repeated three times, and the average value was used for analysis. Data were recorded under steady-state conditions, approximately 10 seconds after each load change, to ensure stable voltage and current.

The collected data were processed using Microsoft Excel to calculate transformer efficiency, copper losses, and the relationship between load resistance and these parameters. Data transformations were performed using a linear scale, and graphical representations were generated for visual analysis.

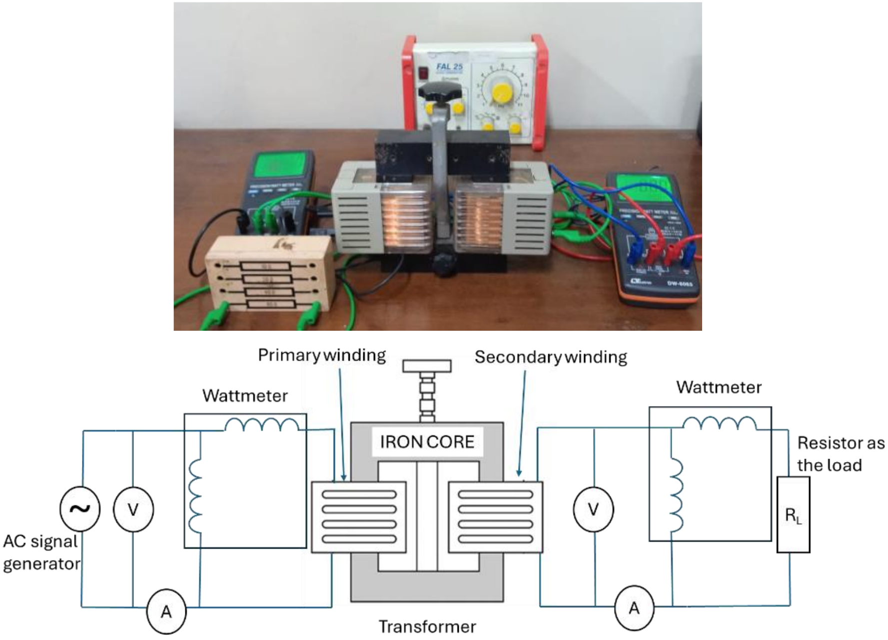

Figure 1. Experimental setup for measuring transformer copper loss.

Systematic measurements are taken for both the primary and secondary quantities, including primary voltage (V_1), primary current (I_1), secondary voltage (V_2), secondary current (I_2), input power (P_{in}), and output power (P_{out}). These data are used to calculate total copper loss (P_{cu}) using the equation:

$$P_{cu} = I_1^2 R_1 + I_2^2 R_2 \tag{1}$$

where R_1 and R_2 are the resistances of the primary and secondary windings, respectively, measured using a digital multimeter. Since the secondary current depends on the load resistance R_L and secondary voltage, the relationship is given by:

$$I_2 = \frac{V_2}{R_L}, \qquad I_1 = aI_2 \tag{2}$$

where $a = \frac{N_2}{N_1}$ is the turns ratio. Substituting into the copper loss formula yields:

$$P_{cu} = \left(\frac{V_2^2}{R_L^2}\right)(a^2 R_1 + R_2) \tag{3}$$

This equation shows that the total copper loss is inversely proportional to the square of the load resistance. The relationship between copper loss and transformer efficiency is established using the following definition of efficiency:

$$\eta = \frac{P_{out}}{P_{in}} = \frac{P_{out}}{P_{out} + P_{cu} + P_{fe}} \tag{4}$$

Assuming the core loss (P_{fe}) is constant and independent of R_L, efficiency will decrease as copper loss increases.

The experimental data are analyzed by plotting the relationship between copper loss and load resistance, as well as the relationship between efficiency and copper loss. The copper loss graph is compared to the theoretical model derived above. To evaluate the accuracy of the model against actual data, two statistical metrics are used: Root Mean Square Error (RMSE) and the coefficient of determination (R^2). RMSE measures the deviation of predictions from actual data [17], while R^2 indicates how well the variability in the data is explained by the model [18]. These metrics were computed in Microsoft Excel by comparing measured values to values predicted by the theoretical model.

The RMSE was calculated using the following equation:

$$RMSE = \sqrt{\frac{1}{n}\sum_{i=1}^{n}(y_i - \hat{y}_i)^2} \tag{5}$$

where y_i is the observed (experimental) value, $\hat{y}_i$ is the predicted (theoretical) value, and n is the number of data points.

The coefficient of determination (R^2) was calculated using:

$$R^2 = 1 - \frac{\sum_{i=1}^{n}(y_i - \hat{y}_i)^2}{\sum_{i=1}^{n}(y_i - \bar{y})^2} \tag{6}$$

where $\bar{y}$ is the mean of the observed values. RMSE quantifies the average error between the measured and predicted values, while R^2 indicates how well the experimental data fit the theoretical model, with values closer to 1 indicating a stronger correlation.

RESULTS AND DISCUSSION

This study examined the characteristics of copper loss (P_{cu}) in two transformer configurations: step-up (500 turns primary and 1000 turns secondary) and step-down (1000 turns primary and 500 turns secondary), under varying load resistances (R_L). The aim was to evaluate the conformity between theoretical models and experimental data across different load resistance values.

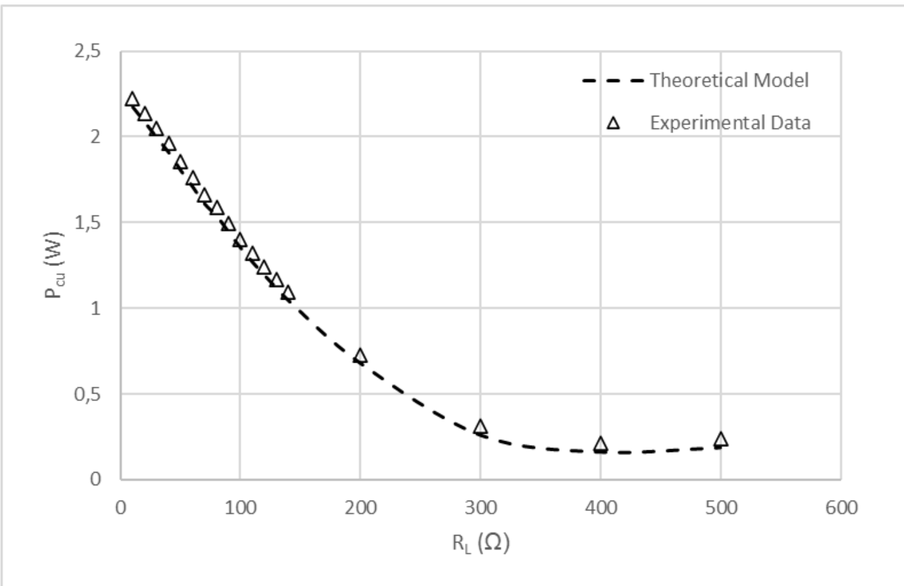

Figure 2. Graph of copper loss (P_{cu}) versus load resistance (R_L) in the step-up transformer.

For the step-up transformer in Figure 2, the data show that copper loss decreases nonlinearly as RL increases. At low load resistance (e.g., RL = 10 Ω), the load current is high, resulting in significant copper losses. As RL increases, current decreases, significantly reducing copper losses. The Root Mean Square Error (RMSE) value of 0.0761 W and the coefficient of determination (R^2) of 0.985 indicate that the model fits the experimental data very well. The nonlinear decrease in copper loss as load resistance increases can be explained by equation 3. As the load resistance increases, the current decreases rapidly (nonlinearly), and since copper loss depends on the square of the current, this leads to a quadratic reduction in power loss. This explains why the initial portion of the graph shows a steep decline in copper loss, which then flattens out at higher load resistances.

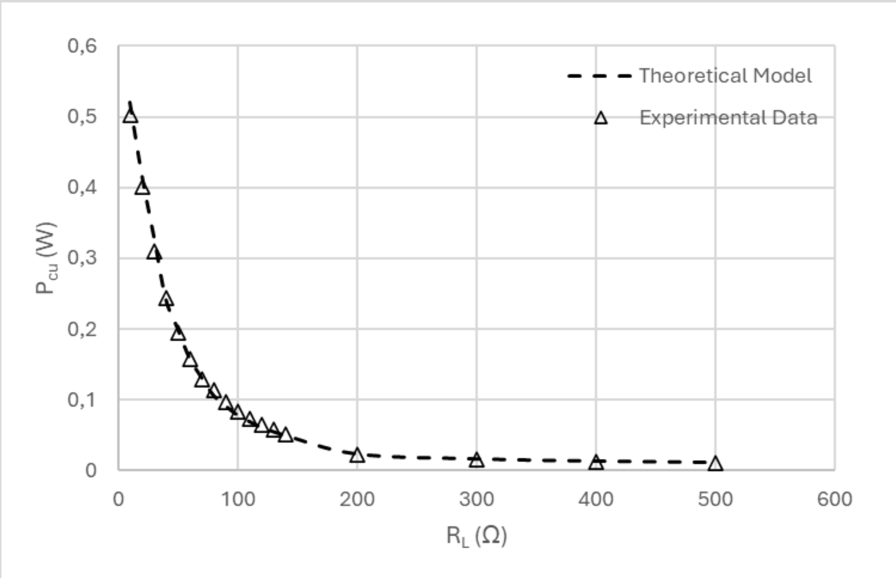

Figure 3. Graph of copper loss (P_{cu}) versus load resistance (R_L) in the step-down transformer.

For the step-down transformer in Figure 3, a similar trend is observed: increasing load resistance results in a decrease in copper loss, albeit on a smaller scale compared to the step-up configuration. This is due to the transformation ratio decreasing voltage and increasing current on the secondary side. Nevertheless, the results show that at RL values above 100 Ω, both the theoretical model and experimental data converge and stabilize near zero. The RMSE of 0.0066 W and an R^2 value of 0.998 suggest that the theoretical model closely represents the actual system behavior.

The comparison between the two configurations indicates that copper loss is more significant in the step-up transformer because the secondary winding carries a lower current but higher voltage. In contrast, the step-down transformer tends to produce lower copper losses, as the high current on the secondary side is supported by a shorter winding and lower system impedance [19].

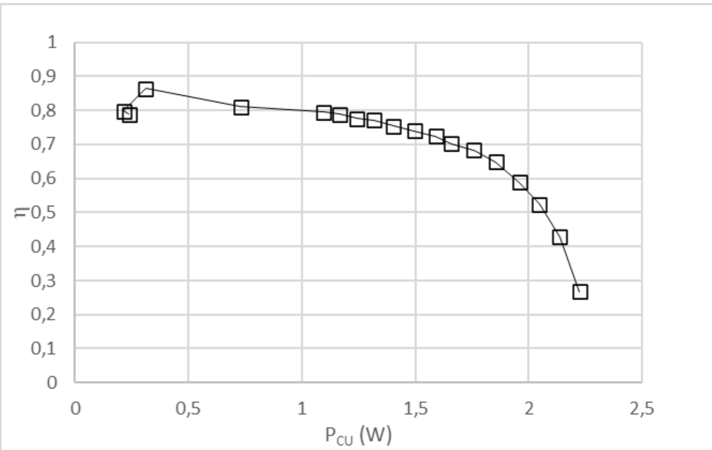

Figure 4. Graph of transformer efficiency (η) versus copper loss (P_{cu}) in the step-up transformer.

As shown in Figure 4, the efficiency of the step-up transformer initially increases with rising copper loss (P_{cu}), reaching a peak efficiency of approximately 0.87 when $P_{cu} \approx 0.3$ W. Beyond this point, efficiency begins to decline as copper losses increase. This pattern indicates an optimal operating point at which maximum efficiency occurs. The subsequent drop in efficiency at higher copper loss values indicates that increased load resistance leads to higher current on the secondary side compared to the primary, significantly increasing copper losses due to heating in the windings. Furthermore, when $P_{cu} > 2$ W, efficiency sharply drops to around 0.25, indicating operation far from optimal conditions.

This phenomenon occurs because copper losses increase quadratically with current, while output power does not increase proportionally due to the voltage drop caused by winding resistance. As a result, although input power remains high, output power decreases, leading to a decline in efficiency.

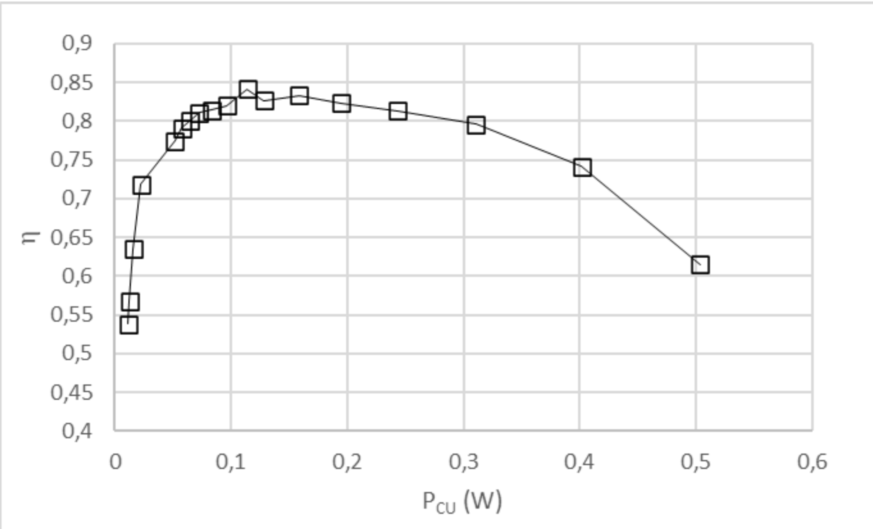

Figure 5. Graph of transformer efficiency (η) versus copper loss (P_{cu}) in the step-down transformer.

In Figure 5, a similar pattern is observed. Efficiency increases with rising copper loss (P_{cu}), reaching a peak at around $P_{cu} \approx 0.12$ W, with efficiency approaching 0.85. After this peak, efficiency decreases more gradually compared to the step-up transformer. This indicates that the step-down transformer maintains stable efficiency over a wider load range before experiencing significant degradation.

The difference in characteristics between step-up and step-down configurations can be attributed to the turn and current ratios between the primary and secondary sides. The step-up transformer has higher current on the primary side, resulting in greater copper losses in the primary winding. In contrast, the step-down transformer experiences high current on the secondary side, but since this is the load side, copper losses can be more precisely managed through resistive load control in the experiment.

The nonlinear increase in copper losses with increasing load resistance observed in this study is consistent with the findings reported by Özçelik and Aycan [20]. Their experimental investigation demonstrated that copper losses rise quadratically with load current, confirming the physical principle that copper loss is proportional to the square of the current flowing through the transformer windings. This aligns well with our observations, where copper loss decreases sharply at low load resistance due to high current and gradually levels off as load resistance increases.

Furthermore, Özçelik and Aycan found that iron losses remain nearly constant regardless of load variation, supporting the assumption in our theoretical model that iron losses are unaffected by load and primarily influenced by applied voltage. Their findings on power factor improvement and voltage regulation behavior under different loads also parallel the efficiency trends observed in our experiments, where transformer efficiency peaks at moderate loads before declining due to increased copper losses. This consistency with previous experimental studies reinforces the validity of the theoretical model used and highlights the importance of appropriate load management to optimize transformer efficiency and minimize losses in practical applications.

Overall, the results of this study demonstrate a strong consistency between the theoretical model and experimental data in describing the relationship between load resistance, copper loss, and transformer efficiency in both configurations. The high R^2 values and low RMSE values in both cases indicate that the model can accurately represent the physical behavior of the system.

The coefficient of determination (R^2) values obtained—0.985 for the step-up transformer and 0.998 for the step-down configuration—indicate an excellent fit between the theoretical model and the experimental data. An R^2 value close to 1.0 suggests that nearly all of the variability in the measured copper loss can be explained by the mathematical model, reinforcing its predictive accuracy. Similarly, the Root Mean Square Error (RMSE) values, which are 0.0761 W and 0.0066 W respectively, are very low in magnitude. RMSE represents the average deviation between the predicted and actual data points; the smaller the value, the more robust and reliable the experimental data.

Together, these metrics validate that the theoretical model not only approximates the behavior of the system under ideal conditions but also aligns closely with real-world measurements, confirming the experiment's reproducibility and reliability. These results further justify the use of this experiment as a valid educational model in practical laboratory settings. In terms of performance characteristics, the step-up transformer exhibits higher copper losses at low loads but with a slightly higher peak efficiency compared to the step-down transformer. Conversely, the step-down transformer tends to have a more controlled copper loss profile and a more stable efficiency range across varying load resistances. These findings underscore the importance of selecting suitable transformer configurations tailored to load conditions and system requirements to optimize efficiency and minimize power losses.

Additionally, the transformer operates more efficiently at higher resistive loads because lower currents result in reduced copper losses across the windings. However, this comes at the cost of reduced power transfer to the load, especially when the resistance becomes too high. This trade-off is a critical concept in transformer design and practical system optimization, especially when balancing energy efficiency and usable output power.

The experimental findings of this study carry significant implications for practical transformer design and load management strategies. The nonlinear relationship between load resistance and copper loss highlights the importance of selecting appropriate load levels to minimize power loss, especially in systems operating near full capacity. By carefully matching transformer ratings with typical load profiles, engineers can reduce energy waste, improve efficiency, and extend the lifespan of transformers—key considerations in industrial and distribution transformer applications. In vocational education, integrating experimental results into laboratory modules provides students with exposure to real-world system behavior. Understanding the direct impact of load resistance on energy loss helps future technicians and engineers develop more energy-conscious designs and maintenance strategies.

Future research could explore additional variables, such as core material properties, temperature effects, and different frequencies, to simulate industrial operating environments more accurately. Further studies might also investigate larger-scale transformer configurations or test the system under dynamic, time-varying loads. These investigations would not only enhance the theoretical model but also support the design of more robust and efficient power systems.

CONCLUSIONS

This study demonstrates that the value of load resistance has a significant influence on copper loss in transformers. The experimental results support the theoretical model, which states that copper loss is inversely proportional to the square of the load resistance. In the step-up transformer configuration, copper loss tends to be greater—particularly under low-load conditions—although the maximum efficiency achieved is slightly higher. Conversely, the step-down transformer exhibits better efficiency stability across a wider range of loads. Importantly, the close agreement between the theoretical model and experimental data—evidenced by high R^2 and low RMSE values—validates the accuracy and applicability of the theoretical model under practical conditions. This validation is a key contribution of the study, demonstrating the model's reliability for real-world transformer analysis and educational use.

The observed inverse nonlinear relationship between load resistance and copper loss also has broader implications for transformer design and operation. Understanding this behavior can inform strategies to optimize transformer loading, reduce long-term energy losses, and minimize operational costs—especially in industrial systems operating near full capacity. From an educational perspective, the experimental approach used in this study provides a valuable tool for vocational learning. By integrating Theory with real-world data, students gain a clearer understanding of electrical efficiency, transformer behavior, and load management. The findings can be directly applied to the development of laboratory modules that bridge academic knowledge with industrial practices, supporting competency-based education in electrical engineering. The high coefficient of determination (R^2) and low root mean square error (RMSE) values for both configurations indicate a strong agreement between the theoretical model and the experimental data. This confirms the reliability of the experimental approach in accurately examining the relationship between load resistance and copper loss.

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