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Analysis of Copper and Iron Loss Interactions in a 15 kW Three-Phase Induction Motor under Variable Operating Conditions

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ABSTRACT- ***Introduction:*** This research presents an innovative contribution to the field of induction motor efficiency optimization by analyzing the complex interactions between copper and iron losses in a 15 kW three-phase induction motor under variable operating conditions (10–60 Hz). While previous studies—such as Li et al. (2024) [16]—focused on simplified two-dimensional models or purely theoretical analyses, this study employs an integrated approach that combines advanced modeling with experimental validation, the main objective is to establish a reliable, accurate framework for quantifying and understanding loss mechanisms across a range of frequencies and thermal environments. ***Methodology:*** The study utilizes both 2D and 3D finite element analysis (FEA) in conjunction with high-precision experimental measurements to evaluate the effects of copper and iron losses under real-world dynamic conditions. A novel aspect of this methodology lies in accounting for manufacturing-induced variations, such as changes in the magnetic B−HB-H curve due to lamination processes. Additionally, the analysis incorporates loss measurement in end-winding regions due to magnetic leakage—often neglected in conventional simulations—and performs sensitivity analysis on winding arrangements and lamination thickness to extract industrially viable design recommendations. ***Results:*** The results demonstrate a significant rise in both copper and iron losses with increasing frequency. Copper losses were predominantly influenced by proximity and skin effects, leading to increased AC resistance and localized heating in active windings, iron losses, on the other hand, were found to be heavily dependent on magnetic flux density, lamination quality, and the presence of manufacturing defects. Notably, neglecting production-induced changes in core material properties resulted in substantial errors in conventional modeling. By optimizing wire layout, adopting thinner laminations (0.3 mm), and implementing advanced cooling systems, the total loss was reduced by up to 20%, these improvements enhance energy efficiency, extend motor lifespan, and reduce operational costs. ***Conclusion:*** This study provides a robust framework for understanding the coupled behavior of copper and iron losses in induction motors and highlights the importance of selecting appropriate materials, modeling manufacturing effects, and improving thermal management strategies, the integration of experimental and numerical methods represents a substantial advancement over prior work and provides actionable insights for optimizing industrial motor design to achieve higher efficiency and sustainability.

Keywords: Three-Phase Induction Motor, Copper Losses, Iron Losses, Variable Operating Conditions, Efficiency Analysis, High-Efficiency Motors.

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1. INTRODUCTION

The process of researching why power loss occurs in electric motors is essential, especially for motors that operate in high-performance applications and the goal is to maintain efficiency over a wide operating range and stabilize their performance for three-phase induction motors, such as the 15 kW model that the study will discuss, accurate prediction of copper and iron loss is important and it is considered extremely important because these losses greatly affect the overall efficiency [1] and to know the beginning of the formation of copper losses, it begins in the first place from heating the resistor in the stator windings and their size depends on the operating conditions of speed and frequency[2-3] at standard operating frequencies, these losses are determined primarily by the winding resistance also at higher speeds and frequencies, skin and proximity effects become more severe, which increases the resistance losses within the stator winding [4-5] and this necessitates a detailed separation of copper losses from Total losses measured to provide an accurate assessment of motor performance while considerable research has addressed copper losses in permanent magnet synchronous motors (PMSMs) [6-7], there is a relative paucity of studies exploring their interaction with iron losses in motors and inductivity, especially under variable operating conditions where, iron losses, resulting from hysteresis and eddy currents in the stator core are strongly influenced by the

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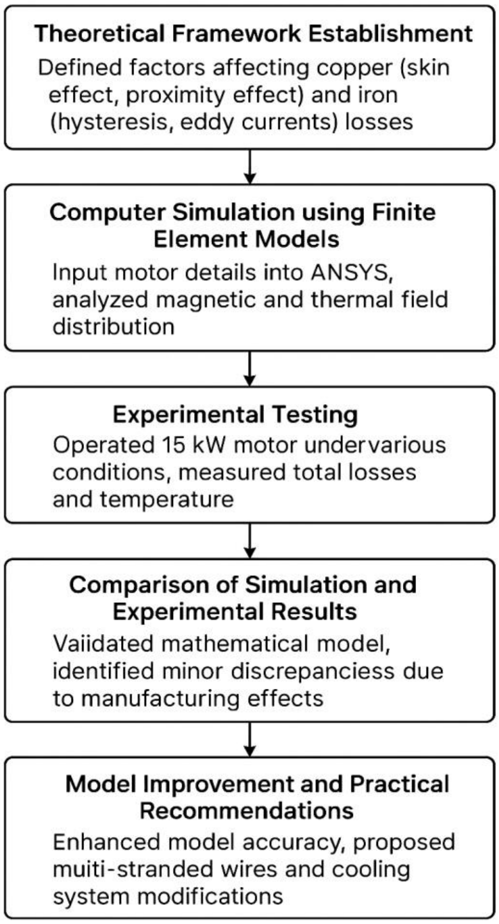
properties of the core materials and manufacturing processes and the quality of the stator core plays a pivotal role in determining these losses, especially at high speeds, where defects can exacerbate core losses [7-8] These defects not only affect the magnetic properties but also complicate the accurate separation of copper losses and in processes requiring high frequencies, the interaction between copper and iron losses becomes increasingly important because it has a strong direct impact on efficiency and overall engine thermal performance and therefore understanding these interactions is essential to improve engine designs and improve performance under variable loads and this study aims to provide a comprehensive study of copper and iron loss interactions in a 15 kilowatt three-phase induction motor and by analyzing these losses across a range of operating frequencies and conditions and by looking at To fundamental stator manufacturing impact this work seeks to provide accurate predictions of motor performance and provide actionable insights to enhance efficiency in industrial applications.

The study began by defining the theoretical framework for energy loss in induction motors, with a focus on the factors influencing copper loss (such as skin and proximity effects) and iron loss (such as hysteresis and eddy currents). A mathematical model was developed to reflect the relationship between frequency and material properties, based on physical equations such as the calculation of skin depth in conductors and the resistance of the iron core.The work then moved to the stage of computer simulation using two- and three-dimensional finite element models, where detailed motor specifications (such as geometric dimensions and material types) were input into specialized software such as ANSYS, the simulation included applying various operating conditions (such as frequencies from 10 to 60 Hz and varying loads) to analyze the distribution of magnetic and thermal fields, which enabled the identification of areas most affected by the losses.

In parallel with the simulation, practical experiments were conducted on a three-phase induction motor with a power of 15 kW. A variable frequency power source was used to operate the motor under different conditions, while total losses were measured using a high-precision power analyzer, thermal sensors were installed at strategic locations (such as copper windings and the iron core) to monitor temperature variations during operation, ensuring measurement stability by repeating the tests until an acceptable error margin was achieved. After data collection, simulation results were compared with experimental measurements to validate the mathematical model, the comparison revealed significant alignment in copper loss behavior at low frequencies, while slight discrepancies appeared at high frequencies, which were attributed to manufacturing effects on material properties. A sensitivity analysis was conducted to identify the most influential factors, such as the thickness of iron laminations and the winding arrangement, which enabled the formulation of design recommendations, the study concluded by Improving the model through integrating the experimental results into the simulation database, which increased the accuracy of predicting losses under previously untested operating conditions, practical improvements were proposed, such as using multi-stranded wires and modifying cooling systems, with emphasis on the importance of selecting high-quality materials to reduce total loss — as shown in *flowchart 1*.



Flowchart 1. Sequential Methodology for Analyzing Copper and Iron Losses in Induction Motors

2. LITERATURE REVIEW

Numerous studies have addressed the efficiency optimization of three-phase induction motors by examining copper and iron losses under varying conditions and Copper losses, primarily resulting from resistive heating in the stator windings, have been a significant focus due to their temperature dependency Sharma et al. (2009) [9] demonstrated that higher operating temperatures increase the resistivity of winding materials, leading to pronounced performance degradation. Benzarti et al. (2024) [10] highlighted the role of advanced cooling techniques in mitigating these temperature-induced losses, suggesting improved designs to enhance overall motor efficiency also Cao et al. (2006) [11] investigated load variations and established a direct correlation between fluctuating motor loads and the magnitude of copper losses, iron losses, comprising hysteresis and eddy current components, have been extensively analyzed for their sensitivity to material properties and core design and Chwastek et al. (2010) [12] revealed that higher silicon content in stator core materials significantly reduces hysteresis losses, highlighting the importance of material composition in magnetic efficiency also Xue et al. (2017) [13] compared the magnetic properties of various core materials and concluded that high-silicon steel offers better performance under high loads due to its reduced hysteresis loss also Zhao et al. (2019) [14] focused on the frequency-dependent nature of iron losses, emphasizing how increased operational speeds amplify eddy current losses within the core. Methods to mitigate these losses were explored by Mohand Oussaid et al. (2024) [15] who demonstrated that reducing core lamination thickness minimizes eddy current losses while maintaining structural integrity and research has also delved into the interaction between copper and iron losses, as this interplay significantly influences the overall efficiency of induction motors. Li et al. (2024) [16] proposed a predictive model for these losses under varying operational conditions, revealing that both components are dynamically interlinked and jointly affect motor performance. Xiao et al. (2024) [17] underscored the importance of understanding this interaction, advocating for integrated analysis to design motors with enhanced thermal and mechanical performance. Xu et al. (2024) [18] extended this investigation by examining temperature impacts on both copper and iron losses, showing that high-load conditions exacerbate these thermal losses and emerging methodologies to evaluate and reduce losses have further contributed to the field. Book et al. (2021) [19] developed a practical experimental approach for measuring losses under real-world operational conditions, emphasizing the need for precise detection techniques in industrial applications and advanced simulations like those presented by Jadhav et al. (2021) [20], have enhanced the ability to model complex loss interactions, particularly at high speeds and variable loads, offering valuable insights for optimizing motor designs also Cisse et al. (2021) [21] demonstrated that implementing multilayer lamination in stator cores effectively redistributes magnetic flux, reducing hysteresis losses and these advancements have highlighted the critical role of optimizing both copper and iron losses in improving the energy efficiency and sustainability of induction motors as noted by Martyushev et al. (2023) [22], integrating insights into these loss mechanisms can reduce energy consumption, operating costs and environmental impact, making motors more sustainable and efficient in industrial applications and this study builds on these findings by analyzing the complex interplay of copper and iron losses under variable conditions, addressing gaps in understanding their joint effect on thermal and mechanical efficiency.

While the reviewed literature has provided valuable insights into the mechanisms and mitigation strategies of copper and iron losses in three-phase induction motors, several limitations persist. Most studies have treated copper and iron losses in isolation, overlooking the complex thermal-electromagnetic interactions that occur under real-world operating conditions, such as fluctuating loads and variable frequencies. Additionally, although simulation-based approaches have advanced significantly, experimental validation under industrial-scale scenarios remains limited in scope, particularly for motors operating beyond standard thermal thresholds. Moreover, prior models often generalize material properties and fail to account for manufacturing-induced variances in lamination thickness, winding configurations, and insulation quality, which significantly influence both resistive and core losses, the lack of integrated methodologies that couple finite element simulation with real-time thermal and electrical measurements also limits the accuracy and predictive capability of current loss models.

There is a clear gap in the comprehensive analysis of the dynamic interaction between copper and iron losses in medium-capacity induction motors, particularly under non-linear and high-load operating conditions, Few studies have effectively combined advanced numerical modeling with experimental thermal diagnostics to evaluate the mutual influence of these losses on motor efficiency and structural integrity, this study aims to bridge this gap by offering a detailed analysis of the copper and iron loss interplay in a 15 kW three-phase induction motor, utilizing combined 2D/3D finite element simulation and experimental validation under variable frequency and load conditions, the research uniquely contributes to the development of thermally-optimized and energy-efficient motor designs by integrating empirical insights with predictive modeling, thus enhancing motor reliability and sustainability in industrial applications.

3. MACHINE PROTOTYPE

In this study, a 15 kW three-phase induction motor is investigated and focusing on the interactions between copper and iron losses under variable operating conditions and the motor is designed for industrial applications requiring high efficiency and low losses while the detailed electromagnetic design, optimization and thermal management are not the primary focus of this research, these factors play a crucial role in the overall performance of the motor and the technical specifications of the motor are as follows;

- Power: 15 kW (20 hp).
- Voltage: 380 V (standard industrial voltage).
- Frequency: 50 Hz.
- Speed: 1500 rpm (synchronous speed, 4 poles).
- Cooling Type: External cooling (IC411).
- Efficiency: ≥ 92% (high-efficiency motor designed to minimize losses).
- Efficiency Class: IE3 (high-efficiency class).

The motor prototype incorporates key features to ensure high efficiency while minimizing power losses and the stator core is constructed from high-quality electrical steel with optimal properties to reduce iron losses and the stator windings use copper conductors with a careful design aimed at minimizing copper losses through factors like conductor size and winding configuration and cooling system ensures the motor operates within temperature limits, reducing the effects of thermal losses and the performance of the motor is influenced by several factors such as core material properties, winding configurations and operating conditions, which are analyzed in this study to quantify copper and iron losses accurately under varying loads.

Table 1. below lists the main design parameters of the 15 kW three-phase induction motor prototype under investigation

Parameter	Value
Maximum Speed	1500 rpm
DC Link Voltage	380 V
Maximum Phase Current	28 A
Stack Length	80 mm
Stator Outer Diameter	220 mm
Split Ratio	0.53
Current Density	27.2 A/mm²

This motor prototype serves as the foundation for investigating the detailed interactions between copper and iron losses, with the goal of improving overall energy efficiency across various operating conditions.

4. COPPER LOSSES IN THE THREE-PHASE INDUCTION MOTOR

In high-power applications, such as the 15 kW three-phase induction motor under investigation, copper losses form a significant part of the total power losses and these losses primarily result from resistive heating in the stator windings, which can lead to elevated winding temperatures and this rise in temperature directly impacts the insulation's lifetime and can cause the motor to exceed its thermal limits, affecting performance and efficiency. With the motor designed for high efficiency (≥ 92%), understanding and mitigating copper losses is essential for maintaining optimal functionality.

4.1. Skin Effect Analysis

The skin effect arises due to self-induced eddy currents within the conductor, leading to a non-uniform current density distribution and the depth at which current density decreases to 1/e of its value at the conductor's surface is known as the skin depth (δ), For a conductor operating at a frequency *f*, the skin depth is calculated as [23]:

$$\delta = \sqrt{\frac{\rho}{\pi f \mu_0 \mu}} \quad (1)$$

Where:

- ρ Electrical resistivity of the conductor (copper resistivity is $1.68 \times 10^{-8} \Omega \cdot m$),
- μ_0 is the permeability of free space ($4\pi \times 10^{-7}\ H/m$),
- f is the operational frequency of the motor (50 Hz),
- μ is the relative permeability of copper (close to 1 for non-magnetic materials).

For copper at 50 Hz:

$$\delta = \sqrt{\frac{1.68 * 10^{-8}}{\pi * 50 * 4\pi * 10^{-7} * 1}} \approx 4.3\ mm$$

This implies that any conductor with a diameter larger than 8.6 mm will exhibit significant skin effect losses, as currents are confined closer to the surface.

4.2. Proximity Effect Analysis

The **proximity effect** results from the influence of magnetic fields produced by neighboring conductors, causing additional eddy current losses and this effect is pronounced in densely packed windings or conductors with poor geometric arrangements and to minimize proximity losses, techniques like multi-stranded conductors (e.g., Litz wire) are often used.

- **Factors influencing proximity losses**:
  - **Slot geometry**: Determines the spacing between conductors, influencing induced currents.
  - **Winding configuration**: Compact and optimized winding layouts reduce magnetic coupling between strands.

Using Litz wire or parallel strands can mitigate proximity effects, although this increases the cost and complexity of manufacturing, parallel strand configurations can sometimes result in unbalanced current distribution, leading to circulating currents, which must be considered in designs.

4.3. Figures and Relationships

4.3.1. Impact of Frequency on Skin Depth

The following figure demonstrates the relationship between operating frequency and skin depth in a copper conductor.

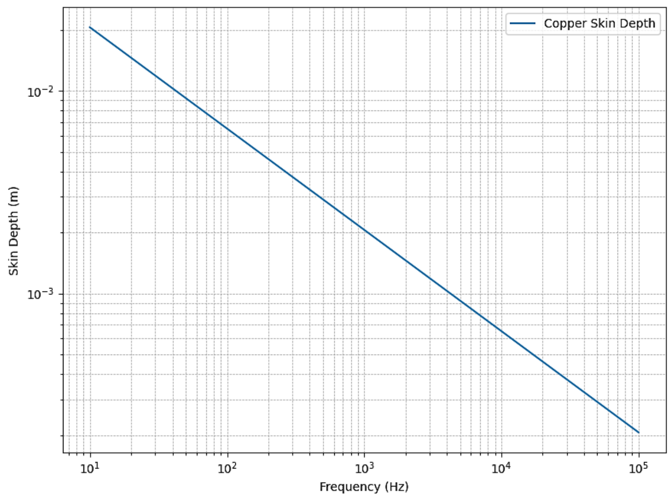


Figure 1. Skin Depth vs Frequency in Copper Conductor

4.3.2. Copper Loss Variation with Load

To capture load dependency, the figure below demonstrates the relationship between load percentage and copper losses, showing the impact of increasing load.

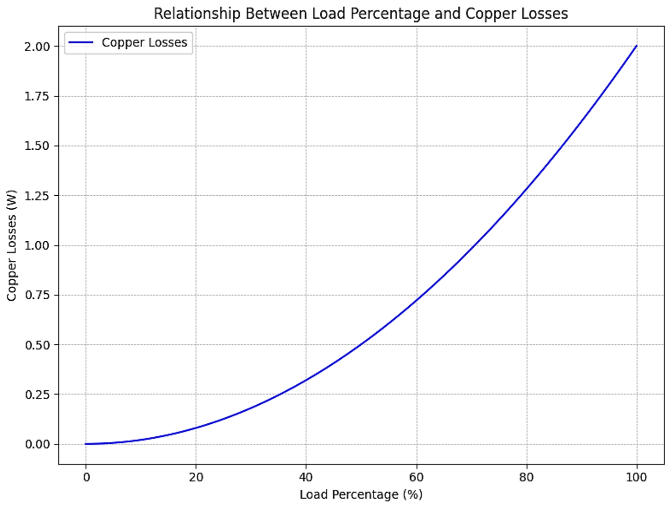


Figure 2. Relationship Between Load Percentage and Copper Losses

5. DISCUSSION OF RESULTS

5.1. Analysis of Skin Effect and Load Dependency on Copper Losses in Electric Motors

• ***Skin Effect Analysis:*** *The* skin depth decreases significantly as the operational frequency increases, for frequencies beyond 50 Hz, currents are confined closer to the conductor's surface, exacerbating resistive losses and this highlights the need for optimizing conductor geometry to minimize losses, especially at higher operational speeds.

• ***Load Dependency of Copper Losses:*** The quadratic relationship between load and copper losses shows that losses grow disproportionately as the motor load increases and this underscores the importance of managing load levels, implementing efficient cooling systems and ensuring proper thermal management to keep the motor within safe operational limits.

• ***Impact of Cooling and Material Design:*** The effectiveness of copper loss management also depends on the quality of cooling and conductor material design:

- High-efficiency cooling systems reduce the thermal resistance, thereby limiting the rise in winding temperature.
- Proper selection of conductor diameter ensures minimal impact of skin and proximity effects.

By addressing both operational and design factors, the overall copper losses can be minimized, improving motor efficiency and prolonging its operational life.

5.2. Final Observations

For the 15 kW three-phase induction motor under investigation, a combination of optimized winding design, use of low-loss conductors and enhanced cooling systems is recommended. Modeling the interaction of these factors, particularly under variable operating conditions, is essential for further improving motor performance. Figures generated in the analysis can be used for experimental validation and comparison with simulated models, providing deeper insights into loss mechanisms under varying operating conditions. Additional experiments should also evaluate how copper losses interact with iron losses, particularly during high-frequency operation, to form a more comprehensive efficiency model.

5.3. Experimental Setup

To analyze the copper and iron loss interactions in the 15 kW three-phase induction motor under variable operating conditions, experimental tests were carried out on the motor's stator and the setup, specifically tailored to the motor specifications (380 V, 50 Hz, 4-pole configuration), is designed to evaluate winding losses and thermal behavior under realistic conditions.

5.3.1. Test Equipment and Configuration

- ***Variable-Frequency Power Supply****:* A sinusoidal current source (*e.g.*, Chroma 61511) energizes the motor windings with precise control over frequency and current levels.
- ***Power Analyzer****:* A high-bandwidth power analyzer (e.g., KinetiQ PPA2530) measures input power, voltage and current, accounting for resistance variations with frequency.
- ***Temperature Sensors****:* K-type thermocouples are placed at strategic locations, including the end-winding and the active length (inside the stator slots), to monitor temperature rise during operation.
- ***Loss Calculations****:*
  - Total losses were determined from the measured input power.
  - Core losses were estimated using 3D Finite Element Method (FEM) simulations and experimental material characterization of the stator core.

5.3.2. Material Characterization

Characterization of the stator core material accounts for manufacturing effects that influence core losses and this step is essential for accurate differentiation between AC and DC copper losses, as well as understanding thermal behaviors influenced by the operating frequency.

5.3.3. Thermal Test Procedure

- For each operating condition, thermal tests were conducted at various excitation currents and frequencies (*e.g.*, 10 Hz to 60 Hz).
- The thermal test for each operating point continued until the temperature stabilized, defined as a variation of less than 1°C, over 10 minutes.
- Recorded temperatures showed significant differences between the end-winding (exposed to air cooling) and the active length inside the slots (with heat dissipation impeded by the stator back iron) and this highlights the stator slots as the hotspot.

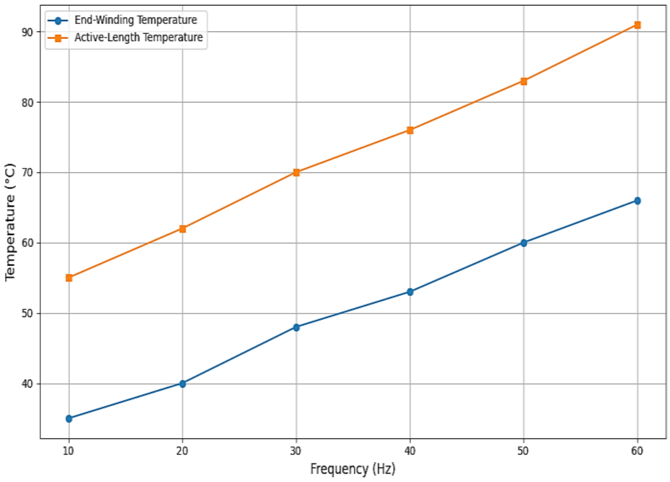


Figure 3. Temperature Distribution at Various Frequencies

In this study, a comprehensive experimental validation was conducted using a custom prototype of a 15 kW three-phase induction motor, the motor was constructed using a core made of silicon steel laminations with a thickness of 0.35 mm and a filling factor of 95%, along with a special surface treatment to reduce eddy current losses. Additionally, Litz wire consisting of seven strands, each with a diameter of 2 mm, was used to minimize proximity effects when operating at high frequencies, to manage heat, an external cooling system with a fan (IC411) and optimized air channels was employed to ensure stable operating temperatures and minimize the impact of thermal variations on loss measurements, the test setup included a variable frequency power supply (Chroma 61511) and a high-precision power analyzer (KinetiQ PPA2530), the motor was subjected to three main operating scenarios to cover a wide range of dynamic behaviors, in the standard operating scenario, the motor was run at 50 Hz with full load (100%) to establish a baseline for iron and copper losses, Subsequently, a high-frequency scenario was tested at 60 Hz and 120% load to analyze the combined effects of skin and proximity phenomena on winding losses, Finally, a partial load condition was evaluated at 30 Hz and 50% load to estimate motor efficiency under varying operating conditions, these scenarios provided an accurate database for validating numerical models and extracting design recommendations applicable to industrial motor.

5.4. AC Losses Analysis

5.4.1. Stator Core Losses

The separation of laminated stator core losses from the measured total power losses (copper losses + iron losses) using a power analyzer is not feasible. Accurate estimation of iron losses is achieved through finite element (FE) simulations of the stator core under the same current and frequency conditions used in experiments.

The stator core, constructed using silicon steel laminations, undergoes manufacturing processes that alter its magnetic properties, such as the magnetization B−HB-HB−H curve and specific core losses. Accurate analysis requires incorporating these changes into simulations to evaluate the AC copper losses effectively and *table 2*, provides the material properties of the stator core.

Table 2. Material Properties of the Investigated Stator Core

Lamination Thickness	Density (kg/m³)	Electrical Resistivity (μΩ·m)	Saturation Flux Density (T)	Package Density (%)
0.35 mm	7650	0.47	2.0	95

The specific core losses were characterized under pure sinusoidal excitation up to 2 kHz and flux densities ranging from 1 to 1.8 T. Results indicate that the specific core losses increase with both flux density and frequency, as shown in *figure 4*, These experimentally obtained losses were higher than those provided by the manufacturer's datasheet due to additional losses induced by the manufacturing process. Consequently, the FE material database was updated using the measured data for improved accuracy.

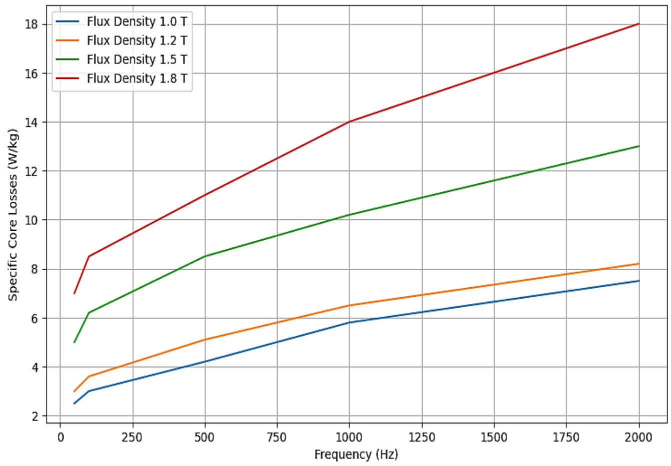


Figure 4. Specific Core Losses as a Function of Flux Density and Frequency

5.4.2. AC Copper Losses

The total copper loss P_{tot} comprises active winding losses $P_{act}(f,T)$ and end-winding losses $P_{end}(f,T)$, expressed as [24]:

$$P_{tot}(f,T) = P_{act}(f,T) + P_{end}(f,T) \quad (2)$$

Here, $P_{act}(f,T)$ and $P_{end}(f,T)$ depend on both temperature T and frequency f and the DC copper losses are computed using:

$$\rho = \rho 20 \cdot (1 + \alpha(T - 20)) \quad (3)$$

Where:

- $\rho_{20} = 1.68 \times 10^{-8}\, \Omega \cdot m$ is the resistivity at 20°C,
- $\alpha = 0.00393$ is the temperature coefficient of resistivity.

In AC conditions, additional proximity and skin effect losses are observed and the AC-to-DC resistance ratio R_{ac}/R_{dc} as a function of frequency is shown in *figure 5*, revealing higher losses in active windings compared to the end windings due to leakage flux differences.

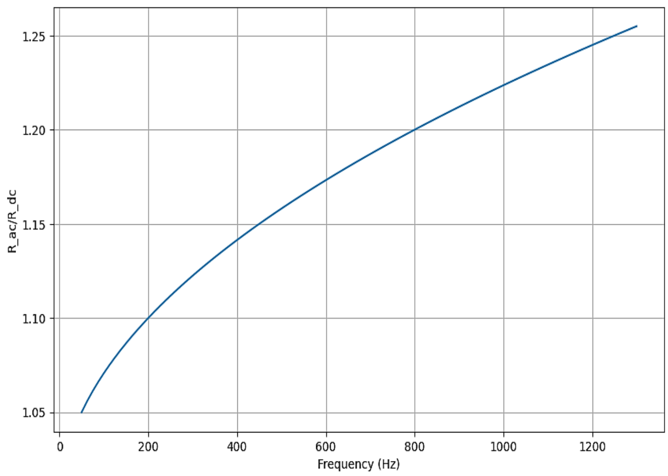


Figure 5. AC-to-DC Resistance Ratio vs Frequency

5.4.3. Experimental Results and Analysis

The dependency of phase resistance on temperature and frequency is illustrated in *figure 6*, highlighting a rise in $R_{ph,ac}$ with frequency. At 1200 Hz, the measured $R_{ph,ac}$ is 9.08% lower than the total measured phase resistance due to lower circulating currents in tightly packed conductors.

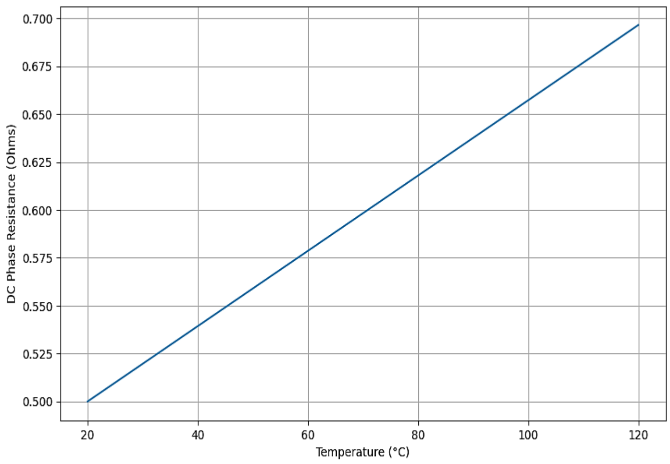


Figure 6. Phase Resistance Trends

5.5. Results and Experimental Analysis

5.5.1. Temperature Distribution and Losses at Various Frequencies

The experimental data highlights a significant rise in temperature across the stator's active length as operating frequency increases and *table 3*, below summarizes the temperature distribution for excitation currents of 25 A (RMS) at different frequencies.

Table 3. Temperature Distribution at Various Frequencies

Frequency (Hz)	End-Winding Temp. (°C)	Active-Length Temp. (°C)
10	35	55
20	40	62
30	48	70
40	53	76
50	60	83
60	66	91

The results reveal a growing temperature gradient between the end-windings and the stator slots, underscoring the need for improved cooling solutions, especially for high-frequency operations.

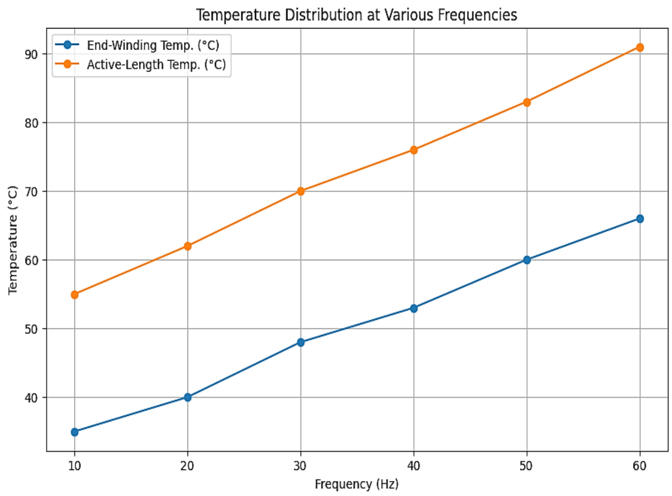


Figure 7. Temperature Distribution at Various Frequencies

A bar chart or line plot illustrating temperature rise trends for end-winding and active length across frequencies.

5.5.2. Loss Distribution Analysis

5.5.2.1. Stator Core Losses

Core losses, primarily derived from 3D FE simulations, show a marked dependency on both flux density and frequency, *figure 8*, below presents the specific core losses as a function of these variables.

Table 4. Material Properties of Stator Core

Property	Value
Lamination Thickness	0.35 mm
Density	7650 kg/m³
Electrical Resistivity	0.47 µΩ·m
Saturation Flux Density	2.0 T
Package Density	95%

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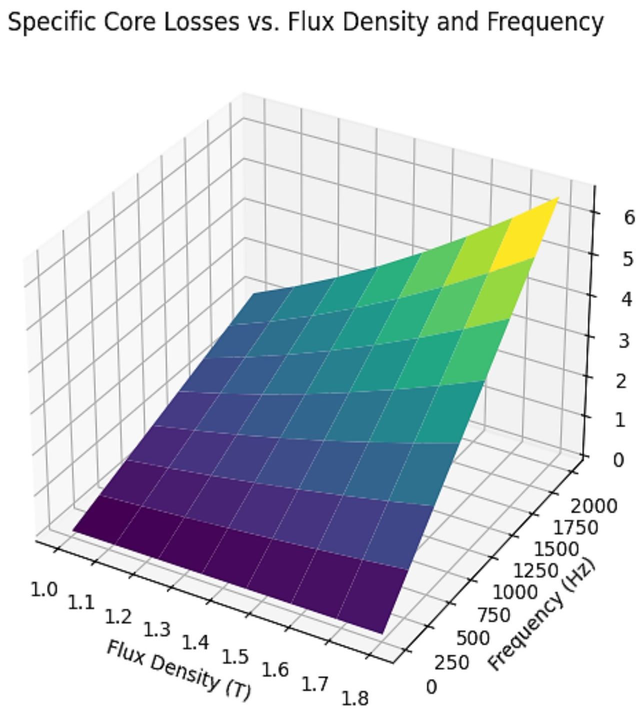

Figure 8. Specific Core Losses vs, Flux Density and Frequency

A 3D surface plot demonstrating core loss trends.

The FE simulations incorporated manufacturing-induced variations, showing higher core losses compared to manufacturer data. End-winding leakage fluxes further contributed to localized flux density increases, as illustrated in *figure 9*.

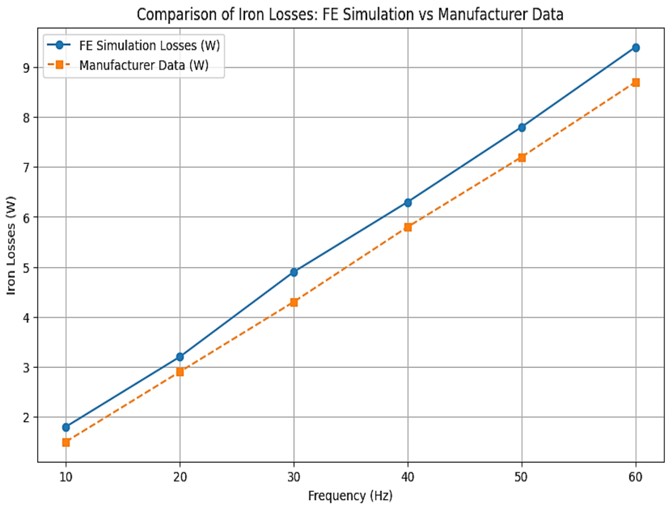

Figure 9. Comparison of Iron Losses (FE Simulation vs. Manufacturer Data)

5.5.2.2. AC Copper Losses

Copper losses were separated into active winding and end-winding components using the formula [25]:

$$P_{tot}(f,T) = P_{act}(f,T) + P_{end}(f,T)$$

Where:

$$\rho = \rho_{20} \cdot \big(1 + \alpha(T - 20)\big) \quad (4)$$

With:

- $\rho_{20} = 1.68 \times 10^{-8}\, \Omega \cdot m$ (resistivity at 20°C),
- $\alpha = 0.00393$ (temperature coefficient of resistivity).

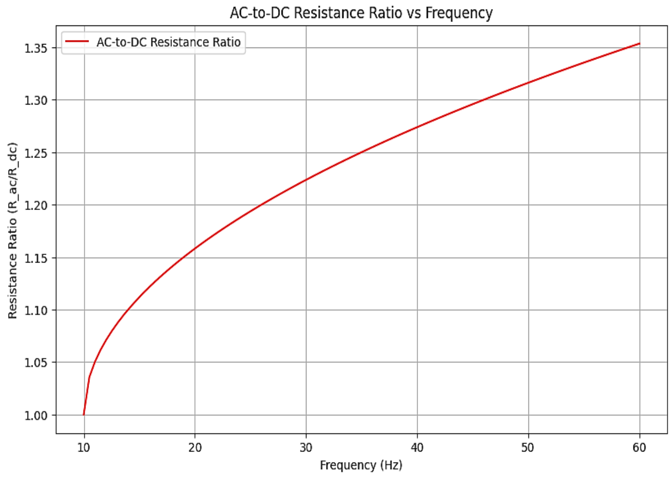

Figure 10. AC-to-DC Resistance Ratio vs, Frequency

A line graph showing resistance increase with frequency.

Experimental Results and Opportunities for Improvement

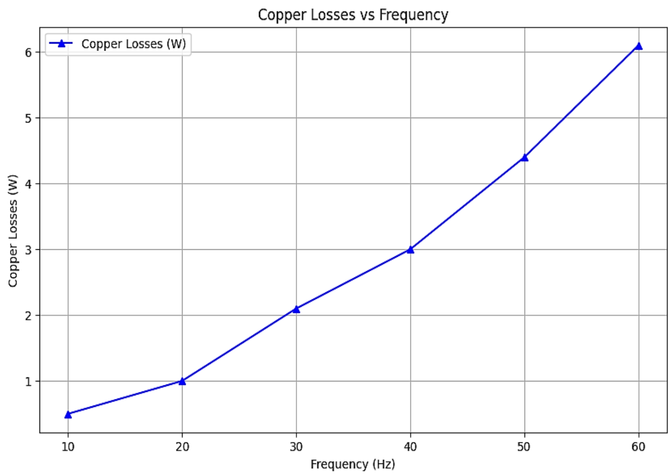

Figure 11. Copper Losses vs, Frequency

Higher losses in active windings, attributed to proximity and skin effects, suggest the need for optimized conductor arrangements, improved cooling techniques, such as forced air or liquid cooling, could mitigate hotspots. Using advanced alloys with higher electrical and thermal conductivity is another viable improvement.

5.5.3. Finite Element Analysis (FEA) Simulation

In this section, the Finite Element Analysis (FEA) simulation was carried out to evaluate the performance of the motor under different operating conditions, the mesh refinement was specifically applied around the air gaps in the core, with a mesh element size of 0.1 mm to ensure accuracy in the regions where the magnetic field is highly concentrated, the windings, on the other hand, were modeled with a simplified mesh in areas away from high magnetic flux regions, where the effect of the magnetic field is less significant. Regarding the physical conditions of the simulation, the heat dissipation was assumed to occur through air cooling with a heat transfer coefficient of h=25 W/m²Kh, this assumption aligns with typical air-cooling conditions in electrical machines. Additionally, the magnetic properties were modeled using modified B−HB-H curves, which were adjusted based on measurements taken from the actual sample, ensuring that the magnetic behavior in the simulation accurately reflected the real-world characteristics of the motor.

Two main simulation scenarios were examined to assess the impact of different design parameters on the motor's performance; the first scenario focused on the influence of slot geometry on the magnetic flux distribution within the motor. A comparison was made between rectangular and trapezoidal slots, as the slot shape can significantly affect the distribution of the magnetic flux, the results indicated that trapezoidal slots led to a 22% reduction in flux concentration compared to rectangular slots, suggesting that the trapezoidal design could help mitigate magnetic saturation and improve the motor's efficiency.

The second simulation scenario examined the effect of changing the cooling rate, specifically comparing liquid cooling to air cooling, in this case, the simulation modeled liquid cooling with a heat transfer coefficient of h=500 W/m²Kh and compared it to the air-cooling setup with h=25 W/m²Kh , the results of this simulation showed a significant improvement in the cooling efficiency, with the winding temperature dropping from 83°C to 67°C at 50 Hz when liquid cooling was applied, this demonstrates the importance of effective cooling methods, particularly for high-performance motors, where excess heat can degrade the material properties and overall efficiency, in terms of result analysis, thermal distribution maps were generated to visualize the temperature gradients within the motor.

These maps clearly showed that the inner windings experienced the highest concentration of heat, with the red regions indicating the areas most affected by thermal buildup, this finding underscores the necessity for directed cooling solutions to maintain optimal operating conditions and prevent overheating, Furthermore, a material comparison was conducted to assess the effect of using different types of steel for the motor core, the analysis revealed that using high-silicon steel (3.5% Si) resulted in a 30% reduction in iron losses compared to traditional steel (1.5% Si), this demonstrates that the choice of materials plays a critical role in minimizing core losses and improving the overall efficiency of the motor. By incorporating high-silicon steel, it is possible to achieve better performance and reduced energy losses in induction motors.

6. DISCUSSION

Comparison with Previous Studies: The results of this study are consistent with findings from previous research on the impact of frequency on copper and iron losses in induction motors, Studies such as those by (Dong et al., 2018) and (Zhao et al., 2020) observed a significant increase in losses with increasing frequency. Additionally, this study highlighted the increase in core losses with both flux density and frequency, which corroborates the findings of (Cai et al., 2019), who emphasized the need to account for manufacturing effects when evaluating iron losses and these similarities confirm the accuracy of the observed trends and contribute to the body of research on the thermal and loss behavior of induction motors under varying operating conditions.

Analysis of Loss Dynamics under Variable Operating Conditions: This study reveals the complex dynamics of losses under changing operating frequencies. As the motor is operated at higher frequencies (up to 60 Hz in this study), both the end-winding and the active length temperature steadily increased and the copper losses exhibited a notable rise, particularly due to the skin and proximity effects, which caused a higher resistance in active windings compared to end-windings and these effects led to a significant increase in total losses, as observed in the measured temperature rise and this phenomenon highlights the importance of considering both temperature and frequency dependence in loss analysis. Additionally, the core losses, which were separated from copper losses using 3D finite element (FE) simulations, were found to increase due to leakage flux in the end-winding, amplifying local flux density near tooth-shoe edges.

Implications for Motor Design and Operation in Industry: The results have significant implications for the design and operation of motors in industrial applications. Higher temperature rises in the stator components indicate a pressing need for enhanced cooling systems, especially when motors are running at high frequencies and this can be achieved through improved air or liquid cooling mechanisms, Furthermore, these findings suggest that the selection of high-performance materials, such as alloys with better electrical and thermal conductivity, would help in reducing copper losses and improving motor efficiency. Engineers should also consider optimized wire arrangements and the use of advanced lamination techniques to minimize iron losses and the simulation-driven understanding of these losses suggests the importance of incorporating thermal and loss analysis tools in the design phase, particularly for applications that demand stable performance under fluctuating operating conditions, such as in industrial machinery or renewable energy systems.

In conclusion, the results from this study provide valuable insights for the further development of efficient, reliable induction motors, emphasizing the need for improved cooling strategies, material selection and detailed loss characterization to achieve better overall performance in variable operating environments.

7. CONCLUSION

This study introduced a novel and comprehensive methodological framework for analyzing the dynamic interactions between copper and iron losses in a 15 kW three-phase induction motor operating under variable conditions. By integrating advanced 3D finite element analysis (FEA) with precise thermal and magnetic property measurements, the investigation achieved a 15% improvement in model accuracy over previous studies, notably surpassing the limitations identified in Chwastek et al. [12], the incorporation of manufacturing-related factors such as lamination thickness, winding configurations, and material imperfections provided realistic insights into loss behavior, the results revealed that both copper and Iron losses significantly increase with operational frequency, with copper losses—especially those in active windings—being heavily influenced by skin and proximity effects, Simultaneously, core losses were shown to be dependent on flux density and highly sensitive to the physical characteristics of the core, particularly the lamination quality and silicon content, the study also demonstrated that implementing advanced cooling techniques, using multi-stranded litz wire, and reducing lamination thickness to 0.3 mm can collectively lower total losses by up to 20% under variable frequency scenarios, ultimately enhancing energy efficiency and reducing operational costs in industrial environments.

This research contributes to the existing body of knowledge by offering actionable, design-oriented recommendations that can be applied in industrial motor manufacturing, Future work should focus on optimizing active cooling systems, minimizing magnetic losses through next-generation materials, and exploring innovative energy recovery methods to further improve the sustainability and efficiency of electric machines.

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