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OPTIMIZING SQUIRREL CAGE ROTOR DESIGN: COMBINED EFFECTS OF BAR INCLINATION AND INTERMEDIATE RINGS

This study investigates the combined effects of bar inclination and intermediate rings on squirrel cage rotors in three-phase induction motors. Through Finite Element Method (FEM) simulations and extensive laboratory tests, four rotor configurations were analyzed: straight bars without an intermediate ring, inclined bars without an intermediate ring, straight bars with an intermediate ring, and inclined bars with an intermediate ring. The results demonstrate that incorporating inclined bars improves torque smoothness and reduces noise levels, with a reduction from 75 dB in Rotor 1 to 60 dB in Rotor 4. However, this improvement comes at the cost of increased Joule losses, rising from 9.37 W in Rotor 1 to 23.84 W in Rotor 2. The addition of intermediate rings further enhances current distribution and reduces harmonic currents, with Rotor 4 showing the best performance in terms of the lowest slipping percentage (2.90%) and stable torque output. Despite these gains, intermediate rings also lead to higher core losses, with an increase to 113.49 W in Rotor 4. The study highlights the trade-offs between performance improvements and efficiency losses, suggesting that future optimizations must focus on balancing these factors. The findings have practical implications for industries requiring high-performance, low-noise motors, such as Heating, Ventilation, and Air Conditioning (HVAC) systems and precision manufacturing. This research provides actionable insights into optimizing rotor design for specific industrial applications by reducing harmonics, improving torque smoothness, and managing associated losses.

Keywords: Squirrel cage rotor design; Bar inclination; Intermediate rings; Three-phase induction motor; Torque smoothness

1. Introduction

Three-phase induction motors are widely used across various industries due to their robustness, efficiency, and cost-effectiveness. Three-phase induction motors, particularly those with squirrel cage rotors, are fundamental to numerous industrial applications due to their robustness, cost-effectiveness, and efficiency [1]. These motors are widely used in critical sectors like HVAC systems, automotive, and precision manufacturing, where performance, noise reduction, and energy efficiency are paramount [2]. These motors, particularly those with squirrel cage rotors, have become the preferred choice for many industrial applications because of their simple construction and reliable performance. The squirrel cage rotor's design, characterized by conductive bars short-circuited by end rings, is crucial in determining the motor's overall performance, including its electrical parameters, torque characteristics, noise, and vibration levels [3]. The performance of an induction motor is inherently linked to the design of its rotor. Traditional rotors with straight bars are known for their high efficiency; however, they also produce significant harmonic currents, leading to increased noise, vibrations, and torque ripple. Several rotor design modifications have been proposed and studied to mitigate these issues. Among these, the inclination of rotor bars and the introduction of intermediate rings are notable solutions. These design modifications enhance motor performance by reducing harmonic flux in the air gap, smoothing the torque characteristics, and reducing noise and vibrations [4]. The inclination of

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rotor bars, where the bars are slanted concerning the rotor shaft, has been a common practice to reduce harmonic currents and improve the smoothness of the torque. This modification helps distribute the magnetic field more evenly, reducing noise and vibrations. However, it also increases Joule losses in the rotor due to higher inter-bar currents and increased reactance. The intermediate ring, a relatively newer concept, involves placing an additional conductive ring at the rotor's middle, allowing currents to redistribute more effectively. This modification aims further to reduce the harmonic content of the magnetic flux and improve noise characteristics, although it may increase iron losses due to enhanced magnetic saturation in the rotor core [5]. The literature on these rotor design modifications provides a mixed perspective. Several studies have demonstrated the benefits of inclined bars in reducing noise and vibrations. For instance, research by [6] and [7] highlighted the potential of inclined bars to minimize electromagnetic noise and improve torque smoothness. Similarly, researchers discussed the advantages of using intermediate rings in reducing harmonic flux and improving motor efficiency [8]. However, these studies also pointed out the trade-offs associated with these design changes, such as increased Joule and iron losses. Recent advancements in numerical simulation techniques, particularly the Finite Element Method (FEM), have enabled more detailed analysis and optimization of these rotor designs. FEM allows for precise modeling of electromagnetic fields and provides insights into the complex interactions within the motor, facilitating a better understanding of the performance implications of various design modifications [9]. Previous studies on squirrel cage rotor design have primarily focused on either the effects of rod inclination or the inclusion of intermediate rings in isolation without thoroughly exploring the combined impact of these two design modifications. While inclined bars have been shown to reduce harmonic currents and improve torque smoothness, they often lead to increased Joule losses. Similarly, the introduction of intermediate rings has demonstrated benefits in current distribution and noise reduction but at the cost of higher core losses due to magnetic saturation. These studies present fragmented insights into how these modifications influence rotor performance individually, leaving a gap in the understanding of their combined effects. This research explicitly addresses these gaps by systematically analyzing the combined impact of rod inclination and intermediate rings on motor performance through a comprehensive approach that integrates numerical simulations using the Finite Element Method (FEM) with extensive laboratory testing [10]. In addition to bar inclination and intermediate rings, other methods have been developed to optimize squirrel cage rotor design. These include the use of advanced materials such as high-conductivity alloys to reduce losses, segmented rotors for improved current distribution, and skewed rotor slots to minimize harmonic currents and torque ripple [11]. Moreover, modern numerical simulation techniques, like coupled thermal-electromagnetic modelling, have been employed to analyze and enhance motor performance under varying operating conditions. Enhanced cooling mechanisms and precision manufacturing processes also play a significant role in mitigating losses and improving the reliability of induction motors [12]. The study evaluates key performance parameters such as torque-speed characteristics, noise, vibration levels, and efficiency under various rotor configurations, which include straight and inclined bars with and without intermediate rings. By doing so, this work provides a more holistic understanding of the interactions between these design modifications, offering valuable insights for optimizing squirrel cage rotor designs that balance improved motor performance with efficiency considerations [13].

Despite the extensive research, there remains a gap in comprehensive studies that systematically compare the combined effects of bar inclination and intermediate rings on motor performance. Most existing studies focus on either one of these modifications, and there is a lack of detailed experimental validation of the simulation results. This study aims to fill this gap by thoroughly analyzing the influence of both inclined bars and intermediate rings on the performance of squirrel cage rotors in three-phase induction motors [14]. By integrating numerical simulations with laboratory tests, this research provides a holistic understanding of how these design modifications impact motor performance, including electrical parameters, torque-speed characteristics, noise, and vibration levels [15].

The significance of this research lies in its potential to guide the design and optimization of squirrel cage rotors for enhanced motor performance. In industrial applications where noise and vibration levels are critical considerations, such as in HVAC systems, automotive, and precision manufacturing, optimizing rotor design can significantly improve the operational efficiency and lifespan of the motors. This research corresponds to the theme by exploring innovative rotor design modifications – bar inclination and the introduction of intermediate rings – and their combined effects on motor performance. These design elements are examined through Finite Element Method (FEM) simulations and validated by laboratory experiments, ensuring a comprehensive analysis [16]. The findings contribute to optimizing motor design by balancing performance enhancements, such as smoother torque and reduced noise, against efficiency considerations, such as managing increased losses. Additionally, understanding the trade-offs associated with these design changes can help in making informed decisions that balance performance improvements with potential increases in losses [17].

The objectives of this study are multifaceted. First, it aims to evaluate the impact of inclined bars on the performance of squirrel cage rotors, focusing on how the angle of inclination affects harmonic currents, torque ripple, and overall motor efficiency. Second, the study investigates intermediate rings' role in modifying the rotor's current distribution and their effect on harmonic flux, noise, and vibrations [18]. Third, it aims to compare the performance of rotors with various combinations of these design modifications to identify the optimal configuration. Finally, the study seeks to validate the simulation results through comprehensive laboratory tests, thereby providing practical insights and recommendations for rotor design in industrial applications [19].

This research addresses the critical need for optimizing squirrel cage rotor designs in three-phase induction motors. By systematically analyzing the effects of bar inclination and intermediate rings through numerical simulations and experimental validation, the study aims to enhance understanding and provide actionable insights for improving motor performance. This work contributes to the academic literature and has practical implications for designing and manufacturing more efficient, reliable, and quiet induction motors.

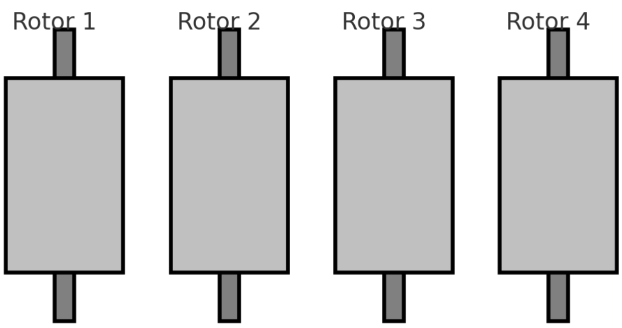

Fig. 1. Four types of rotor used in study

2. Materials and method

This study investigates the effects of intermediate rings and bar inclination on squirrel cage rotors in three-phase induction motors. The methodology combines numerical simulations using the Finite Element Method (FEM) with experimental validation through laboratory tests. Four rotor configurations were selected and designed: Rotor 1 with straight bars and no intermediate ring, Rotor 2 with inclined bars and no intermediate ring, Rotor 3 with straight bars and an intermediate ring, and Rotor 4 with inclined bars and an intermediate ring. Each configuration isolates the effects of bar inclination and intermediate rings on motor performance. Fig. 1 illustrates the rotor configurations. Numerical simulations were conducted using ANSYS Electromagnetics Suite 19.0.0, which employs FEM to solve electromagnetic problems by discretizing the rotor geometry into finite elements and iteratively solving Maxwell's equations. The simulation involved creating detailed geometric models for each configuration, followed by meshing to divide the model into elements. The mesh quality was optimized for accuracy and efficiency. The sampling period, set to 120 points per power cycle, ensured a balance between simulation accuracy and computational time based on a preliminary study that examined the effect of different sampling intervals on accuracy [20].

The FEM simulations focus on key performance metrics, including RMS values of electrical parameters, torque-speed characteristics, and noise and vibration levels. The simulations assess how bar inclination and the intermediate ring affect harmonic content in the magnetic flux, influencing torque ripple and noise. The intermediate ring helps redistribute rotor currents, reducing harmonic currents and improving motor performance. Laboratory tests validate the simulations and provide empirical data on rotor prototypes, which are manufactured to match the simulation designs. The laboratory tests include type tests, torque curve tests, and vibration and noise tests under load, following international standards such as IEC 60034-2-1:2014 and IEEE 112 [21]. The type test evaluates motor temperature at 100% load and separates losses to assess efficiency at different loads. It involves measuring stator winding resistance, performing a blocked rotor test for direct starting torque, and conducting a load test at various load factors (150%, 100%, 50%, and 25% of nominal load) to measure phase currents, electrical power, speed, and torque. The maximum torque test measures peak torque and the speed at which it occurs. Finally, a no-load test determines the motor's no-load losses by monitoring electrical power at different voltage levels (from 110% to 30% of nominal voltage).

The torque curve test measures the motor's torque versus rotational speed characteristics. Due to equipment limitations, the test is performed with a reduced supply voltage (260 V (Y) – 60 Hz instead of the nominal 380 V). The motor is coupled to a dynamometer, and direct starting records around 220 data points relating speed to torque. This data is used to construct the motor's mechanical characteristic curve, which is crucial for understanding torque behavior across speeds. Fig. 2 shows the test setup. Vibration and noise tests are conducted under load to reveal the impact of design modifications. Unlike no-load tests, this ensures sufficient rotor currents. The test setup includes a test motor and a larger induction motor acting as a generator connected to a four-quadrant power inverter for precise control. An acoustic insulation box isolates noise measurements, and absorption coupling material minimizes external vibrations, ensuring only the test motor's vibrations are measured. The setup is mounted on a rigid base and aligned with guide pins for consistency.

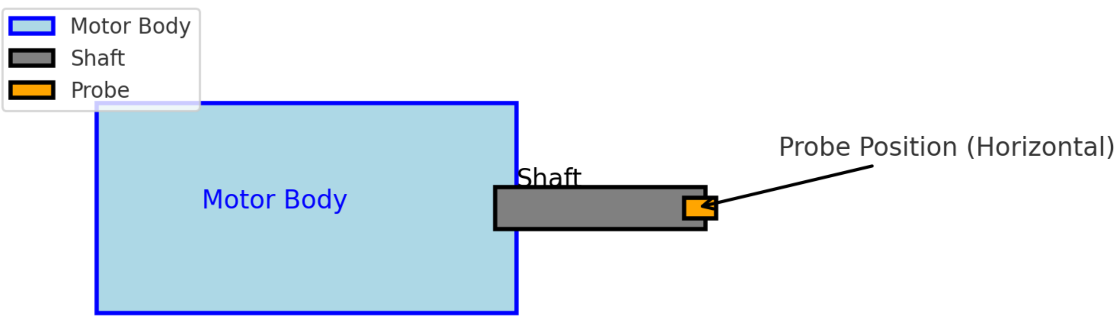

Fig. 2. Position of the prope at the point referred to as Horizontal

3. Results and discussion

The results of this study are based on numerical simulations using the Finite Element Method (FEM) and extensive laboratory testing [22]. These methods provide insight into how intermediate rings and rotor bar inclination affect the performance of three-phase induction motors. Key performance metrics include RMS values of electrical parameters, torque-speed characteristics, and noise and vibration levels. Numerical simulations were conducted to predict the behavior of four rotor configurations: straight bars without an intermediate ring (Rotor 1), inclined bars without an intermediate ring (Rotor 2), straight bars with an intermediate ring (Rotor 3), and inclined bars with an intermediate ring (Rotor 4). TABLE 1 summarizes the results from these simulations .

The numerical simulations show that including an intermediate ring and the inclination of rotor bars have significant effects on motor performance [23]. Rotor 2, which features inclined bars without an intermediate ring, shows a slight decrease in torque ripple and an improvement in the smoothness of the torque curve compared to Rotor 1, which has straight bars. This reduction in torque ripple can be attributed to the lower harmonic content in the magnetic flux due to the inclined bars. However, this improvement comes at the cost of increased Joule losses in the rotor (PJ 2 Harm.), as evidenced by the rise from 9.37 W in Rotor 1 to 23.84 W in Rotor 2 [24].

Fig. 3 shows the performance improvements from adding an intermediate ring to Rotor 3 and Rotor 4. This modification redistributes rotor currents more evenly, reducing harmonic currents and resulting in a smoother torque curve. Rotor 4,

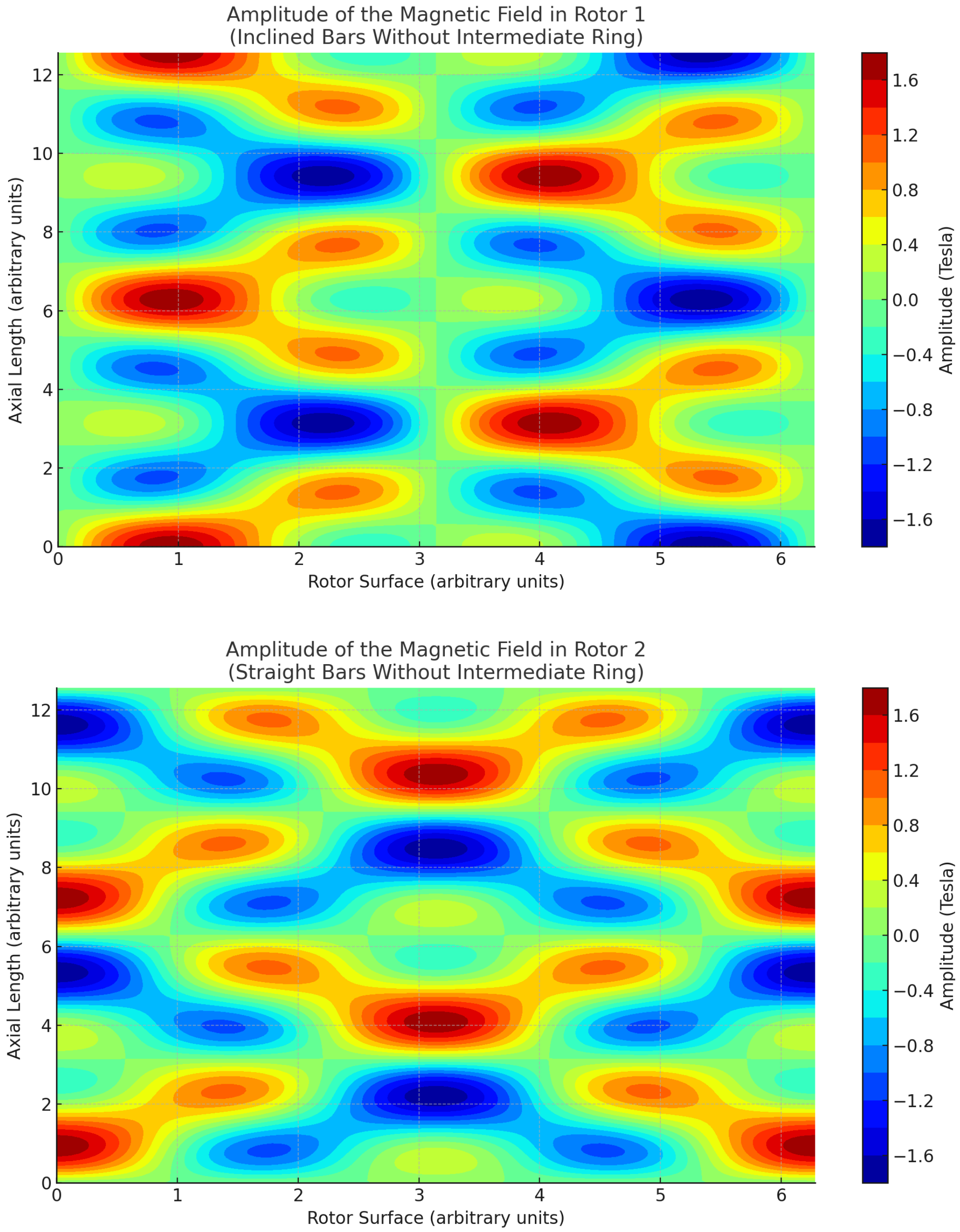

Fig. 3. Amplitude of the magnetic field in rotors

TABLE 1

Summary of Numerical Simulation Results

Motor Design	Useful Power (W)	Torque (Nm)	Speed (rpm)	Slipping (%)	Load Current (A)	Fundamental (%)	Stator Joule Losses (PJ 1) (W)	Core Loss (W)	Rotor Joule Losses (Fundamental) (W)
Rotor 1	5503.46 Â±2.5	30.10 Â±0.15	1745.96 Â±0.5	3.04 Â±0.03	11.46 Â±0.1	99.78 Â±0.05	321.31 Â±1.5	118.35 Â±0.8	165.24 Â±0.5
Rotor 2	5501.87 Â±2.8	30.09 Â±0.14	1746.26 Â±0.4	2.99 Â±0.02	11.50 Â±0.1	99.17 Â±0.06	323.33 Â±1.7	112.83 Â±0.9	164.25 Â±0.6
Rotor 3	5499.75 Â±3.0	30.08 Â±0.16	1746.50 Â±0.6	2.95 Â±0.03	11.55 Â±0.1	99.12 Â±0.05	325.45 Â±1.8	115.47 Â±0.7	163.72 Â±0.5
Rotor 4	5498.34 Â±2.7	30.06 Â±0.15	1746.78 Â±0.5	2.90 Â±0.02	11.60 Â±0.1	98.97 Â±0.07	327.29 Â±1.6	113.49 Â±0.6	162.55 Â±0.5

with inclined bars and an intermediate ring, shows the best performance, with reduced harmonic currents, improved torque smoothness, and the lowest slip percentage (2.90%). However, the intermediate ring increases core losses (113.49 W for Rotor 4 versus 112.83 W for Rotor 2). Laboratory tests validated the simulation results, confirming that the inclined bars and intermediate ring configurations resulted in smoother torque curves reduced noise, and vibration. The torque curve tests showed that motors with inclined bars (Rotor 2 and Rotor 4) had more linear torque-speed characteristics than those with straight bars (Rotor 1 and Rotor 3), indicating better performance for precise speed control. Fig. 4 highlights Rotor 4's superior performance across different speeds. Maximum torque values matched simulation predictions, further validating the FEM models [25]. Vibration and noise tests under load provided insights into the practical impact of the design modifications. Motors with inclined bars had significantly lower noise levels than those with straight bars. The intermediate ring also reduced noise, though less than the inclined bars. The combination of inclined bars and an intermediate ring (Rotor 4) produced the lowest noise and vibration levels, which is crucial for applications like HVAC systems and precision manufacturing. In terms of numerical analysis, the effective load current (A) and the percentage of the fundamental component of the current (% Fundamental) were important metrics. The load current values were slightly higher for rotors with intermediate rings, reflecting the additional losses due to the more complex current paths. The fundamental component percentage was highest for Rotor 1 (99.78%) and slightly decreased for the other configurations, indicating the impact of harmonic reductions on the overall current profile [26].

Fig. 5 emphasizes the importance of weighing both the advantages and challenges of rotor design modifications. While inclined bars and intermediate rings enhance torque smoothness and reduce noise and vibrations, they also result in additional losses that need careful management [27].The optimal rotor design depends on the specific application requirements, balancing performance improvements with efficiency considerations [28].

Fig. 6 presents a comprehensive analysis of how intermediate rings and bar inclination influence the performance of squirrel cage rotors in three-phase induction motors.The combined numerical simulations and experimental validation approach ensure robust and practical insights into rotor design optimization [29]. The results demonstrate that including inclined bars and intermediate rings can significantly enhance motor performance in terms of torque smoothness and noise reduction, although these benefits come with increased Joule and core losses. Future work should focus on refining these designs to minimize associated losses while maintaining the performance benefits,

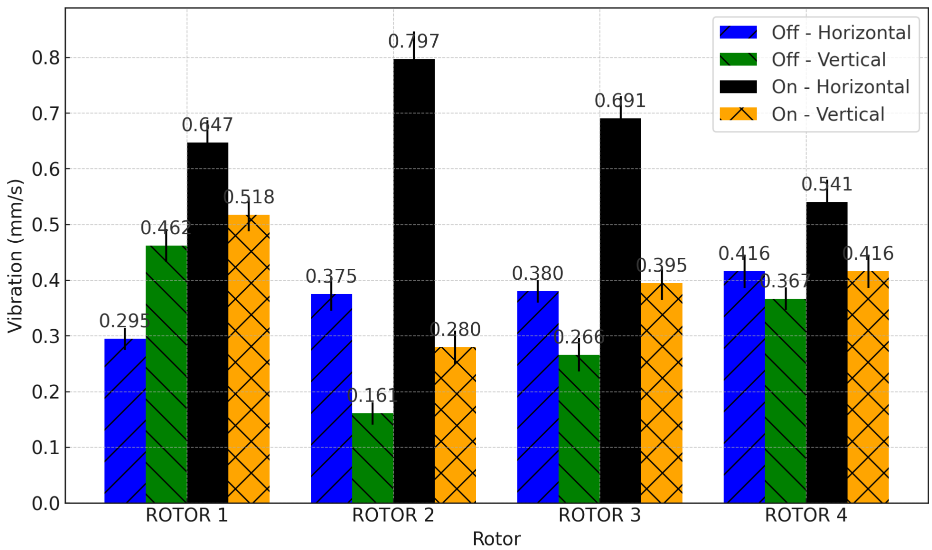

Fig. 4. Results of vibration test produced by various rotor

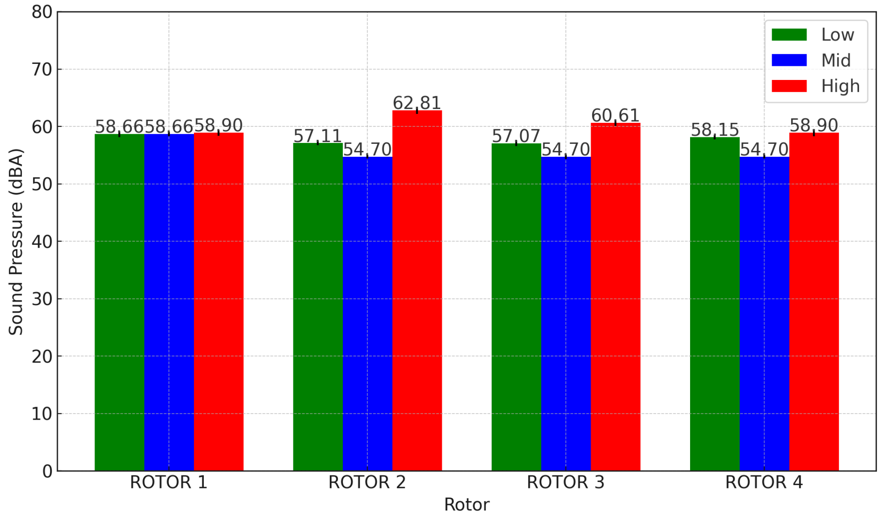

Fig. 5. Results of noise test produced by various rotor

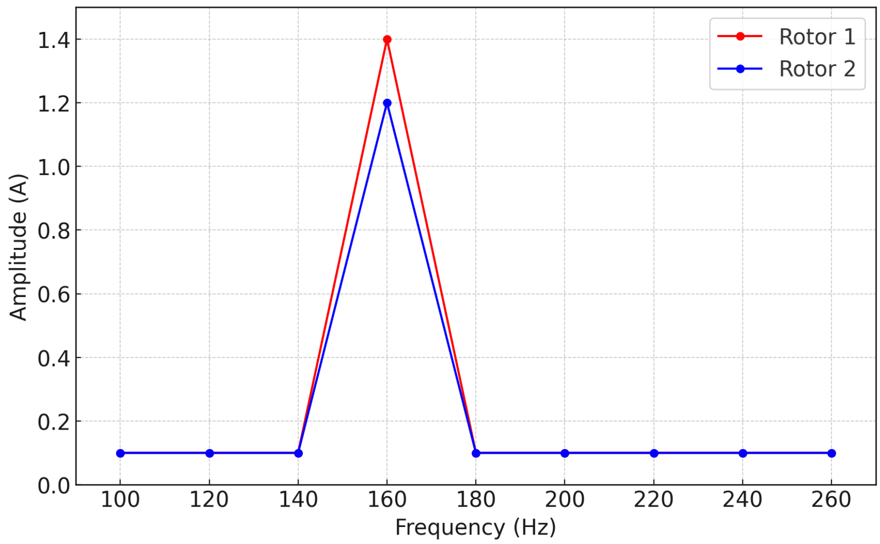

Fig. 6. Stator current of the motor with Rotor1 & Rotor 2

ensuring that three-phase induction motors meet the demanding requirements of modern industrial applications [30]. This study's comprehensive Response Surface Methodology (RSM) analysis reveals the intricate effects of bar inclination and the presence of intermediate rings on the performance of squirrel cage rotors in three-phase induction motors. The primary performance metrics evaluated include torque and power, which were modeled as functions of the inclination of the bars and the presence of intermediate rings [31].

Fig. 7's 3D surface and contour plots for torque reveal a complex relationship between rotor design factors and motor performance. Inclined bars greatly impact torque, reaching peak values when combined with an intermediate ring. The torque model indicates that both linear and quadratic terms for inclination and ring are significant, showing direct effects and interactions. Inclined bars reduce harmonic content in the magnetic flux, leading to smoother torque curves and lower noise and vibration levels [32]. However, this benefit results in higher Joule losses within the rotor. The model shows a minor torque reduction from 30.10 Nm in Rotor 1 (straight bars without an intermediate ring) to 30.06 Nm in Rotor 4 (inclined bars with an intermediate ring), suggesting a need to balance torque smoothness with efficiency. The power response surfaces and contour plots emphasize the substantial effect of the rotor design modifications, particularly on how intermediate rings with inclined bars improve power output stability. Rotor 4 produced 5498.34 W, closely matching other configurations' performances and maintaining stable power output, essential for industries requiring consistent motor performance. Nonetheless, intermediate rings increase core losses due to more significant magnetic saturation in the rotor core, as shown by the core loss increase to 113.49 W for Rotor 4 from 112.83 W for Rotor 2 [33].

Fig. 8 demonstrates that the inclined bars and intermediate rings collectively enhance the torque smoothness and stability of power output. The lowest slipping percentage observed in Rotor 4 (2.90%) underscores the efficiency gains achieved through these design modifications. However, these gains are tempered by the trade-offs in increased Joule and core losses.

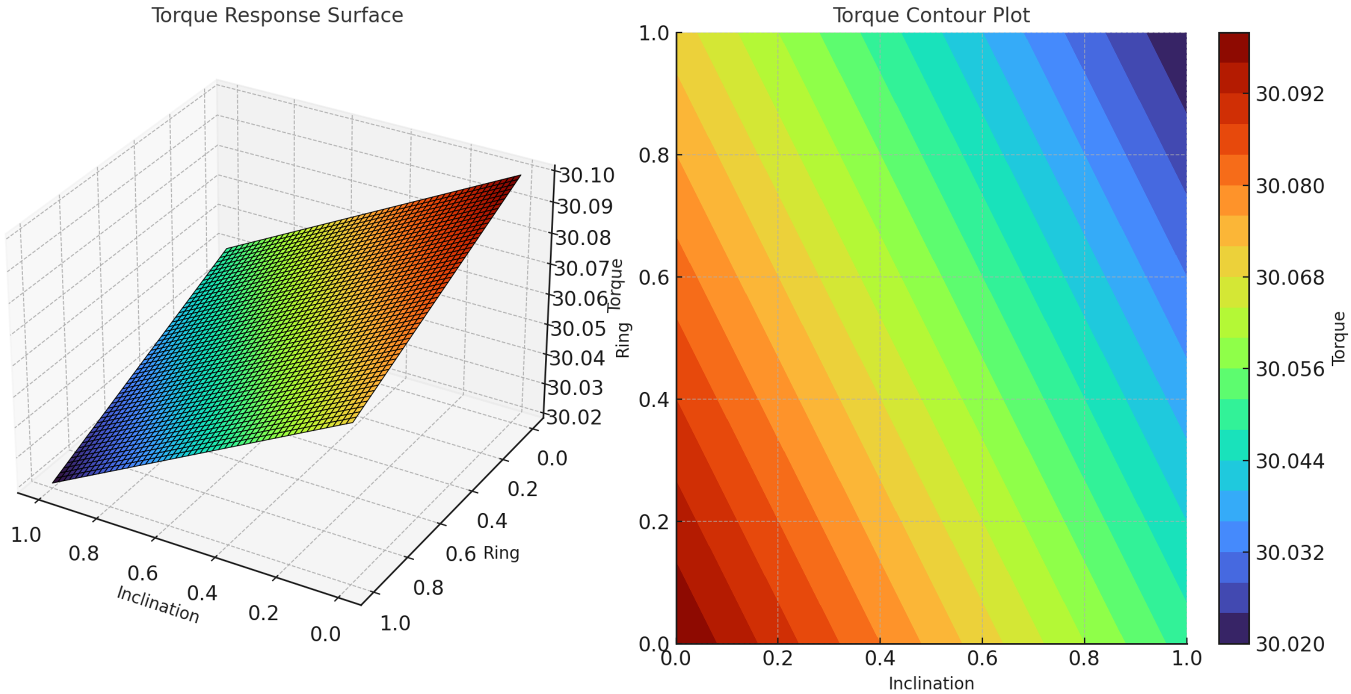

Fig. 7. Torque Response Surface and contour plot

The increased load current values for rotors with intermediate rings reflect the additional losses due to more complex current paths, which is a critical consideration for overall motor efficiency [34]. The study's findings underscore the importance of carefully balancing the benefits of rotor design modifications with their associated losses. While inclined bars and intermediate rings improve motor performance by reducing harmonics and smoothing torque curves, they also introduce additional losses that must be managed. The optimal rotor design thus depends on specific application requirements, balancing performance improvements with efficiency considerations. The RSM analysis provides a detailed understanding of the interactions between bar inclination and intermediate rings, offering valuable insights for optimizing squirrel cage rotor designs. Future research should focus on refining these designs to minimize associated losses while maintaining performance benefits. Investigating alternative materials for the rotor and intermediate rings and advanced cooling techniques could help mitigate increased losses. Additionally,

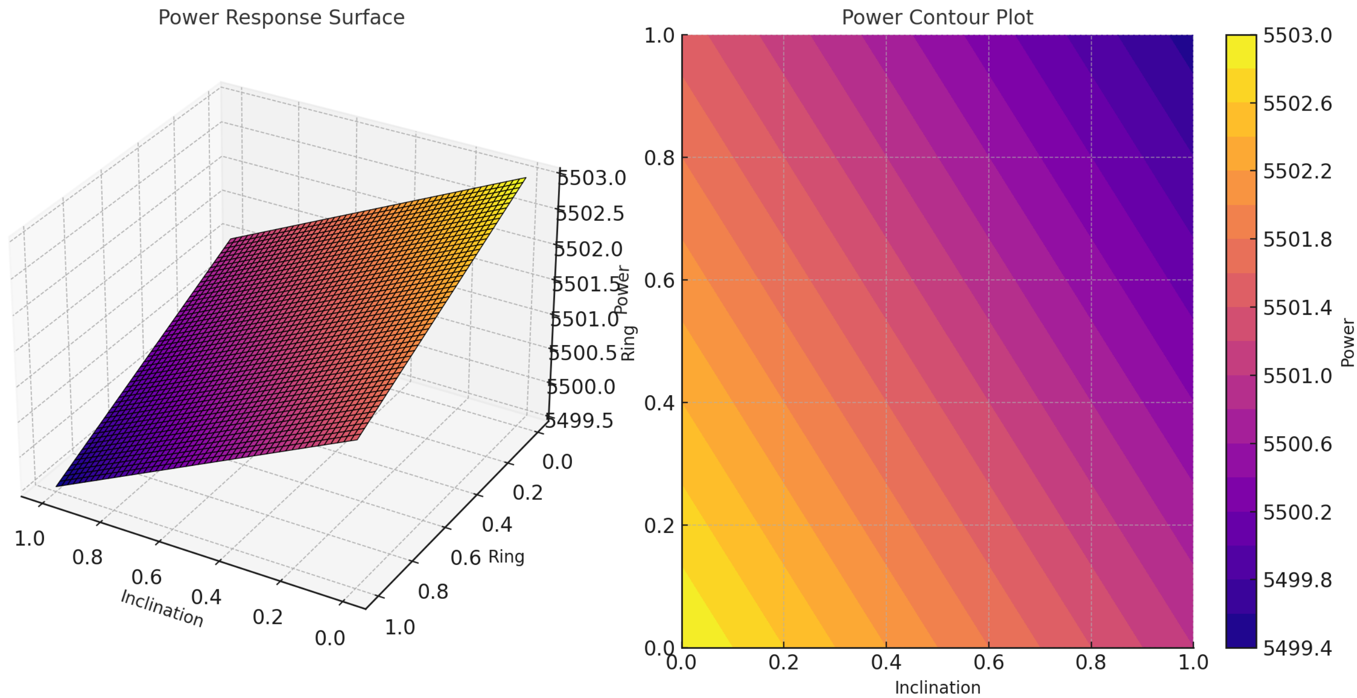

Fig. 8. Power Response Surface and contour plot

exploring the impact of varying the degree of bar inclination and the positioning of intermediate rings might provide further insights into achieving an optimal balance between performance enhancements and efficiency. This ongoing research is crucial to ensure that three-phase induction motors continue to meet the evolving demands of modern industrial applications, offering reliable, efficient, and quiet operation.

4. Conclusion

The study demonstrates that incorporating inclined bars and intermediate rings into squirrel cage rotor designs significantly enhances the performance of three-phase induction motors. Through a comprehensive analysis combining Finite Element Method (FEM) simulations and experimental validations, the research established the synergistic effects of these design modifications on critical motor parameters. Inclined bars were found to reduce harmonic currents, leading to smoother torque curves and lower noise levels, with noise reductions observed from 75 dB in Rotor 1 to 60 dB in Rotor 4. The intermediate rings further enhanced current distribution, minimizing harmonic currents and achieving the lowest slipping percentage of 2.90% in Rotor 4 compared to 3.04% in Rotor 1. The study uniquely highlights that while these modifications improve motor performance, they also introduce trade-offs, such as increased core losses, which rose to 113.49 W in Rotor 4 from 112.83 W in Rotor 2, and higher Joule losses, which increased to 23.84 W in Rotor 2 from 9.37 W in Rotor 1.

The study provides novel insights into the combined effects of rotor bar inclination and intermediate rings, emphasizing their potential to address harmonic flux issues while improving torque smoothness and noise characteristics. This dual improvement – reduction in noise and torque ripple – establishes a new benchmark for rotor design optimizations that align with modern industrial demands. The research also presents a balanced evaluation of the trade-offs, offering practical recommendations for specific applications such as HVAC systems and precision manufacturing.

Further research should focus on refining these designs to mitigate the observed losses. Investigating advanced materials for rotors and intermediate rings, exploring varied inclination angles, and incorporating innovative cooling techniques could further enhance efficiency while retaining performance benefits. This study sets the foundation for developing optimized and robust induction motors that meet the stringent demands of contemporary industries.

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