

Optimal Design of Induction Motor Using Parametric Winding Optimization with FEA

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ABSTRACT.

This paper presents a comprehensive parametric optimization study of a three-phase squirrel cage induction motor to enhance its electromagnetic performance by systematically varying the number of conductors per slot and wire diameter. The analysis of 154 design cases was performed using ANSYS RMxpert. The number of conductors per slot ranged from 39 to 65, and the wire diameter varied from 0.60 mm to 0.70 mm. The original motor design, which had 40 conductors and a 0.67 mm wire diameter, showed significant performance issues. These included low efficiency (80.17%), a poor power factor (0.749), severe magnetic saturation (2.403 T), and a high magnetizing current (3.455 A). Conversely, the optimized configuration, which employed 49 conductors and a 0.66 mm wire diameter, demonstrated considerable advancements. The efficiency rose to 82.45%, reflecting a 2.28 percentage point improvement; the power factor was enhanced to 0.870; and the stator tooth flux density was reduced to 1.547 T. Furthermore, total losses were diminished by 75.9 W, and the stator phase current was lowered by 14.7%, from 5.38 A to 4.59 A. Transient finite element analysis, performed using ANSYS Maxwell 2D, supported these results, thereby confirming the smooth torque response, balanced sinusoidal currents, and stable power conversion. The strong correlation between RMxpert parametric trends and Maxwell time-domain validation reinforces the physical relevance of the observed performance gains. Consequently, this study demonstrates that a systematic optimization of stator winding parameters offers a cost-effective method for significantly improving induction motor efficiency, eliminating the necessity for modifications to magnetic materials or core geometry, and thus providing a valuable reference for both industrial motor design and energy efficiency enhancements.

Keywords: Induction motor, efficiency optimization, parametric study, finite element analysis, conductors per slot, wire diameter, magnetic saturation.

1. Introduction.

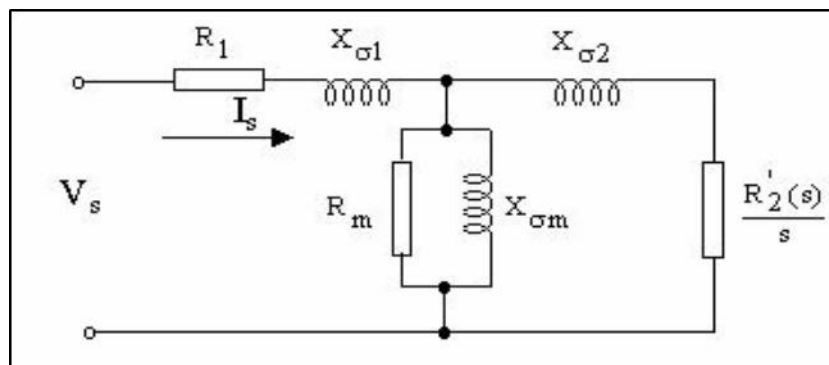
Three-phase induction motors are widely regarded as essential components in industrial and commercial settings worldwide. These motors are popular because they are durable, simple to build, and inexpensive. In addition, these motors require less maintenance than other types (Boglietti et al., 2008; Yetgin and Turan, 2014). Electric motor-driven systems account for over 40% of the world's total electricity use, with induction motors being the most common type. Consequently, even modest enhancements in the efficiency of these motors can yield substantial energy savings internationally, thereby aiding in the reduction of carbon emissions and the attainment of sustainability objectives (De Almeida et al., 2019; de Souza et al., 2024). Despite their numerous advantages, induction motors suffer from inherent drawbacks, such as low power factor and high magnetizing current compared to synchronous motors (Rezaeealam, 2021; Carbonieri and Bianchi, 2021). Additionally, internal losses consist of several components: copper losses in the stator and rotor, iron losses in the magnetic core, mechanical losses (friction and ventilation), and stray losses (Boldea and Nasar, 2010; Boglietti et al., 2003). These combined losses limit the highest possible efficiency, particularly in low-power motors (Dorrell, 2014). As international efficiency standards, such as IEC 60034-30-1, are used to classify efficiency from IE1 to IE4, become more stringent, designers are forced to reconsider traditional designs and find practical ways to improve efficiency without significantly increasing costs (Alberti et al., 2014; Tumbek et al., 2015). A multitude of investigations have focused on enhancing induction motor performance through alterations to various design parameters. Slot geometry optimization is a crucial aspect, as the arrangement and measurements of stator and rotor slots significantly affect flux density, power factor, and starting torque (Mahmouditabar and Baker, 2023; Williamson and McClay, 1996). Optimized closed rotor slots improve starting performance, and rotor slot designs are adjusted to create specific speed torque characteristics (Zhang et al., 2012). The shape of the slots significantly affects both torque ripple and mechanical vibrations (Yetgin and Durmuş, 2020). Closed rotor slots that are optimized enhance starting performance, and rotor slot configurations are tailored to produce particular speed torque profiles (Zhang et al., 2012). Slot shape significantly influences torque ripple and mechanical vibrations (Yetgin and Durmuş, 2020). Another important direction is material optimization. The selection of electrical steel sheets and winding conductors is critical to motor efficiency. A comparative analysis of various electrical steel sheets (M15, M19, M36) indicates that M19 exhibits the lowest iron losses and the highest efficiency, as demonstrated by (Aishwarya and Brisilla, 2022). Consequently, using copper in the rotor cage, as opposed to aluminum, can reduce copper losses by up to 15%, which improves efficiency, as (Peters et al. 2003) have shown.. A comparative analysis also corroborated the enhanced performance of copper-cage motors when compared to those with aluminum cages (Marfoli et al., 2021). Moreover, some research has focused on the refinement of geometric and electrical characteristics, encompassing stack length and the quantity of conductors per slot. Increasing the number of conductors in each slot boosts magnetizing reactance and improves the power factor. However, this also increases the flux density in the teeth, which could lead to saturation (Mohamed et al., 2017). Enhancements in these parameters can yield a 3–4 percentage point increase in efficiency, all while maintaining consistent torque (Sarac et al., 2017). The Finite Element Method (FEM), coupled with dedicated software such as ANSYS Maxwell and RMXprt, has gained prominence in the design and optimization of motors. RMXprt facilitates rapid analytical solutions for electromagnetic equations, whereas Maxwell 2D/3D provides highly precise computations of magnetic fields, thermal profiles, and saturation phenomena (Soman et al., 2018). Consequently, these instruments have found extensive application among researchers seeking to refine the design of induction motors

for both electric vehicles and industrial contexts (Mohamed et al., 2019; Mohamed et al., 2017). Despite substantial progress in enhancing induction motors, the majority of research endeavours have concentrated on modifications to slot configurations or the selection of materials. Concurrently, there has been a paucity of studies systematically optimizing both the number of conductors per slot and wire diameter, particularly when accounting for the slot fill factor constraint, which directly impacts manufacturability. This deficiency is noteworthy because winding parameters exert a direct influence on copper losses, magnetizing current, and thermal loading; however, their combined optimization has not been extensively investigated within existing literature. Therefore, this study aims to conduct a thorough parametric analysis. It will examine how the number of conductors per slot (ranging from 39 to 65) and the wire diameter (from 0.60 to 0.70 mm) affect the performance of a 2.2 kW induction motor. This analysis will utilize ANSYS RMxprt to assess a total of 154 unique design configurations. The best designs are chosen by evaluating several factors. These include efficiency, power factor, torque characteristics (like starting, breakdown, and rated torque), starting current, flux density, and magnetizing current. Furthermore, the research offers actionable suggestions for enhancing motor efficiency while ensuring manufacturability, specifically maintaining a slot fill factor of 75% or less. The ensuing segments of this document are organized in the following manner: Section 2 provides a comprehensive exposition of the mathematical modeling pertinent to the induction motor, encompassing its core equations. Section 3 elucidates the methodological framework of the investigation, alongside the parametric design strategy that was utilized. Ultimately, Section 4 offers a presentation and subsequent analysis of the findings, incorporating a comparative assessment of performance metrics between the preliminary and the refined designs. This section concludes the paper by summarizing the main findings and suggesting areas for future research.

2. Mathematical Modeling of Induction Motor.

The mathematical analysis of the three-phase induction motor uses a per-phase equivalent circuit model. This model shows the relationships between the motor's electrical and magnetic properties. The equivalent circuit of the induction motor is shown in Figure 1, as described in several important sources (Pyrhönen et al., 2014; Sawhney, 2017). This model consists of the stator resistance R_1 , stator leakage reactance $X_{\sigma 1}$, rotor resistance referred to the stator R_2' , rotor leakage reactance referred to the stator $X_{\sigma 2}'$, as well as the magnetizing reactance x_m and the equivalent resistance for iron losses R_{fe} . According to (Boldea and Nasar, 2010), the voltage equations for the stator and rotor can be expressed as:

Figure 1:
Equivalent
an induction



circuit of
motor.

$$V_s = I_s(R_1 + jx_1) + E_1$$

$$E_1 = I_2' \left(\frac{R_2'}{s} + jx_2' \right)$$

where V_s is the phase voltage, I_s the stator current, E_1 the induced electromotive force in the stator, I_2' the rotor current referred to the stator, and S is the slip, which represents the difference between synchronous speed and actual rotor speed, as explained by (Sen , 2014) . Electromagnetic torque is one of the key performance indicators of the motor and can be calculated using the relationship presented by (Boldea and Nasar ,2010 ; Chapman , 2012) :

$$T_e = \frac{3}{w_s} \cdot \frac{R_2'}{s} \cdot \frac{E_1^2}{(R_2' / s)^2 + x_2'^2}$$

where $w_s = \frac{2\pi F}{P}$ is the synchronous angular speed. As pointed out by (Pyrhonen et al. , 2009) , torque is directly proportional to the square of the voltage and inversely proportional to the equivalent circuit impedance. Efficiency (η) and power factor (PF) can be obtained from the following equations as given by (Wildi , 2006 and Fitzgerald et al. , 2003) :

$$\eta = \frac{P_{out}}{P_{in}} \times 100\%$$

$$P_{in} = 3V_1 I_1 \cos \phi$$

$$PF = \cos \phi = \frac{P_{in}}{\sqrt{3}V_L I_L}$$

$$\phi = \tan^{-1} \left(\frac{x_m + x_2'}{R_2' / s} \right) - \tan^{-1} \left(\frac{x_1}{R_1} \right)$$

where P_{loss} represents the sum of stator and rotor copper losses, iron losses, mechanical losses, and stray losses, as discussed by (Yamazaki , 2001) . Among the most influential factors on the electromagnetic performance of the motor are the geometric parameters of the stator and rotor (Sawhney , 2006). showed that the stator tooth width (w_t) is determined by the geometric relationship:

$$w_t = \frac{\pi [D + 2(h_{s0} + h_{s1} + h_{s2})]}{Q_s} - b_{s2}$$

where D is the stator inner diameter, $h_{s0} + h_{s1} + h_{s2}$ are the stator slot heights, Q_s the number of slots, and b_{s2} the bottom slot width. These dimensions directly affect the tooth flux density B_t , given by (M. V. N. and M. A. ,2002) :

$$B_t = \frac{\phi_9 / Q_s}{w_t \cdot L_{stack} \cdot k_f} \cdot k_{sat}$$

where ϕ_9 = air-gap flux per pole, L_{stack} = stack length , k_f = stacking factor , and k_{sat} = saturation factor. (Rezaeealam , 2021) observed that the magnetizing reactance (x_m) substantially influences both the magnetizing current and the power factor; its calculation is given by:

$$x_m = \frac{4\mu_0 f (k_w N_{Ph})^2 L_{stak} D}{\pi P_9 k_C}$$

where μ_0 = permeability of free space, k_w = winding factor (0.9577), N_{Ph} = turns per phase, g = air-gap length , and k_C = Carter coefficient, which considers the influence of stator and rotor slot openings on the effective air gap . This relationship demonstrates that the magnetizing reactance is directly proportional to the square of the number of turns (N_{Ph})²; consequently, an increase in the number of conductors per slot elevates x_m , thereby diminishing the magnetizing current and enhancing the power factor. To precisely compute the magnetic field within the motor, while

accounting for the nonlinearity of magnetic materials and the effects of slots, the Finite Element Method (FEM) is utilized. This method is regarded as the most precise approach for analyzing the electromagnetic (Bastos and Sadowski ; 2014 ; Kuczmam and Ivanyi ; 2008) . The designer may learn the machine's behavior via FEM application in electrical machine analysis . By using a finite element technique (FEM), the electromagnetic parameters may be calculated with great precision. Furthermore, using this strategy offers the designer a significant advantage in terms of both time and financial resources . In finite element method (FEM) analysis, the area being studied is divided into a manageable number of separate parts. It is assumed that the target value is uniformly distributed throughout these localized areas. The basic differential equation used to explain the field's evolution is also assumed to hold true for all particles (Hamdi, 2023). FEM, a widely used numerical technique for tackling intricate engineering challenges, is employed to simulate the electromagnetic characteristics of induction motors experiencing faults, such as stator winding short circuits and rotor bar failures. By discretizing motor components into finite elements, the computation of electromagnetic fields, current distributions, and the resultant effects of faults, including torque diminishment, vibration, and thermal stress, is enabled (Khalaf Alqayssi, 2025). A review of induction motor modeling, based on FEM analysis and design methodologies, highlights the considerable time and cost advantages for designers utilizing this approach. Consequently, this method facilitates accurate calculations of electromagnetic parameters and provides a thorough comprehension of machine operation (Hasan and Jumaa, 2023b). Furthermore, a research paper presents a detailed analysis of a single-phase, multi-speed induction motor's performance, with the primary objective of calculating input current, input power, power factor, output power, torque, efficiency, and other intricate computations. The study examined changes resulting from four main modifications: skewing rotor bars, overall width, air gap, and capacitor. The analysis methodology used finite element method (FEM) through ANSYS programs (RMxpert, Maxwell 2D). The results proved the validity of the program's work through comparison with test results from design documents. The highest efficiency obtained was 79.70% at low speed (890 r.p.m.) when the capacitance value was changed to 7.2 μ F (Hasan and Jumaa, 2023a). The magnetic field can be expressed using the magnetic vector potential A through the following differential equation:

$$\nabla \times \left(\frac{1}{\mu(B)} \nabla \times A \right) = J$$

where $\mu(B)$ is the nonlinear permeability dependent on flux density B , and J is the current density. The B-H curves of the materials used (such as electrical steel) are input to accurately represent the nonlinear behavior of the magnetic core (Bianchi, 2005) . This method enables the calculation of magnetic flux distribution in all parts of the motor (teeth, yoke, air gap) and precise identification of saturation regions. It also allows the calculation of iron losses (eddy current and hysteresis) and copper losses in rotor bars while accounting for the skin effect (Boldea and Nasar ,2002) . In this study, ANSYS Maxwell software, which relies on FEM in its 2D version, was used to validate the results of the optimal design and compare them with the original design. The winding parameters are among the most important elements controlled by the designer to achieve the desired motor performance. In this investigation, the number of conductors per slot (N_s) and wire diameter (dw) were chosen as the principal design parameters, given their direct influence on electrical resistance, magnetic reactance, current density, copper losses, and, by extension, efficiency and power factor, as elucidated by (Boldea and Nasar , 2010 ; Pyrhönen et al. , 2009). Furthermore, altering these parameters is practical without requiring modifications to the core slot design or the materials used, thus offering a practical and cost-effective strategy compared to a complete redesign of the magnetic configuration (Sarac et al., 2017; Sarac, 2021). The number of conductors per slot (N_s) is connected to the number of turns per phase (N_{ph}) through the equation

$$N_{ph} = \frac{N_s Q_s}{2 a m}$$

where Q_s is the number of stator slots, a the number of parallel branches, and m the number of phases. The number of turns directly affects the induced electromotive force (E_1), given by (Sawhney , 2006 ;M. V. N. and M. A. 2002) :

$$E_1 = 4.44 f N_{ph} K_w \phi_g$$

This equation shows that increasing the number of turns increases the induced voltage, assuming the magnetic flux stays the same. As a result, the magnetizing current decreases, which improves the power factor (Rezaeealam, 2021). However, adding more conductors also increases the tooth flux density (Bt). If this density goes above the allowed limits, usually between 1.6 and 1.8 T (Hendershot and Miller, 2010), magnetic saturation can occur. This leads to higher iron losses and a decrease in efficiency. Therefore, the number of conductors must be selected so that saturation does not exceed safe limits. The effect of wire diameter (d_w) is evident through its direct influence on the electrical resistance (R_1) of the winding, and thus on copper losses. The resistance can be calculated from . (Boldea and Nasar , 2002 ; Di Tommaso et al. , 2017) .

$$R_1 = \rho_{cu} \frac{N_{ph} l_{mt}}{a A_{cu}}$$

where ρ is the resistivity of copper at operating temperature (75°C), l_{mt} the mean turn length, and A_{cu} the cross-sectional area of a single conductor given by ($A_{cu} = \frac{\pi d_w^2}{4}$) (for round wire). Clearly, increasing the wire diameter increases the cross-sectional area A_{cu} and reduces the resistance (R_1 , thereby reducing copper losses ($P_{cu} = 3 I_s^2 R_1$) (Boldea and Nasar , 2010) . Current density (J_s) in the stator windings is an important indicator of the motor's thermal loading and is calculated by:

$$J_s = \frac{I_s}{A_{cu} n_w}$$

where I_s is the rated phase current, and n_w the number of wires per conductor. Current density determines the winding temperature rise; high values ($> 7 \text{ A/mm}^2$) require better cooling and may reduce the motor's service life (Pyrhonen et al., 2009) . the wire diameter must be selected to keep current density within permissible limits . Finally, the number of conductors and wire diameter together affect copper weight and cost:

$$W_{cu} = 3 N_{ph} l_{mt} A_{cu} n_w \rho_{cu}$$

where ρ_{cu} is the density of copper (8900 kg/m³). From these relationships, N_s and d_w are interdependent variables affecting most key performance indicators: efficiency, power factor, torque, losses, and current density through their influence on magnetizing reactance, tooth flux density , electrical resistance , and current density . Therefore, a comprehensive parametric study of these two variables while keeping other parameters constant allows determination of the optimal design that achieves the highest efficiency while maintaining manufacturability and required dynamic performance.

3. Induction Motor Design.

This section describes the adopted methodology for the design, optimization, and validation of a three-phase squirrel- cage induction motor. The methodology integrates analytical-based modeling using ANSYS RMxpert with two- dimensional finite element analysis in ANSYS Maxwell, enabling both rapid performance evaluation and high- fidelity electromagnetic validation. This combined approach ensures a robust and reproducible

framework suitable for industrial induction motor design and optimization . (Peters et al. , 2003).

3.1. Baseline Motor Design and RMxpert-Based Optimization.

This study used a three-phase induction motor as the main example. The motor had a rated power of 2.2 kW, a voltage of 380 V, a frequency of 50 Hz, and two poles. The motor's original design followed standard industrial specifications, with a rated speed of 2850 rpm and an operating frequency of 50 Hz (Boglietti et al., 2008) . Table (1) presents the basic specifications of the motor under study . The motor was designed using ANSYS RMxpert, a specialized software for analytical design of electric machines, which relies on solving electromagnetic and magnetic equations through fast analytical methods (Iqbal and Agarwal , 2014 ; Prakash and Krishna , 2023) .All geometric dimensions of the stator and rotor were entered, along with the properties of the materials used (steel_1008_new for the magnetic core and copper for the windings)

Table 1. Motor Test Details.

Type of Motor	Romania's Electromotor Company, B3 90L
The Rated Voltage	380 V Y
The Rated of Speed	2850 r.p.m. (slip = 5%)
The Rated of Current	5.0 A
Output Rated Power	2200 W
The Starting of Current / Rated Current	6.50, (I starting = 32.50 A)
The Rated of Torque	7.370 N.m
The Power Factor	0.8550
The Starting of Torque / Rated Torque	2.0
The Maximum Torque / Rated Torque	2.20
The Insulation of Class	F (155°C max.)
Efficiency	0.790
The Rated Output of Power	2.2 kW
The Protection of Class	I P 54

Table 2. The SCIM rotor and stator slot dimensions.

stator slot dimensions(mm)		the rotor slots' dimensions(mm)	
Hs0	0.5	Hs0	1.35
Hs1	1.75	Hs01	0.65
Hs2	5.25	Hs2	8
Bs0	2.45	Bs0	1.5
Bs1	7.5	Bs1	4
Bs2	9.51	Bs2	4

In this study, the number of conductors per slot (N_s) and wire diameter (d_w) were selected as the primary design variables in the optimization process. The choice of these variables is justified by the following reasons (Sarac et al., 2017; Boldea and Nasar, 2002): they directly affect electrical resistance and copper losses, influence magnetizing reactance and magnetizing current, can be adjusted without altering the basic slot geometry, and have a direct impact on the motor's operational characteristics. The variation ranges for each variable were set as follows: number of conductors per slot from 39 to 65 in steps of 2 (39, 41, 43, ..., 65), i.e., 14 values, and wire diameter from 0.60 mm to 0.70 mm in steps of 0.01 mm (0.60, 0.61, ..., 0.70), i.e., 11 values. Thus, a total of $14 \times 11 = 154$ different design cases were obtained and systematically analyzed using ANSYS RMxpert . Table (3) shows the variation ranges for each variable.

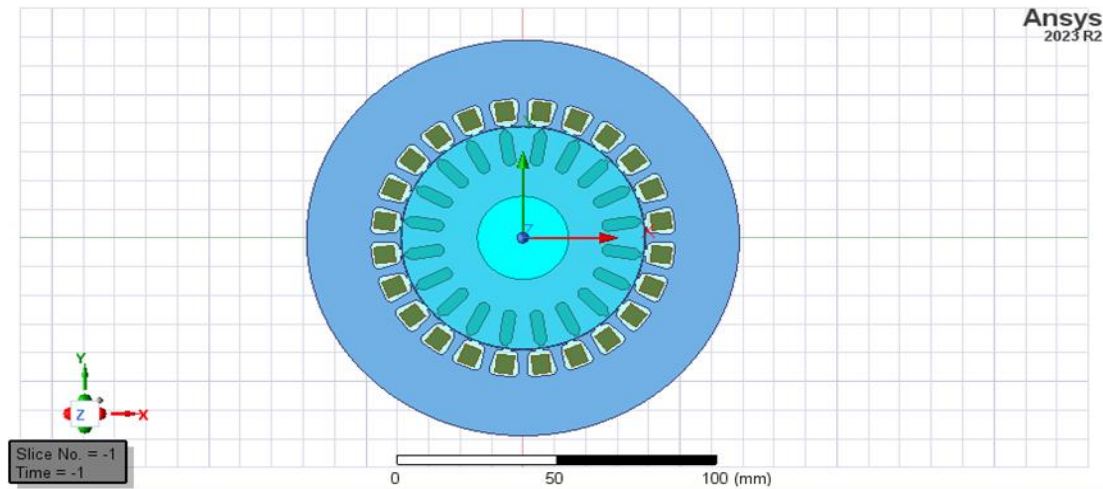
Table (3) variation ranges in the parametric study.

Variable	Symbol	Range	Number of values
Conductors per Slot	N_s	(39-65) steps 2	14
Wire Diameter	d_w	(0.6 – 0.7) step 0.01	11

For the comprehensive evaluation of each design case, a set of key performance indicators (KPIs) extracted from the RMXprt results were adopted (Tumbek et al., 2015; Mohamed et al., 2019): efficiency (η) representing the ratio of mechanical output power to electrical input power, power factor (PF) reflecting the proportion of active power to apparent power, total losses (P_{loss}) comprising copper, iron, mechanical, and stray losses, locked-rotor torque, generated at zero speed, breakdown torque as the maximum torque the motor can develop before stalling, rated torque at full load, breakdown current flowing through the windings at breakdown torque, stator tooth flux density as an indicator of magnetic saturation level, and magnetizing current representing the current required to establish the magnetic field in the air gap. The analysis was carried out according to the following steps: **First**, the baseline model was created in RMXprt using the dimensions and specifications listed in Table (1), and its validity was verified by comparing its results with the original design data (Ferkova, 2014). **Second**, a parametric project was set up in RMXprt where the variables Conductors per Slot and Wire Diameter were defined as variable ranges, and all required output results (efficiency, torques, currents, losses, etc.) were linked as output variables. **Third**, 154 design cases were processed in a sequential manner. The program used built-in analytical equations to calculate all performance indicators for each case. Each case took only a few seconds to complete, allowing all cases to be finished in a reasonable time.. **Fourth**, all results were exported to a CSV file containing 154 rows and 22 columns of data, where each row included the key performance indicator values for the corresponding combination of conductors per slot and wire diameter. **Fifth**, based on the extracted data, the cases were sorted by efficiency, and the best four cases were selected based on multiple criteria (efficiency, torques, flux density, and magnetizing current). These cases were then compared with the original design to assess the degree of improvement achieved. . The selection of the optimal design was predicated on a set of prioritized criteria: high efficiency (minimum 82%), a stator tooth flux density not exceeding 1.6 T to prevent saturation, a power factor of at least 0.85, and appropriate starting and breakdown torques for the intended application (starting torque of at least 1.5 times the rated torque, and breakdown torque of at least 2.5 times the rated torque). In accordance with these specifications, the design incorporating 49 conductors per slot and a wire diameter of 0.66 mm was identified as the most favorable overall design. In addition, four different, improved configurations were presented for comparison and evaluation.

4. Finite Element Modeling and Maxwell 2D Validation.

To evaluate the enhanced design's performance beyond the constraints of steady-state analytical approaches, the initial and refined RMxpert models were imported into ANSYS Maxwell 2D



(version 2023 R2) for a detailed finite

Figure 2. The design of SCIM.

element analysis Maxwell 2D employs a time-domain transient formulation, which effectively captures nonlinear electromagnetic behaviors, such as magnetic saturation, slotting harmonics, and flux leakage, as shown by (Sarac ,2021). The finite element model included detailed representations of the stator core, rotor core, squirrel-cage rotor bars, air gap, and windings. Nonlinear B–H characteristics were assigned to the magnetic materials to enable a realistic simulation of saturation effects . Furthermore, appropriate boundary conditions and excitation sources were implemented to replicate the rated operating conditions .The Maxwell simulations were mainly conducted to validate the electromagnetic torque characteristics, stator current waveforms, flux linkage properties, and power conversion efficiency under transient conditions, using the optimal winding configuration (49 conductors per slot, 0.66 mm wire diameter) determined from the RMxpert parametric study. Figure (2) shows a cross-section of the induction motor model created in ANSYS Maxwell.

5. Results and Discussion.

After executing 154 design cases using ANSYS RMxpert, the results were collected and analyzed to determine the effect of the number of conductors per slot and wire diameter on the motor's key performance indicators. The findings indicated that both variables significantly influenced efficiency, power factor, losses, and torque. Generally, it was found that augmenting the number of conductors per slot enhances the power factor, attributable to an increase in magnetizing reactance and a decrease in magnetizing current; however, this also elevates tooth flux density, potentially causing saturation if the allowable limits are surpassed (Boldea and Nasar, 2010; Sarac et al., 2017).Conversely, increasing wire diameter diminishes electrical resistance, thereby reducing copper losses, yet it also elevates the slot fill factor, which may impact manufacturability (Boldea and Nasar, 2002).All results were exported to a CSV file containing 154 cases, and analyzed to select the best designs. Table (4) presents the best four cases selected based on criteria of efficiency, power factor, flux density, and magnetizing current. The cases are arranged in descending order of efficiency,

Table 4. Best Four Cases from the Parametric Study.

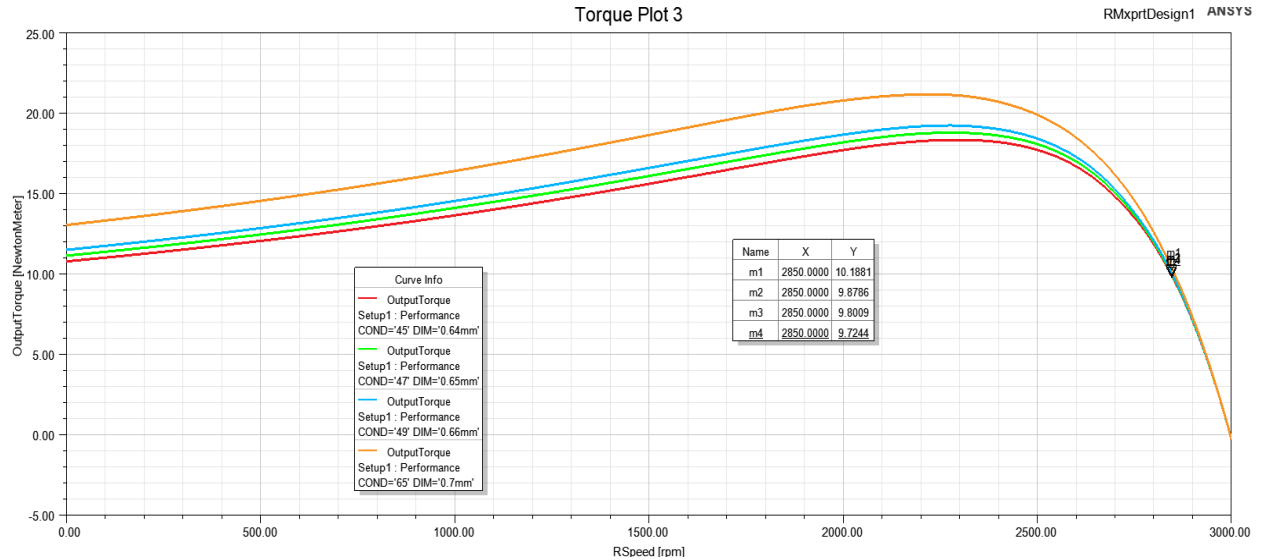
Case	Case A	Case B	Case C	Case D
Conductors (N_s)	49	47	65	45

Case	Case A	Case B	Case C	Case D
Wire Diameter d_w	0.66	0.65	0.7	0.64
η (%)	82.45	82.12	83.64	81.77
PF	0.870	0.87	0.86	0.875
Rated Torque (N·m)	7.25	7.25	7.24	7.25
Breakdown Torque (N·m)	19.22	18.78	21.15	18.33
Locked-Rotor Torque (N·m)	11.5	11.14	13.04	10.78
Stator Phase Current (A)	4.59	4.61	4.53	4.62
Breakdown Phase Current (A)	17.83	17.63	19.40	17.42
Total Losses(W) ploss	468.3	479	430.3	490.4

From Table 4, it's clear that Case C, with 65 conductors and a 0.70 mm wire diameter, had the best efficiency (83.64%), the lowest total losses (430.3 W), and the highest locked-rotor torque (13.04 Nm) and breakdown torque in contrast, Case A, which incorporated 49 conductors with a 0.66 mm diameter, exhibited an efficiency of 82.45%, demonstrating a strong balance across all assessed parameters. This particular configuration yielded a power factor of 0.870, a locked-rotor torque of 11.50 Nm, a breakdown torque of 19.22 Nm, a stable rated torque of 7.25 Nm, and a low stator phase current of 4.59 A. Case D, characterized by 45 conductors and a 0.64 mm diameter, attained the highest power factor (0.871) and the lowest breakdown current (17.42 A); nevertheless, its efficiency was the lowest among the cases examined, at 81.77%. Case B, which utilized 47 conductors and a 0.65 mm diameter, demonstrated intermediate performance, with an efficiency of 82.12% and a favorable equilibrium across the other parameters. These findings are consistent with established mathematical principles: an increase in the number of conductors leads to a rise in magnetizing reactance and an improved power factor, while also slightly reducing stator phase current due to the enhanced power factor; the rated torque remained nearly constant across all designs, suggesting that the optimization preserved output capability (Rezaeealam, 2021; Pyrhönen et al., 2009). It's important to note that Case C, despite its high efficiency, shows significantly higher breakdown current and stator phase current.

6. Performance curve Analysis.

Figure (3) presents the torque versus speed curves. At the specified operational speed, the torque measurements span from 9.72 Nm to 10.19 Nm . Case C exhibits the greatest torque, registering at 10.19 Nm, whereas Case A presents a similar value of 9.80 Nm . Within the breakdown torque range of 2400–2600 rpm, Case C again displays the highest breakdown torque, measured at 21.15 Nm, succeeded by Case A with a value of 19.22 Nm . Increasing the number of turns (N_s)



to 65, along with larger dw , improves the overload capacity. This happens because a higher N_s increases the magnetic loading, and a larger dw reduces rotor resistance, which together boosts torque production. However, this improvement also leads to higher current and a greater risk of saturation (Tumbek et al., 2015).

Figure 3. RMxprt Output Torque vs Speed

All configurations successfully deliver the specified output power of 2.2 kW at the designated speed of 2850 rpm. Case C demonstrates superior output power within the medium speed spectrum, specifically between 2000 and 2500 rpm, whereas Case A maintains a stable performance within the rated operational domain. It is noteworthy that an increase in N_s correlates with an enhanced power generation capacity at elevated speeds. This phenomenon can be attributed to the fact that a higher magnetizing reactance facilitates improved flux utilization, thereby allowing for greater power output at increased speeds, as indicated by (Sarac et al., 2017).

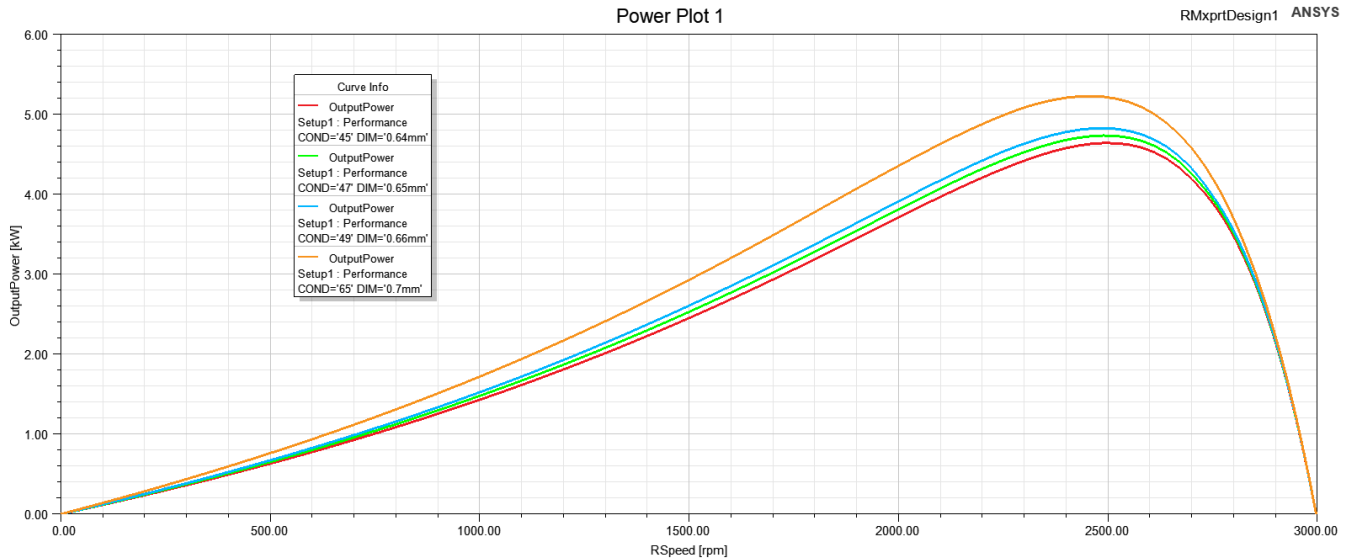
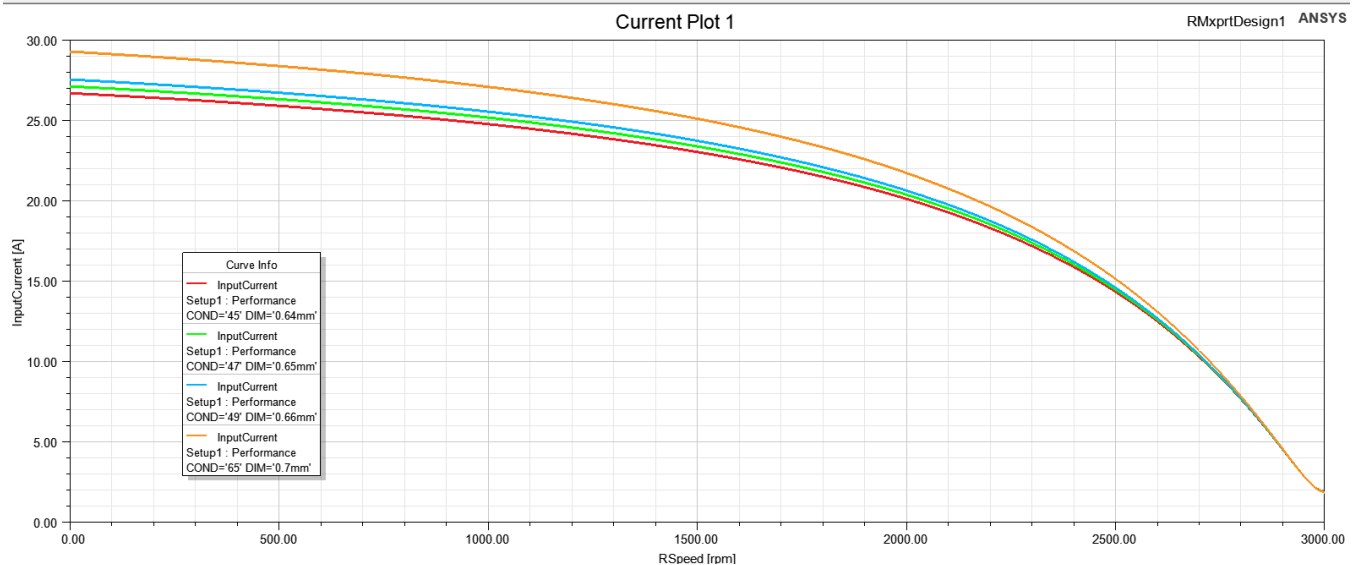


Figure 4. RMxprt Output Power vs Speed.

Figure 5 shows the curves of rated current versus speed, along with the original design. The original design's highest current, 5.38 A, occurs at its rated speed, while Case C shows the lowest current, 4.53 A. Case A shows a current of 4.59 A, which is a 14.7% decrease. It's important to note that all the optimized designs show a lower current compared to the original design. This is because a better power factor reduces the magnetizing current, and lower resistance reduces copper losses, both of which lower the total current (Boldea and Nasar, 2010). Therefore, the



engineering result is that a lower current reduces copper losses (calculated as I^2R) and improves thermal performance.

Figure 5. RMxprt Stator Current vs Speed.

Figure (6) shows the power factor versus speed curves. At rated speed, Case D demonstrates the most favorable power factor (0.871), succeeded by Cases A and B (0.870), and subsequently Case C (0.868). Each of the optimized designs presents a marked enhancement compared to the original configuration (0.749). It is noteworthy that the power factor increases with $N s$ to a certain extent, before experiencing a slight decline. This phenomenon can be attributed to the fact that magnetizing reactance escalates with $N s$, thereby diminishing magnetizing current;

nevertheless, an excessive N_s induces saturation, which in turn reduces effective reactance (Rezaeealam, 2021)

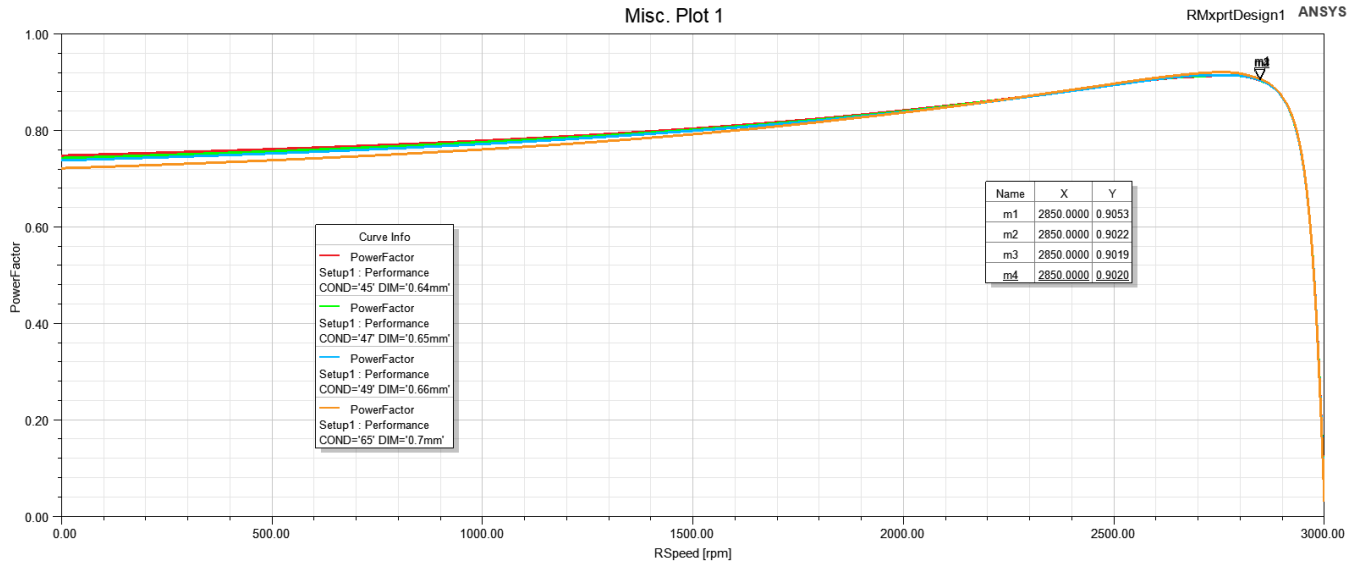
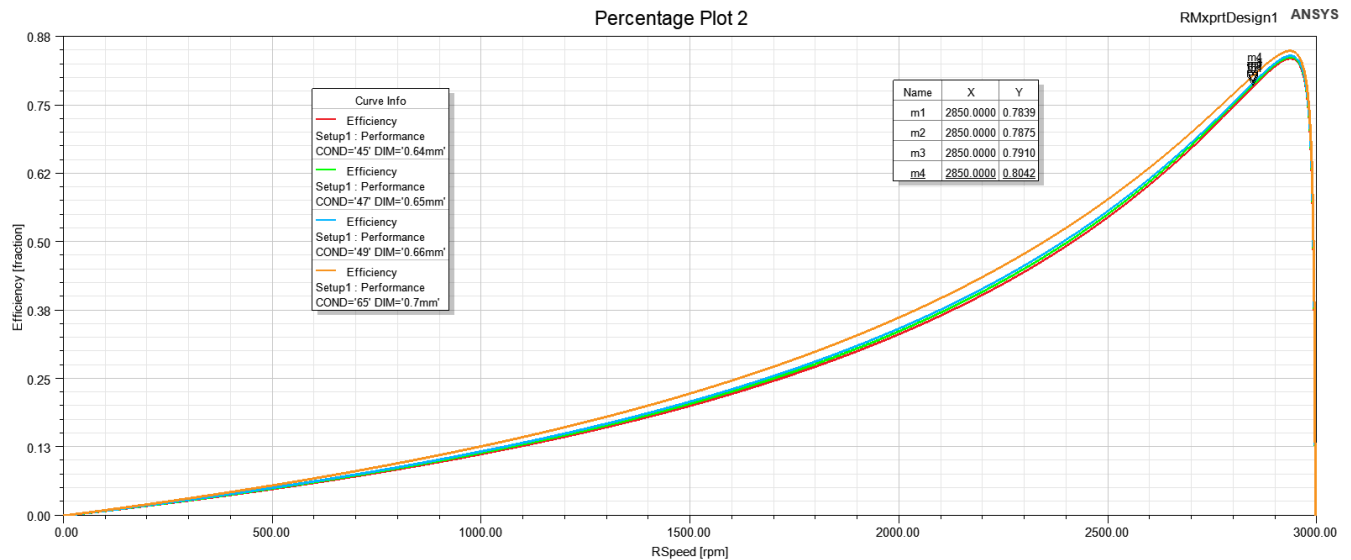


Figure 6. RMxprt Power Factor vs Speed

Figure 7 presents the efficiency-speed curves. Case C demonstrates superior efficiency throughout the entire speed spectrum, achieving a peak of 83.64% at the rated speed. Case A exhibits an efficiency of 82.45%, succeeded by Case B at 82.12%, and Case D at 81.77%. Analysis reveals a positive correlation between efficiency and both N_s and d_w . This is attributable to the fact that an increase in N_s elevates magnetizing reactance, thereby diminishing magnetizing current;



conversely, a larger d_w reduces copper losses (Pyrhönen et al., 2009). From an engineering perspective, the small difference of 0.33% between Cases A and B suggests that moderate improvements in N_s and d_w can produce results close to the best possible, without making manufacturing difficult..

Figure 7. RMxprt Efficiency vs Speed .

Based on the combined RMxprt analysis shown in Figure 8, the best winding design is the one with 49 conductors per slot and a wire diameter of 0.66 mm (Case A). Unlike traditional methods that treat winding parameters as secondary, these findings show that N_s and d_w

directly affect copper losses, magnetizing current, and the resulting efficiency and power factor (Sarac et al., 2017; Iqbal and Agarwal, 2014).

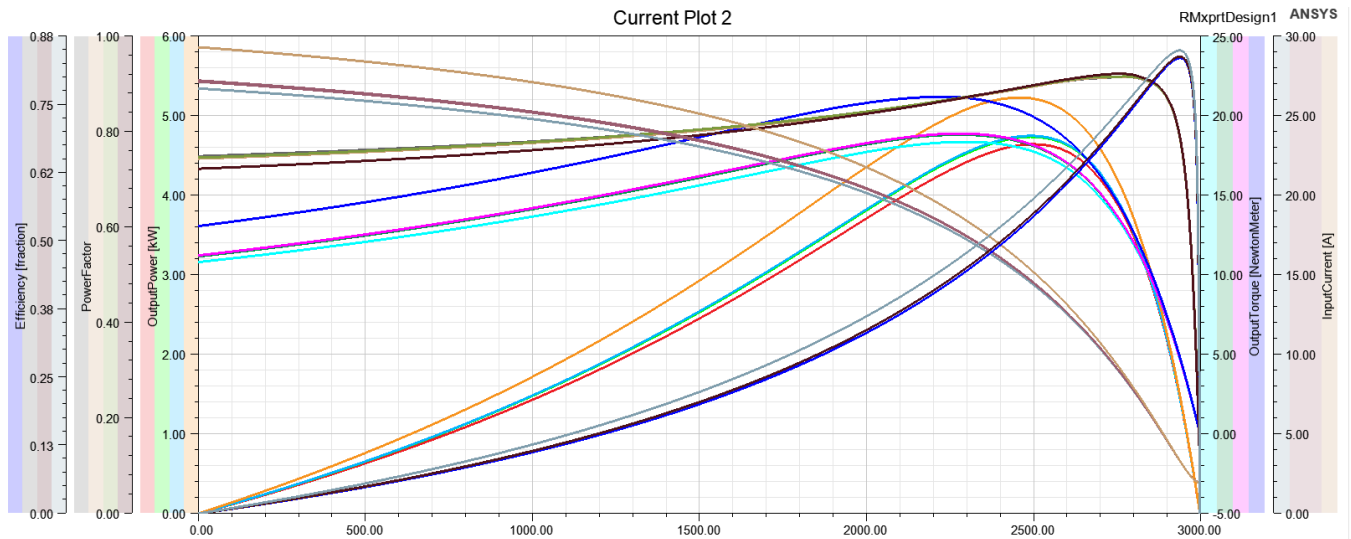
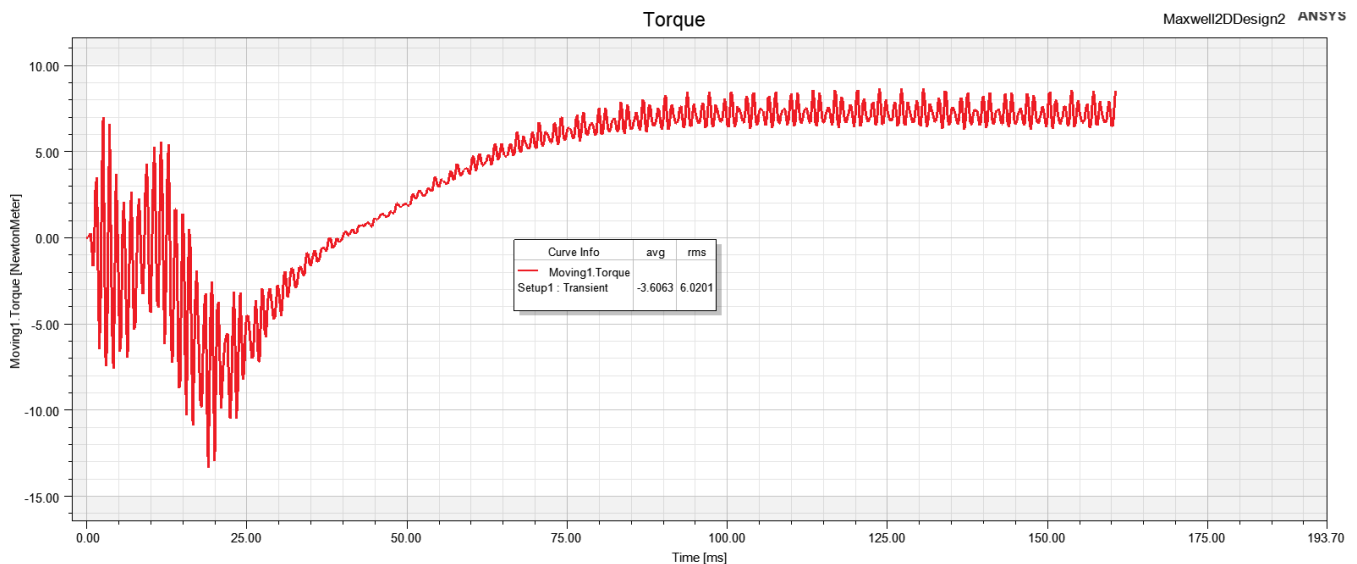


Figure 8. Optimal design selection within the investigated design space.

7. Maxwell Optimization 2D Validation of the Optimal Design (Case A).

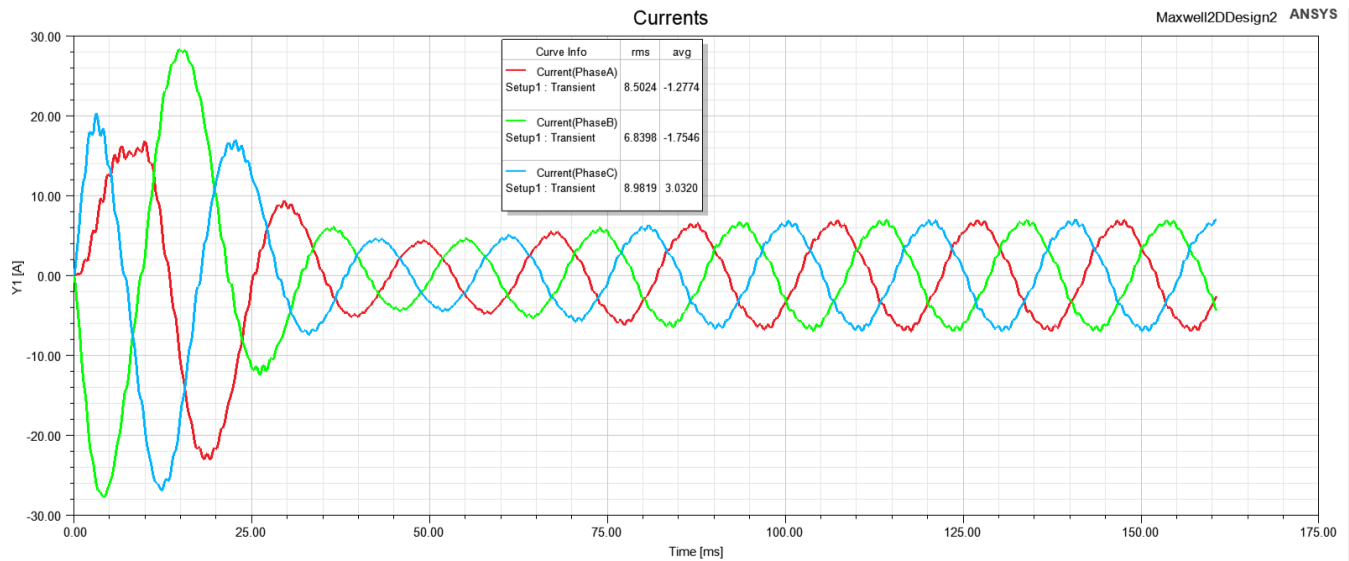
Although RMXprt analysis provides reliable performance trends in steady-state, Maxwell 2D transient field analysis results are essential to verify that the optimal design retains its advantages under transient electromagnetic conditions. Therefore, a detailed transient finite element analysis was performed for the optimal design (49 conductors, 0.66 mm). Figure 9 presents the electromagnetic torque waveform, as computed by Maxwell, within the time domain. After the initial transient period, the waveform exhibits a smooth torque



profile, distinguished by minor fluctuations around the average torque value. This finding supports the existence of low torque ripple and consistent mechanical performance, which stems from the improved air-gap flux distribution and reduced slot harmonics inherent in the optimized design, as evidenced by (Chapman, 2012; Bianchi 2005).

Figure 9. Maxwell electromagnetic torque waveform.

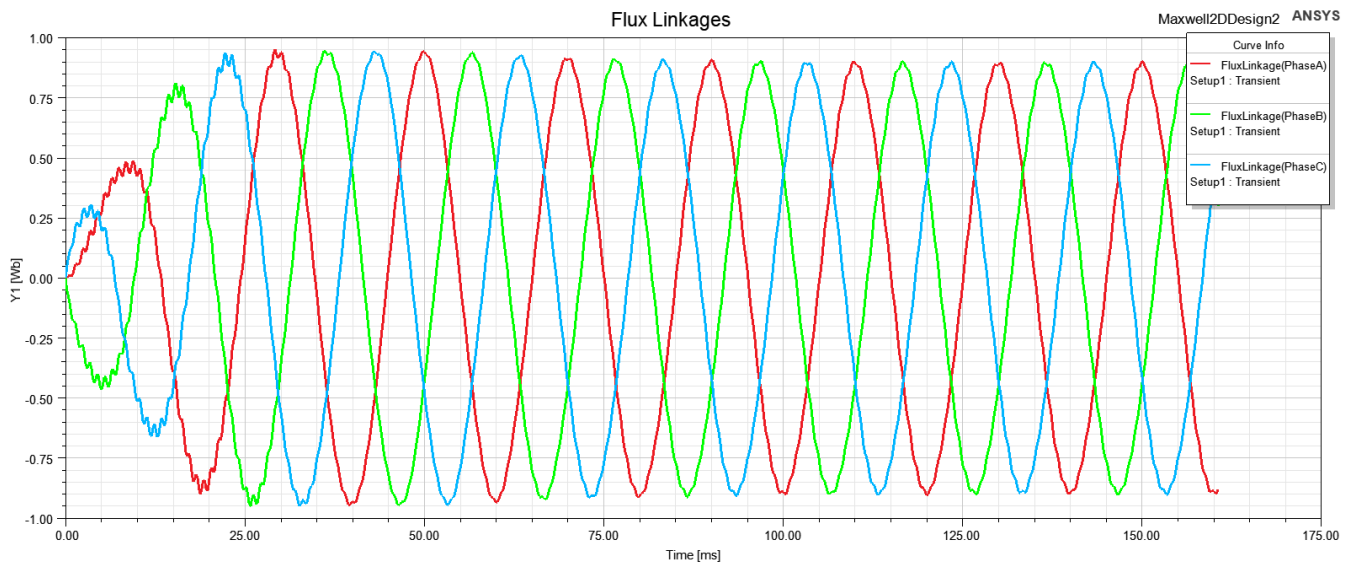
The simulated three-phase currents in Figure (10) exhibit balanced sinusoidal waveforms with equal amplitudes and a 120-degree phase shift. The lack of waveform distortion implies a low degree of saturation and harmonic distortion, thus providing temporal confirmation of the



reduced magnetizing current, as inferred from the power factor data within RMxppt (Rezaeealam, 2021; Bastos and Sadowski, 2014).

Figure10. Maxwell phase currents.

The flux linkage waveforms depicted in Figure 11 exhibit symmetry and an approximate sinusoidal shape, with uniform peak values across all phases. This feature supports a balanced magnetic circuit and offers direct evidence, obtained through the finite element method, that



stator tooth saturation has been effectively mitigated in the optimized design (Bastos and Sadowski, 2014; Hendershot and Miller, 2010).

Figure 11. Maxwell flux linkages .

Finally, the transient power analysis in Figure (12) shows the electrical and mechanical power waveforms. After the starting transient, electrical power stabilizes at approximately 2.65 kW and mechanical power at approximately 2.2 kW, corresponding to the calculated efficiency (83%) and confirming efficient energy conversion (Yamazaki,2001)

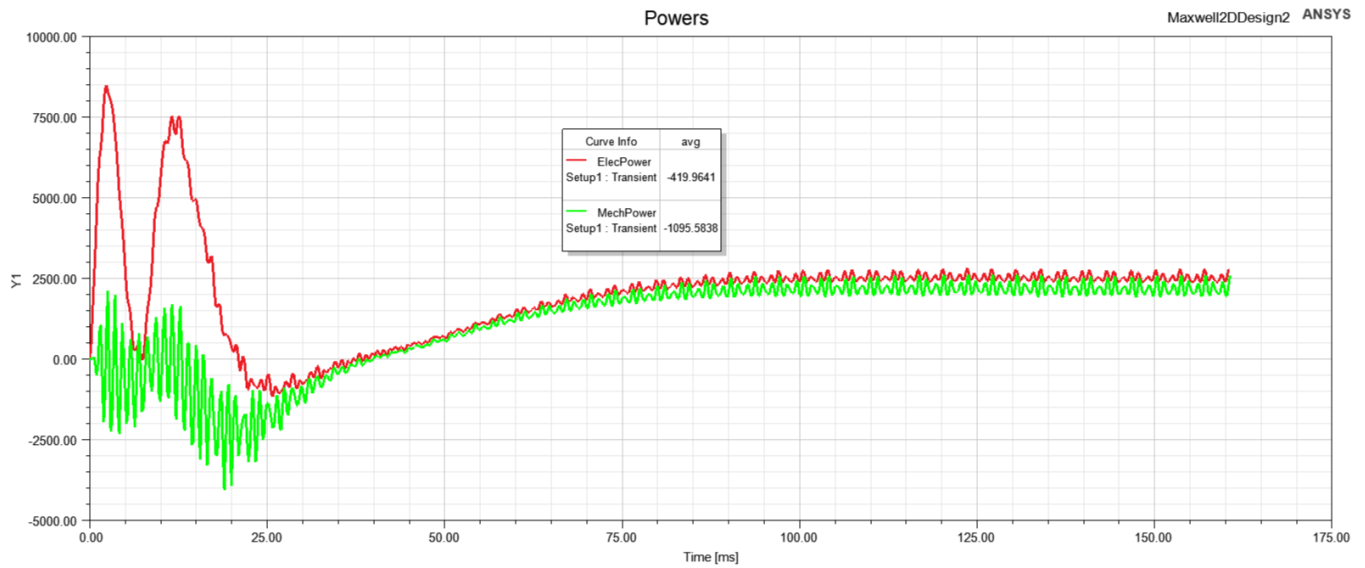
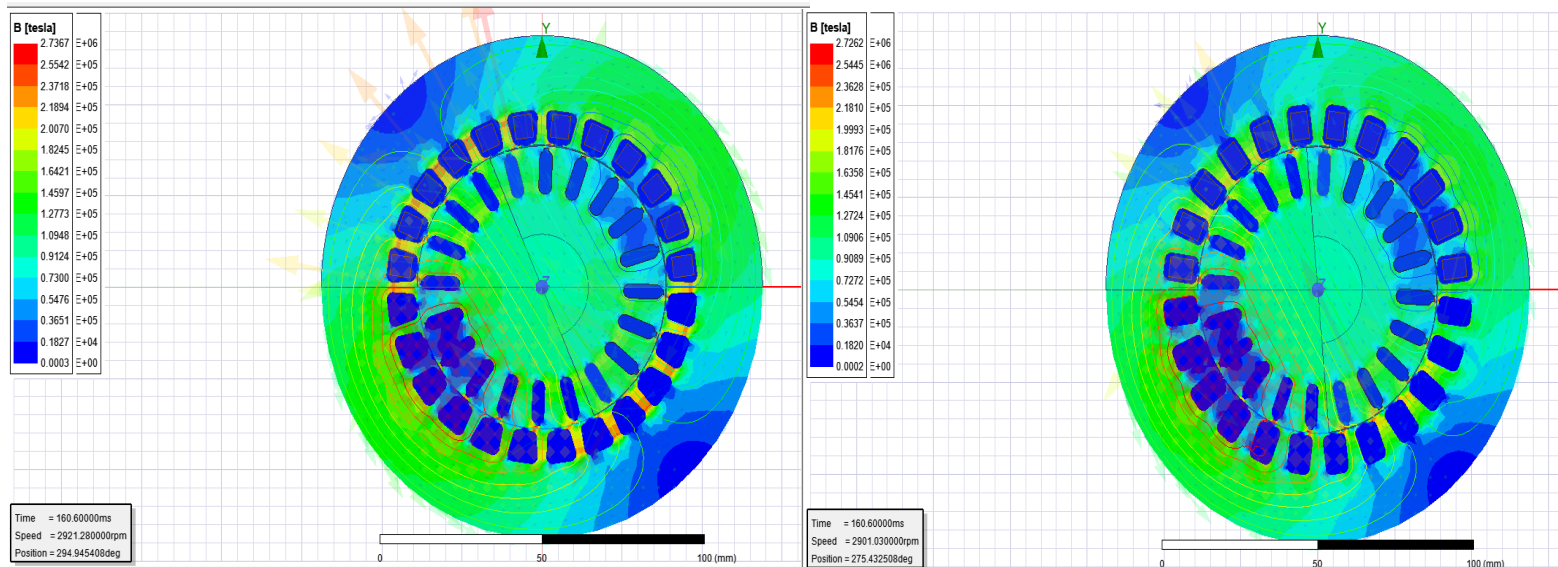


Figure 12. Maxwell electrical and mechanical power waveforms .

Figure (13) shows the magnetic flux density distribution in the motor cross-section for both the original and optimal designs. It should be noted that the RMxprt analytical model predicted a peak flux density of 2.403 T for the original design, while Maxwell 2D transient FEA yielded a higher value of 2.73 T. This discrepancy is expected, as FEA captures nonlinear saturation effects and local flux concentrations more accurately than the analytical equivalent circuit approach. For the optimized design, both methods show good agreement (1.547 T from RMxprt vs. 1.55 T from Maxwell 2D), confirming that the design operates safely below the saturation limit. In the initial design (Figure 13-a), the stator teeth are characterized by dark red areas, signifying significant magnetic saturation, with flux density values reaching 2.73 T. This saturation effect results in heightened iron losses, a diminished power factor, and an increase in motor temperature. Conversely, the optimal design, as illustrated in Figure 13-b, exhibits a more uniform distribution; the flux density is diminished to approximately 1.55 T, a value that remains



beneath the prescribed safety limit of 1.6 T.

It is significant that the peak flux density within the configuration is reduced from 2.73 T to 1.55 T, thus mitigating the areas of intense saturation. Reason: Increasing the number of conductors from 40 to 49 increases the number of turns, thereby increasing magnetizing reactance X_m and improving flux distribution. This improvement reduces iron losses, enhances the power

factor, and increases the reliability and lifespan of the motor (Boldea and Nasar, 2010; Sarac et al., 2017; Hendershot and Miller, 2010).

(a) (b)
Figure 13. Magnetic flux density distribution: (a) Original design, (b) Optimized design.

The strong agreement between the RMXprt-based parametric trends and the Maxwell 2D validation confirms that the observed performance improvements are physically meaningful, not just numerical artifacts. The best design, which uses 49 conductors and a 0.66 mm diameter, significantly improves the magnetic field distribution. This, in turn, reduces saturation, enhances the power factor, and consistently increases efficiency (Mohamed et al., 2017; Iqbal and Agarwal, 2014). Table 5 summarizes the key performance indicators for both the original and improved designs. This allows for a comparison of the overall effect of the proposed winding parameter optimization on the electromagnetic performance of the induction motor being studied. The optimal design was found using RMXprt optimization and then validated with Maxwell 2D

Table 5. Performance comparison between the baseline induction motor and the optimized design.

Parameter	Baseline Design	Optimized Design
Efficiency (%)	80.17	82.45
Power Factor	0.749	0.870
Peak Flux Density (T)	2.403	1.547
Breakdown Torque (N·m)	21.54	19.22
Starting Current (A)	20.40	17.83

As can be seen from Table (5), there is a clear improvement in the electromagnetic performance of the induction motor. The optimization process yields a motor efficiency enhancement, elevating it from 80.17% to 82.45%, while simultaneously improving the power factor from 0.749 to 0.870; this suggests a substantial decrease in magnetizing current. Furthermore, the peak flux density within the stator teeth diminishes from 2.403 T to 1.547 T, thereby validating the efficacy of the modified configuration in mitigating the magnetic saturation issue within the stator teeth, as documented by (Hendershot and Miller, 2010). It is also observed that the optimized configuration exhibits a commendable breakdown torque of 19.22 Nm and a reduced starting current of 17.83 A, thereby confirming the improved configuration's effectiveness in augmenting the electromagnetic performance of the induction motor. Therefore, the findings underscore that the performance of the induction motor can be significantly improved by adjusting the number of conductors per slot and the wire diameter. From an engineering practice perspective, it can be stated that the proposed optimization strategy for improving the efficiency of an industrial electrical machine is associated with specific manufacturing aspects related to changes in the winding parameters within the stator structure. As explained, no additional magnetic materials or cooling systems are required to implement this optimization method; however, it is necessary to implement changes in the manufacturing process related to the winding that forms the stator structure of the industrial electrical machine. Compared to other optimization strategies for improving the efficiency of industrial electrical machines that require the use of high-performance magnetic materials or control systems, it can be stated that optimizing winding parameters involves relatively simple changes in the winding process, making it more feasible for industrial practice in terms of costs (Iqbal and Agarwal, 2014; Di Tommaso et al., 2017).

8. Conclusion

This research has shown that the parameters of the stator winding, specifically the number of conductors per slot and the wire diameter, are not simply secondary design details. Instead, they are crucial electromagnetic factors that control saturation behavior, power factor, and efficiency in industrial induction motors. Through a methodical integration of RMxpert based parametric optimization and two-dimensional transient finite element validation, this study elucidates a definitive and physically substantiated correlation between winding configuration and energy conversion efficacy. The research indicates that the number of conductors in each slot significantly affects magnetic saturation in the stator tooth area. Specifically, increasing the conductor count from 40 to 49, along with a wire diameter change from 0.67 mm to 0.66 mm, raises magnetizing reactance. This, in turn, reduces the magnetizing current by 48.6% (from 3.455 A to 1.775 A) and lowers the stator tooth flux density from a critical saturation level of 2.403 T to a more manageable 1.547 T. As a result, this reduction in saturation directly decreases iron losses and improves the power factor, increasing it from 0.749 to 0.870. Consequently, the optimized wire diameter's impact on stator resistance resulted in a 14.7% decrease in stator phase current (from 5.38 A to 4.59 A) and a 12.6% reduction in breakdown current (from 20.40 A to 17.83 A). The most effective design, among the configurations examined, incorporated 49 conductors per slot and a 0.66 mm wire diameter, consistently yielding the most favorable balanced performance: an efficiency of 82.45% (a 2.28 percentage point enhancement compared to the original design), a power factor of 0.870, and a reduction in total losses of 75.9 W relative to the baseline, all while maintaining a constant output power of 2.2 kW. Although the design featuring 65 conductors and a 0.70 mm wire diameter demonstrated a higher efficiency (83.64%), it was ultimately not selected due to manufacturability limitations (the slot fill factor exceeding 75%) and an elevated breakdown current, which would have jeopardized thermal reliability. The efficacy of the suggested optimal design was further substantiated via Maxwell 2D transient analysis. Finite element simulations demonstrated a smooth electromagnetic torque profile characterized by minimal ripple, balanced and sinusoidal stator currents, symmetrical flux linkages, and stable electrical-to-mechanical power conversion. The strong correlation between RMxpert steady-state trends and Maxwell time-domain validation offers persuasive support for the physical significance of the observed performance enhancements, thereby ruling out the possibility of these being merely artifacts of simplified analytical assumptions. Future research will explore several directions. First, it's crucial to experimentally validate the simulation results by building a prototype and conducting laboratory tests to see how well it works in real-world situations. Following this, coupled electromagnetic-thermal finite element methods should be used for thermal analysis. This approach will help confirm the temperature distribution and ensure that insulation class standards are met. Moreover, the optimization framework can be expanded to include more design variables, such as the shape of the stator slots, the length of the air gap, and the choice of core material. As a result, the proposed methodology can be applied to motors with different power ratings and pole configurations.. This will create general design guidelines for energy-efficient induction motors that can be used in various industrial settings. In summary, this research highlights that intelligently optimizing stator winding parameters is a practical and cost-effective way to improve induction motor performance, without requiring more active material or making manufacturing more complex. The presented optimization validation framework and derived design insights provide a practical reference for the development of high-efficiency induction motors compliant with modern energy efficiency standards, and can be readily extended to other motor ratings and industrial applications.

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