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Investigating the Impact of Different Magnetic Wedges on Efficiency of Small Induction Motors

Serhat Doğan[1], Sibel Zorlu Partal[2], Bilal Gümüş[1]

[1]Department of Electrical and Electronics Engineering, Dicle University Faculty of Engineering, Diyarbakır, Türkiye
[2]Department of Electrical Engineering, Yıldız Technical University Faculty of Electrical and Electronics, İstanbul, Türkiye

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WHAT IS ALREADY KNOWN ON THIS TOPIC?

- *Magnetic wedges are widely recognized in large-power motors for their role in improving efficiency through the reduction of magnetizing current, core losses, and harmonic distortions.*
- *These benefits are achieved through the homogenization of flux distribution, which enhances overall motor performance.*

WHAT THIS STUDY ADDS ON THIS TOPIC?

- *This study delivers a systematic analysis of magnetic wedges in small-power induction motors, addressing notable deficiencies in the current literature and expanding the understanding of their application in this context.*

Corresponding author:
Serhat Doğan

E-mail:
serhat.dogan@dicle.edu.tr

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ABSTRACT

In this study, the effects of magnetic wedges on the performance of small-power induction motors are thoroughly investigated. In order to improve motor efficiency and reduce losses, three magnetic wedges with different relative magnetic permeability values are analyzed and compared to a reference motor without a magnetic wedge. Electrical losses are computed using the Finite Element Method (FEM) in ANSYS Electronics Desktop, while thermal analysis is conducted through the FEM-based Steady-State Thermal program. The transient and steady-state losses are evaluated, and the results indicate that the use of magnetic wedges significantly enhances motor efficiency, primarily by reducing winding losses and minimizing temperature rise. Furthermore, magnetic wedges positively impact torque fluctuations in both transient and steady-state conditions, improving motor stability. The study confirms that the degree of efficiency improvement is directly related to the relative magnetic permeability of the wedge. Motors using a wedge with higher permeability show better performance, with a greater reduction in losses and temperature, and an improvement in torque stability. These findings show that magnetic wedges, typically used in large power motors, can also offer significant advantages in efficiency, torque stability, and temperature control when applied to small-power induction motors.

Index terms—Finite Element Method (FEM), induction motor, magnetic wedge, motor efficiency, thermal analysis

I. INTRODUCTION

Induction motors have a wide range of applications today and are widely used in many sectors, from household applications to space technology. Efficiency is of great importance in the design of these motors, and various methods such as mechanical improvements and the development of drive systems have been applied to increase efficiency. One of the methods used to improve the efficiency of induction motors is the use of magnetic wedges in the design. However, magnetic wedges have so far been used in large power induction motors. Today, since energy efficiency plays a key role in energy conversion, efficiency applications are increasing in every field. Accordingly, the use of magnetic wedges in the design of small power induction motors is expected to become widespread. Magnetic wedges are obtained from a mixture of different materials. The main objective of this study is to investigate the effects of different magnetic wedges used in small power induction motors on motor efficiency and performance. Thus, it will contribute to the designers in selecting magnetic wedges that will increase efficiency in small power induction motor design.

The air gap in induction motors significantly increases the reluctance of the magnetic flux path and, therefore, reduces the magnetic coupling between the stator and rotor windings. The high reluctance caused by the air gap requires more magnetizing current to achieve the desired flux level [1]. This increases the starting current, core, and copper losses, especially at start-up, and

- *Through a thorough and rigorous analytical approach, it explores the effects of magnetic wedges on the relationship between electrical losses and thermal heat dissipation, providing fresh perspectives on the thermal management issues unique to small-power induction motors..*

adversely affects the performance of the motor. One of the methods used to minimize these negative effects is to place a suitable magnetic wedge in the stator slot [2].

The open slots in the stator core facilitate the insertion of conductors and provide low leakage flux between the open-mouthed stator slot teeth [3, 4]. However, this may distort the air gap geometry and negatively affect the magnetic flux density in the air gap [3, 5, 6]. Magnetic wedges are used to reduce this negative effect and make the magnetic flux density more uniform. Magnetic wedges are widely preferred, especially in machines with high output power [5]. However, they can also be used in small power machines [7]. Magnetic wedges increase the efficiency of the motor by reducing the magnetizing current and regulating the flux density [8, 9].

Another problem caused by the stator slot is that the irregular air gap leads to harmonic components [6]. These harmonic components adversely affect the motor performance, causing torque fluctuations, temperature rise, core losses, and idling losses [10, 11,12]. Especially, machines with open-mouth slotted stators usually have high-frequency flux fluctuations, which increase losses and decrease efficiency [6, 11, 13].

Magnetic wedges provide a more uniform magnetic flux density by closing the open-mouth stator slot opening. This makes the magnetic flux more homogeneous on both the stator teeth and the slot surface [5]. It also reduces the temperature rise and magnetic losses in the machine by preventing high flux density in the stator teeth [14]. Thus, the stator phase and leakage inductance increase while the magnetizing current decreases [5, 9, 15]. Closing the slot opening helps to reduce the harmonic oscillations in the magnetic field [7, 16, 17]. The reduction of harmonic oscillations improves motor efficiency by reducing losses, vibrations, and noise [16].

The use of magnetic wedges has a direct impact on motor efficiency. As it is known, motor losses usually occur in the core and winding structures. The reduction in core and copper losses positively affects motor efficiency and extends the life of the motor [18, 19]. Magnetic wedges are generally manufactured from materials with high relative magnetic permeability and low electrical conductivity values [20, 21]. Typically, a magnetic wedge contains 70% iron powder, 20% epoxy resin, and 10% glass material [15, 19, 21, 22].

Magnetic wedges also affect the temperature distribution in motors. Temperature increases as a result of core and winding losses, which can affect the performance and lifetime of the motor. Therefore, minimizing losses is important to prevent temperature increases. Uneven flux distribution or variable magnetic fields caused by open-mouthed stator slots lead to the generation of eddy currents, resulting in additional losses and temperature increases [23].

Table I presents a comprehensive overview of the studies examined, offering a comparative literature review to underscore the significance of the addressed research topic. The recent literature demonstrates a growing focus on the use of magnetic wedges, particularly in high-power applications, highlighting their significant benefits in enhancing efficiency and reducing losses. However, a critical gap exists in understanding the effects of magnetic wedges on temperature distribution, an aspect that remains largely unexplored. This is especially notable given the limited studies addressing magnetic wedge applications in low-power machines, particularly induction motors. While some investigations have evaluated the impact of magnetic wedges on small-power machines, thermal distribution analyses have not been sufficiently explored. This study addresses the need for comprehensive research on the thermal implications of magnetic wedges in induction motors, particularly in low-power applications, to address this notable deficiency in the current body of knowledge.

The findings of this study provide valuable contributions to the existing literature by investigating in depth the effects of different types of magnetic wedges on the overall motor efficiency and temperature distribution in small power induction motors. The effects of magnetic wedges on motor performance have been discussed in detail in the above literature survey. However, the outstanding aspect of this study is that it investigates the effects of magnetic wedges with different relative magnetic permeability values on motor efficiency through modeling. In addition, another important contribution of this research is that it addresses the lack of sufficient investigation of the effect of different types of magnetic wedges in the literature, especially in small power motors. By filling this gap, this study provides critical data for small power engines and enriches the body of knowledge in this field. The findings are an important resource for

TABLE I. OVERVIEW OF MAGNETIC WEDGE APPLICATIONS AND RESEARCH GAPS IN ELECTRICAL MACHINES

Ref.	Machine Type	Machine Power	Research Method	Magnetic Wedge Type	Target Application	Results and Findings	Deficiencies in the Literature
[24]	Permanent Magnet Synchronous Motor (PMSM)	High power	Analytical modeling	Conductive wedge	Reducing magnetic induction distortion	The magnetic wedge reduced distortion by 40%. Slot spread increased, but efficiency decreased.	Lack of wedge height optimization in open slots.
[25]	Line start Permanent Magnet Synchronous Motor (LS-PMSM)	740 kW	Analytical modeling, experimental	Magnetic and non-magnetic wedges	Improve magnetic density distribution, reduce torque ripple, enhance efficiency	Magnetic wedges reduced eddy current losses by 7.292 kW, decreased torque ripple rate by 3.35%, improved efficiency by 0.73%,	Limited studies on magnetic wedge application in LS-PMSM.
[26]	Inner rotor Brushless DC Motor (BLDC)	1 kW	Analytical modeling	Wedge-shaped permanent magnets	Electric vehicle (EV) traction motor	Reduced cogging torque by 8% compared to traditional designs. Enhanced performance with lower iron and copper losses.	Limited studies on wedge-shaped rotor designs, particularly in real-world Electric vehicle applications.
[27]	Permanent Magnet Synchronous Motor (PMSM)	380kW	Analytical modeling, experimental	Magnetic sloe wedge (MSW), non-MSW	High-speed train	Reduced Alternating Current (AC) winding losses by 60% using optimal conductor segmentation and MSW. Validated output performance with 96.9% efficiency.	Thermal interaction and loss impact during real-world train driving cycles remain underexplored.
[28]	Wound rotor synchronous machine (WRSM)	12 kVA	Analytical modeling, experimental	Stainless steel magnetic wedge	Aircraft WRSM	Reduced harmonic content in no-load voltage, decreased core loss, improved efficiency by 3%, and enhanced power factor.	Lack of comprehensive studies on the use of stainless steel magnetic wedge in WRSM
[29]	Synchronous reluctance machine (Axially)	27 kW	Analytical modeling	Semi-magnetic wedge	Micro gas turbine applications	Reduced rotor losses and enhanced machine efficiency by optimizing wedge permeability, height, and protrusion.	Lack of extensive studies on wedge design optimization for high-speed (100 krpm) applications.
[6]	Induction motor	3 kW	Analytical modeling	Different relative magnetic wedge	High-speed and precision application	Reduced torque ripple, vibration, and noise; improved motor efficiency.	Lack of guidelines for optimal magnetic wedge height.
[30]	Permanent Magnet Synchronous Motor (PMSM)	1.4 kW	Analytical modeling	Uniform and non-conventional magnetic wedges	High torque and low-speed industrial motors	Reduction in magnet losses, slight efficiency improvement at intermediate and full loads, reduced cogging torque.	Limited studies on the application of magnetic wedges in PMSM with fractional-slot concentrated windings.

engineers and researchers in the process of developing more efficient solutions in machine design. For this purpose, this study investigates the effects of three different types of magnetic wedges on the efficiency and performance of small power induction motors. As a result of this investigation, the effects of magnetic wedges on motor efficiency, torque, and current values are obtained.

In the second part of the study, the theoretical background is presented. Information about the motor and the analysis method used for the analysis, as well as the properties of the magnetic wedges investigated, are presented. In the third section, the effects of different types of magnetic wedges on motor currents and torque are analyzed in transient and steady-state and are presented in comparison with the reference motor without magnetic wedges. In the fourth section, the thermal analysis results of the motor with the magnetic wedge, which shows the best performance in terms of efficiency, are shown in comparison with the reference machine. In the last section, section five, the results obtained are discussed.

TABLE II. DESIGN PARAMETERS OF THE INDUCTION MOTOR

Features	Values
Output power	7.5 kW
Rated voltage	380 V
Rated current	13.59 A
Output torque	48 Newton-meter
Rated speed	1471 rpm
Number of poles	4
Load type	Constant power, no load
Number of stator slot	48
Stator outer diameter	210 mm
Stator inner diameter	148 mm
Number of rotor slots	44
Rotor outer diameter	147.3 mm
Rotor inner diameter	48
Air range	0.7 mm
Stator and rotor core length	250 mm
Core steel type	Steel 1008

II. ELECTROMAGNETIC AND THERMAL RELATIONSHIP IN THE INDUCTION MOTOR

In order to accurately determine the temperature distributions, it is necessary to determine the loss values of the machine, especially the winding and core losses. In this study, a 7.5 kW three-phase induction motor is investigated. First, an analytical analysis of the motor is performed, and the design parameters based on this analysis are presented in Table II. After obtaining the results of the analytical analysis, a numerical analysis is carried out using the two-dimensional FEM for a more detailed investigation. This method allowed a more accurate prediction of the temperature distributions of the engine.

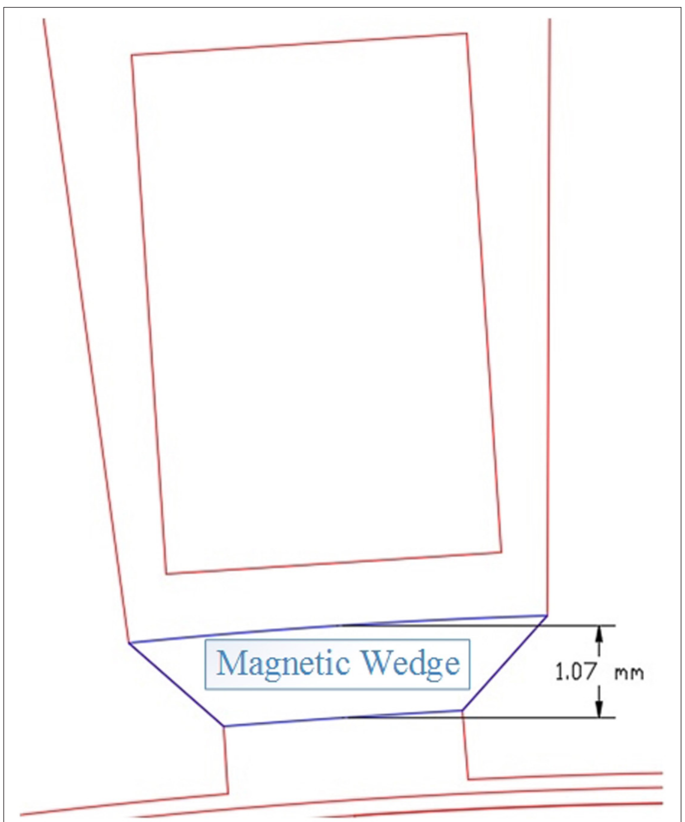

Fig. 1. Magnetic wedge inserted in the stator slot.

A. Magnetic Slot Wedge Design

In order to study the effect of the magnetic wedge on the temperature distribution, analytical analyses are carried out for both cases with and without the magnetic wedge. The magnetic wedge was modeled using a Computer Aided Design (CAD) program to be placed in the stator slots of the reference motor. Fig. 1 shows the positioning of the 1.07 mm high magnetic wedge. In order to fully evaluate the effect of the magnetic wedge, the stator slot needs to be completely closed. This approach allows for more regularization of the irregular magnetic flux density distributions.

The relative magnetic permeability value increased by the magnetic wedge achieves the same magnetic flux density with lower magnetic field strength. According to Ampere's Law,

$$\int_{l_\Gamma} H.dl = i_{enc,\Gamma} \quad (1)$$

Where H is the magnetic field strength, dl is an incremental segment in the path, l_Γ denotes a path, and $i_{enc,\Gamma}$ is the total current enclosed by that path. By using the magnetic wedge, the total relative magnetic permeability of the magnetic circuit is increased. This allows the material to reach the saturation limit later. The relationship between magnetic field strength (H) and magnetic flux density (B) in magnetic materials is expressed by the following [31, 32, 33]:

$$M = \chi H \quad (2)$$

$$B = \mu_0 (H + M) \quad (3)$$

$$B = \mu_0 (1 + \chi) H \quad (4)$$

$$B = \mu_0 \mu_r H \quad (5)$$

Where μ_0 is the magnetic permeability of free space, M is referred to as the magnetization. The magnetization refers to the flux density resulting from the material. Magnetic susceptibility (χ) shows how a material reacts to a magnetic field and is defined as in (2). χ is known as susceptibility and is dimensionless. μ_r is the relative magnetic permeability.

$$\mu_r = 1 + \chi \quad (6)$$

$$\mu = \mu_0 \mu_r \quad (7)$$

$$B = \mu H \quad (8)$$

As mentioned above, the magnetic flux density becomes more homogeneous by optimizing the relative magnetic permeability (μ_r) and magnetic susceptibility (χ magnetization). The magnetic wedge increases the magnetic permeability in the air gap of the magnetic circuit. This improves sensitivity by increasing the total relative magnetic permeability in the magnetic circuit. A higher μ_r and χ enable the magnetic circuit to operate more effectively. In (9), for constant magnetic flux density (B), when μ_r increases, H decreases and

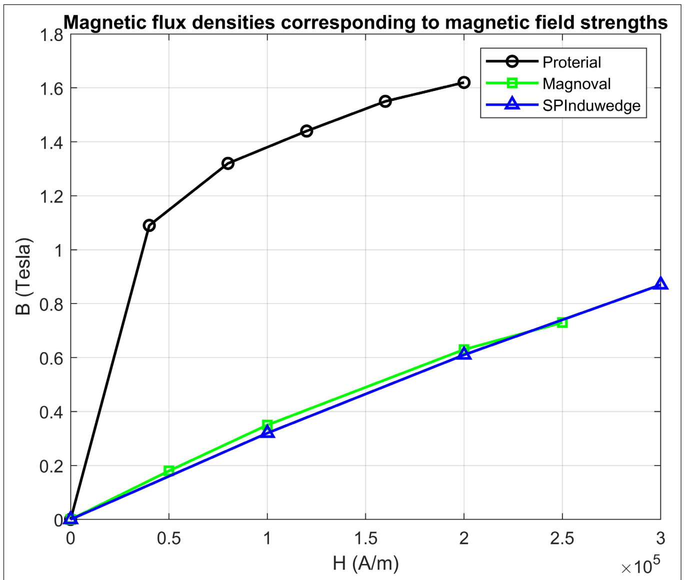

Fig. 2. Magnetic flux densities corresponding to magnetic field strengths of different magnetic wedges.

therefore the magnetization current will decrease in a proportional ratio.

$$H\downarrow = \frac{B}{\mu_0 \mu_r \uparrow} \quad (9)$$

$$H\downarrow \Rightarrow I_{enc,\Gamma}\downarrow \quad (10)$$

(9) and (10) are the equations obtained for only one conductor. Considering the total conductor value for a machine, the total current (I) is equal to the sum of the load current (I_{load}) and the magnetization current (I_m).

$$H\downarrow \Rightarrow I_m\downarrow \quad (11)$$

$$I\downarrow = \mathrm{I_m}\downarrow + I_{load} \quad (12)$$

$$P_{loss}\downarrow \propto I^2\downarrow \quad (13)$$

Reduction of I_m with the use of magnetic wedge, the total current (I) reduce. This directly affects the winding loss.

With developing technologies, manufacturers are working on magnetic wedge designs with higher permeability values. In this study, magnetic wedges with different relative permeability were investigated. For this purpose, numerical analyses of motors using SPInduwedge F High Performance, Magnoval 2067, and Proterial branded commercial magnetic wedges were performed. The information about the magnetic wedge materials used in the analysis was obtained from the manufacturers. SPInduwedge contains 10% glass cloth, 20% epoxy resin, and 70% iron powder, while Magnoval 2067 contains 7% glass cloth, 18% epoxy resin, and 75% iron powder. Proterial does not contain epoxy resin but is made of glass cloth and iron powder only.

Among the most important properties of a magnetic wedge are the relative permeability and conductivity values [20, 21].

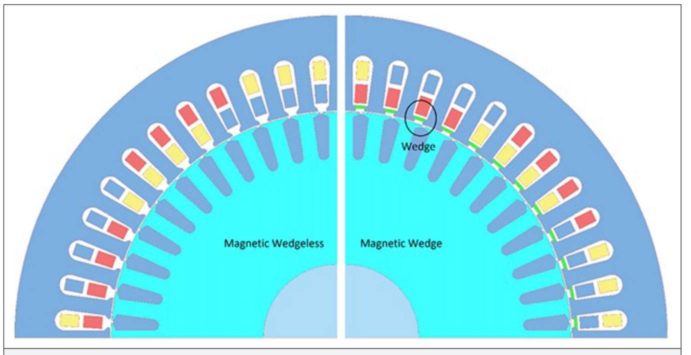

Fig. 3. Two-dimensional cross-sections of the induction motor with and without magnetic wedge.

Therefore, in order to obtain accurate analysis results, these values must be obtained completely from the manufacturers' data sheets. Relative magnetic permeability values are obtained using the magnetization curve *B(H)*, which gives the variation between magnetic field strength and magnetic flux density. Fig. 2 shows the magnetic flux densities corresponding to the magnetic field strength of three different magnetic wedges. The data used in this study are obtained from manufacturers' datasheets and reflect experimentally validated results. The magnetic wedges are exposed to a specified magnetic field strength, and the corresponding magnetic flux density values are recorded. These values are then utilized to determine the relative magnetic permeability of the materials. By integrating this data into the material library of ANSYS Maxwell, the magnetic properties of the materials are accurately represented for simulation purposes. In addition, in numerical analyses performed using FEM, accurate processing of the relative magnetic permeability values of the material properties is critical for obtaining reliable results.

When the relative permeability values presented by the manufacturers are analyzed, it is observed that the magnetic wedge of the Proterial brand has a higher relative permeability value compared to the others. Proterial has succeeded in increasing the magnetic particle density by not using epoxy resin in the content of its magnetic wedges with the new technologies it has developed. This innovation allowed for a higher relative permeability value compared to conventional magnetic wedges. According to the manufacturers' data sheets, the maximum relative magnetic permeability values of SPInduwedge, Magnoval 2067, and Proterial magnetic wedges with respect to magnetic field intensity [*μ(B)*] are 3.4, 2.9, and 7.6, respectively. These results show that the Proterial magnetic wedge has a larger relative magnetic permeability value than the others.

B. Two Dimensional Analysis of the Induction Motor

In order to comparatively evaluate the effect of the magnetic wedge, numerical analyses were performed for the unwedged and wedged cases using the same motor geometry. Fig. 3 shows the two-dimensional core, winding, and rod structures of the reference motor without and with a wedge. In these figures, the blue, red, and yellow coils represent phases A, B, and C, respectively. A two-layer winding type is used in the stator slots. In the image on the right, a 1.07 mm high green trapezoidal magnetic wedge is placed just below the stator slots. Appropriate material definitions were made in order to perform the analysis correctly. In the numerical analysis process, the magnetic effect of the motor shaft was ignored.

Steel 1008 material was preferred for the stator and rotor cores, copper for the stator windings, and aluminum for the rotor rods. For the magnetic wedge, the relative magnetic permeability values are defined according to the manufacturer's data sheets [34, 35, 36]. The magnetic wedge is not used in the initial analysis of the reference motor. In order to accurately determine the temperature distributions of the motor, the core and winding losses must be determined.

C. Impact of Losses on Heat Distribution

In section 2.1, the relationship between magnetic flux density and magnetic field strength depending on the magnetic wedge design is discussed. This is important for understanding the temperature effect on the induction motor. According to the basic principle of thermodynamics, the relationship between heat energy (*Q*, joule or watt-second) and power (*P*, in watts) is expressed as in (14) [37, 38, 39, 40]:

$$Q = P_{loss}.t \tag{14}$$

Where *t* represents time (seconds). This equation establishes that the heat energy produced in a system over time is directly proportional to the power dissipation. The total heat flux (*Q*) emitted from the motor is dependent on its total surface area (*A*) and is calculated as in (15):

$$Q = \int_A q dA \tag{15}$$

According to Fourier's law of heat conduction, the heat flux passing through a unit surface (q, W/m^2) is calculated as in (16) [39, 40]:

$$q = -k\nabla T \tag{16}$$

Where *k* is the thermal conductivity of the material, ∇T is the temperature gradient (*K/m*). This equation highlights that the rate of heat transfer through a material is proportional to the thermal conductivity of the material and the temperature gradient across it. The analysis of magnetic wedge design and its influence on thermal and electromagnetic behavior underscores its importance in induction motor optimization. By reducing magnetic field non-uniformity, magnetic wedges not only improve motor efficiency but also mitigate thermal stresses by ensuring consistent heat distribution.

III. TRANSIENT AND STEADY STATE ANALYSIS OF THE INDUCTION MOTOR

In order to obtain the effect of different types of magnetic wedges on motor efficiency and performance, analyses have been performed for the induction motor considered with FEM. For this purpose, firstly, the analysis is performed for the motor without a magnetic wedge. The results obtained will be taken as a reference. For this reason, reference machine results are defined for the results obtained without a magnetic wedge. Then the analysis is repeated for different types of magnetic wedges.

In order to accurately assess the effect of the magnetic wedge, the transient dynamics of the reference motor before reaching steady-state operating conditions must be analyzed in detail. This analysis provides a more accurate understanding of the changes in the motor's performance and the effects of the magnetic wedge. During the transient state, the motor exhibits an operating characteristic above the rated values, and this characteristic is critical for detecting events that adversely affect the motor performance. Therefore, performance parameters such as transient current, torque, and losses must be carefully analyzed.

When the transient analysis of the reference motor is analyzed, undesirable results are observed, especially in the first 50 ms. Fig. 4 shows the torque-time graph of the reference motor. The maximum torque value calculated at start-up is 347.27 N.m. At steady state, the average torque value was calculated as 50.57 N.m. In the first 50 ms time period, the reference motor operates above the nominal values, indicating an undesirable situation.

The performance results obtained by using different types of magnetic wedges are shown in Fig. 5. These comparisons are important to understand how the magnetic wedge affects the transient performance of the motor. It is observed that torque fluctuations are reduced in the transient state. In the steady state, the motor exhibits less torque ripple compared to the reference motor.

It is observed that the magnetic wedge significantly reduces the maximum torque value at the start of the motor. There is also a small reduction in the average torque over the rated operating range. This may need to be re-evaluated according to the characteristics of the driven load. However, one of the most important advantages of using a magnetic wedge is the reduction of torque fluctuations.

As shown in Fig. 6, the steady-state torque fluctuations can be minimized by increasing the relative permeability values of the magnetic wedges. In the motor using the Proterial magnetic wedge, it is observed that the transient torque ripple peak values are lower compared to other magnetic wedges. However, there is a slight increase in the reverse peak values compared to the others. In addition, the steady-state torque ripple values are quite close to each other. This result shows that the magnetic wedges reduce the transient torque oscillations of the motor and hence the starting current.

Another important parameter is the current drawn by the motor from the grid. Fig. 7 shows the current draw of each phase of the reference motor. In the transient case, the maximum instantaneous current value is recorded as 162.84 A in phase B. In the steady state, the effective currents of phases A, B, and C are 14.77 A, 13.74 A, and 14.54 A, respectively. These current values indicate that the losses

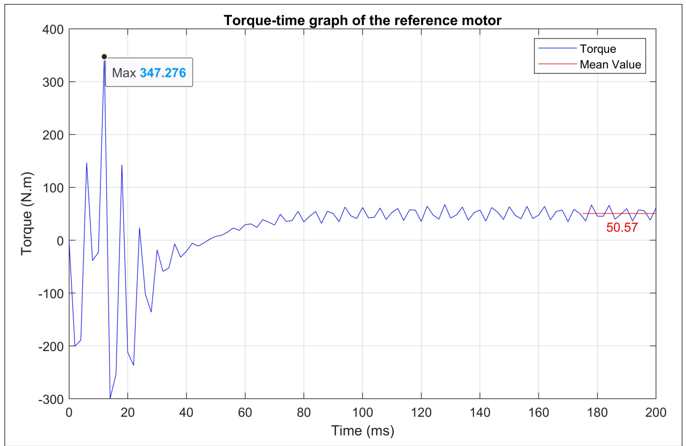

Fig. 4. Torque-time graph of the reference motor during transient and steady state.

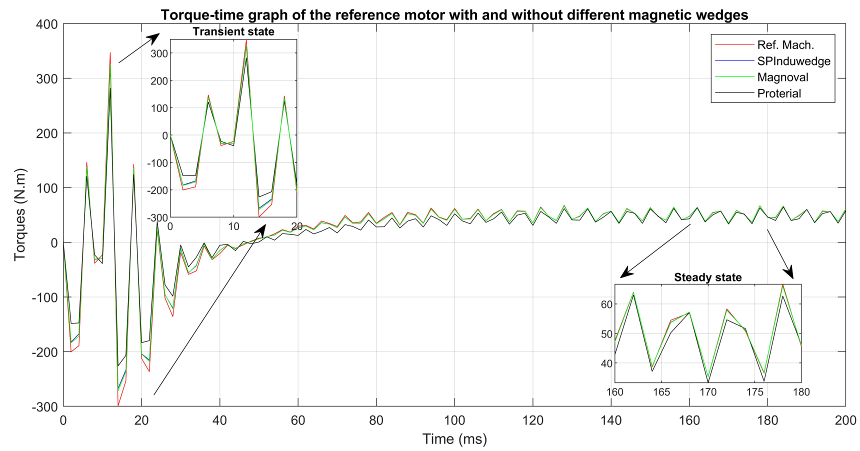

Fig. 5. Torque-time graph of the reference motor with and without different magnetic wedges.

are at a maximum level during the transient, and accordingly, the temperature values will be high.

The highest current value among the three phases is observed in phase B during the transient. Therefore, phase B is taken into consideration when comparing the magnetic wedges. When Fig. 8 is examined, it is seen that the lowest instantaneous current value drawn in phase B is obtained with the use of the Proterial brand magnetic wedge. This finding provides an important indication to better understand the effects of the magnetic wedge on motor performance.

The variation of the core losses of the investigated machines with respect to time is shown in Fig. 9. As a result of the comparisons with the reference motor, it is found that the core loss values are quite close to each other. However, it may not always be possible to achieve the desired levels in terms of core losses in small power motors with the use of magnetic wedges. This is an important factor to consider when evaluating the effects of magnetic wedges on performance.

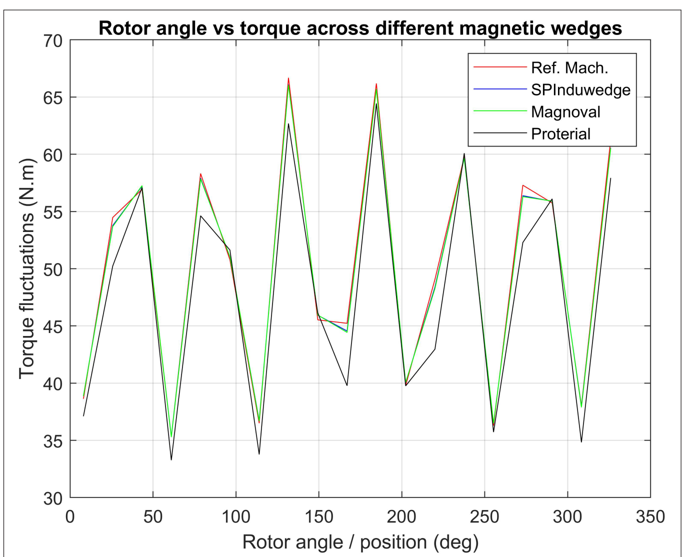

Fig. 6. Steady-state torque fluctuations of reference motor with and without different magnetic wedges.

Fig. 10 shows the losses depending on the current flowing through the windings. When analyzed, it is clearly seen that the winding losses are much larger than the core losses. This raises the possibility that the temperature distributions are higher in the windings. In particular, the Proterial branded magnetic wedge was observed to effectively reduce the losses during the transient. This finding highlights the positive effect of the magnetic wedge on winding losses and offers a potential solution to improve the overall performance of the machine.

Table III compares the performance of the reference motor with motors using different magnetic wedges, highlighting the superiority of the Proterial brand magnetic wedge, particularly in terms of transient and steady-state torque performance. In transient torque changes, Proterial provides the best improvement with a 21.38% reduction compared to the reference motor, while in steady-state torque, it enhances motor stability with a 4.17% decrease. Furthermore, the winding losses decreased by 9.7%, reducing total losses from 613.30 W in the reference motor to 555.26 W. This reduction in losses enhances motor efficiency by minimizing energy losses. However, the power factor of the motor with the Proterial

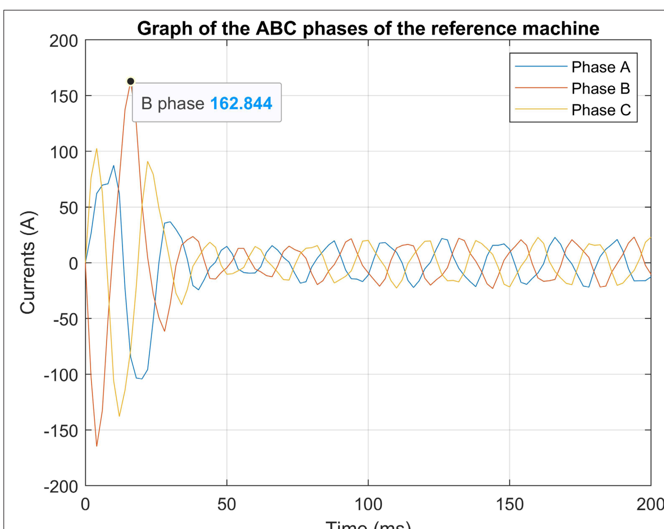

Fig. 7. Current-time graph of A, B, and C phases of the motor.

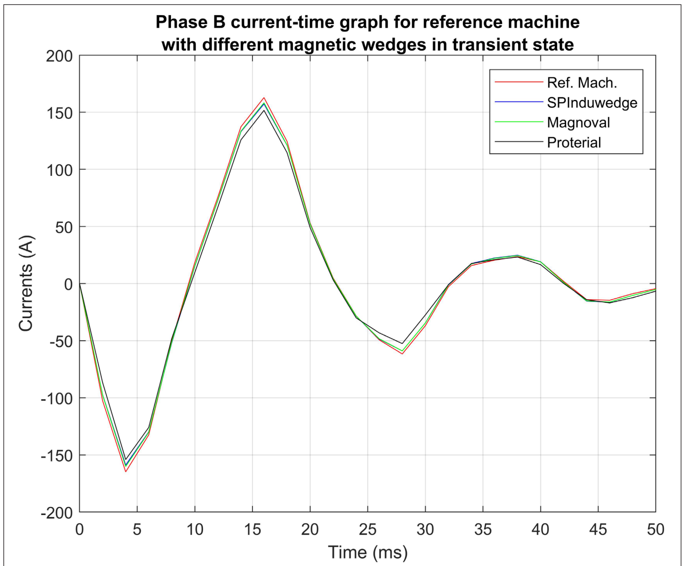

Fig. 8. Phase B current-time graph for reference motor with different magnetic wedges.

wedge is recorded as 0.88, slightly lower than others. This condition aligns with the findings of a study [6] in the literature that the power factor can be improved when the relative magnetic permeability is increased, but the power factor can be negatively affected if the magnetic wedge height is increased. This difference can be easily compensated for with compensation systems. Moreover, the geometrical dimensions (height and volume) of the magnetic wedges used in this study are kept constant. This approach is favored to enable an objective comparison of the effects of different types of magnetic wedges. Therefore, the reduction in the power factor is related to the height value of the material rather than the properties of the magnetic material.

The Proterial brand magnetic wedge increases efficiency to 92.86%, providing a significant advantage in reducing energy consumption and costs, especially for low-power motors. In addition, another study in the literature reported that the use of magnetic wedges initially reduces core losses up to a certain percentage, but when this percentage is exceeded, losses increase again [41]. Therefore, the selection of a magnetic wedge with appropriate relative magnetic permeability is critical for optimizing motor performance.

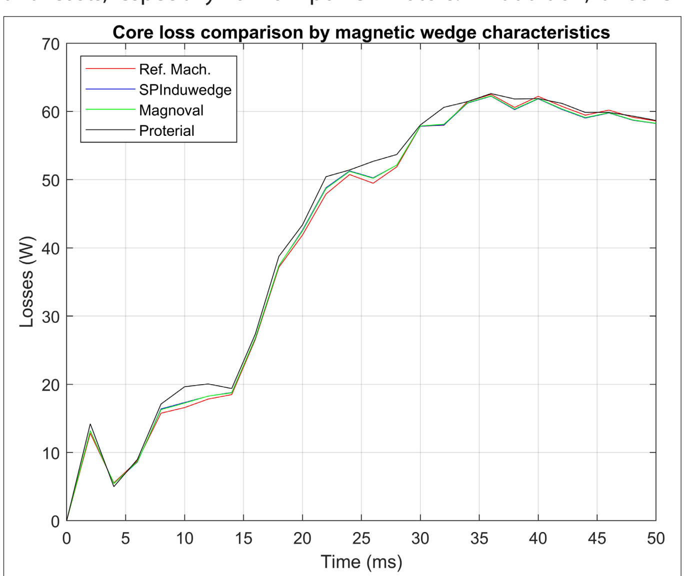

Fig. 9. Comparison of core losses based on different magnetic wedges.

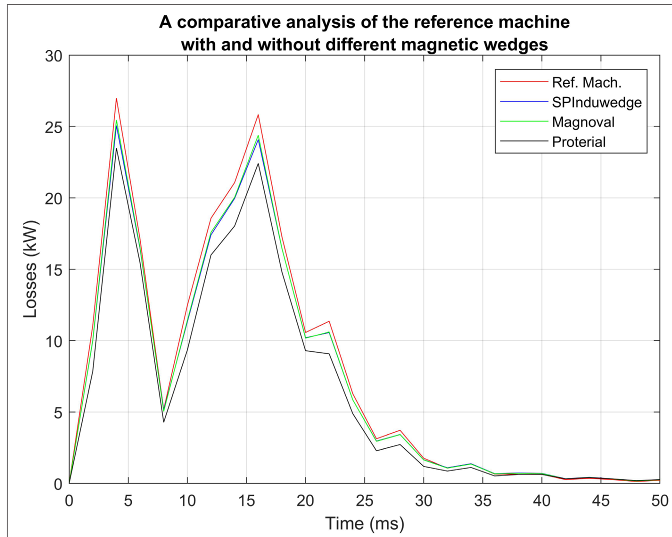

Fig. 10. Winding losses-time graph of the reference motor with and without different magnetic wedges.

When the general evaluation is made for this section, the reduction in transient torque fluctuations and current peaks achieved by magnetic wedges directly translates into reduced mechanical wear on motor components such as bearings, shafts, and rotor systems. Additionally, the decrease in current peaks minimizes the associated thermal stresses on the windings, which can prevent insulation degradation and overheating. As a result, these improvements are crucial for motor performance and reliability, as they can mitigate mechanical and thermal stresses on motor components, potentially extending the motor's operational lifetime and enhancing its reliability.

IV. THERMAL ANALYSIS OF THE INDUCTION MOTOR

In this section, the thermal analysis results of the induction motor are presented. The results of the analysis of the reference motor and the motor using Proterial magnetic wedge, which improves the efficiency the most, are compared. For the thermal analysis of the motor, the losses obtained by two-dimensional numerical analysis are used. In this analysis, the properties of the materials that make up the motor are defined in order to accurately predict the temperature distributions of the motor. Table IV shows the properties of the materials used in the structure of the motor. These material descriptions have been carefully chosen to improve the accuracy and reliability of the thermal analysis results.

Thermal analysis is performed by examining the temperature distribution under certain boundary conditions. These boundary conditions were established by determining the temperature source and heat dissipation. In Table V, the temperature source is defined as electrical losses. The ambient temperature is assumed to be 40°C, which aligns with the standards set by the National Electrical Manufacturers Association, specifying this value as the reference for motor design [42, 43, 44, 45]. This assumption reflects the typical

TABLE III. PERFORMANCE COMPARISON OF THE REFERENCE MOTOR WITH AND WITHOUT DIFFERENT MAGNETIC WEDGES

Machine Type/Features	Ref. Mac. (Wedgeless)	SPInduwedge	Magnoval	Proterial
Relative magnetic permeability (μ_r)	–	3.4	2.9	7.6
Efficiency (%)	92.66	92.72	92.72	92.86
Change of efficiency (%)	–	+0.06	+0.06	+0.22
Steady state torque average (N.m)	50.28	50.02	49.98	46.88
Transient max. peak to peak torque (N.m)	646.61	589.51	598.04	508.36
Change of transient max. peak to peak torque values (%)	–	−8.83	−7.51	−21.38
Steady state peak to peak torque (N.m)	30.18	29.35	29.37	28.92
Change of steady state peak to peak torque values (%)	–	−2.72	−2.68	−4.17
Core loss (W)	56.86	56.85	56.86	57.55
Change of core loss (%)	–	−0.01	0.0	+1.21
Winding loss (W)	389.71	384.46	383.69	352.08
Change of winding loss (%)	–	−1.35	−1.55	−9.67
Total loss (W)	613.30	605.18	604.04	555.26
Change of total loss (%)	–	−1.32	−1.51	−9.46
Power factor	0.90	0.90	0.90	0.88

TABLE V. BOUNDARY CONDITIONS AND RELATED PARAMETERS USED IN THERMAL ANALYSIS

Temperature Source	Heat Dissipation (Convection)	Coefficient of Thermal Conductivity	Ambient Temperature
Electrical losses (winding and core)	Stator surface	45.0 (W/m^2.°C)	40°C

operating conditions of motors and facilitates the accurate evaluation of critical design parameters such as reliability, performance, and insulation class. Moreover, it represents the common environmental conditions encountered in industrial and commercial applications, ensuring the relevance and applicability of the analysis.

The coefficient of thermal conductivity describes the ability of a material to conduct heat. The coefficient of thermal conductivity of the Steel 1008 material used in the stator core is 45.0 W/m^2 °C [45]. Since the stator core is in contact with the external environment, heat dissipation occurs mainly through the stator surface. This is an important factor affecting the overall thermal performance and temperature distribution of the motor.

TABLE IV. THERMAL CONDUCTIVITY PROPERTIES OF MATERIALS USED IN THE MOTOR

Materials	Location	Thermal Conductivity (W/m^2.°C)
Steel 1008	Stator and rotor core	45.0
Copper	Stator winding	400.0
Aluminum	Rotor bars	237.50
Stainless Steel	Shaft	13.8

Once the boundary conditions are determined, thermal analyses are carried out on both the reference motor (without the wedge) and the motor with the Proterial magnetic wedge integrated. Since the windings play an important role in the temperature distribution of a motor, special attention is paid to the time frames of the transient and steady states of the windings. In this context, the temperature distributions of the reference motor and the reference motor with the magnetic wedge are analyzed and obtained for the time intervals 0–50 ms (transient state) and 170–200 ms (steady state). These analyses provide critical data to evaluate the effects of the magnetic wedge on the thermal performance of the motor.

When the transient analysis Fig. 11 is evaluated, a significant decrease in the temperature distribution is observed with the use of a magnetic wedge. While the maximum temperature value in the stator windings decreased by 47°C, a decrease of approximately 10°C was recorded in the rotor bars. When the steady-state analysis Fig. 12 is evaluated, a slight temperature decrease is observed in both the stator windings and rotor bars.

In Table VI, the maximum temperature values clearly show the effect of the use of magnetic wedges on the temperature distribution. These findings reveal that magnetic wedges are an important tool for optimizing engine performance.

V. CONCLUSION

This study comprehensively investigates the effects of different types of magnetic wedges on the performance of small-power induction motors. One of the key contributions of this research is its

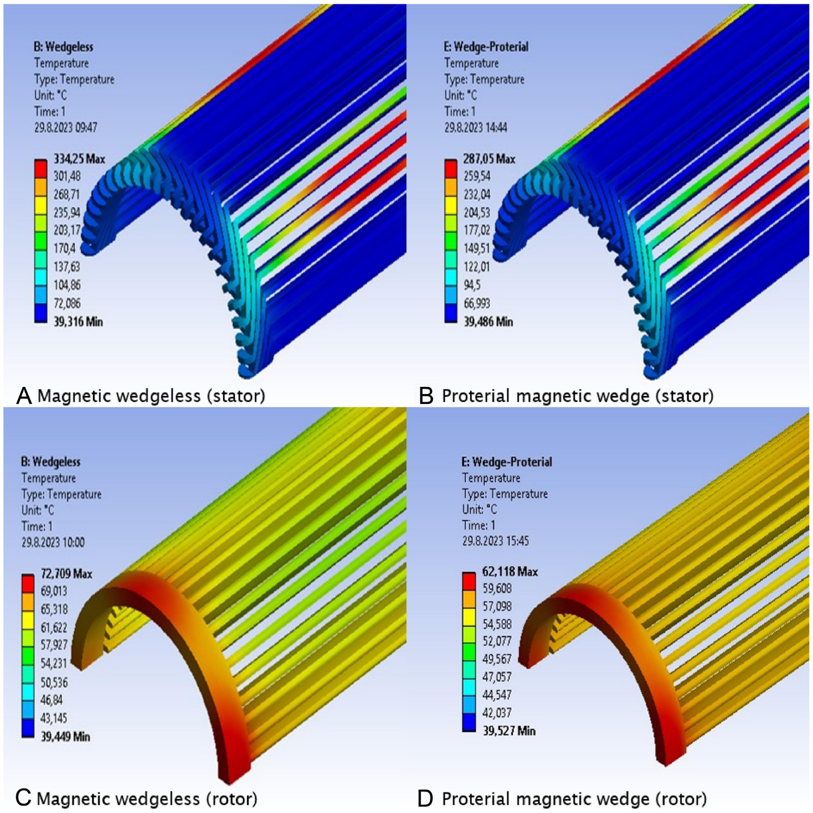

Fig. 11. Temperature distribution of the stator and rotor in transient state with and without magnetic wedges.

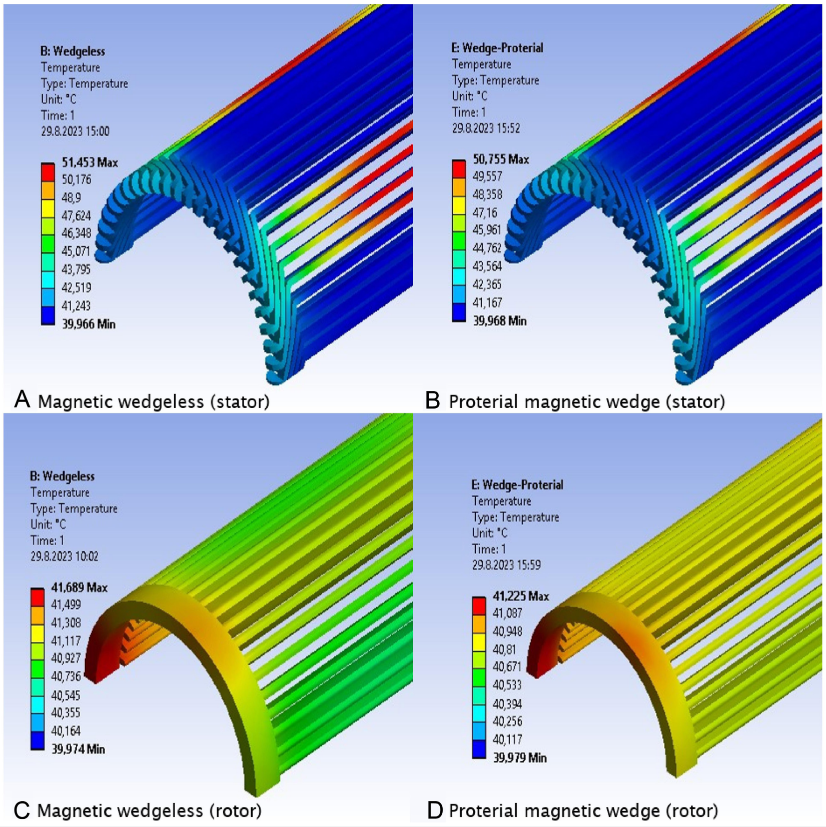

Fig. 12. Temperature distribution of the stator and rotor in steady state with and without magnetic wedges.

TABLE VI. IMPACT OF THE MAGNETIC WEDGE ON TEMPERATURE DISTRIBUTION IN TRANSIENT AND STEADY STATES

	Transient State		Steady State	
Machine Type	**Max. Stator Winding Temperature (°C)**	**Max. Rotor Bar Temperature (°C)**	**Max. Stator Winding Temperature (°C)**	**Max. Rotor Bar Temperature (°C)**
Ref. Machine (Wedgeless)	334.25	72.70	51.45	41.68
Proterial	287.05	62.11	50.75	41.25

emphasis on thermal analysis, which sets it apart from other studies in the literature. Unlike prior works, this study clearly demonstrates the potential of magnetic wedges to reduce motor temperatures, offering valuable insights into their thermal performance benefits.

The Proterial magnetic wedge, while exhibiting high relative magnetic permeability, shows a slight decrease in the power factor. This aligns with findings in the literature suggesting that an increase in wedge height can negatively affect the power factor. In this study, the geometric dimensions (height and volume) of all magnetic wedges were kept constant to ensure an objective comparison. Consequently, the reduction in the power factor is attributed to the height of the wedge rather than the material properties.

The thermal analysis in this study highlights the temperature-reducing effects of magnetic wedges. This finding underscores the ability of magnetic wedges to mitigate temperature rise within the motor, preventing insulation degradation and enhancing the motor's operational lifespan.

FUTURE RESEARCH DIRECTIONS INCLUDE:

- Applicability to different motor types: Investigating the thermal effects of magnetic wedges on high-power motors or specialized applications.
- Geometric optimization: Examining how variations in wedge height and volume influence both temperature distribution and power factor.
- Industrial applications: Exploring the integration of thermal analysis findings into commercial motor designs and their potential to reduce energy costs.
- This study not only highlights the benefits of magnetic wedges in improving efficiency and torque stability but also demonstrates their critical role in motor temperature management. These findings offer a comprehensive perspective on the long-term performance and reliability advantages of magnetic wedges in small-power induction motors.

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Serhat Doğan received his B.Sc. degree in Electrical and Electronics Engineering from Fırat University, Elazığ, Turkey, in 2017. He worked as a Wireline Logging Engineer at TPIC until 2020. In 2021, he began his M.Sc. studies in Electrical Engineering at Yıldız Technical University, Istanbul, Turkey. He is currently pursuing a Ph.D. degree and working as a Research Assistant at Dicle University. His research interests include electrical machines and power electronics.

Sibel Zorlu Partal received her B.Sc., M.Sc., and Ph.D. degrees from Yıldız Technical University in the field of Electrical Engineering. She is currently an Associate Professor with the Faculty of Electrical and Electronics at Yıldız Technical University. Her general research areas include Power Electronics, Theory and Design of Electrical Machines, and Electric Motor Drives.

Bilal Gümüş received his Bachelor's degree in 1992 from Istanbul Technical University, his Master's degree in 1997 from Fırat University, and his PhD degree in 2004 from Fırat University. He is the Head of the Electrical Machinery Division of the Electrical and Electronics Engineering Department at Dicle University. He currently works as a Full Professor in the same department. His general areas of research include Electrical Machines, Power Electronics, and Renewable Energy Sources.