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Development of Synchronous Reluctance Motor for Industrial Application

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Abstract

Synchronous reluctance motors offer promising advantages for industrial applications, including improved efficiency and reduced maintenance requirements. However, their widespread adoption is hindered by design complexities and performance limitations. This study focuses on addressing these challenges by developing a customized 24kW synchronous reluctance motor for industrial use, with a specific emphasis on centrifugal pumps. The research introduces a novel rotor design incorporating carefully designed flux barriers and flux carriers. Comprehensive machine analysis is conducted using the finite element method and Motor Solve software, while particle swarm optimization techniques are employed to enhance performance. Extensive simulations explore various machine parameters, and practical testing is conducted to validate the results and determine the optimized torque achievement. The results demonstrate significant improvements in the motor's performance. Compared to conventional induction motors used in similar applications, the optimized synchronous reluctance motor exhibits enhanced efficiency and smoother operation. The motor achieves notable advancements in terms of speed, efficiency, and torque characteristics, making it a valuable solution for industrial applications. The findings highlight the potential of the developed synchronous reluctance motor for industrial use. The motor design showcases excellent thermal performance, consistent steady-speed operation, and improved efficiency. This study contributes to the advancement of synchronous reluctance motor technology, showcasing its effectiveness and viability in diverse industrial settings. By addressing design complexities and optimizing performance, this research bridges the gap between the potential of synchronous reluctance motors and their practical implementation in industrial applications. Valuable insights are provided for the development of efficient and reliable synchronous reluctance motors in industrial systems.

Keywords: *Synchromous reluctance motort;Flux barrier;Stator winding;Rotor design;Motor solversoftware*

1. Introduction

This Synchronous reluctance motors (SynRM) have emerged as promising electromechanical energy converters for modern mechatronic systems [1-4]. With their simple rotor design, absence of windings and permanent magnets, and low moment of inertia, SynRM offers attractive features.

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These motors meet stringent energy efficiency requirements by minimizing bearing assembly temperatures, reducing stator winding overheating, and achieving excellent overall efficiency without rotor windings [5]. Furthermore, SynRM designs emphasize optimal compatibility with existing induction motor manufacturing processes. While the concept and principles of synchronous reluctance motors have been known since the early 20th century [6, 7], their widespread adoption was hindered until the advent of power electronics in the late 20th century.

In 2012, ABB, a leading player in the SynRM industry, introduced a product range with capacities ranging from 17kW to 350kW [8–10]. According to ABB, drive systems employing SynRM can achieve losses reduction of 10 to 20% compared to induction motors of the same size, while also meeting stringent energy efficiency regulations. Maintaining the same energy efficiency class allows for a reduction in the motor's overall size by one axis height step. However, the lack of mass manufacturing has limited the widespread use of SynRM in Russian developments. To successfully integrate this innovative motor type into various systems, comprehensive theoretical studies and experimental data comparing SynRM with other motor types, such as induction motors, synchronous motors with permanent magnets, and switched reluctance motors, are crucial. This work presents the development and experimental study findings of a 24kW rated power synchronous reluctance motor. Through theoretical analysis and experimental validation, this study aims to elucidate the properties and functionality of SynRM, providing valuable insights for its potential applications in diverse systems.

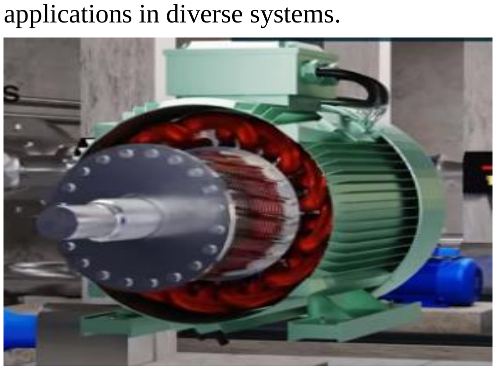


Fig. 1. Synchronous reluctance motor general view of the constructions

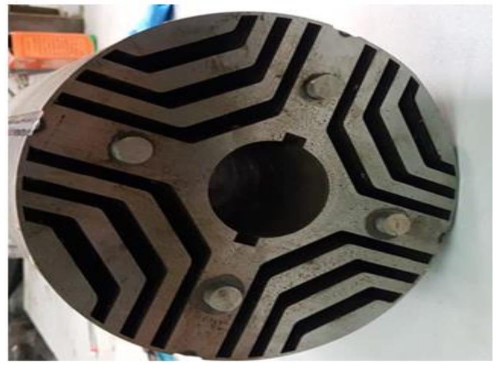


Fig. 2. Synchronous reluctance motor rotor

2. Methdology

The methodology employed in this study combines theoretical analysis, computational modeling, and experimental validation to design and develop an optimized synchronous reluctance motor (SynRM) for industrial applications. The design process begins by thoroughly analyzing the motor's specifications, including the stator geometry and rotor configuration. Insights from the finite element method (FEM) and Motor Solve software are utilized to investigate the motor's electromagnetic behavior in detail [11-12]. This analysis aids in making informed design decisions to enhance motor efficiency. A key focus of the methodology lies in the development of innovative winding configurations and the meticulous design of rotor flux barriers and flux carriers. Through iterative simulations, advanced optimization techniques like particle swarm optimization (PSO) are employed to refine these design elements, aiming for robust performance across varying operating conditions. Practical testing plays a vital role in validating the effectiveness of the proposed design. Experimental setups are utilized to compare different winding gauge sizes, enabling the identification of the optimal wire size for improved speed performance. These practical tests provide valuable data to verify the simulation results and further refine the motor design. To ensure the motor's suitability for industrial applications, various machine parameters are evaluated through extensive simulations and practical experimentation. This evaluation process considers factors such as torque characteristics, efficiency, thermal performance, and reliability [13-14]. The methodology aims to align the motor design with the specific requirements and challenges posed by industrial systems. By integrating theoretical analysis, computational modeling, and experimental validation, this methodology offers a comprehensive approach to designing and developing a high-performance SynRM optimized for industrial use. It leverages advanced simulation tools and practical testing to provide valuable insights into the motor's behavior and performance, enabling its successful integration into diverse industrial systems.

2.1 Design Considerations of Synchronous Reluctance Motor

When it comes to the design of synchronous reluctance motors (SynRM), careful consideration of three primary categories of parameters is essential, as they have a profound impact on the motor's efficiency and performance. These design considerations are crucial for optimizing the motor's operation and ensuring its suitability for various industrial applications. By carefully analyzing and fine-tuning these parameters, designers can achieve remarkable improvements in motor performance, efficiency, and reliability

2.1.1. Design Parameters of Stator Geometry

The stator geometry parameters, including the number of slots, poles, outer and inner diameters, and other geometric features, directly influence torque generation, magnetic flux distribution, and overall motor size. Optimizing these parameters is crucial for achieving desired performance characteristics, such as improved torque production and efficient power conversion. Careful selection and configuration of stator geometry are essential for designing high-performance synchronous reluctance motors.

2.1.2. Design Variables or Microscopic Parameters

The design variables, often referred to as microscopic parameters, are intricately linked to the shape and construction of the rotor in synchronous reluctance motors (SynRM). Precise adjustment of these minute characteristics is vital for optimizing motor performance. Advanced computer techniques, such as the finite element method (FEM), are employed to analyze and optimize the rotor's shape, considering factors like flux barriers, flux carriers, and the selection of materials. Optimizing these design variables plays a crucial role in minimizing losses, enhancing torque production, and improving the overall efficiency of the motor. By carefully fine-tuning the rotor's shape and optimizing the placement of flux barriers and carriers, designers can improve the motor's magnetic flux distribution, reduce losses associated with eddy currents or hysteresis, and enhance the motor's overall efficiency. This optimization process often involves iterative simulations and computational modeling to find the optimal combination of variables that result in superior motor performance. The meticulous consideration and optimization of these microscopic parameters significantly contribute to achieving high-performance synchronous reluctance motors, enabling them to meet the specific requirements of diverse industrial applications while maximizing energy efficiency and reliability.

2.1.3. Target Variables

The target variables encompass the desired performance measurements of synchronous reluctance motors (SynRM). These variables include speed characteristics, torque production, and efficiency, which are critical for evaluating motor performance. The design optimization process aims to achieve the highest possible motor performance based on these target characteristics. By carefully selecting and optimizing the stator and rotor design parameters, designers can tailor the motor's performance to meet specific industrial application requirements. The desired performance goals, such as high-speed operation, optimal torque production, and energy efficiency, guide the selection and configuration of these design parameters. Designers utilize a combination of analytical calculations, simulations, and experimental testing to optimize the motor's performance with respect to the target variables. Through iterative design iterations and evaluations, the motor's characteristics are fine-tuned to achieve the desired speed, torque, and efficiency levels. By focusing on the target variables and optimizing the motor's design accordingly, synchronous reluctance motors can be tailored to deliver superior performance and efficiency, ensuring they meet the specific performance goals of diverse industrial applications. In SynRM design, while the stator geometry parameters play a significant role in determining the overall motor characteristics, the rotor structure has a major influence on performance variations compared to other motor types. The use of transversally laminated stator structures, similar to induction machines, highlights the critical role of rotor design in enhancing

SynRM performance. Leveraging existing induction manufacturing lines and utilizing reluctance rotors offer a practical and effective construction method for SynRM, leveraging the unique features of synchronous reluctance technology while utilizing readily available components. By carefully considering and optimizing these design parameters within the three categories mentioned above, synchronous reluctance motors can be designed to achieve superior performance, improved efficiency, and meet the specific requirements of various industrial applications.

2.2 Rotor Design Specifications of SynRM Rating

In the design of a synchronous reluctance motor (SynRM), the rotor plays a crucial role in determining the motor's performance and efficiency. Various specifications and parameters need to be considered to ensure optimal rotor design for a given SynRM rating. These specifications include factors such as rotor construction type, number of poles, and power rating. By carefully designing the rotor, engineers can enhance the motor's operation and achieve the desired performance characteristics. Let's explore the important rotor design specifications in detail Here are the below figures and tables shows the characteristics of the suggested synchronous reluctance motor.

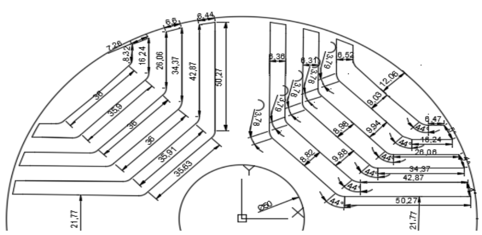


Fig. 3. The rotor design parameters [9]

The figure shows a detailed technical drawing of a rotor of an electric motor. It includes key features such as radial and angular slots, dimensional annotations, curved sections, and complex slot shapes. These specifications are essential for optimizing the rotor's performance, ensuring mechanical stability, and maximizing electromagnetic efficiency. The precise measurements and material specifications depicted in the drawing are critical for accurate manufacturing and proper functioning of the rotor.

3. Simulation and Experimental Results

Approach involving simulation and experimental results is employed. Through simulations, we can model and analyze the motor's behavior under various operating conditions, allowing for the evaluation of different design configurations and parameters. This enables the identification of optimal settings that maximize performance and efficiency while meeting specific application requirements. Additionally, experimental testing provides real-world validation of the simulation results and further insights into the motor's performance characteristics. By combining simulation and experimental results, engineers can iteratively refine the motor's design, leading to continuous improvements and enhanced performance of synchronous reluctance motors. To optimize the performance of the synchronous reluctance motor (SynRM), a systematic approach was adopted by inputting specific design variables into Simcenter Motor Solve software. This sophisticated tool facilitated comprehensive analysis and simulation of the motor's behavior under various operating conditions. Meticulously selected design variables were inputted into the software to facilitate the design and optimization process. The resulting simulation and experimental results provide valuable insights into the motor's performance characteristics. Please refer to Table 1 and Table 2 for the design specifications and corresponding results obtained using Simcenter Motor Solve software.

Table 1 shows the design parameters of 24kW motor

Parameters	Symbols	Values	Units
Rated Power	P	24	KW
Rated Current	I	26	Aump
Stator Diameter	Ds	200	Mm
Rotor Diameter	Dr	188	Mm
Air gap	G	1	Mm
Machine Length	L	200	Mm
Number of stator poles	Ns	3	-
No: of rotor flux barrier		3	

Rotor flux barrier edge angle	deg	4	0
Number of Phases	M	3	-
Synchronous Speed	nN	1500	Rpm
Phase Voltage	Vdc	380	V
Number of turns	Np	12	Trun
Shaft diameter	dsh	50	Mm
Average torque	Tav	154	Nm
Saliency ratio		0.7	
Frequency	f	50	Hz

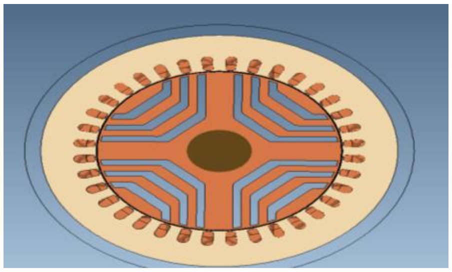


Fig. 4. Simulation of Motor

TABLE II. Prototype Design

Parameter	Units	Value	Symbol
Number of phases	-	3	*m*
total flux barriers	-	3	-
speed	rpm	1500	*nN*
Number of turns	turns	12	*Np*
Number of stator poles	-	4	*Ns*
frequency	Hz	50	*f*
Rated current	Amps	26	*I*
angle of edges	o	4	*deg*
Rated power	kW	24	*P*
Saliency ratio		0.7	
Phase Voltage	V	380	*Vdc*
Stator diameter	mm	310	*ds*
Air-gap	mm	1	*g*
Machine length	mm	200	*l*
Average torque	Nm	154	*Tav*
diameter	mm	188	*dr*
Shaft diameter	mm	50	*dsh*

3.1. Graphical Analysis of Results Obtained by Motor Solver Software

In the pursuit of designing an optimized synchronous reluctance motor for a centrifugal pump, the Motor Solve software played a pivotal role in simulating and analyzing the motor's performance. Figure 4 presents a visual representation that showcases the complete structure and arrangement of the motor, offering an insightful graphical depiction of its design principles and the relative positioning of its essential components. This comprehensive graphical analysis serves as a powerful tool, providing a clear understanding of the motor's overall appearance and layout. It enables to visually evaluate the effectiveness of the design features and make informed decisions regarding further optimization and performance enhancement.

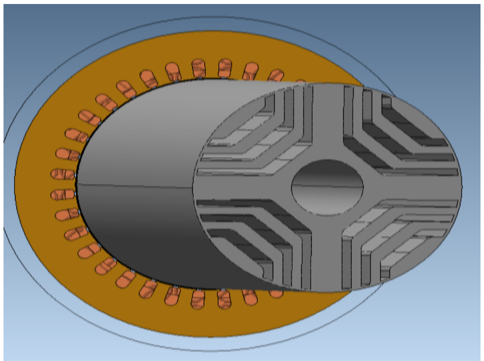


Fig. 5. The stator and rotor of synchronous reluctance motor

The figure 5 offers an illustration of a synchronous reluctance motor, focusing on its rotor and stator components. The rotor, depicted in gray, features slots and flux barriers designed to guide magnetic flux and enhance torque production. The central hole in the rotor allows for mounting onto the motor shaft. The stator, shown in orange, encompasses windings that generate a rotating magnetic field to interact with the rotor. This magnetic interaction facilitates the conversion of electrical energy into mechanical energy, resulting in motor rotation. The rotor's anisotropic magnetic properties, achieved through its flux barriers, optimize the motor's efficiency and performance. The synchronous reluctance motor design aims to minimize energy losses associated with hysteresis and eddy currents, ensuring high efficiency. Additionally, the precise control of the rotor's position relative to the rotating magnetic field enables applications requiring accurate speed and position control.

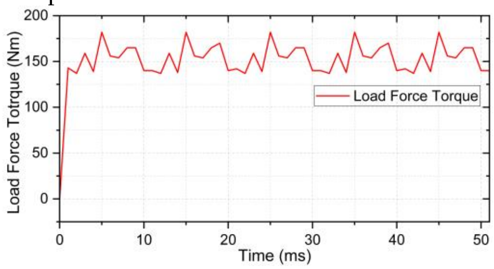


Fig. 6. Torque Characteristics of Motor

Figure 6 is a graph representing the torque characteristics of a motor over time. The graph shows the load force or torque on the y-axis (measured in units such as Newton-meters) and time on the x-axis (in milliseconds). Key observations include an initial torque spike at the motor's start, followed by stabilization and periodic fluctuations in torque. After an initial transient period, the motor enters a steady-state operation with minor torque variations. The graph's analysis highlights the motor's start-up behavior, variability in load, and the motor's ability to maintain consistent torque despite load fluctuations, indicating good performance and adaptability.

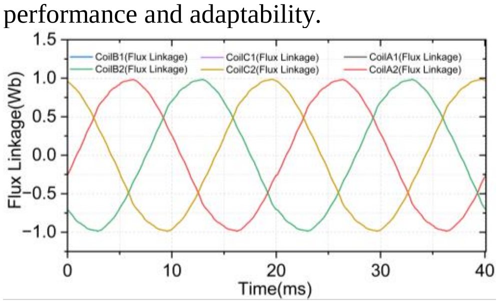


Fig. 7. Flux linkage Characteristics of motor

Figure 7 is a graph depicting the flux linkage characteristics of a motor over time. Flux linkage refers to the measure of magnetic flux interacting with the coils of the motor. The graph displays flux linkage curves for six different coils identified as CoilA1, CoilA2, CoilB1, CoilB2, CoilC1, and CoilC2. Each coil exhibits a sinusoidal waveform, representing the alternating nature of the magnetic field generated by the motor. The waveforms show a phase shift between the coil pairs, indicating a polyphase system, likely a three-phase motor. This phase shift ensures proper synchronization of the magnetic fields and efficient torque generation. The graph's analysis highlights the sinusoidal variation of flux linkage, initial transients during motor start-up, steady-state operation, and the significance of phase relationships for synchronized magnetic fields.

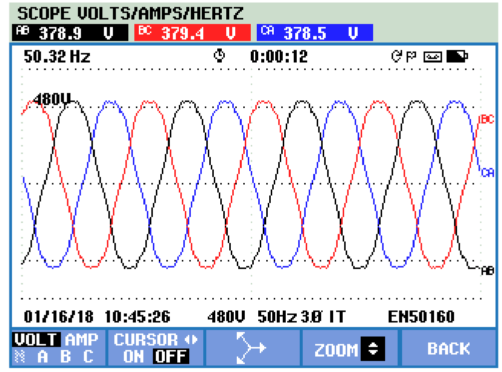


Fig. 8. Three phase voltage characteristics

The figure 8 depicts the voltage characteristics of a three-phase motor. The graph displays the voltage levels of each phase over time, providing valuable information about the motor's performance and operation. The three distinct curves represent the voltage levels of each phase, allowing for a detailed analysis of the motor's voltage behavior.

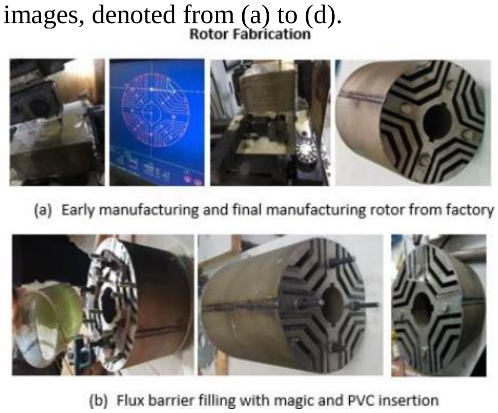
3.2. Hardware Results

In this section we will discuss the findings and observations from the hardware analysis conducted on the three-phase motor. This section will provide insights into the voltage characteristics and performance of the motor, based on the obtained hardware results. By examining the voltage levels of each phase over time, we can gain a better understanding of how the motor operates and assess its overall performance.

Fig. 9. Hardware and experimental setup of motor testing Motors

Figure 9 shows all the experimental setup component which used in our research. By these components we compare the results of voltage current and RPM with our software result

The below figure illustrates the rotor fabrication process for an electric machine, showcasing the various stages involved. Each stage is represented by different labeled images, denoted from (a) to (d).



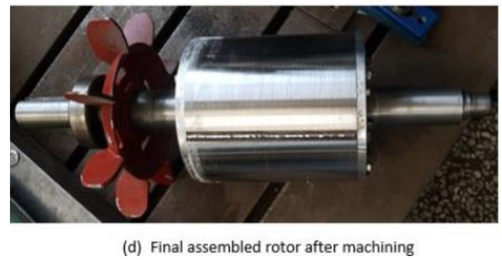


Fig. 10. Rotor assembled stages (a and b)

Figure (a) provides a comprehensive view of the rotor manufacturing process within a factory environment. The series of images showcases the different phases involved in the manufacturing process. The first image captures the initial manufacturing setup or preliminary machining steps, indicating the early stages of production. The second image displays a computer screen featuring a computer-aided design (CAD) of the rotor, highlighting the use of digital design and planning in the manufacturing process. Subsequent images depict the rotor at various stages of manufacturing, ultimately revealing the final manufactured rotor with discernible slots and distinct features. This series of images effectively illustrates the progression of the rotor manufacturing process from its early stages to the final product. Figure (b) presents a sequence of images that depict the process of filling the flux barriers within the rotor with a substance known as "magic" and the simultaneous insertion of PVC. These images showcase a crucial step in the manufacturing process aimed at regulating the magnetic flux within the rotor. The flux barriers play a vital role in achieving optimal operational efficiency. The images effectively demonstrate the process of filling these barriers with the "magic" substance and the insertion of PVC, which likely serves purposes such as insulation or structural support. Through this series of images, the figure provides visual insights into the intricate procedure involved in optimizing the magnetic flux characteristics of the rotor.

Figure (c) displays an image of the assembled rotor with the shaft, fan, and bearing components before the final machining phase. The presence of the fan suggests its role in facilitating cooling, while the bearings ensure the rotor's smooth and stable rotation. Although the rotor appears relatively complete, it still requires final machining to achieve precise dimensions and an optimal surface finish. Figure (d) represents the final assembled rotor after undergoing the machining process. The image portrays a rotor with a smooth and finished surface, indicating that it has undergone precision machining. At this stage, the rotor is ready for installation within an electric machine, as it has achieved the necessary dimensions and surface quality necessary for optimal performance.

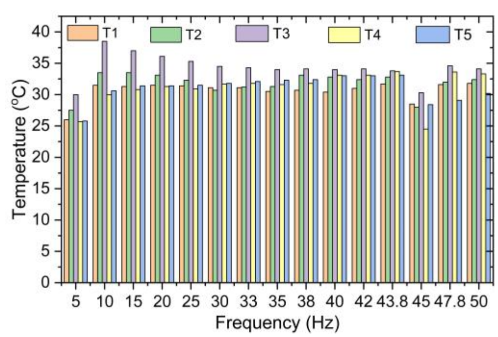


Fig. 11. Thermal results at different speed

The provided bar chart presents the temperature results for five different measurement points (T1, T2, T3, T4, T5) at various frequencies. The x-axis represents the frequency in Hertz (Hz), ranging from 5 Hz to 50 Hz, while the y-axis denotes the temperature in degrees Celsius (°C), ranging from 0°C to 45°C. Each measurement point is represented by a specific color in the legend: T1 (blue), T2 (orange), T3 (gray), T4 (yellow), and T5 (light blue). Upon analysis, it is observed that the temperatures generally increase with increasing frequency at all measurement points. Minor variations in temperature readings suggest slight differences in heat generation or dissipation. Notable observations include relatively low temperatures ranging from approximately 25°C to 30°C at 5 Hz and higher temperatures exceeding 35°C at 50 Hz. Certain frequencies exhibit peaks and troughs, such as 25 Hz displaying relatively higher temperatures compared to neighboring frequencies. In terms of a comparative analysis, T2 and T4 consistently exhibit slightly higher temperatures across most frequencies, while T1 and T5 often show the lowest temperatures, indicating better cooling or less heat generation. T3 consistently falls between the highest and lowest temperature readings, displaying moderate temperatures. Overall, this bar chart provides valuable insights into the temperature variations at different frequencies and measurement points, facilitating a better understanding of heat distribution and potential cooling requirements.

4. Conclusion

In conclusion, the design and development of the 27kW synchronous reluctance motor presented in this work represent a remarkable advancement in industrial motor technology the utilization of an alternative to induction motors, specifically the synchronous reluctance motor, has provided significant benefits. The absence of rotor winding in the robust rotor design has led to a 30% reduction in copper losses, improved thermal performance, increased mechanical robustness, and simplified manufacturing processes compared to the induction motor. These advantages make the synchronous reluctance motor more efficient for hardware implementation in various applications. .By incorporating innovative design elements, such as a novel flux barrier and flux carrier with a double-layer winding configuration, the motor exhibits enhanced efficiency and performance characteristics. The utilization of advanced computational tools like the finite element method (FEM) supported by Motor Solve software, along with practical testing, enabled comprehensive analysis and optimization of various machine parameters. The results obtained from extensive simulations and experimental validation highlight the immense potential of the designed synchronous reluctance machine for industrial applications. Notable advantages, such as stable speed operation, commendable thermal performance, and optimized efficiency, further underscore its suitability for diverse industrial settings. Additionally, the comparison of different winding gauge sizes emphasizes the importance of meticulous design considerations in achieving improved speed performance. The designed synchronous reluctance machine showcased in this work has diverse applications, including electric vehicles, HVAC systems, industrial automation, compressors, pumps, renewable energy generation, and home appliances. Its high efficiency, stable speed operation, and compact size make it an attractive choice for various industries, contributing to energy efficiency and sustainable technological advancements. Overall, this research showcases the significant strides made in the field of industrial motor technology and sets the stage for further advancements in energy-efficient and high-performance motor designs.

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