Transactions on Machine Intelligence 6(3) (2023) 160-165

ISSN Online: 2821-1693

Transactions on Machine Intelligence

Journal Homepage: https://tmachineintelligence.ir/index.php/TMI

Numerical Analysis of The Effect of Rotor Slot Opening on Induction Motor Performance Using Finite Element Method

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ARTICLE INFO

Article History:
Received 4 April 2023
Received in revised form 27 May 2023
Accepted 8 July 2023
Available online 20 September 2023

Keywords:
Induction Motor, Slot Opening, Numerical Analysis, Finite Element Method

ABSTRACT

This study investigates the influence of rotor slot opening width on the operational performance of squirrel cage induction motors. Although these motors are widely favored across numerous industrial applications due to their robust and straightforward construction, achieving optimal design accuracy remains a persistent challenge. Conventional design approaches typically rely on analytical equations, which often fail to account for complex phenomena such as leakage flux paths and magnetic saturation effects with sufficient precision. While finite element methods (FEM) offer enhanced accuracy by providing detailed electromagnetic analysis, their computational demands render them inefficient for iterative use in optimization-based design processes. As a result, there is a pressing need for empirical design guidelines that balance accuracy with computational efficiency and can be seamlessly integrated into analytical design methodologies. In this context, the present work examines the performance implications of varying rotor slot openings—ranging from fully closed to fully open configurations. By systematically analyzing how these geometric changes affect motor characteristics, the study offers practical insights that can be used to refine analytical models and support more efficient, yet reliable, design strategies. The findings contribute valuable recommendations for motor designers seeking to enhance performance predictions while minimizing computational overhead.

1. INTRODUCTION

Induction motors have gained widespread usage across industries due to their simplicity, sensor-less speed control, low manufacturing costs, and high efficiency [1,2]. However, the analytical design algorithms employed for these motors often lack the necessary accuracy [3-5]. Inaccurate motor parameters in these algorithms can significantly impact motor performance. Enhancing the precision of analytical algorithms requires the incorporation of finite element methods, considering factors such as the exact waveform of the MMF, leakage fluxes, edge effects, and slot opening width. However, integrating finite element methods in design algorithms can lead to increased complexity and time consumption due to iterative loops. The primary role of finite element methods in design algorithms is to provide precise tables or rules that empower designers to select variables efficiently and achieve desired outcomes. This research seeks to evaluate the sensitivity of induction motor performance to the rotor slot

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http://dx.doi.org/10.47176/TMI.2023.160

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opening width. Limited research has been conducted in this area, and there is currently no established standard for determining the width of rotor slot openings.

According to Reference [6], including pole shoes can elevate motor performance, but it also raises the cost and complexity of the production process. By altering the stator slot opening width in increments, this study demonstrated a correlation between heightened pole shoes and improved motor performance; however, this increase was accompanied by an elevation in both winding complexity and machine manufacturing processes. In reference [7], the implications of modifications to the width of the machine slot opening and its obliqueness on induced voltages in the shaft were investigated.

2. LITERATURE REVIEW

The performance of induction motors is of utmost importance in various applications, including electric vehicles and industrial systems. As such, there has been a significant interest in the numerical analysis of the effect of rotor slot opening on induction motor performance using the finite element method. The following literature review aims to integrate and synthesize the provided research findings to highlight the current state of knowledge in this area and identify potential future research directions. Mei, Zuo, Lee, and Kirtley (2020) conducted a study on the modeling and optimizing method for axial flux induction motors of electric vehicles. The authors utilized the finite element method to analyze the performance of the induction motor, focusing on the effect of rotor slot opening. Their findings provided valuable insights into the impact of rotor slot opening on motor efficiency and output characteristics [8].

Building upon this, Saneie and Nasiri-Gheidari (2021) investigated the performance of outer-rotor single-phase induction motors based on magnetic equivalent circuit analysis. The authors demonstrated the importance of considering the rotor slot opening in the design and analysis of induction motors, particularly in single-phase configurations. Their findings contributed to a deeper understanding of the interplay between rotor slot opening and motor performance [9]. In a similar vein, Yang, Ding, Sun, Ji, and Zhao (2019) explored the design and analysis of a novel wound rotor for a bearingless induction motor. The study focused on the structural aspects of the rotor, including the slot opening, and its impact on the overall motor performance. The authors highlighted the need for further research into optimizing the rotor slot opening to enhance motor efficiency and reliability [10].

Moreover, Yuan, Wang, Zhang, Dai, Liu, and Wang (2021) implemented the particle finite element method for large deformation analysis, providing a unique perspective on the numerical analysis of induction motor performance. While their study did not directly address the rotor slot opening, the methodology and insights gained from their research can be applied to investigate the effect of rotor slot opening on motor behavior [11].

Finally, an article by Jing, Tang, Wang, Ben, and Qu (2022) presented a performance analysis of magnetically geared permanent magnet brushless motors for hybrid electric vehicles. Although their focus was not specifically on rotor slot opening, the findings underscored the significance of advanced analytical techniques in evaluating motor performance, which can be extended to investigate the effect of rotor slot opening [12].

In summary, the literature reviewed above reflects the growing interest in numerically analyzing the effect of rotor slot opening on induction motor performance using the finite element method. These studies have shed light on various aspects of motor design, structural analysis, and performance evaluation. However, there are still knowledge gaps that warrant further investigation. Future research directions could include a more comprehensive exploration of the impact of rotor slot opening on motor efficiency, the development of advanced modeling and optimization techniques, and the integration of novel materials and technologies into motor design. By addressing these gaps, researchers can contribute to the advancement of induction motor technology and its applications in various fields.

3. INTRODUCING THE INDUCTION MOTOR UNDER STUDY

The induction motor under study in this paper is a one-sided disc-type squirrel cage induction motor. The stator of this motor consists of a rolled sheet of silica steel and has a three-phase winding. The rotor is made of CK45 iron, which is integrated. The cage is also made of aluminum. Fig. **1** shows the motor structure under study.

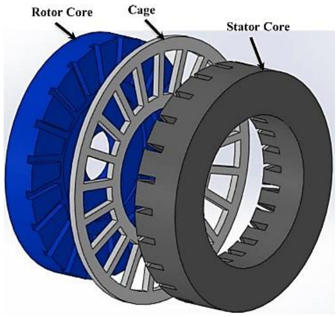

Fig. 1. The structure of the induction motor under study

4. FINITE ELEMENT SIMULATION

The finite element method is recognized as a highly effective and precise tool for analyzing the behavior of electric machines. It differs from analytical methods, which often rely on oversimplified assumptions, as the finite element model generally closely mirrors the actual model being studied. For instance, when conducting finite element analysis, one may readily account for the nonlinear impacts of B-H properties and iron saturation, as well as the influence of teeth, the non-sinusoidal distribution of windings, and the distribution of leakage fluxes. Moreover, unlike analytical models, finite element modeling does not necessitate imposing a set of unrealistic constraints on the distribution of the magnetic field. For instance, the analytical model for a disc-type machine typically assumes that the magnetic field in the air gap is solely axial. Conversely, the analysis of finite elements obtains the field distribution in air gap from the numerical solution of Maxwell equations and can include all components. However, implementing finite element methods in design algorithms results in complex and time-consuming convergence. To achieve the desired level of accuracy in design results, it is essential to provide experimental rules supported by numerical analysis. Our goal is to provide designers with appropriate results. This paper evaluates the effect of altering the width of the rotor slot opening on the performance of a disc-type induction motor through finite element simulations. The design information of the induction motor under study is given in Table 1.

In the most accurate case, the 3D model of an electric machine can be used in the analysis of its finite elements, which of course will require a lot of computational time. Regardless of the edge effects, the 2D model of the machine can be used with good approximation in the analysis of its finite elements. In the 2D model of a disc-type machine, it is assumed that the magnetic field intensity and magnetic flux density do not have a radial component and only have axial and circumferential components, which is not a far from reality assumption. To achieve a 2D model of a disc-type machine, it is enough to cut the machine in the average diameter in a radial direction and open the circle of the machine in a straight line. Fig. **2** shows a 2D view of the disc-type induction motor under study with a rotor slot width of 2 mm and under nominal conditions.

Table 1. The design information of induction motor under study

Quantity	Value
Motor output power	$P_{out}=2\ hp$
Terminal voltage	$V_{t,L-L}=380\ V$
Input current	$I_{Phase}=3\ A$
Power factor	*0.9*
Number of phases	$m=3$
Frequency	$f=50\ Hz$
Rotor speed	$n_m=1500\ rpm$
Number of stator slots	*24*
Number of rotor slots	*21*
Number of windings turns per phase	$N_s=544$
Connection type of armature windings	Star
Coil pitch	5/6
Wire diameter	$d_{wire}=0.75\ mm$
Axial thickness of stator core	$L_s=31\ mm$
Airgap length	$g=1\ mm$

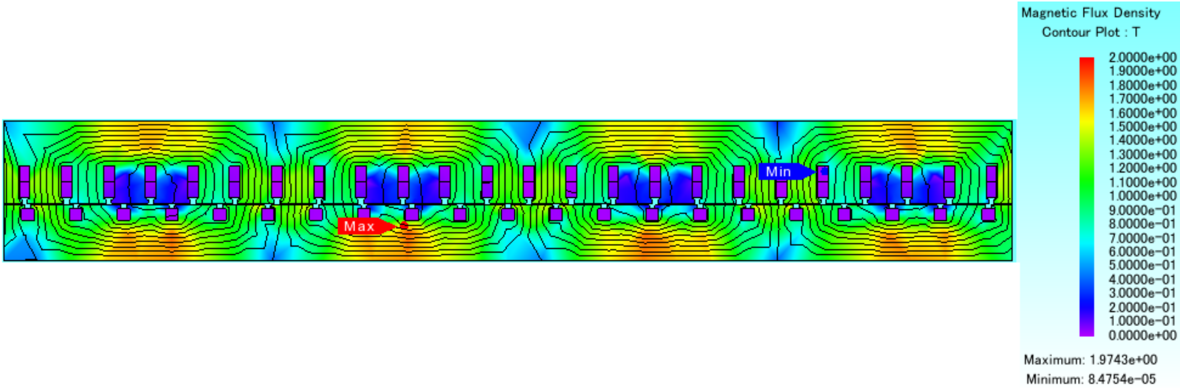

Fig. 2. Flux density distribution of induction motor under study in 2D view

The analysis and evaluation of the disc-type induction motor's performance for varying widths of the rotor slot opening is presented below. The rotor slot opening width is gradually changed from being fully closed in one-millimeter increments to a fully open state of 7 mm. The motor's operational parameters are measured while maintaining a constant load.

Figure 3 depicts the changes in the stator input current corresponding to different rotor slot opening widths. The current input to the motor increases when in a fully closed state, as depicted in this figure. This is caused by the complete closure of the slot opening, increasing the leakage flux of the rotor, leading to more current being utilized to produce the MMF and to supply the load. A further issue is that when the rotor slot opening widens, the impedance of the rotor branch decreases significantly, resulting in an increase in the input current.

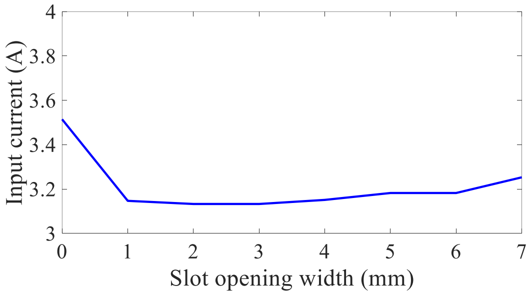

Fig. 3. Variations of stator input current relative to variations of rotor slot opening width

The changes in the power factor of the machine relative to the changes in the width of the rotor slot are shown in Fig. **4**. It is clear that when the slot opening is completely closed, the power factor of the machine decreases strongly due to the increase in the leakage reactance of the rotor. This decrease also occurs in the uncontrolled increase in the width of the rotor slot opening.

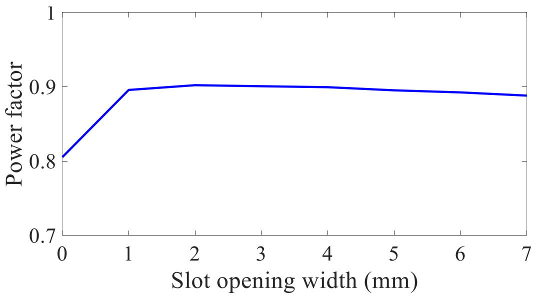

Fig. 4. Variations of power factor relative to variations of rotor slot opening width

Fig. **5**, Fig. **6**, and Fig. **7** show changes in input power, copper losses and motor efficiency for changes in rotor slot opening width, respectively.

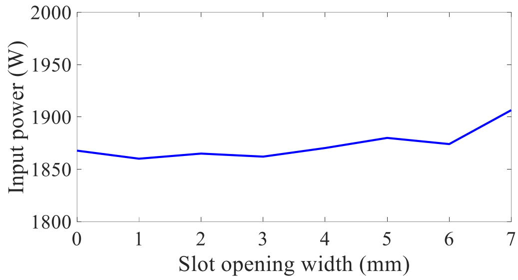

Fig. 5. Variations of input power relative to variations of rotor slot opening width

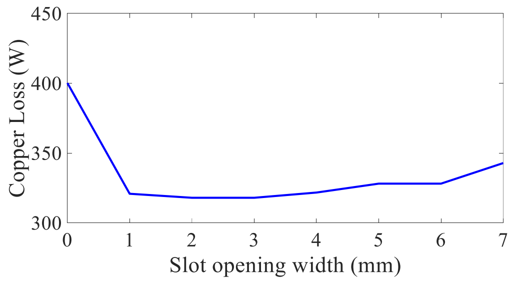

Fig. 6. Variations of copper losses relative to variations of rotor slot opening width

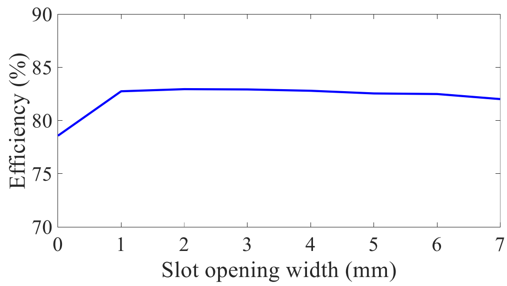

Fig. 7. Variations of the efficiency of motor relative to variations of rotor slot opening width

The findings reveal that closing or excessively enlarging the rotor slot opening negatively impacts the motor's performance. However, selecting a slot width that amounts to roughly 30% of the rotor slot width yields beneficial results.

5. CONCLUSIONS

The research highlights the limitations of existing design methods that rely solely on analytical relationships, especially in assessing the sensitivity of factors like rotor slot width. The current design practices, dominated by analytical approaches, lack the precision required for evaluating the intricate influence of variables. Consequently, designers often need to accept a considerable margin of error when employing time-consuming numerical methods. This study addresses the gap by leveraging finite element methods to thoroughly analyze the impact of rotor slot opening width on disc-type induction motor performance. The numerical simulations suggest that a rotor slot opening width around 30% of the rotor slot width could lead to favorable outcomes.

CONFLICTS OF INTEREST

The authors declare no conflict of interest.

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