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The Effect of Rotor Slot Number on the Performance of Asynchronous Motors in Light Electric Vehicle

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Light electric vehicles provide significant advantages in reducing environmental pollution and increasing efficiency in urban transportation. The performance of the motor directly affects the overall performance of electric vehicles. This study investigates the performance analysis of asynchronous motors designed for light electric vehicles used in urban transportation. The initial design parameters of the motor are specified, and various motor structures designed with changes in the rotor slot number are presented. Additionally, the effects of the slot number on the motor's magnetic circuit and performance are discussed. Finite Element Analysis (FEA) is used to investigate the motor's performance. Performance parameters such as efficiency, magnetic flux density, weight, starting torque, and power factor are obtained for different slot numbers. The results indicate that the rotor slot number is a critical design parameter affecting motor performance. In particular, it is stated that maximum efficiency can be achieved with a certain slot number, but an excessive increase in the slot number may have adverse effects on performance.

Keywords: *Asynchronous motor, Finite element method, Light electric vehicle, Slot number*

1. Introduction

The development of industry and rapidly increasing population have accelerated environmental pollution and global warming. Increased awareness of these issues has led to the implementation of various measures. As a solution, electric vehicles have begun to gain popularity as an alternative to internal combustion engines powered by fossil fuels. Unlike internal combustion engines, electric vehicles do not harm the environment due to carbon emissions during operation. Additionally, electric vehicles surpass internal combustion engines in terms of high efficiency, high torque, and low losses. The increasing use of electric vehicles has led to intensive research on different motor types and structures [1,2].

The increasing trend towards electric vehicles has led to numerous research and the development of various motor designs such as direct current (DC), synchronous and asynchronous, and reluctance motors for these vehicles. With the widespread adoption of electric vehicles, the exploration of the mentioned motors and the process of introducing different designs have accelerated. The selection of motors used in electric vehicles involves various criteria such as cost, power density, efficiency, and losses [3,4].

Due to their high efficiency at low speeds in early prototypes and hybrid vehicles, DC motors have been commonly used. However, compared to other types of motors, DC motors have higher losses, relatively lower efficiency, and require continuous maintenance due to brushes. For these reasons, their usage in contemporary electric vehicle applications has become limited. Brushless DC motors (BLDC), which have become widely used in recent electric vehicles, provide high torque and power density. However, their structures, particularly the permanent magnets, make them relatively expensive. In addition to costs, the use of cooling systems in vehicles is required due to the demagnetization issue of permanent magnets at high temperatures. Permanent magnet synchronous motors, which offer high efficiency, high power density, and high torque, are extensively used in today's electric vehicles. However, similar to BLDC motors, the cost of permanent magnets and the risk of demagnetization due to high temperatures are considered disadvantages [5-9]. Recently gaining popularity, synchronous reluctance motors offer high efficiency and robustness. However, they come with certain disadvantages, such as noisy operations and high torque fluctuations. Despite these drawbacks, synchronous reluctance motors, being a promising motor, are currently used in heavy-duty vehicles and are anticipated to become more widespread in the future [10,11].

Another motor type extensively used in electric vehicles is the asynchronous motor. Although they have a lower power density compared to permanent magnet motors, asynchronous motors have a simple structure and high durability. Additionally, they are temperature-resistant due to the absence of permanent magnets in their structure, and they do not carry the risk of demagnetization. Moreover, asynchronous motors are more attractive in terms of cost and reliability compared to other motors. For these reasons, they are widely employed in today's electric vehicle [12-14]. An asynchronous motor designed for a specific purpose can provide similarly high efficiency as magnet machines.

In the study, the effect of the rotor slot number on the performance of the squirrel-cage asynchronous motor for light electric vehicles has been investigated. The second section presents the characteristics of the designed motor, and the third section provides performance analyses.

2. Designed Asynchronous Motor

The preference for light electric vehicles in urban transportation can play a significant role in reducing environmental damage. The performance of the motor in light electric vehicles directly determines the overall performance of the electric vehicle [15]. Therefore, any improvements made to the motor will directly impact the performance of the vehicle. As is known, electric vehicles utilize the motors of various structures. Asynchronous machines are preferred in many industrial applications thanks to their robust structures. The performance of these motors can be improved by structural modifications. In the design phase of the asynchronous motor, it is necessary to examine electromagnetic, thermal, and mechanical solutions together. As a result of all these examinations, a commercially viable product with the desired performance can be developed. Numerous analyses are required for conducting detailed investigations. The execution of these analyses with the desired precision is time-consuming. Finite Element Analysis (FEA) can be employed to examine the performance of asynchronous motor. This provides benefits to the designer in terms of both time and effort. The parameters of the designed motor in the study are given in Table 1.

Table 1. *Motor parameter.*

Parameter	**Value**
Rated power (kW)	10
Pole number	4
Stator slot	36
Stator outer diameter (mm)	202
Rotor outer diameter (mm)	124.25
Stack length (mm)	190
Stator skew	1
Stator material	M43
Rotor material	M43
Squirrel cage material	Aluminum

The 2D model of the initial designed asynchronous motor used in SEA with defined master-slave boundary conditions is given in Figure 1.

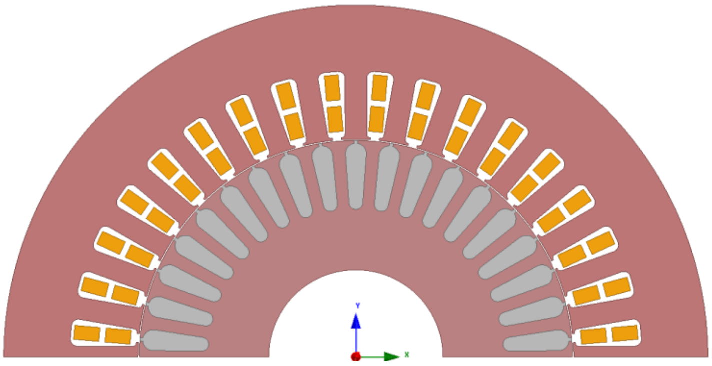

Figure 1. *The initially designed motor model..*

In the study, the rotor slot numbers have been designed as 26, 28, 30, 32, 34, and 38 with fixed slot dimensions. The designed slot structures are given in Figure 2.

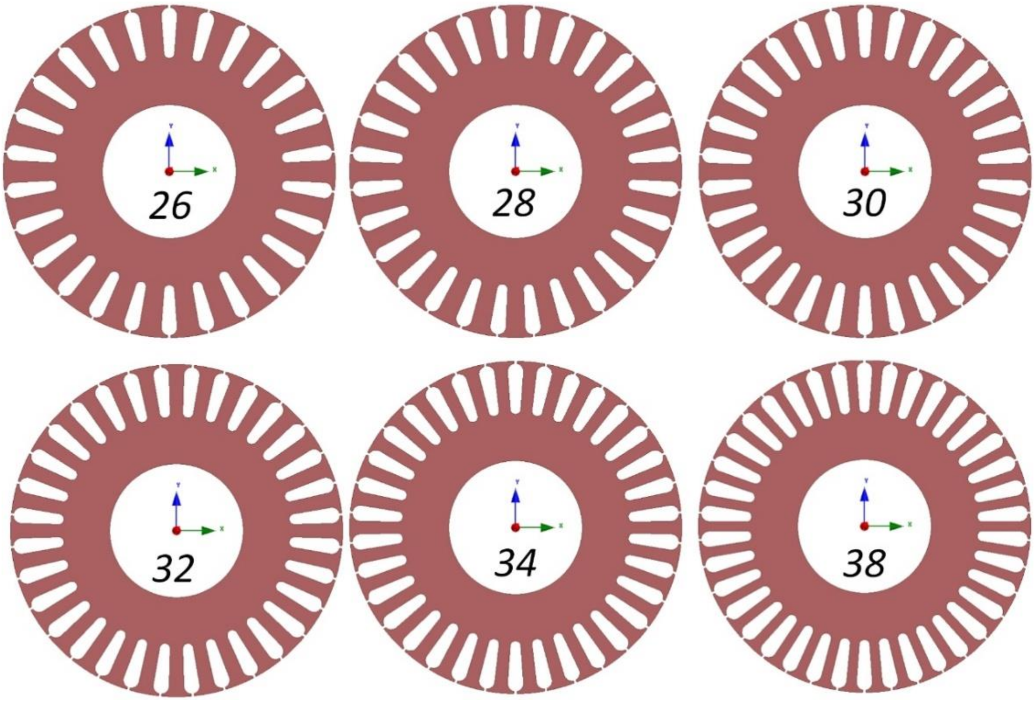

Figure 2. *Rotor structures with different number of slots.*

The slot geometry was kept constant in order to keep the slot fill factor at the desired level (44.5%). Therefore, with the increase in the number of slots in the fixed rotor outer diameter, narrowing of the slot teeth occurred. The increase in the slot number will affect the magnetic circuit and, consequently, the performance of the motor. Increasing the number of slots provides a more effective distribution of the magnetic flux for the rotor. However, saturation in the teeth is possible after a certain number of slots. Therefore, it is necessary to make a balanced design.

3. Performance Analysis of the Motor

In electric machines, achieving the expected performance under desired constraints at reasonable costs requires various analyses. The evaluation of electromagnetic, thermal, mechanical, and material issues together is a time-consuming process. The Finite Element Method (FEM) has been effectively used to solve complex problems, especially in the field of engineering [16]. FEM enables the solution of quantities expressed by partial differential equations in a specific region. During the solution stage, the model to be analyzed is divided into a finite number of elements called as mesh. The interactions between these elements are then added to each other in a chained manner. The desired parameters can be obtained by solving the resulting equation [17]. With FEM, magnetic field analyses, thermal analyses, structural analyses, analyses of electrical and thermal losses, and performance under variable load conditions can be obtained for the motor. In the study, the mesh structure of the design with a rotor slot number of 30 is illustrated in Figure 3.

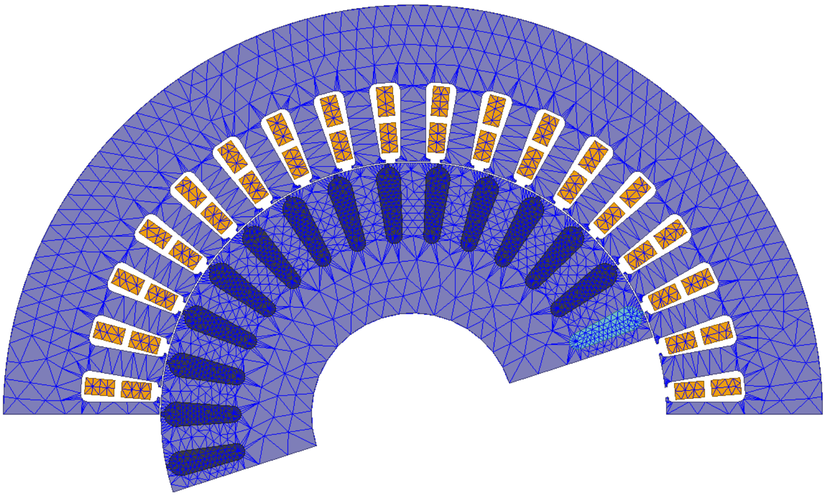

***Figure 3**. Mesh structure of motor.*

In the study, the rotor slot number has been determined as a variable. The stator/rotor outer and inner radius have been kept constant. The stator slot number was set at 36. In asynchronous machines, the rotor slot number is an important design parameter that affects efficiency, power factor, and flux density. The rotor slot numbers have been designed as 26, 28, 30, 32, 34, and 38. The performance values obtained from the FEM analyses are given in Table 2.

***Table 2.** Motor performance values.*

Parameter/Rotor slot number	**26**	**28**	**30**	**32**	**34**	**38**
Efficiency (%)	84.90	85.49	85.89	86.14	86.27	85.18
Stator teeth flux density (T)	1.212	1.207	1.185	1.165	1.137	1.165
Rotor-teeth flux density (T)	1.408	1.478	1.535	1.601	1.664	1.959
Rotor-yoke flux density (T)	1.230	1.243	1.253	1.271	1.273	1.308
Total net weight (kg)	42.01	42.06	42.12	41.35	42.23	42.34
Starting torque (Nm)	53.38	59.47	65.57	71.88	77.10	90.33
Power factor	0.875	0.886	0.892	0.893	0.891	0.827

The change in performance parameters with an increase in the slot number of the motor is examined in Table 2. As the slot number increases from 26 to 38, there is a general trend of improvement in the motor's efficiency. Particularly, the maximum efficiency (86.27%) is observed at 34 slot numbers. However, when the slot number is 38, there is a decrease to 85.18%. This suggests that an increasing slot number beyond a certain point may have a negative impact on efficiency. The reason for this is the saturation caused by the narrowing of the slot.

The magnetic flux density in rotor teeth also varies with the slot number. While the stator tooth flux density shows a general decreasing trend as the slot number increases, the rotor tooth flux density increases. This indicates that the distribution of the magnetic field within the motor changes depending on the slot number. The rotor core flux density follows a similar trend, showing a slight increase as the slot number increases. When examined in terms of weight, approximately the same weight values have been obtained. Magnetic flux distributions have been analyzed on a cross-section of the core and have been presented in Figure 4.

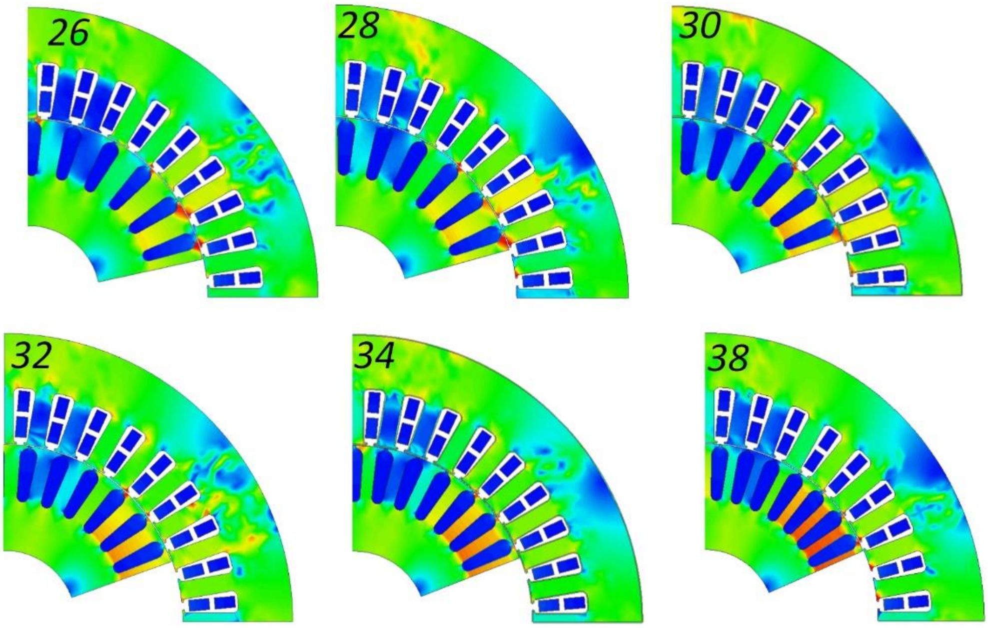

Figure 4. *Magnetic flux density*

When Figure 4 is evaluated together with Table 2, it can be observed that the increase in the rotor slot number leads to an increase in flux density. Especially in the 38-slot, the magnetic flux density value in the rotor slots has reached the saturation region. This situation causes both efficiency and power factor to decrease. Another important parameter is the starting torque. The variation in the slot number and the change in motor torque with speed have been presented in Figure 5.

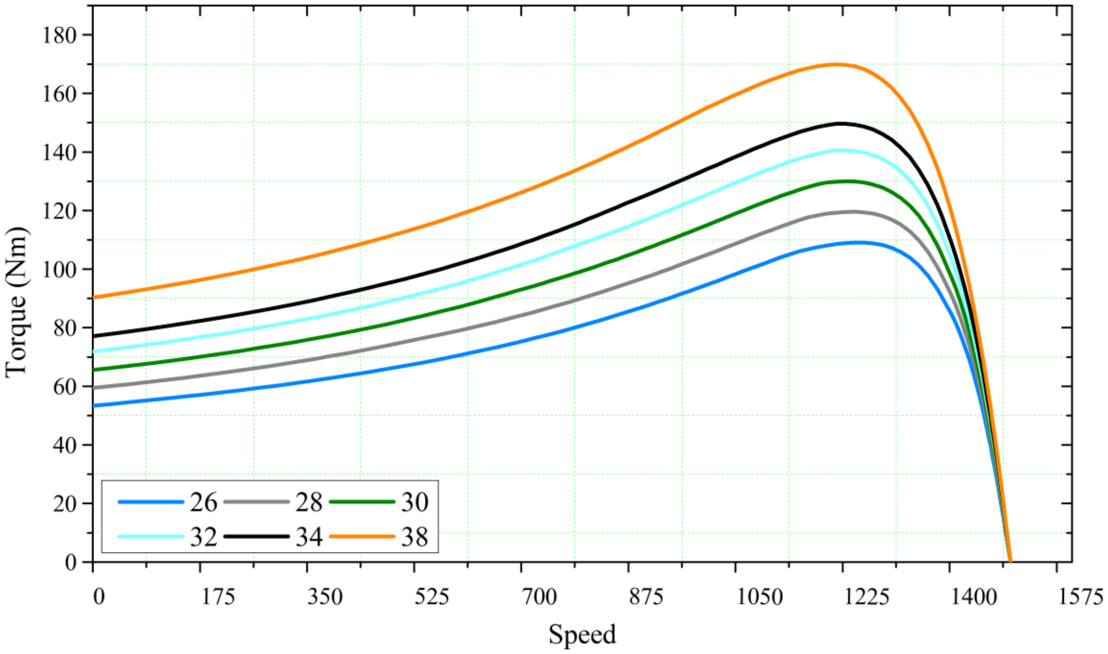

Figure 5. *Magnetic flux density*

Especially in vehicles that will operate within the city, high starting torque is expected during continuous stop-and-go duties. When Figure 5 is examined, it can be seen that as the rotor slot number increases, the starting torque also increases. However, magnetic saturation limits the increase in the number of slots.

3. Conclusion

In this study, the design and FEM analyses of a squirrel-cage asynchronous motor for light electric vehicles have been carried out. The study investigated the effects of varying the rotor slot number on the behavior of the motor. According to the FEA results, an increasing trend in the efficiency of the motor has been observed with an increase in the rotor slot number. In particular, the maximum efficiency (86.27%) has been achieved at 34 slot numbers. However, an increase in the slot number to 38 resulted in a decrease, and the efficiency dropped to 85.18%. When analyzed in terms of magnetic flux density, it has been determined that an increase in the slot number led to an increase in flux density in the rotor teeth. It has been determined that in the structure with 38 slots, the rotor slots reach saturation, leading to negative effects on both efficiency and power factor. Examining the starting torque, an increase in the starting torque has been observed with an increase in the rotor slot number. In conclusion, this study indicates that the rotor slot number is a critical parameter in the design of asynchronous motors used in light electric vehicles, and an increasing slot number beyond a certain point can negatively impact performance.

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