AN FEM BASED ANALYSIS OF IMPACTS OF ROTOR SLOTS NUMBERS IN THE CHARACTERISTICS OF MEDIUM RATED SQUIRREL CAGE INDUCTION MOTOR

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ABSTRACT: *Rotor slots play an important role in the performance characteristics of squirrel cage induction motors. Not only the rotor slot geometry parameters but also number of rotor slots considered for the modelling of rotor highly influence the performance indicators and parameters. The number of rotor slots effect the equivalent circuit parameters, performance indicators, magnetization characteristics, and flux distribution of the SCIM. In this research work, for a fixed value of number of stator slots, four possible values of the rotor slots such as 28, 30, 32, and 34 are considered for the performance analysis of SCIM. A medium-rated general purpose SCIM with 3 kW, 50 Hz, and 400 V is modelled in finite element based Ansys Electronics Desktop software platform. The RMxprt design of the motor is used for the performance comparison of SCIM, and the analysis is extended to Maxwell2D design analysis to investigate flux distributions in each case of number of rotor slots. The results show that the number of rotor slots significantly impacts the overall performance of the SCIM. In addition, the rotor slots of 28 and 30 provide better performance in terms of performance indicators, magnetic characteristics, and flux distributions while the rotor slots of 32 and 34 offer better break down torque.*

Keywords: Squirrel cage induction motor, Rotor slots, Stator slots, Finite element method, Flux distribution

1. INTRODUCTION

AC motors are preferable over the DC motors due to the commutation free mechanisms (Cai, Wu, Zhou, Liang, & Wang, 2021). The AC motors include induction motors and permanent magnet synchronous motors, where the IMs are more favourable for many applications, including domestic, industrial, and propulsion-related applications because of their lower cost due to the lack of permanent magnets (Juhaniya, Ibrahim, Zainuri, & Zulkifley, 2022). The IMs can be further divided into squirrel cage induction motor (SCIM) and wound rotor induction motor (WRIM) induction motor according to the rotor construction (Pyrhonen, Jokinen, & Hrabovcova, 2008). Since wound rotor-type motors are more expensive and also complex in construction, the squirrel cage rotor motors have become a promising option for most industrial and domestic application (Rahmat, Yahya, & Suffer, 2019). In addition, SCIM has some special characteristics such as simple in construction, self-starting, low lost, and need less maintenance.

The design of the rotor of SCIM determines not only the equivalent circuit parameters, performance indicators, magnetization characteristics, and flux distribution but also, the power, torque, current, speed, efficiency, etc. The rotor modelling includes the appropriate selection of rotor slot shapes, rotor slot geometry parameters, and number of rotor slots. The rotor slot geometry parameters and rotor slots number used for the rotor constructions are directly involved in the computation of resistance and reactance of the rotor (Iqbal & Agarwal, 2014). In particular, the number of rotor slots directly involves the losses calculation of IM with impact the efficiency and torque performance of the motor (Leicht & Makowski, 2019).

There are several research studies have been done with design of rotor for SCIM in which some works deal with rotor slot design and investigating impact of number of rotor slots. A research work in (Yetgin, Turan, Cevher, Çanakoğlu, & Gün, 2019), deals with modelling of SCIM using an analytical model implemented in software platform and the effect of the magnetic load coefficient on the performance of SCIM is tested via graphical representation. A research work in which the effects due to the rotor slots number on the performance of SCIM is tested using an analytical model of motor (Kappatou, Gyftakis, & Safacas, 2007) and the variation of efficiency with different number of rotor slots is studied. Effects of rotor slot shapes on the performance of SCIM are tested with different configurations of rotor slot (Leicht & Makowski, 2019) and dependency of the performance of IM for various shapes of slots is studied. The optimal design of stator and rotor slots are modelled for SCIM suitable for electric vehicle applications by using opposition based jellyfish search optimization algorithms (Juhaniya, Ibrahim, Zainuri, Zulkifley, & Remli, 2022) in which slots geometric parameters are tuned to maximize the performance measures of IM. An analysis with induction motor with the scope of improvement of output power quality by limiting the losses was done with the FEM method by considering the design of rotor winding pattern (Iqbal & Agarwal, 2014).

In the above-mentioned existing research studies with SCIM rotor modelling, most of the works have been done to investigate the impact of rotor slot shapes and parametric geometries in the performance of the SCIM. Impacts of number of rotor slots is discussed in a research work but limited to the investigation with few performance indicators. On the other hand, effect on the magnetic characteristics such as stator tooth flux density, rotor tooth flux density, saturation factor, and airgap flux are not taken into account for the analysis. Furthermore, the flux distribution of SCIM with different number of rotor slots is not considered in depth. In addition, some works involve with analytical modelling of SCIM whereas it doesn't have the capability to visualize the magnetic and electric field distribution of the motor.

Therefore, this study utilizes the FEM of analysis for the implementation and simulation of SCIM to perform precise analysis to study about the impact of number of rotor slots on the overall performance. The effects of number of rotor slots on the performance indicators, equivalent circuit parameters, magnetic characteristics, and flux density distributions are tested and analysed with Ansys Electronics Desktop software environment by using RMxpert and Maxwell2D designs. The following section describes the methodology used to carried out this research work. The results obtained from the simulation work are analysed and discussed in section 3 and eventually, the conclusion of the research work is drawn in section 4.

2. METHODOLOGY

A 3 kW, 50 Hz, and 400 V SCIM is developed in Ansys Electronics Desktop software platform. The medium rated motor is selected for this study since they are preferably used in most of the domestic and industrial applications. The main design specifications of the modelled motor are given in Table 1.

Table 1. Motor Main Design Specifications

Parameters	**Value**
Power output (kW)	3
Frequency (Hz)	50
Input voltage (V)	400
No. of Phases	03
No. of Poles (P)	04
Synchronous speed	1450
(rpm)	75°C
Design temperature	

Based on the specification of the motor, other design parameters are modelled by considering single cage design for stator and rotor slots since they are simple and lower-cost type of slots. Figure 1 shows a cross section of the implemented motor.

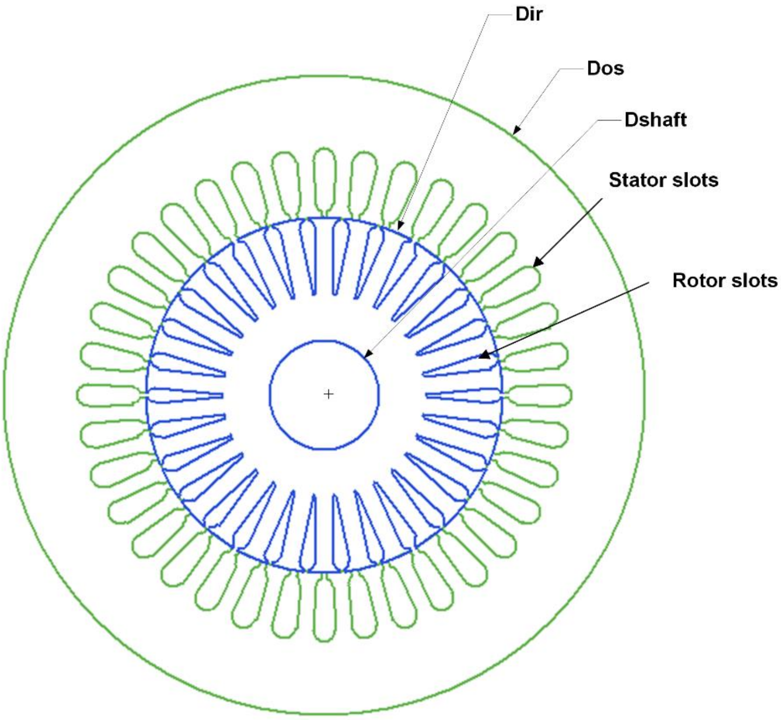

Figure 1. Cross Sectional View of Motor Cross Section.

According to the main design specifications given in Table 1, the main dimensions of the motor is determined as given in Table 2 (Boldea & Nasar, 2010). The derivation of these dimensions by using the main design specifications are explained in (Juhaniya, Ibrahim, Zainuri, & Zulkifley, 2022).

Table 2. Motor Design Parameter Specifications

Parameters	Value
Stator Outer Diameter (D_{os})	173.4 mm
Stator inner radius	97.2 mm
Rotor outer radius (D_{or})	96.5 mm
Rotor inner radius	30 mm
Airgap length	0.35 mm
Stack length	137 mm
Number of stator slots	36

The number of stator slots can be calculated by using the following formula (Boldea & Nasar, 2010):

$$N_s = N_P q N_{ph} \quad \text{.......(1)}$$

where, N_s, $N_P, q,$ and N_{ph} are number of stator slots, number of poles, number stator slot per pole per phase, and number of phases, respectively.

After the calculation of number of stator slots, the possible number of rotor slots can be considered by using the table given in (Boldea & Nasar, 2010). In general, number of rotor slots should not equal to the number of stator slots. Therefore, number of possible rotor slots values for the four pole three phase SCIM with 36 stator slots are 28, 30, 32, 34, 45, and 48. Meanwhile, the IM with number of rotor slots is less than the number of stator slots, is considered to reduce the harmonics effect and stray losses of the motor (Tiecheng, Ping, Qianfan, & Shukang, 2005). As a result, number of rotor slots values are considered for this analysis are 28, 30, 32, and 34. For each case of rotor slot number, performance of the motor is simulated and recorded. The following section presents the results obtained from the simulation and their discussion.

3. RESULTS AND DISCUSSION

The SCIM is implemented by using FEM analysis software Ansys Electronics Desktop software environment using a PC of 2.4 GHz and 8 GB RAM. The results obtained from the simulation are analysed by categorizing them such as impact on equivalent circuit parameters, performance indicators, magnetic characteristics, and flux distribution as discussed in the following sub sections.

3.1 Impact of Number of Rotor Slots on Equivalent Circuit Parameters

The equivalent circuit parameters are recorded for each value of number of rotor slots to investigate the effect of rotor slots. The results are shown in Table 3.

Table 3. Equivalent Circuit Parameters for Various Number of Rotor Slots

Parameters	**Value (Ω)**			
	28	30	32	34
Stator resistance	1.75	1.75	1.75	1.75
Stator leakage reactance	2.18	2.153	2.1	2.04
Rotor resistance	0.99	0.94	0.89	0.845
Rotor reactance	3.32	2.86	2.41	2.01
Magnetization reactance	63.31	59.68	52.97	44.89

The result given in Table 3 shows that leakage reactance of the stator, resistance and reactance of the rotor, and magnetization reactance values are decreased with the increase of number of rotor slots values. This is due to the increase in effective area of the rotor slots with increase in slot numbers while keeping rotor slot parametric geometries as constants. Therefore, the rotor slots number equals to 34 provides lower resistance and reactances which result the reduction in copper losses produced by rotor resistance. However, reduction in magnetization reactance causes the increase in magnetization current of the IM that may generate additional heat and saturation effect in the motor. Furthermore, it can be observed that the stator resistance values remain at 1.75 Ω for all possible case of rotor slot numbers. This happens due to the fixed values of stator slot number (36) and stator geometries. The following section describes the effects on performance indicators of the SCIM.

3.2 Impact of Number of Rotor Slots on Equivalent Circuit Parameters

The variation of performance indicators at rated condition of the IM are listed in Table 4 to observe the influence of number of rotor slots on the performance indicators.

Table 4. Variation of Performance Indicators for Various Number of Rotor Slots

Parameters	**Values (Ω)**			
	28	30	32	34
Efficiency (%)	91.23	91.11	90.75	89.91
Rated torque (Nm)	19.53	19.51	19.48	19.47
Rated slip (%)	2.23	2.11	1.95	1.91
Rated speed (rpm)	1466.7	1468.6	1470.1	1471.1
Breakdown torque (Nm)	80.92	84.49	88.34	91.91
Power factor	0.78	0.77	0.74	0.69
Stator copper losses (W)	193.2	199.3	216.81	250.11
Rotor copper losses (W)	68.11	64.22	60.97	58.49
Total losses (W)	291.32	293.45	307.82	338.56

Table 4 shows that the efficiency of the motor is much improved when rotor slots are set at 28. This happens due to the lowest total losses resulting from significant reduction in stator copper losses. Although the stator resistance remains constant when rotor slots are varied, the stator copper losses improve when rotor slots numbers are increased. The reason for increase in stator copper losses is the increase in the magnetization current results from lower magnetization reactance causes the higher stator current. On the other hand, rotor copper losses slightly decrease with the rotor slots due to the reduction of rotor resistance.

Although, the stator reactance reduces, the power factor is not improved with the increase in rotor slots because of significant reduction in efficiency. Furthermore, there is no considerable change in rated torque of the motor when variating the number of rotor slots. In addition, the breakdown torque is much improved when rotor slots are set at 34 due to the reduction in stator and rotor reactances. In terms of power factor, efficiency, and losses, the SCIM with rotor slots at 28 shows best performance to be used in domestic and industrial related applications. Since, breakdown capability of the motor is higher when rotor slot is set at 34, this kind of motor can be useful for the electric vehicle related application which requires higher breakdown torque. The following subsection describes the magnetic characteristics of the SCIM for various numbers of rotor slots.

3.3 Impact of Number of Rotor Slots on Equivalent Circuit Parameters

It is important to analyse magnetic characteristics of the motor to protect it from burning and saturation effect. This subsection describes the effects on magnetic characteristics of the motor for the various number of rotor slots. Table 5 shows the variation of magnetic characteristics of the SCIM.

Table 4. Variation of magnetic characteristics for various number of rotor slots

Parameters	**Values (Ω)**			
	28	30	32	34
Stator tooth flux density (T)	1.613	1.611	1.621	1.623
Rotor tooth flux density (T)	1.629	1.684	1.761	1.831
Stator yoke flux density (T)	1.097	1.099	1.112	1.109
Rotor yoke flux density (T)	0.832	0.831	0.838	0.842
Air gap flux density (T)	0.789	0.789	0.789	0.789
Teeth saturation factor	1.591	1.681	1.891	2.24
Total saturation factor	1.701	1.792	2.000	2.34

According to the results, the flux densities at stator tooth, rotor tooth, stator yoke, rotor yoke, and airgap are within the IM design constraints as in (Akhtar & Behera, 2018). In addition, the air gap flux density is same for all case resulting from constant airgap length considered for the analysis. On the other hand, for the rotor slot values of 28, 30, and 32, the teeth saturation factor and total saturation factors are not exceeding the 2 which the acceptable limit for IM design. When rotor slots number is set at 34, the saturation factors are little bit higher than permissible limits due to the higher magnetization current and saturation of magnetic material. Therefore, SCIM operates close to saturation level when it has 34 number of rotor slots. Furthermore, flux distribution of the motor will help to get clear picture about distribution of this flux densities. The flux density distributions of the motor for different number of rotor slots are discussed in the following subsection.

3.4 Flux Density Distributions of SCIM for Various Number of Rotor Slots

The finite element simulations for flux density distributions are obtained by using Maxwell2D transient analysis model of Ansys Electronics Desktop. The flux density distributions for various number of rotor slots are observed as given in Figure 2. It can be clearly seen that the number of rotor slots used for the rotor construction highly impact the flux distribution of the motor.

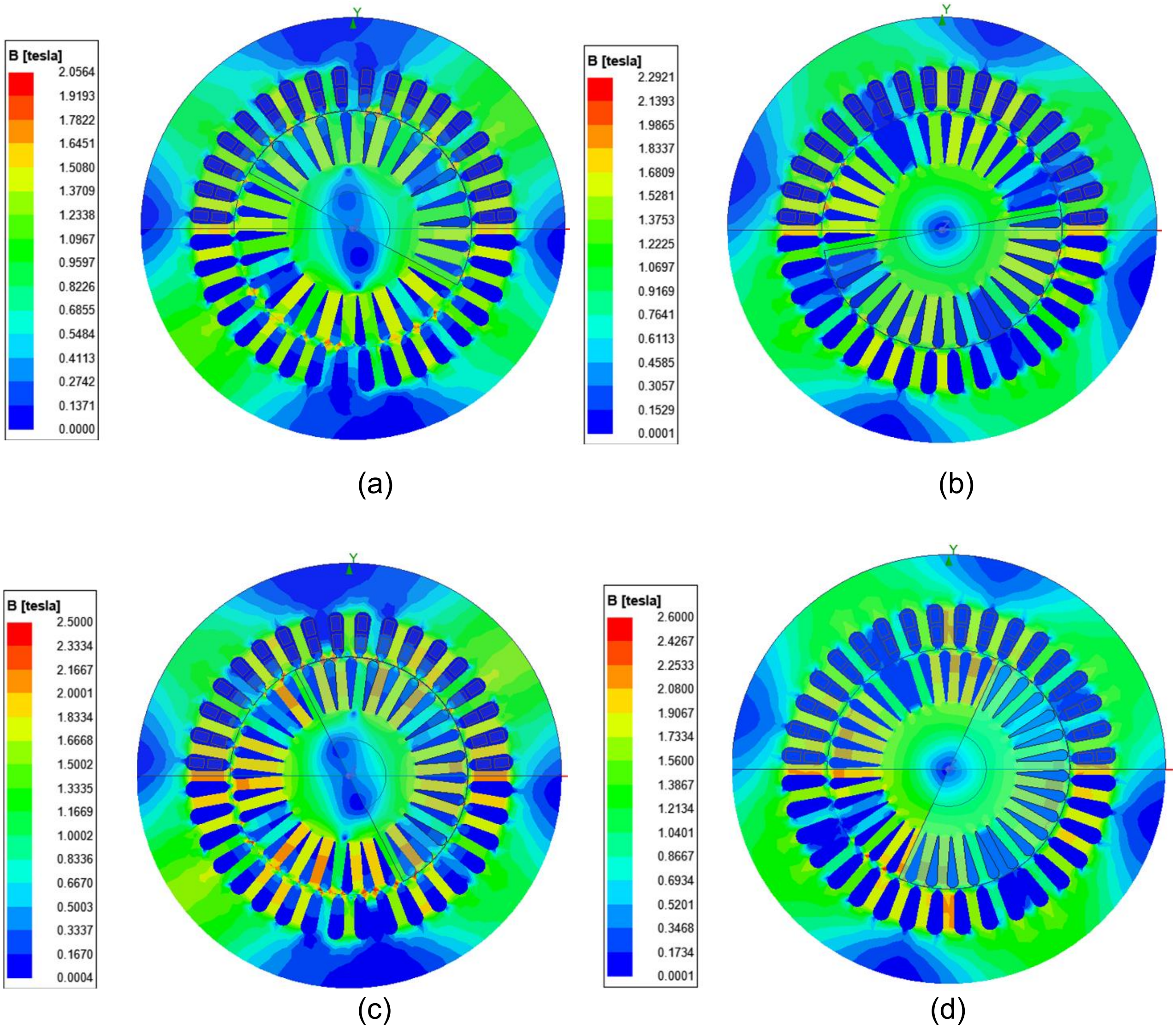

Figure 2. Flux Distribution of the Motor for Various Number of Rotor Slots; (a) for 28, (b) for 30, (c) for 32, and (d) for 34.

According to Figure 2, the rotors with 32 and 34 slots have high flux densities which reach 2.5 T and 2.6 T, respectively. Although, these higher flux densities appear in few places of the motor cross section, they may cause saturation effect which is not considered as normal operating condition of the IM. Furthermore, IM needs some special design concern to limit the higher magnetization current effect. On the other hand, for the rotor slots 28, and 30, the flux densities are at 2.06 T and 2.29 T, respectively, within the constraint for the SCIM operates under the typical operating conditions. In addition, as discussed in previous subsections, magnetization reactances for rotor slots of 28, and 30 is higher than the other cases under the consideration. Therefore, higher magnetization reactances reduce the magnetization currents, result the flux densities within the permissible limit.

4. CONCLUSION

The number of rotor slots used for the construction of rotor of SCIM plays an important role in determining the overall performance characteristics. The impacts on the equivalent circuit parameters, performance indicators, magnetization characteristics, and flux density distribution for the rotor slot numbers of 28, 30, 32, and 34 are tested and analysed to showcase the performance of 3 kW medium rated SCIM. Although, the rotors with 32 and 34 number of slots provide better rotor resistances to limit the copper losses and improved breakdown torques, the other main performance indicators such as efficiency, rated torque, power factor, and total losses are much better for the cases 28 and 30 rotor slots. In addition, Magnetic performance of the IM is within the acceptable limit, when 28 and 30 number of slots are considered. Furthermore, the maximum flux densities for 28 and 30 number of slots are 2.06 T and 2.29 T, respectively which seem to be the typical operating conditions. On the other hand, the flux densities reach up to 2.5 T and 2.6 T for the 32, and 34 number of rotor slots which are not favourable to operate under the normal condition. Therefore, the rotor slots numbers 28 and 30 are more suitable for the motor under the consideration. Further work can be extended by considering thermal effect of the SCIM for various number of rotor slots.

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