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Investigating Impact of Rotor Slot Design on Torque of Medium Rated Squirrel Cage Induction Motor

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Abstract - **The modeling of the rotor of a medium-rated squirrel cage induction motor depends on the design parameters of the rotor slot, which control the overall performance characteristics of the motor. Among all performance measures of induction motors, rated torque takes important attention because it is the key measure determines the characteristics of the induction motors. Variation of rotor slot geometries affects the resultant resistance and reactance of the rotor, which highly impact the losses, output power, and speed characteristics. In this research work, a parametric study on three rotor slot parameters, namely, rotor slot depth (Hr), rotor slot opening height (Hor), and rotor slot tooth width (Btr), is carried out by using an analytical model of squirrel cage induction motor. A medium-rated general-purpose squirrel cage induction motor with 7.4 hp, 60 Hz, and 460 volts is modeled in the MATLAB software platform. Developed analytical model of induction motor is further validated with Ansys Electronics Desktop finite element modelling software platform. The dependency of each parameter on rated torque is tested as a two-dimensional plot, which has been extended into a four-dimensional scatter plot. From the individual and four-dimensional plots of the motor obtained through the simulation of the motor model in the MATLAB software environment, it has been proven that rotor slot parameter modelling has a high impact on the rated torque of the medium-rated induction motor.**

Keywords: *Squirrel cage, Torque, Rotor slot, Tooth width, Analytical model*

I. INTRODUCTION

Induction motors are one of the main types of ac motors, which can be divided into squirrel cage induction motors (SCIM) and wound rotor induction motors based on the construction of the rotor (Chapman, 2005). Since wound rotor-type motors are more expensive and also more complex in construction, squirrel cage rotor motors have become a promising option for most industrial and domestic applications (Rahmat, Yahya, & Suffer, 2019). Furthermore, squirrel cage motors are simple in construction, self-starting, low-loss and need less maintenance. Although these types of motors have many advantages, they suffer from some shortcomings, such as lower torque capability and lower efficiency due to the higher degree of losses related to rotor and stator (Wang, Ching, Huang, Wang, & Xu, 2021). The torque capability of a squirrel cage induction motor is a major issue that limits the use of induction motors in modern energy conversion systems, particularly in electric vehicle applications and also in automated industrial applications (Cao, Bukhari, & Aarniovuori, 2019). The design of the rotor is an important concern during the modelling phase of SCIM as it determines the performance of the motor. The geometry parameters of a rotor slot need to be modelled properly to meet desired performance characteristics of the SCIM (Leicht & Makowski, 2019). Based on the geometry of the rotor slot, the resultant resistance and reactance of the rotor of SCIM are calculated. The resistance and reactance values are key factors involved in the calculation of losses and output power, which influence the torque performance of the SCIM. Therefore, the effect of these rotor slot parameters on torque needs to be tested to improve the rated torque of the motor.

Several research studies have been done with modelling of rotor for induction motors, some of which involve with rotor slot design in SCIM. A research work in (Akhtar, Behera, & Parida, 2014) deals with modelling of SCIM using an analytical model implemented in software a platform and the effect of the magnetic load coefficient on the performance of SCIM was tested via graphical representation. A research work in which the impact of the number of rotor slots on the performance of SCIM is tested using an analytical model of motor (Joksimović, Kajević, Mezzarobba, & Tessarolo, 2020). The effect of rotor slot shapes on the performance of SCIM is tested with different configurations of rotor slots (Makhetha, Muteba, & Nicolae, 2019). A SCIM model has been implemented using the finite element method (FEM) of analyzing electrical motors to compare the existing core loss estimation models (Dlala, 2009). The slits' effect on the stator and rotor slot is tested considering the performance measures efficiency and torque (Arslan, Oy, & Tarimer, 2017). A research work on SCIM investigates the effect of rotor bar and stator bar shapes on the performance of the motor by using two-dimensional analysis of the Ansys FEM software platform, and the optimal modelling of SCIM is simulated through the optimization process with a binary-coded genetic algorithm. Overall parameters of motor are considered as the variables for the optimization and the objective functions are the efficiency and pull-out torque of the motor (Çunkaş & Akkaya, 2006). An analysis of induction motor with the scope of improving of the output power quality by limiting the losses was done with the FEM method by considering the design of the rotor winding pattern (Iqbal & Agarwal, 2014).

In the above-mentioned existing research works with SCIM rotor modelling, a few works use analytical modelling of the motor. Even if some works deal with rotor modelling, there is no research that analyzes the effect of each geometry parameter of rotor slot on rated torque of IM in depth. The rest of the research works involves the FEM method implementation of SCIM using two-dimensional analysis, which is less flexible due to computation issues (Erhunmwun & Ikponmwosa, 2017). On the other hand, FEM is not suitable for the preliminary design phase of the motor, including the parametric study, particularly for optimal modelling and rated torque-related analysis (Juhaniya, Ibrahim, Zainuri, & Zulkifley, 2022). This research work illustrates a study investigating the effect of three rotor slot parameters, namely slot opening height, depth of rotor slot, and rotor slot width, on the rated torque of the SCIM by using an analytical model of the motor implemented in the MATLAB software platform. The following section describes the methodology used for research work. The results obtained from the simulation are analyzed and discussed in Section 3, and eventually the conclusion of the research work is drawn in Section 4.

II. MATERIALS AND METHODS

An analytical model of a squirrel cage induction motor has been implemented in the MATLAB software platform, and simulations with the implemented motor model by varying rotor slot parameters have been plotted to observe the dependency of rotor slot parameters on the rated torque. The first part deals with a mathematical model of an induction motor by considering all design principles. A three-phase medium-rated squirrel cage induction motor with 7.4 hp, 60 Hz, and 460 V is selected for modelling since the motor with this rating can be used for both domestic and industrial purposes. The second part involves the graphical representation of the variation of rotor slot parameters with efficiency as two-dimensional plots and a four-dimensional scatter plot.

A. MODELLING OF SQUIRREL CAGE INDUCTION MOTOR

General specifications of the analytically modelled IM on the MATLAB platform are given in Table 1.

Table 1. Main specifications of SCIM

Parameters	Values
Output power (hp)	7.4
Frequency (Hz)	60
Rated Voltage (V)	460
Power Factor	0.83
No. of Phases	3
No. of Poles (P)	4
No. of turns per phase	180
Rotor type	Squirrel cage
Stator winding connection	Star

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 types of slots. Figure 1 shows a quadrant view of the motor cross-section, and the values of all the main dimensions mentioned in Figure 1 are given in Table 2.

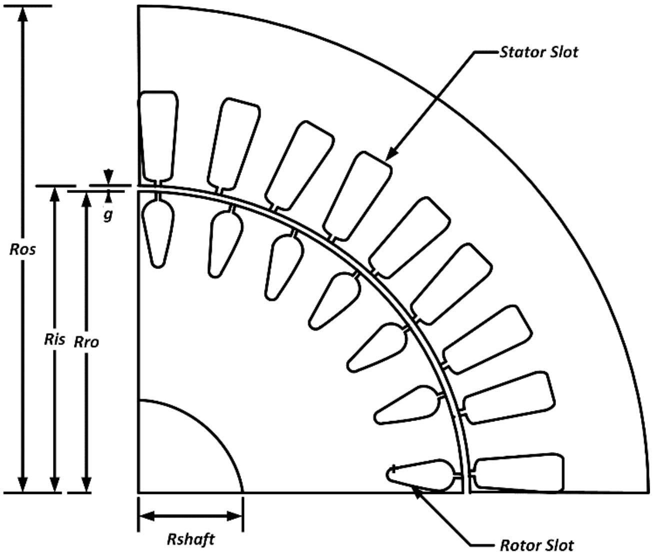

Figure 1: Quadrant View of Motor Cross Section

The values of all main dimensions are calculated by using the main specifications in Table 1 as illustrated in (Boldea & Nasar, 2010).

Table 2. Main dimensions of SCIM

Parameters	Values
Stator outer diameter	180 mm
Stator inner diameter	111.6 mm
Rotor outer diameter	110.9 mm
Core length	132 mm
Airgap length	0.35 mm
Rotor shaft diameter	35 mm
No. of stator slots	36
No. of rotor slots	28

The equations involves with the evaluation of main dimensions are given as follows (Boldea & Nasar, 2010):

$$S_{gap} = \frac{K_E P_{out}}{\eta \cos\varphi} \tag{1}$$

$$D_{is} = \sqrt[3]{\frac{p^2 S_{gap}}{2\pi\lambda f_o C_o}} \tag{2}$$

$$K_E = 0.98 - \frac{0.005p}{2} \tag{3}$$

The stator slot used in the induction motor modelling can be a trapezoidal or round semi-closed slot (Tarımer, Arslan, & Güven, 2012). In this research work, the trapezoidal shape is used because it provides favorable electromechanical characteristics for medium-rated induction motors (Juhaniya, Ibrahim, Zainuri, Zulkifley, & Remli, 2022). The stator slot model used for the stator design is given in Figure 2. All stator slot dimensions are marked in Figure 2. The values used for those stator slot dimensions are represented in detail in Table 3. All stator slot parameters are considered constant values throughout this research work.

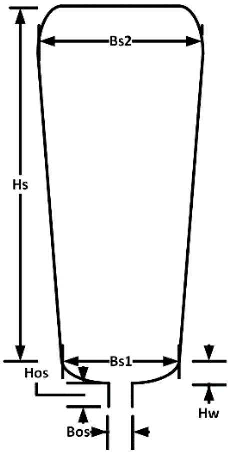

Figure 2: Design of stator slot

Table 3: Stator slot parameter settings

Parameters	Values/(mm)
Bos	2.5
Bs1	5.2
Bs2	9.4
Hos	2
Hw	1.5
Hs	20.5

The resistance and the reactance of the stator can be found as follows (Boldea & Nasar, 2010):

$$R_1 = \frac{\rho_{cu} L_c W_N}{A_{co}\, a_p} \tag{4}$$

$$X_1 = \frac{4\mu_0 \omega L\, {W_N}^2 \lambda_s}{pq} \tag{5}$$

$$\lambda_S = \left[\frac{2(H_S)}{3(B_{S1} + B_{S2})} + \frac{2H_w}{(B_{OS} + B_{S1})} + \frac{H_{OS}}{B_{SO}}\right]\left[\frac{1+3K_B}{4}\right] \tag{6}$$

where R_1 and X_1 represent the stator resistance and stator reactance, respectively, W_N is the number of conductors per slot, ρ_{cu} denotes conductivity of the material, L_c is the total length of stator turn, L refers the stack length, A_{co} refers magnetic wire cross section of the stator conductor, a_p is number of parallel paths, p is number of poles, q denotes number of stator slot per pole per phase. K_B refers the coil span to pole pitch ratio ω is the angular frequency, λ_s refers to the stator slot permeance and μ_0 is the permeability.

B. MODELLING OF ROTOR SLOT

The analytical equations related to rotor slot design and efficiency are derived (Boldea & Nasar, 2010). Figure 3 shows the geometry of the rotor slot used for the analysis.

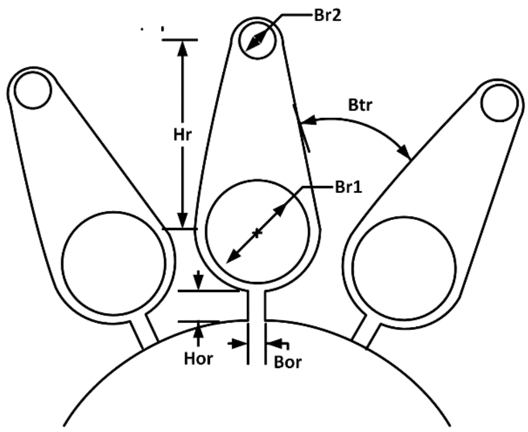

Figure 3: Design of rotor slot

In this research work, correlation between the three-rotor slot parameters Hr, Hor, and Btr and the rated torque of the motor is to be tested within the MATLAB platform. Therefore, it is important to derive a formula for the rated torque of the motor in terms of rotor slot parameters. The formula for the calculation of rotor resistance and reactance can be obtained using the rotor slot geometries considered for this work, Hr, Hor, and Btr. The resistance and reactance of the rotor are computed as follows (Boldea & Nasar, 2010):

$$R_2 = \frac{4m([W K_{w1}])^2 \rho_{cu}}{N_r}\left[\frac{L K_R}{A_r} + \frac{l_{er}}{2A_{er}\sin\left(\frac{\pi P}{N_r}\right)^2}\right] \tag{7}$$

$$X_2 = \frac{4(W K_W)^2 \omega \mu_o L K_X \lambda_r}{N_r} \tag{8}$$

$$\lambda_r = 0.66 + \frac{2H_r}{3(Br1 + Br2)} + \frac{H_{or}}{B_{or}} \tag{9}$$

where R_2 and X_2 represent the rotor resistance and rotor reactance, respectively, m refers number of phases, W is number of turns per phase, K_w represents winding factor, ρ_{cu} denotes conductivity of the material, L is the stack length, A_r and A_{er} are the overall areas of the rotor slot and end ring, respectively, K_R, K_X are the skin effect coefficients of the rotor resistance and reactance, respectively, l_{er} is the length of the end ring, N_r refers to the number of rotor slots, ω is the angular frequency, λ_r refers to the rotor slot permeance and μ_o is the permeability.

The formula for the calculation of rated torque can be derived as follows:

$$\tau_{rated} = \frac{3P_1 {V_{ph}}^2 R_2}{\omega S\left[\left(R_1+(1+\frac{X_1}{X_m})\frac{R_2}{S}\right)^2+\left(X_1+(1+\frac{X_1}{X_m})X_2\right)^2\right]} \tag{10}$$

where V_{ph} is the input phase voltage, R_1 and X_1 are stator resistance and reactance, respectively, and S refers to the slip of the motor. The flow chart used for the analytical implementation of SCIM is depicted in Figure 4.

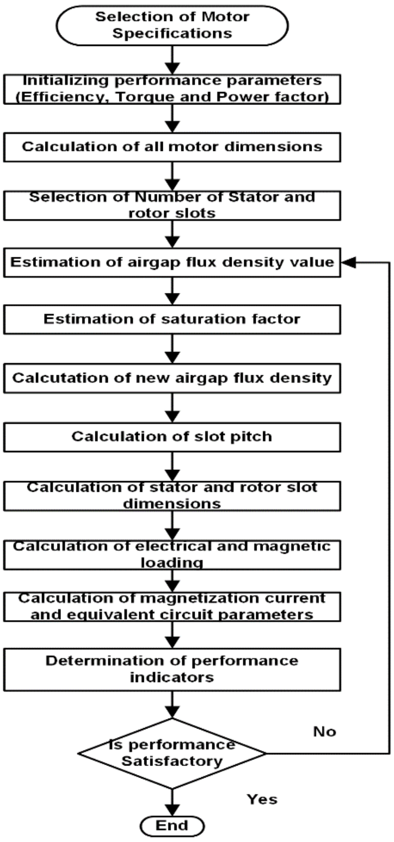

Figure 4: Flow chart for implementation motor model in MATLAB

In order to test the dependency of the three rotor slot parameters Hor, Hr, and Btr, the analytical model of the SCIM is created in the MATLAB environment after formulas for the rated torque in terms of rotor resistance and reactance are derived. In order for performance to be considered good, efficiency must not fall below 89%, and other performance metrics like power factor and rated torque must be within the allowable range. Subsequently, the developed motor is validated using the FEM model of IM. After validation, the efficiency output of the motor has been recorded and plotted to show the dependency after the motor has been implemented, with three parameters of the rotor slot being varied. The findings of the MATLAB simulation are thoroughly detailed in the next section.

III. RESULTS AND DISCUSSION

Initially, the induction motor is coded for a fixed value of the rotor slot geometries and the performance of the motor is plotted. Figure 5 represents the variation of rated torque with motor speed for a constant geometry of rotor slot. The initial settings for the rotor slot parameters Hr, Hor, and Btr are 10 mm, 5 mm, and 5 mm, respectively. The rated torque at initial settings is observed at 34.8 Nm at the rated speed of 1754 rpm (rotor speed).

Subsequently, the individual variations of rotor slot parameters (Hr, Hor, and Btr) are observed and discussed in the following subsections.

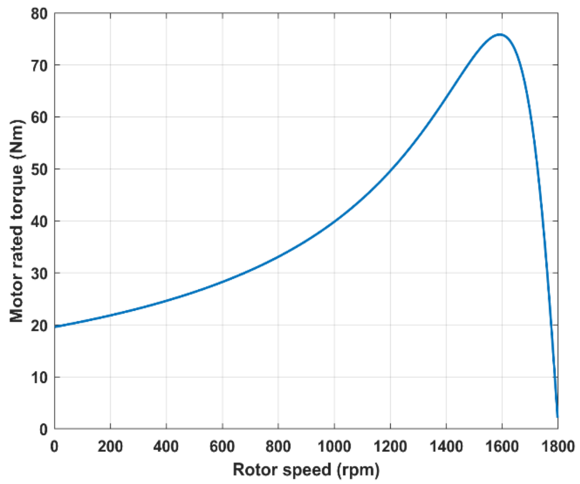

Figure 5: Variation of rated torque with rotor speed at initial settings

A. VALIDATION OF DEVELOPED INDUCTION MOTOR WITH FEM METHOD

The developed IM has been tested with Ansys Electronics Desktop FEM software for validation purposes. The FEM of IM is developed by using the Rmxprt model, and then it is further analyzed by creating a Maxwell 2D model of IM for the transient analysis. The FEM model provides a rated torque value of 34.78 Nm at a speed of 1754.1 rpm, which is very close to the results obtained from the analytical model of IM. In addition, flux density constraints for the stator and rotor teeth of IM are given as 2.1 T and 2.2 T, respectively (Boldea & Nasar, 2010; Juhaniya, 2023). Moreover, the magnetic flux density distribution of the developed IM is simulated from the Maxwell 2D model of the IM, as shown in Figure 6.

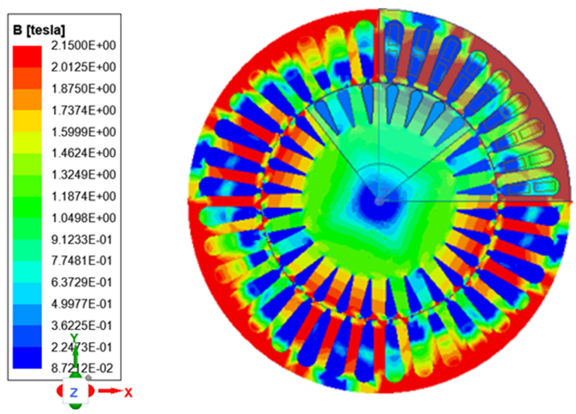

Figure 6: Variation of rated torque with rotor speed at initial settings

The maximum flux density of the stator and rotor yoke of the developed IM is 2.1 T, which is close to the design constraints of the stator and rotor densities. However, some areas in the stator yoke has high flux density which can be tackled considering the higher value for the stator outer diameter. Therefore, it is evident that the designed analytical model operates below the saturation point of the core material. The maximum flux densities occur near the stator and rotor tooth wedge areas, along with some yoke areas of the stator which are close to the saturation level. As a matter of fact, the flux distribution proves that the designed motor will operate within the flux density constraints.

B. INDIVIDUAL VARIATION OF ROTOR SLOT PARAMETERS WITH RATED TORQUE

Individual variations of three selected parameters of the rotor, namely, Hor, Hr, and Btr, with torque are plotted to investigate the dependency of rotor slot design on the rated torque of the SCIM. Figure 7 illustrates the variation of rated torque with Hr.

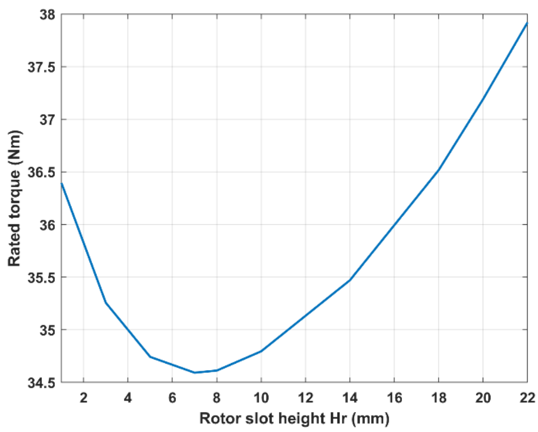

Figure 7: Variation of rated torque with Hr

The Hr value is increased from 1 mm to 22 mm while keeping the Hor and Btr values at 1mm and 5 mm, respectively. From the graph, it can be seen that the torque at the rated condition is affected by the rotor slot height. In addition, the larger value of Hr gives higher rated torque. When the deepness of the rotor slot increases, the area will increase, which causes lower rotor resistance. Therefore, the losses related to rotor resistance will be reduced, which leads to a decrease in slip of the motor and an increase in rated torque for larger Hr. Although the reactance increases with the increase in rotor slot height, due to the high impact of the motor speed and slip on the rated torque, it shows an increment. The highest rated torque of 37.8 Nm is obtained when Hr is set at 22 mm.

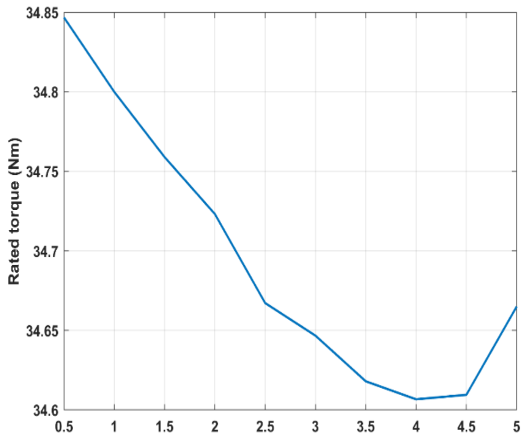

Figure 8: Variation of rated torque with Hor

The variation of efficiency with slot opening height Hor is given in Figure 8. Both Hr and Hor show similar variation profiles with efficiency.

The Hor is varied from 0.5 mm to 5 mm, whereas the Hr and Btr values are kept at 10mm and 5 mm, respectively. The rated torque has acceptable best values for lower values of Hor because Hor is in the area near the airgap length, which is tightly coupled with the stator flux lines. Furthermore, for the lower values of Hor, rotor reactance has decreased because of a smaller leakage flux. When comparing the variation of Hr and Hor with the rated torque, Hr shows more impact on the rated torque since it has a high influence on the rotor resistance and reactance value. The highest value, 34.85 Nm, is obtained when Hor is set at 0.5 mm. In addition, the influence of rotor tooth width Btr on rated torque is depicted in Figure 9.

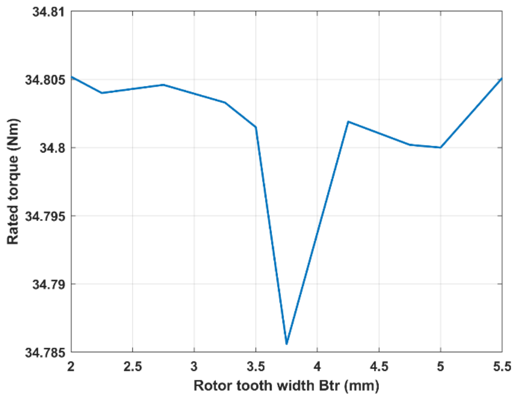

Figure 9: Variation of rated torque with Btr

Btr is varied from 2mm to 5.5 mm, whereas Hr and Hor values are kept constant at 10mm and 1 mm, respectively. Rated torque variation with Btr shows a completely different profile when compared with the variation of rated torque with Hr and Hor. Since Btr has a high influence on air gap flux density rather than much influence on the resistance and reactance values of the rotor slot, it shows a different profile with rated torque. The rated torque gains only 0.005 Nm when compared with the value at initial settings. In addition, variation of rated torque is not significantly varied in the case of Btr variation, but it has less impact on the torque performance of the motor.

The simultaneous analysis of these parameters will have a greater effect on deciding the impact of rotor slot parameters on the rated torque of the motor. The following sub-section describes the analysis of rated torque by amalgamating all three rotor slot parameters taken into account.

C. VARIATION RATED TORQUE WITH ALL SELECTED PARAMETERS

Individual variations of all parameters with rated torque have been tested as a first part of the results. Since analyzing all parameters together will give more significant outcome for the analysis, variation of rated torque with all three rotor slot parameters has been plotted as a four-dimensional scatter plot. Figure 10 represents a four-dimensional scatter plot of all three parameters versus rated torque.

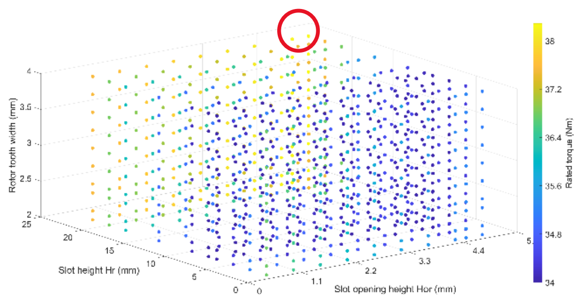

Figure 10: Variation of rated torque with all selected parameters

According to the 4-Dimensional scatter plot of all parameters with rated torque, the highest torque at 38 Nm is obtained, and all parameters are set at their maximum values as marked by the circle. At the maximum value of rated torque, the values of Hr, Hor, and Btr are 22 mm, 5mm, and 5-5.5 mm, respectively. Based on the color variation, it is clearly shown that Hr has a higher impact on torque performance than Hor and Btr. It is evident that the rated torque is improved by 3.2 Nm in comparison with the rated torque at the initial settings.

IV. CONCLUSION

This research work carries out an analysis of the influence of rotor slot geometry parameters on rated torque. Individual variations of three selected parameters with rated torque are plotted using an analytical model of an induction motor implemented in the MATLAB software environment. The developed IM is validated with FEM analysis with Ansys. From the individual variation plots, it is evident that these three-rotor slot parameters have a high impact on the efficiency of the squirrel cage induction motor, which happens because of variation in rotor resistance and reactance and also variation in flux linkage due to the variable geometry of the rotor slot. For individual analysis, torque can be improved by 2.8 Nm, 0.05 Nm, and 0.005 Nm for Hr, Hor, and Btr, respectively. The result of simultaneous analysis of rotor slot parameters with rated torque provides a 3.2 Nm improvement in torque when Hr, Hor, and Btr are set at 22 mm, 5mm, and 5-5.5 mm, respectively. Therefore, the performance of the motor can be improved by selecting better values of these geometry parameters to obtain adequate rated torque. Further work will encompass the application of the optimization process of the motor using metaheuristic algorithms to maximize the performance measures of not only the efficiency but also the torque and power factor of the motor considering the different outer diameter values for stator.

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