Analysis of the Effect of Rotor Slot Type on Torque Ripple in Induction Motors by Finite Element Method

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Abstract: Induction motors are the most widely used motors in industry and home applications due to their robust structure, cheapness, low maintenance and high efficiency. The torque-speed characteristic, which is one of the most critical parameters of induction motors, is highly influenced by rotor slot structures. Therefore, slot type and slot sizing should be performed properly to maximize motor performance during the design process of the induction motor. In the design stage of the induction motor, the choice of rotor slot structure, as well as other parameters are of great importance, while effects such as torque ripple, acoustic noise, and mechanical vibrations should be taken into consideration topics for motor designers. In this study, the effects of torque ripple in induction motors and the changes of torque ripple in different rotor slot structures are investigated. The analyses are performed using the Maxwell RMxprt program. Firstly, static motor models were created and analyzed in the RMxprt program. Afterward, 2-D models of the motors are created and analyzes are carried out to obtain torque ripple changes. 7 different slot geometries are used in the rotor slot structure. Rotor slot geometry with minimum torque ripple and the best performance criteria are determined from the motor models. A 90 kW, 3-phase, squirrel cage induction motor is used as the motor model. According to the obtained results, there was a 31.6% difference between the lowest and the highest torque ripple ratio.

Keywords: Induction motor, torque ripple, finite element method, rotor slot types.

How to cite this article
Yetgin A. G., Durmus, B., “Analysis of the Effect of Rotor Slot Type on Torque Ripple in Induction Motors by Finite Element Method”, El-Cezeri Journal of Science and Engineering, 2020, 7(2); 536-542.

Asenkron Motorlarda Rotor Oluk Tipinin Moment Dalgalanması Üzerindeki Etkisinin Sonlu Elemanlar Yöntemi ile Analizi

Öz: Asenkor motorlar, sağlam yapıları, ucuz olmaları, az bakım gereksinimleri ve yüksek verimleri nedeniyle sanayi ve ev uygulamalarında yaygın kullanılmaktadırlar. Asenkor motorlarının en kritik parametrelerinden birisi olan moment hız karakteristiği rotor oluk yapılımasına oldukça bağlıdır. Bu nedenle, asenkor motorunun tasarım sürecinde motor performansını en üst düzeyde çıkarmak için oluk tipi ve oluk boyutlandırması düzgün şekilde seçilmesi oldukça önemlidir. Asenkor motorun tasarım aşamasında, rotor oluk yapısının ve diğer parametrelerin seçimi büyük önem taşır, moment dalgalanması, akustik gürültü ve mekanik titreşim gibi etkenlerin etkili olduğu göz önünde bulundurulmalıdır. Bu çalışmada, asenkor motorlarda moment dalgalanmasını etkileyen oluk tipi ve oluk boyutlandırması analizleriyle ele alınmıştır. Analizler Maxwell RMxprt programı kullanılarak yapılmıştır. İlk olarak RMxprt programında statik motor modelleri oluşturulmuş ve analizler gerçekleştirilmiştir. Daha sonra motorların 2-D modelleri oluşturulmuş ve moment dalgalanmasına, akustik gürültü ve mekanik titreşim gibi etkenlerin etkisi analiz edilmişdir. Motor modeli olarak 90 kW, 3 fazi, sincap kafesli asenkor motor kullanılmıştır. Elde edilen sonuçlar göre, moment dalgalanması %31.6’lık bir fark olduğunu göstermiştir.

Anahtar kelimeler: Asenkor motor, moment dalgalanması, sonlu elemanlar yöntemi, rotor oluk tipi.
1. Introduction

The Induction Motor (IM) is widely used in industrial applications as a result of its robustness, low price, reliability and easy maintenance [1]. Besides, induction motors have been gaining increasing interest as a potential electrical machine type to compete with permanent magnet machines for traction applications that require variable speed and torque using power electronic converters. This is due to their rugged structure, technology maturity, and the elimination of expensive rare earth permanent magnets. Nevertheless, the parasitic effects such as torque ripple, acoustic noise, and mechanical vibrations remain challenging issues for machine designers. Analytical studies can provide physical insights to the problems, but cannot offer results as accurate as those of numerical calculations such as Finite Element Analysis (FEA) [2].

Torque ripple is caused by an interaction between the non-sinusoidal flux distribution from both stator and rotor currents and the Magneto-motive Force (MMF). The non-sinusoidal nature of the flux distribution can be attributed to two sources: the time harmonics produced by the inverter and the spatial harmonics from the machine design itself, due to the finite number of stator and rotor slots, discrete number of stator windings, and iron saturation effects [2]. Also, this component can be influenced by changes to the geometry of the machine design, the number of poles, the magnet angle, and the slot opening width are important parameters to have a look at [3].

Torque ripple have negative effects on induction motor performance and are as follows: Reduce the efficiency, increase the losses and reduce the life of the spare parts [1], it causes additional harmonic loss and it will try to induce speed ripple in a low inertia system [4], it causes acoustic noise and mechanical vibration [5], and it affects machine performance significantly in high precision position control applications [6].

Researchers have started to work on this subject in recent years in order to reduce the effect of torque ripple. Dip and friends’ paper implements a simple technique for the Direct Torque Control (DTC) of an induction motor which overcomes the trouble of high torque ripple afflicting the conventional DTC technique, this technique is quite simple and is appropriate for modern digital signal processors (DSPs) [7]. Ho-Hyun and his colleagues’ paper aims to reliably evaluate the torque ripple of an optimal designed 3-phase induction motor using the measurement uncertainty theory [8]. In Te-Jen and friends’ article, model predictive torque control based on particle swarm optimization is proposed to modify the model predictive torque control in order to improve the control qualities, especially the steady-state torque ripples [9]. Koushik and et al.’s paper aims at further reduction in the pulsating torque by employing advanced bus-clamping switching sequences, which apply an active vector twice in a sub-cycle [10]. Ouahid and friends stated that torque ripple of induction motor can be significantly reduced by using Power Control Pulse Width Modulation (PCPWM) inverter [11]. Abdelli’s paper describes a torque ripple reduction technique with constant switching frequency for direct torque control of an induction motor. Their method enables a minimum torque ripple control. They propose a control technique for induction motor in order to obtain a constant switching frequency and hence a torque ripple reduction [12]. In Kaboli and colleagues’ paper, the effect of flux reference value on the torque ripple of a direct torque controlled induction motor is analyzed. The effect of flux value on torque ripple in a wide range of speed variations is investigated [13]. Ranjit and Inderpreet present a Dynamic Fuzzy Logic based on Prediction Direct Torque Control (DFL PDTC) technique to reduce torque ripples within the squirrel cage induction motor. They stated that this DFL and PDTC combination reduces the high amount of torque ripple and improves the starting conditions in both low and high mechanical speeds of the motor [14].

When the studies in the literature are examined, it is seen that additional hardware and software tools such as power electronics, control algorithms, drive systems are used to reduce torque ripple.
In this study, to see the effect of torque ripple, induction motor models with different rotor slots have been created and rotor slot geometry with minimum torque ripple and best performance have been found. The objective of the paper is to determine which rotor slot type produces the least torque ripple ratio from motors with the same power, specification, and size.

2. Method and Motor Models

In motors with many design parameters such as induction motors, static and transient analyzes are difficult and time-consuming processes. Software such as the finite element method can easily perform both static and transient analyzes of the motor according to analytical methods. Besides, the accuracy of the obtained results is clearer. In this study, motor models were made in the Maxwell RMxpert program [15]. First, the geometric values of the motors, the materials, and the stator and rotor slot geometries were determined and static analyzes were performed. Then, transient analyzes were performed to obtain the change of torque ripple from motor models.

Nameplate values of 3-phase, squirrel cage induction motor used in the study are given in Table 1 [16].

Table 1. Induction motor nameplate values.

| Parameters          | Value     |
|---------------------|-----------|
| Power               | 90 kW     |
| Voltage             | 380 V     |
| Current             | 168 A     |
| Connection          | Star      |
| Frequency           | 50 Hz     |
| Power Factor        | 0.81      |
| Rotor Speed         | 1463 rpm  |
| Nominal Torque      | 587 N.m   |
| Number of Stator Slot | 48       |
| Number of Rotor Slot | 38       |

In this study, 7 different geometries are used in rotor slots of induction motor. Rotor slot height and rotor slot mouth opening values were taken the same except slot 6 and slot 7.
The differences in rotor slots are that the slot lower and upper width values and the end portions of the slots have a round or rectangular structure. Also, slot wedge height and width values are selected different values in order to avoid saturation between air-gap length and wedge. 2-D Maxwell image of the analyzed motor model (rotor slot geometry: Slot 1) is given in Figure 1.

7 different rotor slot geometries created for the analysis of torque ripple values are given in Figure 2. In motor models, dimensioning of stator frame and dimension values of stator slot geometry, winding structure, and core properties were taken the same. All parameters of the slot 7 except the slot height are the same as slot 1.

![Figure 2. Rotor slot geometries used in modeling.](image)

The values of the rotor slot parameters of the motor models are given in Table 2. Rotor slot height values are taken equally in other motor models except slot 6 and slot 7. Values are given in mm.

| Parameters          | Symbol | Slot 1 | Slot 2 | Slot 3 | Slot 4 | Slot 5 | Slot 6 | Slot 7 |
|---------------------|--------|--------|--------|--------|--------|--------|--------|--------|
| Slot Height         | $h_r$  | 22.5   | ---    | 33     | ---    | 14     | 5.5    | ---    |
| Slot Mouth Opening  | $b_{r0}$ | 1.5    | ---    | ---    | ---    | ---    | ---    | ---    |
| Slot Upper Width    | $b_{r1}$ | 5.5    | 8      | 8      | 8      | 6      | 8      | 14     |
| Slot Lower Width    | $b_{r2}$ | 8      | 8      | 8      | 8      | 9      | 14     | 5.5    |
| Slot Wedge Height   | $h_l$  | 1      | 1.5    | 2      | 1.5    | 1.5    | 1.5    | 1      |
| Slot Wedge Width    | $h_r$  | 3      | 3      | ---    | 2      | 2      | ---    | 3      |
| Radius              | $R_s$  | ---    | 4      | 0      | 2      | 0      | ---    | ---    |

2.1. Torque ripple analysis

Torque ripple ($T_{max} - T_{min}$) value has been stated to increase the average torque value in some studies in the literature [17]. At first glance, this may result in an increase in output power, but the values of the other motor parameters to be considered here. For this reason, taking a complete performance evaluation by taking into consideration the critical parameters such as losses and efficiency will be effective in achieving healthier results.

The ratio of torque ripple ($\% T_{ripple}$) in induction motors can be calculated using the formula given in Eq. 1 [18]. In the equation, $T_{max}$ is the maximum torque value, $T_{min}$ is the minimum torque value, $T_{avg}$ is the average torque value.

$$\% T_{ripple} = \frac{T_{max} - T_{min}}{2 \cdot T_{avg}}$$ (1)
3. Analysis Results

The torque changes obtained for 7 different rotor slot geometries analyzed by the finite element method are given in Figure 3.

![Figure 3. Torque changes for motor models.](image)

When Figure 3 is examined, it is seen that each rotor slot geometry performs different torques and torque ripple ratio for 200 ms. It is seen that the minimum torque value is obtained from slot 6 with -823 N.m, and the highest torque value is obtained from slot 3 with 613 N.m.

The maximum, minimum, average torque values and the ratio of torque ripple obtained from each rotor slot geometry are given in Table 3.

| Parameters | Slot 1     | Slot 2     | Slot 3     | Slot 4     | Slot 5     | Slot 6     | Slot 7     |
|------------|------------|------------|------------|------------|------------|------------|------------|
| $T_{\text{max}}$ | 582.2743   | 574.6702   | 613.3173   | 595.9205   | 577.3838   | 526.2253   | 505.2949   |
| $T_{\text{min}}$ | -684.1060  | -668.9161  | -721.1488  | -706.2841  | -662.3002  | -823.6511  | -646.738   |
| $T_{\text{avg}}$ | 304.7123   | 282.7433   | 327.7394   | 296.9112   | 310.1991   | 296.8937   | 219.0371   |
| $\% T_{\text{ripple}}$ | 2.0779     | 2.1991     | 2.0358     | 2.1929     | 1.9982     | 2.2733     | 2.6297     |

When Table 3 is examined, it is seen that torque ripple ratios obtained from motor models with equal rotor slot height values vary between 2% and 2.2%. It is observed that the small changes in
these ratios are caused by the lower and upper width values of the slots and the round or rectangular structure of the slots. The fact that the torque ripple ratios obtained from the motor models having the same slot height value is close to each other shows that the effect of other slot parameters is limited. It is seen that the torque ripple ratio increases if the slot geometry is a circle. This results in a reduction in the tooth width due to the slot geometry, which in turn causes the magnetic flux lines to oscillate in the air gap part without being able to fully migrate to the rotor.

It shows that the torque ripple ratio obtained from slot 7 increases rapidly with increasing slot height value. It is also seen that the minimum average torque value is obtained with 219 N.m of this slot type. Besides, although the maximum torque ripple ratio is obtained from slot 7, the torque oscillation value in this slot is the smallest with 1156 N.m.

As a result of static analysis, it was determined that the nominal torque values of the motor models have been changed ranged between 583 N.m and 588 N.m. It is concluded that the slot type to be selected for this motor model is the slot 5 type which gives the minimum torque ripple ratio.

4. Conclusions

In this study, the torque ripple ratios of the motor were determined by using the finite element method for 7 different slot geometries. According to the obtained results, it was concluded that the upper and lower width values of the slot did not make an effective difference in the torque ripple ratio. It was seen that the torque ripple ratio increased and the average torque value decreased with increasing slot height value. Considering that there is a ratio of 31.6% between the lowest and highest torque ripple ratio, it is seen that the slot height is the critical parameter for the torque ripple ratio. The effect of such a ratio on the vibration and noise of the motor will be more clearly recognized. It was also found that the maximum torque ripple ratio does not mean that it would have the largest torque oscillation.

In the future studies, different rotor slot geometries can be analyzed by optimizing the slot height value.

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