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RESEARCH ARTICLE

A NEW MOTOR DESIGN METHOD for INCREASING the AVERAGE TORQUE VALUE in SWITCHED RELUCTANCE MOTOR

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ABSTRACT

Switched reluctance motors have been widely used in industry in recent years. One of its most important advantages is its high-power density and its independence from rare magnet poles. In this study, a new motor design is proposed to increase the average and maximum torque values of a 2.2 kW switched reluctance motor. In the proposed design, slits are opened in the poles in the rotor core. Magnetic field and potential vector distributions, inductance, current and torque values are obtained for reference and slitted motor models. Analyzes were made using the Maxwell 2-D program. According to the results, it is determined that the proposed motor design for the same size and power values provides an improvement in the average and maximum torque values.

Keywords: *Switched Reluctance Motor, Slitted Motor, Torque Analysis*

1. INTRODUCTION

Many applications in the industry require the design and use of electrical machines with a large power-weight ratio. In most of these applications, while high efficiency is required, machines that provide high torque and operate at high speed are required. In this context, Switched Reluctance Motors (SRM) are known to operate at high torque or exceptionally high speeds, making them an ideal machine for such applications [1]. Switched reluctance motors have become one of the preferred electric motor types in industrial applications due to their simple structure, low cost and high torque density, high speed capacity [2], superior features such as robust structure and high reliability [3], high efficiency [4]. In recent years, with the use of SRM in various applications such as electric vehicles, aviation, ships, wind power generation and household appliances, improving motor driver and motor performance has become a priority for researchers [4]. Studies carried out in order to increase the performance of SRM can be grouped into two groups. The first of these is the work on the geometric structure of the motor. The second one is the studies on the motor driver circuit / control. On the basis of these studies, it is aimed to reduce the torque oscillations, one of the biggest disadvantages of SRMs, and to increase the average torque value.

Aydoun et al., in their studies, made a performance evaluation using grain-oriented electrical steel and non-oriented electrical steel in the rotor core of a switched reluctance motor. They have shown that the grain-oriented electrical steel motor model provides a 16% improvement in the average torque value of the motor [1]. Han et al. evaluated the starting performance of a 12/8 pole switched reluctance motor in their study. According to their results, they showed that as the stator pole arc coefficient value increased, the starting torque of SRM increased and the starting torque of SRM could be improved by decreasing the air gap length appropriately [5]. Gondaliya and Tita carried out a new design of a new outer rotor switching reluctance motor and performed a performance comparison with an internal rotor SRM. According to their results, they stated that the torque value of outer rotor SRM is higher and this will result in a reduction in the size and cost of the motor [6]. Vattikuti et al. proposed a high torque and low loss reluctance machine design in their studies. They stated that the proposed segmented switched reluctance motor was 14% lighter than the variable switched reluctance motor (for the same frame) due to structural changes in geometry, and that an improvement in torque was achieved by 62% [7].

In this study, in order to increase the performance of the switched reluctance motor, slits were opened in the rotor poles. The purpose of these slits is to improve the magnetic flux value and to allow the flux lines to enter the inner parts of the rotor without dispersing. In addition, an additional air gap electromagnetic torque is provided thanks to the variable air gap reluctance thanks to the opened slits. In this context, three slits were opened on each of the rotor poles to create a variable reluctance effect. While the width of the slits is 0.1 mm, the depth is equal to the height of the pole. Magnetic field distribution, vector potential distribution, change of torque, current and inductance values for reference and slit motor models are analyzed.

The mathematical model and formulations of the switched reluctance motor is given in the second section of the study. The proposed slitted motor model is presented in the third section and the analysis results obtained from the models are given in the fourth section. In the last section, results and discussion are given.

2. SRM MATHEMATICAL MODEL

As with all electric motors, accurate determination of motor parameters is essential for simulation applications and motor control methods. This is particularly important in switched reluctance motors, which is a function of phase inductance and torque of the non-linear rotor position. These parameters can be obtained by analytical calculations, finite element method or measurements if the motor is produced [8].

In order to obtain the equivalent circuit of a switched reluctance motor, the mutual inductance between phases must be neglected due to it is too small [9]. The voltage applied to a phase is obtained by adding the voltage drop on the resistor and the flux linkage ratio and it is given in Eq. 1 [10].

$$V = R_s i + \frac{d\lambda(\theta,i)}{dt} \tag{1}$$

In the expression, R_s is the resistance per phase, i is the phase current, θ is the rotor position, and λ is the flux linkage value per phase given in Eq. 2 [11].

$$\lambda = L(\theta,i)i \tag{2}$$

In the expression, L refers to the winding inductance depending on the rotor position and phase current. Phase voltage is given in Eq. 3 [10].

$$
\begin{aligned}
v &= R_s i + \frac{d\{L(\theta,i)i\}}{dt} = R_s i + L(\theta,i)\frac{di}{dt} + i\frac{d\theta}{dt}\cdot\frac{dL(\theta,i)}{d\theta} \\
&= R_s i + L(\theta,i)\frac{di}{dt} + \omega_m i\frac{dL(\theta,i)}{d\theta}
\end{aligned} \tag{3}
$$

The three terms on the right side of this equation refer respectively to the voltage drop on the winding resistance, the inductive voltage drop on the phase winding and the electromotive force (emf) induced in the phase winding. The induced emf in the phase winding is given in Eq. 4 [10].

$$
e = \omega_m i\frac{dL(\theta,i)}{d\theta} = K\omega_m i \tag{4}
$$

Here K can be taken as an emf constant similar to a series excited DC machine. ω_m is the angular speed. From the voltage and induced emf expressions, the equivalent circuit for single phase of SRM is generated and is given in Figure 1.

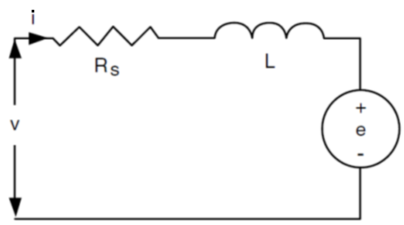

Figure 1. Single phase equivalent circuit model of SRM [10].

The motor's input power is obtained by multiplying the voltage value with the current, and it is given in Eq. 5 [11].

$$
pi = vi = R_s i^2 + i^2\frac{dL(\theta,i)}{dt} + L(\theta,i)i\frac{di}{dt} \tag{5}
$$

After the input power is obtained, the air gap power of the SRM is obtained. Air gap power can be written as in Eq. 6.

$$
P_{airgap} = \omega_m T_e \tag{6}
$$

The electromagnetic torque expression obtained in the air gap in the switched reluctance motor is given in Eq. 7. The expression can be thought as the value of the electromagnetic torque produced by deriving the co-energy stored in the magnetic core by the phase winding according to the rotor position [12]. It is assumed that the material used in the model is ideal, so there is no magnetic saturation.

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$$T_e = \left.\frac{\partial W^{'}(\mathrm{i},\theta)}{\partial \theta}\right|_i$$
$$W^{'}(\mathrm{i},\theta) = \frac{1}{2}L(\theta)i^2 \tag{7}$$
$$T_e = \frac{1}{2}i^2\frac{dL(\theta)}{d\theta}$$

As can be understood from the statement, it is seen that the air gap electromagnetic torque in switched reluctance motors changes depending on the current, inductance and rotor position.

The winding inductance value is obtained by dividing the number of phase windings (N) by the total reluctance ($\Re$) value of the magnetic circuit of the motor and is given in Eq. 8 [12].

$$L = \frac{N^2}{\Re} \tag{8}$$

Reluctance value is calculated separately for magnetic core and air gap parts and is given in Eq. 9 [12]. In the expression, R_{core} and R_{gap} represent the reluctance value of the magnetic core and the air gap length, respectively, l and l_g are the length of the magnetic path and the air gap length, S is the area, μ_0 and μ_r, respectively, the permeability of free space and the magnetic material.

$$\Re_{core} = \frac{l}{\mu_0 \cdot \mu_r \cdot S}; \quad \Re_{gap} = \frac{l_g}{\mu_0 \cdot S} \tag{9}$$

In SRM, torque always tries to move the rotor to the highest inductance position. The inductance values obtained while the rotor is moving from the misaligned position to the aligned position are given in Figure 2 [13]. If the stator and rotor cores are aligned, a minimum air gap length occurs and naturally, minimum reluctance occurs. Thus, the inductance value is maximum. In the opposite case, it is seen that the inductance is at a minimum level.

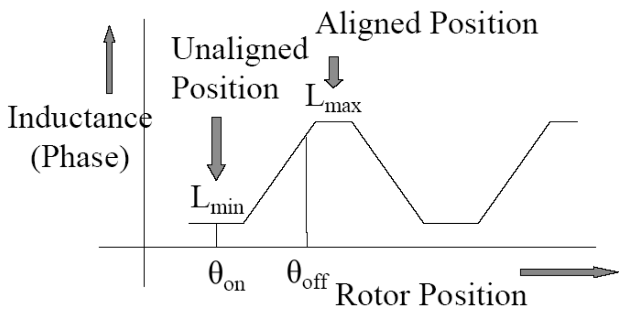

Figure 2. Change of inductance according to rotor position [13].

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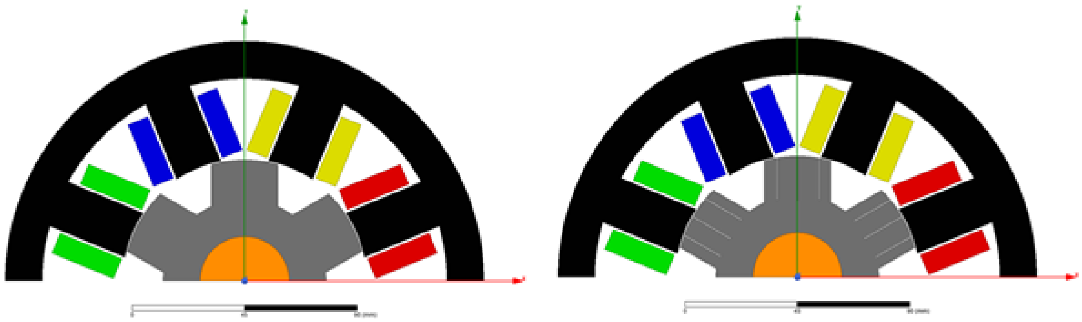
3. PROPOSED MOTOR MODEL

The stator of the SRM is made of silicon alloy steel material with inward protruding poles. The number of stator poles can be even or odd, but most of them are manufactured in even numbers. The rotor of SRM is made of silicon steel material, also silicon alloy with outward protruding poles. The number of rotor poles is also preferably even and less than the number of stator poles [14]. The features and dimensions of the reference motor used in the modeling are given in Table 1. The motor stator and rotor poles are determined as 8 and 6, respectively. 1008 steel was used as magnetic material. Stator pole winding number is 51.

Table 1. Specifications and dimensions of reference motor [15].

Parameters	**Values**
Power [kW]	2.2
Voltage [V]	230
Stator Outer Diameter [mm]	194
Stator Inner Diameter [mm]	99
Rotor Outer Diameter [mm]	98
Number of Stator/Rotor Poles	8/6
Stator/Rotor Yoke Thickness [mm]	15/15
Stator/Rotor Embrace	0.5/0.5
Shaft Diameter [mm]	36
Length [mm]	110

The cross-sectional images of the reference motor model and the proposed motor model are given in Figure 3.



(a) (b)

Figure 3. Cross-sectional view of motor models (a) Reference motor model (b) Slitted motor model

In the study, a slitted structure is proposed in order to increase the torque value of the switched reluctance motor. In the proposed slitted structure, slits are opened in the rotor poles. The depth of the slits is equal to the depth of the rotor pole. The width of the slits was chosen 0.1 mm in order to avoid saturation in the rotor poles. Choosing wide slits reduces the rotor pole tooth thickness, which causes saturation in the rotor poles. Likewise, if the number of slits in the rotor poles is high, saturation occurs in the rotor poles. Three slits are made on each rotor pole. The main purpose of opening the slits is to increase the length of the air gap between the stator and rotor poles and accordingly to

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increase the reluctance value. The detailed section view of the proposed slitted motor model is given in Figure 4.

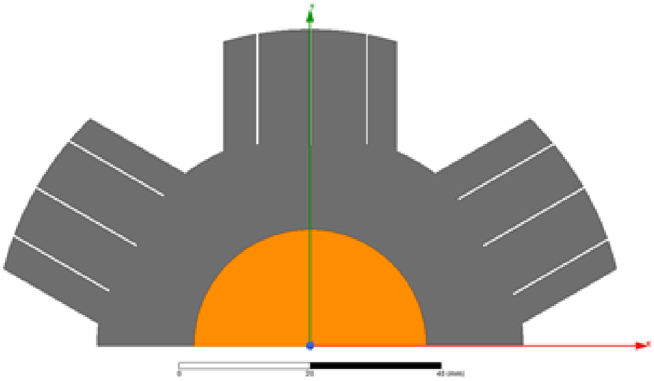

Figure 4. Detailed section of the slitted motor model.

4. OBTAINED RESULTS

RMxprt is an interactive software package used to design and analyze electrical machines. It is a template-based electrical machine design tool that provides fast and analytical calculations of machine performance. Various machines can be simulated and performance analysis can be performed using RMxprt. With the help of Maxwell, static electric fields, static magnetic fields, time varying magnetic fields and transient state analysis can be performed [14].

The analysis of reference and slitted motor models have been solved in Ansys Maxwell 2-D transient solver. The torque, current and inductance changes of each motor model are obtained. Torque changes for reference and slitted motor models are given in Figure 5. In Table 2, average and maximum torque values of both motor models are given.

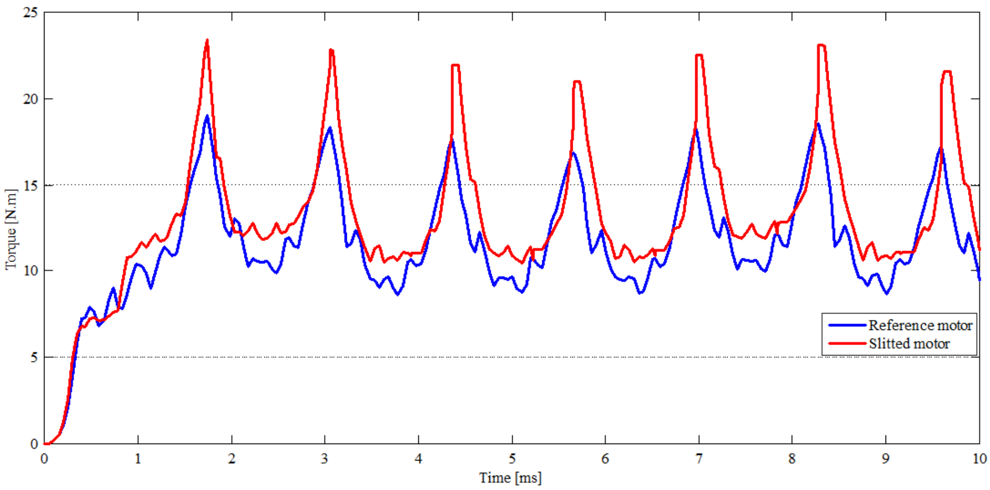

Figure 5. Torque variation for reference and slitted motor models.

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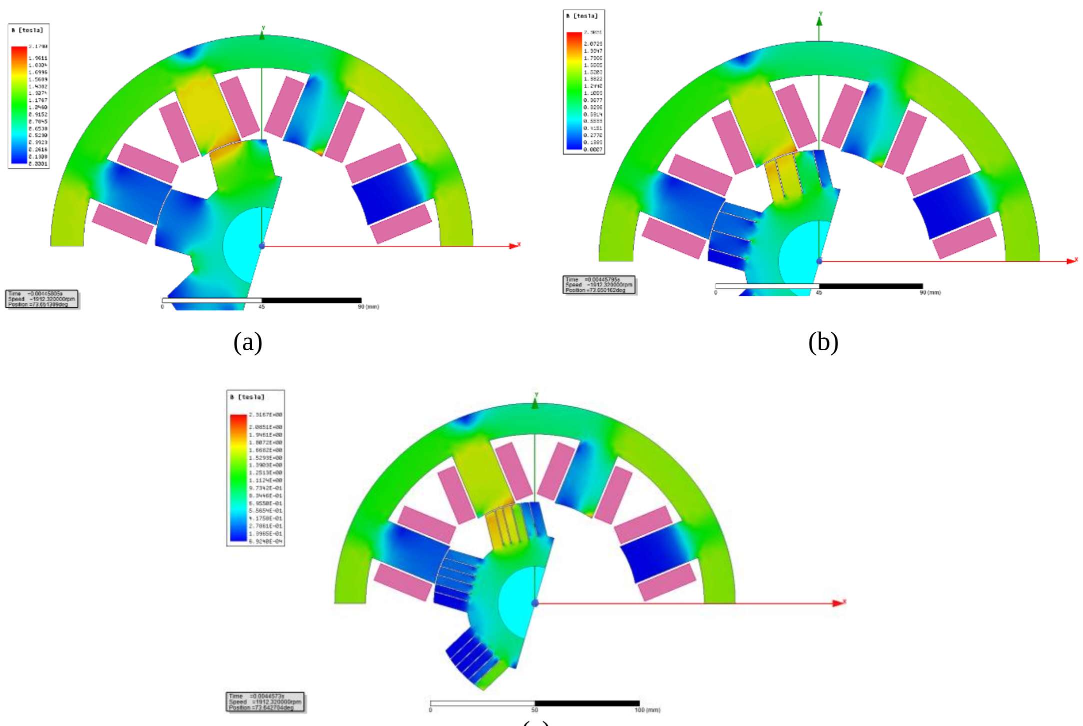
Table 2. Maximum and average torque changes for reference and 3 slitted motor models.

Torque	Reference Motor [N.m]	Slitted Motor [N.m]	Relative Difference [%]
Maximum	19.0308	23.4392	+ 23.164
Average	11.5928	12.9987	+ 12.127

When Figure 5 and Table 2 are examined, it is seen that the torque values obtained from the slitted motor model increase. It was determined that the average torque increased by 12.127 % and the maximum torque by 23.164 %.

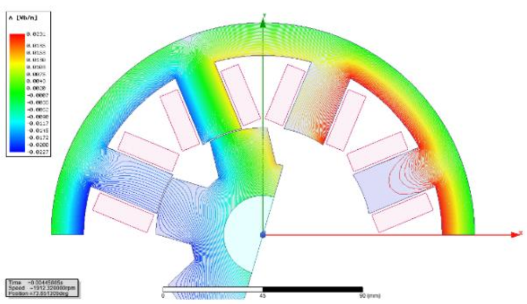
In addition, for making a healthy verify, a 5 slitted motor model has been solved in transient solver. The magnetic flux density distribution of the reference and different slitted motor models are given in Figure 6 (a), (b) and (c). When the figure is examined, it is seen that the flux density values are approximately the same.



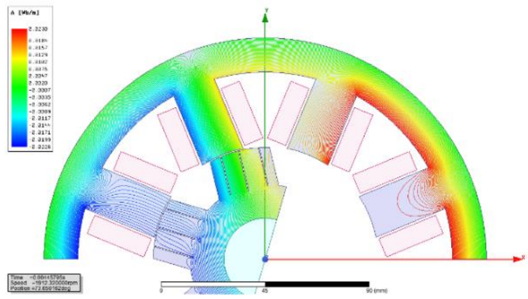
(a) (b) (c)

Figure 6. Magnetic flux density distribution (a) Reference motor model (b) 3 slitted motor model (c) 5 slitted motor model.

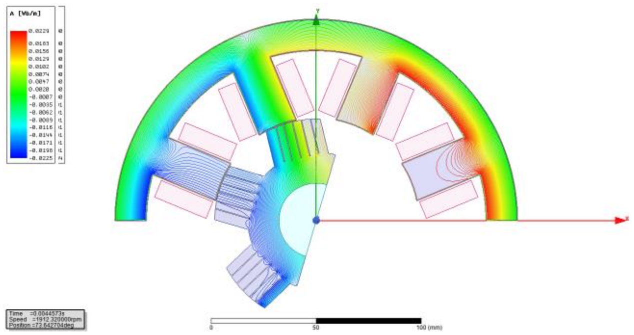
In Figure 7, the distribution of magnetic flux lines for reference and different slitted motor models are given. It is seen that flux lines can be directed by using slits.



(a)



(b)



(c)

Figure 7. Magnetic vector potential distribution (a) Reference motor model (b) 3 slitted motor model (c) 5 slitted motor model.

Figure 8 shows the current values obtained from the reference and slitted motor models. A slight increase has been observed in the current values obtained from the 3 slitted motor model. There has no difference between the 3 slitted and 5 slitted motor current waveforms. For this reason, only 3 slitted motor current graph has been given in the text. This increase is the biggest factor in increasing the torque.

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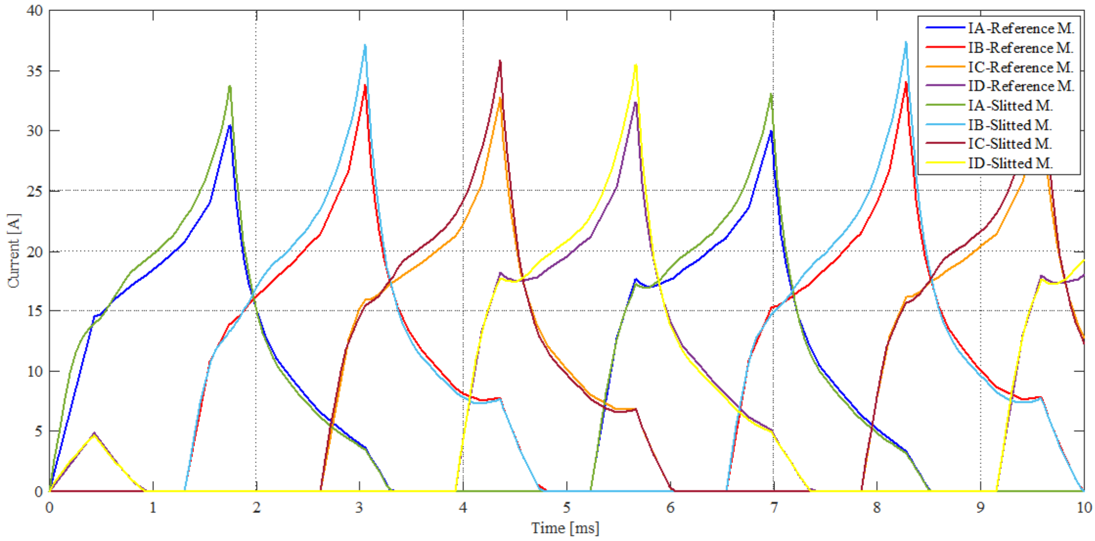

Figure 8. Current graph for reference and slitted motor models.

Inductance values obtained from both motor models are given in Figure 9. With the use of the 3 slitted structure, there has been a decrease in the inductance values due to the increase in reluctance in the rotor part. Also there has not been a significant inductance difference between 3 slitted and 5 slitted motor rotor models. For this reason, only 3 slitted motor graphs are given in the text. Although this situation seems to be a negative effect for the torque, it causes the voltage drop on the coils to decrease.

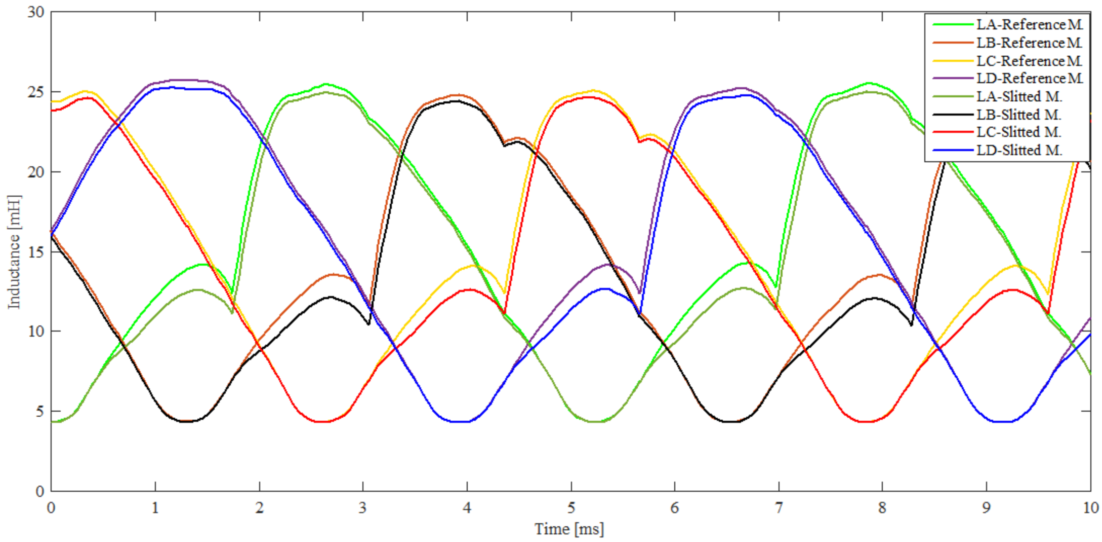

Figure 9. Inductance graph for reference and slitted motor models.

5. CONCLUSION

In this study, a new reluctance motor rotor structure design is proposed in order to increase the average and maximum torque values of the switched reluctance motor. In the proposed design, slits are opened in the rotor poles. The torque, current, inductance, magnetic flux density and magnetic vector potential changes of reference and slitted motor models are obtained.

Due to the increase in the reluctance value with the proposed motor model, a decrease has occurred in the inductance values. In the current values, it was determined that the values obtained from the slitted motor model increased by an average of 4% compared to the reference motor. This increase in current value resulted in an increase in torque values of the switched reluctance motor. Thanks to the proposed slitted structure, an increase of 12.127% in the average torque value and a 23.164% increase in the maximum torque value has been achieved. In terms of magnetic field distribution and magnetic vector potential values, it is seen that the changes obtained from both models coincide with each other.

The major objective of this study is, showing the booster effect of airgap reluctance on electromagnetic torque of slitted motor model. Only, if slot pole combinations are change, torque ripple effect can be controlled or modified on new designs. In this study, with same slot-pole configurations, only the booster effect of slit reluctances have been studied. Therefore, booster effect of airgap reluctance and inductances have been showed, how the average electromagnetic torque of proposed motor model has been increased.

A simple information can be given for stator and rotor structures material. Steel_1008 lamination has been used on transient solver while numerical modelling. Core loss model choice of the material has not been used while transient solver working. Reference and slitted models have been made from same lamination. Therefore, only average torque increasing effect with airgap reluctance has been observed. There will be a supplementary study about material effect can be conducted for future work. It has been shown that the average and maximum torque values can be increased for the same size and power values thanks to the proposed structure.

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