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An Approach for Reducing Torque Ripples on Permanent Magnet Synchronous Motors: Slitted Stator Core

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Keywords: Traction motors, Permanent magnet synchronous motor, Torque ripple, Stator core design, Reluctance torque improve, Slitted stator core structure

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ABSTRACT

Recently permanent magnet synchronous motors (PMSMs) have been used in many traction applications. Although they have many advantages about energy saving, power-torque density and efficiency, main disadvantage of these motor type is torque ripples. In general, there are two ways for reducing the torque ripples. These methods are motor core magnetic design method and current control method. In this study, slitted stator core teeth geometry has used for reducing the torque ripple. One of the basic missions of slitted cores is generating the useful reluctance torque and helping the more symmetrical distribution of the flux density on magnetic cores of the motor. In this study, an outer rotor PMSM has been used for required performance comparisons. There have been two numerical models created for the performance analysis of outer rotor PMSM. Primarily, a classical analytical outer rotor PMSM model has been created and dynamical analysis of this model has been operated with Finite Element Analysis simulation programme. Afterwards, another FEA performance analysis for same physical and electrical featured but slitted stator core numerical model of outer rotor PMSM has been achieved. Magnetic flux density distributions, torque ripple values and other performance values of each prototype motor have been given in study. When the obtained performance values evaluated, torque ripple value of slitted core PMSM has been %6 less than traditional outer rotor PMSM, besides it has been shown that, mean torque value of slitted core PMSM is 3 Nm bigger than classical outer rotor PMSM.

Daimi Mıknatıslı Senkron Motorlarda Moment Salınımlarını Azaltmak İçin Yeni Bir Yöntem: Slitli Stator Yapısı

ÖZ

Son zamanlarda sabit mıknatıslı senkron motorlar (SMSM'ler) birçok elektrikle tahrik uygulamasında kullanılmaktadır. Enerji tasarrufu, güç, moment yoğunluğu ve verimlilik açısından birçok avantajları olmasına rağmen, bu motor tiplerinin ana dezavantajı moment dalgalanmalarıdır. Genel olarak, moment dalgalanmalarını azaltmanın iki yolu vardır. Bu yöntemler, motor nüvesi manyetik tasarım yöntemi ve akım kontrol yöntemidir. Bu çalışmada, moment dalgalanmasını azaltmak için yarıklı stator nüvesi diş geometrisi kullanılmıştır. Dilimlenmiş stator nüvesinin temel görevlerinden biri, yararlı relüktans momentini üretmek ve akı yoğunluğunun motorun manyetik nüveleri üzerinde daha simetrik dağılımına yardımcı olmaktır. Bu çalışmada, gerekli performans karşılaştırmaları için bir dış rotorlu SMSM kullanılmıştır. Dış rotorlu SMSM'nin performans analizi için oluşturulmuş iki sayısal model vardır. Öncelikle klasik bir analitik dış rotor SMSM modeli oluşturulmuş ve bu modelin dinamik analizi Sonlu elemanlar analizi (SEA) yapan simülasyon programı ile çalıştırılmıştır. Daha sonra, dış rotorlu SMSM'nin aynı fiziksel ve elektriksel özellikli ancak yarıklı stator nüvesi nümerik modeli için başka bir SEA performans analizi gerçekleştirilmiştir. Çalışmada her bir prototip motora ait manyetik akı yoğunluk dağılımları, moment dalgalanma değerleri ve diğer performans değerleri verilmiştir. Elde edilen performans değerleri değerlendirildiğinde, yarıklı nüveye sahip SMSM'nin moment dalgalanma değeri, geleneksel dış rotorlu SMSM'ye göre %6 daha az olmuş, ayrıca yarıklı nüveli SMSM'nin ortalama moment değerinin klasik dış rotorlu PMSM'ye göre 3 Nm daha büyük olduğu görülmüştür.

Anahtar Kelimeler: Elektrikle tahrik motorları, Sabit mıknatıslı senkron motor, Moment dalgalanması, Stator nüve tasarımı, Relüktans moment iyileştirmesi, Yarıklı stator nüve yapısı

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1. Introduction

PMSMs are used in many industrial applications in order to their compact structure [1], high torque density, high airgap flux density, high acceleration specs and their good power/weight specs with regard to other electric motors used in industry [2]. Today in order to evolution of hard magnetic materials and improvements on electric motor manufacturing aspects in industry, PMSMs are used on the structures of hybrid electric vehicles, electric vehicles and fuel cell electric vehicle technology [3]. Besides, PMSMs are also used in high performance positioning systems that used on CNCs [4]. Although the advantages, PMSMs have some disadvantages. The most important disadvantages are their torque ripple and cogging torque effects. Especially, these effects are unwanted situations on sensitive control applications. Though, they can cause the acoustic noise and resonances on mechanical components of the traction systems [5].

There are two methods in order to get a better torque profile (in order to decrease the cogging torque effect) on PMSMs. One is about designing the PMSM. This method contains lots of applications. Suitable installing the stator windings, assigning the suitable magnet-pole embrace ratios, using the suitable skewed stator lamination packaging and shifting the magnet pole [2] positions are some of the cogging torque minimization techniques. Main disadvantage of these techniques is implementation cost [6]. Second method is well power electronic control techniques. These control techniques are implemented on PMSMs easily and cheaply but, the shaft torque is never best [4].

Yan et all. have suggested an adjustable dynamical programme (ADP) for minimizing the cogging torque ripples. An optimal controller, dynamical programming theory and strategical iteration methods are used for achieving the minimum mean torque error value. It has showed that better torque ripple performance and shorter dynamical adjusting time on steady state condition of ADP [7].

Tao et all. have suggested a new IARC controller for current controllers in order to minimize the torque ripples on PMSM traction systems. IARC has been suggested with forecasting of back EMF harmonics and a practical torque production model. Also, it has been designed with current loop model in order to minimize the torque ripple [8].

Hwang et all. have studied on an application that minimize the mechanical ripple and noise. Application consisted on a notched rotor design. A comparable electromagnetic design has been achieved with similar dimensional rotor and stator structures of different motor models. The difference is notched rotor structure that provides the appropriate ripple and noise value [9].

Hasanien has suggested a digital observer controller for minimum torque ripple value on PMSMs. Suggested controller has achieved dynamical response on rated operation with interrupted load conditions [10]. Flieller et. all have suggested an artificial intelligence method to minimize the torque ripples for trapezoidal back EMF PMSMs. It has suggested that control schemes in order to produce optimal stator currents for better electromagnetic torque value (or speed) and minimum ohmic losses. It has been showed that the validity of AI method from appropriate simulation and experimental results that obtained motor prototype [11].

Ilka et al. applied the Non-Dominant Sequence Genetic Algorithm-II (NSGA-II) method, which is a multi-objective optimization method, to obtain the optimum design of a surface-mounted Permanent Magnet Synchronous Motor in order to reduce the cogging torque without changing the output torque. According to the simulation results, they show that the cogging moment is significantly reduced while the output torque has a slight decrease compared to the nominal value [12].

Ali et al. examined the effects of curvature of permanent magnets and the design factors of the slot opening to minimize the value of the cogging torque in a high-power permanent magnet synchronous motor. The obtained results show the effect of applying the slot opening and a significant reduction in the knocking torque due to the curvature of the permanent magnets [13].

Duan et al. revealed the change in magnetic material performance with temperature for PMSM and analyzed the effect of eccentric magnetic pole structure on the cogging torque at different temperatures [14].

In their study, Abbaszadeh and Maroufian modeled a permanent magnet synchronous motor using the Magnetic Equivalent Circuit method and calculated values such as magnetic flux density and magnetic field density. The output torque produced was calculated using the Maxwell Stress Tensor method. Also, a new method of cogging torque minimization based on torque fluctuation from an auxiliary winding is proposed. According to the results obtained, they showed a significant reduction in the amplitude of the torque ripple [15].

In their study, Yu et al. developed a method to optimize the torque performance of the SPMSM in order to ensure that the proposed motor is not smaller than the average torque of the reference motor and to reduce the cogging torque value. In this method, they tried to obtain a new design by using the structural parameters of the engine using the Response Surface Methodology (RSM) and Non-Dominated Sorting Genetic Algorithm-II (NSGA-II) methods [16].

A new method has been suggested for minimizing the cogging torque value on PMSMs in this study. In this method, slits have been implemented on PMSM stator teeth. Main purpose of this implementation, occurring an extra reluctance in airgap region of the motor and providing the penetration of the smooth flux outer surface region of stator core. In order to correct implemention of the slits on teeth, slit widths have been chosen 0.1 mm and slit heights have been chosen sum of the height of stator teeth and magnet height. Compared flux density distributions, torque ripples, mean torque values have been given in fourth chapter that have been obtained reference and slitted PMSM models.

2. Design of Outer Rotor PMSM

Designing of the high efficient and high energy density PMSM traction motors that used in industrial applications is a preferred method. Generally, PMSMs are manufactured with the magnet poles on the rotors. For this purpose, total ohmic losses are comparable less than conventional synchronous motors. Though, PMSMs are high efficient electrical motors that used on industry.

Main dimensions of PMSMs are specified with analytical equations with respect to their mechanical shaft power. Basic analytical modelling principle of specifying the dimensions is specifying the total volume of the motor and derivation of the stator and rotor dimensions from total volume value.

Equation (1) specifies the basic apparent power of an electrical machine. "K_w" is the winding distribution coefficient, "$\overline{B}$" is the flux density distribution, "ac" is the electrical loading value, "D" is the stator diameter, "L" is the length of stator core and the "n" rated speed of the motor. Also, it can be calculated that the total volume (D^2L) of outer rotor Hub PMSM.

$$S = 1.11\, K_w\, \pi^2\, \overline{B}\, ac\, D^2 L\, n\, 10^{-3}\ \text{kVA} \tag{1}$$

It has to be calculated the stator per pole flux value for in order to calculate the conductor number per slot (2). After this calculation, in order to specify the stator per phase turn number, stator slot-pole numbers can be used (3). Using these parameters, number of conductors per slot can be specified. Calculating the flux per pole value, "$\overline{B}$" magnetic loading, "Y" pole pitch and "L" stator core length parameters are used.

$$\emptyset_m = \overline{B}\, Y\, L \tag{2}$$

In order to calculate the number of turns per phase "N_{ph}" (3), the parameters "E_{ph}" (back EMF value of per phase), "K_w" (the winding distribution coefficient), "f" (grid frequency) and "$\emptyset_m$" (flux per pole) are used.

$$N_{ph} = \frac{E_{ph}}{4.44\, K_w\, f\, \emptyset_m} \tag{3}$$

According to the mechanical power spec of system that is driven by an outer rotor hub PMSM, electrical and physical parameters of a 2 kW Hub PMSM have been given in Table1.

Table 1. Electrical and physical parameters of a 2 kVA Hub PMSM

Parameter	Value	Unit
Output Power (S)	2	kW
Reference Speed (n)	700	rpm
Stator Slot Number	24	slot
Motor Pole Number	22	pole
Winding Dist. Coeff. (K_w)	0.95	---
Stator Diameter	238	mm
Stator Core Length	100	mm
Machine Length (L)	309	mm
Flux per pole ($\emptyset_m$)	39	mWb
Number of Turns per Phase (N_{ph})	40	turn
Number of conductors per slot	10	---

3. Slits Effects on Electrical Motors

According to machine type, main torque ripple components are cogging torque ripple and torque ripple on PMSMs has been given in Figure 1.

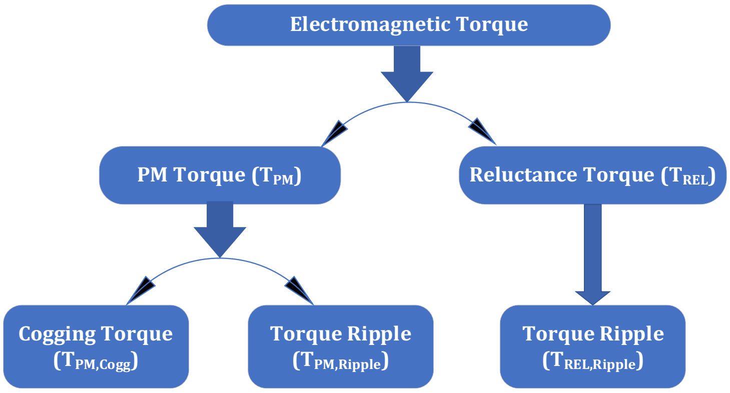


Figure 1. Torque ripple components of PMSMs [5]

For the salient rotor topologies like reluctance motors, interior magnet PMSMs, PM assisted synchronous reluctance motors, additional torque ripples can be occurred from the interaction between the stator flux and the rotor reluctance harmonics. These harmonics, as shown in Figure 1, can be caused by magnets or by changing the air gap magnetic resistance value. However, in Permanent magnet or magnet assisted motors, the cogging torque that occurs when a magnet pole passes through a stator slot region can also produce torque ripple.

Cogging Torque is the result of the interaction between the magnet pole area and the reluctance variations of rotor position. It is independent from stator current. PM torque ripple is the result of the interaction between the high degree harmonics of magnet pole fluxes and stator flux.

In recent years, slitted core structures are frequently used on designing of electrical machines. Slit dimensions that used on several designs show different values. Additionally, it can be seen that slits are used on the stator cores or rotor cores or both for several electrical machine designs. Main purpose of the usage of the slits is smooth flux distribution on laminations or cores. It helps to decrease the leakage fluxes and helps the increase of useful flux that circulates in the core. There are many studies on this purpose in the literature.

Klima et. all have studied for increasing the performance of an induction motor in order to open the slits on induction motor's rotor core. It has been helped the decrease the additional rotor losses, torque ripple and undesirable magnetic forces. They have suggested that decreasing the rotor eddy current losses in order to use the slit number between 25 and 30. In terms of torque ripple, it can be chosen odd slit numbers like 27, 29 or 31 etc. From looking point of magnetic force, similarly it can be chosen odd slit numbers [17].

Nerg et. all have studied on a solid rotor induction motor. They have opened slits on solid rotor. They have examined on torque ripple and unbalanced magnetic interaction effect between stator and rotor cores. They have showed that, odd number of rotor slits have effected on less torque ripple. Also, they have showed that the effect of loading on unbalanced magnetic interaction amplitude and odd slit number [18].

Yetgin and Turan have studied on 56 different 3 kW induction motor models and, they have showed that usage of optimal slit width and length from these models. According to this study, it has been showed to improve the maximum efficiency, optimum slit width can be chosen 0.1 mm and the optimum slit height can be chosen about core teeth height. For optimal dimensions of slits, they have showed that the increase on motor efficiency about 1.86 percent [19].

Viorel et. all have used slits for improving the synchronous reluctance motor performance [20]. Chan and Hamid have made an analogous study on switched reluctance motor structure. Results had indicated that a flattop current waveform and higher power could be achieved without an increase in peak current magnitude [21].

Li et. all have studied for decreasing the armature reaction of a hybrid excited machine implemented slits on rotor core. They have showed that the application help for decrease the eddy currents [22].

Slit widths and heights have an important effect on motor performance [23]. Geometrical aspects can be showed on Figure 2 [24].

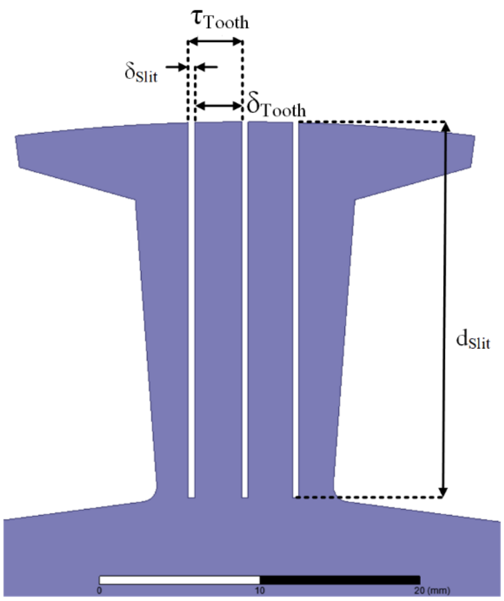


Figure 2. Establishing the slits on the core

According to Figure 2, there are two important equations to determine the rotor tooth pitch.

$$\tau_{tooth} = \frac{\pi . D_r}{Q_r} \quad (4)$$

$$\tau_{tooth} = \delta_{tooth} + \delta_{slit} \quad (5)$$

Here, Q_r is the number of rotor slots, D_r is the diameter of the rotor, τ_{tooth} is the tooth pitch, δ_{tooth} is the tooth width, δ_{slit} is the slit width, and d_{slit} is the slit depth.

4. Simulation Study and Results

A prototype electric car traction motor has been designed and simulated in this study. Main purpose of this study, minimization of torque ripples and increasing the mean shaft torque of the PMSM motor. A

24 slot 22 pole PMSM hub motor is designed for prototype electric car traction system. Mean weight of the prototype electric car is about two hundred kilograms. Mean speed of the car is 50 kilometers per hour. For 16 inches tyre hubcap diameter, mean speed of the tyres are about 700 rpm. In these conditions, mean shaft power is about 2000 Watts for 100 V, 30 Ah battery supply.

To simulate the traction motor performance, a finite element method simulation programme is used [25]. A transient simulation is conducted for observing the torque ripples of the classical Hub PMSM and slitted stator Hub PMSM. Similarly, another observation is achieved on two of the models that have different shaft torques.

Figure 3 shows the two types of stator cores. First stator core is classical Hub PMSM and second stator core is the slitted stator core Hub PMSM of prototype electric car. Third equipment is the PM steel rotor core of the prototype electric car Hub PMSM. Dimensions of the stator cores of two types are same.

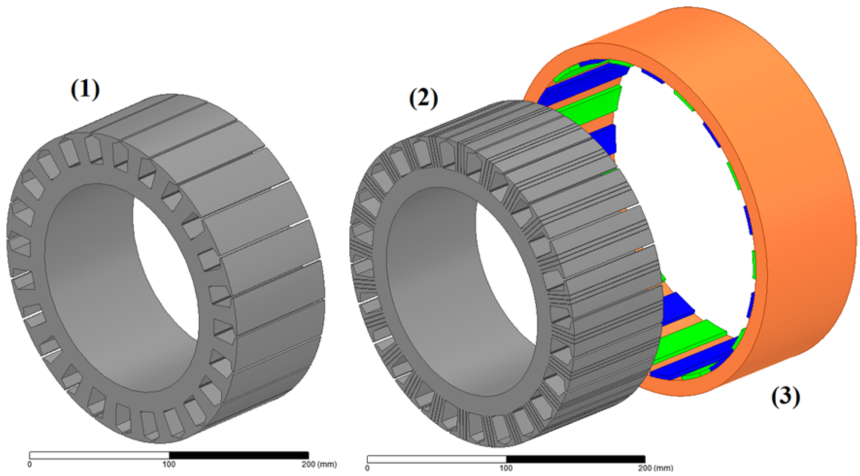


Figure 3. Two types of stator cores: Classical stator Hub PMSM (1), Slitted stator core Hub PMSM (2), PM steel rotor core of the prototype electric car Hub PMSM (3)

One rotor core and magnet poles has been used with the two of the stator cores. Same laminated material has been used on two of the stator cores. From the winding topology perspective, same concentrated winding topology has been used for two types of the stator cores. Figure 4 shows the mutual concentrated winding topology and mutual magnet poles of the two types of PMSMs. Similar conductor material and diameter have been used for winding structures.

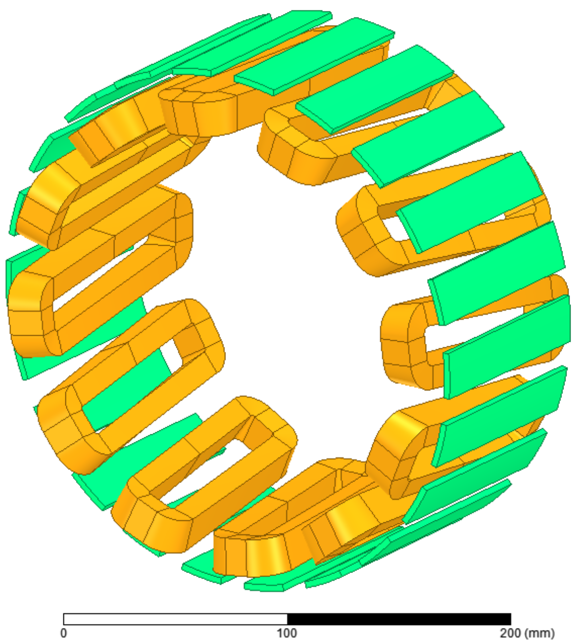


Figure 4. Mutual concentrated winding topology and mutual magnet poles of the two types of PMSMs

Transient dynamical analysis has been conducted for conventional Hub PMSM and slitted stator Hub PMSM and performance observation has been achieved on solutions of the transient analysis. Figure 5 shows the comparison between the different operation times of conventional Hub PMSM. First sample shows the flux density distribution of conventional Hub PMSM at starting up (0^{th} second). Second sample shows the flux density distribution of conventional Hub PMSM at steady state condition (40^{th} milliseconds). Flux density distributions show the saturated regions of stator cores upper areas of the teeth. There is no dangerous flux distribution at start-up time and steady state time zone.

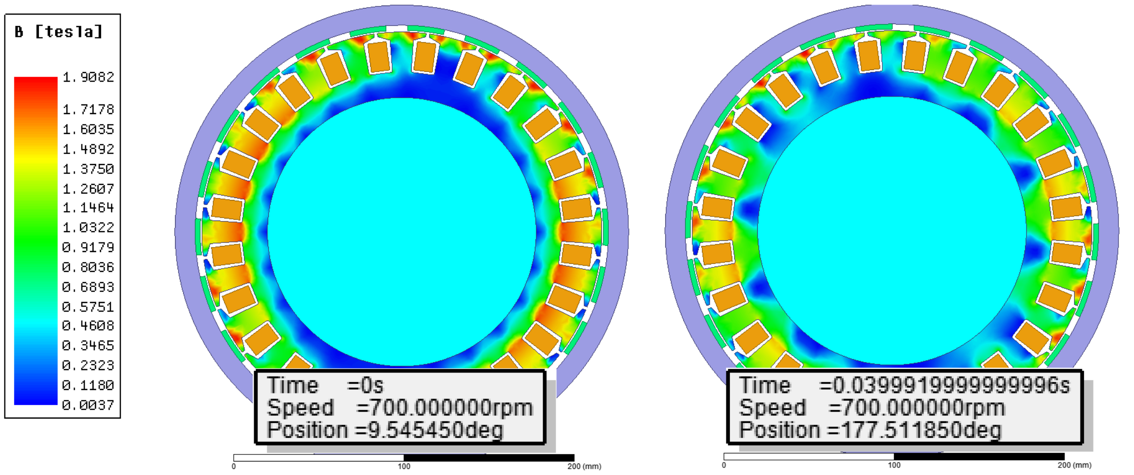


Figure 5. Comparison flux density distributions between the different operation times (1): Start-up position, (2): Steady state position of conventional PMSM

Figure 6 shows the comparison between the different operation times of slitted stator Hub PMSM. First sample shows the flux density distribution of slitted stator Hub PMSM at starting up (0^{th} second). Second sample shows the flux density distribution of slitted stator Hub PMSM at steady state condition (40^{th} milliseconds). Flux density distributions show the saturated regions of stator cores upper areas of the teeth. There is no dangerous flux distribution at start-up time and steady state time zone.

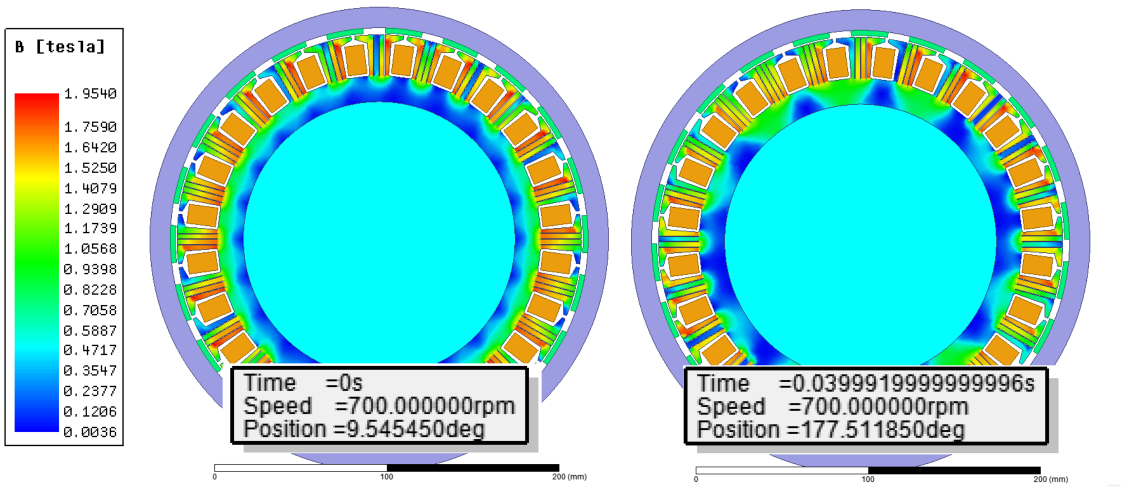
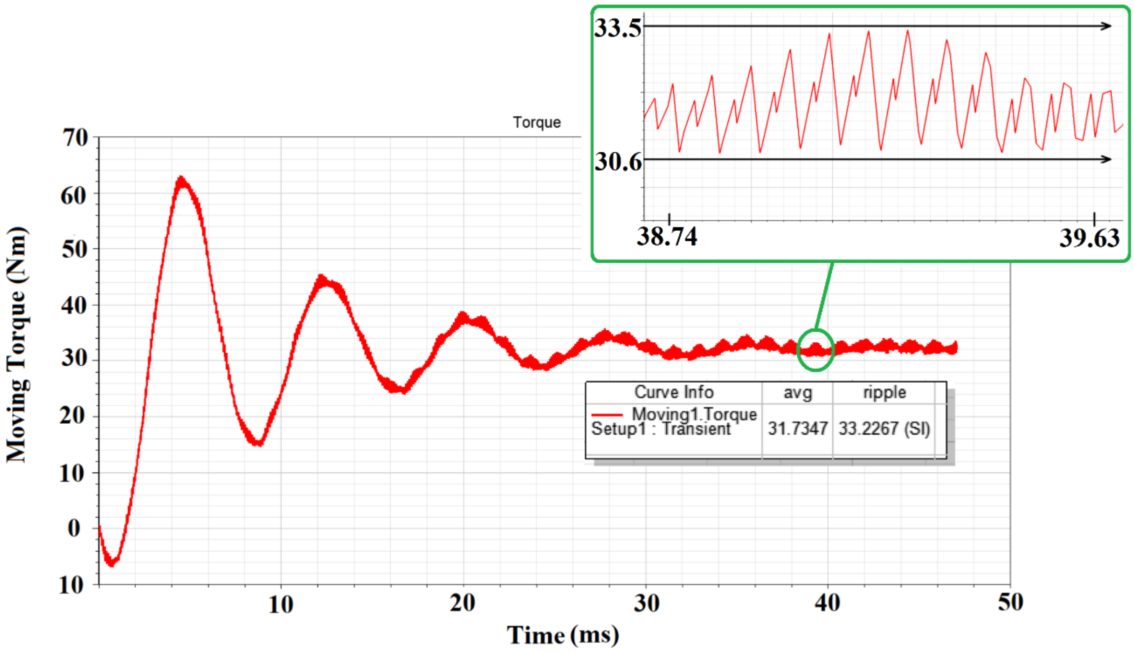
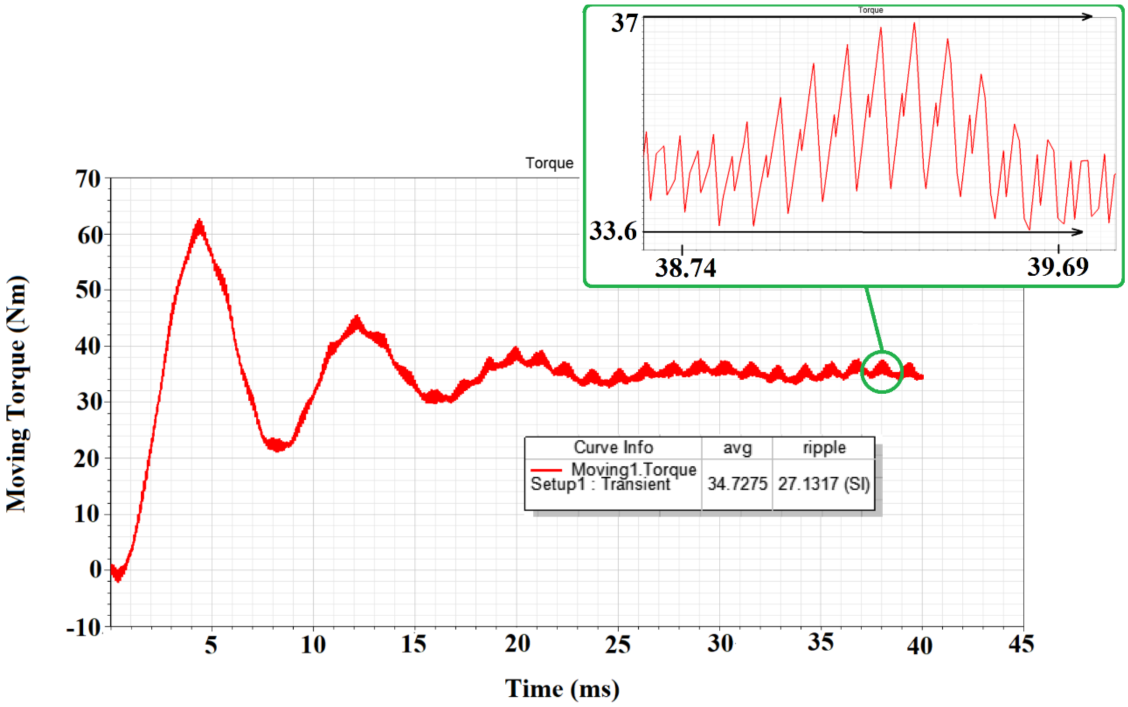


Figure 6. Comparison flux density distributions between the different operation times (1): Start-up position, (2): Steady state position of slitted stator PMSM

Finally, Figure 7 (a) shows torque and torque ripple performance for conventional Hub PMSM. Also Figure 7 (a) shows the starting up operation of conventional Hub PMSM. Figure 7 (b) shows the starting up operation of slitted stator Hub PMSM. When a comparison is made for two of the graphs, conventional Hub PMSM is operated with a 31 Nm average shaft torque value and about 33 percent torque ripple value. Although, slitted stator Hub PMSM is operated with a 34 Nm average shaft torque value and about 27 percent torque ripple value. Slitted stator Hub PMSM has showed better output shaft torque and torque ripple value with respect to conventional Hub PMSM.



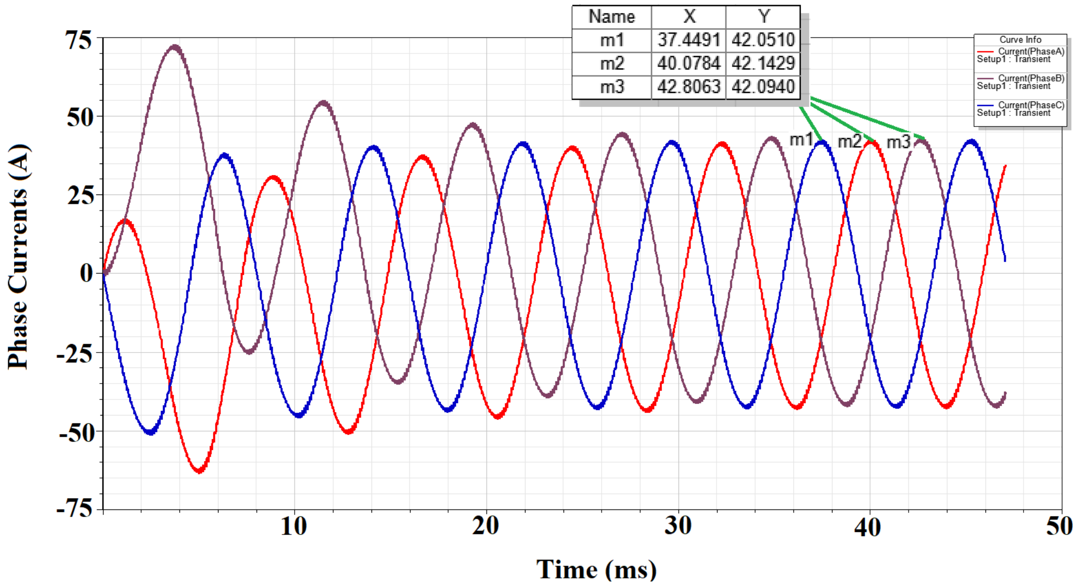
(a)



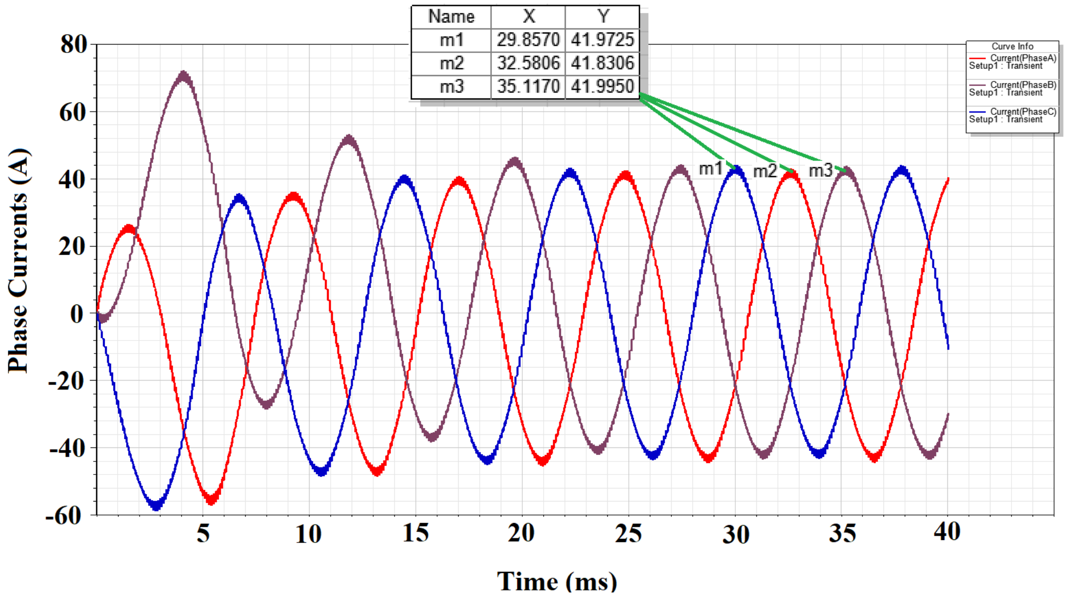
(b)

Figure 7. (a) Steady state torque and torque ripple performance and of conventional PMSM (b) Steady state torque and torque ripple performance and of slitted PMSM

In terms of the feasibility of the idea, a comparison can also be made between phase currents. Accordingly, the phase currents of classical and slitted PMSMs are compared in Figure 8 (a) and (b). The torque performance values in Figure 8 were obtained at the maximum phase current value of 42 A in the stable region.



(a)



(b)

Figure 8. (a) Steady state phase currents performance of conventional PMSM (b) Steady state phase currents performance of slitted PMSM

When a detailed examination is made on the current graphs, it is seen that the phase currents of both models reach a maximum value of 42 A in the steady state region. Thus, it is seen that the current values obtained in the steady-state condition for the classical Hub PMSM and the slitted Hub PMSM are almost the same. From this point of view, it is seen that both the average torque value increased and the torque ripple value decreased with the proposed method without changing the current value per phase in the motor.

5. Conclusions

Slitted motor designs have been applied in many different types of motors such as solid rotor induction motor, induction motor, synchronous reluctance motor, hybrid excited machine in recent years. In this study, the slitted structure was applied to the PMSM motor.

A prototype electric car traction motor has been designed and simulated in this study. Main purpose of this study, minimization of torque ripples and increasing the mean shaft torque of the PMSM motor. A new method has been suggested for minimizing the cogging torque value on PMSMs in this study. In this method, slits have been implemented on PMSM stator teeth. Main purpose of this implementation, occurring an extra reluctance in airgap region of the motor and providing the penetration of the smooth flux outer surface region of stator core.

In order to correct implementation of the slits on teeth, slit widths have been chosen 0.1 mm and slit heights have been chosen sum of the height of stator teeth and magnet height. According to this study, conventional and slitted stator core structures have been examined. It has been showed that, 6 percent better output torque ripple and 3 Nm extra output shaft torque achieved for slitted stator structure with respect to conventional stator structure of Hub PMSM.

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Conflict of Interest Statement

The authors declare that there is no conflict of interest.

References

[1] B. Adhavan, M. S. Birundha, C. S. Ravichandran and V. Jagannathan, "Torque ripple reduction in permanent magnet synchronous motor using fuzzy logic control," *Australian Journal of Basic and Applied Sciences*, vol. 7, no. 7, pp. 61-68, 2013.

[2] R. Abdelmoula, N. B. Hadj, M. Chaieb and R. Neji, "Reducing torque ripples in permanent magnet synchronous motor," *Journal of Electrical Systems*, vol. 13, no. 3, pp. 528-542, September 2017.

[3] I. Benhamida, A. Ameur, K. Kouzi and B. Gaoui, "Torque ripple minimization in predictive torque control method of pmsm drive using adaptive fuzzy logic modulator and ekf estimator," *Journal of Control, Automation and Electrical Systems*, vol. 30, pp. 1007–1018, 2019. doi:10.1007/s40313-019-00505-7

[4] S. Brock and J. Deskur, "A practical approach to compensation of torque ripple in high-precision permanent magnet motor drives," *Proc. Of the Int. Conf. on Electrical Drives and Power Electronics*, Dubrovnik, Croatia, September 26 – 28, 2005.

[5] G. Dajaku and D. Gerling, "New methods for reducing the cogging torque and torque ripples of pmsm," *Proc. of the 4th Int. Electric Drives Production Conference*, *EDPC 2014*, Nuremberg, Germany, 30 September-01 October 2014.

[6] P. Yi, X. Wang, Z. Zhou and Z. Sun, "Optimization and implementation of three-phase pmsm current harmonic decomposition technique," *SAE Technical Paper*, vol. 2019-01-0604, pp. 1-8, 2019. doi:10.4271/2019-01-0604

[7] T. Yan, Q. Liu, B. Dou, Q. Li and B. Li, "An adaptive dynamic programming method for torque ripple minimization of pmsm," *Journal of Industrial and Management Optimization*, vol. 17, no. 2, pp. 827-839, March 2021. doi:10.3934/jimo.2019136

[8] R. Tao, J. Ma and H. Zhao, "Torque ripple minimization in pmsm based on an indirect adaptive robust controller," *Mathematical Problems in Engineering*, vol. 2017, pp. 1-10, October 2017. doi:10.1155/2017/9512351

[9] M. H. Hwang, H. S. Lee and H. R. Cha, "Analysis of torque ripple and cogging torque reduction in electric vehicle traction platform applying rotor notched design," *Energies,* vol. 11, pp. 1-14, November 2018. doi:10.3390/en11113053

[10] H. M. Hasanien, "Torque ripple minimization of permanent magnet synchronous motor using digital observer controller," *Energy Conversion and Management*, vol. 51, no. 1, pp. 98–104, January 2010. doi:10.1016/j.enconman.2009.08.027

[11] D. Flieller, N. K. Nguyen, P. Wira, G. Sturtzer, D. O. Abdeslam and J. Merckle, "A self-learning solution for torque ripple reduction for non-sinusoidal permanent magnet motor drives based on artificial neural networks," *IEEE Transactions on Industrial Electronics,* vol. 61, no. 2, pp. 655–666, February 2014. doi:10.1109/TIE.2013.2257136

[12] R. Ilka, Y. A. Beromi and H. Yaghobi, "Cogging torque reduction of permanent magnet synchronous motor using multi-objective optimization", *Mathematics and Computers in Simulation*, vol. 153, pp. 83–95, 2018. doi:10.1016/j.matcom.2018.05.018

[13] A. J. Ali, A. H. Ahmed and B. M. Saied, "Cogging torque mitigation for pmsm using stator slots design and magnets skewing," *2nd International Conference on Electrical, Communication, Computer, Power and Control Engineering ICECCPCE19*, Mosul, Iraq, 13-14 February 2019, pp. 240-245, 2019. doi:10.1109/ICECCPCE46549.2019.203781

[14] X. Duan, X. Zhang, Y. Tang and M. Hao, "Cogging torque reduction in pmsm in wide temperature range by response surface methodology," *Symmetry*, vol. 13, pp. 1-17, 2021. doi:10.3390/sym13101877

[15] K. Abbaszadeh and S. Maroufian, "Cogging torque reduction in pmsm motor by using proposed new auxiliary winding," *Amirkabir University of Technology (Tehran Polytechnic)*, vol. 46, no. 1, pp. 11-17, Spring 2014. doi:10.22060/eej.2014.436

[16] Y. Yu, Y. Pan, Q. Chen, D. Zeng, Y. Hu, H. H. Goh, S. Niu and Z. Zhao, "Cogging torque minimization of surface-mounted permanent magnet synchronous motor based on rsm and nsga-II," *Actuators*, vol. 11, pp. 1-13, 2023. doi:10.3390/act11120379

[17] J. Klima, J. Nerg, J. Barta and O. Vitek, "The impact of the rotor slit number on the behavior of high-speed induction motor," *Przegląd Elektrotechniczny*, vol. R. 94 NR 5/2018, pp. 7-13, 2018. doi:10.15199/48.2018.05.02

[18] J. Nerg, T. Aho and J. Pyrhönen, "Effect of odd number of rotor slits on the performance of a high- speed, high-power, solid-rotor induction motor," *Proc. of the 6th WSEAS/IASME Int. Conf. on Electric Power Systems, High Voltages, Electric Machines*, Tenerife, Spain, December 16-18, pp. 100-105, 2006.

[19] A. G. Yetgin and M. Turan, “Efficiency optimization of slitted–core induction motor,” *Journal of Electrical Engineering*, vol. 65, no. 1, pp. 60–64, January 2014. doi:10.2478/jee-2014-0009

[20] I. A. Viorel, I. Husain, I. Chişu, H. C. Hedeşiu, G. Madescu and L. Szabo, “Reluctance synchronous machine with a particular cageless segmental rotor,” *Proc. of the Int. Conf. on Electrical Machines, ICEM 2002*, pp. 1-6, 2002.

[21] S. Chan and M. N. Hamid, “Finite-element study on a two-phase switched reluctance motor with split rotor poles,” *Proc. of the Int. Conf. on Power Electronics and Drives Systems, IEEE PEDS 2005,* 28 November-1 December 2005, pp. 1156-1160, 2005.

[22] L. Li, A. Foggia, A. K. Lebouc, J. C. Mipo and L. Kobylansky, “Some armature reaction compensation methods numerical design of experiments and optimization for a hybrid excitation machine,” *Proc. of the Int. Electric Machines and Drives Conference, 2009 IEEE*, Miami, FL, USA, 03-06 May 2009, pp. 832-838, 2009.

[23] M. O. Gulbahce, D. T. Mcguiness and D. A. Kocabas, “Shielded axially slitted solid rotor design for high-speed solid rotor induction motors,” *IET Electric Power Applications*, vol. 12, no. 9, pp. 1371-1377, November 2018. doi:10.1049/iet-epa.2018.5210

[24] M. O. Gülbahçe, “Contributions to reduce rotor harmonic losses in solid rotor induction machine for high speed drive applications,” Ph.D. dissertation, Istanbul Technical University, Graduate School Of Science Engineering And Technology, Istanbul, Türkiye, June 2019.

[25] Ansys Electronics Desktop 2018.2.0.

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