Cogging Torque Reduction in External Rotor PM Synchronous Motors by Optimum Pole Embrace

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***Abstract*—In this paper, a 4 kW external rotor permanent magnet (PM) synchronous motor was designed. It is aimed to obtain minimum cogging torque and minimum torque ripples by optimum pole embrace ratio. Conceptual design was modeled and analyzed by 2D finite element analyses (FEA). Low order harmonics of the induced phase voltages and torque ripples are investigated. According to optimization results, an external rotor PMSM was obtained with low cogging torque and low torque ripple. The designed PMSM was compared with a commercial inner rotor PMSM and much better performance results are taken.**

Keywords*— *PM synchronous motor, external rotor, embrace, cogging torque, elevator traction machine.

I. INTRODUCTION

Instead of low efficiency induction motors, PM synchronous motors have been used for a while in gearless elevator traction systems. While some of these motors are external rotor, most of them have internal rotor structure. In this study; it has been designed an external rotor PMSM instead of an internal rotor PMSM by considering cogging torque and torque ripple criterions.

In order to provide comfortable travels in elevator systems, vibration and noise of traction motors should be reduced to minimum values. The most important cause of these vibration and noise is the cogging torque and torque ripples in traction machines. It has been studied on different techniques for obtaining smooth output torques [1]. The first major technique is to pay attention to the motor's geometrical design for achieving the ideal form of trapezoidal or sinusoidal waveforms. The second major technique is actively controlling the excitation current waveforms to modify the nonideal characteristics of the machine or inverter. Skewing of the stator, magnets or step skewing methods are exact solutions for minimizing cogging torque; but they are costlier processes and have some difficulties at manufacturing. Therefore, the pole embrace parameter is selected to reduce torque ripple in this study.

Reference [2] developed a novel analytical approach to predict the cogging torque in PMSMs based on analytical field solution obtained from conformal transformation. It was derived the cogging torque not only from air-gap, but also from the slot regions of PMSM and their results show good agreement with Finite Element Method (FEM) results. Step skewing of rotor techniques including both conventional and herringbone styles are used for reducing the cogging torques and torque ripples [3-5]. While herringbone rotor step skewing technique have slightly higher cogging torque and back electromotive force (EMF) harmonics, the accurate conventional step skewing can eliminate all EMF harmonics and cogging torques. Several studies about pole embrace effect to cogging torque are shown that choosing the exact pole embrace ratio can eliminate the undesirable components and it can be obtained the lowest cogging torque values [6-8].

In this study, a 4 kW external rotor gearless elevator PMSM with 630 kg load capacity was designed. Cogging torque results of the designed motor were compared with a commercial motor. All the analysis and experimental test results of the commercial elevator PMSM are available in [9] and [10]. In the first section, literature studies about cogging torque and ripple torque are mentioned. In the second section, external rotor PM motor topology and the basic parameters of designed motor were explained. Cogging torque minimization techniques are examined in the third section. Pole embrace effect and analysis results of the designed PMSM are investigated in section four. Finally, the results are discussed in conclusion section.

II. EXTERNAL ROTOR PMSM DESIGN

External rotor motor construction has some advantages and disadvantages compared to inner rotor designs. Designers must choose motor types considering these constraints. The advantages of external rotor designs over inner rotor designs can be listed as follows [11];

- They have high inertia and low cogging torque.
- They offer the opportunity to obtain torque at maximum level with the possibility of wider air gap.
- They have more stable low speed performances.
- They are ideal for quiet environments due to low operating noise.
- The external rotor designs are axially shorter than the inner rotor designs for the same performance level.

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There are also some disadvantages of the external rotor motor structure. External rotor designs have higher heating rates. Some of the designed parameters of external rotor PMSM and commercial inner PMSM are shown in Table 1. 3D model of the PMSM is shown in Fig. 1. As it can be seen, the designed and commercial motors have same outer diameter, stack length, output power, rated speed and air gap values. But the rotor topologies are different. According to these constraints, the motors' cogging torque and efficiency results are compared in section 4.

TABLE I. MOTOR PARAMETERS OF DESIGNED AND COMMERCIAL PMSM

	Designed PMSM	**Commercial PMSM**
Motor outer diameter (mm)	242	242
Stack length (mm)	150	150
Number of poles	20	16
Rated output power (kW)	4	4
Rated voltage (V)	380	360
Wire size (mm)	0.8	0.85
Circuit type	Y	Y
Rated speed (rpm)	159.2	159.2
Frequency (Hz)	26.53	21.2
Air Gap (mm)	1	1

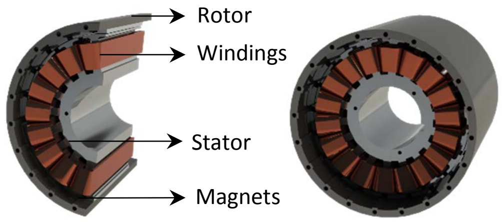


Fig. 1. Section and full views of designed PMSM.

III. COGGING TORQUE MINIMIZATION

One of the most important parameters in electric motor design is cogging torque. Cogging torque, which causes the motor to vibrate and decrease its life, is tried to be reduced minimum levels during the design. Stator slots or rotor magnets can be skewed to minimize the cogging torque, or slot numbers and slot openings can be arranged to achieve the lowest cogging torque. Stepped skewing of magnet blocks, selection of the appropriate magnet arc [12] or shifting of magnets [13] are other methods for reducing cogging torque in PMSMs. Some of the cogging torque reducing methods are shown in Fig. 2 [14].

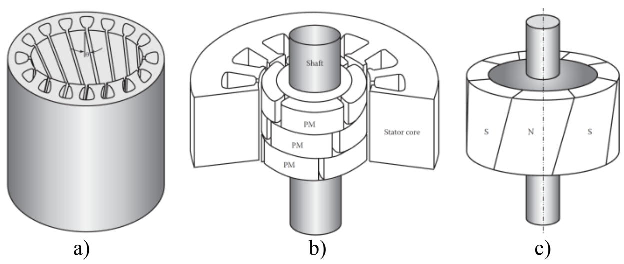


Fig. 2. Some of the cogging torque reducing methods: a) Stator skewing, b) stepped skewing of magnets, c) Magnet skewing.

Output torque quality and smoothness can be improved with minimizing the cogging torque and harmonic content in the back EMF [15]. The fundamental cogging torque is given with (1) which proves that, cogging torque occurs because of interaction between the stator teeth and magnets [13]. Here, $\emptyset_g$ is the magnet flux crossing through the air gap, R is air-gap reluctance and θ is the position of the rotor [16]. According to (1), if R does not change while rotor rotates, the derivative is zero and this means cogging torque is also zero.

$$T_{cog} = -\frac{1}{2}\emptyset_g^2\frac{dR}{d\theta} \quad (1)$$

The air-gap reluctance varies periodically with the rotation of the rotor. Due to the various air-gap reluctance, cogging torque varies periodically as a Fourier series which shown in (2) [17]. T_{mk} is Fourier coefficient, m is the least common multiple of the number of stator slots and the number of poles and k is an integer.

$$T_{cog} = \sum_{k=1}^{\infty} T_{mk}\sin(mk\theta) \quad (2)$$

Another method for calculating cogging torque is proposed like in (3) with using electrical angular position instead of mechanical angular position [18]. Here, θ_e is electrical angular position of the rotor, Φ is magnetic flux which is calculated over a surface of magnet perpendicular to its magnetization direction, μ_0 and μ_r are the permeability of vacuum and the relative permeability of the magnet material, respectively [14]. l_m is the magnet length along the magnetization direction, B_r is the remanent magnetic flux density at H = 0 and p is the number of magnet pole pairs.

$$T_{cog} = \frac{1}{2}pB_r\frac{l_m}{\mu_0\mu_r}\frac{d\Phi}{d\theta_e} \quad (3)$$

According to (3), the amplitude of cogging torque is directly proportional with number of magnet pole pairs, remanent magnetic flux density, magnet length along the magnetization direction and variation of the magnetic flux with respect to rotor electrical position. The cogging torque is inversely proportional with permeability of vacuum and the relative permeability of the magnet material. Various approaches can be performed with using (3) for reducing cogging torque [17].

IV. OPTIMAL POLE EMBRACE AND ELECTROMAGNETIC ANALYSIS RESULTS

There are many parameters that affect output power and torque in electric motor design and production. Achieving the greatest output power and torque at optimum dimensions is what many motor designers want first. The motor efficiency is obtained by dividing the mechanical power taken from the motor shaft to the electrical power given to the motor. Parameters affecting the output power of the motor also affect the efficiency of the motor.

In this study, Ansys RMxprt and Maxwell modules are used for initial machine design and 2D FEM analyses are done according to best performance results. Most attention is given to pole embrace parameter for minimum cogging torque. Pole embrace is the ratio of magnetic pole arc to pole pitch as shown in Fig. 3. The values used in this study are calculated according to this formula. After various optimizations, the parameters which gave minimum cogging torque are obtained.

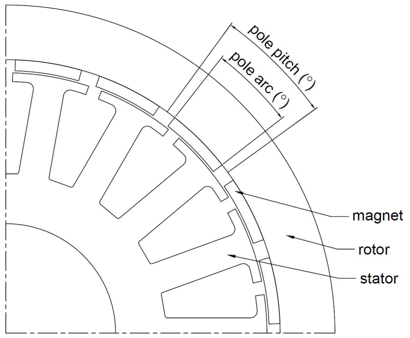
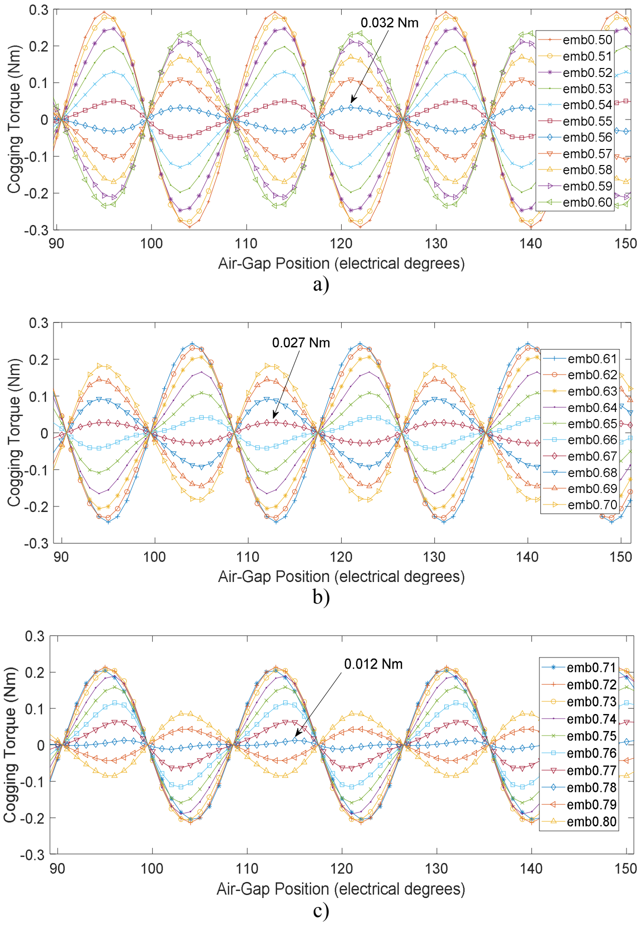


Fig. 3. Pole Embrace: The ratio of magnetic pole arc to pole pitch.

The optimum value for pole embrace can be found with (4) [13]. Here, α_m is pole embrace, n is an integer, N_{sm} is number of slots per pole and v is a varied parameter between 0 and 1 to minimize cogging torque [4].

$$\alpha_m = \frac{n+v}{N_{sm}} < 1 \tag{4}$$

The cogging torque graphs between 0.5 and 0.9 embrace values with the step of 0.01 are shown in Fig. 4. When Fig. 4 is examined, the embrace affect to the cogging torque can be easily seen. The four embrace values which create minimum cogging torques are selected for FEM analysis. When the embrace values are 0.56, 0.67, 0.78 and 0.88; the cogging torque values are 0.032 Nm, 0.027 Nm, 0.012 Nm and 0.047 Nm respectively.



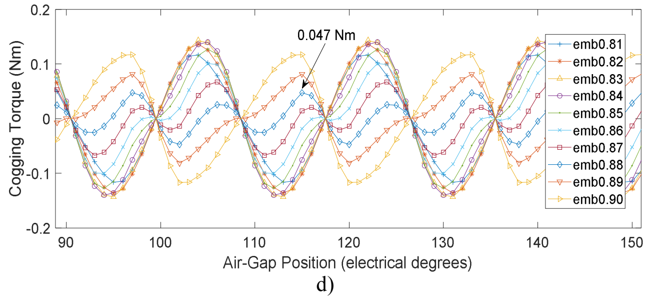


Fig. 4. Cogging Torque-Air-Gap Position Graphs: Embrace Ratio; a) 0.5-06, b) 0.6-0.7, c) 0.7-0.8, d) 0.8-0.9.

According to these embrace values, 2D FEM analyses were done and the Fast Fourier transform (FFT) performed on the induced phase voltages as seen in Fig. 5. The fundamental harmonics (at 26. 53 Hz) are achieved 242.9 V, 243.5 V, 208.8 V and 243.6 V for the embrace values of 0.56, 0.67, 0.78 and 0.88 respectively.

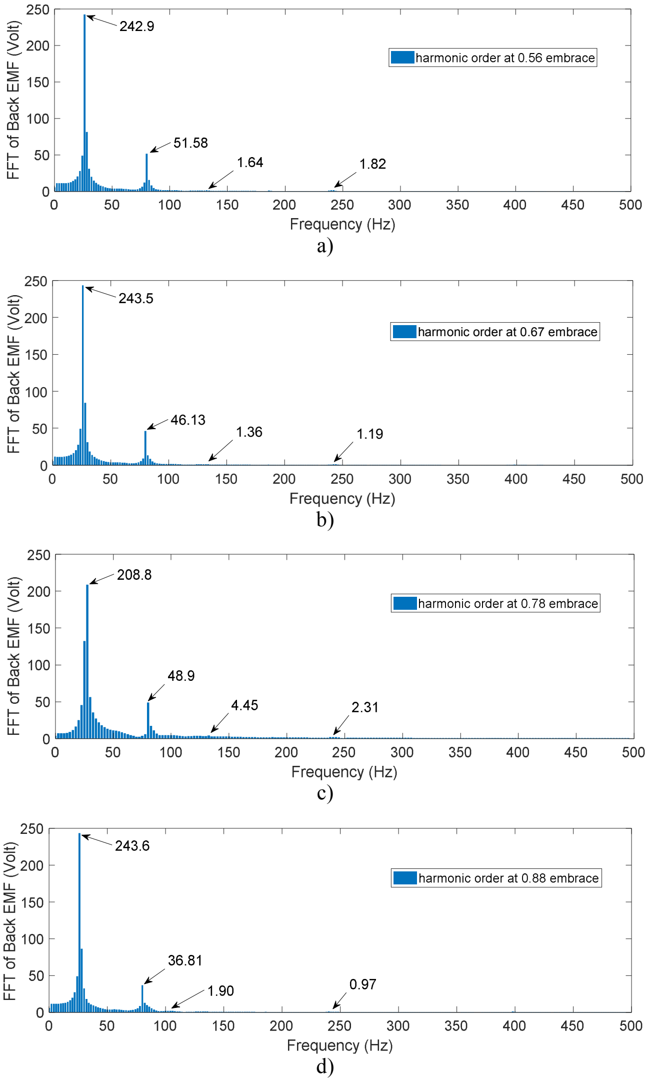


Fig. 5. FFT of Induced Voltages: Embrace Ratio; a) 0.56, b) 0.67, c) 0.78, d) 0.88

As it is known, the most dominant harmonics are the low order harmonics, most attention must be given to low order harmonics for minimum torque ripples at the output torque. The 3rd harmonics (at 79.59 Hz) are achieved 51.58 V, 46.13

V, 48.9 V, 36.81 V and the torque ripples are achieved 7.4 Nm, 7.3 Nm, 10.8 Nm, 19.8 Nm for the embrace values of 0.56, 0.67, 0.78 and 0.88 respectively. According to these data and motor design knowledge, the embrace value is chosen as 0.78. Output torque graph of the designed external rotor PMSM is shown in Fig. 6. It can be seen the torque ripple is %4.47 of the average output torque.

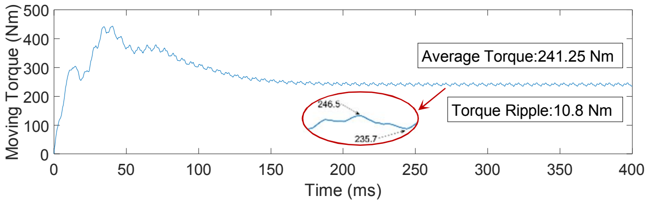


Fig. 6. Output Torque graph of designed PMSM

Fig. 7 shows how moving speed occurs from start to settling of the motor. After 0.2 s from start-up, average speed and torque values are settling to 159.2 rpm and 241.25 Nm. The efficiency of the designed external rotor PMSM is shown in Fig. 8. After optimization of stator slots and windings, the efficiency is obtained as %86.6 and this value is much better than %74 which is the efficiency of compared commercial inner rotor PMSM. The minimum cogging torque is obtained 0.012 Nm and this value is much less than 2 Nm which is the cogging torque value of compared PMSM.

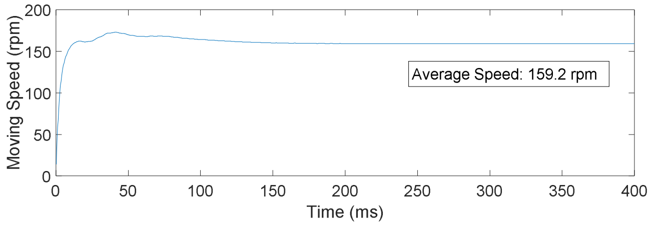


Fig. 7. Spee-Time graph of designed PMSM

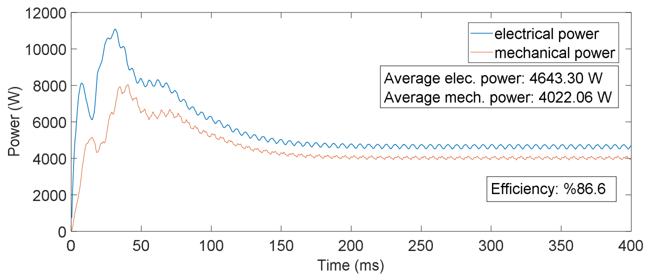


Fig. 8. Efficiency graph of designed PMSM

V. Conclusion

In this study, an external rotor PMSM was designed achieving the minimum cogging torque. Even there have been various methods, the pole embrace parameter which is a low cost and proven method was selected for reducing cogging torque. After optimization of motor parameters, minimum cogging torque and best efficiency were obtained as 0.012 Nm and %86.6. These results were compared with a commercial gearless inner rotor PMSM which has the same geometric values like stack length, outer diameter and air-gap length. It can be seen from the results the designed external rotor gearless PMSM is superior to commercial PMSM and it can be easily used in elevator traction systems.

Acknowledgment

This study has been supported by The Scientific and Technological Research Council of Turkey (TUBITAK) with the Project No. 218M615. The author M. Soyaslan also offers acknowledgement to TUBITAK for its 2211-C program support. Finally, thanks to Research Fund of the Sakarya University for their support (Project No. 017-50-02-017).

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