A Study on Characteristics of PM Synchronous Motors according to Pole-Slot Combinations for Electrical Power Steering Application

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Abstract — This paper presents the most proper pole and slot combination of a permanent magnet synchronous motor (PMSM) for an electrical power steering (EPS) application. To do that, the characteristics of three PMSMs, which have the same performance but different pole and slot combinations, are compared. At that time, the characteristics such as cogging torque and radial force of each model are obtained by finite element analysis (FEA). In the end, the pole and slot combination presented in this paper satisfies the required performance in the EPS without rotor or stator skew and minimizes the space harmonic of radial force critical in respect of noise and vibration.

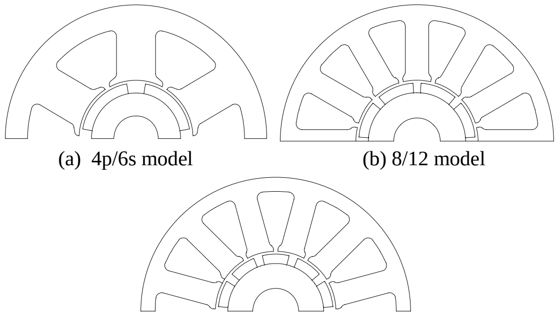
I. INTRODUCTION

Recently, an electric power steering (EPS) is more and more becoming favored as the alternative of a hydraulic power steering (HPS) because of the advances in electrical machines, sensors and control electronics [1]. The EPS presents several advantages over the conventional HPS, e.g., improved fuel economy, ability to provide assist even when the engine is off, and elimination of the hydraulic fluid, significant energy savings.

A permanent magnet synchronous motor (PMSM) has been applied for the performance improvement of the EPS. Because the PMSM has many advantages such as high efficiency and high power density, it is especially suitable for automotive applications where space and energy savings are critical. In this paper, the characteristics of the PMSM are investigated according to the pole and slot combinations for the EPS. it should exhibit the following characteristics:

1) Production of smooth torque with minimum ripple, for an accurate steering control.
2) High efficiency, since the electrical energy is directly provided inside the vehicle.
3) Easy manufacture, because minimum manufacturing process is needed due to a large number of vehicles produced every year,.

When the motor is applied for the EPS, it should run quietly and without vibration. A major drawback to PMSM is, however, the cogging torque that is inherent in their design. These electromagnetic forces which are composed of the tangential component such as the cogging torque and torque ripple, and radial component can lead to various problems such as mechanical vibration and acoustic noise in drive systems [3]. Minimizing these electromagnetic forces is considerably significant in the design of a PMSM.



(a) 4p/6s model (b) 8/12 model (c) 10/12 model

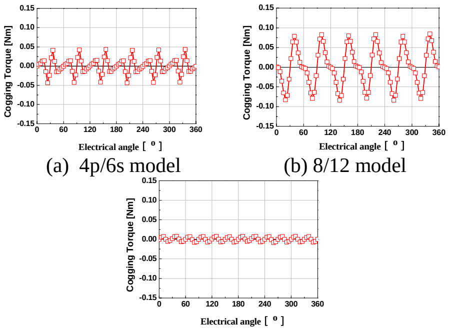
Fig. 1. Cross-sections of PMSM models (a) 4p/6s model; (b) 8p/12s model; (c) 10p/12s model

So, a variety of methods for reducing the cogging torque such as skewing the stator slots and/or rotor magnet, shaping the magnets, optimizing the pole-arc to pole-pitch ratio of the magnets, etc., have been proposed [4]. Up to now, to reduce the cogging torque, techniques such as skewing of either stator slot and/or rotor magnet have been mostly carried out for a PM motor. However, because of the large number of vehicles produced ever year, the minimum manufacturing process and designing process are further important. Thus, we propose the pole and slot combination of the PMSM that satisfies the required performance in the EPS without application of skewing of either stator slot or rotor magnet and minimized the radial force critical in respect of noise and vibration.

Three PMSMs which have the same performances but different combination of pole and slot are investigated. First, by using finite element analysis (FEA) and Maxwell stress tensor method, the radial force and cogging torque of each motor are obtained. Next, the results are compared with test results. It will be shown that the well-suited choice of pole and slot combination in the design stage of the PMSM allows the required performances of the EPS without an additional manufacturing process such as the skew in the rotor or stator.

TABLE I
SPECIFICATIONS OF STUDY MODELS

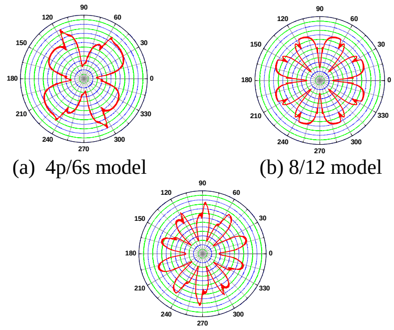
Item	model		
	4p/6s	8p/12s	10p/12s
Rated output power [W]	800		
DC link voltage [V]	12		
Rated torque [Nm]	3.0		
Rated speed [rpm]	2500		
Residual magnetization [T]	1.286		
Cogging torque [mNm]	Peak 15		



(a) 4p/6s model (b) 8/12 model

(c) 10p/12s model

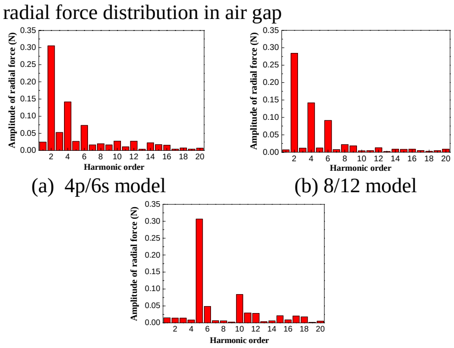
Fig. 2. The comparison of cogging torque



(a) 4p/6s model (b) 8/12 model

(c) 10p/12s model

Fig. 3. The radial force distribution in air gap



(a) 4p/6s model (b) 8/12 model

(c) 10p/12s model

Fig. 4. Space harmonic of radial force

II. Analysis Model

Three PMSMs designed for EPS applications are studied, as sketched in Fig. 1. In order to secure miniaturization and manufacturing efficiency of the motor, it has concentrated winding, because concentrated winding can reduce the motor volume and make manufacturing to be simple compared with the distributed winding. The specifications of these three models are listed in Table I.

III. Electromagnetic Finite Element Analysis

A. Cogging Torque

In its most fundamental form, cogging torque can be represented by

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

where ϕ_g is the air gap flux, R is the air gap reluctance, and θ is the position of the rotor [1]. Because of this periodicity, cogging torque can be expressed as a Fourier series

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

where m is the least common multiple of the number of stator slots and the number of poles, k is an integer, and T_{mk} is a Fourier coefficient. Using (2) the cogging torque of these three models are calculated and shown in Fig. 2. In Fig. 2 (c), the peak-to peak cogging torque of the 10p/12s model is smaller than others. This result satisfies the required performance without rotor or stator skew.

B. Radial force

The radial force of PMSM can be well calculated in the Maxwell stress tensor method. The total force density of the radial component can be obtained as

$$p_r = \frac{B_r^2 - B_t^2}{2\mu_0} \quad (3)$$

where μ_0 is the permeability of air, B_r and B_t are the flux densities of the radial and tangential components. Using (3), the radial forces of these three models are calculated and shown in Fig. 3. The harmonic components of these radial computations have been validated by FEA. As the result of analysis, the stator natural frequencies of the 10p/12s model are not similar to the space harmonic of radial force compared to models. Therefore, the noise and vibration of the 10p/12s model will be smaller than other models.

IV. Experimental Verification and Analysis

The investigation is validated by FEA and measurements. The detailed experimental analysis results and discussion will be presented in final paper.

V. Conclusion

The pole and slot combination presented in this paper satisfies the required performance in the EPS without rotor or stator skew and minimizes the radial force critical in respect of noise and vibration. The proposed the pole and slot combination is very powerful and industrially applicable to EPS, because that allow the required performance to be obtained without application of an additional manufacturing process.

VI. References

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