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Article

Step-Skew Rotor Design of Surface Permanent Magnet Synchronous Machine for EPS System using Cycloid Curve

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Abstract: This study examines the step-skew design of cogging torque reduction for SPMSM (Surface Permanent Magnet Synchronous Motor) in EPS (Electric Power Steering) System. In this paper, a cycloid curve on the magnet shape is proposed to reduce the cogging torque for rotor step skew design. Based on the same rotor step-skew design, an evaluation index is used and determined to compare the proposed and conventional magnet shape design. The proposed and conventional design methods are compared using numerical method such as FEM (Finite Element Method).

Keywords: rotor step-skew, cogging torque, surface permanent magnet synchronous machine, magnet shape, cycloid curve, eccentric curve

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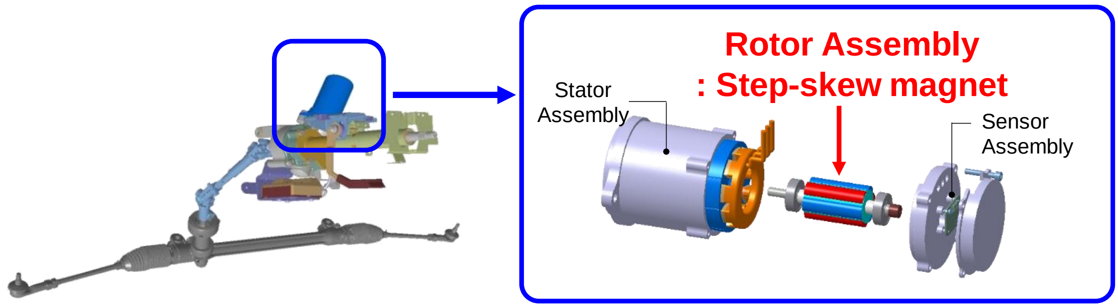
1. Introduction

As the regulation for CO_2 reduction and fuel efficiency improvement increases, electrified systems have been widely used such as power train and chassis systems. In electrified system in vehicle, EPS (Electric Power Steering) is the most representative electrified system in chassis system as shown in Figure 1. In EPS system, a PMSM (Permanent Magnet Synchronous Motor) has been mainly adopted due to high torque density and efficiency [1-3]. However, cogging torque reduction is the key design quality factor to enhance steering feeling and driving stability at high speed in EPS system [4]. For this reason, SPMSM (Surface Permanent Magnet Synchronous Motor) which has magnet outside rotor core has been widely used to reduce cogging torque, compared to IPMSM (Internal Permanent Magnet Synchronous Motor) which has magnets inside rotor core [5].

Cogging torque is a torque pulsation due to the change of magnetic resistance at no-load drive. This cogging torque depends on the shapes and material properties of the rotor, stator, and magnet [6]. In this reason, design methods to reduce cogging has been studied extensively in various ways. Previous studies showed that applying eccentricity to the rotor shape and a notch to the stator shape improved cogging torque [7].

Blum et al. and Fei et al. reduced cogging torque by applying skew to the rotor [8]. Jung et al. improved cogging torque by applying cosine function curve in the rotor core with the enhanced flux density waveform [9]. Kim et al. and Coenen et al. analyzed the period and amplitude of the additional cogging torque that occurs when a tolerance occurs in the motor [10,11]. In past studies, cycloid curves have been widely applied in mechanical fields, e.g., in speed reducers and oil pumps [12].



(**a**) (**b**)

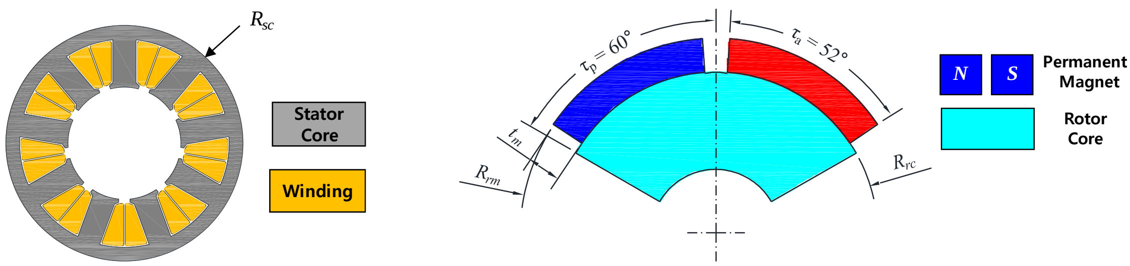
Figure 1. EPS (Electric Power Steering) system in vehicle: (**a**) Configuration of EPS system; (**b**) SPMSM (Surface Permanent Magnet Synchronous Motor) used in EPS system.

However, in the study by Park, Lim, and Lee [13], the cycloid curve was applied to the rotor of a motor. In their study, it was also verified that cogging torque was improved for a motor to which a cycloid curve was applied. However, the combination method for shape and skew design is not reported and its effectiveness is not also verified.

In this study, a cycloid curve on the magnet shape is used to reduce the cogging torque with the combination methods for rotor step skew design. Based on the same rotor step-skew design, an evaluation index δq is used and determined to compare the proposed and conventional magnet shape design. The proposed and conventional design methods are compared using numerical method such as FEM (Finite Element Method).

2. Analysis model

In this study, the motor type is SPMSM as shown in Figure 2. Figure 2 (a) and (b) show also the cross-sectional view of stator and rotor core in Figure (1) respectively. The numbers of slot and pole in this study are 9 and 6 respectively. In the case of Figure 2 (b), the numbers of poles are 2 with 1/3 model of rotor core which are equivalent to 6 poles. Table 1 shows the detail specifications of stator and rotor core as shown in Figure 2.



(**a**) (**b**)

Figure 2. Stator and rotor core for analysis model: (**a**) Stator core with 9 slots; (**b**) Rotor core and magnet with 2 poles (1/3 model).

Table 1. Main specification for analysis model

Symbol	Variable name	Unit	Value
-	Type	-	SPMSM
-	Phase/Pole/Slot	-	3/6/9
R_{sc}	Radius of stator core	mm	42
R_{rm}	Radius of rotor	mm	19
t_m	Magnet thickness	mm	3.3
τ_a	Magnet pole pitch	Degree	60
τ_p	Manet pole angle	Degree	52
L_{ag}	Air gap length	mm	1
L_{stk}	Stack length	mm	57

Based on the specification of analysis model as shown in Figure 2 and Table 1, an evaluation index δq is used to compare the proposed and conventional of magnet curve, which is expressed as red dotted line in Figure 3. δq is the air gap length on the q axis that is electrically at 90 degrees to the axis of the center axis d axis which the magnetic flux of rotor magnet.

The length of δq can be described in Figure 3. In this paper, the δq is defined as the distance from the intersection point of the extended curve for the magnet shape (red dotted line in Figure 3) and the q axis to the intersection point of the rotor outer radius R_{rm} and the q axis.

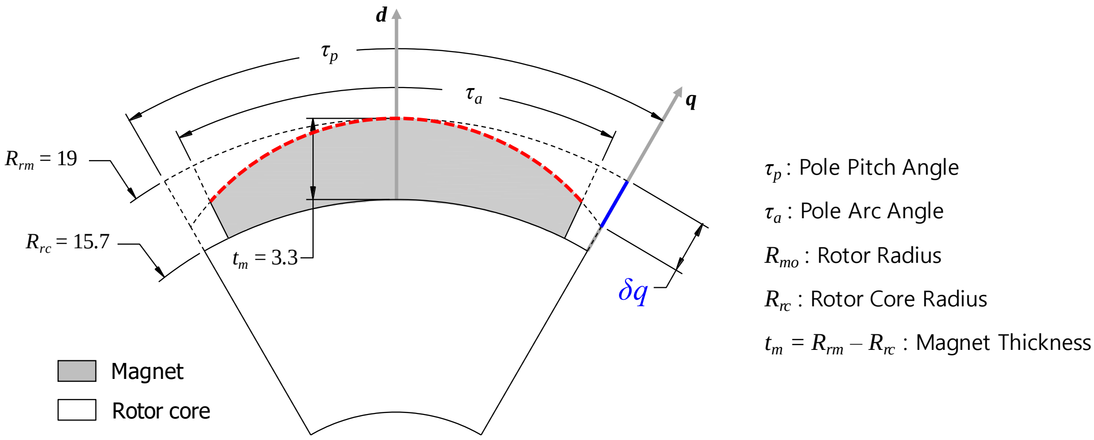


Figure 3. Definition of δq to compare the proposed and conventional magnet curve.

3. Proposed model for magnet shape

The eccentric curve has been generally used in the magnet shape of SPMSM to reduce cogging torque and torque ripple [10]. In this study, the eccentric curve, which has an eccentricity from its center, is used to compare the proposed curve on the magnet shape as shown in Figure 4. In order to apply the eccentric circle to the magnet shape, the known parameters are decided. The known parameters are δq , R_{rm} , t_m and N_p (The numbers of pole). The unknown parameters of eccentric circle radius R_{ec} and eccentricity ε_{ec} can be calculated by using geometrical relation as shown in Figure 4 [13].

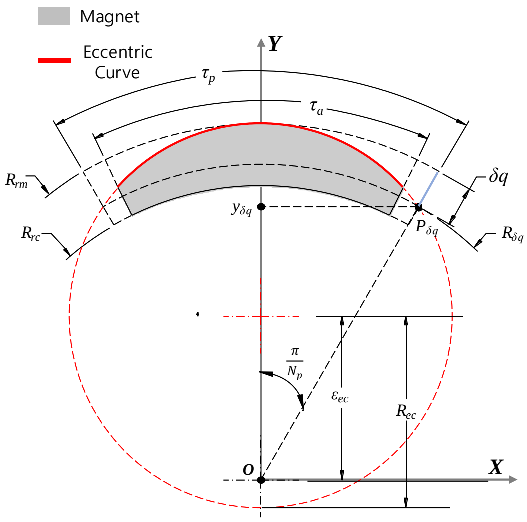
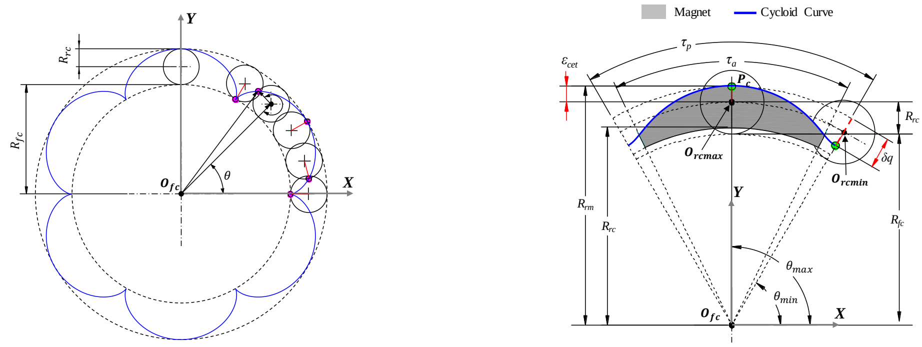


Figure 4. Definition of eccentric curve for the conventional curve on the magnet.

The proposed curve for the magnet shape is cycloid curve. A cycloid is the curve traced by a point in or on rolling circle with radius R_{rc} as the rolling circle rolls along a fixed circle with radius R_{fc} without slippage as shown in Figure 5 (a). In order to apply cycloid curve to the magnet shape in the same procedure of eccentric cure, the known parameters are also decided. The known parameters are those of eccentric curve such as δq , R_{rm} , t_m and N_p. The unknown parameters of R_{fc} , R_{rc} , and eccentricity of cycloid curve ε_{cet} can be also calculated by using geometrical relation as shown in Figure 5 (b) [13].

Figure 4 shows the cycloidal curve trajectory of 6 poles magnet for the rotor model given in Figure 2 (b). In addition, Figure 4 (a) shows the trajectory of cycloid curve for 6 poles of rotor without δq. In contrast to Figure 4(a), Figure 4 (b) shows the trajectory of cycloid curve with a certain value of δq for 1 poles of rotor.



(**a**) (**b**)

Figure 5. Definition of cycloid curve for the conventional curve on the magnet: (**a**) Trajectory of cycloid curve for 6 poles of rotor; (**b**) Trajectory of cycloid curve on the magnet with 1 pole and δq.

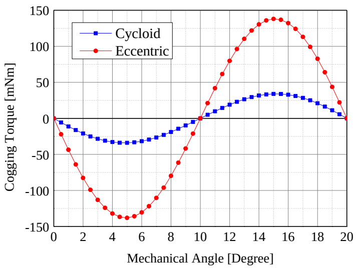
Based on the design procedure of the conventional and proposed curve on the magnet for a given value of δq , the calculation of cogging torque is conducted. As described in the Introduction, a cogging torque is a torque pulsation due to the change of magnetic resistance at no-load drive. Generally, the equation of cogging torque T_{cog} is expressed in Equation (1) [14].

$$T_{cog}(\theta) = \frac{L_{stk}}{\mu_{air}} \int_0^{2\pi} r\, B_r\, B_\theta\, r\, d\theta \tag{1}$$

In Equation (1), θ is the rotational position of rotor, L_{stk} is the stack length of motor core, μ_{air} is the permeability of air, r is the radius of rotor, 2π is the 1 period of cogging toque pulsation, B_r is the magnetic flux density into radial direction and B_θ is the magnetic flux density into tangential direction. Additionally, Cogging torque has also the period of torque pulsation for a given number of pole and slot as shown in Equation (2).

$$\theta_{cog} = \frac{360^\circ}{LCM(N_p,\ N_s)} \tag{2}$$

In Equation (2), θ_{cog} is the mechanical angle of 1 period for cogging torque pulsation, N_p and N_s denote the number of pole and slot respectively and LCM means Least Common Multiple. In order to calculate cogging torque, analytical method is a possible solution as shown Equation (1). However, it is relatively difficult to calculate cogging torque as following. First, non-linear properties of magnetic materials such as permanent magnet and electric core. Second, complex geometry of magnet shape such as conventional and proposed curve. In this study, Numerical method or FEM (Finite Element Method) is used in order to calculate cogging torque.



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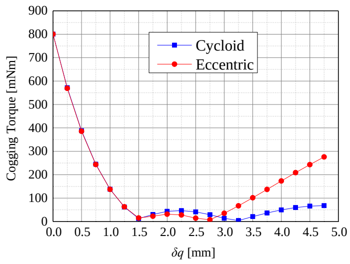


(**b**)

Figure 6. Calculation results of cogging torque: (**a**) Wave form of 1 period for cogging torque pulsation; (**b**) Peak to peak values of cogging torque at δq ($0 \le \delta q \le 4.75$).

Figure 6 shows the calculation results of cogging torque. Figure 6 (a) shows the wave form of 1 period for cogging torque pulsation. As described in Equation (2), the mechanical angle of cogging torque θ_{cog} for Figure 6 (a) is 20° at δq =4.75mm with 6 Poles and 9 Slots for this analysis model in Table 1. Figure 6 (b) shows the peak to peak values of cogging torque at δq $(0 \le \delta q \le 4.75)$.

Based on the conventional and prosed curve on the magnet shape, the step skew design, which is the method of cogging torque reduction as explained in the Introduction, is described to reduce cogging torque additionally. Step skew angle θ_{Nskew} is found by dividing by $Nstep$ in Equation (2). Equation (3) shows the calculation of θ_{Nskew}.

$$\theta_{Nskew} = \frac{360^\circ}{N_{step}\ LCM(N_p,\ N_s)} \tag{3}$$

In Equation (3), N_{step} is the number of step and θ_{Nskew} is the step-skew angle with N_{step}. In this study, 3 step-skew is used to compare the conventional and proposed curve on the magnet shape. Figure 7 (a) and (b) show Skew angle $\theta_{cog} = 20^\circ$ in Equation (2) and Step Skew Angle $\theta_{3skew} = 6.67^\circ$ in Equation (3) with 6 poles and 9 slots for L_{stk} = 57mm, respectively.

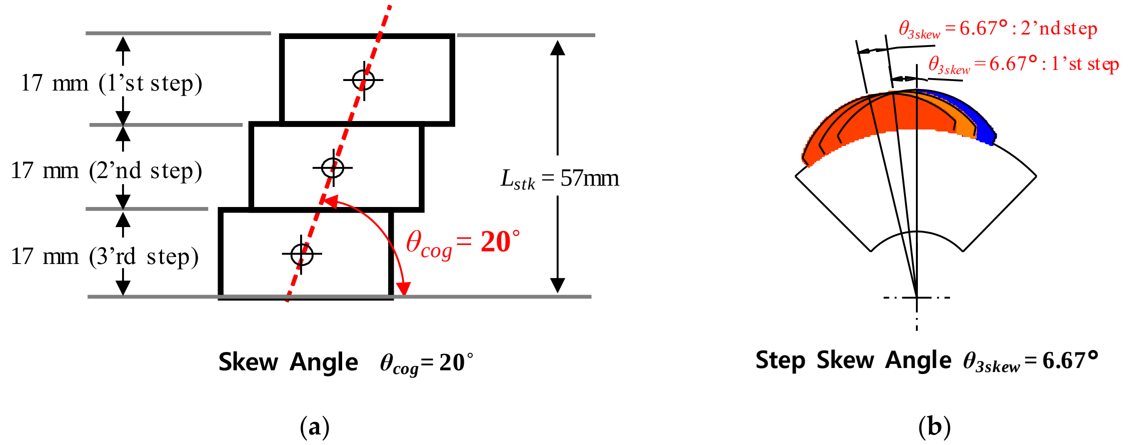


Figure 7. Skew angle and Step-skew angle for 6 poles and 9 slots: (a) Skew Angle θ_{cog} = 20°; (b) Step Skew Angle θ_{3skew} = 6.67°.

In this study, δq is selected as 4.5 considering the performance variation due to the manufacturing tolerances. 3D models for the cycloid curve on the shape magnet is shown in Figure 8 (a) with 3 step-skew of Figure 7. In Figure 8 (b), the wave-forms of 1 period for cogging torque pulsation is shown for 3 step-skew model of the eccentric and proposed curve at δq =4.5.

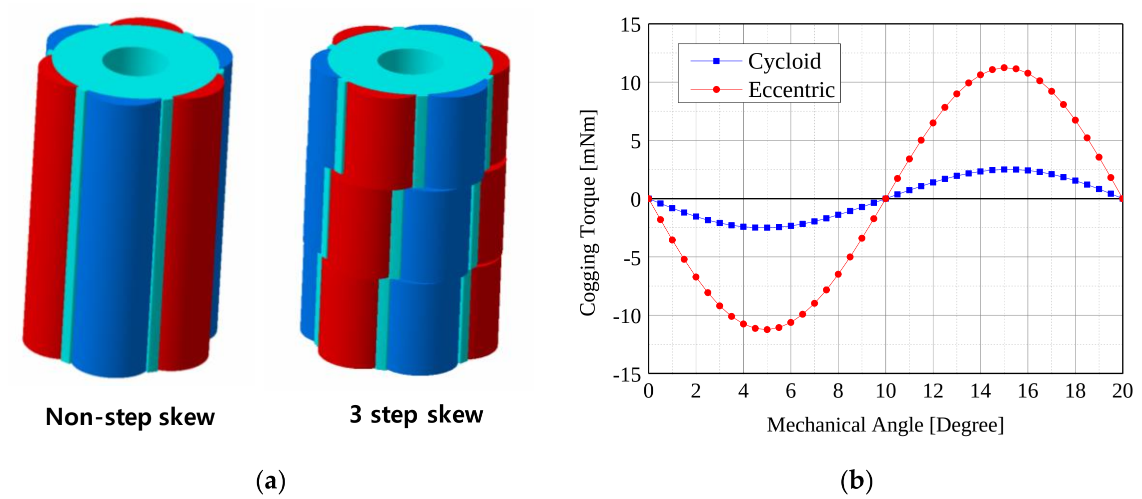


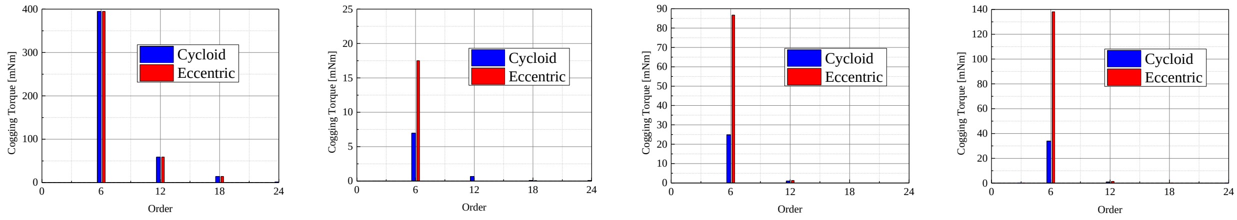
Figure 8. 3 step-skew model and calculation results: (a) 3D models of Non-step skew and 3 step-skew for the cycloid curve at δq =4.5; (b) Wave-forms of cogging torque for 3 step-skew model at δq = 4.5.

Table 2 shows the peak to peak values of cogging for the Non-skew and 3 step-skew model with the eccentric and cycloid curve on the magnet δq = 4.5.

Table 2. Cogging torque for the Non-skew and 3 step-skew model δq = 4.5

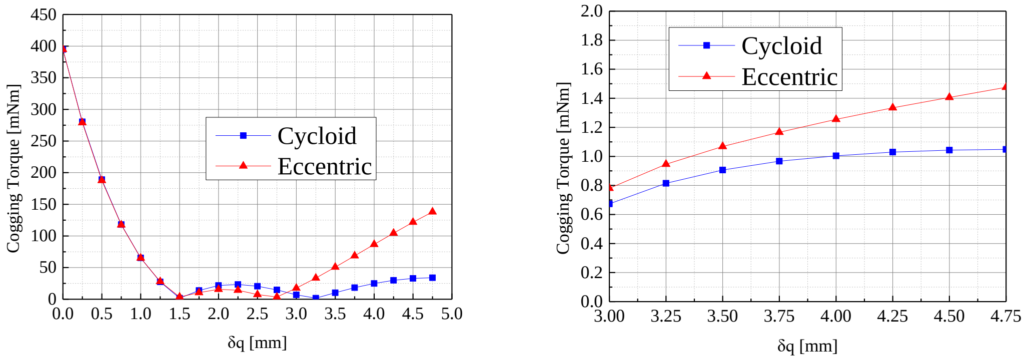
Skew model	Proposed model (Cycloid model)	Conventional model (Eccentric model)	Unit
Non-skew	64	236	mNm
3 step-skew	2.5	11	mNm

In order to explain the effective cogging reduction mechanism for the cycloid curve on the magnet, order analyses are conducted for the eccentric and cycloid curve on the magnet with the non-skew step rotor. The electric fundamental order of PMSM with 6 poles and 9 slots in Table 1 is 6 for the 360 mechanical degree. In addition to the fundamental order, the *6n* orders with the positive integer of *n* are also generated. Table 3 shows the analysis results of cogging torque wave form in Figure 20 with *6n* orders for the eccentric and cycloid curve on the magnets. As shown in Figure 9, the 6'th orders are dominant orders for the cogging torque at the given values of δq. Figures 10 (a) and (b) show the cogging torque of 6'th and 12'th order for the value of δq. As shown in Figure 10 (a), the 6'th order of cogging torque for the eccentric curve on the magnet increases sharply after $\delta q = 3.0$.



(a) (b) (c) (d)

Figure 9. $6n$'th cogging torque for the eccentric and cycloid curve on the magnet : (a) $\delta q = 0.0$; (b) $\delta q = 3.0$; (c) $\delta q = 4.0$; (d) $\delta q = 4.75$.



(**a**) (**b**)

Figure 10. Cogging torque of the 6'th and 12'th order for the eccentric and cycloid curve on the magnet: (a) 6'th order cogging torque; (b) 12'th order cogging torque.

4. Discussion

This study proposed the design method of magnet shape with step-skew model to reduce cogging torque. The prosed design method was verified through numerical analysis compared to the conventional model.

As shown in Table 1, the cogging torque for the proposed model is reduced by 72% compared to the conventional model in case of non-skew model. In case of 3 step-skew model, the cogging torque for the proposed model is reduced by 77% compared to the conventional model. Based on the order analysis of cogging torque wave form, 6'th order cogging is the most dominant cogging torque in the proposed and conventional model. Compared to the proposed model, the 6'th order cogging torque in the conventional model increased sharply as the δq increases. In this reason, the proposed model is an effective design method with any step-skew model for cogging torque reduction. The proposed design will be also a cost-effective design method to reduce manufacturing cost considering the number of step-skew for a required cogging torque value. As a future study, the prototype for the proposed model will be built and its cogging torque reduction will be verified.

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Conflicts of Interest: The authors declare no conflict of interest.

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