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RESEARCH ARTICLE

Analysis of Optimal Rotors Skew to Improve the Total Harmonic Distortion of Back Electromotive Force in MG-PMSM for Traction

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ABSTRACT This paper presents optimal rotor permanent magnet (PM) and rotor pole-piece skew to improve the total harmonic distortion (THD) of the back electromotive force (Back-EMF) in magnetic geared permanent magnet synchronous motor (MG-PMSM) for traction. MG-PMSM is a system that integrates a magnetic gear and a PMSM which can minimize the size of the driving system and reduce power loss because there is no mechanical friction unlike the existing motor. For this reason, it is more advantageous in terms of output density and efficiency. However, MG-PMSM has a pole-piece rotor for magnetic flux modulation, which can produce additional spatial harmonics in back electromotive force (back-EMF). In addition, this motor has inevitable to have a salient permanent magnet structure for the stator due to magnet loss, and in the case of winding methods, fractional slot concentrated winding (FSCW) is mainly used, which also causes additional harmonics. THD in back-EMF adversely affects torque ripple and make accurate position control difficult. Therefore, in this paper, THD in back-EMF is reduced by focusing on the optimal rotors skew. Considering the characteristics of MG-PMSM, skew is applied to each rotor, and then compared and analyzed with the proposed model.

INDEX TERMS Magnetic gear, permanent magnet synchronous motor (PMSM), skew, total harmonic distortion (THD), traction motor.

I. INTRODUCTION

Recently, various studies related to life cycle cost (LCC) and high efficiency have become important in driving systems such as railway and electric vehicles [1]. In particular, the traction motor has the greatest influence on the output and determines the performance of driving system. Accordingly, research on motor design is being actively conducted, and the trend is gradually changing from an induction motor to a PMSM with high power density [2]. Despite this effort, the current driving system still has some problems. For example, this system is complicated because it is divided into

a mechanical gear and an electric motor. In the case of a railway vehicle, it may be difficult to install them due to size limitation in the lower space of the vehicle. In addition, the mechanical gear has power transmission loss in friction or wear, and continuous maintenance is required to manage it [3], [4], [5].

To solve this problem, MG-PMSM, which combines a magnetic gear and PMSM in an integrated form, is being newly studied [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15]. This motor has a double rotor structure and rotates at different speeds due to the magnetic flux modulation effect by the pole-pieces [16], [17]. Since it transmits power in a non-contact, there is little mechanical loss and maintenance is not required. Fig. 1 shows the change from the conventional

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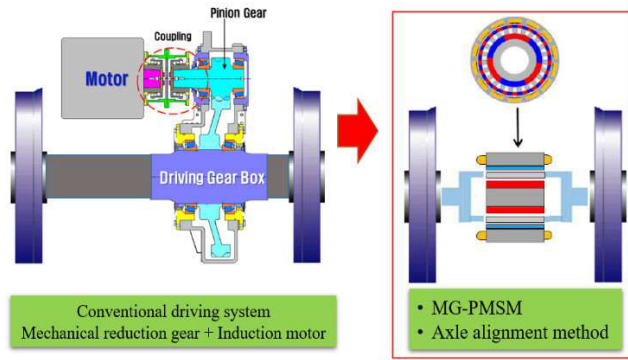


FIGURE 1. Comparison of conventional driving system (reduction gear + electric motor) and MG-PMSM in railway vehicle.

driving system to the MG-PMSM in railway vehicle. The conventional driving system takes up a lot of space because it mainly uses vertical gears. Therefore, MG-PMSM is more advantageous in power density for the total system.

However, MG-PMSM also has a disadvantage, which is that the THD in back-EMF is higher than that of other motors. The harmonics of the back-EMF make accurate position control difficult and adversely affect torque ripple [18]. There are three representative factors that increase the THD in back-EMF of MG-PMSM: magnetic flux modulation effect, salient outer permanent magnet structure, and FSCW [19]. Except for the winding method, the other two factors are characteristics occur only in MG-PMSM. The existing motors improve this by modifying the rotor or stator shape, but in MG-PMSM, this is inherently high and has a limit to improving by design.

Therefore, in this paper, optimal rotor PM and rotor pole-piece skews are introduced. In general, skew is widely used to reduce the cogging torque by shifting the phase of rotor. With this principle, a formula for calculating the optimal skew angle to minimize a specific order harmonic of the back-EMF was derived. In this motor, since it is a double rotor, different skew angles should be applied to each, and the new skew method was proposed in consideration of it. To verify this, before applying the skew, the back-EMF harmonic order was checked through the prototype and FEA analysis results, and then confirmed how much THD was reduced through the proposed optimal rotors skew.

II. PRINCIPLE OF MG-PMSM

A. OPERATING PRINCIPLE

The operating principle of MG-PMSM is basically the same as that of a magnetic gear [16]. Fig. 2 shows a cross-sectional view of MG-PMSM and a linear magnetic gear. As shown in Fig. 2, the magnetic gear part occupies the inside of this motor, and rotating magnetic field of the stator synchronizes the inner permanent magnet. In this paper, it is assumed that the outer permanent magnet attached to the stator is fixed and the pole-pieces composed of ferromagnetic material rotates. Fig. 3 shows fundamental harmonics of the magnetomotive

force (MMF) $F_{in,out}$ generated by the inner or outer permanent magnets and the relative permeance P_r of the pole-pieces in magnetic gear. The equation for these can be expressed as follows using the Fourier series.

$$F_{in} = \sum_{m=1,3,5 \dots} F_m \sin mp_{in}(\theta - \omega_{in}t) \quad (1)$$

$$P_r = P_o + \sum_{k=1,2,3 \dots} P_k \sin kN_{pp}(\theta - \omega_{pp}t) \quad (2)$$

$$F_{out} = \sum_{n=1,3,5 \dots} F_n \sin np_{out}\theta \quad (3)$$

where $F_{m,n}$ is the MMF amplitude of the m and n -th order harmonic; P_k is the permeance amplitude of the k -th order harmonic; N_{pp} is the number of pole-pieces; $p_{in,out}$ is the number of the inner or outer PM pole pairs; $\omega_{in,pp}$ is the mechanical speeds of inner rotor and pole-piece rotor; and θ is the air-gap circumferential position. Just as the MMF of PM or armature in the PMSM is modulated by the slotting effect, the air-gap flux density of the magnetic gear is also expressed as the product of the MMF of PMs and relative permeance of pole-piece. Thus, the modulated air-gap flux density can be expressed as follows.

$$B_{in} = P_o \sum_{m=1,3,5 \dots} F_m \sin mp_{in}(\theta - \omega_{in}t) - \frac{1}{2} \sum_{m=1,3,5 \dots} \sum_{k=1,2,3 \dots} F_m P_k \left\{ \begin{aligned} &\cos(mp_{in} + kN_{pp}) \left(\theta - \frac{mp_{in}\omega_{in} + kN_{pp}\omega_{pp}}{mp_{in} + kN_{pp}}t \right) \\ &- \cos(mp_{in} - kN_{pp}) \left(\theta - \frac{mp_{in}\omega_{in} - kN_{pp}\omega_{pp}}{mp_{in} - kN_{pp}}t \right) \end{aligned} \right\} \quad (4)$$

$$B_{out} = P_o \sum_{n=1,3,5 \dots} F_n \sin np_{out}\theta - \frac{1}{2} \sum_{n=1,3,5 \dots} \sum_{k=1,2,3 \dots} F_n P_k \left\{ \begin{aligned} &\cos(np_{out} + kN_{pp}) \left(\theta - \frac{kN_{pp}\omega_{pp}}{np_{out} + kN_{pp}}t \right) \\ &- \cos(np_{out} - kN_{pp}) \left(\theta - \frac{-kN_{pp}\omega_{pp}}{np_{out} - kN_{pp}}t \right) \end{aligned} \right\} \quad (5)$$

where, $B_{in,out}$ is the modulated magnetic flux density in inner or outer air-gap, P_o and P_r are dc component and amplitude

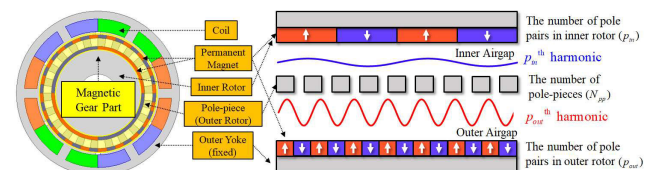


FIGURE 2. Cross-sectional view of MG-PMSM and linear magnetic gear for explaining the modulated magnetic flux density [17].

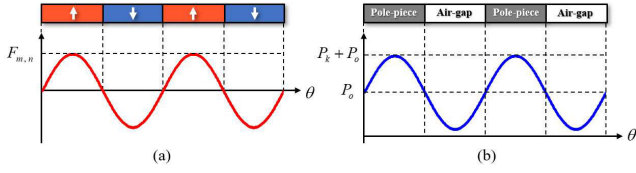


FIGURE 3. The fundamental harmonics of MMF in permanent magnets and relative permeance in pole-pieces. (a) MMF. (b) relative permeance.

of relative permeance in pole-pieces, respectively. In order to generate a steady torque and a gear ratio, the two modulated magnetic flux densities should have the same the number of pole and speed, respectively. Accordingly, when $k = m = n = 1$, the magnetic gear part can be operated only when the following equations are satisfied [5].

$$p_{out} = p_{in} \pm N_{pp} \quad (6)$$

$$\omega_{in} = \frac{\pm N_{pp} \omega_{pp}}{p_{out} \pm N_{pp}} \quad (7)$$

B. ROTORS SKEW IN MG-PMSM

In the case of the conventional PMSM, the motor is skewed to permanent magnets to reduce the cogging torque. Since cogging torque is caused by the difference in magnetic reluctance between the permanent magnets and the teeth of stator at no load. Therefore, the period angle of the cogging torque (K_{cog}) can be expressed as the least common multiple (LCM) of the number of poles (n_r) and the number of slots (n_s), as shown in (8). Fig. 4 shows the ideally skewed model and cogging torque waveforms of each phase when applying the optimal skew angle to the permanent magnet. The ideally skewed model in this paper is to explain the optimal skew angle, and is three steps skewed model ($S_m = 3$) without harmonic of the cogging torque. As shown in Fig. 4, the middle model has zero phase angle ($\theta_{PM} = 0$), and the upper and lower models (leading and lagging) is shifted by $+\theta_{PM}$ or $-\theta_{PM}$. Thus, the optimal skew angle (θ_{cog}) can be expressed as (9) and this is the angle at which the value of the cogging torque is zero, ideally. With reference to above method, if the n -th harmonic of back-EMF (N_{th}) is targeted rather than the cogging torque, the optimal skew angle to minimize the magnitude of N_{th} can be obtained. Since N_{th} corresponds to the cycle of the cogging torque, optimal skew angle (electric angle, $\theta_{har(e)}$) can be expressed as (10) in PMSM [18], [20].

$$K_{cog} = \frac{360}{LCM(n_r, n_s)} \quad (8)$$

$$\theta_{cog} = \frac{K_{cog}}{S_m} \quad (9)$$

$$\theta_{har(e)} = \frac{360}{N_{th}} \times \frac{1}{S_m} \quad (10)$$

In the case of MG-PMSM, unlike conventional PMSM, it contains pole-pieces, which also rotate in the same direction and different speed as the inner rotor. For this reason, the MG-PMSM should be skewed not only to the inner rotor but also to the outer rotor(pole-pieces) as shown in Fig. 5.

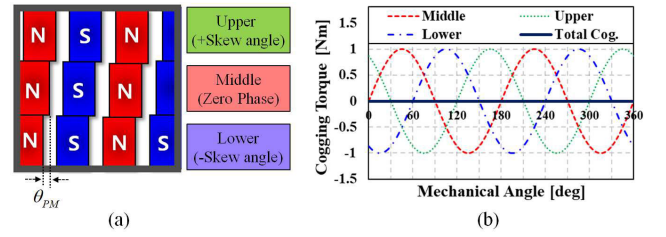


FIGURE 4. Cogging torque waveform when permanent magnet skew is applied to PMSM. (a) side view. (b) cogging torque.

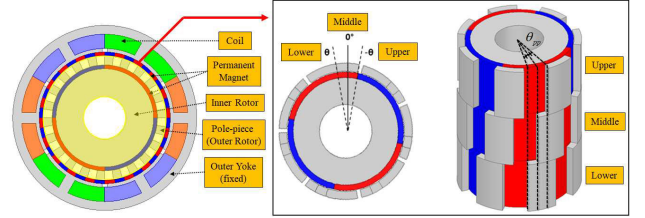


FIGURE 5. 2D and 3D models to explain skewing to pole-pieces.

Therefore, if the electric angle is converted to a mechanical angle from (10), the optimal inner and outer rotor skew angles proposed in this paper can be expressed as (11) and (12), respectively.

$$\theta_{PM-har(M)} = \theta_{har(e)} \times \frac{1}{p_{in}} \quad (11)$$

$$\theta_{pp-har(M)} = \theta_{har(e)} \times \frac{1}{N_{pp}} \quad (12)$$

III. SKEW OF MG-PMSM

A. EXPERIMENTAL VALIDATION AND SPECIFICATION OF MG-PMSM

Fig. 6 shows 800W scaled-down model for electric vehicle and 45kW model for tram, and Table 1 shows the

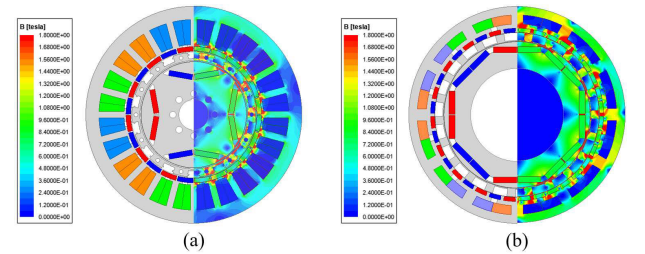


FIGURE 6. Magnetic flux density of 2D FEA models. (a) 800W scaled-down model for electric vehicle. (b) 45kW model for tram.

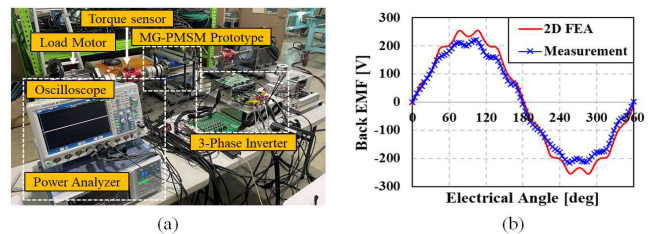


FIGURE 7. Experiments to validate MG-PMSM. (a) M-G set. (b) Phase A back-EMFs of 2D FEA and experiment at no-load.

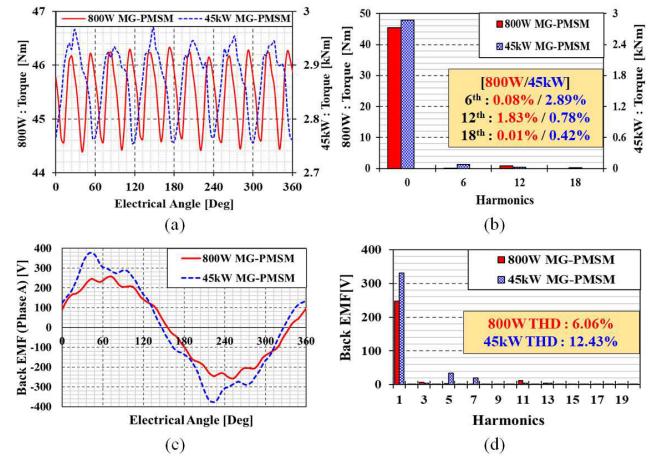
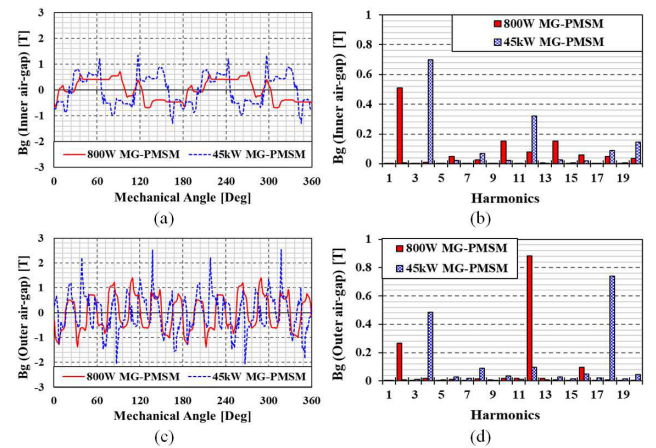
TABLE 1. Specification for 800W and 45kW FEA MG-PMSM.

Specification		
Contents	800W model (FEA)	45kW model
Winding method	Distributed	Fractional Slot Concentrated
Inner poles / Pole-pieces / Outer poles	4 / 14 / 24	8 / 22 / 36
Magnetic material (Core / Magnet)	30PNF1600 / N38UH	30PNF1600 / N45UH
Stator Diameter	164 [mm]	520 [mm]
Axial Length	120 [mm]	204 [mm]
Rated speeds of Inner Rotor / Outer Rotor	1498 / 214 [RPM]	1177 / 214 [RPM]
Derived / Required pole-piece torque	45.47 / 35.70 [Nm]	2.87 / 2.05 [kNm]
Current / Turns	2.1 [A_{rms}] / 65	107 [A_{rms}] / 18
Phase Voltage	258.40 [V_{peak}]	376.63 [V_{peak}]
Efficiency	92.54 [%]	95.65 [%]
Power factor	0.91	0.86

specifications for these. As shown in Fig. 7, 800W model was manufactured as a prototype and shows no-load back-EMFs of 2D FEA and experiment. The maximum values of no-load back-EMFs have an error of about 13.4%, because repulsive force and fringing effect are very large due to the structure of MG-PMSM that the permanent magnets look at each other. In addition, the smaller axial length compared to the diameter of the magnetic gear part, the larger the leakage flux generates [21]. Therefore, the error can be considered appropriate and can prove the validity of 2D FEA. Accordingly, skew analysis to be described later was performed based on FEA analysis.

B. ORIGINAL MG-PMSMS WITHOUT SKEWED

Fig. 8 shows the rated torque of pole-pieces and back-EMF of phase A when skew is not applied. Since the final output of the MG-PMSM is the pole-piece part, it can be confirmed that the pole-pieces torque at the rated speed is 45.47Nm(800W) and 2.87kNm(45kW), respectively, which satisfy the required torque. In addition, harmonics multiple of 6 in the torque waveform generate torque ripple, and it can be inferred that the torque ripple of the 45kW model is approximately larger based on the ratio of the n-th harmonic to the dc component [22]. Also, as shown in the fast Fourier transform (FFT) of back-EMFs, it can be seen that 800W model has relatively high 3rd and 11th harmonics, and 45kW model has high 5th and 7th harmonics. In particular, 45kW model has a higher THD compared to the 800W model. This reason is that is more advantageous to apply the FSCW because it is necessary to maximize the magnetic flux modulation effect to increase torque of MG-PMSM, but this is the cause of increasing THD. In addition, the loss of outer permanent magnet in MG-PMSM is very large, and it is almost inevitable to apply the saliency to outer magnet to reduce it. This saliency has been applied to 45kW model more significantly, and this is also a factor that increases THD. The THD of back-EMF is closely related to the torque ripple, so the torque ripple of

**FIGURE 8.** Electromagnetic field analysis results (2D FEA) of 800W and 45kW MG-PMSMs without skew at full load. (a) Rated torque of pole-pieces waveform. (b) Rated torque of pole-pieces spectra. (c) Back-EMF waveform (A phase). (d) Back-EMF spectra.**FIGURE 9.** Electromagnetic field analysis results (2D FEA) of 800W and 45kW MG-PMSMs without skew at full load. (a) Inner air-gap magnetic flux density waveform. (b) Inner air-gap magnetic flux density spectra. (c) Outer air-gap magnetic flux density waveform. (d) Outer air-gap magnetic flux density spectra.

45kW is 14.11%, which is larger than that of 4.34% in 800W model.

Fig. 9 shows the inner and outer air-gap magnetic flux densities when skew is not applied. The 2nd harmonic of the inner air-gap magnetic flux density and the 12th harmonic of the outer air-gap magnetic flux density in the 800W model are respectively caused by the number of pole pairs of the inner and outer permanent magnets, which are the fundamental harmonics for the electrical angle. In the same way, in the 45kW model, 4th of the inner and 18th of the outer refer to these respectively. Most of the other harmonics are modulated components that necessarily occur as expressed in (4) and (5). These harmonics also a factor in increasing THD of back-EMF in MG-PMSM.

C. PM AND PP SKEW OF MG-PMSMS

Fig. 10 shows the electromagnetic characteristics results when the skew is applied to inner permanent magnet (PM)

and pole-pieces (PP) respectively in 800W model. For 800W model, the 3rd and 11th harmonics are relatively high, so magnitudes of back-EMF for these are shown. As shown in Fig. 10(b) and (d), it can be seen that THD according to PM skew angle has a waveform similar to 11th harmonic because it is dominant. Also, as shown in Fig. 10(a) and (b), when PM skew angle is 20 degrees, THD and 11th harmonic are the lowest, but the derived torque is only slightly higher than the required torque. However, as mentioned above, MG-PMSM has a large axial leakage, so it may be difficult to determine that it is a satisfactory value. Therefore, considering torque, torque ripple and THD, it can be seen that about 8 degrees is most advantageous in PM skew. Here, compared to the original model, torque was decreased by about 3.03% and THD by about 29.68%. In addition, as shown in Fig. 10(c) and (d), when the skew is applied to PP, it can be seen that the target value changes sensitively according to the skew angle because the PP electrical angle for one rotation of the mechanical angle is larger than that of the PM rotor. Likewise, considering 3 targets, about 2 degrees can be seen as the best. Here, compared to the original model, torque was decreased by about 6.86%, and THD by about 24.54%.

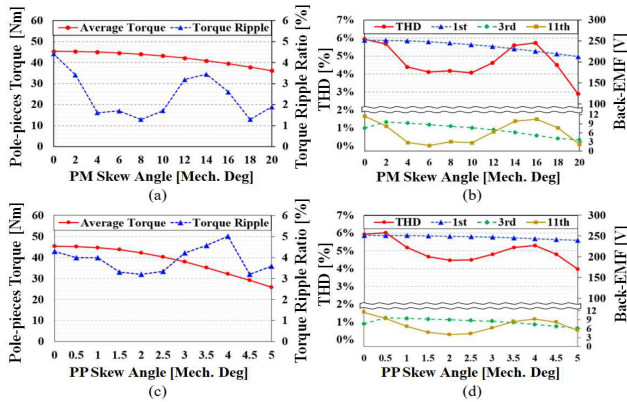


FIGURE 10. Electromagnetic characteristics for PM and PP skew in 800W model at full load. (a) Rated torque with skewed. (b) THD and back-EMF with PM skewed (phase). (c) Rated torque with PP skewed. (d) THD and back-EMF with PP skewed (phase).

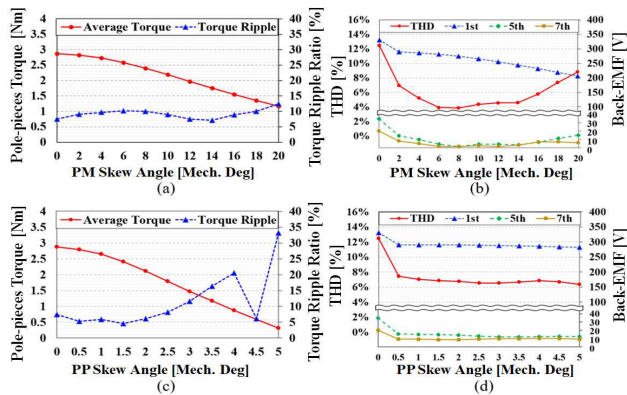


FIGURE 11. Electromagnetic characteristics for permanent magnet skew and pole-pieces skew in 45kW model at full load. (a) Rated torque with skewed. (b) THD and back-EMF with PM skewed (phase). (c) Rated torque with PP skewed. (d) THD and back-EMF with PP skewed (phase).

Fig. 11 shows the electromagnetic characteristic results for 45kW model. This model mainly dominates 5th and 7th harmonics. In addition, it has a larger torque loss as the skew angle increases compared to the model. This is because this model has a larger electrical angle for the same skew angle (mechanical angle) due to the larger number of PM pole pairs and PP than the model, so the target value changes sensitively. In the case of PM skew, about 6 degrees is the best when considering 3 targets. Here, compared to the original model, torque was decreased by about 9.92% and THD by about 68.58%. In the same way, in the case of PP skew, more weight was given to the average torque because THD was almost the same as the skew angle increased. Therefore, based on 0.5 degrees, the torque decreased by about 2.54%, and THD by about 40.44%.

D. PROPOSED SKEW OF MG-PMSMS

In this paper, models with skewed to both PM rotor and PP rotor is proposed. Since the electrical frequencies of the two rotors are the same, different skew angles (mechanical angles) should be applied in consideration of it. In the case of the 800W model, skew angles targeting the 3rd and 11th harmonics are proposed. Using (8) and (9), the PM and PP skew angles for 3rd harmonic are 20deg and 2.86deg, respectively, and the skew angles for 11th harmonic are 5.45deg and 0.78deg. Fig. 12 shows the electromagnetic characteristic results for the original model, PM skew model, PP skew model, PM-PP (3rd order) model, and PM-PP (11th order) model for the 800W model. In both the 3rd and 11th models, the target harmonics are decreased by 83.44% and 93.70%, respectively. The 11th model is more advantageous in terms of torque, because the higher the harmonic order, the smaller the optimal skew angle.

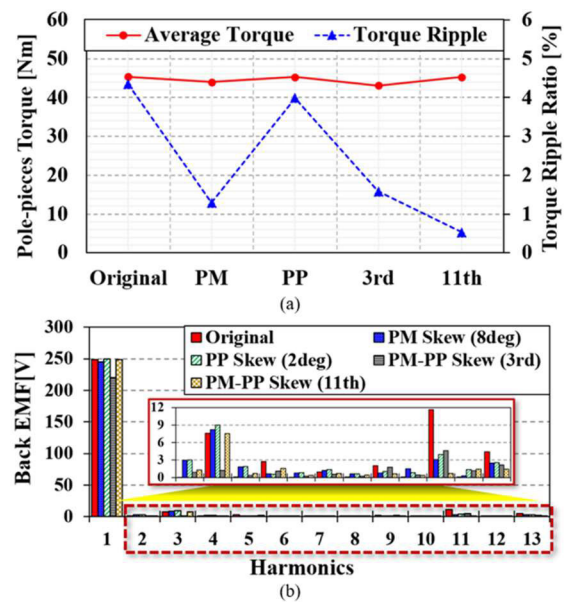


FIGURE 12. Electromagnetic characteristics for all skew in 800W model at full load. (a) rated torque. (b) back-EMF FFT (phase).

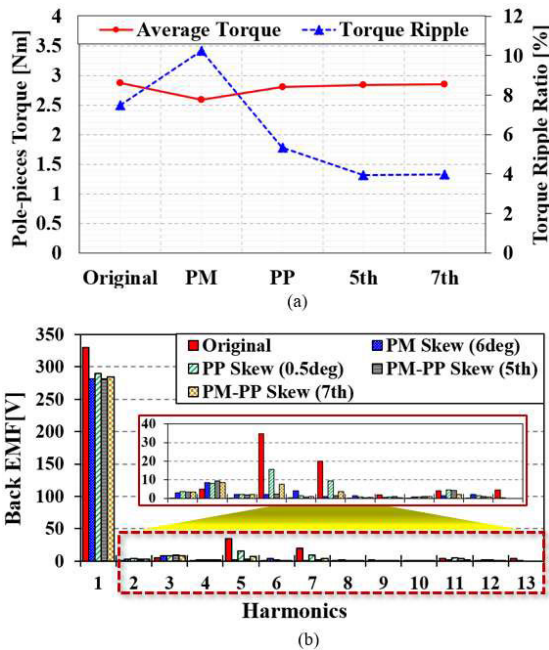


FIGURE 13. Electromagnetic characteristics for all skew in 45kW model at full load. (a) rated torque. (b) back-EMF FFT (phase).

TABLE 2. Skew for 800W and 45kW models.

Specification				
Model	Skew	Torque	Torque ripple ratio	THD (back-EMF)
800W model	Original	45.37 [Nm]	4.34 [%]	5.94 [%]
	PM	44.00 [Nm]	1.29 [%]	4.17 [%]
	PP	45.28 [Nm]	3.99 [%]	4.48 [%]
	PM-PP (3 rd)	43.10 [Nm]	1.58 [%]	2.60 [%]
	PM-PP (11 th)	45.29 [Nm]	0.53 [%]	3.19 [%]
45kW model	Original	2.87 [kNm]	7.49 [%]	12.44 [%]
	PM	2.59 [kNm]	10.24 [%]	3.91 [%]
	PP	2.80 [kNm]	5.35 [%]	7.41 [%]
	PM-PP (5 th)	2.84 [kNm]	3.95 [%]	4.25 [%]
	PM-PP (7 th)	2.85 [kNm]	3.97 [%]	4.63 [%]

Fig. 13 shows the electromagnetic characteristics results for the original model, PM skew model, PP skew model, PM-PP (5th) model, and PM-PP (7th) model for 45kW model. In terms of torque and torque ripple, 5th and 7th showed the best characteristics.

Finally, Table 2 summarizes the analysis results for total skewed models. For the 800W model, the proposed 3rd model has the lowest THD, and the 11th model was the best in terms of torque and ripple. Also, for the 45kW model, the PM skew model has the lowest THD, but the torque loss is significant. Therefore, it can be seen that the proposed 5th and 7th models are the best when all results are taken into consideration. The reason for this is that when the skew is applied to both PM and PP rotor, air gap magnetic flux is generated at the point

where both MMF in PM rotor and permeance in PP rotor have maximum values, so torque loss can be minimized and THD of back-EMF can be reduced.

IV. CONCLUSION

This paper is about an analysis of optimal rotor PM and rotor pole-piece skews for THD reduction of MG-PMSM for traction. MG-PMSM has several factors that can increase THD compared to other motors in terms of electromagnetic characteristics and structure. Since there is a limit to reducing by design, new skew is applied in this paper. The existing skew is mainly for reducing the cogging torque, and the optimum skew angle is derived from periodic angle of the cogging torque. Inspired by the above method, this paper proposes optimal skew angle equations that remove harmonics of a specific order from the phase back-EMF. In order to validate the equations, PM skew, PP skew, and the proposed PM-PP skewed models were compared using the 800W and 45kW model for electric vehicles. As a result, the proposed method had the best characteristics because it was able to reduce the THD of back-EMF while minimizing the torque loss, and it was confirmed that the harmonics of the target order were significantly reduced. This method can be seen to be more efficient with higher harmonic orders.

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