A Study on the Improvement of the Correction Coefficient Considering the 3D Effect of Spoke Type Permanent Magnet Synchronous Motor

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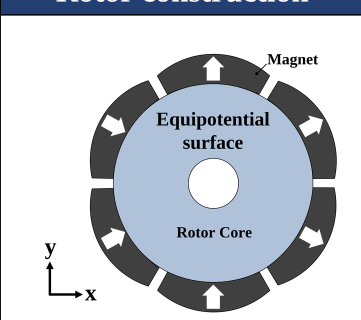
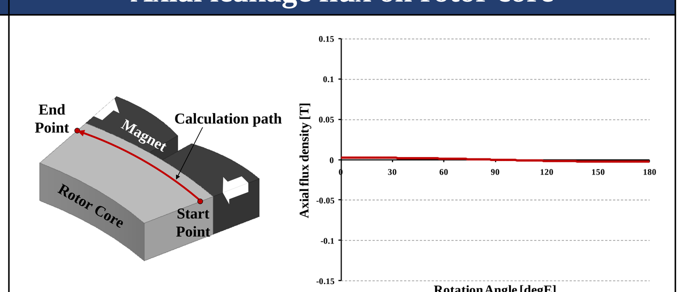
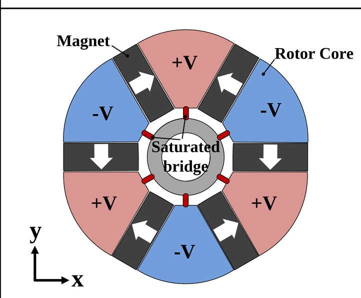
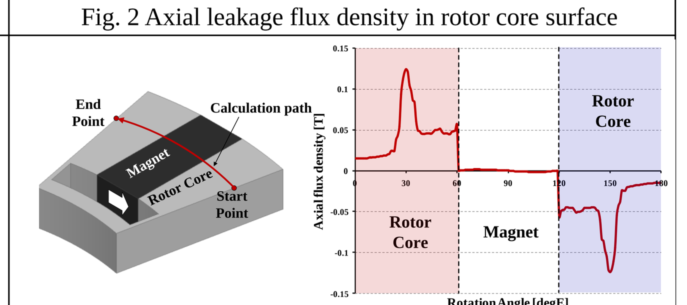
Abstract

In permanent magnet synchronous motors (PMSM) that do not use reluctance torque, the most important performance indicator is the no-load back electromotive force (EMF) that represents the torque constant. In general, the magnetic flux is on a two-dimensional (2D) plane perpendicular to the axial direction. Thus, 2D Finite Element Analysis (FEA) is used for performance analysis of motors. However, in the Spoke type PMSM, which is being actively studied recently due to its high power density, the field flux passes through a three-dimensional (3D) path containing axial components. This is in contrast to the existing field flux of PMSM on a 2D plane perpendicular to the axial direction. Therefore, unlike the PMSM of the magnetic flux non-concentrating type, which can be fairly accurate no-load back EMF analysis even with 2D FEA, analysis of the no-load back EMF of Spoke type PMSM needs to be performed with 3D FEA. In this paper, we propose a correction coefficient that allows us to consider 3D effects due to axial leakage flux and axial linkage flux generated in spoke type PMSM. The proposed correction coefficient is multiplied by Br of the permanent magnet (PM), which enables 2D FEA analysis with fast analysis time similar to 2D FEA and high analysis accuracy of 3D FEA. The validity of the analysis method with the proposed correction coefficient was performed through 2D and 3D FEA for various models.

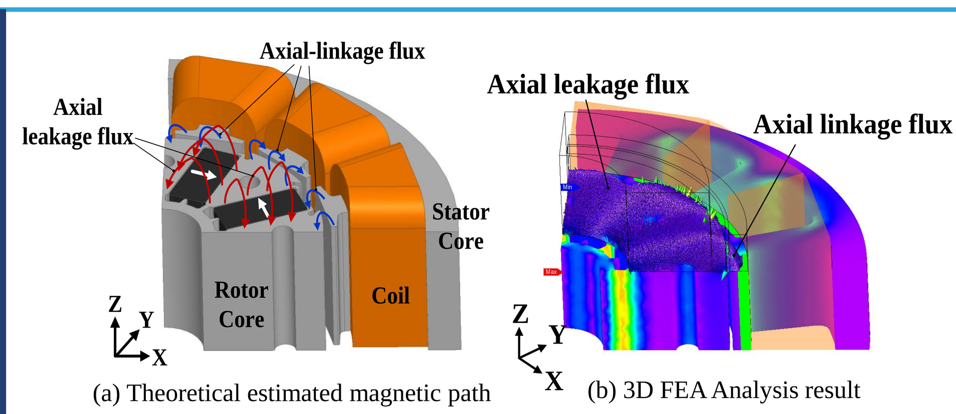
1. Introduction : 3D effect of Spoke type PMSM

Axial Leakage

Type	Rotor construction	Axial leakage flux on rotor core
SPMSM	 Fig. 1 Magnetic potential of rotor	 (a) Calculation path (b) Axial leakage flux density Fig. 2 Axial leakage flux density in rotor core surface
SFMSM	 Fig. 3 Magnetic potential of rotor	 (a) Calculation path (b) Axial leakage flux density Fig. 4 Axial leakage flux density in rotor core surface

Spoke type PMSM rotor cores are separated by nonmagnetic PM and are connected only through a magnetic saturated thin bridge. Since the magnetically saturated core is non-magnetic, each pole of the rotor core is magnetically separated from one another. The magnetic potentials of the poles of the rotor core adjacent to each other in the magnetizing direction of the permanent magnets disposed symmetrically about the rotor pole are the same in magnitude and opposite in polarity. As a result, the magnetic potential difference between the poles of adjacent rotor cores generates a 3D leakage flux through the axial direction

Axial Linkage

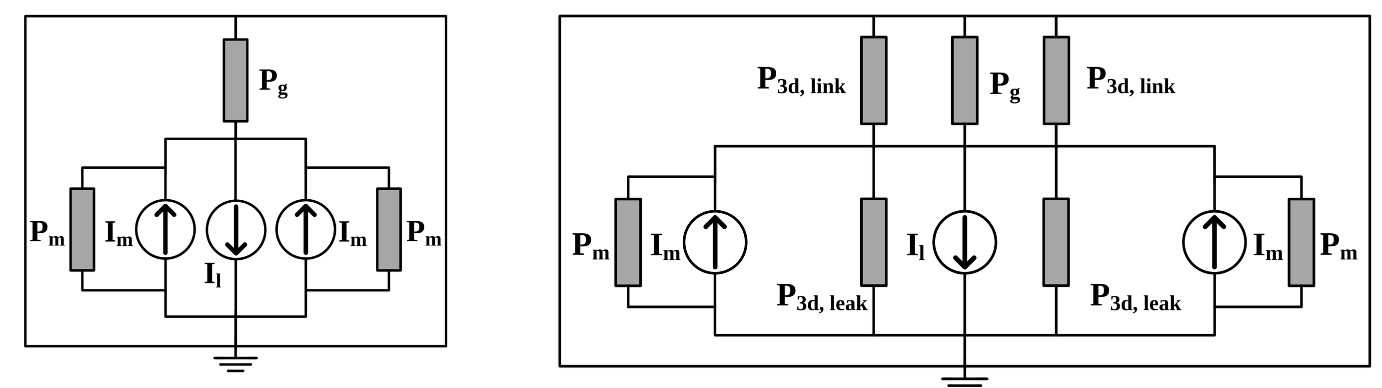


(a) Theoretical estimated magnetic path (b) 3D FEA Analysis result

Fig. 5 3D axial magnetic path in Spoke type PMSM

Recent studies have shown that there are additional 3D linkage flux paths through the axial gap in the air gap between the rotor and stator core at the top and bottom of the stack in the PMSM. This additional linkage flux path is a phenomenon caused by the fringing effect. Also, like the Spoke type PMSM, the magnetic air gap between the stator core and the rotor core is larger in smaller motors.

2. Calibration coefficient calculation process



(a) 2D MEC with Axial magnetic path ignored (b) 3D MEC with Axial magnetic path (leakage & linkage)

Fig. 6. Magnetic Equivalent Circuit of Spoke type PMSM

The linkage flux per pole of the calculated Spoke type PMSM is shown in Eq. (1) by using the MEC of Fig. 2 (a) in which axial magnetic paths are ignored. In Equation (1), all terms are linear functions of the stack length L_s. Using this, each term in Eq. (1) can be represented by the stack length L_s and the terms excluding it.

$$\lambda_{2D,L_s} = \frac{\left(2I_m - I_l\right)P_g}{P_g + 2P_m} = \frac{I_m^* P_g}{P_g + 2P_m} = \frac{\phi \cancel{L_s} M_1 L_s}{M_1 \cancel{L_s} + M_2 \cancel{L_s}} = \frac{\phi M_1 L_s}{M_1 + M_2} \quad \text{------------------------ (1)}$$

Next, the linkage flux per pole calculated with Fig. 2 (b) where the axial magnetic path is considered is shown in Eq. (2). As in equation (1), all terms except for the axial magnetic path in Eq. (2) are linear functions of stack length L_s. Using this, each term in Eq. (2) can be expressed by separating the stack length L_s and the terms excluding it.

$$\lambda_{3D,L_s} = \frac{\left(2I_m - I_l\right)\left(P_g + 2P_{3d,link}\right)}{P_g + 2P_m + 2P_{3d,leak} + 2P_{3d,link}} = \frac{\phi L_s \left(M_1 L_s + M_4\right)}{\left(M_1 + M_2\right)L_s + M_3 + M_4} \quad \text{------------------------ (2)}$$

Now, if the axial magnetic path of the pole (1) is divided into the linkage flux per pole, which is calculated by considering the axial magnetic paths (2), the axial 3D effect of the Spoke type PMSM with 2D FEA The Eq. (3) for the calibration coefficient *k* that can be considered can be obtained.

$$k = \frac{\lambda_{3D,L_s}}{\lambda_{2D,L_s}} = \frac{\dfrac{\cancel{\phi}\cancel{L_s}\left(M_1 L_s + M_4\right)}{\left(M_1 + M_2\right)L_s + M_3 + M_4}}{\dfrac{\cancel{\phi} M_1 \cancel{L_s}}{M_1 + M_2}} = \frac{\left(M_1 + M_2\right)\left(M_1 L_s + M_4\right)}{M_1\left(\left(M_1 + M_2\right)L_s + M_3 + M_4\right)} \quad \text{------------------------ (3)}$$

The value of 3D FEA analysis for the model with the stack length of L_1 divided by the 2D FEA analysis result can be defined as Eq. (4).

$$\frac{\lambda_{3D\ FEA,L_1}}{\lambda_{2D\ FEA,L_1}} = \alpha_1 = \frac{\left(M_1 + M_2\right)\left(M_1 L_1 + M_4\right)}{M_1\left(\left(M_1 + M_2\right)L_1 + M_3 + M_4\right)} \quad \text{------------------------ (4)}$$

Eq. (5) can be obtained by performing the same calculation as in Eq. (4) for a model with stack length L_2.

$$\frac{\lambda_{3D\ FEA,L_2}}{\lambda_{2D\ FEA,L_2}} = \alpha_2 = \frac{\left(M_1 + M_2\right)\left(M_2 L_2 + M_4\right)}{M_1\left(\left(M_1 + M_2\right)L_2 + M_3 + M_4\right)} \quad \text{------------------------ (5)}$$

By solving the Eq. (4) and Eq. (5), M_3 and M_4 can be expressed by the equations of M_1 and M_2 as in Eq. (6).

$$M_3 + M_4 = \frac{\left(M_1 + M_2\right)\left(L_2\left(1-\alpha_2\right) - L_1\left(1-\alpha_1\right)\right)}{\alpha_2 - \alpha_1} \quad \text{------------------------ (6)}$$

To simplify Eq. (4), M_4 in the second parentheses, which is located in the numerator of Eq. (4), must be expressible by the value of M_1. In order to do this, we can derive Eq. (7) using the ratio β of the linkage flux per phase calculated by the 3D FEA of the stack lengths L_1 and L_2 and the Eq. (2).

$$\frac{\lambda_{3D\ FEA,L_2}}{\lambda_{3D\ FEA,L_1}} = \beta = \frac{\dfrac{\cancel{\left(\alpha_2 - \alpha_1\right)}\cancel{\phi}\left(M_1 L_2 + M_4\right)L_2}{\cancel{\left(M_1 + M_2\right)}\cancel{\left(L_2 - L_1\right)}\left(1-\alpha_1\right)}}{\dfrac{\cancel{\left(\alpha_2 - \alpha_1\right)}\cancel{\phi}\left(M_1 L_1 + M_4\right)L_1}{\cancel{\left(M_1 + M_2\right)}\cancel{\left(L_2 - L_1\right)}\left(1-\alpha_2\right)}} = \frac{\left(1-\alpha_2\right)\left(M_1 L_2 + M_4\right)L_2}{\left(1-\alpha_1\right)\left(M_1 L_1 + M_4\right)L_1} \quad \text{------------------------ (7)}$$

Eq. (7) can be summarized as Equation (8). If the left side of Eq. (8) is replaced with *X*, Eq. (8) is expressed as Eq. (9).

$$\beta\frac{\left(1-\alpha_1\right)L_1}{\left(1-\alpha_2\right)L_2} = \frac{M_1 L_2 + M_4}{M_1 L_1 + M_4} \quad \text{------------------ (8)} \qquad M_4 = \frac{M_1\left(XL_1 - L_2\right)}{1-X} \quad \text{------------------ (9)}$$

Now, substituting Eq. (6) and Eq. (9) into Eq. (3) gives the final expression for the calibration coefficient expressed in Eq. (10).

$$k = \frac{\left(\alpha_2 - \alpha_1\right)\left(L_s + \dfrac{\left(L_2 - XL_1\right)}{\left(X-1\right)}\right)}{\alpha_2\left(L_s - L_2\right) - \alpha_1\left(L_s - L_1\right) + \left(L_2 - L_1\right)} \quad \text{------------------ (10)}$$

3. How to use the calibration coefficient

By using the proposed calibration coefficient, the analysis result equivalent to that of 3D FEA can be obtained through 2D FEA. The calibration coefficient is a method of using the new residual magnetic flux density Br * multiplied by calibration coefficient in the 2D FEA instead of the actual residual magnetic flux density Br of the permanent magnet as shown in Eq. (11).

$$B_r^* = kB_r \quad \text{--------------------------------- (11)}$$

4. Verification using commercial 3D FEA SW

To verify the validity of the proposed calibration coefficient, three types of Spoke type PMSM models were used, as shown in Table 1. (Using commercial Jmag Designer V16)

Table 1. Main specifications of verification analysis model

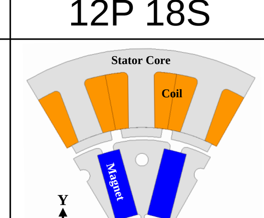
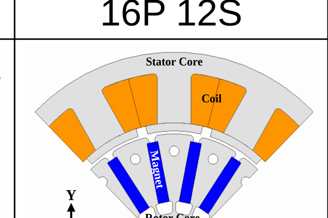
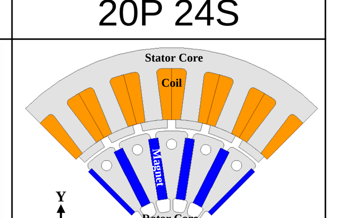
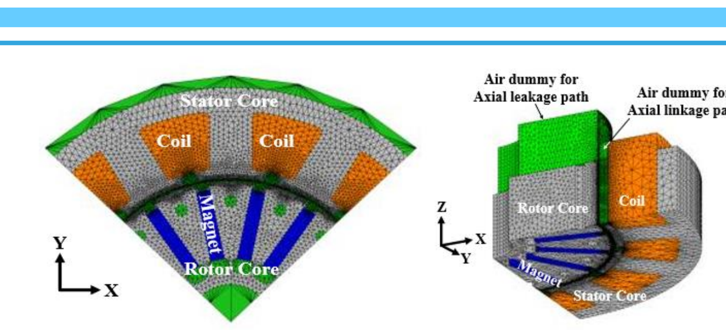
Spec.	Model 1	Model 2	Model 3
Np / Ns	12P 18S	16P 12S	20P 24S
Motor Shape			
Stack length	20, 30, 40	20, 30, 40	20, 30, 40

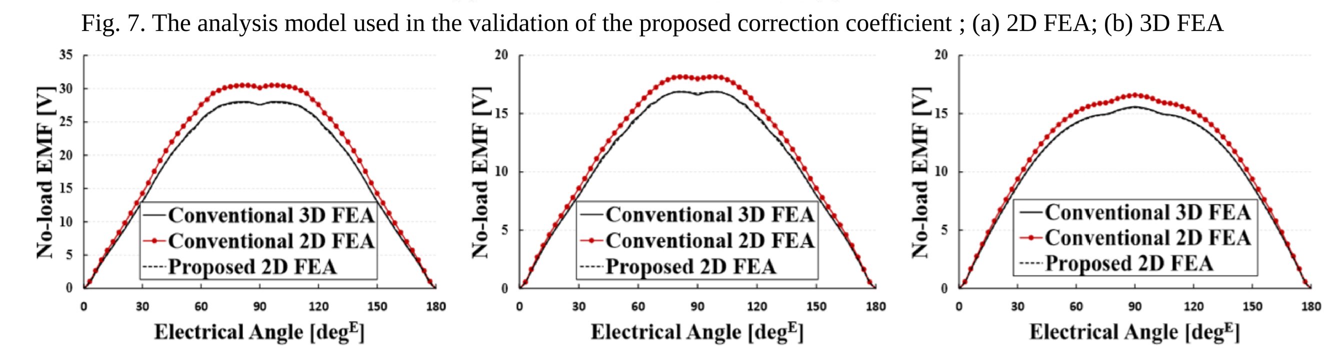
Table 2. Comparison of analysis result and analysis time according to analysis technique

Type	Stack Length	Conventional 2D FEA		Conventional 3D FEA		Proposed 2D FEA (with k)	
		EMF [V_{rms}]	Time[sec]	EMF [V_{rms}]	Time[sec]	EMF [V_{rms}]	Time[sec]
Model 1	20	21.90	52	20.10	6,210	20.27	132
	30	32.85	↑	30.99	15,420	31.18	↑
	40	43.80	↑	41.92	18,576	42.11	↑
Model 2	20	12.84	60	11.96	10,170	12.02	158
	30	19.26	↑	18.35	18,328	18.42	↑
	40	25.67	↑	24.77	21,350	24.83	↑
Model 3	20	12.27	74	11.53	7,446	11.49	169
	30	18.41	↑	17.65	16,388	17.70	↑
	40	254.54	↑	23.79	19,496	23.86	↑



(a) (b)

Fig. 7. The analysis model used in the validation of the proposed correction coefficient ; (a) 2D FEA; (b) 3D FEA



(a) Model 1 (12P18S , Ls = 20mm) (b) Model 2 (16P12S , Ls = 20mm) (c) Model 3 (20P24S , Ls = 20mm)

Fig. 8. No-load EMF analysis results of analysis model

9. Conclusion

Spoke type PMSM has a problem that magnetic fluxes are generated in the axial direction, so that accurate performance characteristics cannot be analyzed with a conventional 2D FEA. While accurate analysis could be performed with 3D FEA, excessive analysis time is typically required. In this paper, the problems of the existing analytical techniques are solved by 2D FEA with correction coefficient that can consider the characteristic change by axial magnetic path. Using the correction factor proposed in this paper, we can secure the fast analysis of 2D FEA and high accuracy of 3D FEA simultaneously. In addition, the process of calculating the correction coefficient is relatively straightforward. It is expected to be of great help to engineers designing Spoke type PMSM for potential applications