Analysis on Design Sensitivity of Permanent Magnet Motor using Lumped Magnetic Circuit Method

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Background

In general, Spoke type Permanent Magnet Synchronous Motor (PMSM) has intense air gap flux density due to its magnet arrangement. However, variation of machine performance is severe due to its design variable which is air-gap length. On the other hand, Surface Mounted PMSM (SPMSM) is less sensitive to change of variables that are mentioned above. Therefore, the sensitivity of the SPM type and Spoke type PMSM due to the variation of air-gap is confirmed through a numerical analysis.

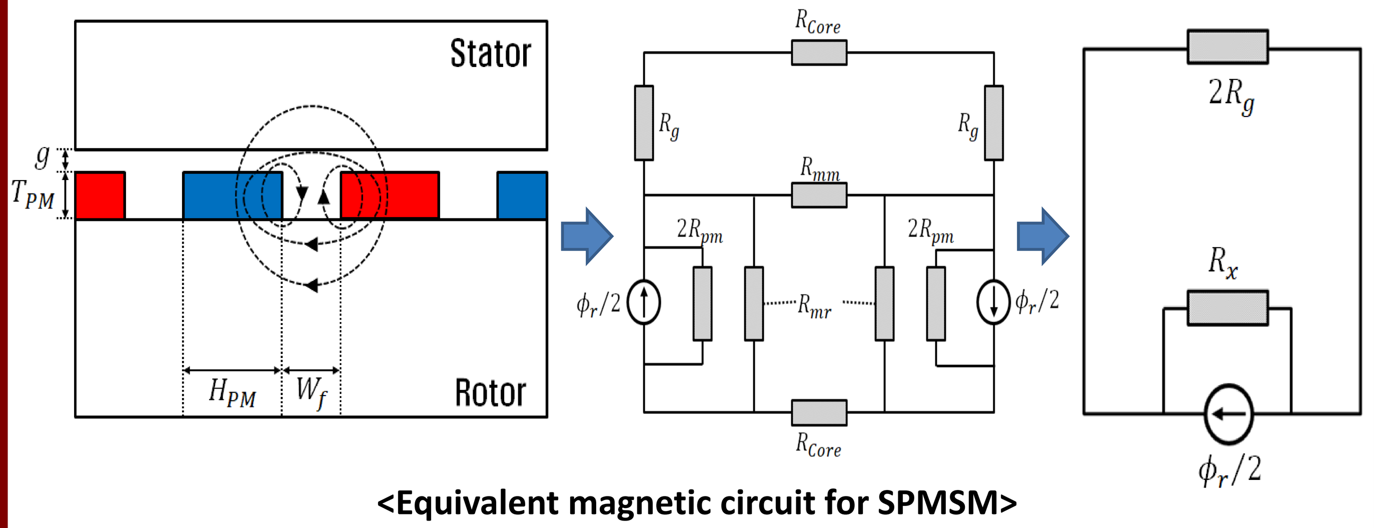
Objectives

- ❖ The air-gap flux density of SPMSM and Spoke type PMSM with respect to air-gap length is examined, in order to identify the sensitivity of performance.
- ❖ It is analyzed numerically based on Magnetic Equivalent Circuit (MEC) method and it is validated through the comparison with FEA results.

Conclusion

- ❖ Considering that air gap flux density of spoke type motor is sensitive to air gap length variance, calculation and analysis was carried out by altering air-gap length from 0.8 mm to 1.4mm with increment of 0.2mm.
- ❖ When motor is designed under equivalent condition, air-gap flux density of spoke type motor was more sensitive compared to that of SPMSM when design parameter is adjusted.
- ❖ The MEC and FEA result is similar also the linear development for spoke type motor and SPMSM is alike in both MEC and FEA analysis.
- ❖ As sensitivity of motor can be predicted using MEC, the issue could be avoided in preliminary design stage.

MEC on SPMSM



<Equivalent magnetic circuit for SPMSM>

• Conventional Equations on Reluctance in the Figure are as follow

$$R_g = \frac{2g}{\mu \cdot H_{PM} \cdot L_{stk}},\ R_{pm} = \frac{T_{PM}}{\mu_{PM} \cdot H_{PM} \cdot L_{stk}}$$

⇒ (g, L_{stk} denote the Air-gap length and Stack length respectively)

• Proposed Equations on Reluctance : R_{mm}, R_{mr}

$$R_{mm} = \frac{\mu_0 L_{stk}}{\pi}\ln\left(1+\frac{\pi g}{W_f}\right) \quad \Rightarrow \quad R_{mm} = \frac{\frac{g}{2\pi}+W_f}{\mu \cdot g \cdot L_{stk}}$$

$$R_{mr} = \frac{\mu_0 L_{stk}}{\pi}\ln\left(1+\frac{\pi g}{H_{PM}}\right) \quad \Rightarrow \quad R_{mr} = \frac{\frac{g}{2\pi}+T_{PM}}{\mu \cdot g \cdot L_{stk}}$$

- A simple expression of error rate within 1.7% was proposed to confirm the sensitivity according to the change of air-gap lengths(g).

- It is assumed that there is no saturation occurring in the iron core, so that the reluctances of iron core are neglected (R_{Core}).

• Air-gap Flux Density Using Proposed Equation

- In the equivalent circuit, expression of R_x is as follow.

$$R_x = (4R_{PM}||2R_{mr}||R_{mm})$$

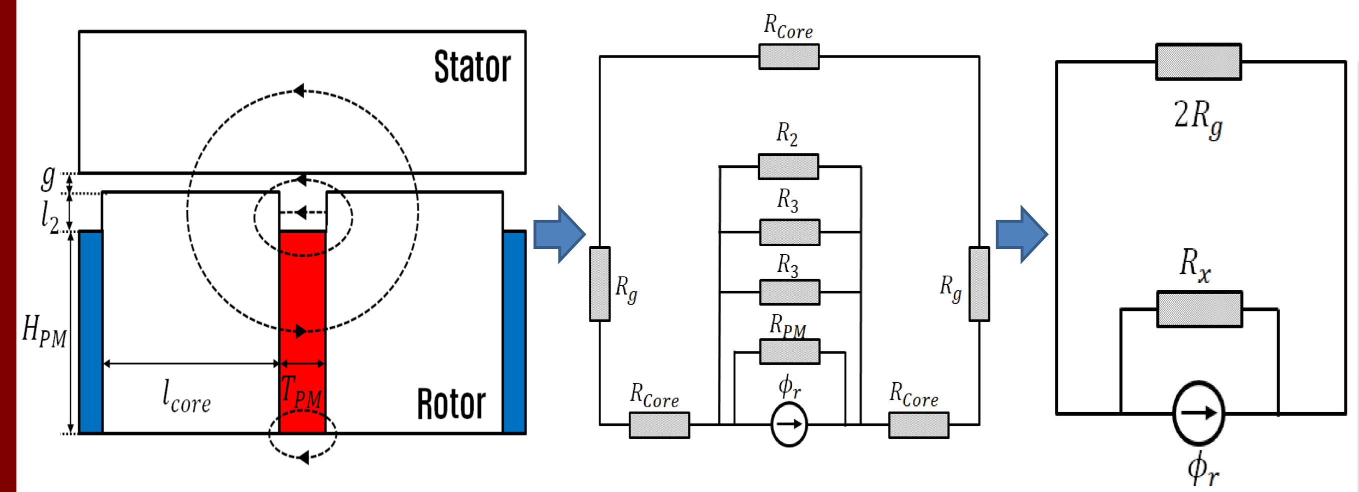
$$B_g = \frac{R_x}{R_x+2R_g}B_r\frac{A_m}{A_g} \quad \Rightarrow \quad (A_m, A_g \text{ is area of magnet and air-gap})$$

• Confirmation of Sensitivity through derivative for Air-gap length

- Through proposed equations, derivative of R_x for air-gap length is simplified.

$$B_g{}' = B_r\frac{A_m}{A_g}\left[\frac{R_x{}'}{R_x+2R_g} - \frac{R_x(R_x'+2R_g')}{(R_x+2R_g)^2}\right]$$

MEC on Spoke PMSM



<Equivalent magnetic circuit for Spoke PMSM>

• Conventional Equations on Reluctance in the Figure are as follow

$$R_g = \frac{2g}{\mu \cdot L_{stk} \cdot l_{core}/2},\ R_{pm} = \frac{T_{PM}}{\mu_{PM} \cdot H_{PM} \cdot L_{stk}}$$

• Proposed Equations on Reluctance : R_2, R_3

$$R_2 = \frac{T_{PM}}{\mu \cdot l_2 \cdot L_{stk}}$$

- R_2 is straight-leakage path between the cores.

$$R_3 = \frac{\mu_0 L_{stk}}{\pi}\ln\left(1+\frac{\pi g}{T_{PM}}\right) \quad \Rightarrow \quad R_3 = \frac{\pi g+T_{PM}}{\mu \cdot g \cdot L_{stk}}$$

- Similar to SPMSM type, to simplify the expression, the reluctance according to the center of the flux path is proposed. (Error rate within 17%, Using Compensating Factor)

- R_3 is circular-leakage path between the cores.

• Air-gap Flux Density Using Proposed Equation

- In the equivalent circuit, expression of R_x is as follow.

$$R_x = (R_{PM}||R_2||R_3/2)$$

$$B_g = \frac{R_x}{R_x+2R_g}B_r\frac{A_m}{A_g} \quad \Rightarrow \quad (A_m, A_g \text{ is area of magnet and air-gap})$$

• Confirmation of Sensitivity through derivative for Air-gap length

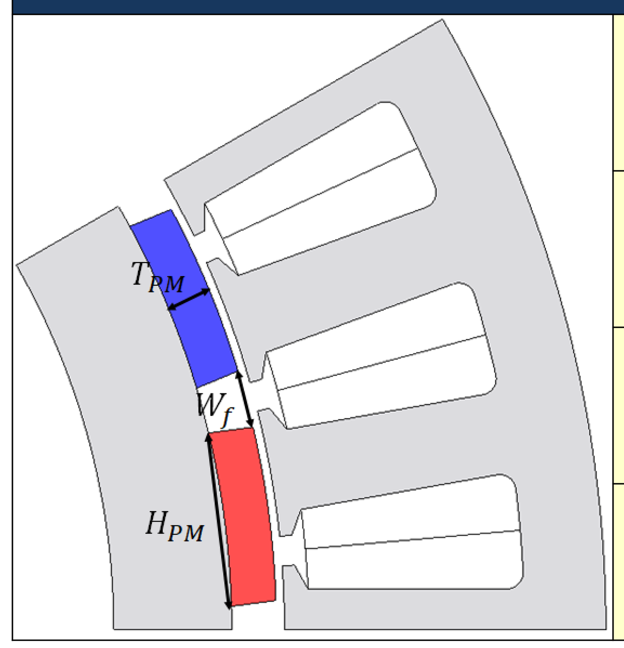
$$B_g{}' = B_r\frac{A_m}{A_g}\left[\frac{R_x{}'}{R_x+2R_g} - \frac{R_x(R_x'+2R_g')}{(R_x+2R_g)^2}\right]$$

Results

FEA Modeling

• Analyzed SPMSM model ($g, L_{stk} = 1\ mm$)

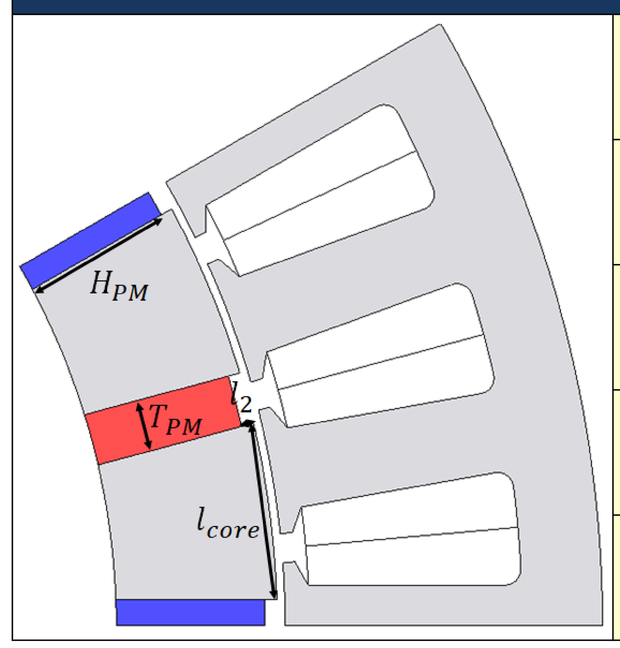
SPMSM



B_r	0.41 [T]
T_{PM}	5.5 [mm]
H_{PM}	21.5 [mm]
W_f	7.14 [mm]

• Analyzed Spoke PMSM model ($g, L_{stk} = 1\ mm$)

Spoke PMSM



B_r	0.41 [T]
T_{PM}	6.5 [mm]
H_{PM}	18.5 [mm]
l_{core}	22.17 [mm]
l_2	1.5 [mm]

MEC Results

• Error rate of Proposed Reluctance ($g, L_{stk} = 1\ mm$)

Parameters		Conventional	Proposed	Error rate
SPM	R_{mm}	6857E+06	6933E+06	1.1%
	R_{mr}	5533E+06	5626E+06	1.68%
SPOKE	R_3	6342E+06	7673E+06	17%

• Variation of Air-gap Flux Density (dB_g) According to Change of Air-gap length(dg)

dg [mm]	SPM dB_g [T]	Spoke dB_g [T]	Interval [T]
0.1	-0.0069	-0.0168	0.0099
0.2	-0.0138	-0.0336	0.0198
0.3	-0.0207	-0.0505	0.0298
0.4	-0.0276	-0.0673	0.0397

- Spoke PMSM is more sensitive to variation of Air-gap length.

FEA Results

• Verification of Analysis Result of MEC and FEA

	g [mm]	MEC [T]	FEA [T]	Error rate [%]
SPM	0.8	0.355	0.349	1.69
	1	0.343	0.335	2.33
	1.2	0.333	0.321	3.60
	1.4	0.320	0.310	3.13
Spoke	0.8	0.456	0.466	2.19
	1	0.422	0.418	0.95
	1.2	0.389	0.378	2.83
	1.4	0.355	0.346	2.54

Presented at the Applied Superconductivity Conference , 2012 Oct. 7 – 12, Portland, Oregon; Session: Nb-based Wires and Tapes II; Program I.D. number: 2MPQ-10