EE568 Project 3: PM Motor Comparison Analysis

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1 Introduction

In this assignment you are going to design several surface-mount PM machines with the following constant parameters:

Surface-mount permanent magnet (SPM) topology is kind of a machine where PMs mounted on the rotor surface, facing to the airgap [**??**].

This project aims to prepare a study similar to what was done by W. L. Soong in his case study on Ferrite versus NdFeB. In his study, Soong replaces rare earth NdFeB magnets with ferrite magnets in an SPM machine. Later, he increases the thickness of the magnets and equalizes the flux density levels on stator tooth and back iron region of the machine with NdFeB magnets and ferrite magnets. Unlike Soong's study, this project sets the stator outer diameter constant.

First, this project designs a SPM in part 2, to analyse the magnetic loading of a machine. Then, in part 3, it determines several machine parameters. The project continues by analysing electric loading of the machine, and the resulting average tangential stress, total force, torque and power output.

This project aims to optimize a SPM machine, in which neodymium magnets.

This project

The starting values are given in Table 1, below.

	symbol	unit	value
number of phases	m		3
number of poles	p		4
motor axial length	l_m	mm	100
air-gap clearance	δ_g	mm	1
magnet to pole pitch ratio			0.8
magnet radial thickness	t_m	mm	4

Table 1: Machine Parameters

2 Q1- Magnetic Loading

This project starts by analysing the magnetic loading of an SPM machine. The stator is assumed to be solid for this part. Additional to the parameters given in Table 1, some extra values are set as starting values. Parameters on rare earth magnet are given in Table 4 and rotor diameter is given in Table 3.

2.1 a. Magnetic Equivalent Circuit, Magnet Load Line and Peak Air-gap Flux Density

Magnetic equivalent circuit for one pole-pair is shown in Fig. 1. Here, each PM is modelled as an MMF source, meaning it's equivalent model is composed of a voltage source with a value of $F = \phi R_m$, and a resistance R_m connected in series.

	symbol	units	value
magnet type			NdFeB N42
shape			radial
relative permeability	μ_r		1.05
coercivity	H_c	A/m	994529

Table 2: Permanent Magnet Parameters

	symbol	unit	value
rotor diameter	D_r	mm	100

Table 3: Rotor Dimensions

Starting with PM #1, the flux ϕ goes through the airgap, modelled as R_g, and splits into two components at the stator back iron. Each half of the flux goes through the back iron, in opposite directions. Here, only one pole-pair is shown, so only one half-of-the-flux is described further. This half flux component then merges with, again what is another half flux component, and travels through the airgap, modelled again as R_g. Then, it travels through PM #2, and splits into two. One of the components merges with another half flux components and goes through PM #1. Hence, the cycle is completed.

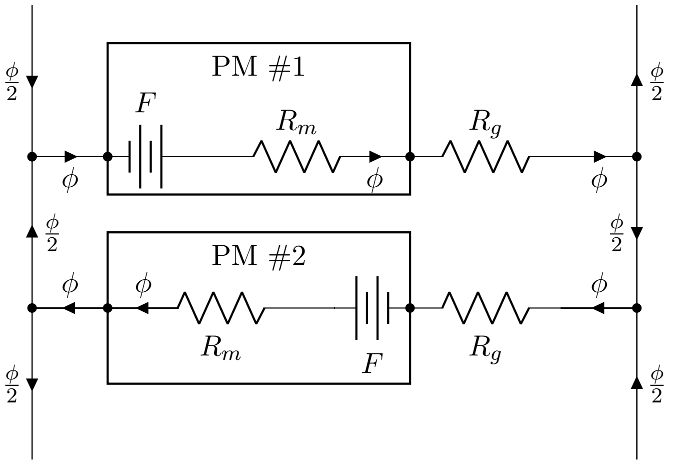

Figure 1: magnetic equivalent circuit for one pole-pair

2.2 b. Magnetic Loading

Magnetic loading of a machine refers to the average airgao flux density over a pole. This value can be calculated by

$$\bar{B} = \frac{p\phi_p}{\pi D_r l} \tag{1}$$

where $\bar{B}$ is specific magnetic loading, p is the number of poles, ϕ_p is flux per pole, D_r is rotor diameter, and l is the axial length of the machine. Equation 1 interprets specific magnetic loading $\bar{B}$ as total flux going out of the rotor surface divided by total rotor surface area.

To find out ϕ_p, machine's magnetic circuit is needed to be analyzed. The magnetic circuit diagram can be seen in Fig. 1.

The magnetic circuit is composed of 2 NdFeB 42 permanent magnets (PM) and 2 instances of airgaps. To analyse this circuit, PM remanence flux density B_r information is required. At this point, relative permeability μ_r and coercivity H_c of NdFeB 42 PM is given as a part of the problem, which can be seen in Table 4. From here; remanence flux density can be found by the following relation:

$$B_r = \mu_0 \mu_r \times H_c \tag{2}$$

where, μ_0 is the permeability of air or vacuum ($\mu_0 = 4\pi \times 10^{-7} A/m$). Hence, magnet remanence flux density is $B_r = 1.31T$. Now,

Neglecting leakage flux:

$$B_m A_m = B_g A_g \tag{3}$$

Assuming infinitely permeable core ($\mu_c = \infty$, where μ_c is the core permeability)

$$\begin{aligned} H_m l_m + H_g l_g &= 0 && (4) \\ H_m l_m &= -H_g l_g && (5) \end{aligned}$$

Now, in the airgap

$$\begin{aligned} B_g &= \mu_o H_g && (6) \\ B_m A_m &= \mu_0 H_g A_g = -\mu_0 H_m A_g \frac{l_m}{l_g} && (7) \\ \frac{B_m}{H_m} &= -\frac{\mu_0 A_g}{A_m} \frac{l_m}{l_g} && (8) \end{aligned}$$

This is the equation of the so-called load-line of the magnetic circuit.

For a material with a linear demagnetisation characteristic:

$$\begin{aligned} B_m &= B_r + \mu_0 \mu_r H_m && (9) \\ H_m &= \frac{B_m - B_r}{\mu_0 \mu_r} && (10) \end{aligned}$$

$$
\begin{aligned}
B_m &= -\frac{A_g l_m}{A_m l_g \mu_r}(B_m - B_r) && (11)\\
B_m\left(\frac{A_g l_m}{A_m l_g \mu_r} + 1\right) &= \frac{A_g l_m}{A_m l_g \mu_r} B_r && (12)\\
B_m &= \frac{\frac{A_g l_m}{A_m l_g \mu_r}}{\frac{A_g l_m}{A_m l_g \mu_r} + 1} B_r && (13)\\
B_m &= \frac{B_r}{1 + \frac{A_m l_g \mu_r}{A_g l_m}} && (14)
\end{aligned}
$$

Assuming $A_g = A_m$, the above equation simplifies to

$$B_g = B_m = \frac{B_r}{1 + \mu_r \frac{l_g}{l_m}} \tag{15}$$

where B_g is the airgap flux density, l_g is the airgap clearance and l_m is the magnet thickness. Here, B_g value corresponds to the peak airgap flux density $\hat{B}_g$. The average airgap flux density corresponds to the RMS value of peak airgap flux density

$$B_{avg} = \frac{1}{\sqrt{2}} \hat{B}_g \tag{16}$$

which corresponds to specific magnetic loading $\bar{B}$ of the machine.

2.3 c. FEA Results

FEMM is used as FEA software.

3 Q2- Electrical Loading & Machine Sizing

3.1 a. Number of Slots

Number of slots for this machine is determined to be 12.

3.2 b. AWG Cable

	symbol	units	value
max. current density	J	A/mm^2	5
coil current	I	A	2.5
fill factor	K_p		0.6

Table 4: Permanent Magnet Parameters

If the maximum current density $\hat{J}$ is set to be $5A/mm^2$ and one conductor is carrying $2.5A$, then the maximum number of conductors there can be in $1mm^2$ is 2, and the total

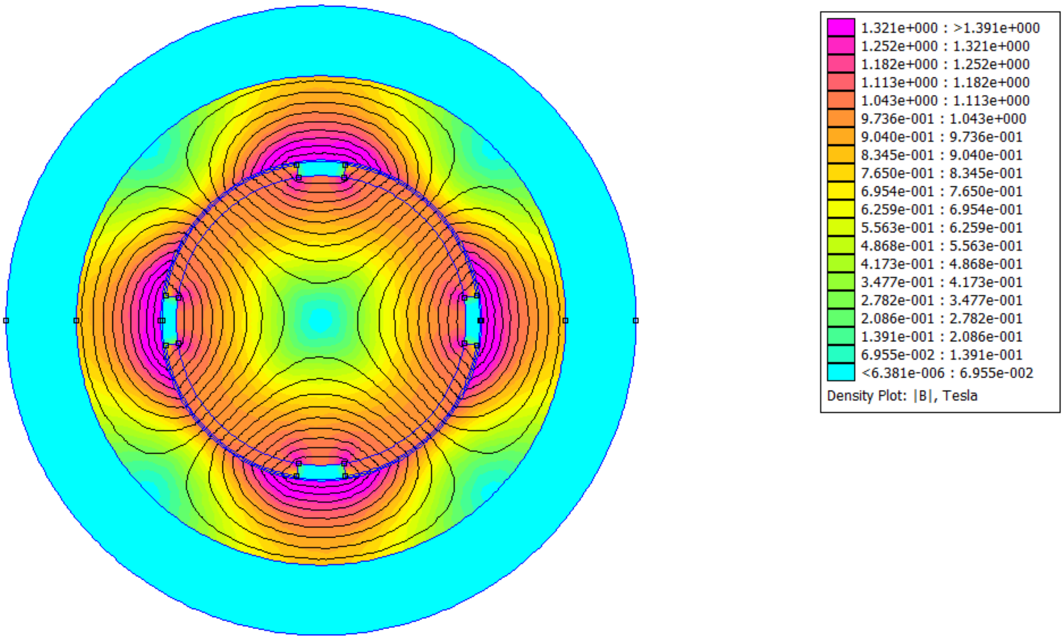

Figure 2: Flux Density Plot

cross-section area of 2 conductors can not be below $1mm^2$. Therefore, the suitable AWG cable chosen for this project is AWG 20. The characteristics of AWG20 cable can be seen in Table 5, below.

AWG	diameter $[mm]$	area $[mm^2]$	resistance/length [mΩ/m]
20	0.812	0.518	33.31

Table 5: AWG 20 characteristics

As can be seen in Table 5, the cross-section area of AWG 20 cable is $0.518mm^2$, which corresponds to $J = 4.83A/mm^2$, below the maximum current density value given for this project. Using any cable with a cross-section area below $0.500mm^2$ with a coil current of $I = 2.5A$ would exceed this current density J limitation.

3.3 c. Slot Height, Number of Coils per Slot, and Back-core Thickness

This part starts by choosing a slot ratio d for the machine. This choice is done in the following fashion. Teeth shape is determined to be rectangular. Then, the slot area is calculated by

where A_s is slot area, N_s is the number of slots, r_{so} is the slot outer radius, r_{si} is the slot inner or stator inner radius, and A_t is the area of tooth.

First, tooth to slot opening ratio is assumed to be 1 to 1. Then,

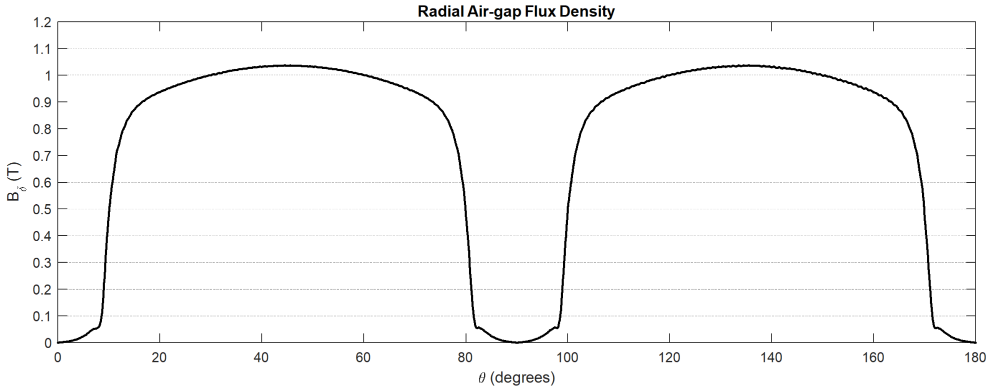

Figure 3: Airgap Flux Density Distribution

$$\tau_{teeth} = \tau_{slot} = \frac{2\pi r_{si}}{2N_s} \tag{17}$$

where τ_{teeth} is the tooth thickness and τ_{slot} is the slot opening.

$$h_t = \frac{r_{si}}{d} - r_{si} \tag{18}$$

where h_t is tooth height. Then, tooth area is calculated by

$$A_t = h_t \tau_{teeth} \tag{19}$$

$$N_s A_s = (\pi r_{so}^2 - \pi r_{si}^2) - N_s A_t \tag{20}$$

Hence, the slot area A_s is calculated.
Then, the number of conductors to be fit in a slot is determined by

$$N_{cond} = \frac{A_s K_p}{A_{cond}} \tag{21}$$

Hence, the number of conductors to be fit in one slot is $N_{cond} = 999$.

3.4 d. Electrical Loading

Now that the number of conductors per slot is determined, the electric loading of the machine can be calculated.

$$\hat{A} = \frac{N_s N_{cond} I}{2\pi r_{si}} \frac{1}{\sqrt{2}} \tag{22}$$

3.5 e. Average Tangential Stress & Total Force

$$l' = l + 2l_g \tag{23}$$

$$\sigma_{tan} = \frac{\bar{A}\hat{B}}{\sqrt{2}} \tag{24}$$

$$F = 2\sigma_{tan}\pi r_r l' \tag{25}$$

$$T = Fr_r = 2\sigma_{tan}\pi r_r^2 l' \tag{26}$$

3.6 f. Expected Power Output

$$P = T \times \omega \tag{27}$$

4 Q3- Comparison & Optimization

4.1 a. Optimum Rotor Diameter

4.2 b. Replacing NdFeB with Ferrite

4.3 c. Optimizing Ferrite Machine

5 Conclusion

References