MIDDLE EAST TECHNICAL UNIVERSITY

DEPARTMENT OF
ELECTRICAL AND ELECTRONICS
ENGINEERING

EE568 - Special Topics on Electrical Machines
Project #3
PM Motor Comparison Analysis

03/05/2020

Raşit GÖKMEN - 2339760

1. Contents

2. Introduction

In this assignment, several surface-mount PM machines are designed and compared. All machines have constant parameters as given below.

- Number of phases: 3
- Number of poles: 4
- Motor Axial Length: 100 mm
- Air-gap clearance: 1 mm
- Magnet to Pole Pitch Ratio: 0.8

3. Magnetic Loading

3.1. Operating Point and Load Line

In this part, a surface-mount PM machine with NdFeB magnet with following parameters and constant parameters given in introduction section is designed. For one pole-pair equivalent magnetic circuit is drawn. By using machine parameters, reluctances of magnet and air gap are calculated. After that, operating magnetic flux density is calculated and load line of magnet is drawn. On this load line operating point of magnet is given. For this operating point, magnetic loading of this machine is calculated. Finally, air gap flux density is obtained by using FEA. FEA result is compared with the analytical result and some comments on this comparison are given.

- Magnet Type: NdFeB N42 grade (μ_r=1.05), radial shaped
- Rotor Diameter: 100 mm
- Magnet Radial Thickness: 4 mm

The equivalent magnetic circuit for one pole-pair is given in Figure 1.

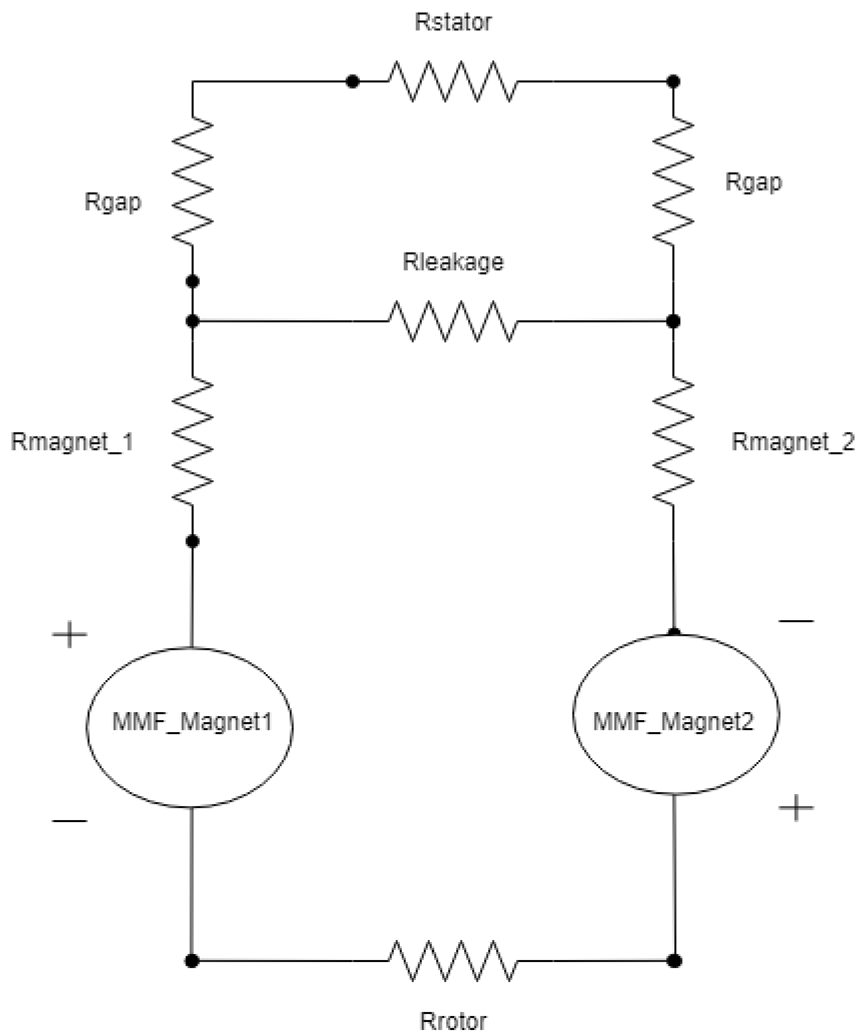

Figure 1. Equivalent magnetic circuit for one pole-pair

Area of magnet, A_{magnet} is given as,

$$A_{magnet} = A_{pole} * \text{ Magnet to Pole Pitch Ratio } = \frac{D_i \pi L}{p} * 0.8 = \frac{0.1 * \pi * 0.1}{4} * 0.8 = 0.0063\ m^2 \tag{1}$$

where, Di: rotor diamater

L: axial length of the motor

p: number of poles

Then, reluctances of magnet and airgap are given as,

$$R_{magnet} = \frac{h_{magnet}}{\mu_r * \mu_0 * A_{magnet}} = \frac{0.004}{1.05 * 4\pi 10^{-7} * 0.0063} = 481194.09\ (1/Henry) \tag{2}$$

$$R_{airgap} = \frac{h_{airgap}}{\mu_0 * A_{magnet}} = \frac{0.001}{4\pi 10^{-7} * 0.0063} = 126313.45\ (1/Henry) \tag{3}$$

MMF of magnet is calculated as,

$$F_{magnet} = B_r * A_{magnet} * R_{magnet} = 3880.35\ (Amperes) \tag{4}$$

$$F_{net} = \Phi_m * R_{eq} \tag{5}$$

where,

$$F_{net} = 2 * F_{magnet} \tag{6}$$

if we ignore leakage flux and assume that rotor and stator are infinitely permeable.

$$R_{eq} = 2 * (R_{airgap} + R_{magnet}) \tag{7}$$

By substituting (6) and (7) into equation (5)

Φ_m is obtained as,

$$\Phi_m = 6.387 * 10^{-3}\ \text{(Weber)} \tag{8}$$

Magnetic flux density is calculated as,

$$B_m = \frac{\Phi_m}{A_{magnet}} = 1.014\ (Tesla) \tag{9}$$

$$H_m = \frac{B_m - B_r}{\mu_r * \mu_0} = \frac{1.014 - 1.28}{1.05 * 4\pi 10^{-7}} = -201.59\ \ (kA/m) \tag{10}$$

where, B_r: residual flux density of N42 NdFeB material which is 1.28 $(Tesla)$

In Fig. 2, load line and operating point of N42 NdFeB is given. As can be seen from appendix A, the residual magnetic flux density is 1.28 $(Tesla)$ and intrisintic coercive force is -955 (kA/m) for N42 NdFeB material. At the operating point, B_m is calculated as 1.014 $(Tesla)$ in equation (9) and H_m is calculated as -201.59 (kA/m)in equation (10).

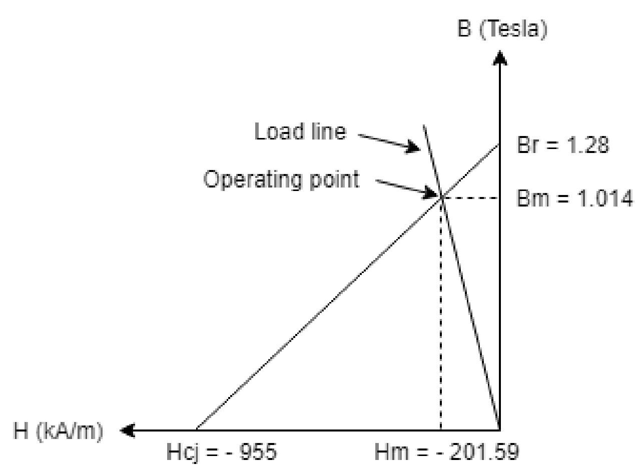

Figure 2. Load line and operating point on B-H curve of N42 NdFeB material

3.2. Magnetic Loading

The magnetic loading of the machine is given as,

$$\bar{B} = \frac{pB_m A_{magnet}}{D_i \pi L} = 0.813\ (Tesla) \tag{11}$$

3.3. FEA Result of Air-gap Flux Density

4-pole SMPMSM is modeled in Ansys Maxwell. The model is shown in Figure 3.

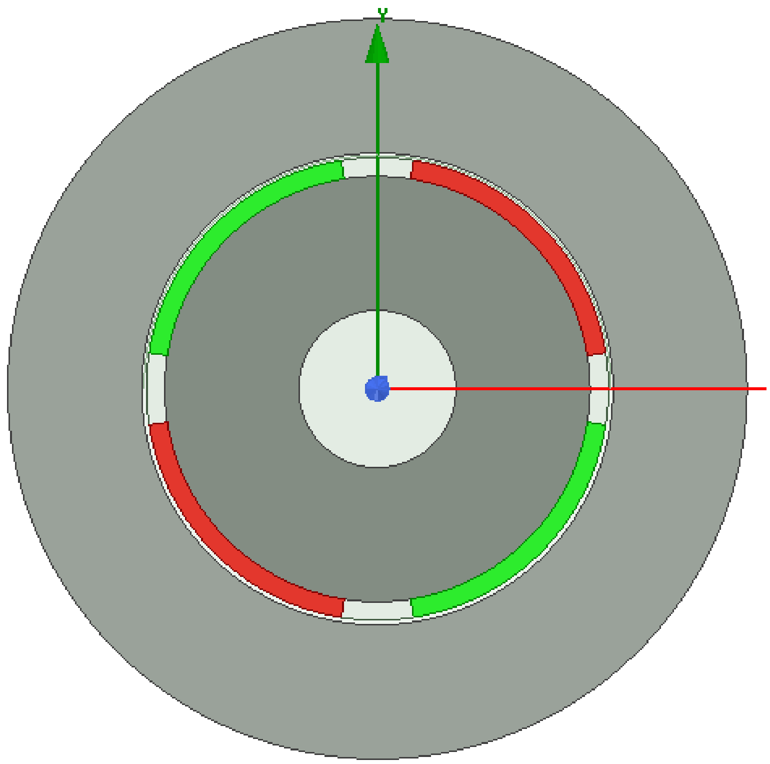

Figure 3. FEA model of 4-pole SM-PMSM

The air-gap flux density distribution at the middle of air-gap for one-pole pair result is obtained by using FEA and given in Figure 4. As can be seen, for the distances enclosing north pole, flux density is positive and for the distances enclosing south pole, flux density is negative as expected. The average flux density is found 0.8T which is very close to analytical result found in equation 11. The slight difference in the FEA result and analytical result is due to the ingorance of leakage flux and assumption of infinitely permeable stator and rotor during analytical calculations.

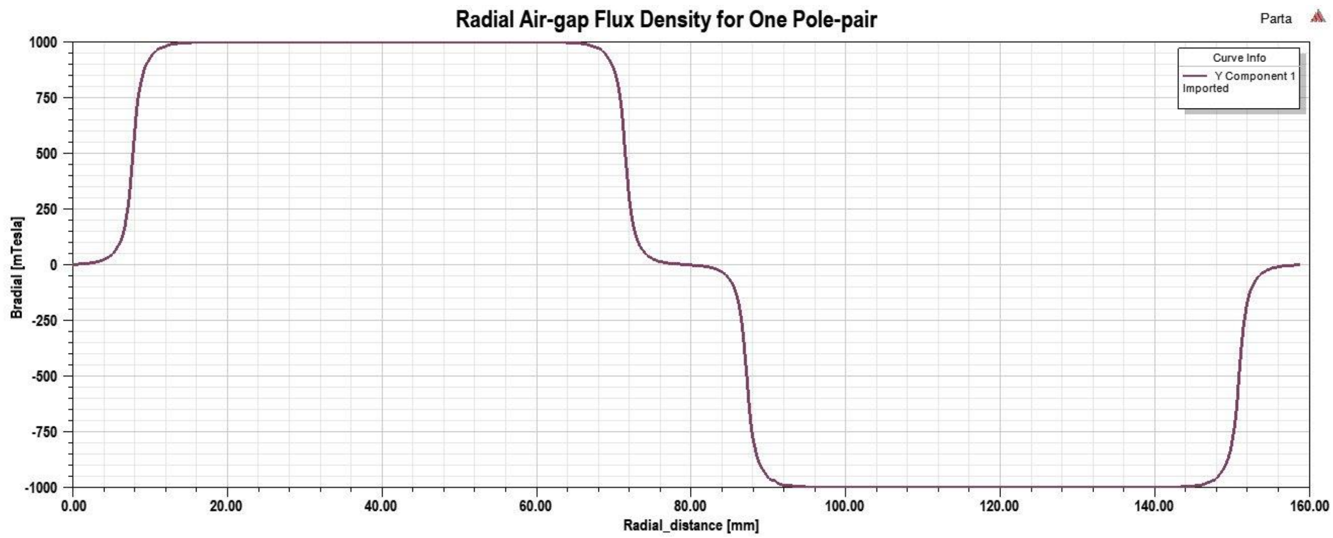

Figure 4. 2D FEA results of air gap flux density at the middle of air-gap

4. Electrical Loading and Machine Sizing

4.1. Selecting number of slots

In this part, the number of slots is choosen by considering better mmf distribution, cost and mechanical limits. The number of slots is generally choosento give a well distributed winding producing a mmf waveform with low harmonic content. The number of slots is defined as,

$$Q = q * p * m \tag{12}$$

where, q: number of slots per phase per pole

p: number of poles

m: number of phases

If q is choosen as 1, it means the windings are concentared which is not prefable for harmonic content of mmf distribution and resultant induced voltages. Therefore, q has to be at least 2. As the q increases, the harmonic content of mmf waveform reduces but on the other hand the cost of manufacturing these slots on the core increases due to increased insulation need and stamping operation. Also, as the number of slots increases, for constant stator inner diameter, the width of teeth and slot decreases and they should not be smaller than the mechanical limits otherwise there will be a tooth bending and/or breakage. Lets choose, q as 2. This will yields number of slots as 24. For this slot number tooth thickness is found as,

$$t_{teeth} = \frac{slot\ width\ ratio * Stator\ circumference}{Number\ of\ slots} = \frac{0.5 * 320mm}{24} = 6.67\text{mm} \tag{13}$$

where, slot width ratio is assumed as 0.5.

stator circumference: $\pi * Inner\ stator\ slot\ diamater(102mm)$

Let's increase q, for q equal to 3, the number of slot becomes 36 and tooth thickness is now equal to 4.45mm.

For q = 4, the number of slots becomes 48 and tooth thickness is 3.34mm.

In order to get not close the mechanical limits and not increase the cost at the same time reducing the harmonic content of mmf waveform, q is choosen as 3 which yields number of slots is equal to 36.

4.2. Selection of suitable wire cable

In this part, diameter of wire is choosen by considering maximum current density,J, as 5 A/mm^2 and maximum fill factor as 0.6. The coil current is given as 2.5A. The minimum wire diameter can be calculated as,

$$A_{wire} = \frac{I}{J} = \frac{2.5A}{5A/mm^2} = 0.5\,mm^2 \tag{14}$$

So, AWG#20 wire cable with 0.518 mm^2 area can be choosen as a wire cable.

4.3. Calculation of slot height, number of coils per slot and back-core thickness

In this part, slot height, number of coils per slot and back-core thickness are calculated. To calculate slot height, slot ratio is choosen. Slot ratio(d) is the ratio of inner stator slot diameter to outer stator slot diamater. Larger slot ratio means smaller slot height and as the slot ratio reduces slot height increases and hence electrical loading increases for the same diameter. It is assumed that we have parallel teeth in our design which is most common design of stator tooth. By the help of parallel teeth slot gets wider with diameter which enables us to use put more coils into the slot. In the class it was shown that for 'thin' parallel teeth slot ratio, d has the optimum value of 0.6. Therefore, slot ratio is choosen as 0.6.

Outer stator slot diamater, D_o can be calculated as,

$$D_o = \frac{D_i}{d} = \frac{102}{0.6} = 170\,mm \tag{15}$$

where, D_i is the inner stator slot diamater which is the sum of rotor diameter and 2*air-gap clearance.

Slot height, h_s can be calculated as,

$$h_s = \frac{D_o - D_i}{2} = 34\,mm \tag{16}$$

As stated in section 4.1, slot width ratio was assumed as 0.5. Teeth thickness was found as 4.45 mm for 36 slots. Therefore, slot width, h_w is also equals to 4.45mm.

For the open slot type, slot area, A_{slot} can be calculated as,

$$A_{slot} = h_s * h_w = 151.3\,mm^2 \tag{17}$$

Then, number of coils per slot can be calculated as,

$$N = \frac{A_{slot} * k_{fill}}{A_{wire}} = \frac{151.3mm^2 * 0.6}{0.518\,mm^2} = 175.25 \cong 175 \tag{18}$$

The back-core flux is equal to half of the flux per pole.

$$B_{backcore} * A_{backcore} = 0.5 * B_m * A_{pole} \tag{19}$$

where, $B_{backcore}$ is assumed as the saturation flux density for the stator iron B_{sat} of 1.5 T.

$A_{backcore}$ can be written as,

$$A_{backcore} = h_{backcore} * k_{stacking} * L_{axial} \tag{20}$$

where, $h_{backcore}$ is the back-core thickness

$k_{stacking}$ is the stacking factor of the core which is assumed 0.95.

L_{axial} is the axial core length which is 100mm.

The back-core thickness for the maximum flux density at the stator back-core be calculated as,

$$h_{backcore} = \frac{0.5*B_m*A_{magnet}}{k_{stacking}L_{axial}B_{backcore}} = \frac{0.5*1.014T*0.0063m^2}{0.95*0.1m*1.5T} = 22.4\,mm \tag{21}$$

Stator outer diameter, D can be calculated as,

$$D = D_o + 2*h_{backcore} = 214.8\,mm$$

4.4. Electric loading calculation

Electric loading of the machine can be calculated as,

$$\bar{A} = \frac{N_{turn,slot}*I*Q}{\pi D_i} \tag{22}$$

where, $N_{turn,slot}$: the number of coils per slot

Di: stator slot inner diameter

I: rms coil current

Q: number of stator slots

If we substitute the values of the parameters in the equation 22, electric loading is found as,

$$\bar{A} = \frac{175*2.5*36}{\pi*102} = 49.15\,(\frac{kA}{m}) \tag{23}$$

In the lecture, usual values of electrical loading for PMSM is presented as 35-65 kA/m. The value that was found in equation 23. above is in this range. It can be said that this design has reasonable electric loading value.

4.5. Calculation of force and tangential stress

Average tangential stress in the rotor surface of the machine can be calculated as,

$$\sigma_{tan} = \frac{A_{rms}\hat{B}cos\Phi}{\sqrt{2}} = \frac{49150*1.014*1}{\sqrt{2}} = 35.24\,kPa \tag{24}$$

cosϕ is taken 1 since it was taken 1 for PMSM in the lecture.

Then, corresponding total force can be calculated as,

$$F_{tan} = \sigma_{tan}S_r \tag{25}$$

where, S_r is the rotor surface area which is defined as,

$$S_r = 2*\ \pi*0.5*D_i*L_{axial}*k_{stacking} \tag{26}$$

$$S_r = 2 * \pi * 0.05 * 0.1 * 0.95 = 0.03\ m^2 \tag{27}$$

By substituting the value found in equation 27 into the equation 25,total force that the machine can produce found as,

$$F_{tan} = 35.24\ kPa * 0.03\ m^2 = 1057.2\ Newton \tag{28}$$

4.6. Calculation of output power of the machine

The power output of the machine can be calculated by using following formula:

$$P = Torque * w_{mech} \tag{29}$$

Torque output of the machine can be calculated from the force value that was found in equation 28.

$$Torque = \frac{F_{tan} * D_i}{2} = \frac{1057.2\ N * 0.1m}{2} = 52.86\ Nm \tag{30}$$

The rotor speed is assumed as 1500 rpm. It should be converted to mech. rad/s before calculating the power.

$$w_{mech} = 1500\ rpm * \frac{2 * \pi}{60} = 157.08 \frac{rad}{s} \tag{31}$$

Then, output power of the machine can be calculated by substituting the values of torque and ww_{mech} found in equation 30 and 31, respectively into the equation 29.

$$P = Torque * w_{mech} = 52.86\ Nm * 157.08 \frac{rad}{s} = 8.3kW \tag{32}$$

5. Comparison and Optimization

In this part, the stator outer diameter is fixed to 160mm and rotor diameter and other parameters are variable. Open slot type with rectangular teeh shape is selected for slot design. In the first part, optimum rotor diameter is calculated for maximum torque output. Then some parameters are calculated again. The design is verified by using FEA and compared with the results of design of section 3. and 4.

5.1. Optimum rotor diameter and slot ratio for maximum torque output

In this part, stator outer diameter is fixed to 160mm and optimum slot ratio and hence rotor diameter are calculated for maximum torque output. Slot ratio,d is defined as,

$$d = \frac{D_i}{D_o} \tag{33}$$

We are assuming that the stator slot have parallel side and rectangular teeth shape. Thus, total current is proportional with (1-d) it means as d reduces for same outer diameter, inner diameter also reduces resulting in longer slot height. Therefore, more coils and hence more currents can be put into the slot. The electric loading and hence shear stress are proportional to (1-d)/d. Rotor volume is proportional to d^2 Therefore, torque is proportional to shear stress and rotor volume.

$$T\ \alpha\ \{\sigma * V_R\}\ \alpha\ \{[(1-d)/d]*d^2\}\ \alpha\ \{(1-d)*d\} \tag{34}$$

As seen from equation 34., output torque is proportional to (1-d)*d and it has maximum value for d=0.5. Therefore, slot ratio, d is choosen as 0.5 for maximum torque output. If we substitute 0.5 into the value of d in equation 33, stator outer slot diameter becomes 2 times stator inner diameter.

$$D_o = 2 * D_i \tag{35}$$

In order to calculate D_i and D_o, we need to know the value of stator back-core thickness $h_{backcore}$.

The magnetic loading of the design is not changed. So, $h_{backcore}$ can be expressed in terms of rotor diameter D_i.

$$h_{backcore} = \frac{0.5B_m * 0.8\pi D_i L_{axial}/p}{k_{stacking} L_{axial} B_{backcore}} = \frac{0.5 * 1.014 * 0.063 D_i}{0.95 * 0.1 * 1.5} = 0.224 D_i \tag{36}$$

$$D_o + 2 * \ h_{backcore} = 160mm \tag{37}$$

$$2 * D_i + 2 * \ 0.224 * D_i = 160mm \tag{38}$$

yields, $D_i = 65.36\ mm$, $D_o = 130.72\ mm\ and\ h_{backcore} = 14.64mm$.

Therefore, for maximum torque output rotor diameter should be $D_i - 2 * h_{airgap} = 63.36\ mm$

Magnetic loading of the machine does not change and it is still equals to $0.813\ (Tesla)$.

It is assumed that, the coil current and maximum current density kept constant. Therefore, selected wire cable is still AWG#20 and selected number of stator slots is still 36.

If, slot width ratio is assumed as 0.5 again, inner slot width becomes,

$$h_{wi} = 0.5 * \frac{\pi D_i}{36} = 2.85\ mm \tag{39}$$

And outer slot width becomes,

$$h_{wo} \ = \ \frac{\pi D_o}{36} - h_{wi} = 8.56\ mm \tag{40}$$

And slot height, h_s is equals to,

$$h_s = \frac{D_o - D_i}{2} = 32.68mm \tag{41}$$

For the open slot type and rectangular teeth shape, slot area, A_{slot} can be calculated as,

$$A_{slot} = h_s * \frac{h_{wi} + h_{wo}}{2} = 186.44\ mm^2 \tag{42}$$

Then, number of coils per slot can be calculated as,

$$N = \frac{A_{slot} * k_{fill}}{A_{wire}} = \ \frac{186.44mm^2 * 0.6}{0.518\ mm^2} = 216 \tag{43}$$

Electric loading of the machine can be calculated as,

$$\bar{A} = \frac{N_{turn,slot} * I * Q}{\pi D_i} = \frac{216 * 2.5 * 36}{\pi * 65.36} = 94.67\ (\frac{kA}{m}) \tag{44}$$

Average tangential stress in the rotor surface of the machine can be calculated as,

$$\sigma_{tan} = \frac{A_{rms} \hat{B} cos\Phi}{\sqrt{2}} = \frac{94670 * 1.014 * 1}{\sqrt{2}} = 67.88\ kPa \tag{45}$$

cosϕ is taken 1 since it was taken 1 for PMSM in the lecture.

Then, corresponding total force and torque can be calculated as,

$$F_{tan} = \sigma_{tan} S_r = 67.88\ kPa * \pi 0.06336 * 0.1 * 0.95 = \ 1283.6\ N \quad (46)$$

$$Torque = \frac{F_{tan} * D_i}{2} = \frac{1283.6\ N * 0.06336m}{2} = 40.66\ Nm \quad (47)$$

Corresponding output power for the same rotational speed of 1500 rpm can be calculated as follows:

$$P = Torque * w_{mech} = 20.33\ Nm * 157.08 \frac{rad}{s} = 6.37\ kW \quad (48)$$

Table 1. Design parameter and performance parameters of two designs

	Design 1	**Design 2**
Stator Outer Diameter	*214.8 mm*	*160 mm*
Rotor Diameter	*100 mm*	*63.36 mm*
Slot Area	*151.3 mm*	*186.44 mm*
Slot Height	*34 mm*	*32.68 mm*
Magnetic Loading	*1.014 T*	*1.014 T*
Electric Loading	*49.15 kA/m*	*94.67 kA/m*
Tangential Stress	*35.24 kPa*	*67.88 kPa*
Total Force	*1057.2 N*	*1286.6 N*
Torque output	*52.86 Nm*	*40.66 Nm*
Speed	*1500 rpm*	*1500 rpm*
Power output	*8.3 kW*	*6.37 kW*

As can be seen from Table 1, design 2 has smaller stator outer diameter, rotor diameter and hence machine volume. On the other hand, it has larger slot are due to the rectangular teeth shape design. Therefore, it has greater electric loading and tangential stress. However, since it has smaller rotor diameter, it has less rotor surface volume and less total force. Due to the small rotor diameter its torque value is smaller than the design 1 even it produces more force. As a results, it has small power output. But even though its small volume, design 2 is better utilized for maximum torque output. If the design 1 is adjusted like that, it would have more torque and power output.

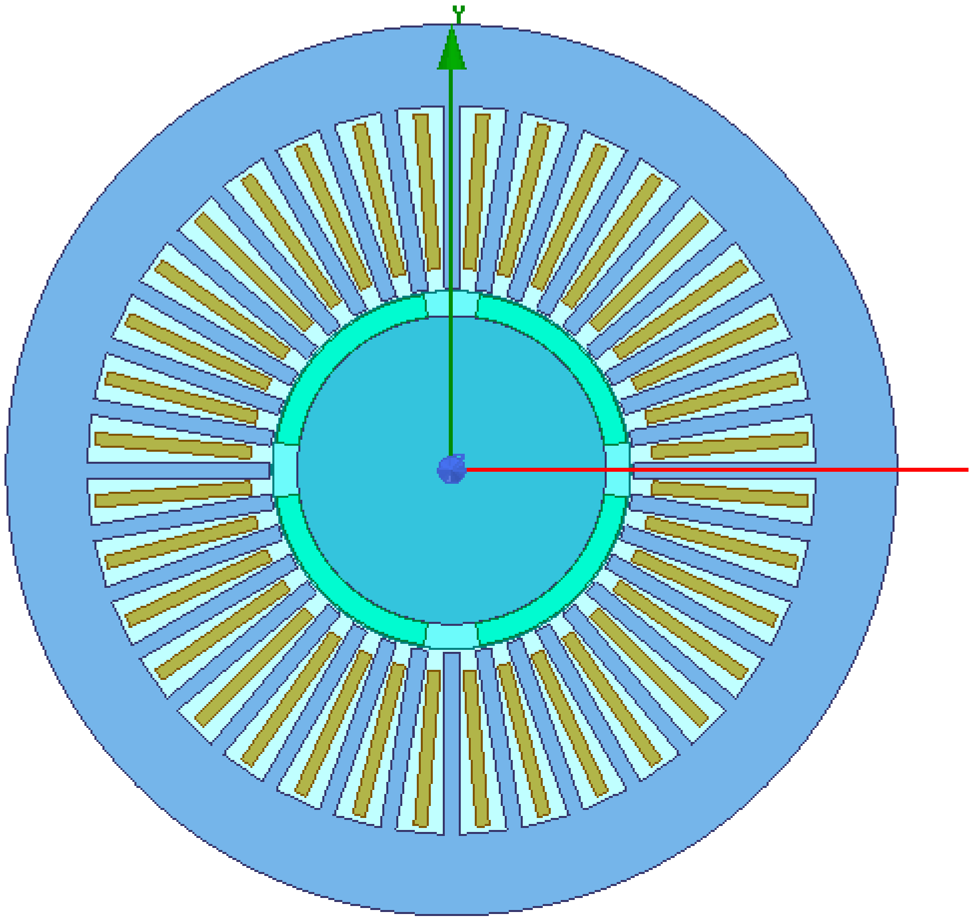

Figure 5. 2D FEA model of design 2

5.2. Changing magnet material with ferrite and comparison

In this part, the magnet material of design 2 in section 5.1 is changed to ferrite material. As we know, ferrite material has remenance flux density about 0.4T. Therefore, magnetic loading of the design is expected to be change. For this design, operating point of magnet now becomes,

$$B_m = 0.317\ (Tesla) \tag{49}$$

And magnetic loading becomes,

$$\bar{B} = \frac{pB_m A_{magnet}}{D_i \pi L} = 0.254\ (Tesla) \tag{50}$$

Electrical loading does not change since machine dimensions are same.

Average tangential stress in the rotor surface of the machine can be calculated as,

$$\sigma_{tan} = \frac{A_{rms}\hat{B}cos\Phi}{\sqrt{2}} = \frac{94670*0.317*1}{\sqrt{2}} = 21.22\ kPa \tag{51}$$

cosϕ is taken 1 since it was taken 1 for PMSM in the lecture.

Then, corresponding total force and torque can be calculated as,

$$F_{tan} = \sigma_{tan} S_r = 21.22\ kPa * \pi 0.06336 * 0.1 * 0.95 = \ 401.27\ N \quad (52)$$

$$Torque = \frac{F_{tan} * D_i}{2} = \frac{401.27\ N * 0.06336 m}{2} = 12.71\ Nm \quad (53)$$

Corresponding output power for the same rotational speed of 1500 rpm can be calculated as follows:

$$P = Torque * w_{mech} = 12.71\ Nm * 157.08 \frac{rad}{s} = 2\ kW \quad (54)$$

Table 2. Design parameters and performance parameters of two design with different permenant magnets

	Design with NdFeB magnet	Design with Fe magnet
Stator Outer Diameter	*160 mm*	*160 mm*
Rotor Diameter	*63.36 mm*	*63.36 mm*
Slot Area	*186.44 mm^2*	*186.44 mm^2*
Slot Height	*32.68 mm*	*32.68 mm*
Magnetic Loading	*1.014 T*	*0.254 T*
Electric Loading	*94.67 kA/m*	*94.67 kA/m*
Tangential Stress	*67.88 kPa*	*21.22 kPa*
Total Force	*1286.6 N*	*401.27 N*
Torque output	*40.66 Nm*	*12.71 Nm*
Speed	*1500 rpm*	*1500 rpm*
Power output	*6.37 kW*	*2 kW*

As can be seen from Table 2, even though both design have same machine dimensions, design with Fe magnet has lower torque and power output. Because, Fe magnet has lower remenance flux density and hence design with Fe material has lower magnetic loading. Thefore, it can be said that the machine with NdFeB magnet has better power density, torque density. But, as one knows, NdFeB magnet cost is much more than Fe magnet. If the cost is not important for the design, one should prefer NdFeB magnet for it’s better power and torque density.

5.3. Optimization of Ferrite machine

In this part, some parameters of ferrite machine are optimized in order to increase performance of ferrite machine. First of all, back core thickness of ferrite machine can be reduced since ferrite machine has lower magnetic flux density. Also, magnet thickness can be increased in order to increase magnet operating flux density. Finally, magnet to pole ratio can be increased but this should be increased in a controlled manner otherwise there would be much leakage flux from magnet to magnet.

Firstly, let’s calculate the optimum back-core thickness.

$$h_{backcore} = \frac{0.5 * B_m * A_{magnet}}{k_{stacking} L_{axial} B_{backcore}} = \frac{0.5 * 0.317 * 0.0063 m^2}{0.95 * 0.1 m * 1.5T} = \ 6.33\ mm \quad (55)$$

As can be seen, if Bm reduced from 1.014 T to 0.317 T , $h_{backcore}$ reduces from 14.64 mm to 6.33 mm. Therefore, magnet thickness can be increased from 4mm to 8mm. Let’s increase the magnet thickness. Now, reluctance of magnet changes. But also MMF of magnet changes. Therefore Bm can be calculated as,

$$\frac{R_m}{R_g} = \frac{\frac{h_m}{g}}{\mu_r} = \frac{8}{1.05} = 7.62 \quad (56)$$

$$B_m = B_r * \frac{R_m}{R_m + R_g} = 0.354\ (Tesla) \quad (57)$$

And magnetic loading becomes,

$$\bar{B} = \frac{pB_m A_{magnet}}{D_i \pi L} = 0.284\ (Tesla) \quad (58)$$

In this part, stator outer diameter is fixed to 160mm and optimum slot ratio and hence rotor diameter are calculated for maximum torque output. As explained in section 5.1, output torque is proportional to (1-d)*d and it has maximum value for d=0.5. Therefore, slot ratio, d is choosen as 0.5 for maximum torque output.

$$D_o = 2 * D_i \quad (59)$$

$$h_{backcore} = \frac{0.5B_m * 0.8\pi D_i L_{axial}/p}{k_{stacking} L_{axial} B_{backcore}} = \frac{0.5*0.354*0.063D_i}{0.95*0.1*1.5} = 0.078D_i \quad (60)$$

$$D_o + 2 *\ h_{backcore} = 160mm \quad (61)$$

$$2 * D_i + 2 *\ 0.078 * D_i = 160mm \quad (62)$$

yields, $D_i = 74.21\ mm$, $D_o = 148.42mm\ and\ h_{backcore} = 5.79mm.$

Therefore, for maximum torque output rotor diameter should be $D_i - 2 * h_{airgap} = 72.21\ mm.$

It is assumed that, the coil current and maximum current density kept constant. Therefore, selected wire cable is still AWG#20 and selected number of stator slots is still 36.

Now, slot width ratio is increased to 0.6 to increase electric loading of machine, inner slot width becomes,

$$h_{wi} = 0.6 * \frac{\pi D_i}{36} = 3.88\ mm \quad (63)$$

And outer slot width becomes,

$$h_{wo} = \frac{\pi D_o}{36} - h_{wi} = 9.07\ mm \quad (64)$$

And slot height, h_s is equals to,

$$h_s = \frac{D_o - D_i}{2} = 37.105\ mm \quad (65)$$

For the open slot type and rectangular teeth shape, slot area, A_{slot} can be calculated as,

$$A_{slot} = h_s * \frac{h_{wi} + h_{wo}}{2} = 240.25\ mm^2 \quad (66)$$

Then, number of coils per slot can be calculated as,

$$N = \frac{A_{slot} * k_{fill}}{A_{wire}} = \frac{240.25mm^2 * 0.6}{0.518\ mm^2} = 278 \quad (67)$$

Electric loading of the machine can be calculated as,

$$\bar{A} = \frac{N_{turn,slot}*I*Q}{\pi D_i} = \frac{278*2.5*36}{\pi*74.21} = 107.32\ (\frac{kA}{m}) \quad (68)$$

Average tangential stress in the rotor surface of the machine can be calculated as,

$$\sigma_{tan} = \frac{A_{rms}\hat{B}cos\Phi}{\sqrt{2}} = \frac{107320*0.354*1}{\sqrt{2}} = 26.86\ kPa \quad (69)$$

cosϕ is taken 1 since it was taken 1 for PMSM in the lecture.

Then, corresponding total force and torque can be calculated as,

$$F_{tan} = \sigma_{tan}S_r = 26.86\ kPa * \pi 0.07421 * 0.1 * 0.95 = 594.9\ N \quad (70)$$

$$Torque = \frac{F_{tan}*D_i}{2} = \frac{594.9\ N*0.07421m}{2} = 22.07\ Nm \quad (71)$$

Corresponding output power for the same rotational speed of 1500 rpm can be calculated as follows:

$$P = Torque * w_{mech} = 22.07\ Nm * 157.08\frac{rad}{s} = 3.47\ kW \quad (72)$$

Table 3. Design parameters and performance parameters of three different design

	Design with NdFeB magnet	**Design with Fe magnet**	**Optimized design with Fe magnet**
Stator Outer Diameter	*160 mm*	*160 mm*	*160 mm*
Rotor Diameter	*63.36 mm*	*63.36 mm*	*74.21 mm*
Slot Area	*186.44 mm^2*	*186.44 mm^2*	*240.25 mm^2*
Slot Height	*32.68 mm*	*32.68 mm*	*37.105 mm*
Magnetic Loading	*1.014 T*	*0.254 T*	*0.284 T*
Electric Loading	*94.67 kA/m*	*94.67 kA/m*	*107.32 kA/m*
Tangential Stress	*67.88 kPa*	*21.22 kPa*	*26.86 kPa*
Total Force	*1286.6 N*	*401.27 N*	*594.9 N*
Torque output	*40.66 Nm*	*12.71 Nm*	*22.07 Nm*
Speed	*1500 rpm*	*1500 rpm*	*1500 rpm*
Power output	*6.37 kW*	*2 kW*	*3.47 kW*

In order to optimize the machine and increase it's performance, magnet thickness was increased. As a result, magnetic loading increased. Slot width ratio was increased resultant in larger electric loading. Stator back-core thickness was reduced and optimized for this magnet since it had a value optimized for NdFeB magnet. Therefore, output torque and power of machine increased while volume of machine kept constant. One major drawback of optimized design with Fe magnet is that it has very high number of turns and electric loading values. Which means there will be higher induced back-emf voltage which is a problem for inverter and power electronic side. These results can be seen from Table 3.

6. Conclusion

In this study, different type of SM-PMSM is designed analytically and verified by using FEA. First design was a 4-pole SM-PMSM with NdFeB magnet. The second one was a 4-pole SM-PMSM with Fe magnet. Finally, second design was optimized by adjustin the magnet thicknes, rotor diameter and slot width ratio. Design steps, design choices are explained clearly. Machine performances are calculated and compared with each other. It was shown that, NdFeB magnet has better magnetic loading due to the it's higher remenance flux density. Fe magnet has lower remenance flux density therefore it has lower magnetic loading. Therefore, the machine with Fe magnet has lower output torque and power. At the final part of this study, the design with Fe machine was optimized. The stator back-core thickness reduced because, the operating flux density is much lower than the design with NdFeB magnet. The reduction from this stator back-core thickness was added to rotor diameter which increased the electric loading of machine. Magnet thickness also increased and therefore magnetic loading was incresed. Therefore, better design was obtained. If the cost is the most dominant concern in the design, one should consider Fe magnet by accepting some performance reduction. Otherwise, NdFeB magnet has better power and torque density without increasing number of turns and hence induced back-emf voltage. Therefore, it should be selected.