

# Project 3

EE568

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## 1)Introduction

In this study, general design of permanent magnet synchronous machine (PMSM) is presented. Firstly, magnetic and electrical loading of a PMSM with NdFeB magnet is considered. According to these values, general parameters will be determined and then these values will be optimized. Then, magnet will be replaced by ferrite magnet and results will be obtained. Then, according to new magnet type, optimization will be performed again and these designs will be compared according to their costs and performance. Also, analytical results will be validated by using Finite Element Analysis (FEA).

## 2)

### 2.1)

In this part, magnetic loading of the machine with the parameters given in Table 1 will be examined.

| Parameters                                    | Value       |
|---|-------------|
| Number of phases                              | 3           |
| Number of poles                               | 4           |
| Motor axial length (mm)                       | 100         |
| Air-gap clearance (mm)                        | 1           |
| Magnet to pole pitch ratio                    | 0.8         |
| Magnet type                                   | NdFeB (N42) |
| Rotor diameter (mm)                           | 100         |
| Magnet thickness (mm)                         | 4           |
| Remanent flux of the magnet ( $B_r$ )         | 1.28        |
| Relevant coercivity of the magnet ( $\mu_r$ ) | 1.05        |

Table 1: Machine parameters

By using the equivalent magnetic circuit given in Figure 1 is used to find magnetic field in the air gap,

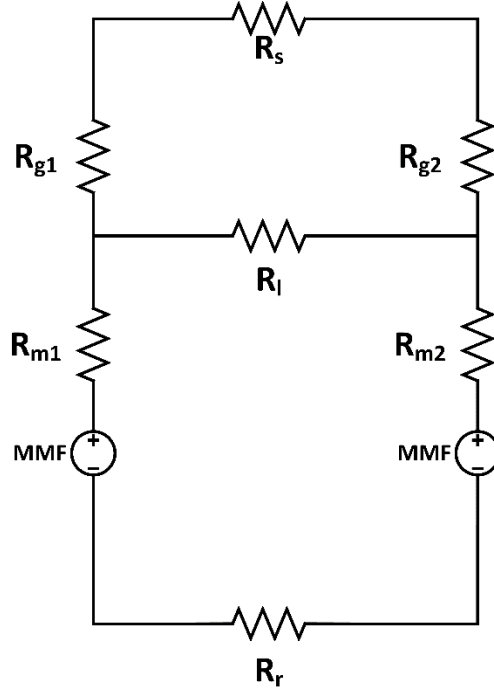


Figure 1: Equivalent magnetic circuit of the machine

Where  $R_s$ ,  $R_r$ ,  $R_l$ ,  $R_g$  and  $R_m$  are reluctances of stator, rotor, leakage, air-gap and magnets, respectively. In this case,  $R_s$ ,  $R_r$  and  $R_l$  are ignored. As a further step, MMF and reluctances of air-gap and magnets are calculated. For this purpose, area of magnet and airgap should be calculated initially.

$$A_m = A_g = \frac{D_i \pi L}{4} * 0.8 = 0.0063 \text{ m}^2 \quad (1)$$

Then, by using general reluctance equation, reluctances can be found easily as follows.

$$R_m = \frac{h_m}{A_m \mu_r \mu_0} = 481194 \left( \frac{1}{\text{Henry}} \right) \quad (2)$$

$$R_g = \frac{\text{air-gap}}{A_g \mu_0} = 126313 \left( \frac{1}{\text{Henry}} \right) \quad (3)$$

Finally, MMF is calculated as follows:

$$MMF = B_r A_m R_m = 3880.34 \text{ (Amperes)} \quad (4)$$

Then, by using equivalent magnetic circuit of the machine and variables that are calculated above, magnetic flux density of the machine can be calculated as follows:

$$B_m = 2 * \frac{MMF}{2 * (R_g + R_m) * A_m} = 1.014 \text{ (Tesla)}$$

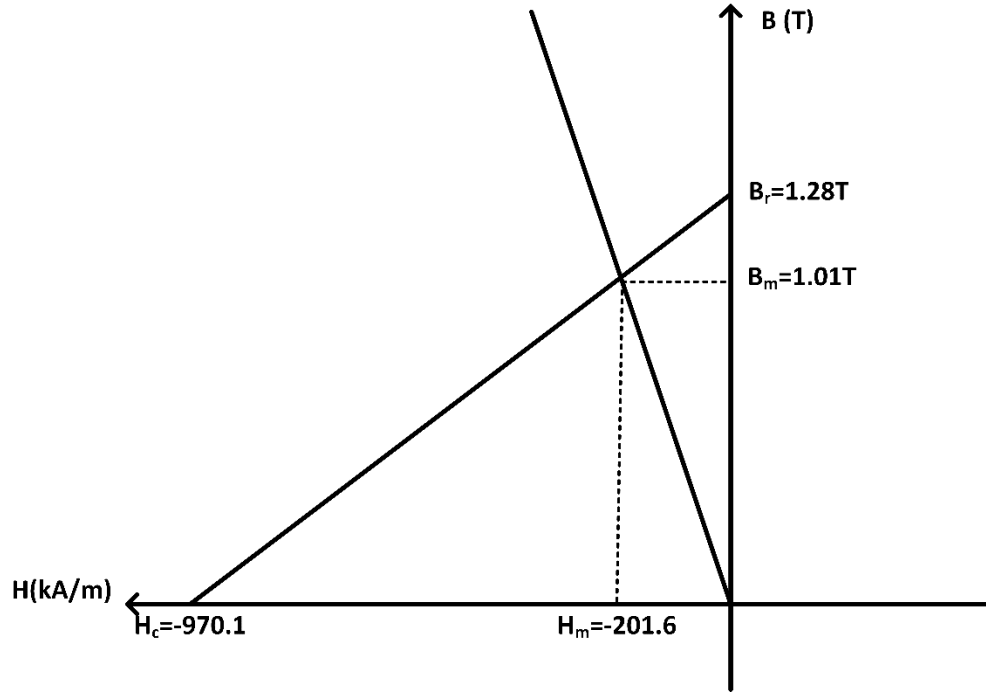


Figure 2: Load line and operating point on the B-H curve

2.2)

Magnetic loading of the machine can be calculated as follows:

$$\bar{B} = \frac{PB_m A_m}{D_i \pi L} = 813.37 \text{ (mT)} \quad (5)$$

2.3)

In this part, FEA validation of above parts is performed. FEA draw of the machine is given in Figure 2 and results are given in Figure 3.

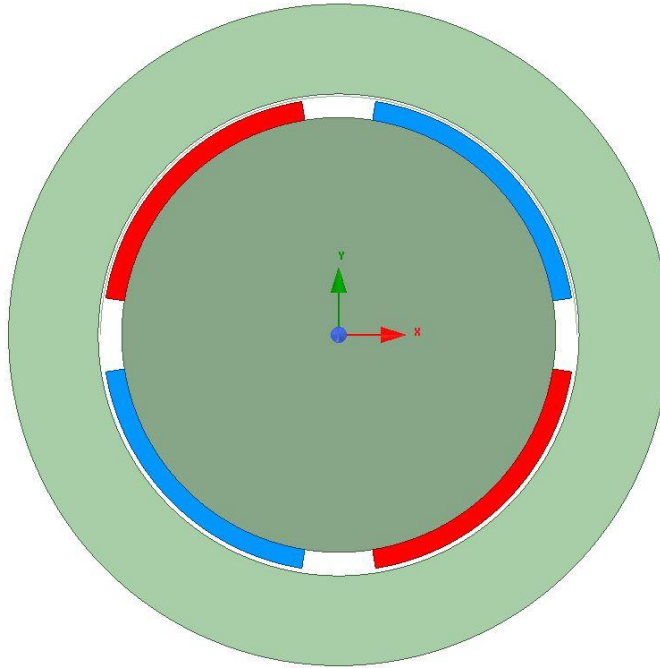


Figure 2: 2D FEA draw of the machine

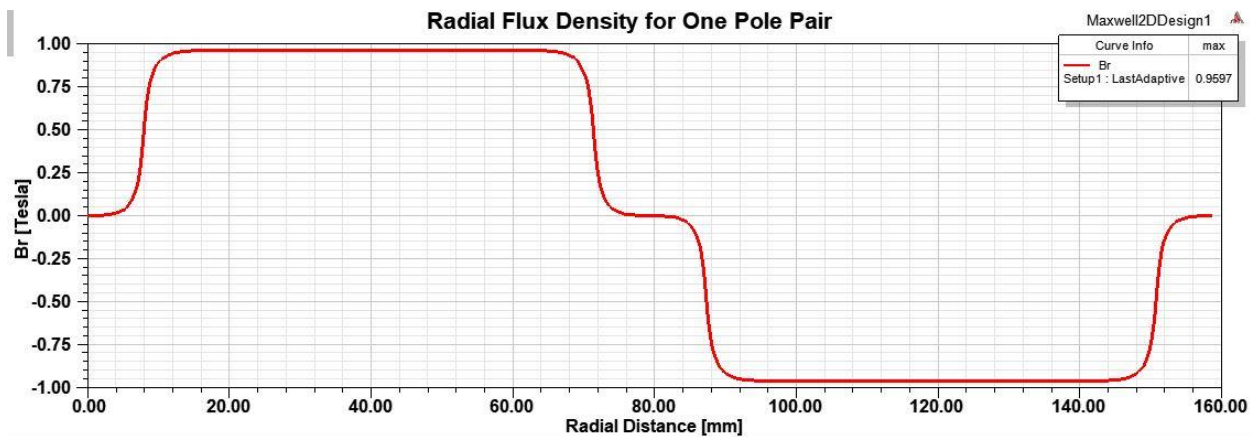


Figure 3: 2D FEA results of air gap flux density at  $r=(R_i + \text{air-gap}/2)$

Analytical results and numerical results are close to each other but they are not equal to each other. While analytical calculations are performed, leakage flux can not be modelled and taken into consideration. However, numerical results includes leakage flux and this result is slightly smaller than analytical result.

3)

3.1)

In this part, slot number of the machine is chosen. In this case,  $q$  is taken two and the corresponding slot number is 24. This is why, fractional slot is not desired due to complicated winding procedure. Also,  $q$  is not taken 1 in order to decrease effects of harmonics and it is not taken more than 2 in order to get higher winding factor.

### 3.2)

In this part, wire diameter should be chosen. For this, the restriction is maximum current density ( $J$ ) in the coil and it is 5 A/mm<sup>2</sup>. Also, coil current ( $I$ ) for this machine is 2.5 Ampere. Then, minimum coil area can be calculated as follows:

$$A_{coil} = \frac{I}{J} = 0.5 \text{ mm}^2 \quad (6)$$

So, the wire diameter is chosen larger than that value in order to make sure that maximum current density in the coil is smaller than 5 A/mm<sup>2</sup>. If frequency is known and larger areas are acceptable, it can be discussed later. Then, AWG20 cable is chosen with 0.518 mm<sup>2</sup> coil area.

### 3.3)

In this part, slot height, turn numbers in a slot and back core thickness are calculated. Firstly, slot ratio should be defined. Slot ratio is the ratio of diameter of inner part of slot to diameter of outer side of the slot ( $D_i/D_o$ ). If it is chosen smaller, corresponding slot height is higher. Generally, it is chosen between 0.5 and 1. In this study, it is chosen as 0.7. Since  $D_i$  is 102 mm,  $D_o$  and slot height  $h_s$  can be calculated easily as follows :

$$D_o = \frac{D_i}{0.7} = 145.7 \text{ mm} \quad (7)$$

$$h_s = \frac{D_o - D_i}{2} = 21.9 \text{ mm} \quad (8)$$

Moreover, turn number for each slot should be calculated. For this, slot area should be calculated. Firstly, the ratio of slot width to teeth width is chosen as 1 in this study. Then, width of a slot can be calculated as follows (rectangular teeth is chosen):

$$h_w = \frac{\pi D_i}{24} = 6.68 \text{ mm} \quad (9)$$

Then, fill factor is taken 0.6 for round wires and turn numbers can be calculated as follows:

$$N = \frac{A_{slot} k_{fill}}{A_{coil}} = (6.68 + 12.39) * 21.9 * \frac{0.6}{2 * 0.518} = 241 \quad (10)$$

Finally, back core thickness can be calculated by using the following equation (which is presented in the class) where  $k_{stacking}$  is the stacking factor of the machine and it is taken as 0.95 in this study and yoke flux density  $B_{yoke}$  is taken 1.2 Tesla according to stator material:

$$h_{st} = \frac{B_m A_m}{2 k_{stacking} L_{axial} B_{yoke}} = 21.25 \text{ mm} \quad (11)$$

### 3.4)

In order to calculate electrical loading, the formula given below is used (It is presented in the class):

$$\bar{A} = \frac{N_{turn,slot} I Q}{\pi D_i} = 201 * 2.5 * \frac{24}{\pi * 0.102} = 45.13 \text{ kA/m} \quad (12)$$

Usual values of electrical loading for PMSM is presented in the class as 35-65 kA/m. The value that is found above is in this range. Therefore, it can be said that chosen parameters are logical by now.

### 3.5)

Average tangential stress of the machine can be found by using the equation given below where  $\cos\phi$  is taken 1 for PMSM:

$$\sigma_{tan} = \frac{A_{rms} \bar{B} \cos\phi}{\sqrt{2}} = \frac{45130 * 1.014}{\sqrt{2}} = 32.36 \text{ kPa} \quad (13)$$

Then, corresponding total force can be calculated as follows where  $S_r$  is rotor surface area:

$$F_{tan} = \sigma_{tan} S_r = 32360 * \pi * 0.1 * 0.1 = 1016.62 \text{ N} \quad (14)$$

### 3.6)

In order to calculate power output of the machine, electrical radial speed of the machine and torque output should be known. Firstly, torque output of the machine can be calculated as follows:

$$T = \frac{F_{tan} D_i}{2} = 50.83 \text{ N.m} \quad (15)$$

Then, rotor speed of the machine is 1500 rpm (mechanically). It can be converted to radial speed by multiplying with  $2\pi/60$  and is obtained as 157.08 rad/sec. Then power output of the machine can be calculated as follows:

$$P = T \omega_{mec} = 50.83 * 157.08 = 7.98 \text{ kW} \quad (16)$$

## 4)

### 4.1)

In this part, the machine outer diameter is fixed to 160 mm and it is optimized in order to obtain maximum torque output. For this, slot ratio is called again which is  $D=(D_i/D_o)$ . Then the relationship between back core thickness ( $h_{st}$ ) and  $D_i$  should be determined. For rectangular

teeth shape, slot are is proportional to  $(1-D^2)/D$  and rotor volume is proportional to  $D^2$ . Then, output torque is proportional to  $((1-D^2)/D)*D^2=(1-D^2)*D$ . So, the optimum  $D$  is 0.58 as calculated in class. Relationship between  $D_i$  and  $D_o$  can be shown as follows:

$$D_o = \frac{D_i}{0.58} = 1.724 * D_i \quad (17)$$

Furthermore, magnet thickness and air-gap clearance is same with the values considered in first question. Thus, magnetic loading of the machine does not change ( $B_m = 1.014$ ). Then, magnet area can be calculated by using the equation ( $A_m = \pi D_i * 0.8$ ). Maximum stator flux density is considered as 0.9 Tesla again and  $k_{stacking}$  is taking 1.2 again. Then, back core thickness of the machine can be calculated as follows:

$$h_{st} = \frac{B_m \pi D_i l}{4} * \frac{0.8}{2k_{stacking} l B_{yoke}} = 0.279 * D_i \quad (18)$$

Then, we can calculate  $D_i$  as follows:

$$D_o + 2 * h_{st} = D_i(1.724 + 2 * 0.279) = 160mm \quad (19)$$

Finally,  $D_i$  can be found as 70.11 mm,  $D_o$  can be found 120.88 mm and  $h_{st}$  can be found 19.56 mm.

#### 4.1.1) Magnetic loading

Magnetic loading of the machine does not change and it is equal to 813.37 mT.

#### 4.1.2) Number of slots

Number of slots is chosen 24 again for the same reasons given above.

#### 4.1.3) AWG cable

Applied current and maximum current density are taken as taken in previous parts. Therefore, chosen cable is taken same and it is AWG20 with the area 0.518 mm<sup>2</sup>.

#### 4.1.4) Slot height, Number of coils per slot and Back core thickness

$D_i$  and  $D_o$  are calculated above and corresponding slot height is calculated as 25.39 mm. Width of slot can be calculated as follows:

$$h_{wi} = \frac{\pi D_i}{\frac{24}{2}} = 4.58 mm \quad (20)$$

$$h_{wo} = \frac{\pi D_o}{24} - h_{wi} = 11.24 mm \quad (20)$$

In order to calculate number of coils per slot can be calculated as follows where fill factor is taken 0.5:

$$N = (h_{wi} + h_{wo}) * 25.39 * \frac{k_{fill}}{2 * A_{coil}} = 232 \quad (21)$$



Finally, back core thickness is calculated above and is found as 19.56 mm.

#### 4.1.5) Electrical loading

Electrical loading of the machine can be calculated as follows:

$$\bar{A} = \frac{N_{turn,slot} I Q}{\pi D_i} = 232 * 2.5 * \frac{24}{\pi * 0.0701} = 63.21 \text{ kA/m} \quad (22)$$

For PMSM, electrical loading is in the range 35-65 kA/m and this value is in the range.

#### 4.1.6) Average tangential stress and Total force

Average tangential force of the previous machine is calculated above and for this machine it can be calculated as follows:

$$\sigma_{tan} = \frac{A_{rms} \bar{B} \cos \phi}{\sqrt{2}} = \frac{63210 * 1.014}{\sqrt{2}} = 45.32 \text{ kPa} \quad (23)$$

Moreover, total force can be calculated as follows:

$$F_{tan} = \sigma_{tan} S_r = 45320 * \pi * 0.0681 * 0.1 = 969.6 \text{ N} \quad (24)$$

#### 4.1.7) Power output of the machine

In order to calculate power output, torque output of the machine should be calculated as follows:

$$T = \frac{F_{tan} D_r}{2} = 33.01 \text{ N.m} \quad (25)$$

Corresponding output power can be calculated as follows:

$$P = T \omega_{mec} = 33.01 * 157.08 = 5.19 \text{ kW} \quad (26)$$

#### 4.1.8) FEA Results

In order to validate analytical results, FEA should be performed. The results should be compared. For this, the machine which is given in Figure 4 will be used.

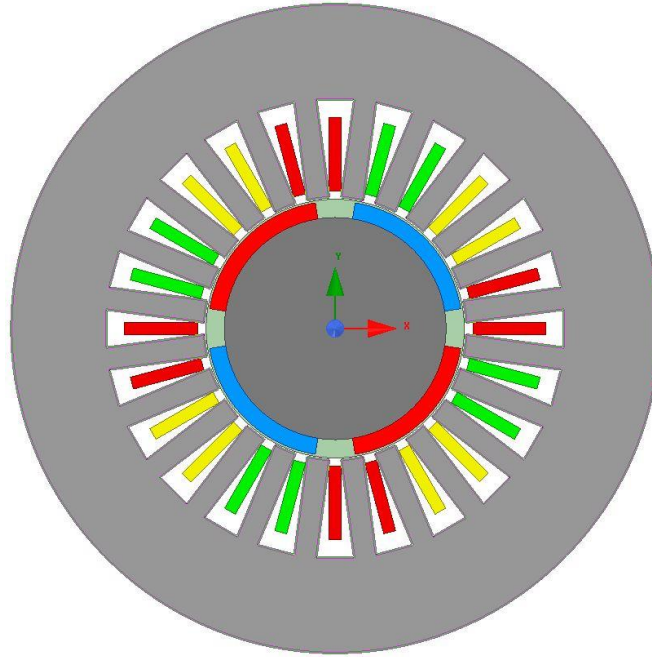


Figure 4: FEA model of the machine

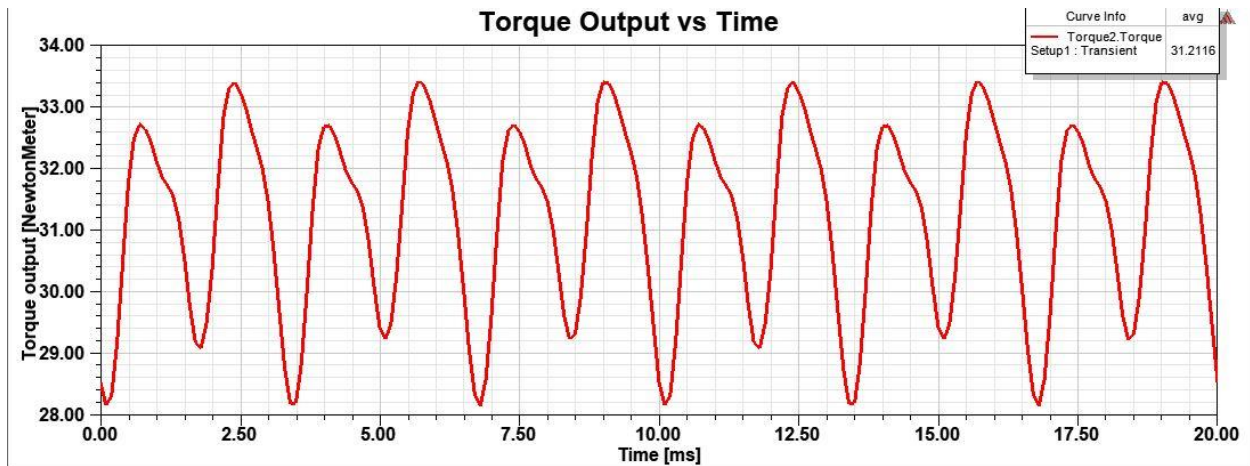


Figure 5: Torque output for the machine(NdFeB)

As can be seen in Figure 5, the average of the machine is 31.21. It is close to analytical result and it is lower than slightly than analytical result. The reason might be slotting effect, and leakage flux. Leakage occurs in magnets and coils.

#### 4.2) Replacing NdFeB with Ferrite Magnet

In this part, NdFeB magnet is replaced with ferrite magnet. Then, how parameters change is considered.

#### 4.2.1) Magnetic loading

$B_r$  of NdFeB is 1.28 T and relative permeability is 1.05. On the other hand,  $B_r$  of ferrite magnet is 0.4 T and relative permeability is 1.05. Then, by using simple relation, magnetic loading of the machine with ferrite magnet can be found as follows by using previous results (1.014 is  $B_m$  of previous part) :

$$B_m = 1.014 * \frac{0.4}{1.28} = 0.317 \text{ T} \quad (27)$$

$$\bar{B} = \frac{PB_m A_m}{D_i \pi L} = 253.6 \text{ (mT)} \quad (28)$$

#### 4.2.1) Electrical loading

Electrical loading does not change and it is 63.21 kA/m.

#### 4.2.2) Average tangential stress and Total force

Average tangential stress can be calculated as follows

$$\sigma_{tan} = \frac{A_{rms} \bar{B} \cos \Phi}{\sqrt{2}} = \frac{63210 * 0.317}{\sqrt{2}} = 14.17 \text{ kPa} \quad (29)$$

Then, total force can be calculated as follows:

$$F_{tan} = \sigma_{tan} S_r = 14170 * \pi * 0.0681 * 0.1 = 303.16 \text{ N} \quad (30)$$

#### 4.2.3) Power output of the machine

Firstly, torque of the machine should be calculated as is calculated as follows:

$$T = \frac{F_{tan} D_r}{2} = 10.32 \text{ N.m} \quad (31)$$

Corresponding power output of the machine as follows:

$$P = T \omega_{mec} = 10.32 * 157.08 = 1.62 \text{ kW} \quad (32)$$

#### 4.2.4) FEA Results

The model which is created for above section and given in Figure 4 is used in this case. Only, permanent magnet model is revised and adopted to ferrite magnet. Beside this, obtained result is compared to analytical result and evaluated. In figure 6, FEA result of the torque is given. This value is close to analytical result however it is lower due to same reasons given in 4.1.8.

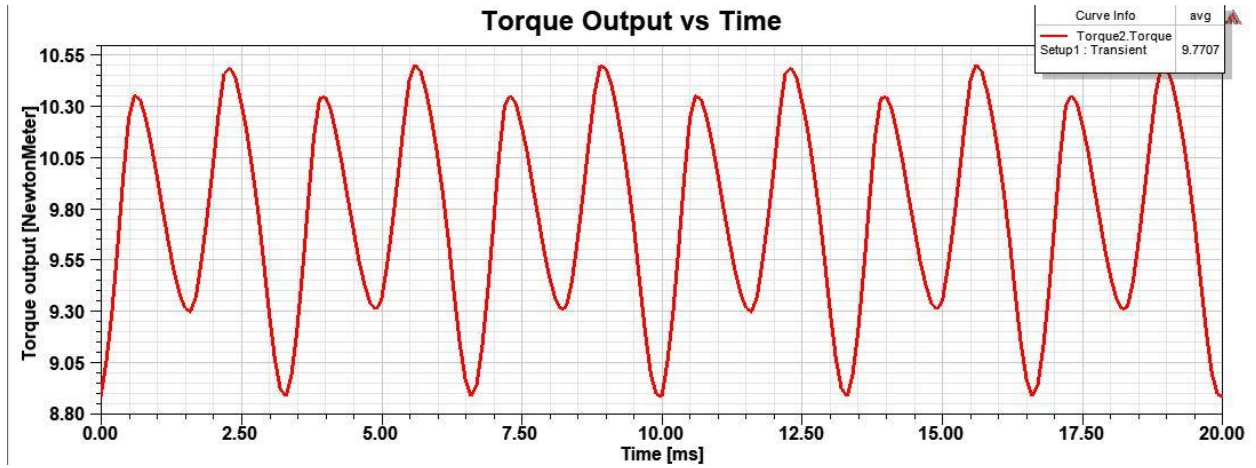


Figure 6: Torque output of the machine (ferrite magnet)

#### 4.2.5) Comparison

For same dimensions of the machines, NdFeB will give higher output torque. The reason is that higher remanent flux density which causes higher magnetic loading. This implies that NdFeB machine will give higher power with same speed. Then, it can be said that power density of the NdFeB machine is higher than ferrite magnet machine.

#### 4.3)

In this part, the machine with ferrite magnet is optimized. For this purpose, magnet thickness is doubled and magnet to pole ratio is fixed to 0.9 in order to increase average flux density. However, it is not increased more since flux leakage increases as well.

##### 4.3.1) B<sub>m</sub> calculating

In order to calculate magnetic loading of the machine, magnetic equivalent circuit and parameters given in part 2 are used.

$$\frac{R_m}{R_g} = \frac{\frac{h_m}{g}}{\mu_r} = 7.62 \quad (33)$$

$$B_m = B_r * \frac{R_m}{R_m + R_g} = 0.354 \text{ Tesla} \quad (34)$$

#### 4.3.2) Number of slots and AWG cable

Number of slots are chosen 24 and AWG20 is used again

#### 4.3.3) Slot height, Number of coils per slot and Back core thickness

In this part, equations (17), (18) and (19) are used.

$$D_o = \frac{D_i}{0.58} = 1.724 * D_i \quad (35)$$

$$h_{st} = \frac{B_m \pi D_i l}{4} * \frac{0.9}{2k_{stacking} l B_{yoke}} = 0.11 * D_i \quad (36)$$

$$D_o + 2 * h_{st} = D_i(1.724 + 2 * 0.11) = 160mm \quad (37)$$

Then,  $D_i$  is calculated as 82.3 mm,  $D_o$  is calculated as 141.89 and  $h_{st}$  is calculated as 9.055.

Inner width of slot is calculated as 5.39 mm, 13.18 mm while its height is 29.80 mm.

$$N = (h_{wi} + h_{wo}) * 29.8 * \frac{k_{fill}}{2 * A_{coil}} = 320 \quad (21)$$

#### 4.3.4) Electrical loading

Electrical loading of the machine can be calculated as follows:

$$\bar{A} = \frac{N_{turn,slot} I Q}{\pi D_i} = 320 * 2.5 * \frac{24}{\pi * 0.0823} = 74.26 \text{ kA/m} \quad (22)$$

For PMSM, electrical loading is in the range 35-65 kA/m and this value is higher.

#### 4.3.5) Average tangential stress and Total force

Average tangential force of the previous machine is calculated above and for this machine it can be calculated as follows:

$$\sigma_{tan} = \frac{A_{rms} \hat{B} \cos \Phi}{\sqrt{2}} = \frac{74260 * 0.354}{\sqrt{2}} = 18.59 \text{ kPa} \quad (23)$$

Moreover, total force can be calculated as follows:

$$F_{tan} = \sigma_{tan} S_r = 18590 * \pi * 0.0803 * 0.1 = 468.97 \text{ N} \quad (24)$$

#### 4.3.6) Power output of the machine

In order to calculate power output, torque output of the machine should be calculated as follows:

$$T = \frac{F_{tan} D_r}{2} = 18.83 \text{ N.m} \quad (25)$$

Corresponding output power can be calculated as follows:

$$P = T w_{mec} = 18.83 * 157.08 = 2.96 \text{ kW} \quad (26)$$

#### 4.3.6) FEA results

In this part, FEA results of analytical work performed in part 4. Torque of the related machine is considered and given in Figure 7. FEA result is smaller slightly.

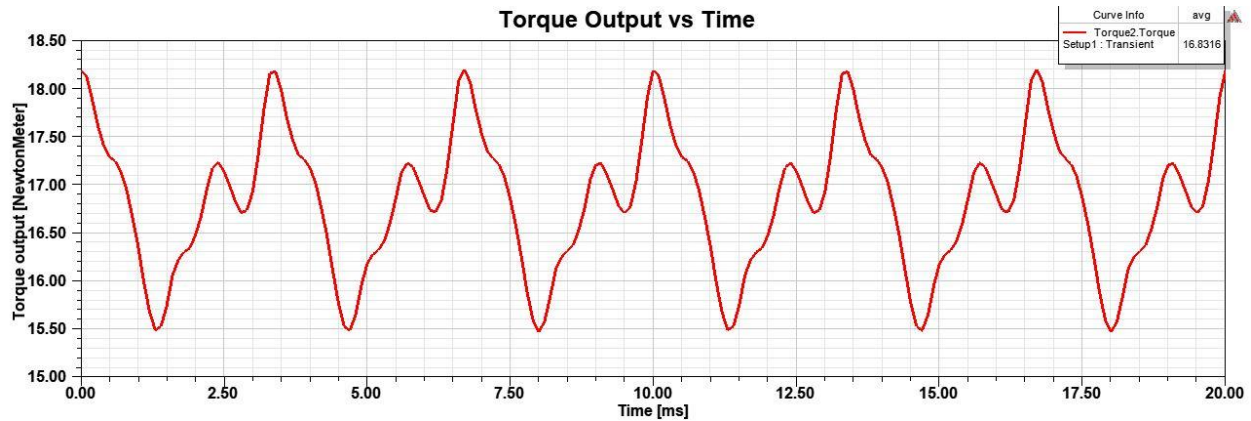


Figure 7: Torque result for ferrite magnet PMSM

#### 4.3.7) Comparison of machines with NdFeB and ferrite magnet

As expected, torque of the machine with ferrite magnet is lower due to lower magnetic loading. However, electrical loading of this machine is higher and it exceeds the values presented in class. Furthermore, its turn number is higher. This implies higher induced voltage and higher drive voltage. This may be problem for driving. On the other hand, price and volume of magnets and coils are detailed in Table 2 when price of NdFeB is taken 156 \$/kg, price of ferrite magnet is taken 25 \$/kg and wire price is taken 0.02 \$/m.

| Parameter                        | Value (NdFeB) | Value (Ferrite) |
|----------------------------------|---------------|-----------------|
| Magnet Volume (cm <sup>3</sup> ) | 41.54         | 95.88           |
| Magnet weight (kg)               | 0.31          | 0.48            |
| Magnet cost (\$)                 | 48.36         | 12              |
| Coil length (m)                  | 456           | 552             |

|                |      |       |
|----------------|------|-------|
| Coil cost (\$) | 9.12 | 11.04 |
|----------------|------|-------|

Table 2: Comparison parameters of two machines

## 5) Conclusion

In this study, general design of PMSM with NdFeB and ferrite magnet is completed and their results are compared to each other. This design procedure is validated by using FEA.