ORTA DOĞU TEKNİK ÜNİVERSİTESİ
MIDDLE EAST TECHNICAL UNIVERSITY

EE 568

Selected Topics on Electrical Machines

Project 3

PM Motor Comparison Analysis

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Introduction

In this project, Surface Mount Permanent Magnet Synchronous Machines are going to be analysed with different design criteria. Throughout the project following parameters are kept constant;

- 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

Q1-Magnetic Loading

In this part, machine is constructed with NdFeB magnets with following parameters;

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

Motor geometry can be seen in Figure 1.

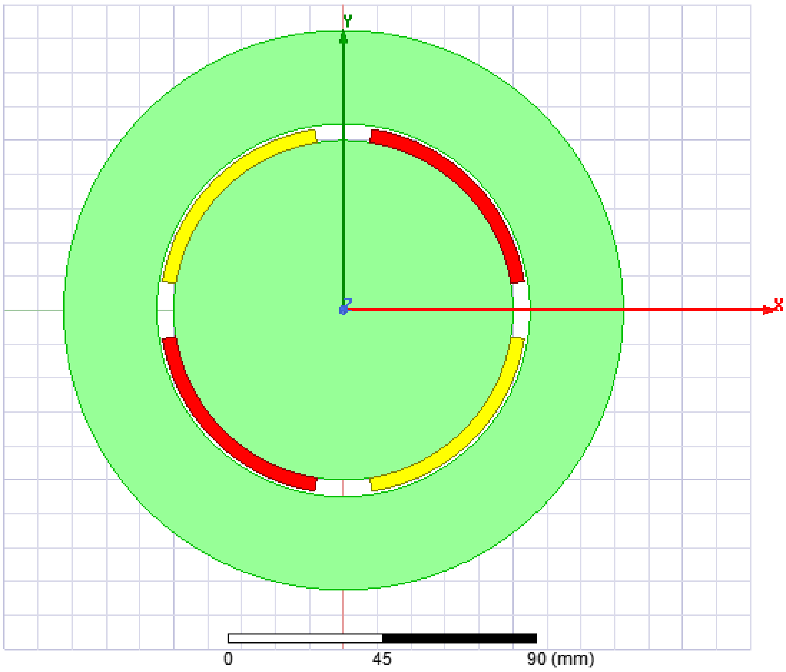

Figure 1: Geometry of constructed machine

Part a)

Magnetic equivalent circuit for one pole pair can be seen in Figure 2. In this figure, MMF_M1 and MMF_M2 show permanent magnet sources whereas R_M1 and R_M2 show reluctances of permanent magnets.

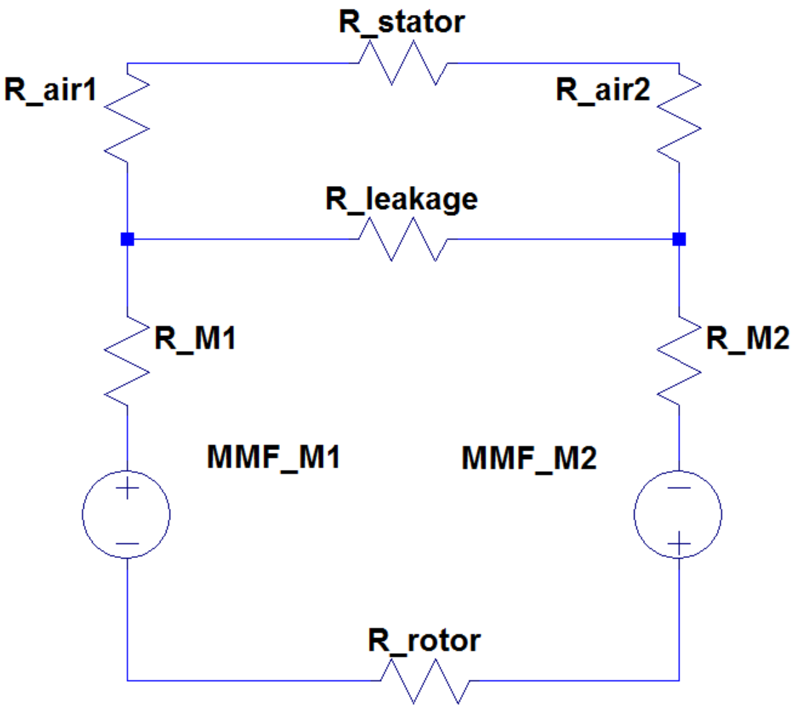

Figure 2: Magnetic equivalent circuit for one pole pair

Some assumptions are made for calculating operating point of the magnet. Stator and rotor reluctances are taken zero and leakage reluctance is taken infinite. Pole area can be calculated as;

$$A_{pole} = \frac{\pi * D_i * L}{p} = \frac{\pi * 0.1 * 0.1}{4} = 0.007854\ m^2$$

Magnet to pole pitch ratio is 0.8 therefore magnet and air gap area can be calculated as;

$$A_{magnet} = A_g = A_{pole} * 0.8 = 0.006283\ m^2$$

Reluctances can be found as;

$$R_{M1} = R_{M2} = \frac{h_{magnet}}{A_{magnet} * \mu_0 * \mu_r} = 482495\ 1/\mathrm{Henry}$$

$$R_{air1} = R_{air2} = \frac{h_{air}}{A_g * \mu_0} = 126658\ 1/\mathrm{Henry}$$

Permanent magnet MMFs can be calculated as;

$$MMF_{M1} = MMF_{M2} = B_r * A_{magnet} * R_{M1} = 3880\ \mathrm{Amperes}$$

By solving magnetic equivalent circuit, magnetic flux density can be found as;

$$B_m = 2 * \frac{MMF_{M1}}{2 * A_{magnet} * (R_{M1} + R_{air1})} = 1{,}014\ \mathrm{Tesla}$$

By using magnet normal curve, operating point of the magnet can be calculated by load line as seen in Figure 3. H_m of the magnet is found as -198.5 kA/m.

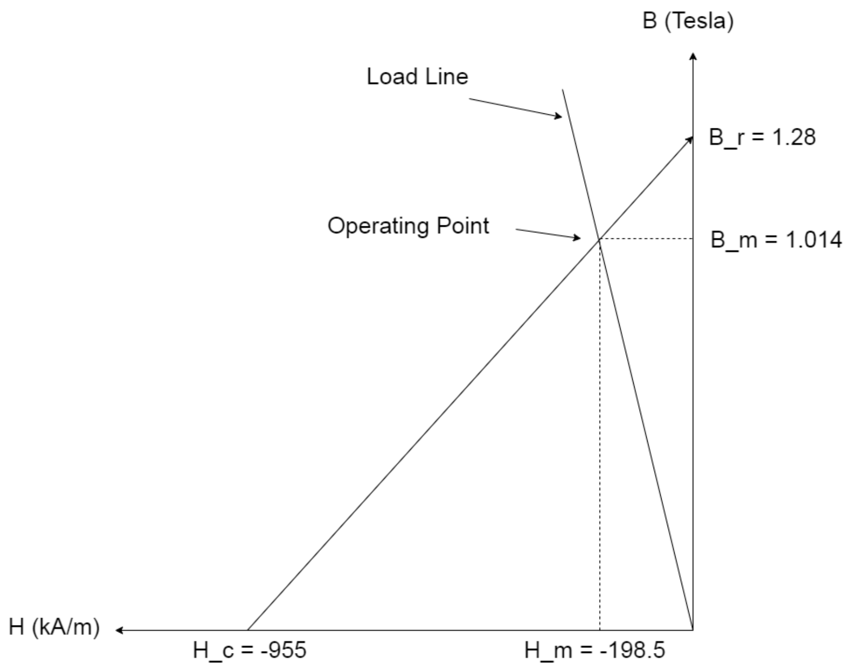

Figure 3: Normal line and load line of the magnet

Part b)

Magnetic loading of the machine can be calculated as;

$$\bar{B} = \frac{p * B_m * A_{magnet}}{\pi * D_i * L} = \frac{4 * 1{,}014 * 0{,}006283}{\pi * 0{,}1 * 0{,}1} = 0{,}8112\ Tesla$$

Part c)

Radial air gap flux density distribution is evaluated by using FEA. Model is constructed as seen in Figure 1. Resultant distribution can be seen in Figure 4.

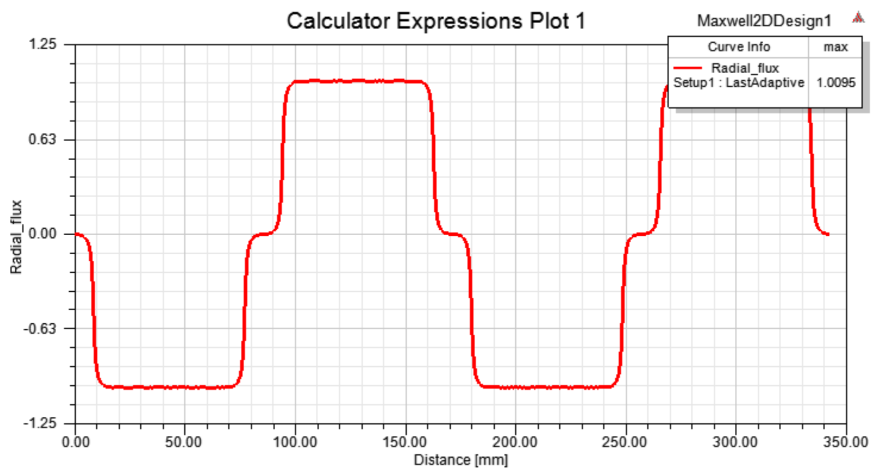

Figure 4: Radial air gap flux density distribution for overall machine

Analytically maximum magnetic flux density is found as 1,014 Tesla which found as 1,0096 in FEA analysis. As seen from results, they can are almost same. In analytical calculations leakage flux is ignored but in FEA analysis it prevents sharp decrease or increase of the flux as seen in Figure 4. Also it can be said from results that leakage component can be ignored.

Q2- Electrical Loading & Machine Sizing

In this part, electrical loading of the machine is investigated by determining slot numbers, types, current densities etc. Also force and power of the machine is found.

Part a)

Slots per pole per phase are chosen as 2 for this design which gives 24 slots for the machine. By choosing 24 slots, MMF harmonics is considered. MMF harmonics will be smaller compared to 12 slots machine. On the other hand construction of the machine may be difficult if the slot number was chosen 36. So, it seems that number of slots are chosen is reasonable. One of the stator tooth's and slots thickness can be calculated as;

$$\tau_{teeth\_and\_slot} = \frac{\pi * D_{stator}}{Q} = 14{,}4\ mm$$

Note that this value is total total tooth and slot thickness. It is assumed that tooth and slot thickness are equal and slot thickness is found to be;

$$\tau_{slot} = 7{,}2\ mm$$

Part b)

It is given that coil current is 2,5 A and maximum current density is 5 A/mm^2. Also maximum fill factor should be 0,6. In order not to exceed maximum current density, minimum area of the wire can be calculated as;

$$A_{wire} = \frac{I}{J} = \frac{2.5}{5} = 0{,}5\ mm^2$$

Therefore, AWG20 cable is chosen which has 0,518 mm^2 area and 0,812 mm diameter. Note that AWG20 cable has 5 A ampacity which can handle given coil current.

Part c)

In order to choose height of the slots, inner diameter to outer diameter ratio is taken as 0,6 for this design, therefore;

$$D_o = \frac{D_İ}{0{,}6} = 183{,}3\ mm$$

Height of the slot can be calculated as;

$$h_s = \frac{D_O - D_İ}{2} = 36{,}67\ mm$$

Turn number for each slot can be calculated by using slot height, slot thickness and fill factor as follows;

$$N = \frac{h_{slot} * \tau_{slot} * fill\_factor}{A_{wire}} = \frac{36{,}67 * 7{,}2 * 0{,}6}{0{,}518} = 305{,}7$$

Number of turns is chosen as 300. Then, back core thickness can be calculated by following formula by taking back core flux density of 1 Tesla;

$$h_{backcore} = \frac{B_m * A_{magnet}}{2 * k_{stacking} * l_{core} * B_{backcore}} = \frac{1{,}014 * 0{,}006283}{2 * 1 * 0{,}1 * 1} = 32\ mm$$

Note that stacking factor which is about construction of laminated steels is taken as 1. Therefore outer diameter of the machine can be calculated as;

$$D_{outer} = D_i + 2 * h_s + 2 * h_{backcore} = 247\ mm$$

Part d)

Electrical loading of the machine can be calculated by following formula;

$$\bar{A} = \frac{N_{turnslot} * I * Q}{\pi * D_i} = \frac{300 * 2{,}5 * 24}{\pi * 0{,}11} = 52{,}09\ kA/m$$

PMSM’s have typical electrical loading values between 35 and 65 kA/m, therefore the calculated electrical loading is reasonable.

Part e)

Average tangential stress can be calculated by using electrical and magnetic loading and taking cosϕ term 1 for PMSM’s, as follows ;

$$\sigma_{tangential} = \frac{\overline{A_{rms}} * \bar{B} * cos\varphi}{\sqrt{2}} = \frac{52{,}09 * 1{,}014 * 1}{\sqrt{2}} = 37{,}35\ kPa$$

PMSM’s have typical average tangential stress between 21 and 48 kPa, therefore the calculated value is reasonable.

Then, total force and torque that machine can deliver can be calculated as;

$$F = \sigma_{tangential} * S_r = \sigma_{tangential} * \pi * D_r * L = 1{,}17\ kN$$

$$T = F * \frac{D_r}{2} = 58{,}67\ Nm$$

Part f)

Expected power output of the machine can be found as follow;

$$P = T * w = 58{,}67 * \frac{1500 * 2 * \pi}{60} = 9{,}215\ kW$$

Q3- Comparison & Optimization

In this part, outer diameter of the machine is fixed to 160 mm which was 247 mm in previous design and other parameters are going to be changed in order to obtain maximum torque output. Note that the parameters given in introduction are also valid.

Part a)

By assuming rectangular teeth shape on the stator, torque output of the machine is proportional with $(1-d^2)d$ which has optimum point of 0,58. Therefore;

$$d = 0{,}58 = \frac{D_i}{D_o} \text{ yields } D_o = \frac{D_i}{0{,}58}$$

Also, back core thickness can be written in terms of D_i. Magnetic flux density is same because magnet and air gap thickness are not changed. Again, back core flux density is taken as 1.

$$h_{backcore} = \frac{B_m * \pi * D_i * L}{2 * k_{stacking} * l_{core} * B_{backcore} * p} = \frac{1{,}014 * \pi * D_i * 0{,}1}{2 * 1 * 0{,}1 * 1 * 4} = 0{,}398 * D_i$$

Outer diameter can be equated to summing of D_o and 2 times back core thickness and parameters can be found as follow;

$$160 = D_o + 2 * h_{backcore} = \frac{D_i}{0{,}58} + 2 * 0{,}398 * D_i = 2{,}52 * D_i$$

$$D_i = 63{,}49\ mm, \qquad D_o = 109{,}47\ mm, \qquad h_{backcore} = 25{,}27\ mm$$

- As magnetic flux density and magnet pitch ratio is same, magnetic loading is not changed ;
$$\bar{B} = 0{,}8112\ Tesla$$
- Number of slot is also taken same with previous design;
$$Q = 24$$
- Coil current and maximum current densities are chosen same as previous design. So AWG 20 cable is selected.
- Slot height is calculated from D_o and D_i;
$$h_{slot} = \frac{D_O - D_i}{2} = 22{,}99\ mm$$
- Assuming rectangular teeth shape with equal thickness for teeth and slot, teeth thickness is;
$$\tau_{teeth} = \frac{\pi * D_i}{2 * Q} = 4{,}15\ mm$$
- Note that slot is not rectangular, it will be same with teeth thickness at the surface of D_i and it will enlarge. Therefore initial thickness is 4,15 mm for slots and final thickness is;
$$\tau_{slot\_final} = \frac{\pi * D_o}{Q} - \tau_{theeth} = 10{,}18\ mm$$
- Number of coils per slot can be calculated as by taking 0,6 fill factor, and it is taken as 190;
$$N_{turnslot} = \frac{h_{slot} * \frac{(\tau_{slot\_final} + \tau_{theeth})}{2} * fill\_factor}{A_{wire}} = 190{,}04$$
- Electrical loading of the machine can be found as;
$$\bar{A} = \frac{N_{turnslot} * I * Q}{\pi * D_i} = \frac{190 * 2{,}5 * 24}{\pi * 0{,}0635} = 57{,}15 \frac{kA}{m}$$

PMSM's have typical electrical loading values between 35 and 65 kA/m, therefore the calculated electrical loading is reasonable.

- Average tangential stress can be calculated by;

$$\sigma_{tangential} = \frac{\overline{A_{rms}} * \bar{B} * cos\varphi}{\sqrt{2}} = \frac{57,15 * 1,014 * 1}{\sqrt{2}} = 40,97\ kPa$$

PMSM's have typical average tangential stress between 21 and 48 kPa, therefore the calculated value is reasonable.

- Total force and torque of the machine can be calculated by using rotor diameter which is 2 mm lower than D_i;

$$F = \sigma_{tangential} * S_r = \sigma_{tangential} * \pi * D_r * L = 40,97 * \pi * 0,0615 * 0,1 = 791\ N$$

$$T = F * \frac{D_r}{2} = 24,34\ Nm$$

- Power output at 1500 rpm can be found as;

$$P = T * w = 24,34 * \frac{1500 * 2 * \pi}{60} = 3,82\ kW$$

In order to verify the designed PMSM, machine model which can be seen in Figure 5 is constructed.

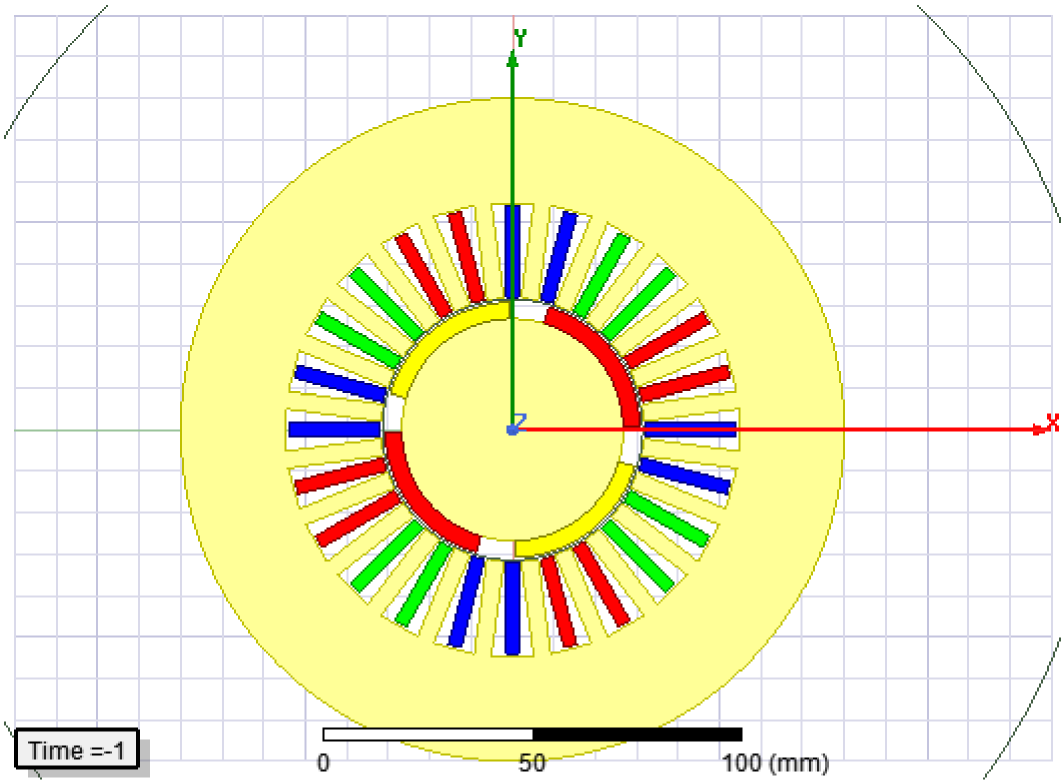

Figure 5: Constructed FEA model

Unfortunately, FEA model couldn't be analysed because of errors. Comparison will be held by analytical results. Machine torque output is much higher in the previous design compared to last design because physical machine sizing is found very much in first design i.e outer diameter of the machine is 247 mm in first design whereas 160 mm in last design. Although magnetic loading of the machines are same with each other, electrical loading differ much therefore tangential stress and torque output differ much.

Part b)

In this part, NdFeB magnets are replaced with ferrite magnets by keeping all dimensions are same. Note that ferrite magnets has B_r value of 0,4 Tesla which was 1,28 Tesla in NdFeB magnets.

- As magnetic circuits for two design are exactly same except MMF sources, maximum magnetic flux density can be calculated from previously calculated NdFeB value;

$$B_{m_{ferrite}} = B_{m\_NdFeB} * \frac{B_{r_{ferrite}}}{B_{r_{NdFeB}}} = 1{,}014 * \frac{0{,}4}{1{,}28} = 0{,}317 \text{ Tesla}$$

- Magnetic loading can be found in same way;

$$\overline{B_{ferrite}} = \overline{B_{NdFeB}} * \frac{B_{r_{ferrite}}}{B_{r_{NdFeB}}} = 0{,}8112 * \frac{0{,}4}{1{,}28} = 0{,}254 \text{ Tesla}$$

- As all mechanical dimensions are kept same, slot area and number of turns of the coils are also same. Therefore electrical loading is exactly same with NdFeB magnets design which is 57,15 kA/m.
- Average tangential stress can be found as;

$$\sigma_{tangential\_ferrite} = \frac{\overline{A_{rms}} * \bar{B} * cos\varphi}{\sqrt{2}} = \frac{57{,}15 * 0{,}317 * 1}{\sqrt{2}} = 12{,}81\ kPa$$

- Total force and torque of the machine can be calculated as;

$$F_{ferrite} = \sigma_{tangential} * S_r = \sigma_{tangential} * \pi * D_r * L = 12{,}81 * \pi * 0{,}0615 * 0{,}1 = 248\ N$$

$$T_{ferrite} = F * \frac{D_r}{2} = 7{,}6\ Nm$$

- Power output at 1500 rpm can be found as;

$$P = T * w = 7{,}6 * \frac{1500 * 2 * \pi}{60} = 1{,}19\ kW$$

As all of the design criteria are kept constant except permanent magnets, all performance parameters such as tangential stress, total force, total torque and power output of the machine decreased with the ratio of $\frac{B_{r_{ferrite}}}{B_{r_{NdFeB}}}$. It can be said that magnet properties directly reflect machine performances if all dimensions and electrical loading kept same.

Part c)

In order to increase performance parameters of the machine, both electrical and magnetic loading should be increased. In order to increase magnetic loading, magnet pitch ratio should be chosen greater than 0,8. On the other hand electrical loading should be improved very much inevitable. Therefore slot/teeth ration should be increased and much more turn ratio can be achieved.

To conclude, ferrite magnet machine will have higher copper cost compared to NdFeB magnet machine. On the other hand, NdFeB magnets have much higher cost compared to ferrite magnets. Therefore, reasonable choose may differ according to availability of the magnets and copper.

Conclusion

In this project, design steps of the PM machines are followed and machines are designed with two different magnet materials, NdFeB and ferrite. Magnetic and electrical loading are investigated. Their importance for the machine performances is evaluated.