METU – EEE

Middle East Technical University – Electrical Electronics Engineering Department

PROJECT REPORT

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within the scope of the course

EE568

SELECTED TOPICS ON ELECTRICAL MACHINES

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PROJECT REPORT NO : 03

PROJECT NAME : PM Motor Comparison Analysis

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Introduction

In this report, we examine the PM motor design. In the design process there are several design parameters that can be determined by designer with respect to some limitations such as machine dimensions, magnetic and electrical loading, cooling etc. The purpose of this project is design with considering these trades off and obtain the optimum design with respect to given specifications.

Constant specifications:

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

1. Magnetic Loading

In this part we are going to design a NdFeB magnet machine with the following parameters:

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

a) Magnetic equivalent circuit, load line and operating point on the B-H characteristics, peak air-gap flux density.

The machine has 4 pole so it contains 2 permanent magnet as shown in fig.1. Also, equivalent magnetic circuit is given in fig.2.

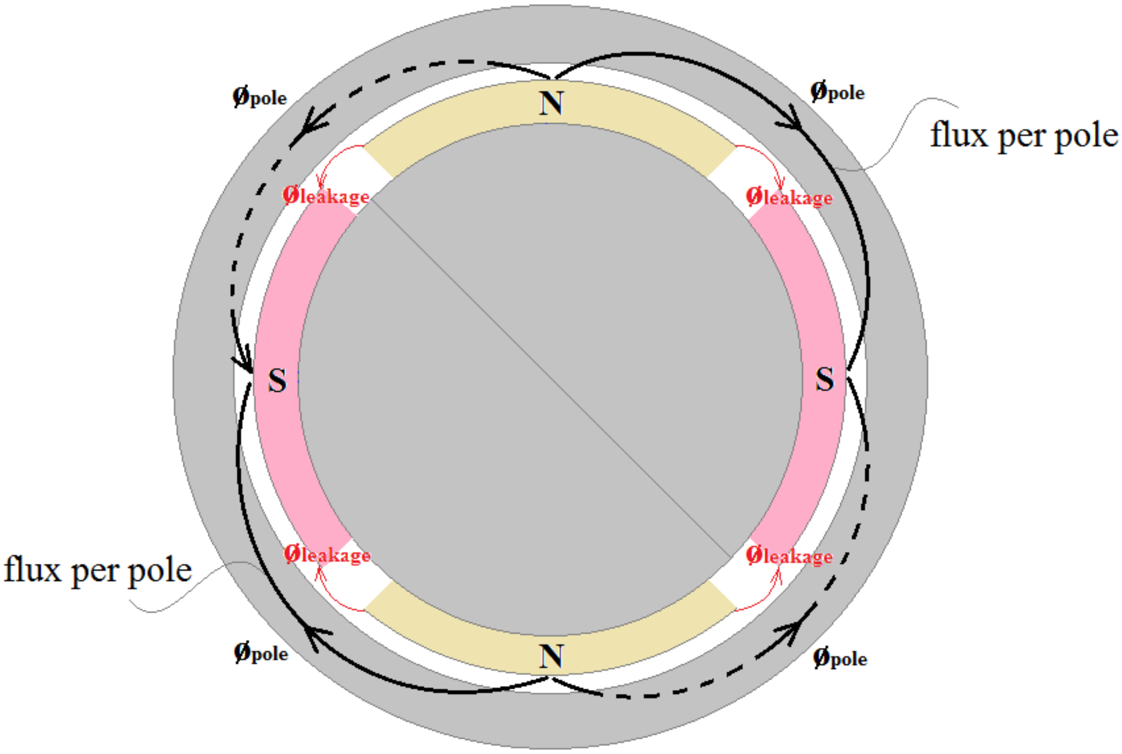


Fig.1: Solid stator machine representation

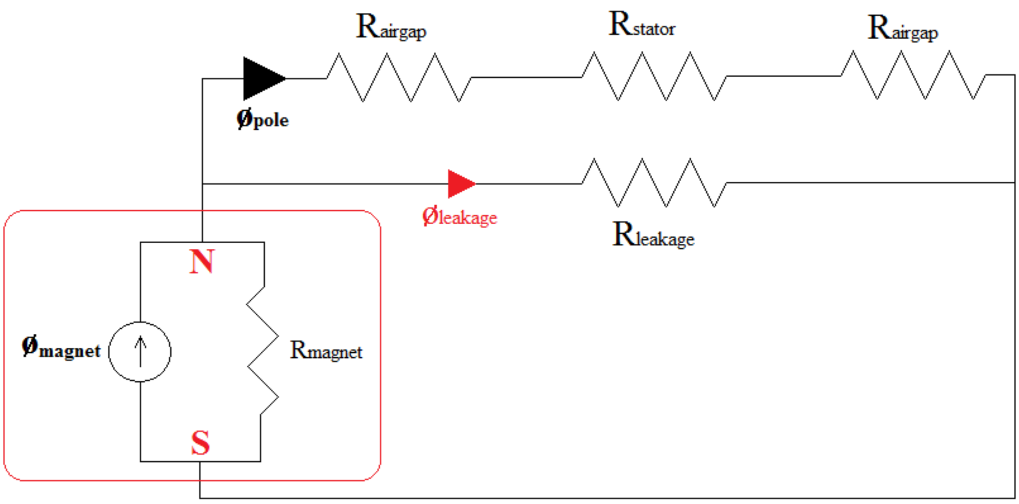


Fig.2: Equivalent magnetic circuit for one pole pairs

To calculate the peak air-gap flux density we have to know the load line and magnet operating point on the B-H characteristic. For this calculation, we determine the magnet geometry on the rotor as shown in figure 3.

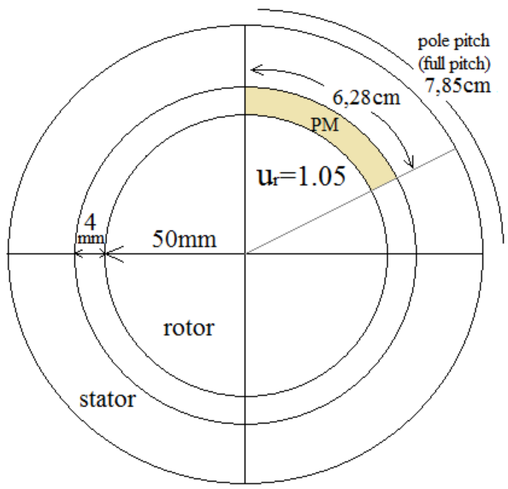


Fig.3: Magnet physical geometry on the rotor with respect to given specifications

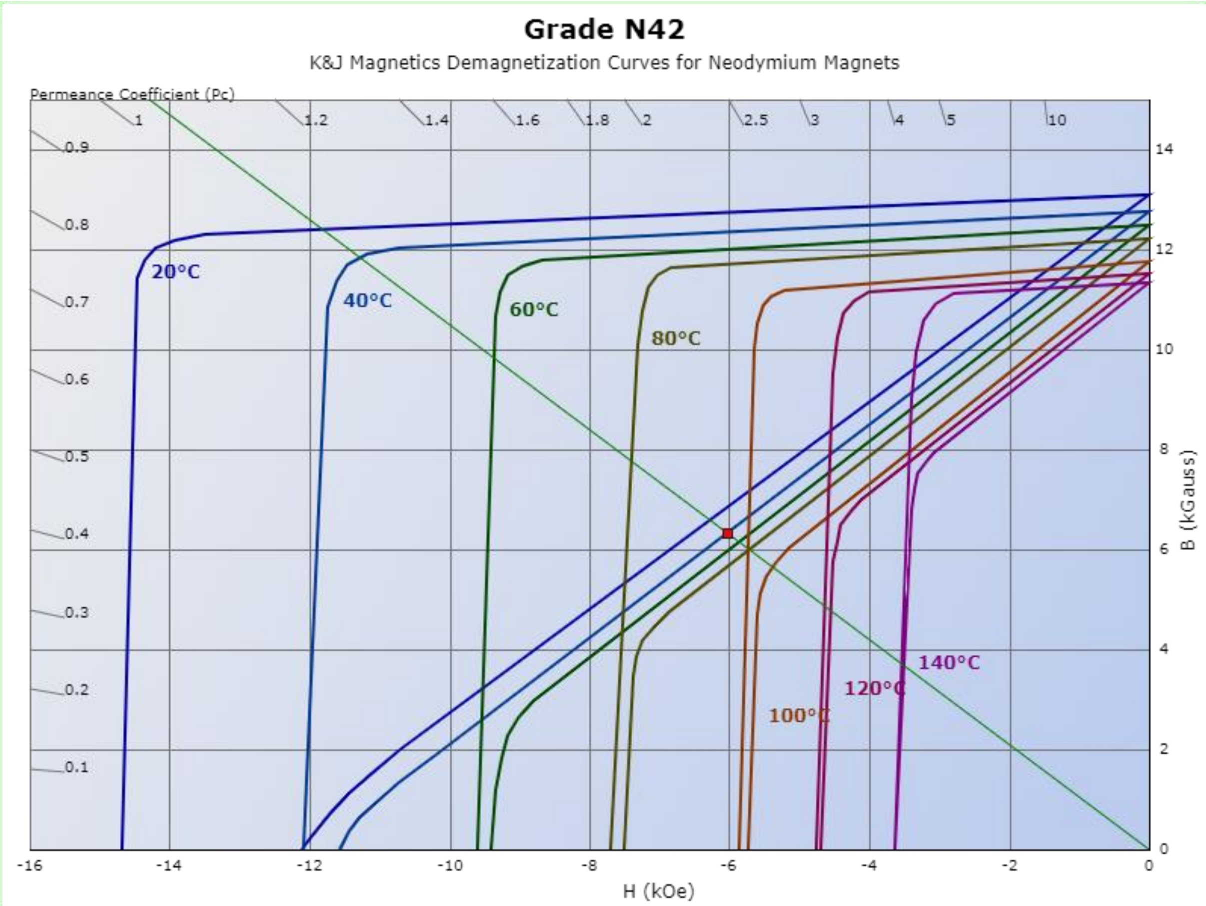


Fig. 4: Load line on the B-H characteristic of the given Neodymium magnet, Permeance Coefficient (Pc): 1.05, B: 6.34 kilogauss, H: -6.03 kilooersted, |BH|: 38.23 mega-gauss-oersted

According to specifications of the magnet, N42 grade magnet load line can obtained as shown in figure 4. If we select the operating temperature as 40'C, we can calculate the max. flux density in air gap using dimensions as shown in below equations:

$$\varphi = B_m \times A_m$$

Where B_m is average magnet magnetic flux, A_m is magnet surface area. If we assume, rotor is surface mount permanent magnet machine, when we calculate the air gap flux density we can use the above equation.

$$A_m = 2\pi r \times l \times 0.8 = 2\pi(0.05 + 0.004) \times 0.1 \times 0.8 = 0.0271\ m^2$$

Where, we assume that the magnet has a cylindrical shape in area calculation. 0.05m is radius of rotor, 0.004m is magnet thickness, 0.1m is axial length of the machine, 0.8 is magnet to pole pitch ratio.

$$B_{m_{average}} = 0.63T,\ \ B_{m_{peak}} = \frac{\pi}{2} B_{m_{average}} = 0.98T$$

$$\varphi_{pole} = 0.63T \times 0.0271m^2 = 0.0171 \frac{Wb}{m^2}\ \ , \varphi_{pole_{peak}} = \frac{\pi}{2} \varphi_{pole} = 0.026Wb/m^2$$

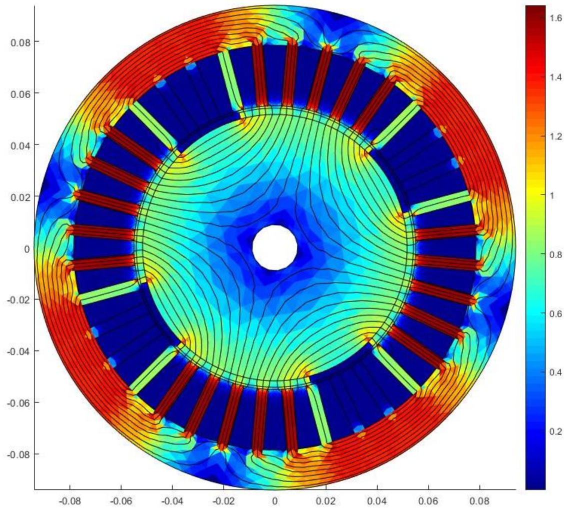
b) Calculate the magnetic loading of the machine for this condition

Magnetic loading can be calculated as mean flux density over the air gap surface:

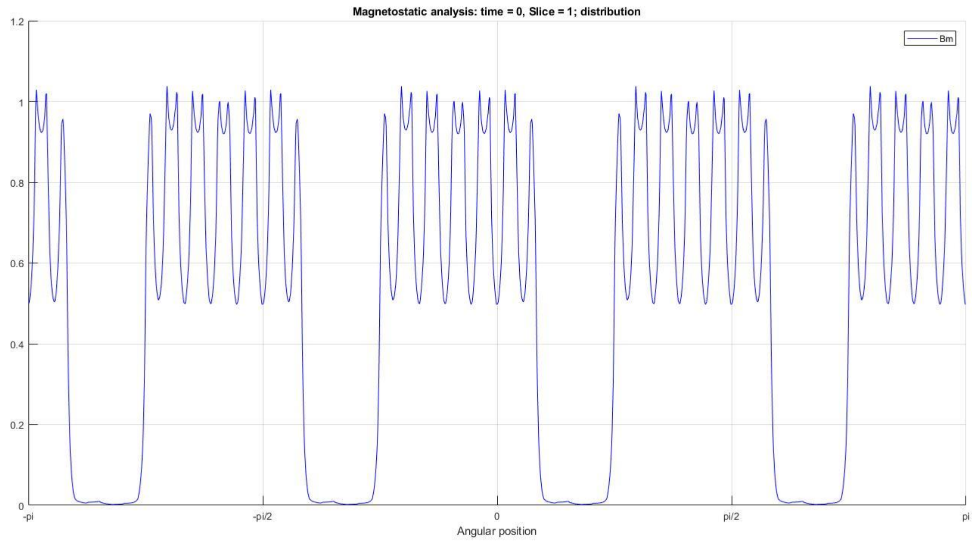
$$B = \frac{p \times \varphi_{pole}}{\pi D_i l} = \frac{4 \times 0.0171}{\pi \times 0.11 \times 0.1} = 1.97\ T$$

Where, pole number p=4, D_i=110mm is the stator bore diameter as 100mm rotor dia. + 4+4mm magnets + 1+1mm air gap.

c) Draw the radial air-gap flux density distribution in the middle of air-gap clearance for a one pole-pair using an FEA tool and compare it with your analytical calculations.



(a)



(b)

Fig. 5: Air gap flux density distribution of the designed machine a) spectrum, b) magnitude

As seen from the figure 5. The average air gap flux density is nearly 0.8T at air gap (the calculated value was 0.98T, tooth and back core are 1.97T). The difference between them can be sourced by mainly leakage fluxes and nonlinearities on the B-H curve of the magnets. The back core flux density is nearly 1.6T while tooth flux density is bigger than back-core because of non-optimized geometry. The tooth flux density is near of the saturation.

2. Electrical Loading & Machine Sizing

In this part, we are going to improve the machine design and to analyze the machine electrical loading and sizing.

a) Choose a suitable number of slots for this machine. Discuss and justify your choice. Please assume open slot shape for the analysis.

If we define $q: slots/pole/phase$, total number of slots $= q \times m \times p$, where p: pole number, m: number of phases. Since harmonic flux components are not desirable, the MMF waveform should approximate a sinusoidal shape as much as possible. Generally, $q = 3$ is sufficient.

$$Total\ number\ of\ slots = q \times m \times p = 3 \times 3 \times 4 = 36\ slots$$

After this determination, we need to check mechanical strength of tooth. The stator bore diameter is 110mm.

$$Tooth\ pitch = \frac{\pi \times 11cm}{36} = 0.95cm \rightarrow contains\ slot + tooth\ length$$

If we select the $q = 2$, the tooth pitch is $1.43cm$.

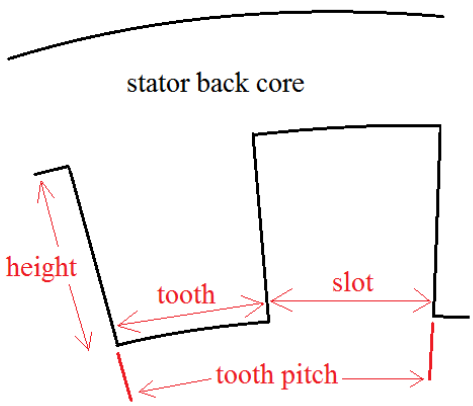


Fig. 6: Stator structure and dimensions

According to figure 5, if we select q=3 instead of q=2, the fluxes concentrate in the tooth and back core dimensions will increase because of sloth height.

b) Assume the coil current is 2.5 A. If the maximum current density is 5 A/mm^2 and maximum fill factor is 0.6, choose a suitable AWG cable.

According to 5 A/mm^2 maximum current density of the copper, we can select the **number 8 in the AWG** table as shown in figure 6. We assume that the tooth pitch and slot pitch is equal to each other for preventing the saturation level at tooth region. The fill factor of the slot is 0.6, so this is mean that copper amount in the slot is 60% of the total slot area. When we calculate the areas with respect to given fill factor limitation, possible options of the structure is given in table 1.

$$total\ slot\ area = slot\ height \times 7mm$$

$$total\ copper\ area = 8.37mm^2 \times number\ of\ conducters$$

$$0.6 = \frac{total\ copper\ area}{total\ slot\ area}$$

Table 1: Possible conductor-slot structures

$number\ of\ conducters$	$slot\ height$	$total\ copper\ area$	$total\ slot\ area$	Possibility
1	4mm	8.37mm^2	28mm^2	No (over dsn.)
2	4mm	16.74mm^2	28mm^2	YES
3	6mm	25.11mm^2	42mm^2	YES
4	7mm	33.48mm^2	49mm^2	No (0.68 fill f.)
5	10mm	41.85mm^2	70mm^2	YES
6	10mm	50.22mm^2	70mm^2	No (0.71 fill f.)

AWG	Diameter		Turns of wire, without insulation		Area		Copper wire							
							Resistance/length[7]		Ampacity,[8] at 20 °C insulation material temperature rating, or for single unbundled wires in equipment for 16 AWG and smaller[9]			Fusing current[10][11]		
									60 °C	75 °C	90 °C	Preece[12][13][14][15]	Onderdonk[16][15]	
	(in)	(mm)	(per in)	(per cm)	(kcmil)	(mm^2)	(mΩ/m[a])	(mΩ/ft[b])	(A)			~10 s	1 s	32 ms
0000 (4/0)	0.4600[c]	11.684[c]	2.17	0.856	212	107	0.1608	0.04901	195	230	260	3.2 kA	33 kA	182 kA
000 (3/0)	0.4096	10.405	2.44	0.961	168	85.0	0.2028	0.06180	165	200	225	2.7 kA	26 kA	144 kA
00 (2/0)	0.3648	9.266	2.74	1.08	133	67.4	0.2557	0.07793	145	175	195	2.3 kA	21 kA	115 kA
0 (1/0)	0.3249	8.251	3.08	1.21	106	53.5	0.3224	0.09827	125	150	170	1.9 kA	16 kA	91 kA
1	0.2893	7.348	3.46	1.36	83.7	42.4	0.4066	0.1239	110	130	145	1.6 kA	13 kA	72 kA
2	0.2576	6.544	3.88	1.53	66.4	33.6	0.5127	0.1563	95	115	130	1.3 kA	10.2 kA	57 kA
3	0.2294	5.827	4.36	1.72	52.6	26.7	0.6465	0.1970	85	100	115	1.1 kA	8.1 kA	45 kA
4	0.2043	5.189	4.89	1.93	41.7	21.2	0.8152	0.2485	70	85	95	946 A	6.4 kA	36 kA
5	0.1819	4.621	5.50	2.16	33.1	16.8	1.028	0.3133				795 A	5.1 kA	28 kA
6	0.1620	4.115	6.17	2.43	26.3	13.3	1.296	0.3951	55	65	75	668 A	4.0 kA	23 kA
7	0.1443	3.665	6.93	2.73	20.8	10.5	1.634	0.4982				561 A	3.2 kA	18 kA
8	0.1285	3.264	7.78	3.06	16.5	8.37	2.061	0.6282	40	50	55	472 A	2.5 kA	14 kA
9	0.1144	2.906	8.74	3.44	13.1	6.63	2.599	0.7921				396 A	2.0 kA	11 kA
10	0.1019	2.588	9.81	3.86	10.4	5.26	3.277	0.9989	30	35	40	333 A	1.6 kA	8.9 kA
11	0.0907	2.305	11.0	4.34	8.23	4.17	4.132	1.260				280 A	1.3 kA	7.1 kA
12	0.0808	2.053	12.4	4.87	6.53	3.31	5.211	1.588	20	25	30	235 A	1.0 kA	5.6 kA
13	0.0720	1.828	13.9	5.47	5.18	2.62	6.571	2.003				198 A	798 A	4.5 kA
14	0.0641	1.628	15.6	6.14	4.11	2.08	8.286	2.525	15	20	25	166 A	633 A	3.5 kA

Fig. 7: AWG table

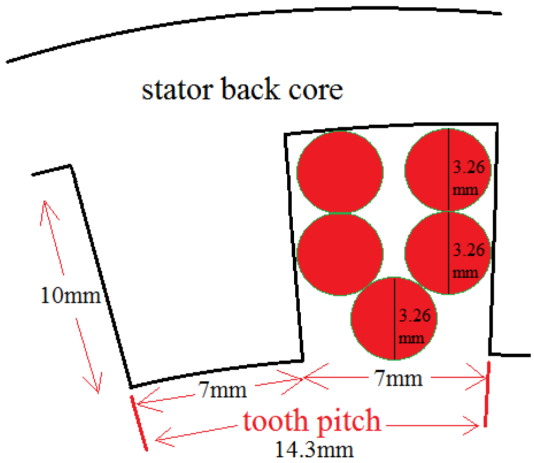


Fig. 8: One of the designed slot with coppers and dimensions for q=2, 24 slots

c) Choose a reasonable slot height, number of coils per slot and a back-core thickness that does not saturate the core. You can use the rule-of-thumbs presented in the lecture and verify your decisions.

If the assume slots gets wider with diameter slots (rectangular teeth), the d ratio (see fig. 8) can be assume as 0.7. This means that the slot height is:

$$d = 0.7 = \frac{110mm}{157.14} \rightarrow slot\ height = 23.57mm$$

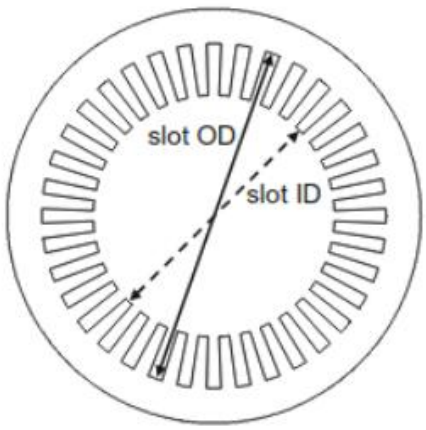


Fig. 9: d ratio on the machine

According to design table of T.Miller (fig. 9), the outer diameter Do is:

$$for\ 4\ pole\ machine \rightarrow \frac{D_o}{D_i} = 1.88, \qquad D_i = 100mm, \qquad which\ yields$$

$$D_o = 188mm, \qquad Back\ core = 15.43mm$$

N Poles	2	4	6	8	10	12
Do/Di	2	1.88	1.78	1.66	1.54	1.43

Source: T.Miller - Electric Machine Design Course, Lecture-5, Slide4

Fig. 10: Design table of Do/Di with respect to pole number

d) Calculate the electrical loading for your design and compare with the usual values presented in the lecture.

According to slot height calculations, we can select the q=3, 36 slots. The tooth pitch is 9.5mm, that can divided as 4mm slot width, 4.5mm tooth width (section 2, part a). Our conductor type was number 8 in AWG (section 2 part b). Slot height was 23.57mm, back core was 15.43mm (section 2, part c). According to these calculations from previous part, we can determine the number of conductor in a slot (fill factor was 0.6).

$$slot\ area = 4mm \times 23.57mm = 94.28mm^2$$

$$fill\,factor = 0.6 \rightarrow max.conductor\ area = 56.56mm^2$$

$$conductor\ number\ in\ one\ slot = \frac{conductor\ area}{one\ conductor\ area} = 6.75\ \approx 6\ conductor\ in\ slot$$

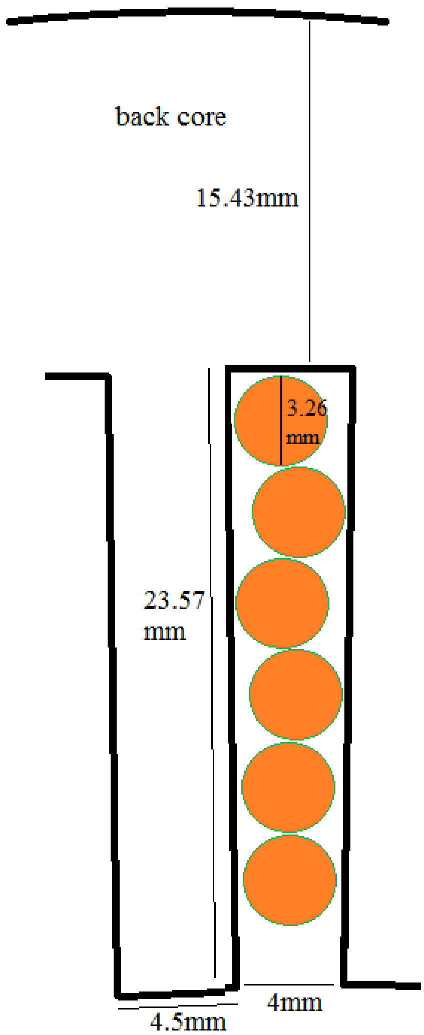


Fig. 11: Calculated dimensions and configuration

$$electrical\ loading = \frac{m \times 2 \times N \times I}{\pi \times D_i}$$

Where, N is turns per phase which is equal to 6x12=72, 2 comes from conductor number in one turn, m is phase number, I is the rms phase current.

$$electrical\ loading = \frac{3 \times 2 \times 72 \times 2.5}{\pi \times 0.11} = 3.125\ kA/m$$

e) Calculate the average tangential stress in the rotor surface, total force that your design can produce.

In Q1-part a, we calculated the $B_{m_{peak}} = 0.98T$ air gap flux density. The electrical loading was $3.125\ kA/m$ calculated in previous part. Rotor diameter was $D_i = 100mm$, length was $l = 100mm$. We assume that there is no phase shift. The tangential stress:

$$\sigma_{Ftangential}(x) = \widehat{B_n} \sin(x)\, \hat{A} sin(x)$$

$$\sigma_{Ftangential\_average}(x) = 0.5 \times 0.98T \times \frac{3.125kA}{m} = 1.53\ kPa$$

The surface area of the rotor: $\pi \times D_i \times l = 0.031m^2$. When we multiply the rotor surface area with average tangential stress, the force is:

$$\pi \times D_i \times l \times \sigma_{Ftangential\_average}(x) = 48.06\ N$$

f) Assuming a rotor speed of 1500 rpm, calculate the expected power output of your machine.

The calculated tangential force occurs everywhere at all radial distance. So, the torque at the circumference is:

$$Torque = 48.06N \times 0.05\ (radius\ of\ rotor) = 2.43\ Nm$$

The speed of the rotor is 1500rpm=157rad/s. Power output:

$$P_{out} = Torque(Nm) \times Speed\ (rad/s) = 381.51\ W$$

3. Comparison & Optimization

In this part, assume the stator outer diameter is fixed to 160 mm, and the rotor diameter and other parameters are variable according to your design. You can assume open slots for this part, rectangular teeth shape is suggested, but please mention and justify any other slot-tooth shape combinations.

a) Try to estimate the optimum rotor diameter and slot ratio for maximum torque output. Calculate the required parameters (electrical loading, magnetic loading, stress etc.) analytically and verify your design in FEA and compare it to the machine you designed in Q1&Q2.

If the $D_o = 160mm, D_i = 85.1mm\ according\ to\ 4\ pole\ machine\ \frac{D_o}{D_i} = 1.88$. Again we select same number of slot in Q1&Q2.

$$Total\ number\ of\ slots = q \times m \times p = 3 \times 3 \times 4 = 36\ slots$$

$$Tooth\ pitch = \frac{\pi \times 85.1}{36} = 7.42mm$$

To prevent the saturation in tooth, we can select the tooth pitch as 5mm and sloth pitch 2.4mm (fill factor is still 0.6).

If we assume again slots gets wider with diameter slots (rectangular teeth), the d ratio (see fig. 8) can be assume as 0.7. This means that the slot height is:

$$d = 0.7 = \frac{85.1}{121.42} \rightarrow slot\ height = 18.21mm, \qquad back\ core = 19.5mm$$

$$slot\ area = 18.21 \times 2.44 = 44.43mm^2, conductor\ area = 26.65mm^2 \rightarrow fill\ f. = 0.6$$

Total conductor number in one slot can be calculated with respect to AWG 11 selection (dia. 2.305mm, area 4.17mm^2).

$$N = \frac{29.82}{4.17} = 6.39\ conductor\ per\ slot\ \approx 6$$

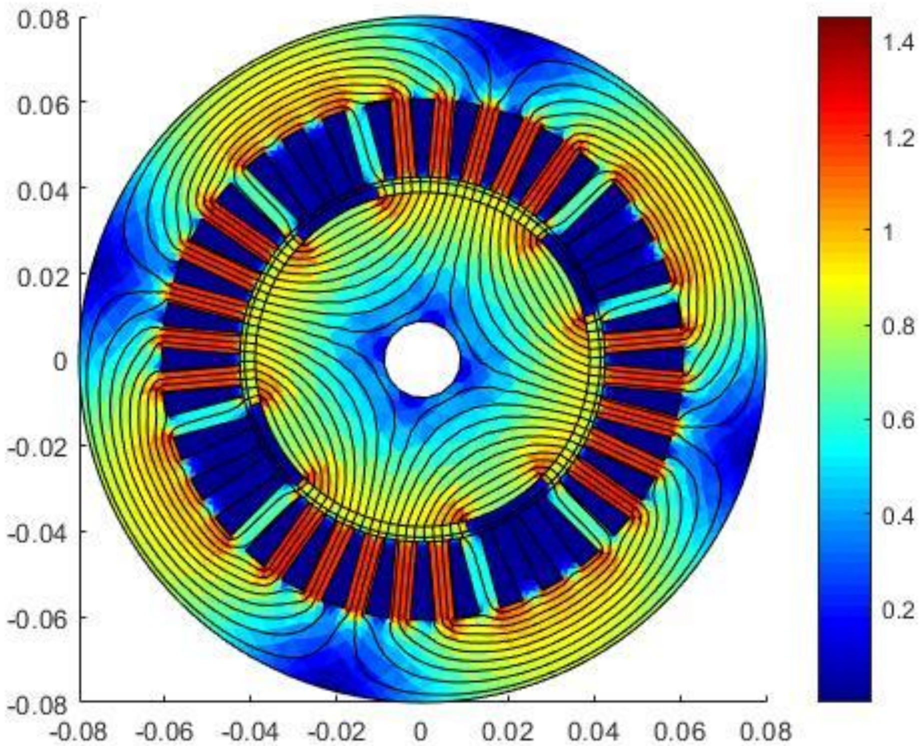
N is turns per phase which is equal to 6x12=72

$$electrical\ loading = \frac{3 \times 2 \times 72 \times 2.5}{\pi \times 0.0851} = 4.039\ kA/m$$

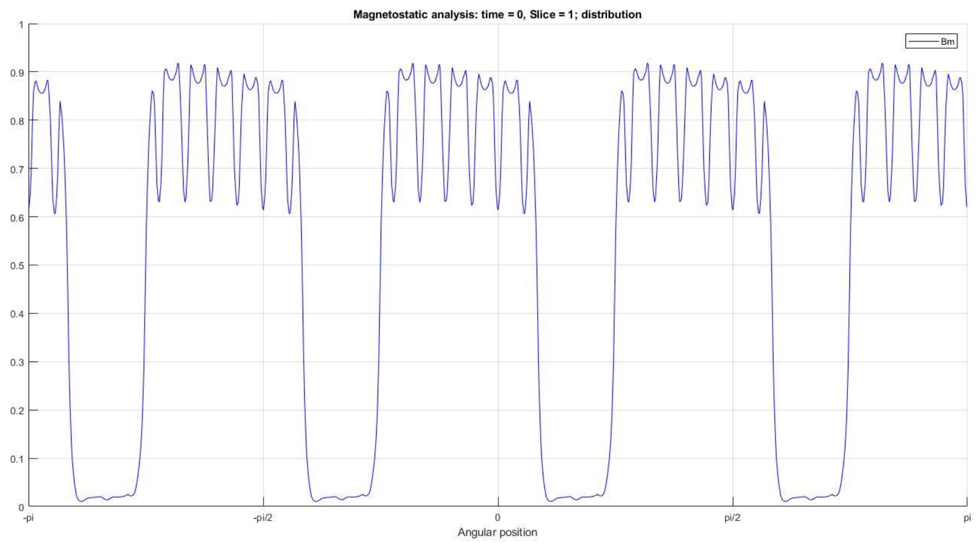
For the same magnet type NdFeB N42,

$$B = \frac{p \times \varphi_{pole}}{\pi D_i l} = 1.9\ T$$

FEA result of the design:



(a)



(b)

Fig. 12: Outer diameter fixed 160mm NdFeB N42 design a) flux density, b) airgap flux graph

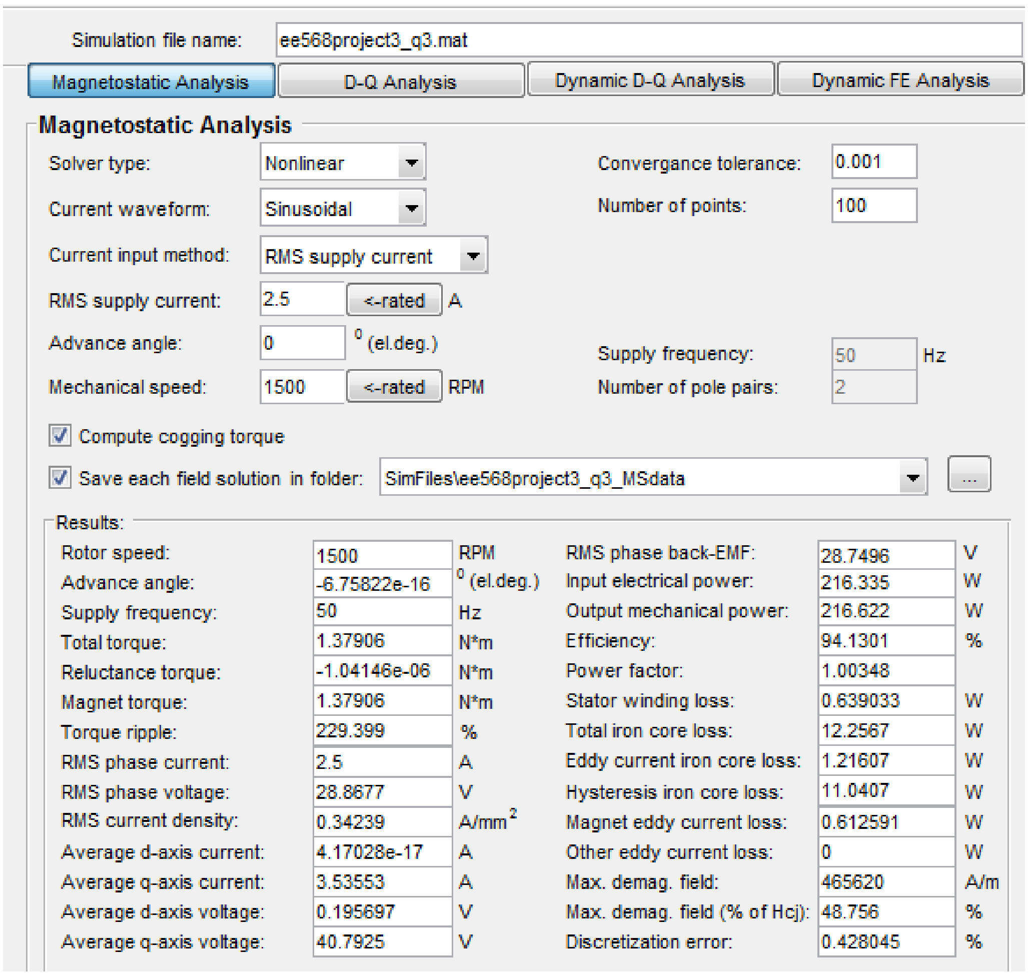


Fig. 13: The FEA results of the designed NdFeB N42 magnet machine at 1500rpm and 2.5A rms excitation, drive type current hysteresis PWM at 500V dc supply voltage.

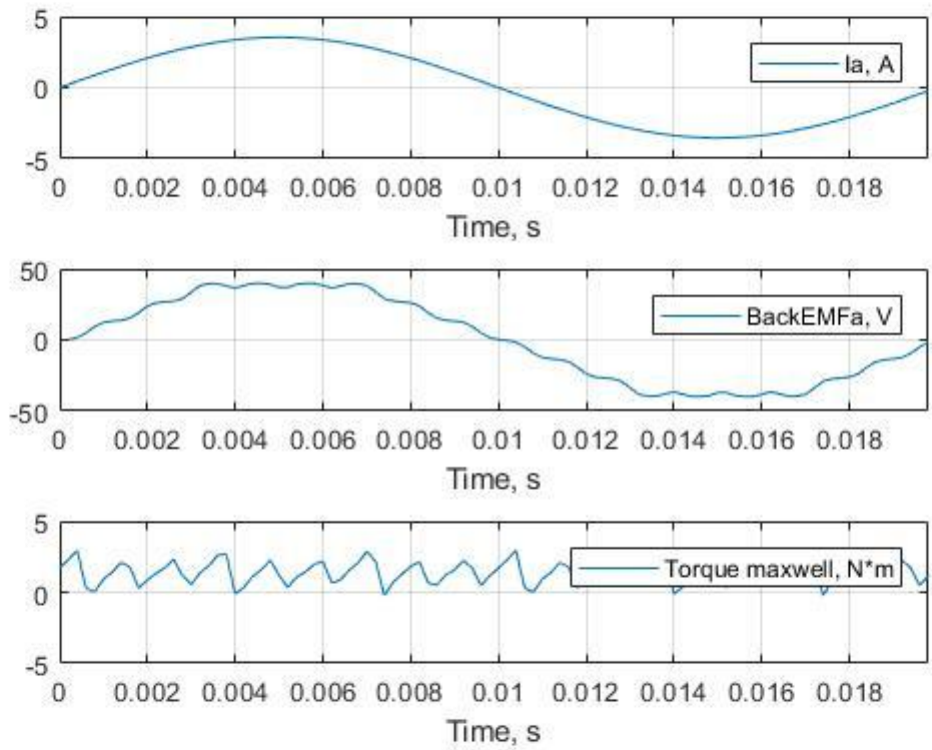


Fig. 14: Phase currents, back emf, torque of the machine at 1500rpm

The machine size is lower than the machine designed in Q1&Q2 (Do_{q1q2}=188mm, Do_{q3}=160mm, Di_{q1q2}=100mm, Di_{q3}=85mm). In this case, we kept the pole number, slot number and magnet type as same as in part Q1&Q2. The tooth pitch is increased; the airgap flux density is nearly same as the Q1&Q2 parts. But, tooth flux density and back core flux density decreases from 1.6T to 1.4T. This means that magnetic loading decreased because of tooth pitch optimization. But this time electrical loading increased because of lower dimension of inner diameter, so machine needs more cooler performance. Overcome this issue, we can locate the conductors one by one from centre to backcore way.

b) Now assume you replaced the NdFeB magnet with Ferrite magnets (Brem=0.4 T) as in the reading material (14/04), while keeping all the dimensions same with the previous part, calculate the machine performance and compare it with the NdFeB design.

When we change the magnet type, the flux density in the air gap will decrease (because of the $Brem_{NdFeB}$=1.39, $Brem_{Ferrite}$=0.4). So the max. torque, output power of the machine decreases. The detailed compared results are given in next figures.

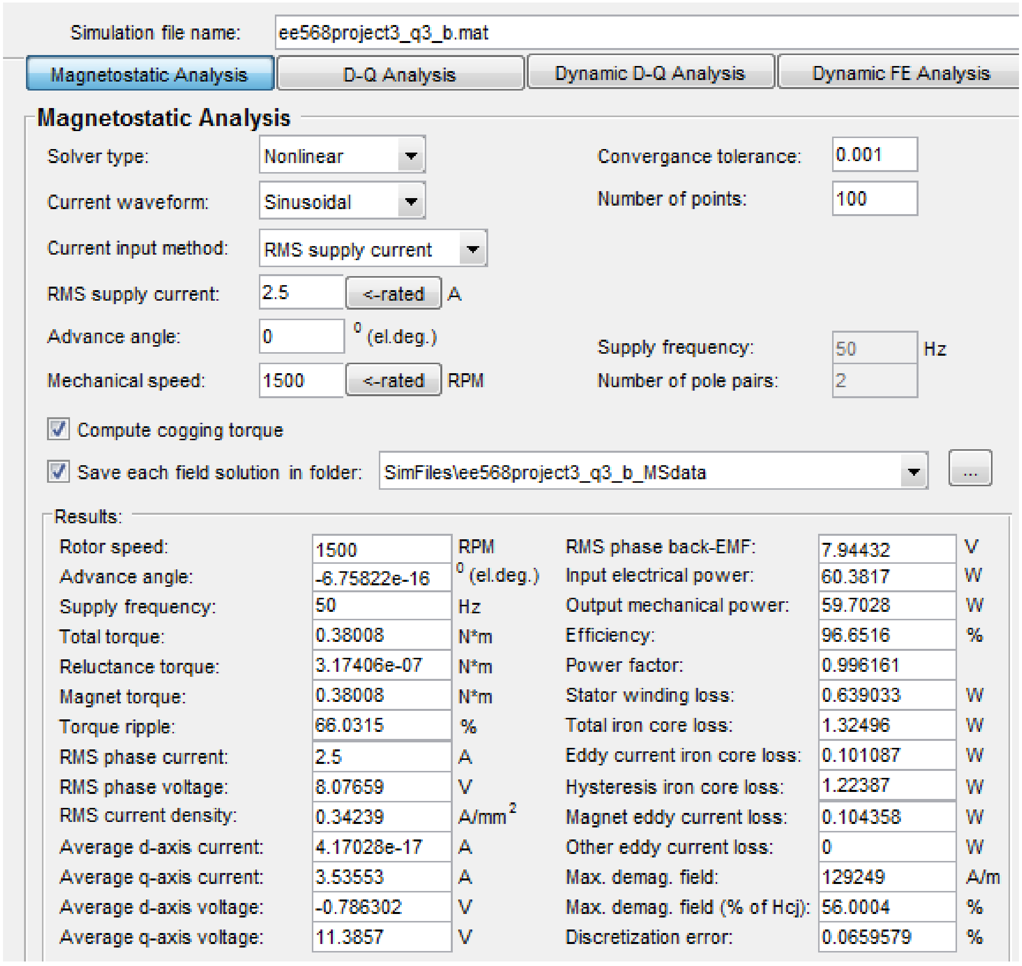
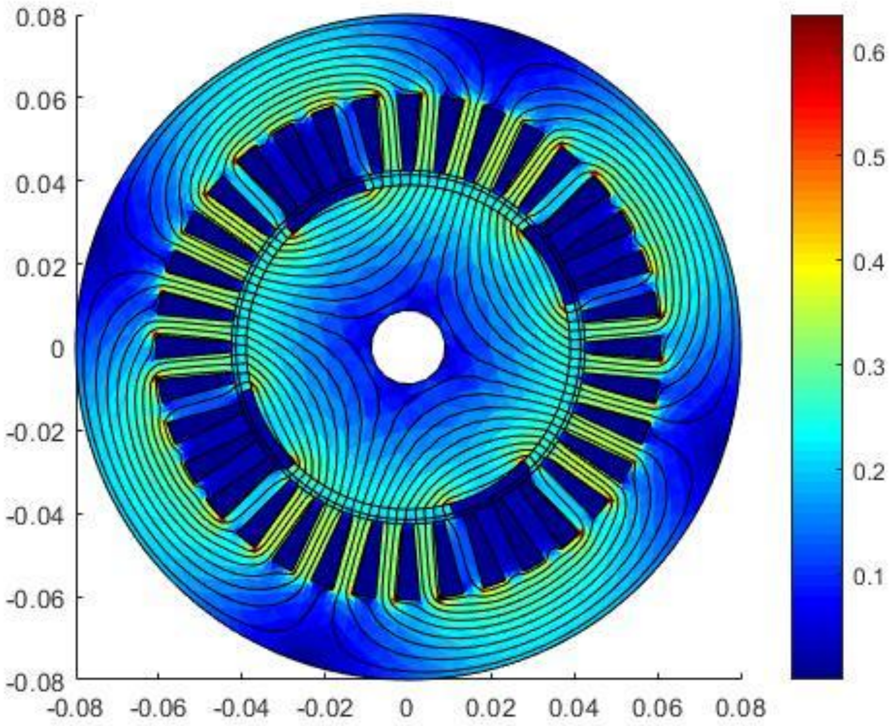
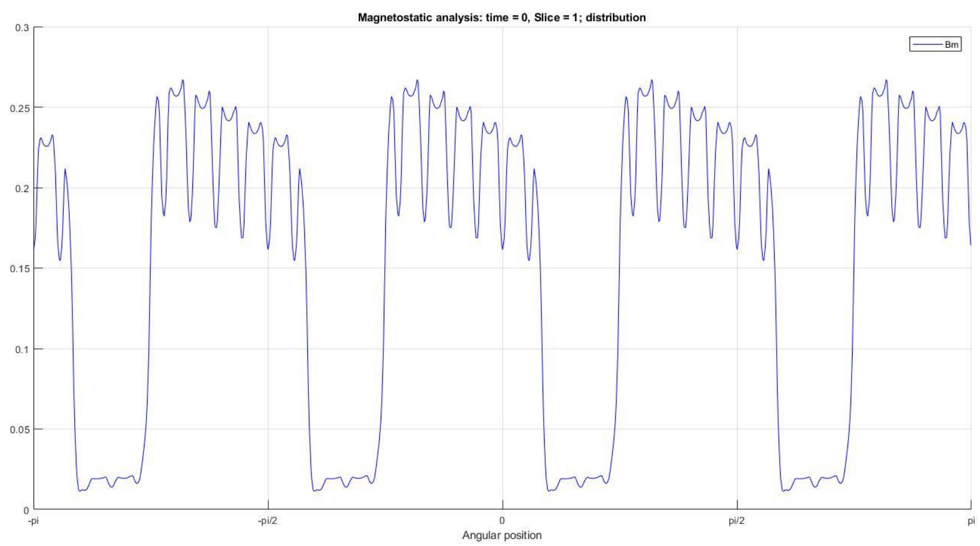


Fig. 15: The FEA results of the designed Ferrite magnet machine at 1500rpm and 2.5A rms excitation, drive type current hysteresis PWM at 500V dc supply voltage.

As shown from the figures, the machine performance decreases as obtained output mechanical power 216W to 60W. Another performance indicator torque decreases from 1.37Nm to 0.38Nm. Magnetic loading of the machine is also decresed that is advantageous for cooling cost of the machine but we need nearly 4 piece ferrite magnet machine for doing same job with NdFeB magnet machine.



(a)



(b)

Fig. 16: Outer diameter fixed 160mm Ferrite magnet design a) flux density, b) airgap flux graph

c) In this part, try to optimize the Ferrite machine by changing the parameters, but the outer diameter is still fixed to 160 mm. Choose the rotor diameter, magnet thickness, slot/tooth ratio to find the maximum torque output. Present a comparison between NdFeB and Ferrite machines

and justify your design decisions. Compare parameters like volume, copper cost, magnet cost etc.

We assume, Do=160mm, 4 pole, 3 phase, SMPM, Ferrite magnet machine. The performance of the machine is analyzed at 1500rpm with 2.5A rms phase current excitation. To increase the performance of this machine we have some optimization tricks. First one is increasing the magnet thickness. This operation increases the magnet cost double. If we increase the magnet thickness, the air gap is also increases automatically. At this time reluctance of the air gap increases and total flux is not increases as same amount as magnet thickness. When we consider the magnet cost this operation is not logical for a mass production. Reducing the rotor size causes the magnets are closed each other and increases the leakage flux via rotor steel. Second thing that we can do reducing the teeth width and back core thickness can be reduced until the saturation. This provides reducing machine size, and smooth slot shapes decreases the slot corner saturations.

According to these consideration optimized design of the ferrite magnet machine.

If the $D_o = 160mm, D_i = 85.1mm\ according\ to\ 4\ pole\ machine\ \frac{D_o}{D_i} = 1.88$. Again we select same number of slot in Q1&Q2.

$$Total\ number\ of\ slots = q \times m \times p = 3 \times 3 \times 4 = 36\ slots$$

$$Tooth\ pitch = \frac{\pi \times 85.1}{36} = 7.42mm$$

To prevent the saturation in tooth, we can select the tooth pitch as 2.4mm and sloth pitch 5mm (fill factor is still 0.6).

If we assume again slots gets wider with diameter slots (rectangular teeth), the d ratio (see fig. 8) can be assume as 0.58 for obtain max torque. This means that the slot height is:

$$d = 0.58 = \frac{85.1}{146.7} \rightarrow slot\ height = 30.81mm, \qquad back\ core = 6.65mm$$

$$slot\ area = 30.81 \times 5 = 154.05mm^2, conductor\ area = 92.43mm^2 \rightarrow fill\ f. = 0.6$$

Total conductor number in one slot can be calculated with respect to AWG 11 selection (dia. 2.305mm, area 4.17mm^2).

$$N = \frac{29.82}{4.17} = 22.16\ conductor\ per\ slot\ \approx 22$$

N is turns per phase which is equal to 22x12=264

$$electrical\ loading = \frac{3 \times 2 \times 264 \times 2.5}{\pi \times 0.0851} = 14.812\ kA/m$$

For the ferrite magnet,

$$B = \frac{p \times \varphi_{pole}}{\pi D_i l} = 0.8\ T$$

FEA result of the optimized design with 2.5mm thickness Ferrite magnet:

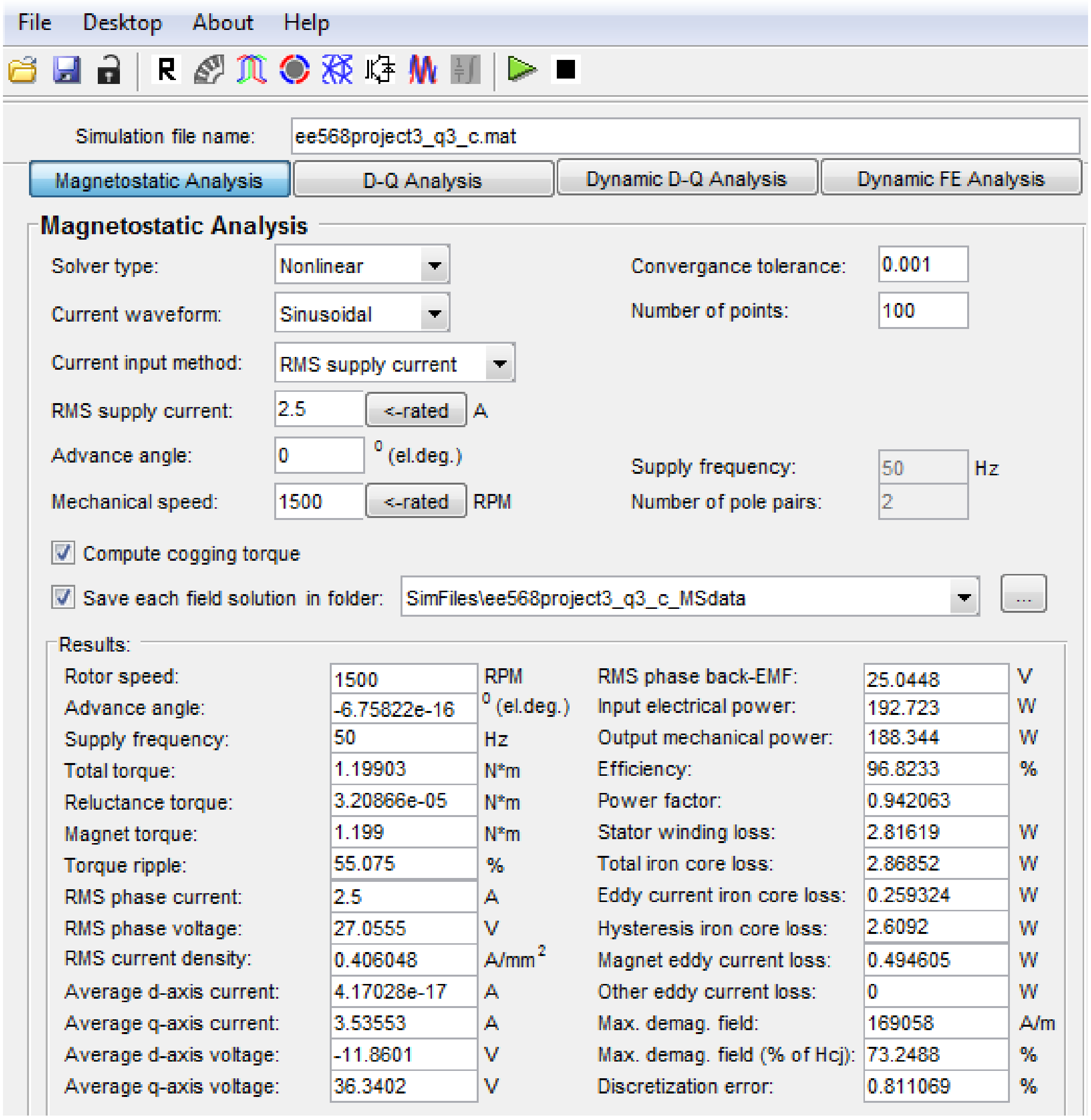
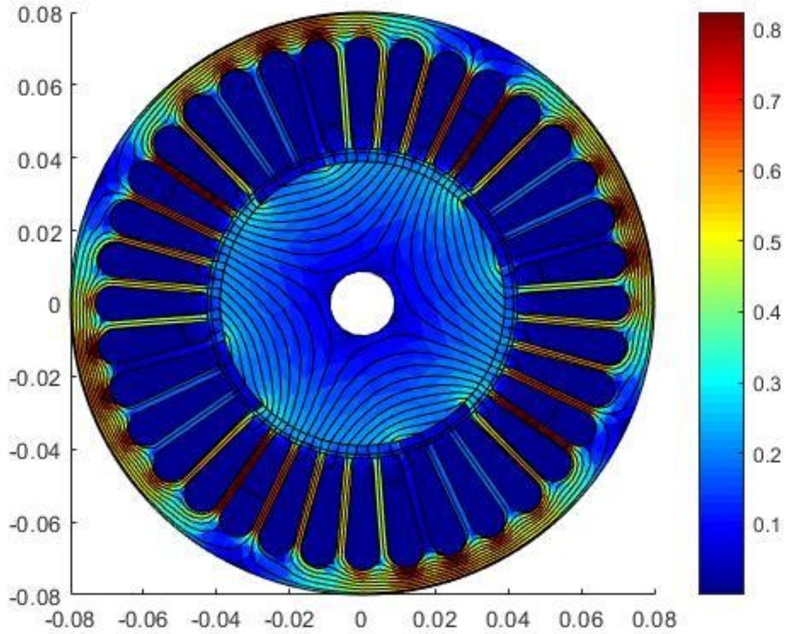
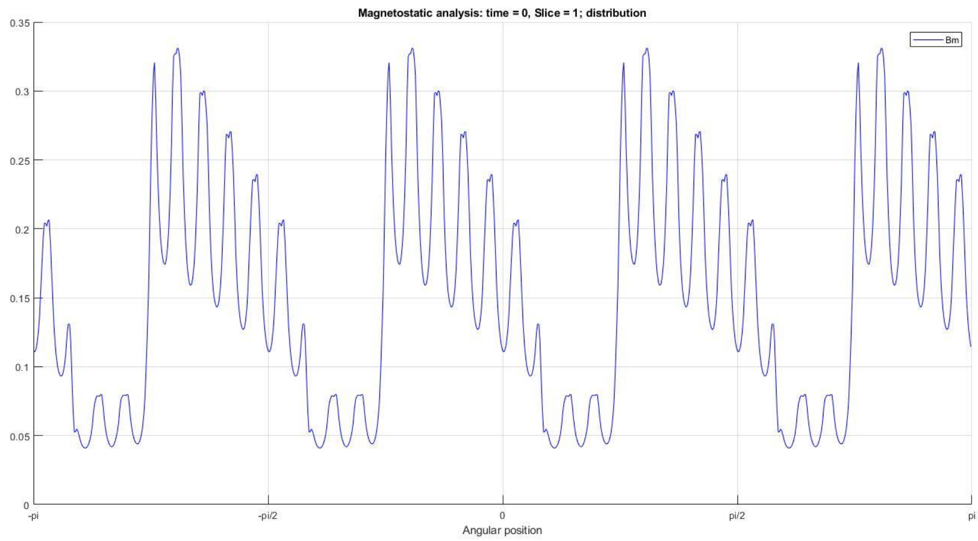


Fig. 17: Optimized ferrite magnet (thickness is 2.5mm) machine design



(a)



(b)

Fig. 18: Outer diameter fixed 160mm Ferrite magnet (thickness 2.5mm) design a) flux density, b) airgap flux graph

FEA result of the optimized design with 5mm thickness Ferrite magnet:

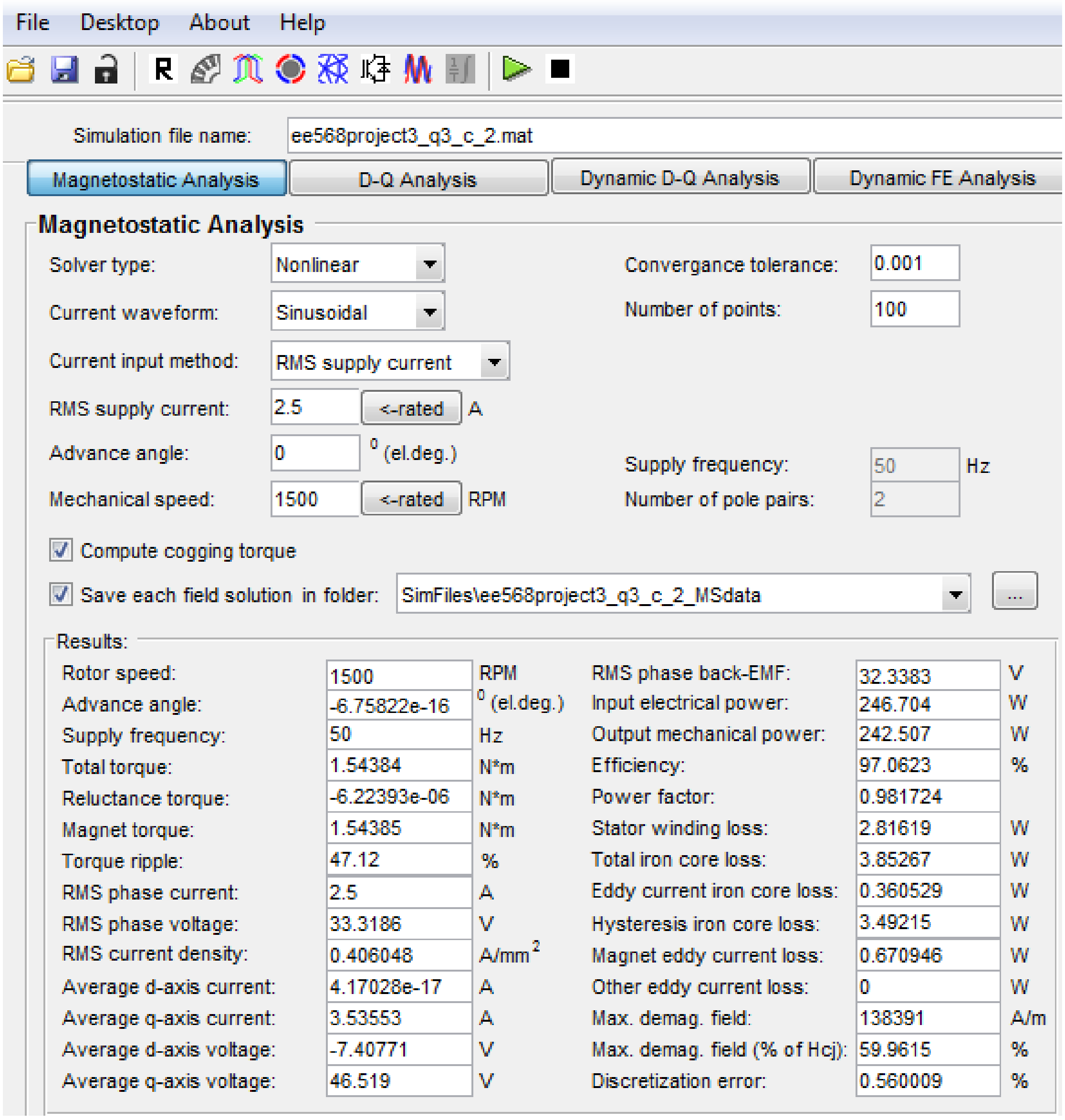
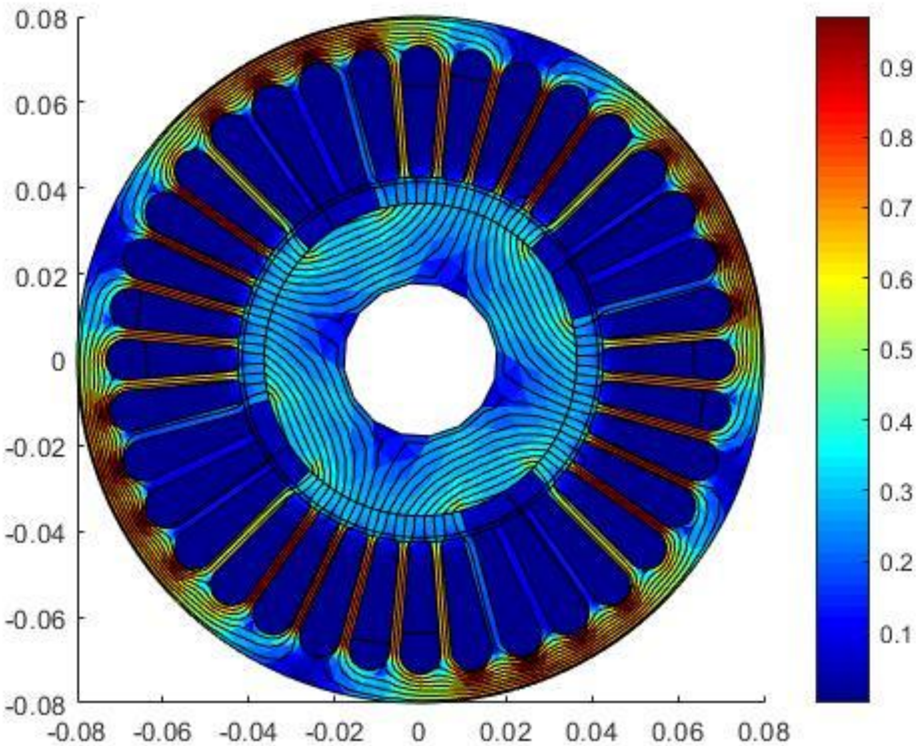
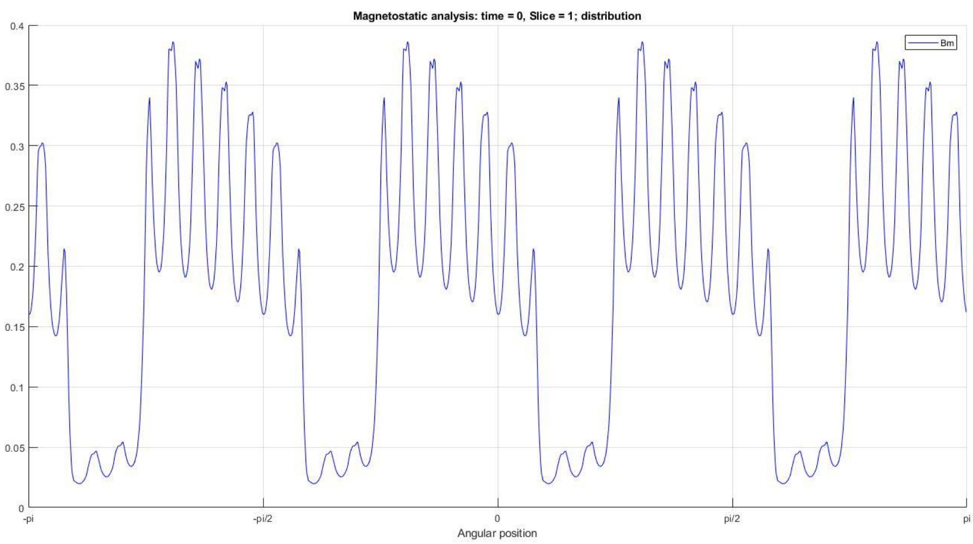


Fig. 19: Optimized ferrite magnet (thickness is 5mm) machine design



(a)



(b)

Fig. 20: Outer diameter fixed 160mm Ferrite magnet (thickness 5mm) design a) flux density, b) airgap flux graph

Conclusion - Comparison

In Q3-part c, we try to optimize the stator back core, tooth width, slot shapes and rotor dimensions without magnet thickness. Because, increasing the magnet thickness by double (cost of magnet also double), effects the magnetic flux density as nearly 18%. For a mass production this optimization depends on the cost of ferrite magnet. In second section the increased magnet thickness effect on the performance is shown.

The output power is improved from 60W to 242W. The total torque is improved from 0.38Nm to 1.54Nm. (for NdFeB N42 machine design 1.37Nm, 216W). The tooth width is kept 2.4mm in last optimized design to provide the mechanical strength (it can be reduced more up to 1.6T). The magnetic loading of the optimized machine reaches 0.9T. Also the saturation points on the corners of the slots are improved with radial slots. Another important thing is shaft area of the optimized machine is doubled to prevent the leakage flux via rotor steel. The flux distrubitions and performance results of FEA analysis are done with motoranalysis-PM program.

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