Electric Machine and Design Analysis (ENM056)

Design Assignment:

Design of a Permanent Magnet Synchronous Motor

for Automotive Application

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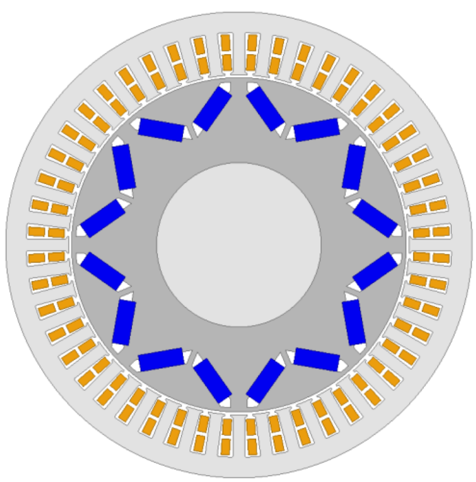
Assignment Description: In this assignment, a reference machine geometry of a permanent magnet machine is provided to the students. Using the reference geometry, the students are then provided with certain guidelines to perform analysis and select parameters to complete the design. The assignment involves four main tasks: 1) magnetic circuit design, 2) stator winding design and 3) resistance and inductance calculation and 4) load calculation. *In order to pass the assignment, the students must answer all the questions in the four tasks and submit a technical report with all relevant figures and answers to the questions. In the technical report detailed calculation steps need not be included.*

Grading: The completion of this assignment is mandatory for passing the course as mentioned in the course PM. The maximum point that can be scored is 20. The criteria for different points are as indicated in the course PM

Introduction: A PM motor is the most common choice for electric propulsion system due to high efficiency and high power and torque density. Some of the popular EVs using a PM motors are Fiat 500e, Chevrolet Spark EV, Volkswagen e-Golf, Ford Focus EV and Chevrolet Bolt. A PM motor as the name suggests uses rare earth permanent magnets in the rotor to produce the rotor flux. The rotor and stator core use laminated steel to reduce circulation of eddy currents. Depending on the arrangement of magnets on the rotor, various rotor designs are possible. Two of the main type of rotor designs are surface and insert mounted. In the surface mounted rotor design, the magnets are glued to the surface which makes it mechanical inferior compared to insert mounted for high speed application like electric vehicles. A variation of insert mounted PMSM that is most commonly used in electric vehicle application uses a V-shape magnet geometry as shown in Figure 1.



V-shape insert mounted

Figure 1: V-shape insert mounted permanent magnet synchronous machine cross-section.

Aim: The aim is for students to use the knowledge learnt in the course to design their own motors (PMSMs for electric vehicles) under given specifications.

Reference Machine: The reference machine is an insert mounted PM with V-shape magnets. The main parameters are presented below along with the description.

Table 1: Given parameters of the reference PMSM

Parameters	**Variable**	**Value**
Outer diameter of stator	OD_{stator}	176 [mm]
Inner diameter of stator	ID_{stator}	124 [mm]
Outer diameter of rotor	OD_{rotor}	122 [mm]
Shaft diameter	ID_{rotor}	60 [mm]
Stack length	L_{stack}	100 [mm]
Slot opening height	Hs0	0.5 [mm]
Slot wedge height	Hs1	0.5 [mm]
Slot body height	Hs2	14 [mm]
Tooth width (parallel tooth)	w_{tooth}	4.4 [mm]
Slot body bottom fillet radius	Rs	0.5 [mm]
Slot Opening	Bs0	2 [mm]
Number of poles	N_{pole}	8
Number of slots	N_{slot}	48
Number of parallel branch		4
Winding layer		2
Coil pitch		5
Wire diameter	D_{wire}	0.75 [mm]
Maximum fill factor of pure Cu	f_{cu}	45%
DC link voltage	V_{DC}	400 [V]

The stack length represents the lamination stack length. The inner diameter of stator is measured from the center of the machine cross-section to the tip of the tooth. The air-gap length can be calculated as

$$l_{gap} = \frac{ID_{stator} - OD_{rotor}}{2}$$

The core material is SURA M250-35A and the B-H curve is provided in Appendix 1

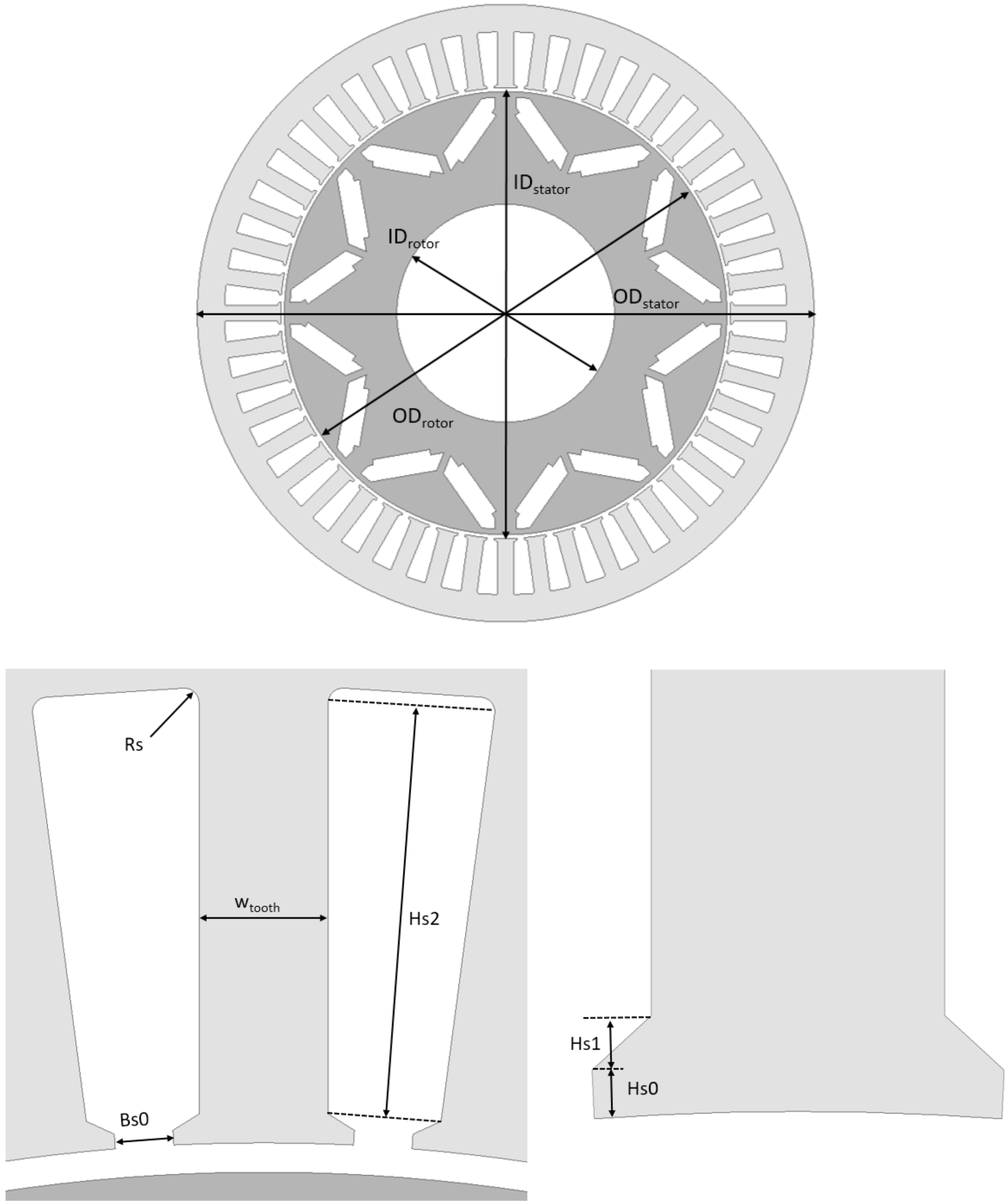


Figure 2: Cross section of a machine indicating the description of geometric parameters

Part 1: Magnetic circuit design

The first part of the assignment deals with the design of magnetic circuit. The magnet material is already selected to be Neodymium Iron Boron (NdFeB). The demagnetization characteristic is presented in Appendix 1 along with the B-H curve of core material. It can be assumed that the demagnetization characteristic is **linear** without any knee point. Also, there is no leakage flux in the magnetic circuit i.e. all the flux produce by the permanent magnets crosses the air-gap and links the stator. The following task should be completed in this part.

1. Why do we analyze only $1/8^{th}$ fraction of the machine?
2. Why do we start by assuming flux density in the air-gap? Why not in other parts of the machine?
3. Write down the equation for calculating MMF drop using Ampere's law.
4. Plot the load line which is flux in the air-gap as a function of total MMF drop in the magnetic circuit. What does the slope of the load line represent?
5. Why is the load line linear for low value of flux? Hint: Compare the MMF drop in the core material and air-gap.
6. Study the demagnetization characteristic of the magnet. Write down the value of open circuit MMF and short circuit flux produced by the magnet.
7. Choose magnet thickness and width to obtain a no-load flux density of 0.7 – 0.9T in the air-gap. Use values which are practical e.g. a magnet thickness is 1 mm could be very difficult to manufacture in reality. Also, too wide magnet may not fit the given rotor geometry.
8. Calculate flux density in the stator tooth and yoke for the selected magnet size.
9. Plot the B-H curve of the core material and indicate the stator tooth and yoke flux density at no-load. Make comments.
10. What happens when you increase the magnet thickness by10%? Explain the impact on the no-load operating point of the magnet. Do similar analysis by changing the magnet width.

Part 2: Stator winding design

In order to generate torque, a current is needed that interacts with the flux generated by rotor. This current flows in the coils present in stator slots which also supplies the active power to produce the torque. It is given that the winding has 2 layers with short pitched coils having coil pitch of 5. The following task should be completed in this part.

1. Calculate the number of coils per phase under each pole pair.
2. Are the coils under each pole pair connected in series or parallel?
3. Calculate slot angle in electrical and mechanical degrees.
4. If the induced voltage of each coil is E, calculate the induced voltage per phase under one pole pair.
5. How is base speed defined?
6. Calculate tooth and slot area.
7. Calculate the total turns per phase in the stator winding such that the base speed is 4000 rpm. Also, calculate the number of turns per coil and conductors per slot.
8. Calculate the uncontrolled induced voltage at maximum speed of 12000 rpm at no-load.
9. Calculated the ratio of line-line induced voltage at 12000 rpm and DC link voltage.

10. Roughly sketch the torque-speed boundary of the machine if the ratio calculated in (9) is equal to 2 and 3 respectively. You should indicate, the maximum speed, base speed and maximum torque in the torque-speed boundary.
11. Explain how you can actually change the ratio calculated in (9) and its impact on machine's performance.
12. Calculate Cu area per slot.
13. Calculate Cu-fill factor. Compare it to the maximum Cu-fill factor and make comments.
14. Make necessary changes such that the Cu-fill factor is close to 45%.

Part 3: Resistance and Inductance calculation

After, the stator winding design is completed, the next step is to calculated the winding inductance and resistance. Therefore, the main tasks are

1. Calculate the per phase resistance of stator winding. Assume end-winding length is 80% of stack length. What determines the end-winding length?
2. Calculate the magnetic permeability of the magnet. How does it compare to air?
3. To calculate reluctance of d- and q-axis flux path.
4. To calculate d- and q-axis inductance at no load.
5. To calculate saliency factor. How does saliency influence torque production? How can you increase saliency?

Part 4: Load calculation

Assuming a current amplitude of 100A and current angle of 90^0. Assume that the rotor speed is 3000 rpm. Hysteresis's co-efficient, K_h = 156.201 and eddy current co-efficient, K_c = 0.0204184.

1. Calculate d- and q-axis currents.
2. Calculate d- and q-axis flux linkages at load condition
3. Calculate d-and q-axis inductances at load condition.
4. Calculate electromagnetic torque and magnitude of terminal voltage.
5. Calculate electrical frequency and magnetic flux density in different parts of the machine.
6. Calculate Cu and iron losses.
7. Calculate input power and shaft power.
8. Calculate efficiency and power factor.
9. Sweep the current angle by step of 10^0 until 180^0 and plot magnitude of terminal voltage and electromagnetic torque against current angle.

Appendix 1

B-H curve data for core material: SURA M235-35A

H_{iron} $[A/m]$	B_{iron} $[T]$
26.8	0.1
35.7	0.2
41.8	0.3
47.5	0.4
53.4	0.5
60	0.6
67.9	0.7
77.5	0.8
90	0.9
107	1
133	1.1
179	1.2
284	1.3
642	1.4
1810	1.5
4030	1.6
7290	1.7
11700	1.8
24000	1.888
48000	1.978
100000	2.083
200000	2.209
400000	2.46

B-H curve data for permanent magnet material: NdFeB

H_{mag} $[A/m]$	B_{mag} $[T]$
-902285	0
-451142	0.5912
0	1.1824

Appendix 2

In the following table, some reference values for the design assignment are presented. Students should note that this does not represent the best design. Therefore, the aim should not be to achieve exactly these values as they are approximations. Students, can compare their results to reference value to verify if they might have made a mistake in their calculations. Some of the design assignment results will change based on the selection of parameters. Hence, only those values are presented which should be in the same order of magnitude irrespective of design selection. Each value is presented with a typical variation range. Again, this does not mean that variations outside the given range is wrong provided, students can motivate their method of calculations.

Parameter	Value	Variation
Cross section of flux path in air gap	2400 [mm^2]	±5%
Cross section of flux path in stator tooth	1100 [mm^2]	±5%
Cross section of flux path in stator yoke	1050 [mm^2]	±5%
Cross section of flux path in rotor yoke	2000 [mm^2]	±5%
Length of flux path in rotor	40 [mm]	±10%
Length of flux path in stator yoke	50 [mm]	±10%
Length of flux path in stator tooth	15 [mm]	±10%
MMF drop in rotor yoke	3 [A-turn]	±20%
MMF drop in stator tooth	40 [A-turn]	±20%
MMF drop in stator yoke	250 [A-turn]	±20%
MMF drop in air gap	550 [A-turn]	±10%
No load flux in the air gap	1.8 [mWb]	±10%
Total number of turns per phase	80	±10%
Slot area	70 [mm^2]	±5%
Tooth area	65 [mm^2]	±5%
Phase resistance	160 [mΩ]	±10%
Reluctance of d-axis flux path	4×10^6	±10%
Reluctance of q-axis flux path	10^6	±10%
Saliency ratio (L_q/L_d)	4	±20%