# Introduction

In this project, an electric machine for heavy duty electric vehicles is designed. The purpose of the designed machine is to use directly with heavy duty platforms without using any gear mechanism. The intended usage of the machine can be exemplified as 10-12 meter public buses, delivery trucks, work trucks like garbage trucks, shuttles etc. In order to meet the specifications of the heavy duty vehicles, 250 kW machine with 1500 rpm nominal speed and 3000 rpm maximum speed is going to be designed.

As the usage of the machine will be heavy duty vehicles, while deciding type of the machine, efficiency should be an important factor. Because power consumption of the heavy duty vehicles are very high and losses should be minimalized. On the other hand, cost of the machine is an important factor but heavy duty machines are expensive itself, so cost of the machine can be handled by vehicle producers. Therefore Permanent Magnet Synchronous Machines can be used for these applications.

Although volumes of the electric machines are very critical in passenger vehicle applications, it can be considered that more volume can be reserved for electric machine in heavy duty vehicles by the help of nature of the vehicle. On the other hand, manufacturing of the machine can be ease by topology selection. Therefore Surface Mount PMSM is selected as topology of the machine.

# Analytical Calculation & Sizing

Some important design criteria for the machine can be stated as follows;

* 250 kW output power at 1500 rpm
* Surface Mount PMSM topology
* Liquid cooling
* Inverter driven with 650V nominal DC-link voltage
* 750-550V DC-link range (1200V Power semiconductors used in inverter)
* Specific Machine Constant

Suggested electrical loading of liquid cooling PMSMs is 150-200 kA/m therefore, 175 kA/m is selected as electrical loading of the machine. On the other hand, magnetic loading of the machines can be obtained from average airgap flux density over a pole which is between 0.8-1.05 T in PMSM, so 1 T of magnetic loading is selected for the design. Also, winding factor of the fundamental component can be considered as 0.95 for initial design. Based on these numbers, specific machine constant can be calculated as follows;

* Rough Dimensions

Air gap of the machine can be defined according to following formula.

For heavy duty machines result of the formula can be increased up to 60%. Therefore, 1.045 mm can be raise up to 1.67 mm. It seems that air gap clearance of the machine can be selected as 1.5 mm for initial design of the machine.

As machine will be driven with inverter and maximum speed is about 3000rpm, by taken switching frequency as 12kHz and electrical frequency should be consider with at least 20 times of switching frequency, maximum electrical frequency can be considered as 600 Hz coincide with 3000 rpm. Therefore pole number of the machine can be chosen as;

Pole number of the machine is chosen as 24, polepair is 12.

Aspect ratio of the machine can be calculated as;

Aspect ratio is found as 0.23. Considering large synchronous machines like used in hydroelectric plants, it is logical to use the formula and applications show that aspect ratios are very small for these types of the machines. But for electric vehicle applications, reserved area for the machine may be considered as cubical. Therefore, overall length and outer diameter of the machine can be designed as close to each other. Therefore aspect ratio of 0.75 will be taken for calcuations.

Outer diameter of the rotor can be calculated as;

Axial length of the machine is 0.75 times of the outer diameter of the rotor and it is 0.239 m.

* Winding Configurations

In order to make winding configuration simple, slot per pole per phase will be taken as 1, and pole numbers was chosen as 24. Therefore number of slots is chosen as 72.

Determination of the number of coils, cable size etc, directly dependent of one phase current of the machine because one of the coil current should be determined. By assuming space vector modulation on the inverter side, maximum phase to phase voltage of the motor terminals at nominal 650Vdc can be obtained from following equation;

Maximum phase current which will be given to the machine can be obtained as follows;

Note that this current is too much for currents for one coil. In order to decrease the coil current, one coil can be made up with many strands which has no impact on turns number but it will help to choose reasonable and applicable cable size. On the other hand, current density of 10 A/mm2 can be taken as machine has liquid cooling infrastructure. Strands number can be selected as 15 in order to decrease area of the cable.

Based on the resultant wire area, AWG14 cable is chosen. Turns number will be calculated after obtaining slot dimensions.

* Other dimensions

Inner diameter of the stator can be calculated from outer diameter of the rotor, magnet thickness and air gap clearance. Magnet thickness is going to be taken as 4 mm whereas other dimensions were determined before.

Stator circumference can be calculated as;

For 72 slot configuration, stator slot length for one slot and one teeth can be calculated as;

Total slot and teeth length at the inner stator circumference is reasonable, therefore 72 slot configuration is feasible.

Assuming rectangular teeth shape, some dimension can be obtained. Outer stator slot diameter can be calculated as;

Height of the slot can be obtained as follows;

As rectangular teeth are chosen, slot dimension can be obtained at initial and final position;

Slot area can be obtained using height of the slot, initial and final thickness as follows;

Number of turns in a coil can be obtained by taking fill factor 0.55 as;

As pole number of the machine is high, outer diameter of the machine can be calculated as 1.3 times of inner diameter of the stator. Therefore, outer diameter is taken as 429 mm. Back core thickness can be obtained from outer diameter as follows;

Electrical loading of the machine was assumed 175 kA/m initially. Based on the obtained data, electrical loading can be calculated as follows;

Note that electrical loading is found a smaller than intended value. This situation is a result of selecting slot height as relatively smaller.

* Material Selection

In order to minimize core losses of the laminations, M250-35A is selected for rotor and stator laminations. This material has loss of 2.35 W/kg. Also relative permeability of the material is 660. [A]

NdFeB magnets are popular in electric vehicle applications. By taking magnet maximum temperature, N42UH grade NdFeB magnets are chosen whose intrinsic and normal curves for different temperatures can be seen in Figure 1.

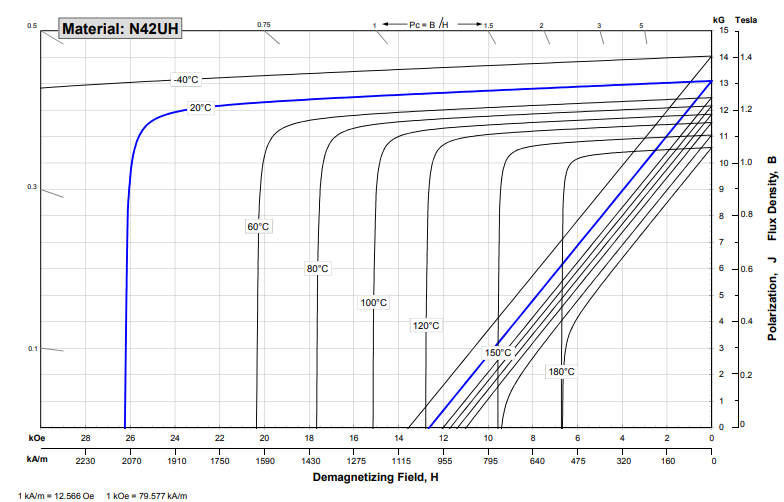


Figure 1: Intrinsic and normal curves of N42UH [B]

# FEA Modelling

Based on the dimensions obtained, machine model is constructed with Maxwell Ansys as seen in Figure 2. Note that machine has 24 pole and 72 slot as a result, machine can be divided into 12 equal segment. In order to reduce simulation time, model is reduced for one pole pair which has 2 magnet and 6 slot.

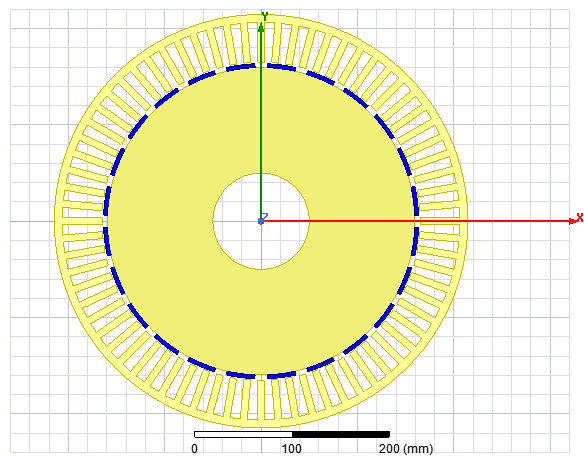


Figure 2: Constructed model

At no load, simulation is analyzed and magnetic field magnitudes can be seen in Figure 3. As seen from this figure, back core is highly saturated and output diameter of the machine should be increased.

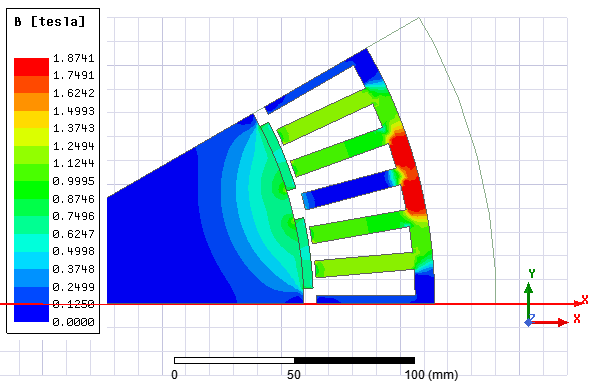


Figure 3: Bmag for initial design

Outer diameter of the machine is increased to 445 mm from 429 mm in order to make prevent saturation of the back core. Resultant B\_mag distribution can be seen in Figure 4. As seen from this figure, back core saturation problem is solved.

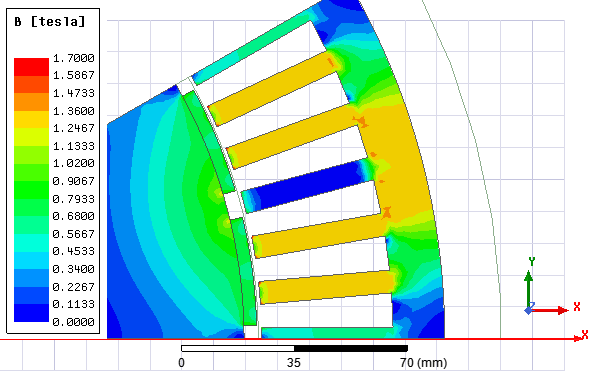


Figure 4: Bmag after output diameter increased

Air gap flux density over a pole is found as seen in Figure 5. Ideally, flux density should be same over a magnet but as seen from the graph, it has considerable decrease in magnitudes for both magnets. These decreases are originated from stator slot structure.

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Figure 5: Air gap flux density

In order to eliminate these defects on the air gap flux density, stator structure opening are closed by arranging slot parameters as seen in Figure 6. Note that while construction of the machine these openings should be open but for simplicity, they can be used as Figure 6 in the simulations.

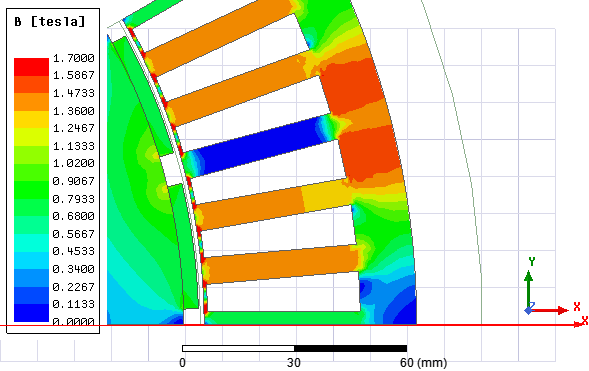


Figure 6:Bmag after closed slot openings

Air gap flux density over a pole after rearrangement of the stator slots can be seen in Figure 7. As seen from graph, defects on the waveform are significantly shrinked.

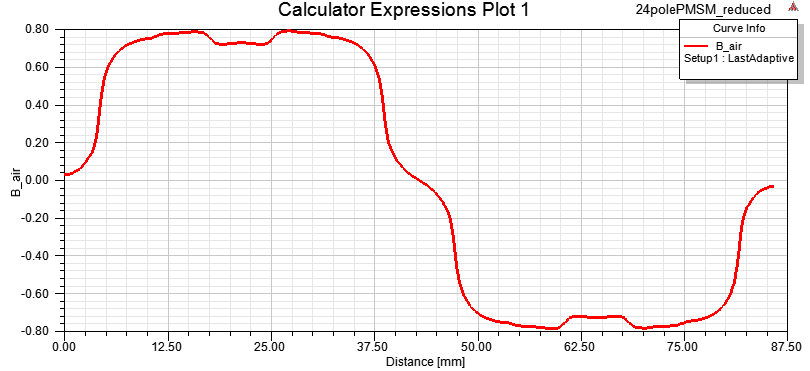


Figure 7: Air gap flux density with closed stator openings

# References

[A] <https://cogent-power.com/cms-data/downloads/m250-35a.pdf>

[B] <https://www.arnoldmagnetics.com/wp-content/uploads/2017/11/N42UH-151021.pdf>