EE568 - Selected Topics on Electrical Machines

Project - 4

Double Stator, Single Rotor Axial Flux Machine Design

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1. Introduction

In terms of flux direction, there are two main types of electrical machines. Those are radial and axial flux machines. In a radial flux machine, flux moves radially. That means flux vector goes from inside of the motor to the outside in radial direction. However, in axial flux motors, flux direction is different. Axial flux machines are constructed like discs and flux goes from one disc to the other in axial direction. Axial and radial flux machines are shown in figure 1.

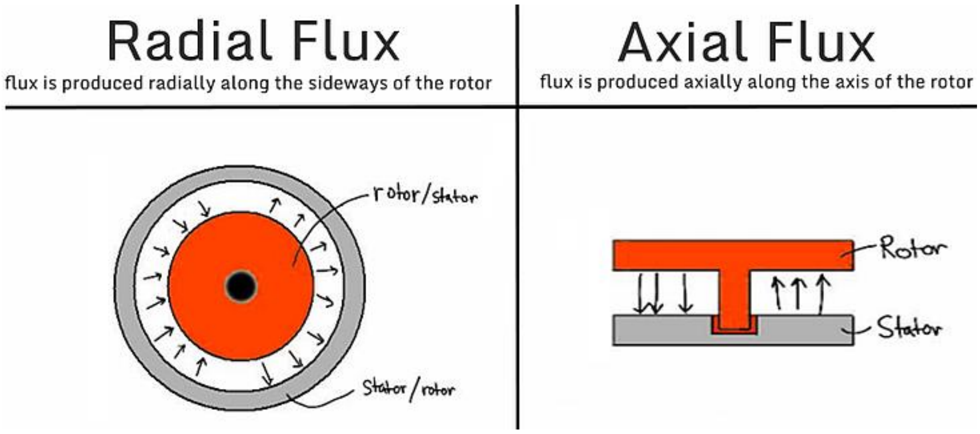

Figure 1 Radial and Axial Flux Machines

Both motor types have advantages and disadvantages. For example, it is easier to increase the torque by larger diameter in axial flux motor. Additionally, axial flux motor airgap area is large. Both these properties increase the torque density of these machines. However generally it is more difficult to manufacture an axial flux machine.

In this study, a direct drive, high torque axial flux machine will be designed. Machine topology is double stator and single rotor. Double stator single rotor topology is shown in figure 2.

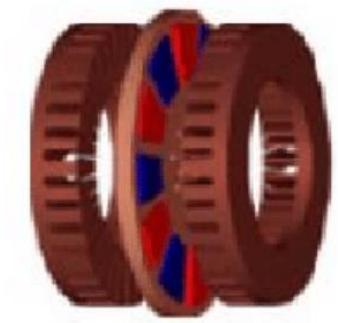

Figure 2 Double stator single rotor

2. Requirements

Motor will be designed for a high torque direct drive application.

Rated Speed: 600 rpm

Rated Torque: 250 Nm

Rated Power: 22 kW

Max outer diameter: 400mm

Supply: Inverter fed from 400 V three phase grid

3. Analytical Calculations

Firstly, motor dimensions should be calculated analytically. Analytical calculations provide a starting point for FEA and optimization steps.

3.1. Supply and Drive

Motor driver will be supplied from 400V grid. However, it can’t be used directly since variable frequency drive will be used. In order to use a vfd, supply should be rectified at first. There are two options. Firstly, diode rectifier can be used. Six diodes with large bus capacitors would do the job. Secondly, an active rectifier can be utilized.

When diode rectifier is used, initial cost is lower. However, diode rectifiers need a large bus capacitor in order to reduce voltage ripple. Additionally, current ripple high and this effects the other grid connected devices nearby. Moreover, since power factor is not controlled, more current is drawn for the same power. Lastly, when a diode rectifier is used, energy can only flow from grid to the DC side, can’t flow back.

When an active rectifier is used, initial cost is higher since there are additional switching devices and controllers. However active rectifier provides in smaller bus capacitor, bidirectional energy flow, reduced grid current and less harmonic disturbance on the grid.

Because of those reasons active rectifier will be used. The simplest method is to use a three phase rectifier with additional LCL filters on the phase connections. This topology results in boost type pfc. In a boost type pfc, output voltage is larger than the input voltage. Also output voltage can be regulated by controlling the transistors. Topology is represented in figure 3.

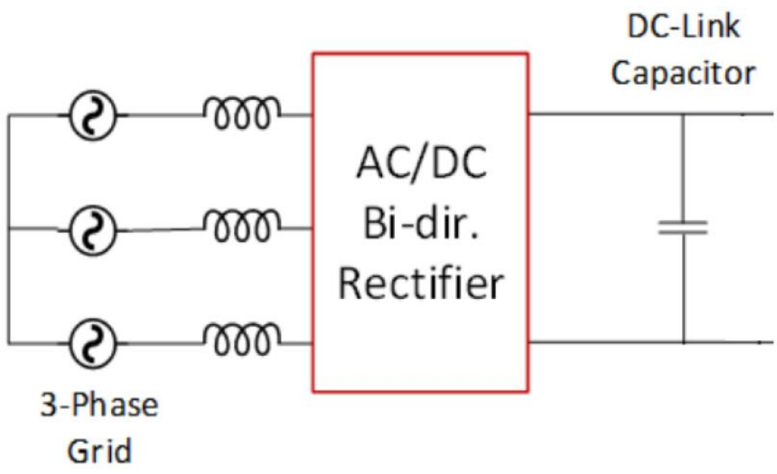

Figure 3 PFC

Now motor voltage can be determined. Input voltage is 400Vrms. Since this voltage is not always constant, limit situations should be considered. Assuming 400V+-15%, max voltage is 460V rms.

$$rectified\ voltage = 460 * \sqrt{2} = 650V$$

Since rectifier is a boost type pfc, minimum regulated output voltage should be 650V for constant DC bus voltage.

SVPWM will be used on the inverter side.

$$V_{motor_{linetoline}} = V_{bus} * 0.612\ for\ SVPWM$$

$$V_{ll} = 650 * 0.612 = 398V_{rms}$$

$$motor\ line\ to\ line\ voltage\ should\ be\ 400V_{rms}$$

3.2. Motor Current and Wire

Since motor power and voltage is known, phase current can be found.

$$P = V_{ll} * I * \sqrt{3}$$

$$22kW = 400 * I * \sqrt{3}$$

$$I = 32\ A_{rms}$$

Taking j = 6 A/mm^2

$$I = J * Area$$

$$32 = 6 * Area$$

$$Area = 5.3\,mm^2$$

Using a 5.3 mm^2 wire would result in 2.6 mm diameter wire. It is impractical to wind thick cables since bending becomes more and more difficult. Because of that two wires in parallel can be used.

Chosen wire: 2x 1.8 mm diameter copper wire in parallel

3.3. Pole-Slot Number, Dimensions

Since outer diameter is limited by 400mm, this can be used as starting point. Taking end winding and mechanical case into account, outer diameter can be 300mm. Design will continue with this assumption. According to [1] analytical optimum value of Do/Di = 0.6-0.7. Using this value, inner diameter should be 200mm.

Do = 300mm

Di = 200mm

Since this is a low speed torque motor, number of poles should be high. Higher pole number increases the operating frequency and decreases the machine size. However, number of poles can't be increased infinitely. When pole number is increased, magnets get smaller. Above some point manufacturing becomes impractical. Additionally, leakage between the poles increase. In order to find a suitable number, smallest dimension on the magnet can be used.

$$l_{inner} = D_{inner} * \pi$$

$$l_{magnet} = \frac{l_{inner}}{pole} * magnet\_embrace$$

If 28 poles used,

$$l_{magnet} = \frac{200mm * \pi}{28} * embrace = 20.2mm * embrace$$

So 28 pole rotor is suitable for manufacturing.

Same satiation is valid for number of slots. If there are too many slots, they become smaller and manufacturing will be more difficult. Additionally, slot number effects the winding factor. Lower winding factor results in larger motor size. In this application, cogging torque needs to be considered. Since this motor will be used in a direct drive machine, cogging torque and torque ripple is important. Some pole slot combinations provide lower cogging torque whereas others produce higher.

Taking all these in consideration, 27 slots can be used. 27 slot 28 pole machine has a winding factor of 0.95 which is a good value. Also 27/28 combination has least common multiplier of 756. That means motor will produce 756 cogging steps per turn. This high value results in smaller steps (less cogging torque).

Pole: 28

Slot: 27

Winding scheme is shown in figure 4.

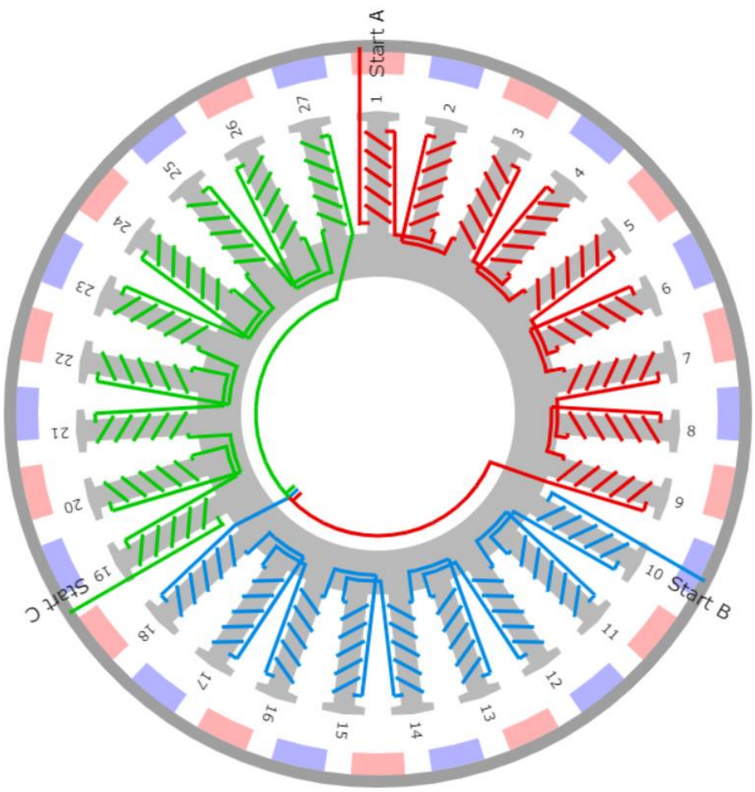

Figure 4 Winding scheme for 27/28 machine

3.4. Induced Voltage and Number of Turns

Number of turns should be calculated.

$$V_{phase} = \phi_{pole} * 4.44 * f * k_w * N_{phase}$$

$$\phi_{pole} = (\pi * \left(D_o^2 - D_i^2\right)B * 2)/pole$$

$$N_{phase} = \frac{slot * 2}{3} * N_{teeth}$$

$$taking\ B = 0.5T\ and\ V_{phase} = \frac{400}{\sqrt{3}}$$

$$231 = 1.402 * 10^{-3}Wb * 4.44 * 140Hz * 0.95 * 18 * N_{teeth}$$

$$N_{teeth} = 15.5\ turns$$

$$so\ 15\ turns\ will\ be\ used\ per\ teeth\ (\frac{30}{slot})$$

N = 15 turns

3.5. Fill Factor

Calculated wire and number of turns must fit in the slot. Wire diameter is 1.9mm and 2 wires in parallel. There are 15 turns around each tooth. That means there will be 60 wires in each slot. Wire placement is shown in figure 5.

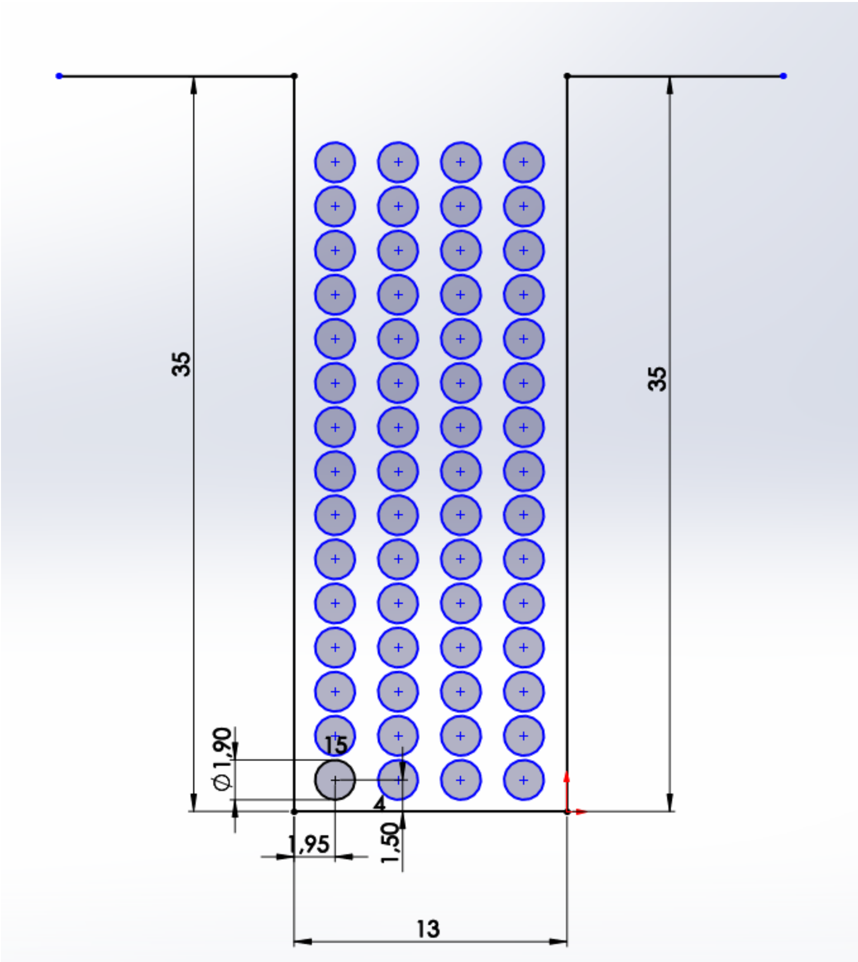

Figure 5 Wire placement

4. FEA Modelling

Machine is simulated with Ansys Maxwell. Machine model is shown in figure 6. In order to reduce simulation time, half symmetry is used. Model is split by ZX axis.

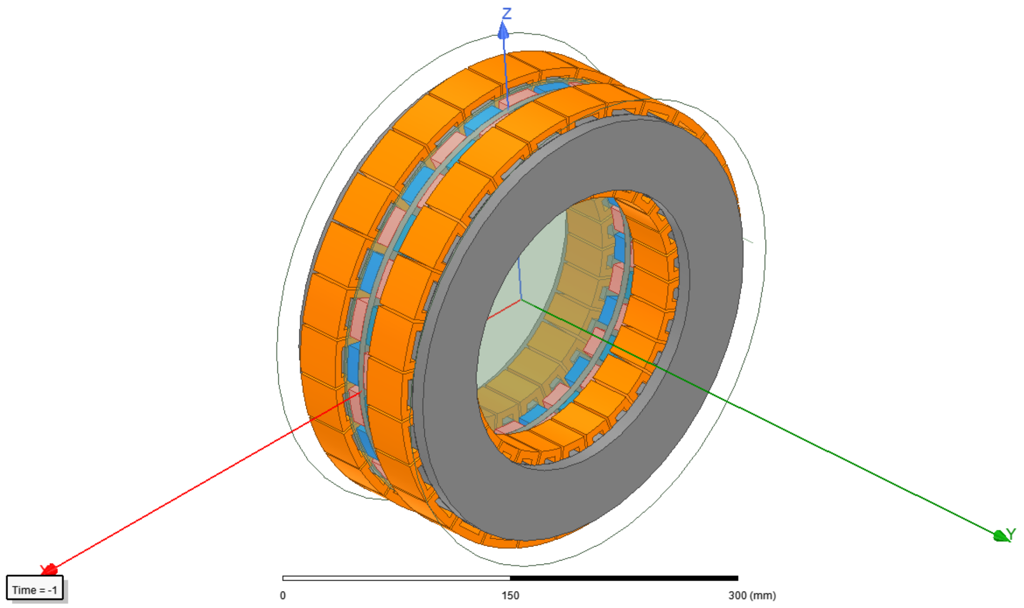

Figure 6 Full machine model

Magnet grade: N35

Magnet thickness: 5mm

Airgap: 1mm (should be higher for mechanical considerations)

Slot width 13mm

Slot height: 35mm

Stator yoke thickness 10mm

Only coils and magnets are selected in figures 7 and 8.

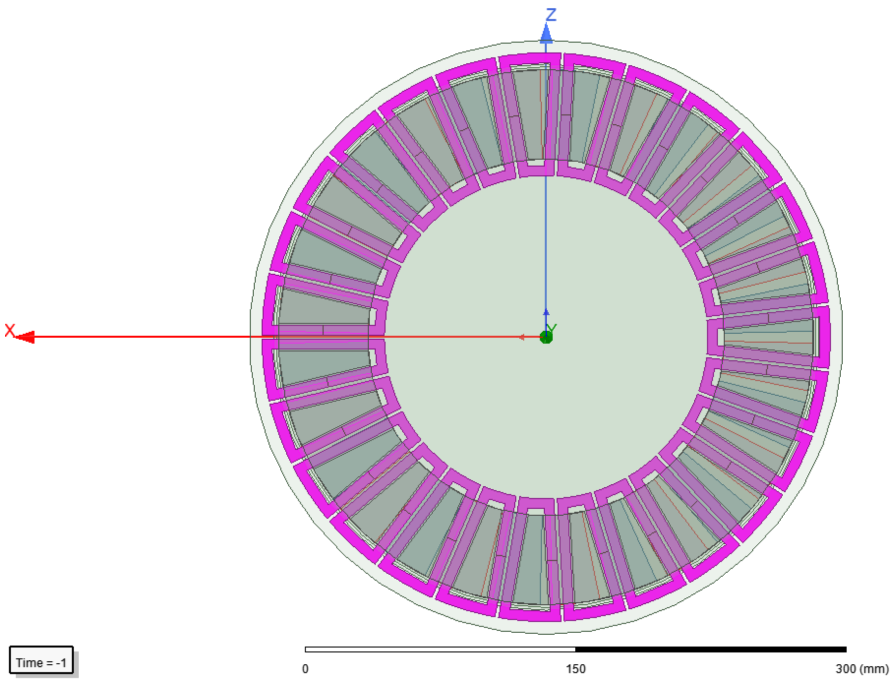

Figure 7 Coils are selected

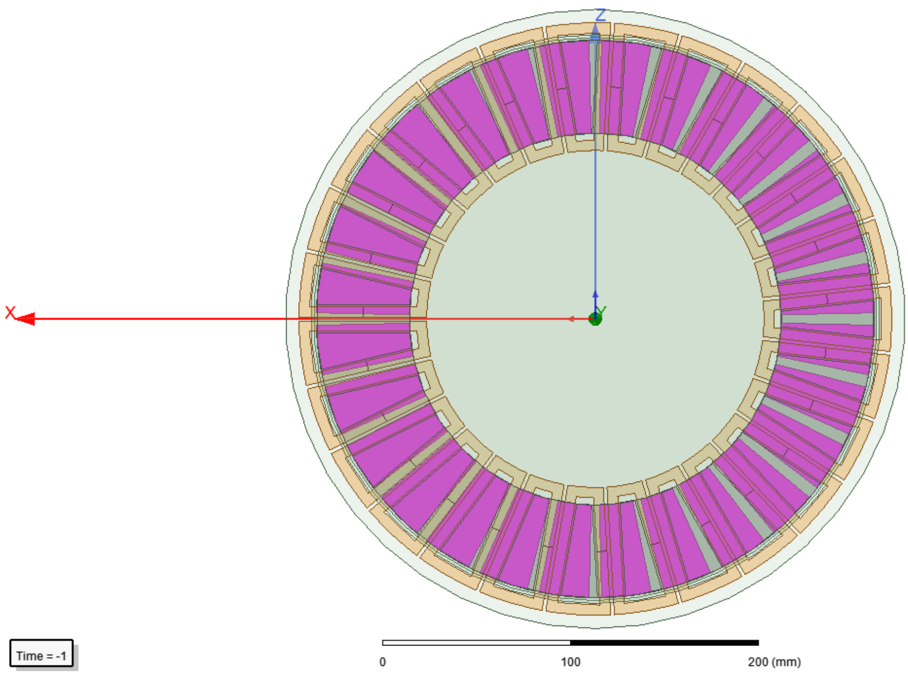

Figure 8 Magnets are selected

Flux density distribution in the tooth is shown in figure 9. Flux density is lower than expected value.

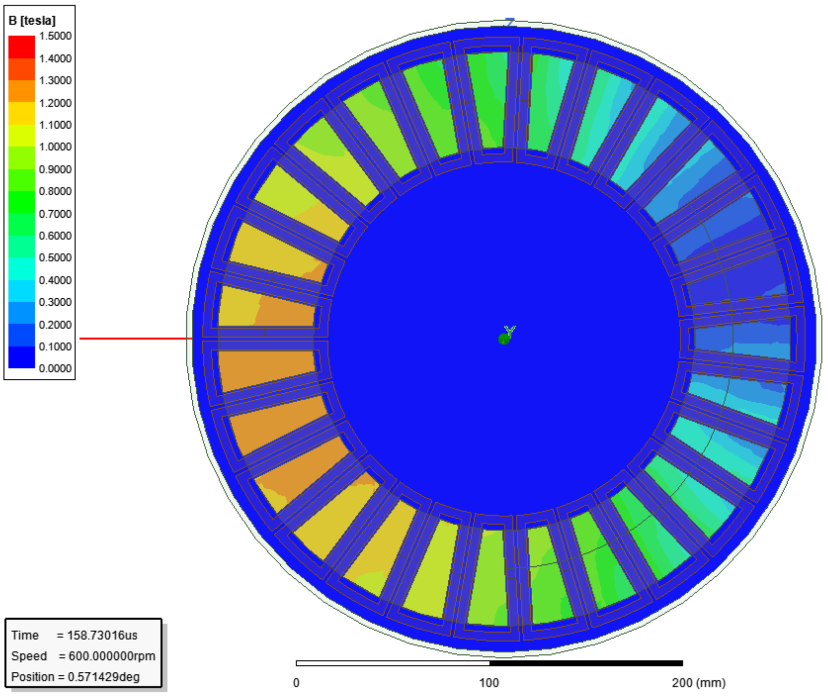

Figure 9 Flux density distribution

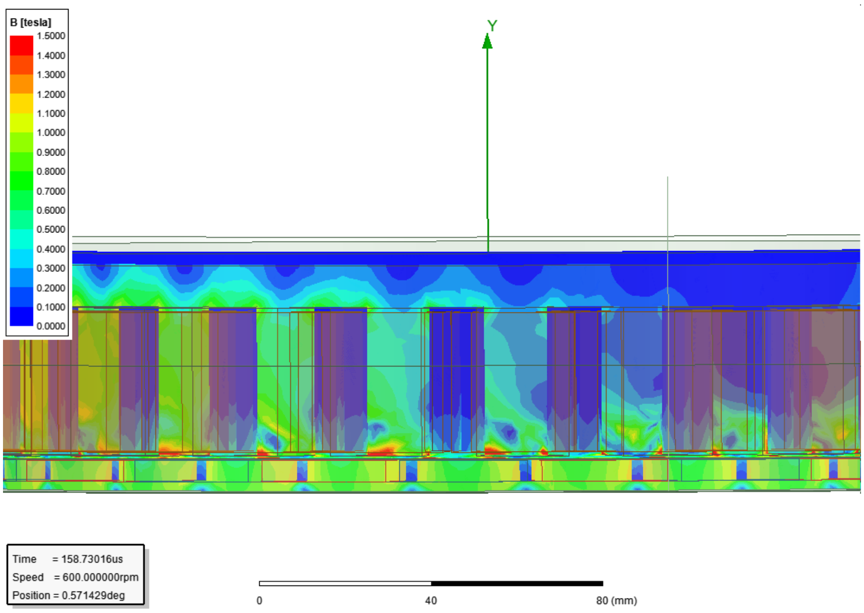

Figure 10 Flux density from radial direction

Induced voltage graph is shown in figure 11. This graph is calculated for single stator. So, actual voltage will be double of this waveform. Smaller waveforms are phase and larger one is line to line voltage. According to the results, line to line peak voltage is around 400V, according to the analytical calculations, it was 400 VRms. This is lower than expected.

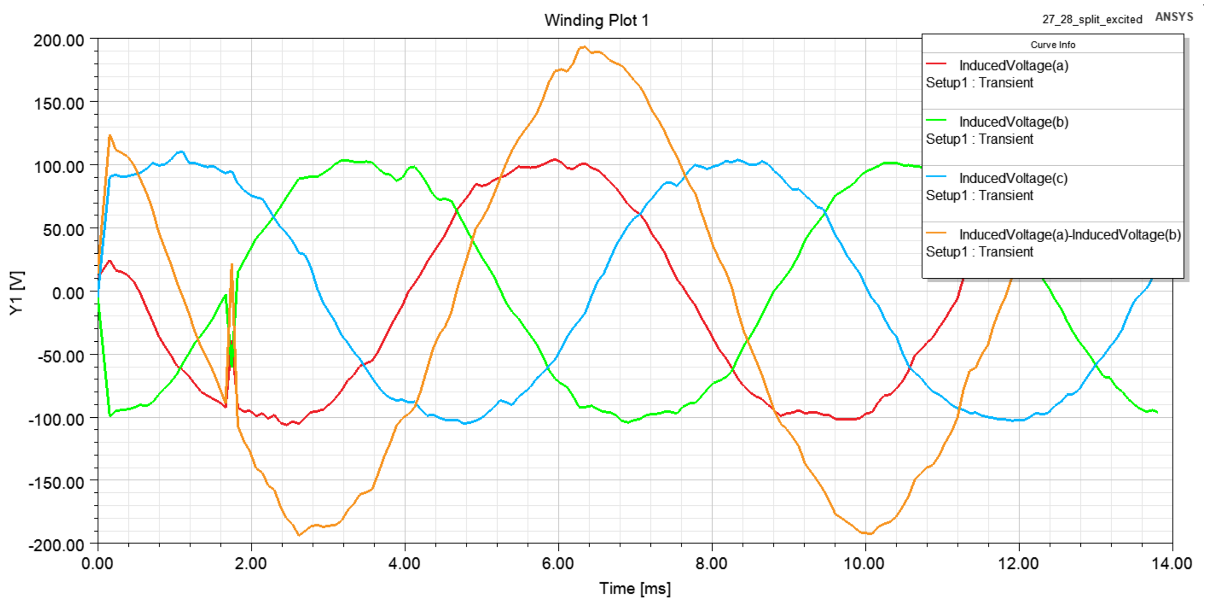

Figure 11 Phase and line to line voltage

5. Comparison and Discussion

- It can be seen that flux density is not distributed homogeneously in the teeth. Flux density is higher on the inside and lower on the outside. Additionally, machine will be built by wrapping the silicon iron. That will cause much lower permeability in radial direction. As a result, inner radius side may saturate while outer radius flux density is lower. Further simulations must be done with lower radial permeability according to available stacking factor. Magnets should be shaped such that, flux density distribution is more homogeneous.
- Core loss should be taken into account. Frequency is relatively small but, machine is large enough to create considerable amount of core loss. It can't be ignored. However, much smaller time step and more detailed meshes are necessary for an accurate core loss estimation. With the available computing power, it was impossible to run these simulations. With a better system and longer time, core loss should be calculated. (27/28 machine was a bad choice for machine symmetry).
- When FEA results are compared with analytically calculated induced voltage, there is a large difference. This is caused by the magnetic loading. In the FEA model, magnetic loading is much smaller than the target value. This is caused by open slots. Open slot structure makes the winding easier. However, effective airgap reluctance is also increased because of the large gaps. For this design, smaller slot opening may be preferred. Yes, winding factor will decrease,

but magnetic loading and window area can be increased. Further simulations should be done. For this study, because of long simulation times, other slot types couldn't be compared.

6. Conclusion

In this study, a double stator single rotor axial flux machine is designed. Design process is started with analytical calculations. Firstly, needed induced voltage calculated according to the supply and power rating. Secondly, wire size and number of parallel strands is determined. After that, number of turns is calculated. Then, slot is designed to fit all the coils completing the analytical calculations part. After that, design is simulated with FEA. According to the FEA results, induced voltage seems to be lower than analytical values. Lastly, design is discussed for improvement.

Reference

[1] Parviainen, A., Niemela, M., Pyrhonen, J., & Mantere, J. (2005). Performance comparison between low-speed axial-flux and radial-flux permanent-magnet machines including mechanical constraints. *IEEE International Conference on Electric Machines and Drives, 2005.* doi:10.1109/iemdc.2005.195948