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EE564 – REPORT/PROJECT.3

TRAIN TRACTION MOTOR DESIGN

V1

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1. MAXWELL-RMXPRT ANALYSIS

1.1. INPUTS

MACHINE:

Name	Value	Unit	Eval...	Description
Machine Type	Three Phase Inductio...			
Number of Poles	6			Number of poles of the machine
Stray Loss Fac...	0.01		0.01	Stray Loss Factor
Frictional Loss	150	W	150W	The frictional loss measured at the reference speed
Windage Loss	0	W	0W	The windage loss measured at the reference speed
Reference Sp...	1520	rpm		The reference speed at which the frictional and windage losses are measured

Figure 1: machine inputs

STATOR:

Name	Value	Unit	Evaluated Value	Description
Outer Diameter	845	mm	845mm	Outer diameter of the stator core
Inner Diameter	601	mm	601mm	Inner diameter of the stator core
Length	454	mm	454mm	Length of the stator core
Stacking Factor	0.95			Stacking factor of the stator core
Steel Type	steel_1008			Steel type of the stator core
Number of Slots	72			Number of slots of the stator core
Slot Type	1			Slot type of the stator core
Lamination Se...	0			Number of lamination sectors
Press Board T...	0	mm		Magnetic press board thickness, 0 for non-magnetic press board
Skew Width	0		0	Skew width measured in slot number

Figure 2: stator inputs

Steel_1008 is chosed as a core material. Figure 3 shows B-H curve of Steel_1008.

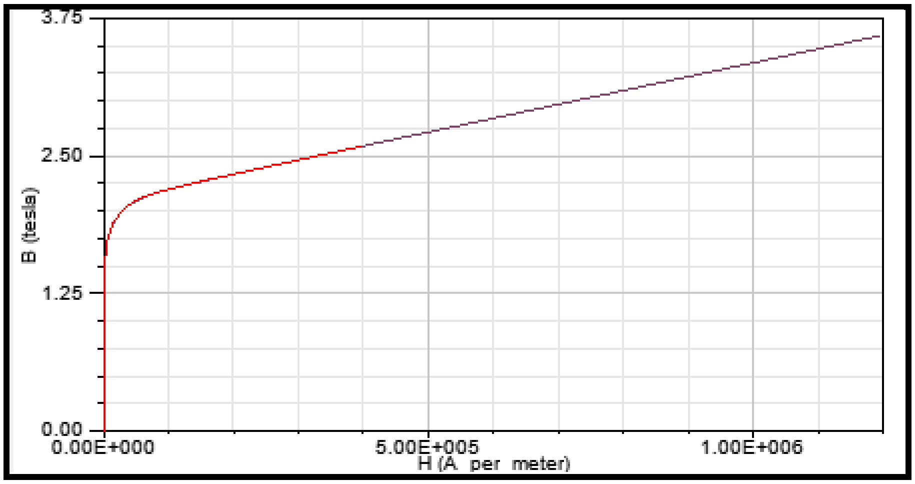

Figure 3: Steel_1008 B-H curve

STATOR SLOTS:

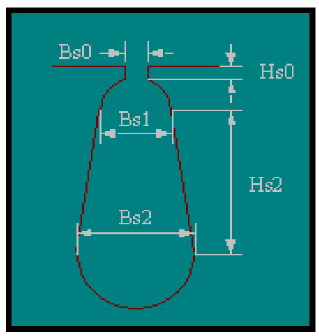

Figure 4: stator slot type:1

Name	Value	Unit	Evaluated Value	Description
Auto Design	☐			Auto design Hs2, Bs1 a...
Parallel Tooth	☑			Design Bs1 and Bs2 ba...
Tooth Width	17	mm	17mm	Tooth width for parallel ...
Hs0	1.5	mm	1.5mm	Slot dimension: Hs0
Hs2	35	mm	35mm	Slot dimension: Hs2
Bs0	3	mm	3mm	Slot dimension: Bs0

Figure 5: stator slots inputs

By chosing parallel tooth option and entering the tooth width value, program assigns the appropriate bs1 and bs2 values.

STATOR WINDINGS:

Name	Value	Unit	Ev...	Description
Winding Layers	2			Number of winding layers
Winding Type	Whole-Coiled			Stator winding type
Parallel Branches	1			Number of parallel branches of stator winding
Conductors per Slot	2		2	Number of conductors per slot, 0 for auto-design
Coil Pitch	10			Coil pitch measured in number of slots
Number of Strands	4		4	Number of strands (number of wires per conductor), 0 for auto-design
Wire Wrap	0	mm		Double-side wire wrap thickness, 0 for auto-pickup in the wire library
Wire Size	Diameter: 5.827mm			Wire size, 0 for auto-design

Figure 6: stator winding inputs

ROTOR:

Name	Value	Unit	Evaluat...	Description
Stacking Factor	0.95			Stacking factor of the rotor core
Number of Slots	84			Number of slots of the rotor core
Slot Type	3			Slot type of the rotor core
Outer Diameter	597	mm	597mm	Outer diameter of the rotor core
Inner Diameter	464	mm	464mm	Inner diameter of the rotor core
Length	454	mm	454mm	Length of the rotor core
Steel Type	steel_1008			Steel type of the rotor core
Skew Width	1		1	Skew width measured in slot number
Cast Rotor	☑			Rotor squirrel-cage winding is cast
Half Slot	☐			Half-shaped slot (un-symmetric)
Double Cage	☐			Double-squirrel-cage winding

Figure 7: rotor inputs

ROTOR SLOTS:

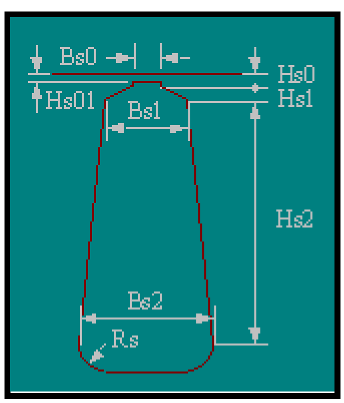

Figure 8: rotor slot type:3

Name	Value	Unit	Evaluated Value	Description
Hs0	1	mm	1mm	Slot dimension: Hs0
Hs01	0	mm	0mm	Slot dimension: Hs01
Hs1	1	mm	1mm	Slot dimension: Hs1
Hs2	17.6	mm	17.6mm	Slot dimension: Hs2
Bs0	2.5	mm	2.5mm	Slot dimension: Bs0
Bs1	11.3	mm	11.3mm	Slot dimension: Bs1
Bs2	12.6	mm	12.6mm	Slot dimension: Bs2
Rs	2	mm	2mm	Slot dimension: Rs

Figure 9: rotor slot inputs

Name	Value	Unit	Evalu...	Description
Bar Conductor Type	aluminum			Select bar conductors Type
End Length	30	mm	30mm	Single-side end extended bar length
End Ring Width	57	mm	57mm	One-side width of end rings (in axial direction)
End Ring Height	18	mm	18mm	Height of end rings (in radian direction)
End Ring Conductor Type	aluminum			Select End ring conductor Type

Figure 10: rotor winding inputs

1.2. OUTPUTS

Given Output Power (kW):	1280
Rated Voltage (V):	1350
Winding Connection:	Wye
Number of Poles:	6
Given Speed (rpm):	1520
Frequency (Hz):	78
Stray Loss (W):	12800
Frictional Loss (W):	150
Windage Loss (W):	0
Operation Mode:	Motor
Type of Load:	Constant Power
Operating Temperature (C):	75

Stator Ohmic Loss	25859.9	W
Rotor Ohmic Loss	6023.7	W
Iron-Core Loss	0.379911	W
Frictional and Windage Loss	153.227	W
Stray Loss	12800	W
Total Loss	44837.2	W
Output Power	1280900	W
Input Power	1325730	W
Efficiency	96.6179	%
Power Factor	0.529739	
Rated Torque	7877.68	NewtonMeter
Rated Speed	1552.7	rpm

Figure 11: rated performance outputs

Stator-Teeth Flux Density	2.07077	tesla
Rotor-Teeth Flux Density	2.37512	tesla
Stator-Yoke Flux Density	1.57484	tesla
Rotor-Yoke Flux Density	2.51527	tesla
Air-Gap Flux Density	0.954975	tesla
Stator-Teeth Ampere Turns	1396.12	A.T
Rotor-Teeth Ampere Turns	2022.74	A.T
Stator-Yoke Ampere Turns	179.722	A.T
Rotor-Yoke Ampere Turns	4414.66	A.T
Air-Gap Ampere Turns	1619.4	A.T
Stator Yoke Correction Factor	0.3195	
Rotor Yoke Correction Factor	0.120801	

Figure 12: rated magnetic data outputs

As shown in Figure 11, magnetic data and power factor are problematic compared with the calculated and assigned values in the project-2. Especially, stator-teeth, rotor-teeth and rotor yoke flux densities seem to be high. Therefore, they need to be decreased. The main idea behind the changes is more the flux area less the flux in corresponding area. Therefore:

- stator tooth width decreased to decrease the stator-teeth flux density.
- Rotor inner diameter is decreased to decrease rotor yoke flux density.
- Rotor slot area is decreased to increse the rotor tooth width.

Some values are changed as folllows:

Stator tooth width:

Tooth Width	17	mm

Rotor inner diameter:

Inner Diameter	415	mm

Hs2, Bs1, Bs2 of the rotor:

Hs2	17.6	mm
Bs0	2	mm
Bs1	6.5	mm
Bs2	7.5	mm

New magnetic data outputs:

	Name	Value	Units
1	Stator-Teeth Flux Density	1.6622	tesla
2	Rotor-Teeth Flux Density	1.66307	tesla
3	Stator-Yoke Flux Density	1.52143	tesla
4	Rotor-Yoke Flux Density	1.63955	tesla
5	Air-Gap Flux Density	1.02368	tesla
6	Stator-Teeth Ampere Turns	179.792	A.T
7	Rotor-Teeth Ampere Turns	83.612	A.T
8	Stator-Yoke Ampere Turns	133.782	A.T
9	Rotor-Yoke Ampere Turns	163.838	A.T
10	Air-Gap Ampere Turns	890.457	A.T
11	Stator Yoke Correction Factor	0.344124	
12	Rotor Yoke Correction Factor	0.326683	

Figure 13: new(corrected) rated magnetic data outputs aftor some changes

New performance data outputs:

Stator Ohmic Loss	8234.52	W
Rotor Ohmic Loss	8040.17	W
Iron-Core Loss	0.414349	W
Frictional and Windage Loss	152.986	W
Stray Loss	12800	W
Total Loss	29228.1	W
Output Power	1279850	W
Input Power	1309080	W
Efficiency	97.7673	%
Power Factor	0.926856	
Rated Torque	7883.63	NewtonMeter
Rated Speed	1550.26	rpm

Figure 14: New(corrected) performance data outputs

Now, problematic values are corrected and close to calculated values

RATED-LOAD OPERATION	
Stator Resistance (ohm):	0.00767243
Stator Resistance at 20C (ohm):	0.00631119
Stator Leakage Reactance (ohm):	0.0904503
Rotor Resistance (ohm):	0.00828364
Rotor Resistance at 20C (ohm):	0.00681396
Rotor Leakage Reactance (ohm):	0.0859588
Resistance Corresponding to Iron-Core Loss (ohm):	4.14257e+006
Magnetizing Reactance (ohm):	4.98192
Stator Phase Current (A):	598.125
Current Corresponding to Iron-Core Loss (A):	0.000182594
Magnetizing Current (A):	151.831
Rotor Phase Current (A):	568.802
Copper Loss of Stator Winding (W):	8234.52
Copper Loss of Rotor Winding (W):	8040.17
Iron-Core Loss (W):	0.414349
Frictional and Windage Loss (W):	152.986
Stray Loss (W):	12800
Total Loss (W):	29228.1
Input Power (kW):	1309.08
Output Power (kW):	1279.85
Mechanical Shaft Torque (N.m):	7883.63
Efficiency (%):	97.7673
Power Factor:	0.926856
Rated Slip:	0.00624215

Figure 15: Rated load operation outpus

Generally, calculated values and simulation outputs are not so much different than each other. However, loss values are smaller in the simulation and therefore simulation efficiency output is 1% higher than that of calculated.

Stator Phase Current	598.125	A
Magnetizing Current	151.831	A
Iron-Core Loss Current	0.000182594	A
Rotor Phase Current	568.802	A
Armature Thermal Load	255.789	A^2/mm^3
Specific Electric Loading	45617.4	A_per_meter
Armature Current Density	5607280	A_per_m2
Rotor Bar Current Density	6319400	A_per_m2
Rotor Ring Current Density	3925940	A_per_m2

Figure 16: Rated electric data output

Current density values are in the appropriate range.

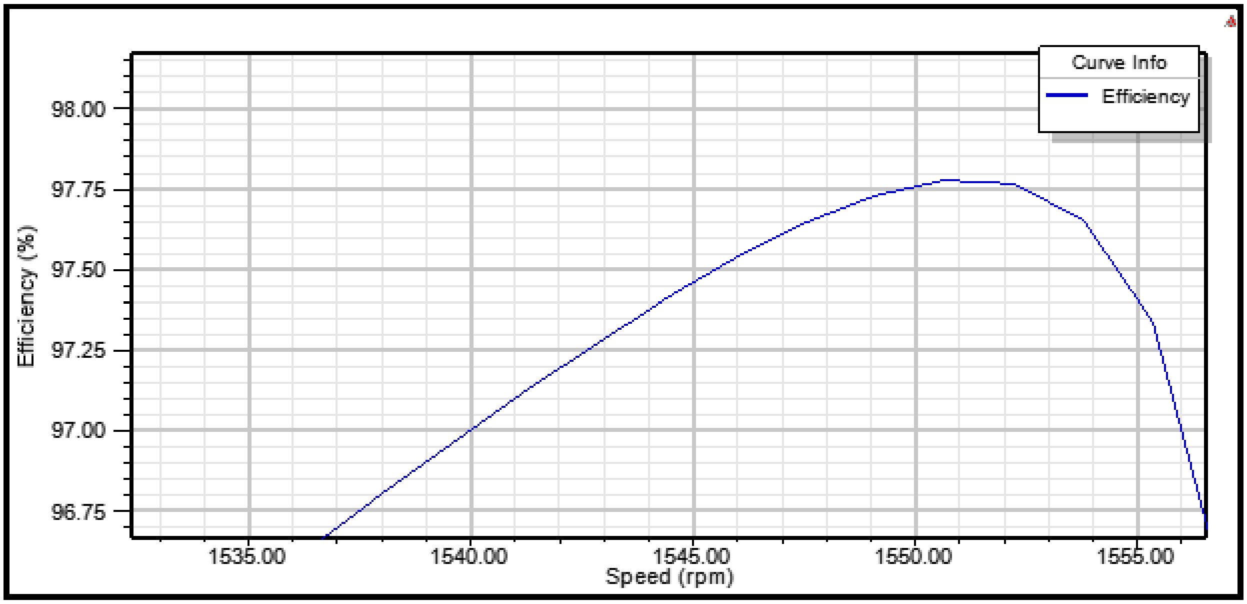

Figure 17: efficiency v.s speed curve @rated speed

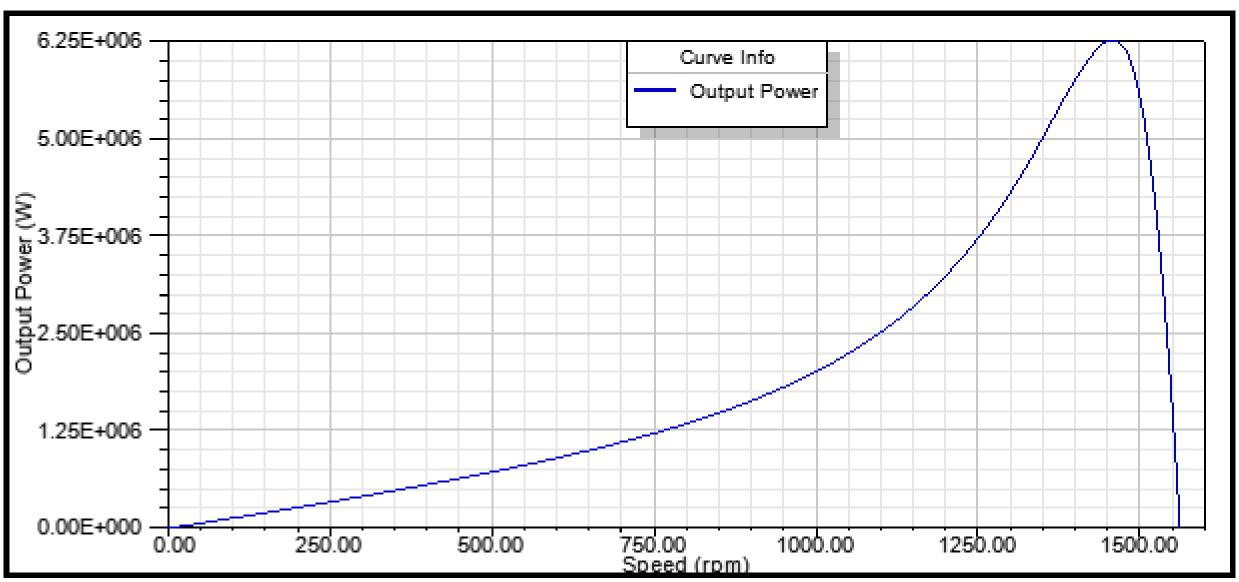

Figure 18: output power vs. speed curve

2. MAXWELL – 2D ANALYSIS

2.1. INPUTS

Design was imported to 2D analysis and some results are as follows:

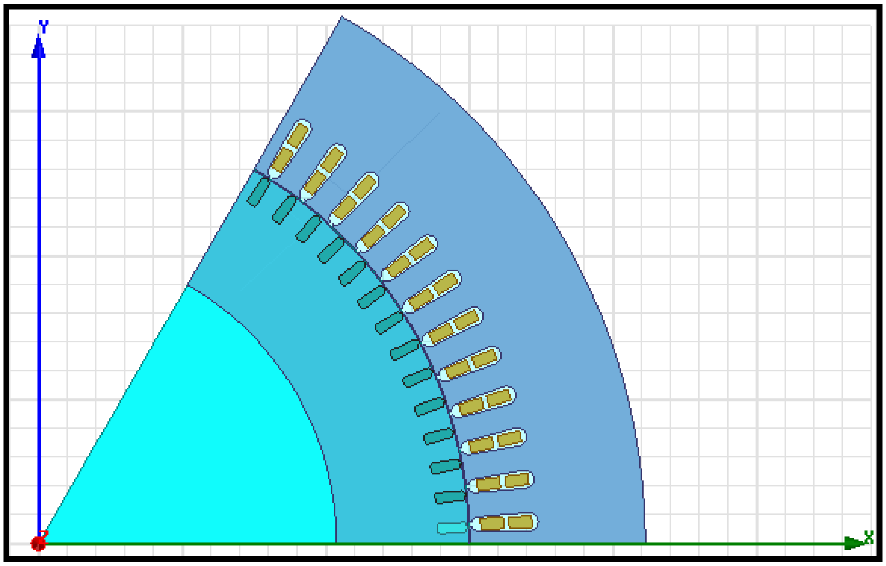

Figure 19: motor pole in XY plane

Lines are added to stator tooth, rotor tooth, gap and yokes to observe the fluxes in corresponding areas.

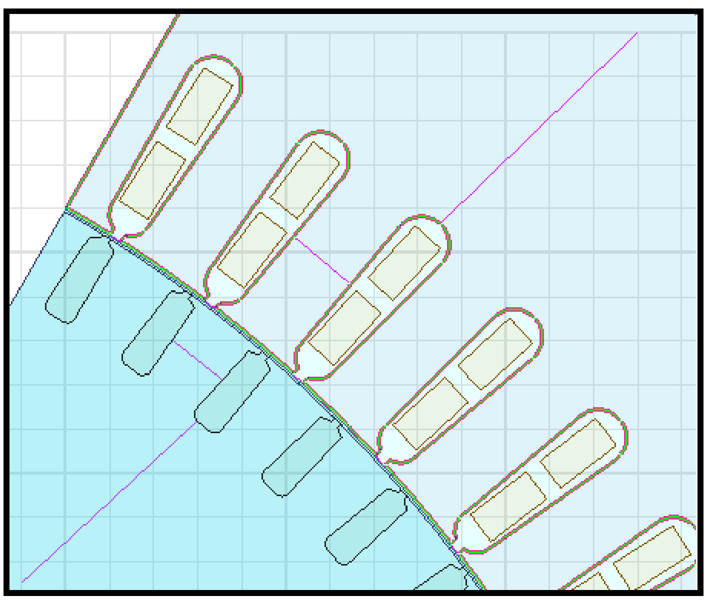

Figure 20: added lines

MESH INPUTS:

Mesh dimensions are assigned as below. Lower the mesh area means higher the accuracy of simulation result however longer simulation time. By trial and error method, mesh dimensions are decided as follows:

Lenght_bar= 5mm

Length_coil= 7mm

Length_main= 24.6mm

SurfApprox_Bar= 1mm

SurfApprox_Main= 1mm

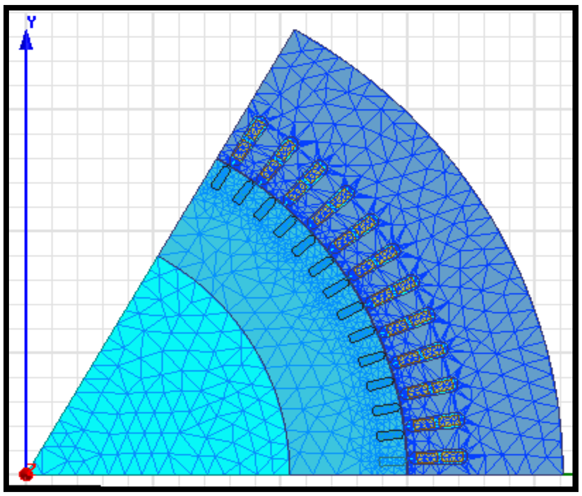

Figure 21: meshes

2.2. OUTPUTS

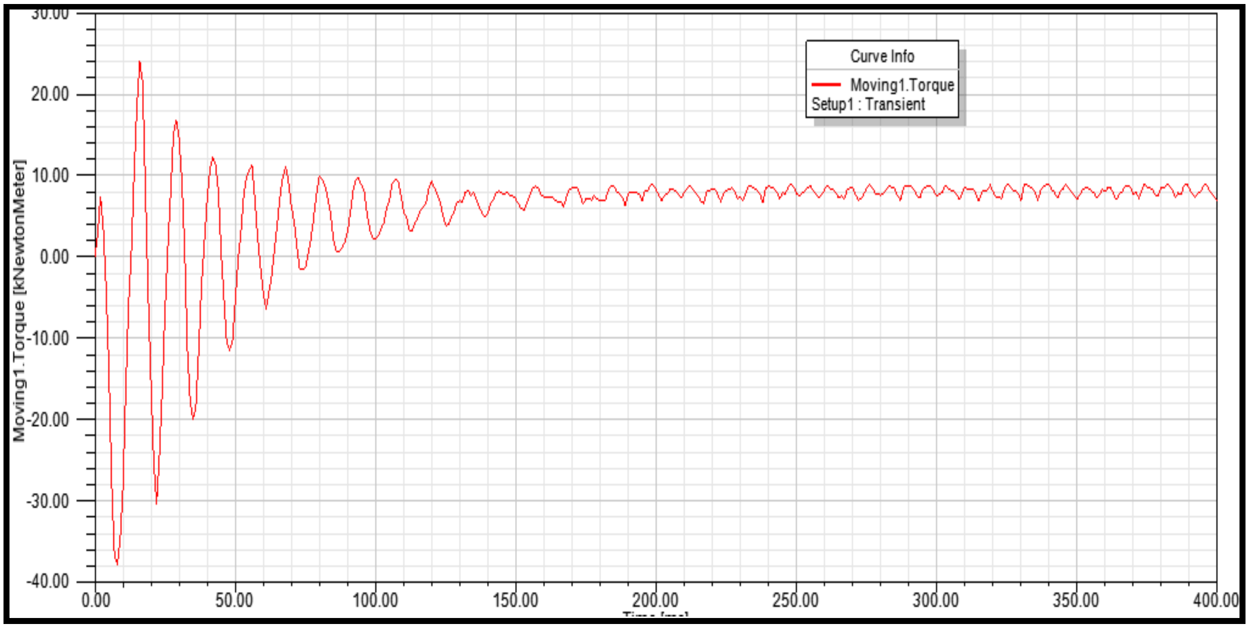

Figure 22: Torque vs time

As seen from above figure, mean torque is close the designed value. However, it has some ossilations on it and that is the cogging torque. We assigned skew width=0 as in Figure 2. By adding some skew to motor, this cogging torque can be aliminated.

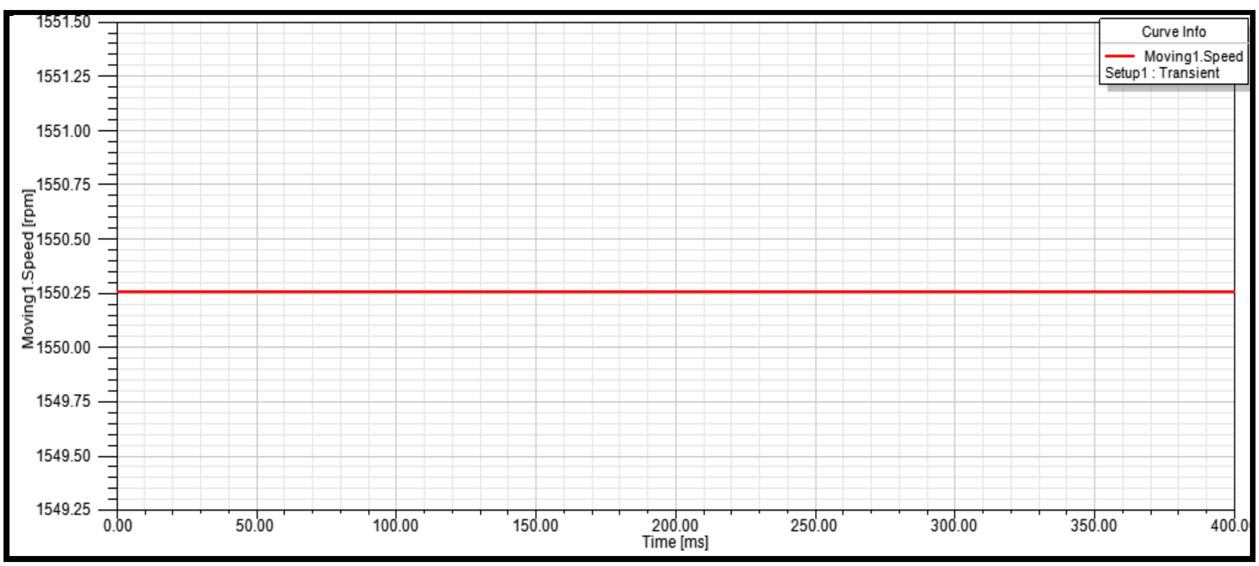

Figure 23: speed vs time

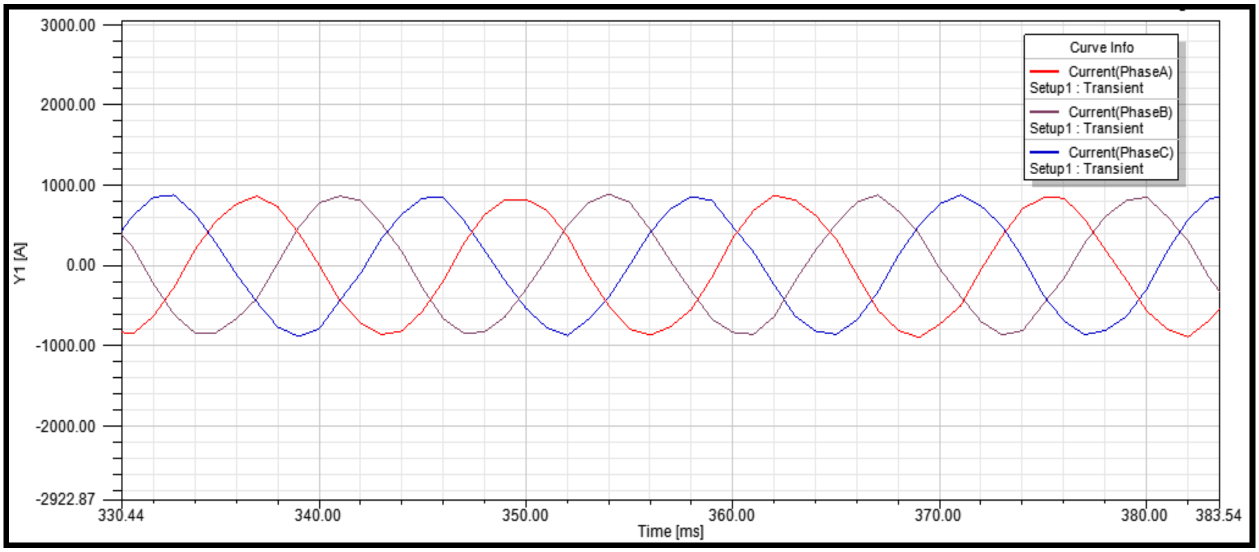

Figure 24: phase currents

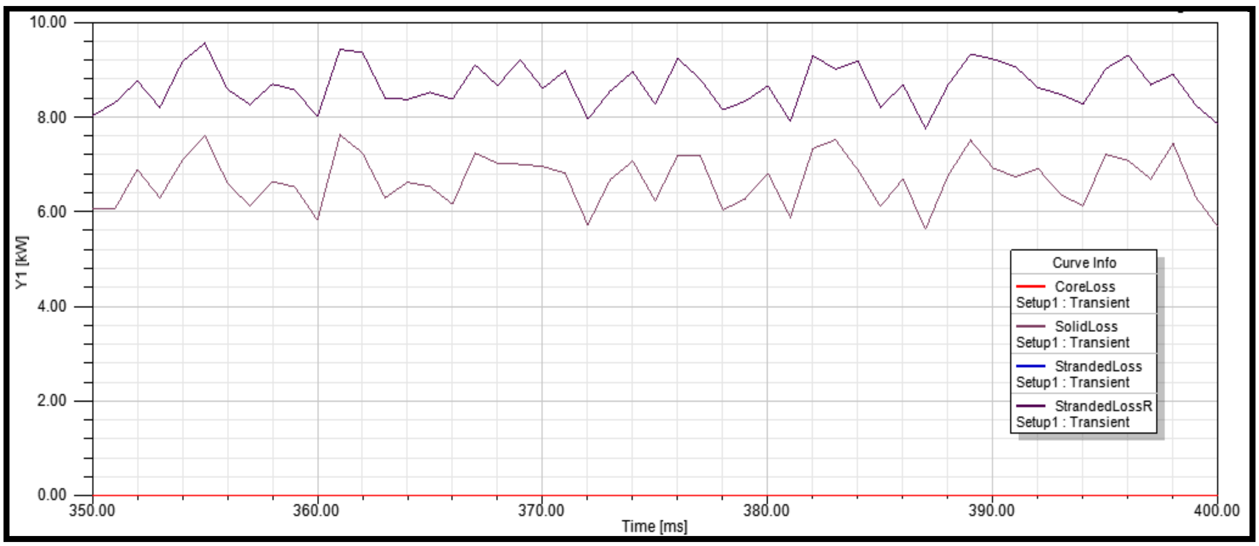

Figure 25: losses in kW

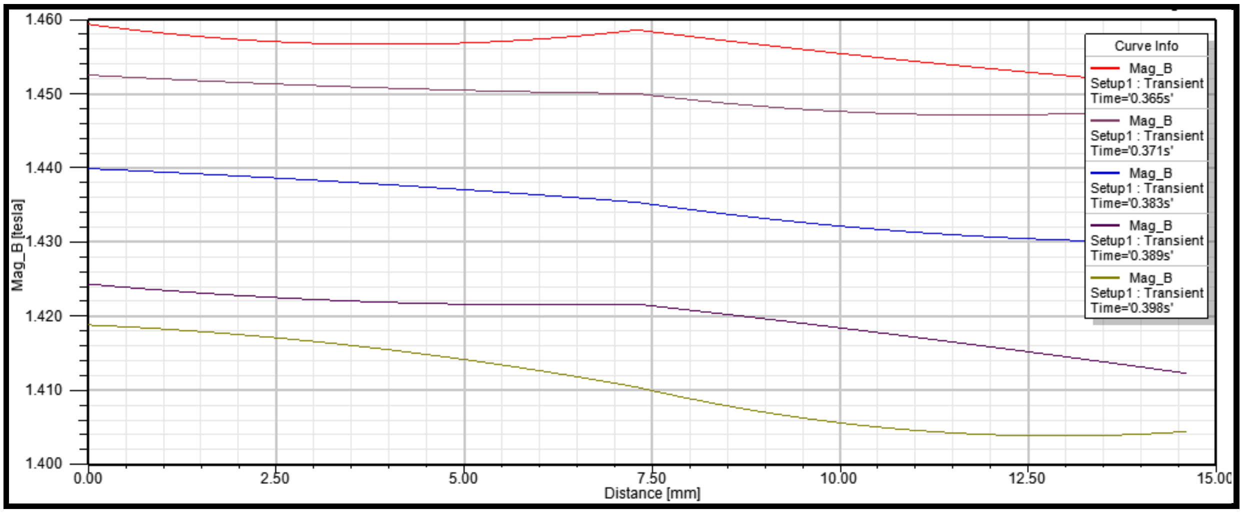

Figure 26: rotor teeth magnetic flux

Figure 26 shows rotor teeth magnetic fluxes for five different time instant. Maximum value is about 1.45 Tesla.

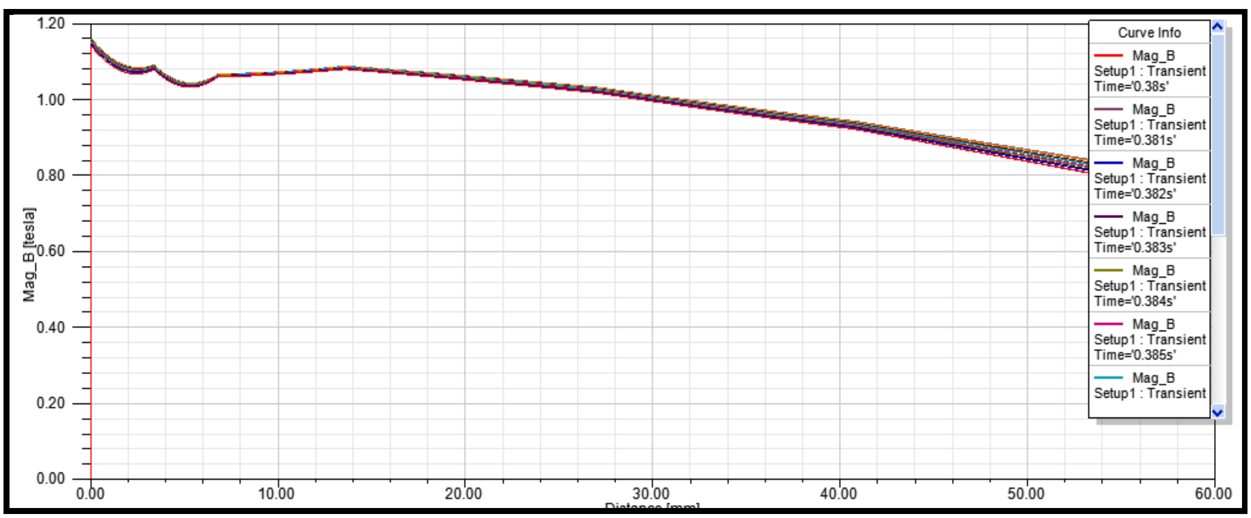

Figure 27: rotor yoke magnetic fluxes

In the first part of the report it is shown that designed values results in high magnetic flux densities in the teeth and yokes. Than, designed values are changed to decrease the high flux to appropriate range. According to RMxprt report rotor yoke is about 1.64 Tesla. However, 2D analysis report gives us a little bit lower magnetic flux density, 1.2T.So be it, there is no probability of saturation.

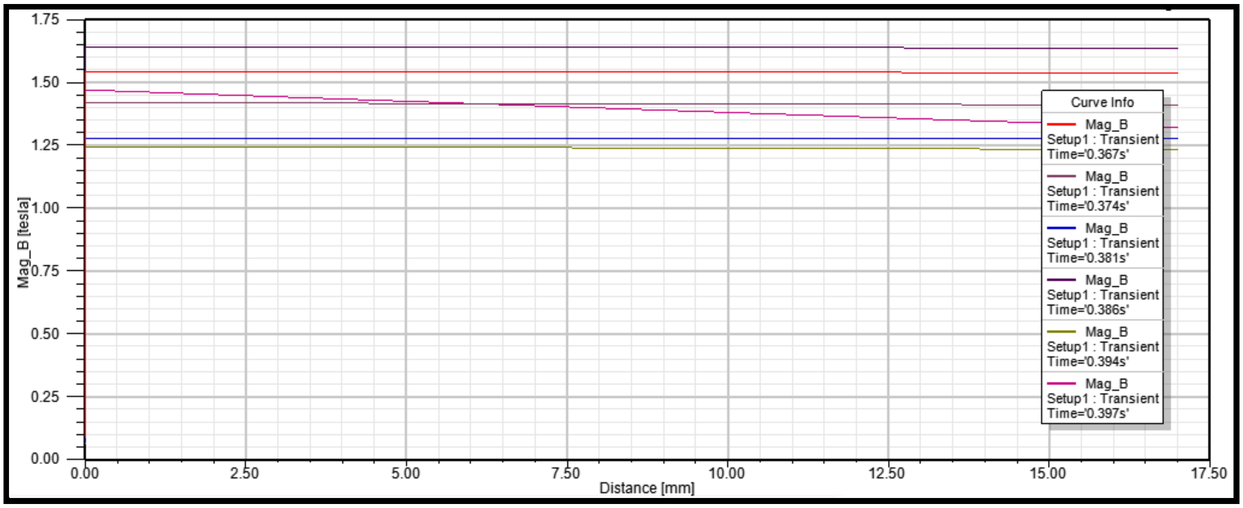

Figure 28: stator teeth magnetic flux densities for different time instants

Maximum magnetic flux density value in stator teeth is about 1.65T

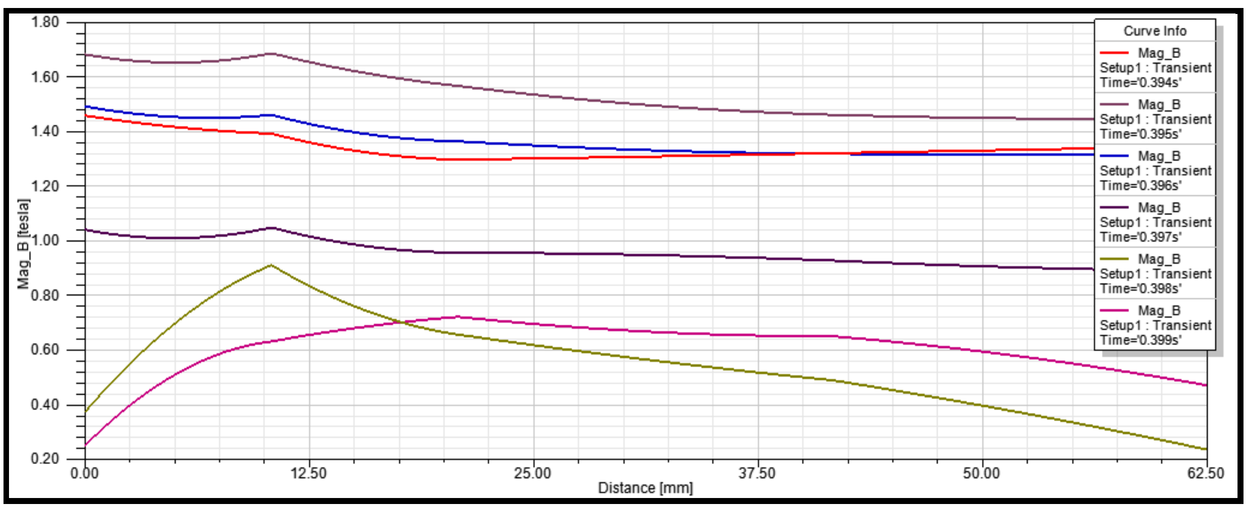

Figure 29: stator yoke magnetic flux densities for different time instants

Maximum magnetic flux density value in stator yoke is about 1.7T

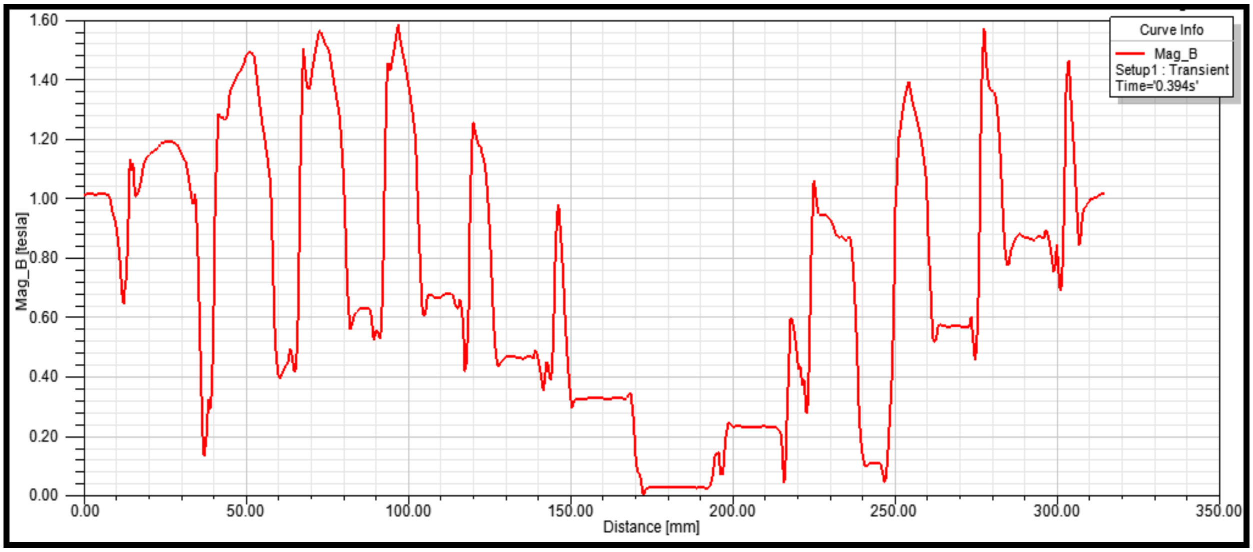

Figure 30: air gap magnetic flux density at time: 0.394s

Magnetic flux density values in teeth, yoke and gap are below the saturation value of the steel_1008 chosen as a core material. Airgap flux density seems abnormal compared with the others. Reason is the lack of meshes in the airgap. Higher number of meshes in gap would solve this problem.

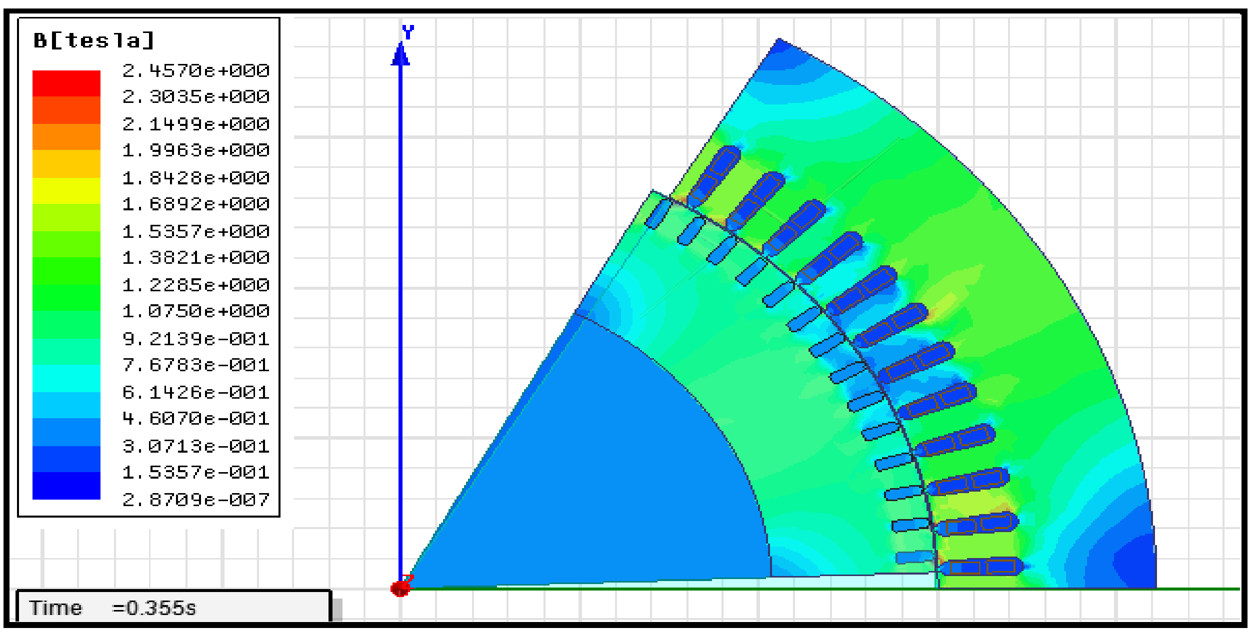

Figure 31: magnetic flux density

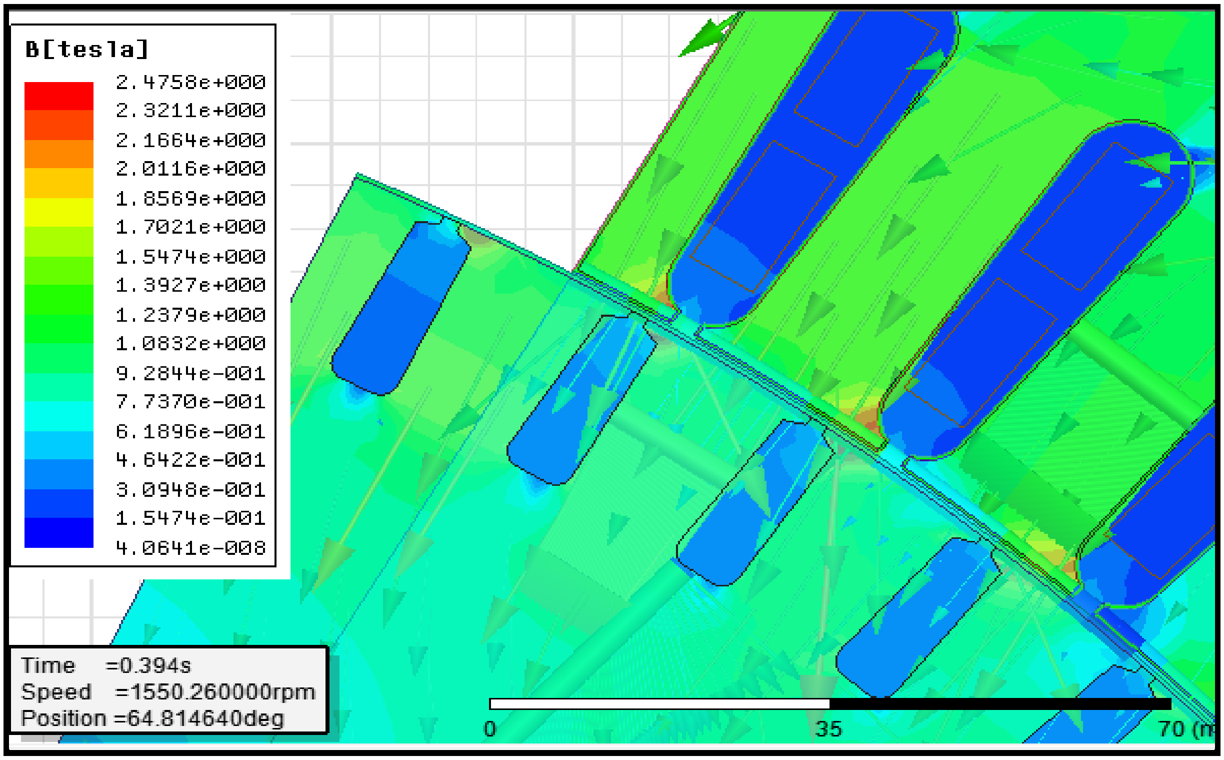

Figure 32: intensive magnetic flux densities at nook of the teeth

Some small areas have criticial values of magnetic flux densities, 1.8-2 T. That can be solved by increasing the hos values of the stator slots or putting smoother edges to slots near that areas.

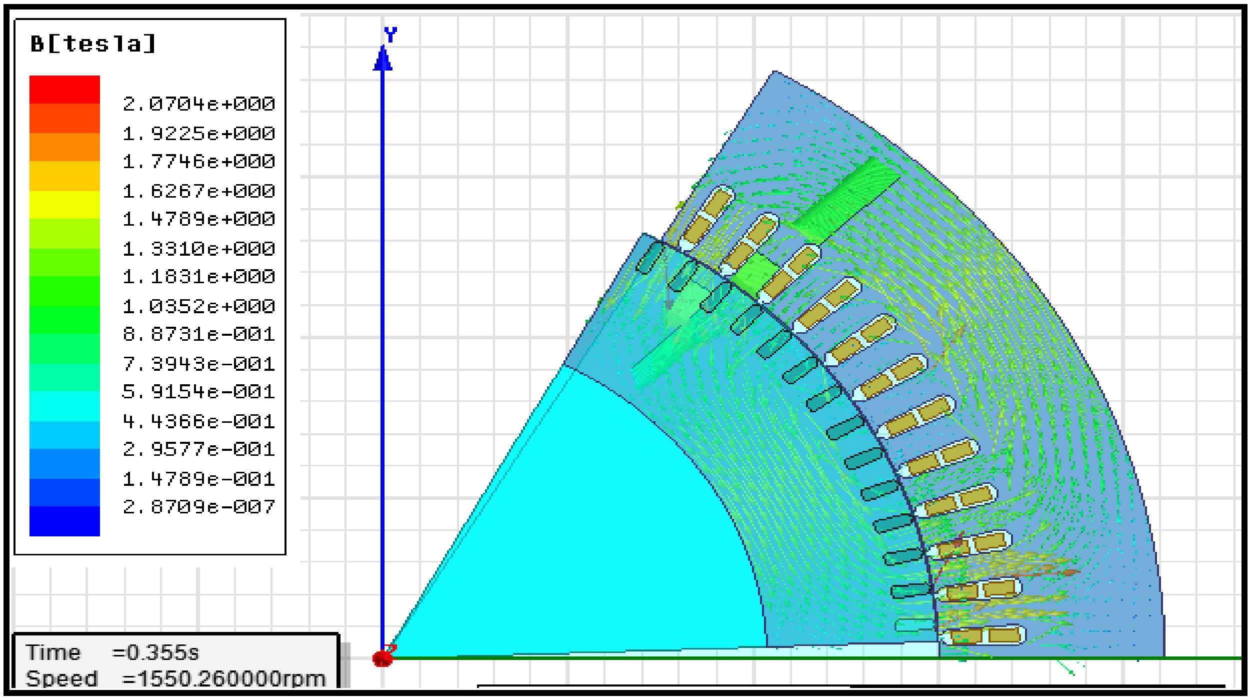

Figure 33: Magnetic flux vectors

3. CONCLUSION

In the second project, a train traction motor (an induction motor) with some specifications was designed. In third project, design is implemented in the Maxwell simulation program to control whether designed values are proper for the design specifications. In this report, simulation inputs and outputs are given as simplificative.

- How is it designed?

Firstly, according to motor's power specification, appropriate Cmech value is assigned. Basically, power level and the torque demand determine the dimentions of motor. For rational sizing, an aspect ratio is calculated and then motor dimentions(outer-inner diameters, gap) are assigned. Outer to inner diameter ratio is depend on the pole number. After that, considering maximum and minimum slot pitches in induction machines, number of phases and rule of thumb in the reference book, stator slot number is assigned as 72. Small number of slots can lead to İncreased leakage inductance , reduced breakdown torque and larger MMF harmonics. On the other hand, large number of slots can lead to high cost. Then, it is assigned two layer winding with chorded coils 5/6 to eliminate the 5th harmonic mainly and some other harmonics. Number of winding in phase is determined by considering voltage, flux and frequency. Then, number of rotor slots is stated by the rules mentioned in the book to avoid harmful torques at positive speed, harmful mechanical vibrations and harmful synchronous torques. Skin depth depends on the frequency and affects the resistance in high frequencies. Skin depth is calculated and proper awg cable is chosed. Cable number and size directly affects the copper loss. Therefore, efficiency andtermal design issue are effected by the this cable selection.

Slot sizing is another important issue. Because slot sizing affects both teeth area and yoke area it also affects the magnetic flux densities in that areas. Generally they are assigned about 1.6 T in teeth and yokes not to saturate the core. Stator conductors are chosed as copper wire and rotor slots are filled with aluminium bars. Aluminium has higher resistance compared with the copper, so it’s loss is higher. But, it is cheaper and improves the starting torque. In thermally criticial applications, copper can be used in the rotor to decrease the loss.

- How is it simulated?

First of all, RMxprt model is implemented. Design values(dimensions, slots, wires, core type) are inserted to program. First results were not proper in terms of magnetic flux density and power factor. Generally, magnetic flux density was really high and above the saturation value of the material. Therefore, slot areas and yoke areas are chnged to adjust the magnetic flux density. The main idea behind the changes was higher the area for flux to flow means lower flux density in that area. After changing the some dimesions, problems are solved. Rated load operation, rated magnetic data and rated performance data outputs show favorable results.

Then, Rmxprt values are transferred to 2D analysis. Magnetic flux densities are observed by putting lines to neccesary places. They are all below the saturation level. Speed and torque values are close the designed values. However, torque has some oscillation on it named as cogging torque. This cogging torque would be eliminated by adding some skew to motor.

3.1. PERSONEL OPINION ABOUT THE LECTURE

I though that it was very intense, rich and useful semester. In spite of that we took the courses EE361 and EE362, motor concept was still blur in my mind until this semester. To be honest, In these lectures, for being succesful, it was somehow enough to be familiar with the earlier year’s exam question. However, in EE564, system and evaluation is changed. I think especially projects helped us to be engaged in motor issue more. Also, they pushed us to learn new programs: iphyton-maxwell.presentations and the final exam concept was also useful for us. On the other hand, visiting the firm, ELSAN, helped us to realize the our designs in mind. Lastly, I am glad to take this course in this semester.