EE564 PROJECT #3
TRACTION MOTOR DESIGN

CİHAN AYDAR
2043677

TABLE OF CONTENTS

LIST OF TABLES

LIST OF FIGURES

1. INTRODUCTION

The main purposes of project are to design a traction squirrel cage induction motor (with copper rotor-bars) and then verify it in a FEA program. Specifications of the motor can be seen as follows.

- Rated Power Output: 1280 kW
- Line-to-line voltage: 1350 V
- Number of poles: 6
- Rated Speed: 1520 rpm (72 km/h) (driven with 78 Hz inverter)
- Rated Motor Torque: 7843 Nm
- Cooling: Forced Air Cooling
- Insulating Class: 200C
- Train Wheel Diameter: 1210 mm
- Maximum Speed: 140 km/h
- Gear Ratio: 4.82

2. MOTOR PARAMETER ESTIMATION

Here motor geometry is determined. All calculation methodology can be seen in Excel file. [1]

Number of Poles	6				
Type of Winding	Integral, Single Layer, Distributed Winding				
Winding Factors	0,9598	0,66667	0,21757	-0,1774	-0,3333
Number of Turns	36				
Fill Factor	0,7				
Winding Connection	wye				
Voltage Rating (V)	1350				
Current Rating (A)	547,43				
Output Power Rating (W)	1280000				
Frequency	78				

Table 1 Winding Design Parameters

Number of StatorSlots	54		

Slots per Pole	9		
Slot per Pole per Phase	3		
Slot Angle (degree)	20	0,34907	
Conductors per Slot	4		
Nphase	36		
Flux per Pole (Wb)	0,05897	0,06514	
Bavg (T)	0,7		
Airgap Clearance (mm)	0,18093		
Torque (N.m)	8041,51		
Speed (rad/s)	159,174	1520	rpm
Maxwell Stress Tensor (N/m^2)	194965		
Number of RotorSlots	62		

Di (m)	0,32639
L (m)	0,24648
Di^2*L	0,02626
Aspect Ratio (L/D)	0,75516
Zq*Qs	216
Specific Electric Loading-q (A/m)	115316
Zq	4
Slot Pitch (mm)	0,01899
Do(m)	0,48959

Table 2 Motor Dimension Calculations

4. DETAILED ANALYSIS AND VERIFICATION

Final optimized values of motor geometry can be seen in following figures. In first simulation with rmxprt, efficiency, magnetic flux densities in stator and rotor cores and power factor values are not compatible with design values. Stator and rotor geometry is finalized as follows.

4.1 INPUTS

	Name	Value	Unit	Evaluated Value	Description	Read-only
	Outer Diameter	490	mm	490mm	Outer diameter of the st...	☐
	Inner Diameter	326	mm	326mm	Inner diameter of the st...	☐
	Length	250	mm	250mm	Length of the stator core	☐
	Stacking Factor	0.95			Stacking factor of the s...	☐
	Steel Type	D21_50			Steel type of the stator ...	☐
	Number of Slots	54			Number of slots of the s...	☐
	Slot Type	1			Slot type of the stator c...	☐
	Lamination Se...	3			Number of lamination s...	☐
	Press Board T...	0	mm		Magnetic press board t...	☐
	Skew Width	0		0	Skew width measured i...	☐

Figure 1 Stator Inputs

	Name	Value	Unit	Evaluated Value	Description	Reac
	Auto Design	☐			Auto design Hs2, Bs1 and Bs2	☐
	Parallel Tooth	☑			Design Bs1 and Bs2 based on Tooth Width	☐
	Tooth Width	15	mm	15mm	Tooth width for parallel tooth	☐
	Hs0	1.5	mm	1.5mm	Slot dimension: Hs0	☐
	Hs2	40	mm	40mm	Slot dimension: Hs2	☐
	Bs0	4	mm	4mm	Slot dimension: Bs0	☐

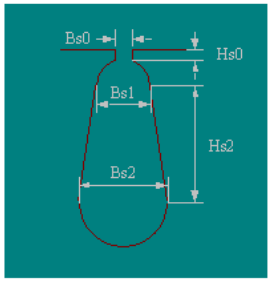


Figure 2 Stator Geometry

	Name	Value	Unit	Evaluated Value	Description
	Winding Layers	2			Number of winding layers
	Winding Type	Whole-Coiled			Stator winding type
	Parallel Branches	1			Number of parallel branches of stat
	Conductors per Slot	4		4	Number of conductors per slot, 0 fc
	Coil Pitch	9			Coil pitch measured in number of sl
	Number of Strands	2		2	Number of strands (number of wires
	Wire Wrap	0	mm		Double-side wire wrap thickness, 0
	Wire Size	Diameter: 10.404mm			Wire size, 0 for auto-design

☐ Show Hidden

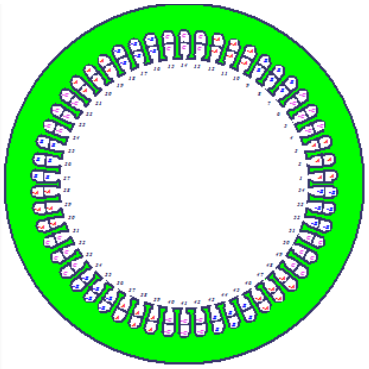


Figure 3 Stator Winding

Winding | End/Insulation

	Name	Value	Unit	Evaluated Value	Description
	Input Half-turn Length	☑			Input half Turn Length
	Half Turn Length	0	mm	0mm	Half-turn length of armature winding
	Base Inner Radius	10	mm		Inner radius of the base corner
	Tip Inner Diameter	2	mm		Inner diameter of the coil tip
	End Clearance	1	mm		End clearance between two adjacent coils
	Slot Liner	1	mm		Insulation: slot liner thickness
	Wedge Thickness	1	mm		Insulation: wedge thickness
	Layer Insulation	0	mm		Insulation: layer insulation thickness
	Limited Fill Factor	0.75			Limited slot fill factor for wire design

☐ Show Hidden

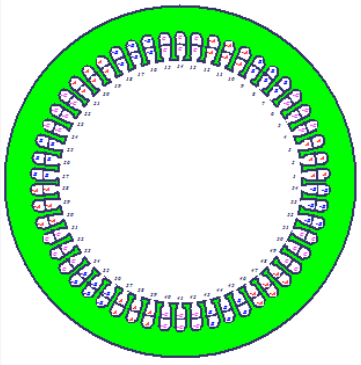


Figure 4 Stator Insulation

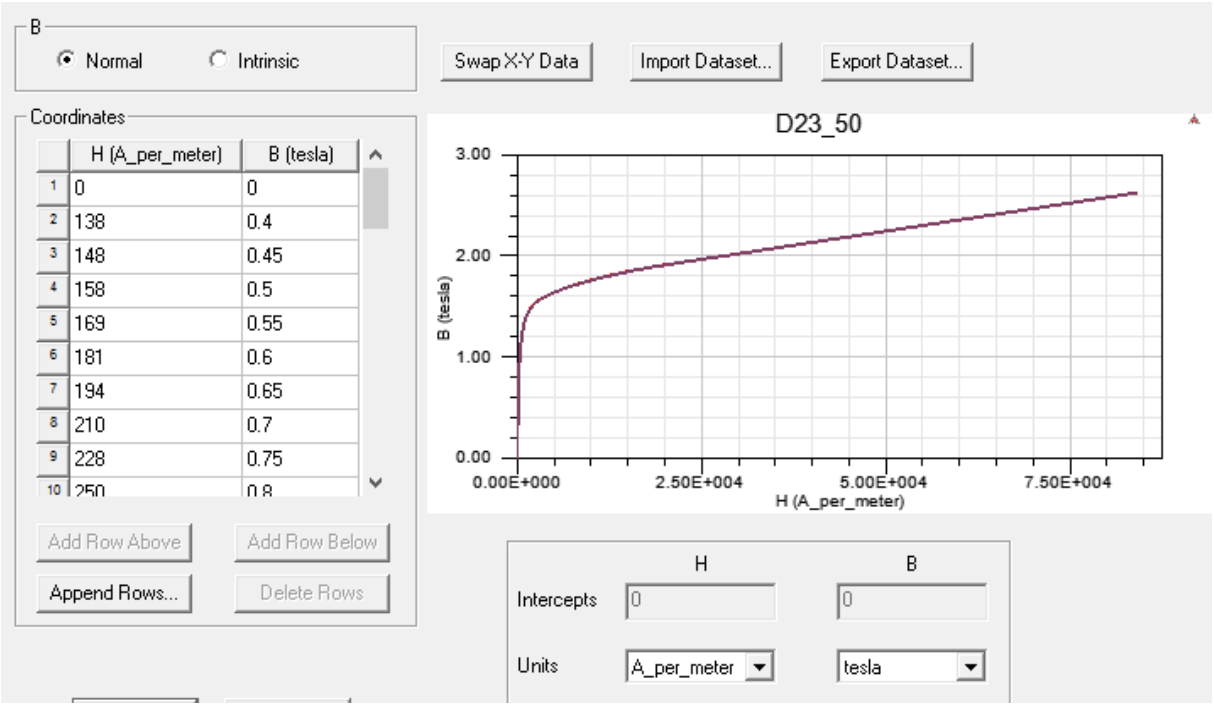


Figure 5 B-H Characteristics

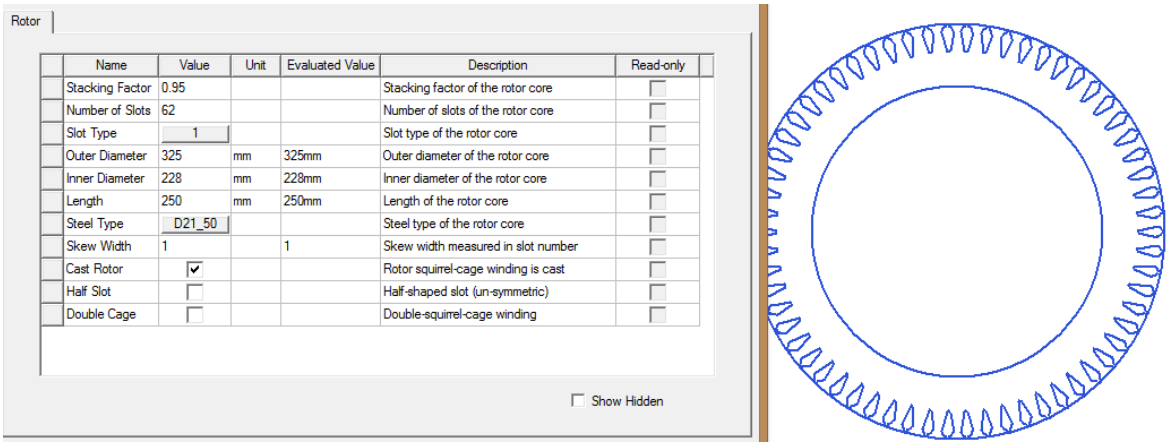


Figure 6 Rotor Structure

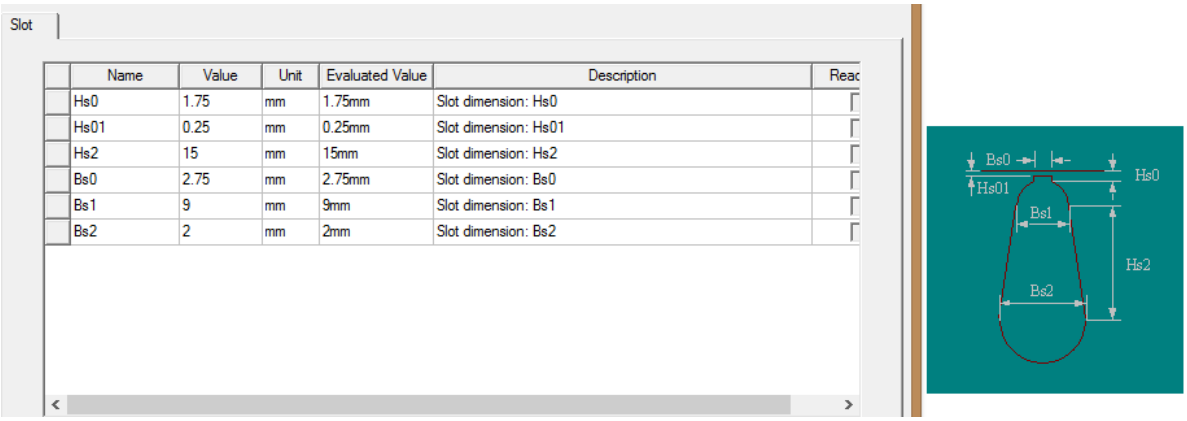


Figure 7 Rotor Geometry

4.2 OUTPUTS

Values in Fig. 8 are compared with the calculated values in previous parts. They are consistent with each other.

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):	11
Windage Loss (W):	11
Operation Mode:	Motor
Type of Load:	Constant Power
Operating Temperature (C):	75

RATED-LOAD OPERATION

Stator Resistance (ohm):	0.00474145
Stator Resistance at 20C (ohm):	0.00390023
Stator Leakage Reactance (ohm):	0.216592
Rotor Resistance (ohm):	0.0121181
Rotor Leakage Reactance (ohm):	0.0491929
Resistance Corresponding to Iron-Core Loss (ohm):	81.9648
Magnetizing Reactance (ohm):	1.05315
Stator Phase Current (A):	942.359
Current Corresponding to Iron-Core Loss (A):	7.6262
Magnetizing Current (A):	593.532
Rotor Phase Current (A):	693.021

Copper Loss of Stator Winding (W):	12631.8
Copper Loss of Rotor Winding (W):	17460.2
Iron-Core Loss (W):	14301
Frictional and Windage Loss (W):	22.5555
Stray Loss (W):	12800
Total Loss (W):	57215.6
Input Power (kW):	1337.38
Output Power (kW):	1280.16
Mechanical Shaft Torque (N.m):	7943.2
Efficiency (%):	95.7218
Power Factor:	0.601129
Rated Slip:	0.0134553
Rated Shaft Speed (rpm):	1539.01

Mechanical Shaft Torque (N.m):	7943.2
Efficiency (%):	95.7218
Power Factor:	0.601129
Rated Slip:	0.0134553
Rated Shaft Speed (rpm):	1539.01

Figure 8 Output Data

Simulation: Setup1 | Performance

Design Variation:

Performance | Design Sheet | Curves

Data: Locked-Rotor Operation

	Name	Value	Units	Description
1	Locked-Rotor Torque	2942.1	NewtonMeter	
2	Locked-Rotor Phase Current	3051160	mA	
3	Locked-Rotor Torque Ratio	0.370392		
4	Locked-Rotor Current Ratio	3.23779		
5	Stator Resistance	0.00474145	ohm	
6	Stator Leakage Reactance	0.213239	ohm	
7	Rotor Resistance	0.0186448	ohm	
8	Rotor Leakage Reactance	0.0426497	ohm	

Figure 9 Locked Rotor Operation

Simulation: Setup1 | Performance

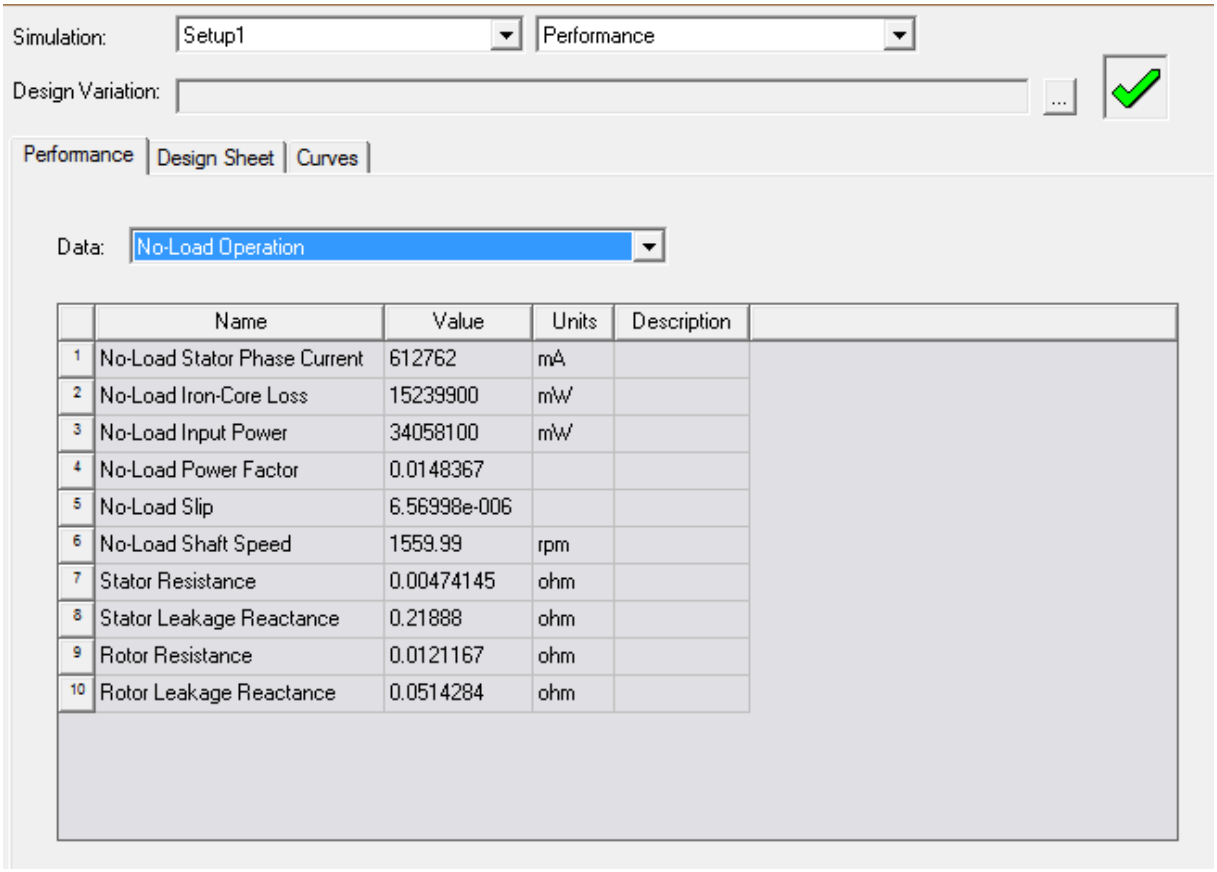
Design Variation:

Performance | Design Sheet | Curves

Data: Material Consumption

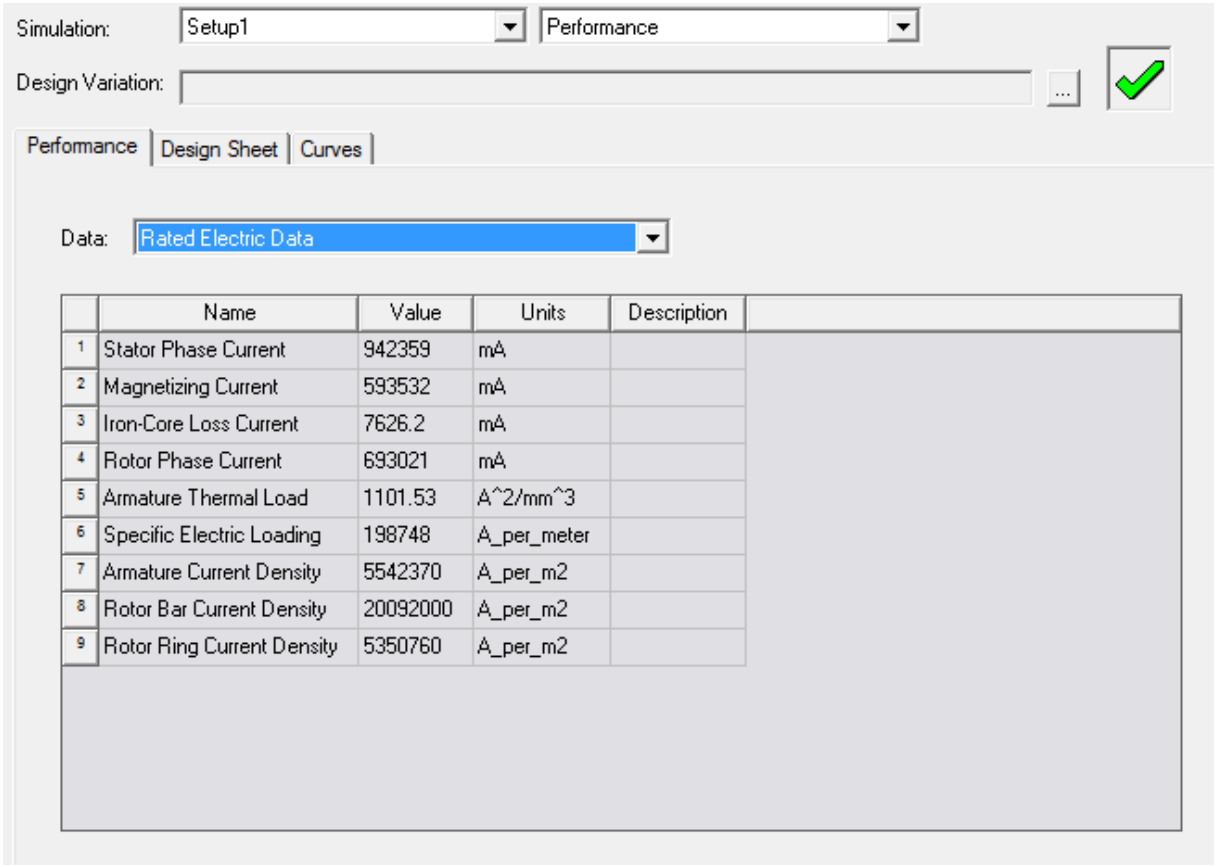
	Name	Value	Units	Description
1	Armature Copper Density	8900	kg_per_m3	Mass Density
2	Rotor Bar Material Density	8933	kg_per_m3	Mass Density
3	Rotor Ring Material Density	8933	kg_per_m3	Mass Density
4	Armature Core Steel Density	7820	kg_per_m3	Mass Density
5	Rotor Core Steel Density	7820	kg_per_m3	Mass Density
6	Armature Copper Weight	168.657	kg	
7	Rotor Bar Material Weight	21.1982	kg	
8	Rotor Ring Material Weight	24.0386	kg	
9	Armature Core Steel Weight	164.987	kg	
10	Rotor Core Steel Weight	64.4723	kg	
11	Total Net Weight	443.353	kg	
12	Armature Core Steel Consumption	296.38	kg	
13	Rotor Core Steel Consumption	155.023	kg	

Figure 10 Material Consumption



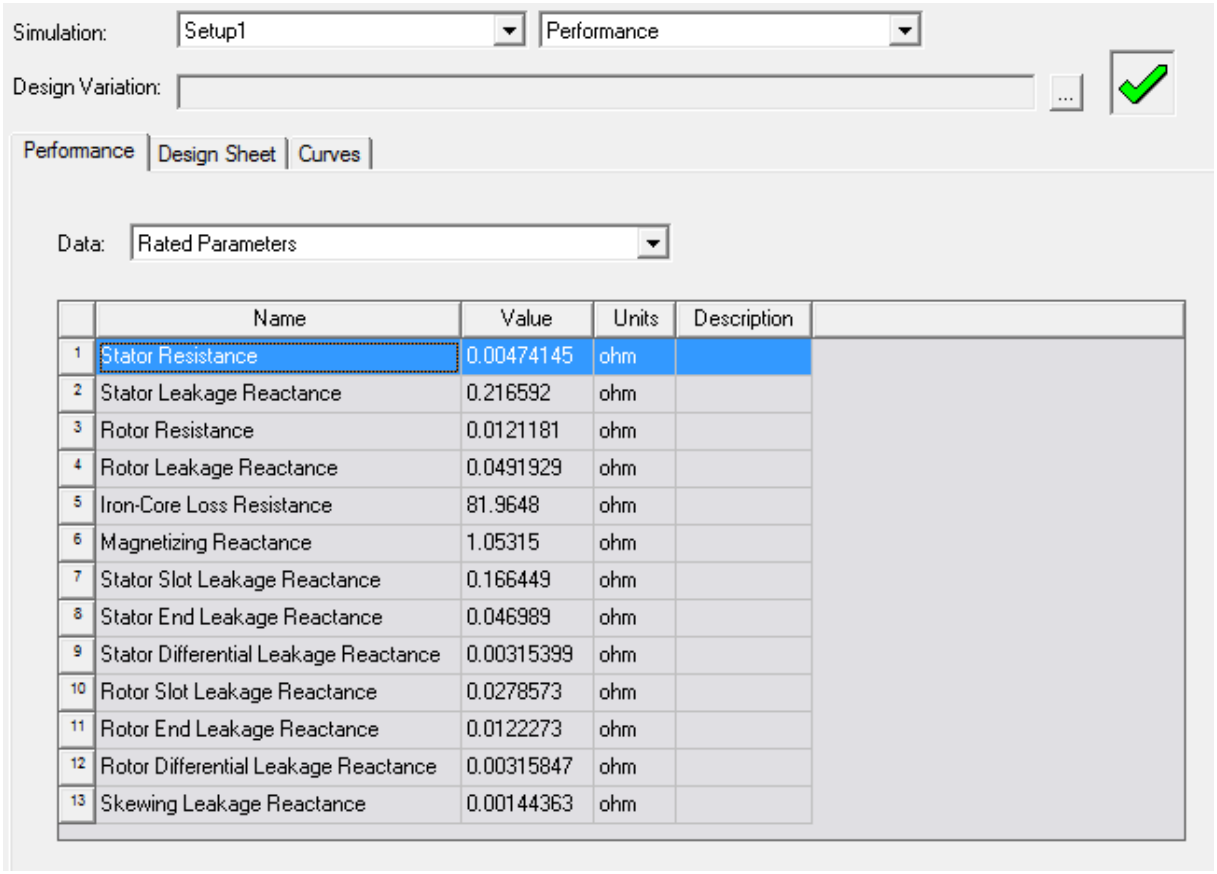
	Name	Value	Units	Description
1	No-Load Stator Phase Current	612762	mA	
2	No-Load Iron-Core Loss	15239900	mW	
3	No-Load Input Power	34058100	mW	
4	No-Load Power Factor	0.0148367		
5	No-Load Slip	6.56998e-006		
6	No-Load Shaft Speed	1559.99	rpm	
7	Stator Resistance	0.00474145	ohm	
8	Stator Leakage Reactance	0.21888	ohm	
9	Rotor Resistance	0.0121167	ohm	
10	Rotor Leakage Reactance	0.0514284	ohm	

Figure 11 No Load Operation



	Name	Value	Units	Description
1	Stator Phase Current	942359	mA	
2	Magnetizing Current	593532	mA	
3	Iron-Core Loss Current	7626.2	mA	
4	Rotor Phase Current	693021	mA	
5	Armature Thermal Load	1101.53	A^2/mm^3	
6	Specific Electric Loading	198748	A_per_meter	
7	Armature Current Density	5542370	A_per_m2	
8	Rotor Bar Current Density	20092000	A_per_m2	
9	Rotor Ring Current Density	5350760	A_per_m2	

Figure 12 Rated Electric Data



	Name	Value	Units	Description
1	Stator Resistance	0.00474145	ohm	
2	Stator Leakage Reactance	0.216592	ohm	
3	Rotor Resistance	0.0121181	ohm	
4	Rotor Leakage Reactance	0.0491929	ohm	
5	Iron-Core Loss Resistance	81.9648	ohm	
6	Magnetizing Reactance	1.05315	ohm	
7	Stator Slot Leakage Reactance	0.166449	ohm	
8	Stator End Leakage Reactance	0.046989	ohm	
9	Stator Differential Leakage Reactance	0.00315399	ohm	
10	Rotor Slot Leakage Reactance	0.0278573	ohm	
11	Rotor End Leakage Reactance	0.0122273	ohm	
12	Rotor Differential Leakage Reactance	0.00315847	ohm	
13	Skewing Leakage Reactance	0.00144363	ohm	

Figure 13 Rated Parameters

Simulation: Setup1 | Performance

Design Variation:

Performance | Design Sheet | Curves

Data: Rated Performance

	Name	Value	Units	Description
1	Stator Ohmic Loss	12631800	mW	
2	Rotor Ohmic Loss	17460200	mW	
3	Iron-Core Loss	14301000	mW	
4	Frictional and Windage Loss	22555.5	mW	
5	Stray Loss	12800000	mW	
6	Total Loss	57215600	mW	
7	Output Power	1280160000	mW	
8	Input Power	1337380000	mW	
9	Efficiency	95.7218	%	
10	Power Factor	0.601129		
11	Rated Torque	7943.2	NewtonMeter	
12	Rated Speed	1539.01	rpm	
13	Rated Slip	0.0134553		

Figure 14 Rated Performance

Simulation: Setup1 | Performance

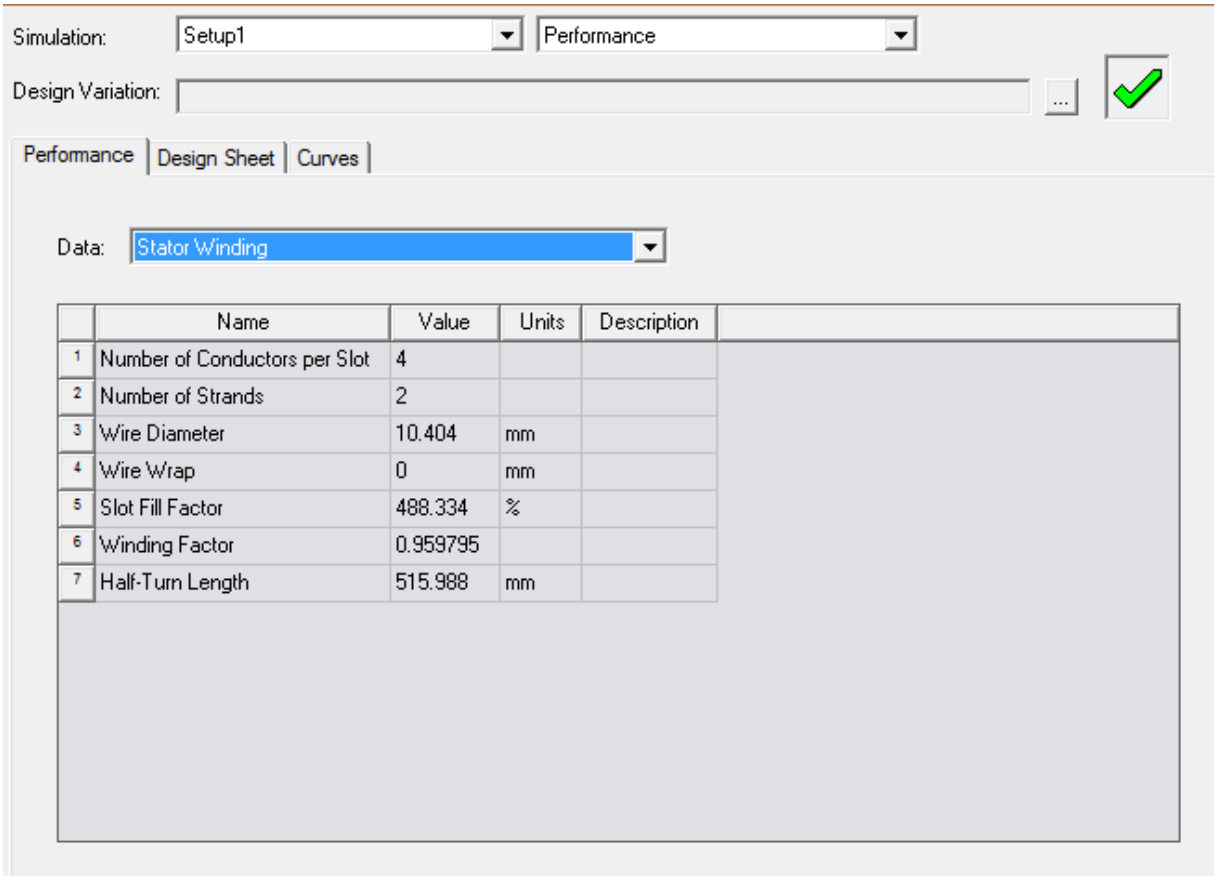
Design Variation:

Performance | Design Sheet | Curves

Data: Stator Slot

	Name	Value	Units	Description
1	Slot Type	1		
2	hs0	1.5	mm	
3	hs2	40	mm	
4	bs0	4	mm	
5	bs1	4.21208	mm	
6	bs2	8.87155	mm	
7	Top Tooth Width	15	mm	
8	Bottom Tooth Width	15	mm	

Figure 15 Stator Slot Geometry



	Name	Value	Units	Description
1	Number of Conductors per Slot	4		
2	Number of Strands	2		
3	Wire Diameter	10.404	mm	
4	Wire Wrap	0	mm	
5	Slot Fill Factor	488.334	%	
6	Winding Factor	0.959795		
7	Half-Turn Length	515.988	mm	

Figure 16 Stator Winding

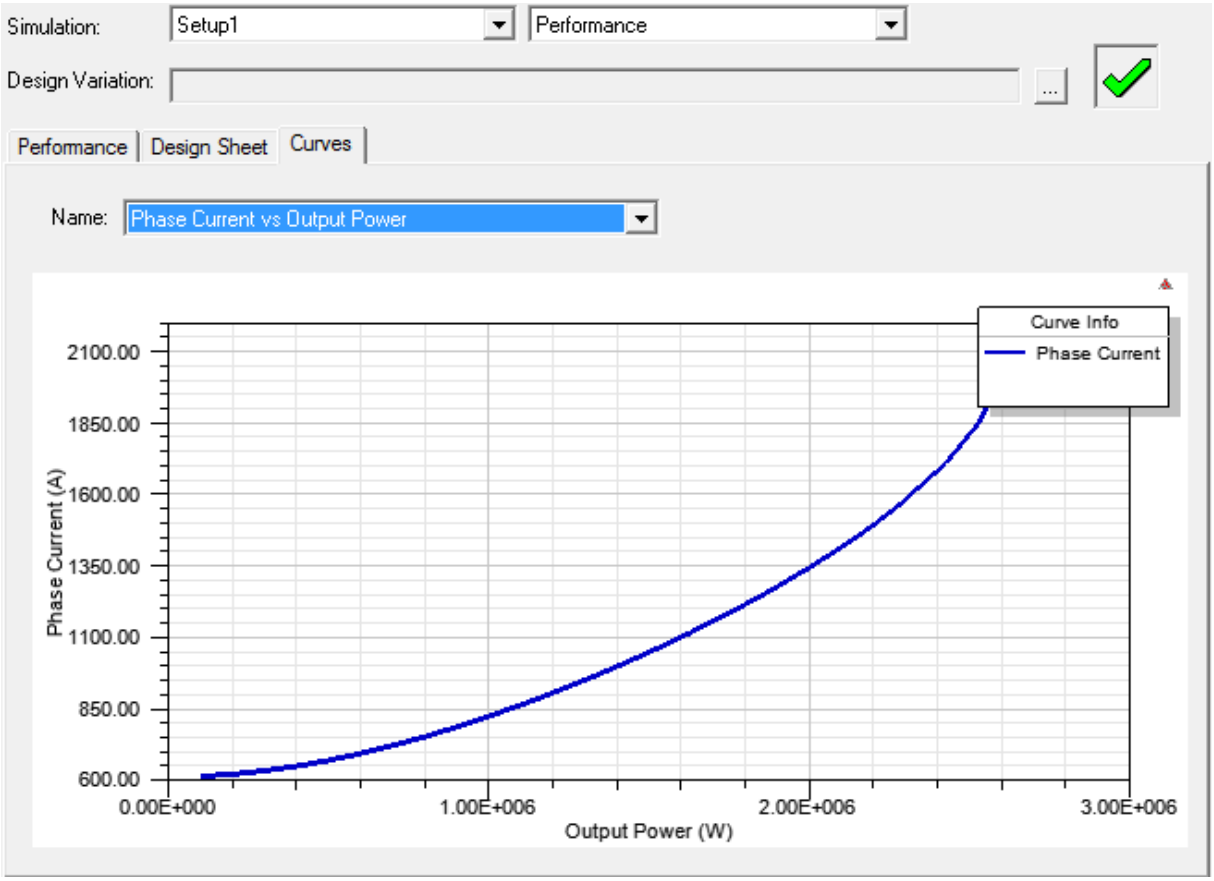


Figure 17 Phase Current vs Output Power

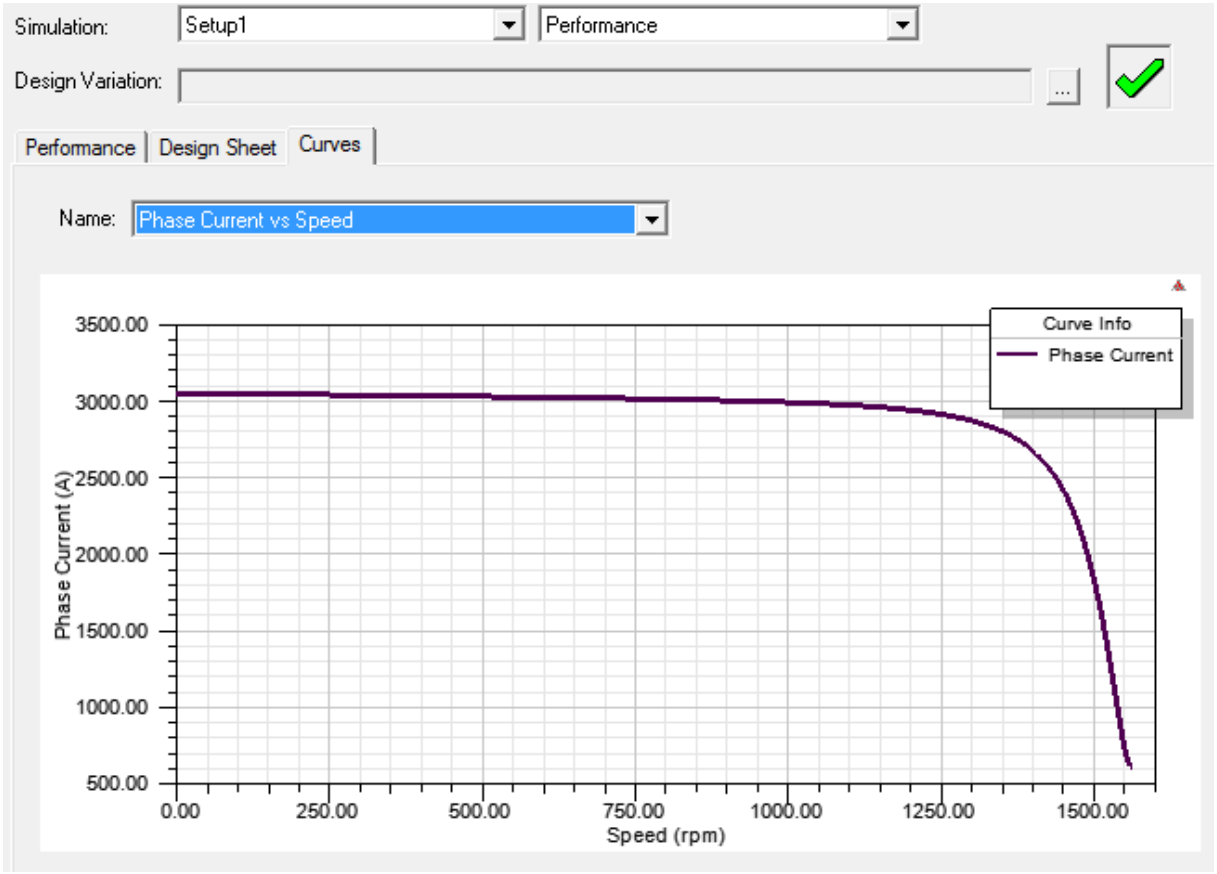


Figure 18 Phase Current vs Speed

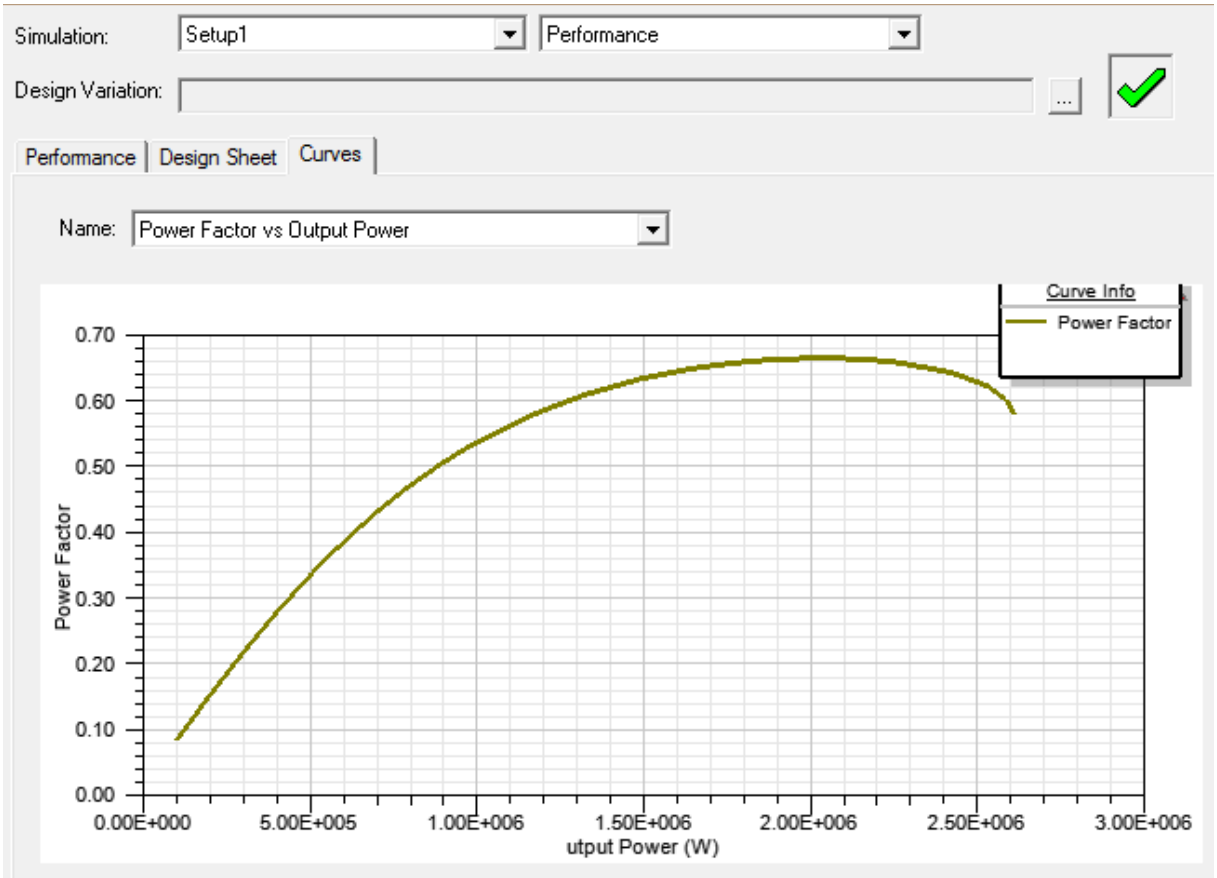


Figure 19 Power Factor vs Output Power

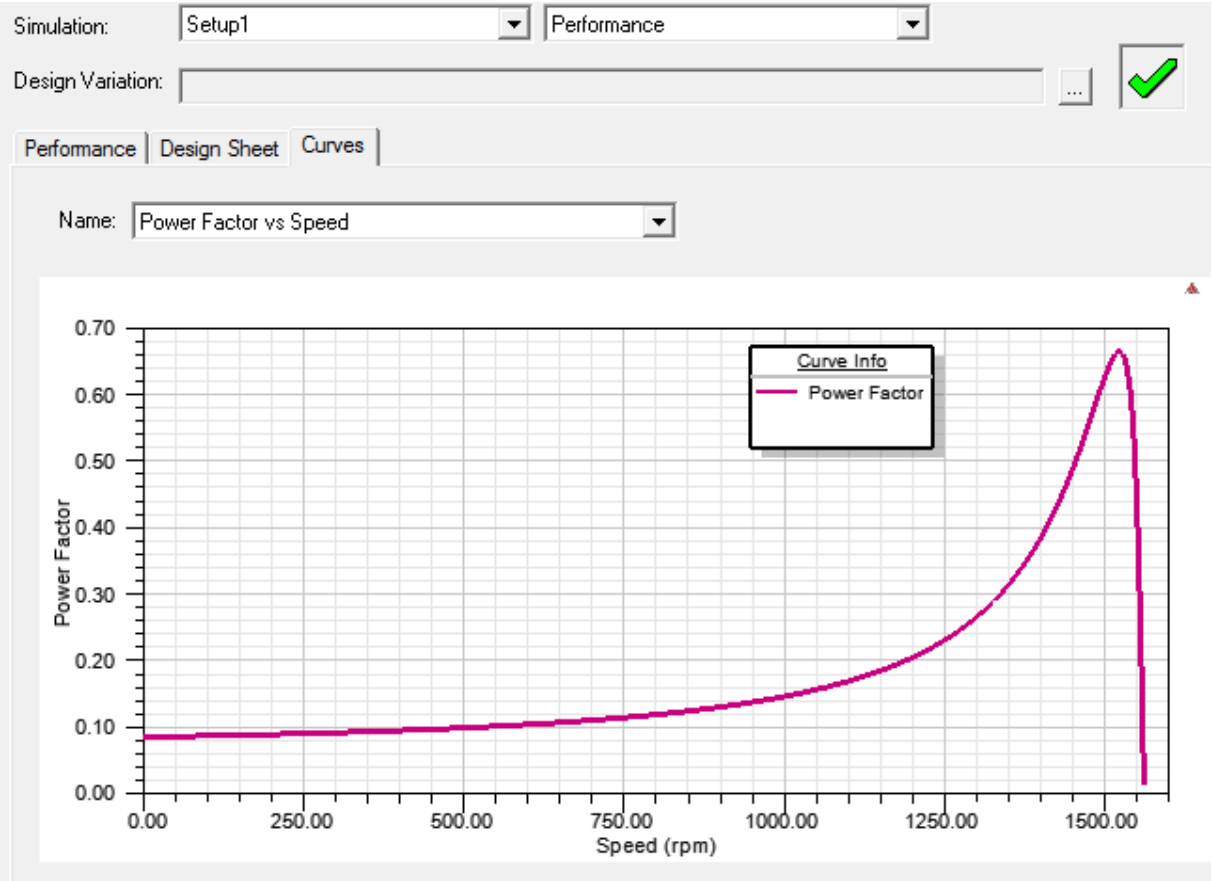


Figure 20 Power Factor vs Speed

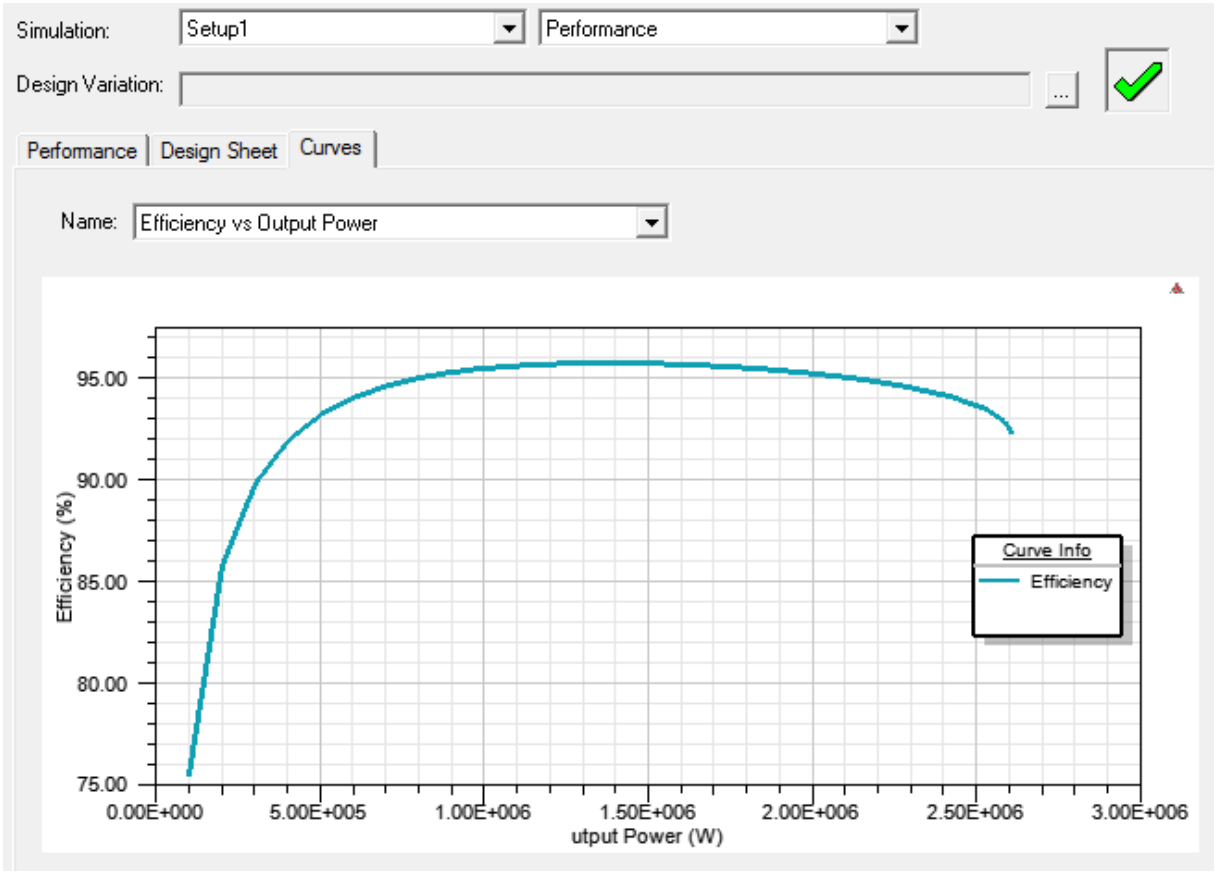


Figure 21 Efficiency vs Output Power

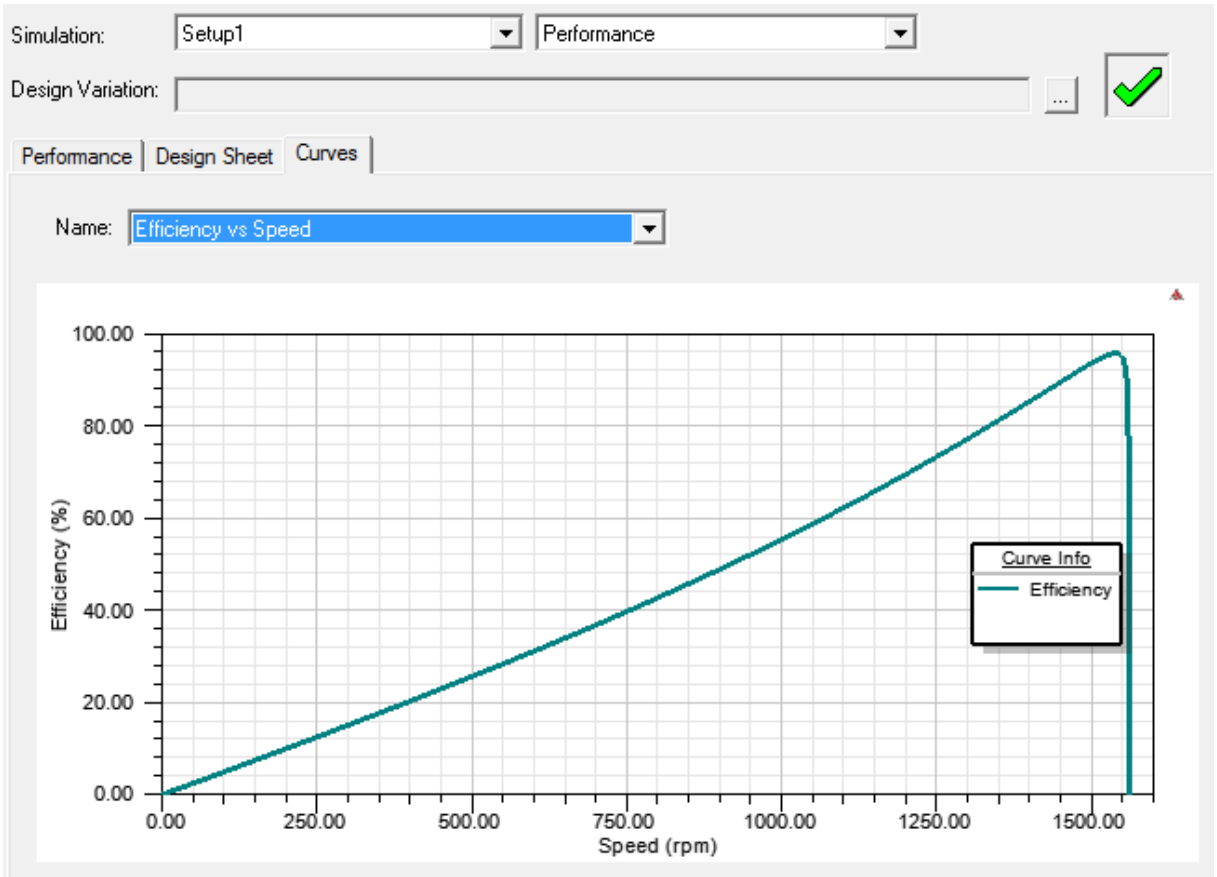


Figure 22 Efficiency vs Speed

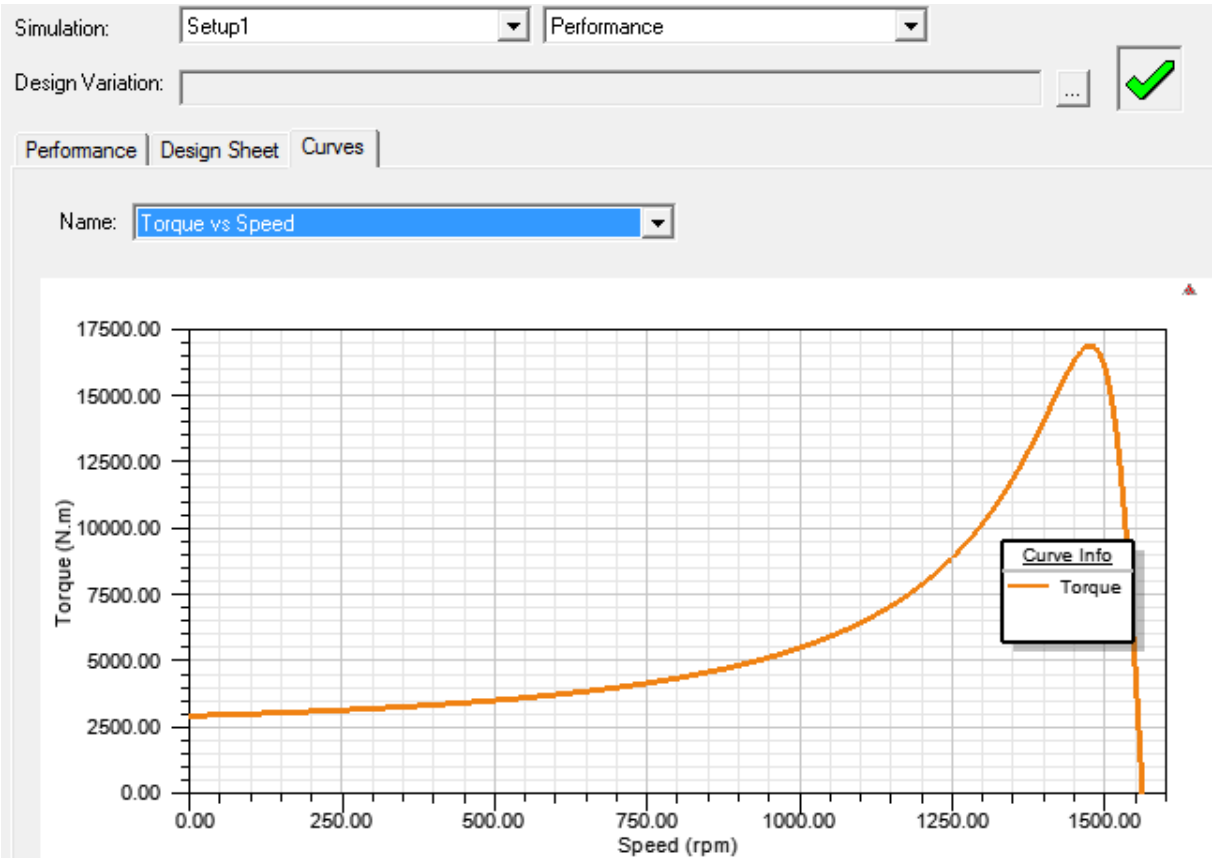


Figure 23 Torque vs Speed

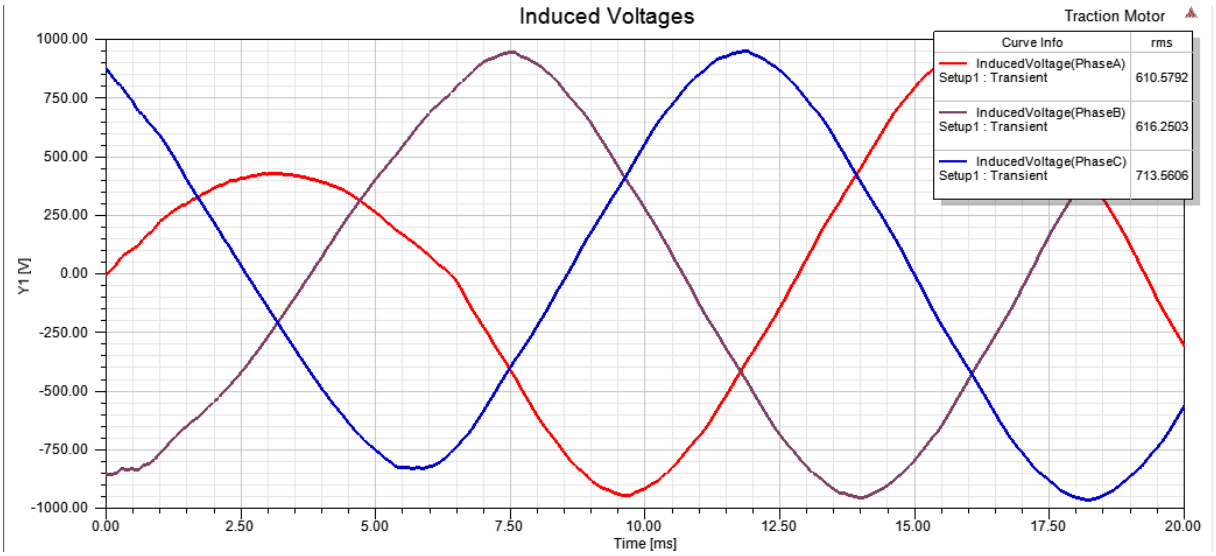


Figure 24 Induced Voltages vs Time

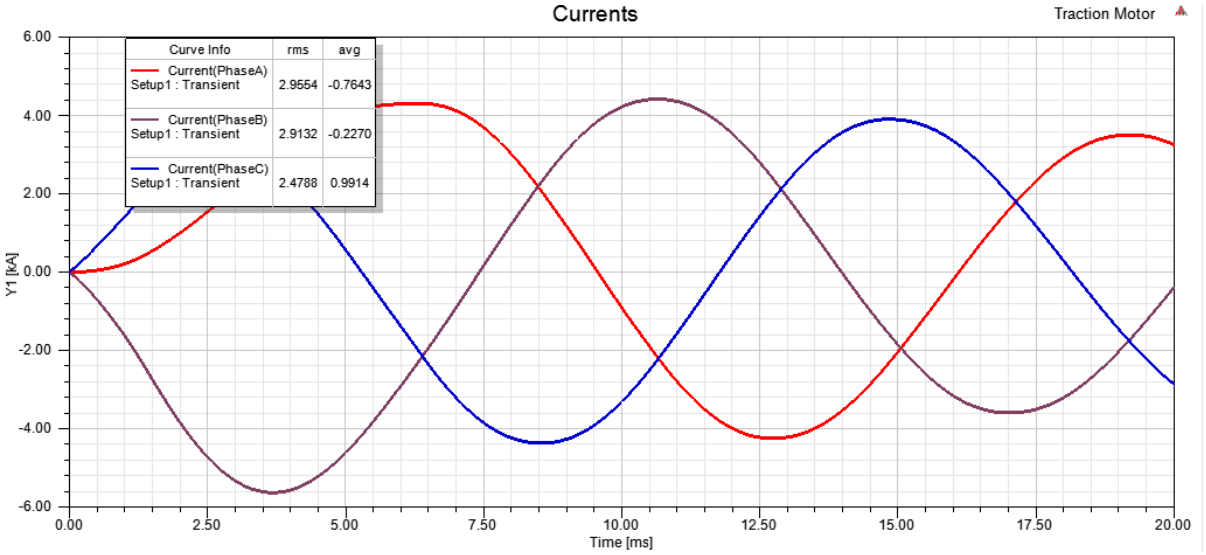


Figure 25 Input Phase Currents

5. CONCLUSION

Basically, algorithm in 2nd project is implemented to design a traction motor. In order to achieve design goals such as overall system efficiency, weight, cost, size, there exist lots of iteration process in Maxwell simulation tool. Firstly, according to given specifications, the relation between torque and motor geometry is found. Here, inner diameter of the core, length of the machine and magnetic flux density in the airgap are unknown. Secondly, suitable length ratio and airgap flux density is chosen. Once they are chosen, basic motor dimensions are determined. Thirdly, in order to get desired emf voltage in the airgap, number of phases and flux per pole are calculated from selection of conductors per slot and pole area considering reasonable magnetic loading value from [1]. Airgap length is calculated from rule of thumb in [1] and then optimized to have optimum magnetizing inductance value. Finally, low number of slots are chosen to have better cooling performance, reduced manufacturing cost, to use slot area more efficiently. In order not to have cogging torque, harmful vibrations and torques, the ratio between number of stator and rotor slots are considered. In addition, rotor slots may be skewed to minimize cogging effect. And then slot dimensions are determined according to back core flux density from saturation point of view of the core. Here copper rotor bars are used to have better efficiency compared to aluminium bars.

All in all, analytical approach is verified via FEA tool as seen above. All design process such as advantages and disadvantages of different stator designs, choices are referred on 'Design of Induction Motors' material [1].

6. REFERENCES

[1] Keysan, O. (2018, 03). *EE564*. Retrieved from Electrical Machine Design: http://keysan.me/ee564/

7. APPENDIX

Three-Phase Induction Machine Design

File: Setup1.res

GENERAL DATA

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): 11

Windage Loss (W): 11

Operation Mode: Motor

Type of Load: Constant Power

Operating Temperature (C): 75

STATOR DATA

Number of Stator Slots: 54

Outer Diameter of Stator (mm): 490

Inner Diameter of Stator (mm): 326

Type of Stator Slot: 1

Stator Slot

hs0 (mm): 1.5

hs2 (mm): 40

bs0 (mm): 4

bs1 (mm): 4.21208

bs2 (mm): 8.87155

Top Tooth Width (mm): 15

Bottom Tooth Width (mm): 15

Length of Stator Core (mm): 250

Stacking Factor of Stator Core: 0.95

Type of Steel: D21_50

Number of lamination sectors 3

Press board thickness (mm): 0

Magnetic press board No

Number of Parallel Branches: 1

Type of Coils: 21

Coil Pitch: 9

Number of Conductors per Slot: 4

Number of Wires per Conductor: 2

Wire Diameter (mm): 10.404

Wire Wrap Thickness (mm): 0

Wedge Thickness (mm): 1

Slot Liner Thickness (mm): 1

Layer Insulation (mm): 1

Slot Area (mm^2): 301.313

Net Slot Area (mm^2): 177.326

Slot Fill Factor (%): 488.334

Limited Slot Fill Factor (%): 75

**** Warning - Result is Unfeasable ****

Slot Fill Factor is beyond its limited value.

Wire Resistivity (ohm.mm^2/m): 0.0217

Conductor Length Adjustment (mm): 0

End Length Correction Factor 1

End Leakage Reactance Correction Factor 1

ROTOR DATA

Number of Rotor Slots: 62

Air Gap (mm): 0.5

Inner Diameter of Rotor (mm): 228

Type of Rotor Slot: 1

Rotor Slot

hs0 (mm): 1.75

hs01 (mm): 0.25

hs2 (mm): 15

bs0 (mm): 2.75

bs1 (mm): 9

bs2 (mm): 2

Cast Rotor: Yes

Half Slot: No

Length of Rotor (mm): 250

Stacking Factor of Rotor Core: 0.95

Type of Steel: D21_50

Skew Width: 1

End Length of Bar (mm): 35

Height of End Ring (mm): 22

Width of End Ring (mm): 65

Resistivity of Rotor Bar

at 75 Centigrade (ohm.mm^2/m): 0.0172414

Resistivity of Rotor Ring

at 75 Centigrade (ohm.mm^2/m): 0.0172414

Magnetic Shaft: Yes

MATERIAL CONSUMPTION

Armature Copper Density (kg/m^3): 8900

Rotor Bar Material Density (kg/m^3): 8933

Rotor Ring Material Density (kg/m^3): 8933

Armature Core Steel Density (kg/m^3): 7820

Rotor Core Steel Density (kg/m^3): 7820

Armature Copper Weight (kg): 168.657

Rotor Bar Material Weight (kg): 21.1982

Rotor Ring Material Weight (kg): 24.0386

Armature Core Steel Weight (kg): 164.987

Rotor Core Steel Weight (kg): 64.4723

Total Net Weight (kg): 443.353

Armature Core Steel Consumption (kg): 296.38

Rotor Core Steel Consumption (kg): 155.023

RATED-LOAD OPERATION

Stator Resistance (ohm): 0.00474145

Stator Resistance at 20C (ohm): 0.00390023

Stator Leakage Reactance (ohm): 0.216592

Rotor Resistance (ohm): 0.0121181

Rotor Leakage Reactance (ohm): 0.0491929

Resistance Corresponding to

Iron-Core Loss (ohm): 81.9648

Magnetizing Reactance (ohm): 1.05315

Stator Phase Current (A): 942.359

Current Corresponding to

Iron-Core Loss (A): 7.6262

Magnetizing Current (A): 593.532

Rotor Phase Current (A): 693.021

Copper Loss of Stator Winding (W): 12631.8

Copper Loss of Rotor Winding (W): 17460.2

Iron-Core Loss (W): 14301

Frictional and Windage Loss (W): 22.5555

Stray Loss (W): 12800

Total Loss (W): 57215.6

Input Power (kW): 1337.38

Output Power (kW): 1280.16

Mechanical Shaft Torque (N.m): 7943.2

Efficiency (%): 95.7218

Power Factor: 0.601129

Rated Slip: 0.0134553

Rated Shaft Speed (rpm): 1539.01

NO-LOAD OPERATION

No-Load Stator Resistance (ohm): 0.00474145

No-Load Stator Leakage Reactance (ohm): 0.21888

No-Load Rotor Resistance (ohm): 0.0121167

No-Load Rotor Leakage Reactance (ohm): 0.0514284

No-Load Stator Phase Current (A): 612.762

No-Load Iron-Core Loss (W): 15239.9

No-Load Input Power (W): 34058.1

No-Load Power Factor: 0.0148367

No-Load Slip: 6.56998e-006

No-Load Shaft Speed (rpm): 1559.99

BREAK-DOWN OPERATION

Break-Down Slip: 0.055

Break-Down Torque (N.m): 16868.7

Break-Down Torque Ratio: 2.12367

Break-Down Phase Current (A): 2177.94

LOCKED-ROTOR OPERATION

Locked-Rotor Torque (N.m): 2942.1

Locked-Rotor Phase Current (A): 3051.16

Locked-Rotor Torque Ratio: 0.370392

Locked-Rotor Current Ratio: 3.23779

Locked-Rotor Stator Resistance (ohm): 0.00474145

Locked-Rotor Stator
Leakage Reactance (ohm): 0.213239

Locked-Rotor Rotor Resistance (ohm): 0.0186448

Locked-Rotor Rotor
Leakage Reactance (ohm): 0.0426497

DETAILED DATA AT RATED OPERATION

Stator Slot Leakage Reactance (ohm): 0.166449

Stator End-Winding Leakage
Reactance (ohm): 0.046989

Stator Differential Leakage
Reactance (ohm): 0.00315298

Rotor Slot Leakage Reactance (ohm): 0.0278572

Rotor End-Winding Leakage
Reactance (ohm): 0.0167335

Rotor Differential Leakage
Reactance (ohm): 0.00315746

Skewing Leakage Reactance (ohm): 0.00144317

Stator Winding Factor: 0.959795

Stator-Teeth Flux Density (Tesla): 2.46744

Rotor-Teeth Flux Density (Tesla): 3.45488

Stator-Yoke Flux Density (Tesla): 3.27224

Rotor-Yoke Flux Density (Tesla): 0.857181

Air-Gap Flux Density (Tesla): 1.8539

Stator-Teeth Ampere Turns (A.T): 3057.43

Rotor-Teeth Ampere Turns (A.T): 3200.06

Stator-Yoke Ampere Turns (A.T): 1844.16

Rotor-Yoke Ampere Turns (A.T): 9.97178

Air-Gap Ampere Turns (A.T): 885.166

Correction Factor for Magnetic
Circuit Length of Stator Yoke: 0.1
Correction Factor for Magnetic
Circuit Length of Rotor Yoke: 0.7
Saturation Factor for Teeth: 8.06929
Saturation Factor for Teeth & Yoke: 10.164
Induced-Voltage Factor: 0.801979

Stator Current Density (A/mm^2): 5.54237
Specific Electric Loading (A/mm): 198.748
Stator Thermal Load (A^2/mm^3): 1101.53

Rotor Bar Current Density (A/mm^2): 20.0921
Rotor Ring Current Density (A/mm^2): 5.35077

Half-Turn Length of
Stator Winding (mm): 515.988

WINDING ARRANGEMENT

The 3-phase, 2-layer winding can be arranged in 9 slots as below:

AAAZZZBBB

Angle per slot (elec. degrees): 20
Phase-A axis (elec. degrees): 110
First slot center (elec. degrees): 0

TRANSIENT FEA INPUT DATA

For one phase of the Stator Winding:

Number of Turns:	36
Parallel Branches:	1
Terminal Resistance (ohm):	0.00474145
End Leakage Inductance (H):	9.58787e-005

For Rotor End Ring Between Two Bars of One Side:

Equivalent Ring Resistance (ohm):	6.64954e-007
Equivalent Ring Inductance (H):	8.36188e-009

2D Equivalent Value:

Equivalent Model Depth (mm):	250
Equivalent Stator Stacking Factor:	0.95
Equivalent Rotor Stacking Factor:	0.95

Estimated Rotor Inertial Moment (kg m^2): 2.13584