EE564 PROJECT #2

MOTOR WINDING DESIGN AND ANALYSIS

CİHAN AYDAR

2043677

TABLE OF CONTENTS

1. INTRODUCTION 3
2. WINDING DESIGN 3
3. MOTOR PARAMETER ESTIMATION 5
4. DETAILED ANALYSIS AND VERIFICATION 6
4.1 INPUTS 6
4.2 OUTPUTS 10
5. CONCLUSION 23
6. REFERENCES 24

LIST OF TABLES

Table 1 Winding Design Parameters 4
Table 2 Winding Design Calculations 4
Table 3 Winding Diagram 5
Table 4 ..... **Hata! Yer işareti tanımlanmamış.**

LIST OF FIGURES

Figure 1 MMF Waveform 5
Figure 2 Stator Inputs 6
Figure 3 Stator Geometry 7
Figure 4 Stator Winding 7
Figure 5 Stator Insulation 7
Figure 6 B-H Characteristics 8
Figure 7 Rotor Structure 8
Figure 8 Rotor Geometry 9
Figure 9 Input Data 9
Figure 11 Locked Rotor Operation 10
Figure 12 Material Consumption 11
Figure 13 No Load Operation 12
Figure 14 Rated Electric Data 12
Figure 15 Rated Magnetic Data 13
Figure 16 Rated Parameters 14
Figure 17 Rated Performance 14
Figure 18 Stator Slot Geometry 15
Figure 19 Stator Winding 16
Figure 20 Phase Current vs Output Power 16
Figure 21 Phase Current vs Speed 17
Figure 22 Power Factor vs Output Power 17

Figure 23 Power Factor vs Speed 18
Figure 24 Efficiency vs Output Power........ 19
Figure 25 Efficiency vs Speed 19
Figure 26 Torque vs Speed 20
Figure 27 Induced Voltages vs Time........ 20

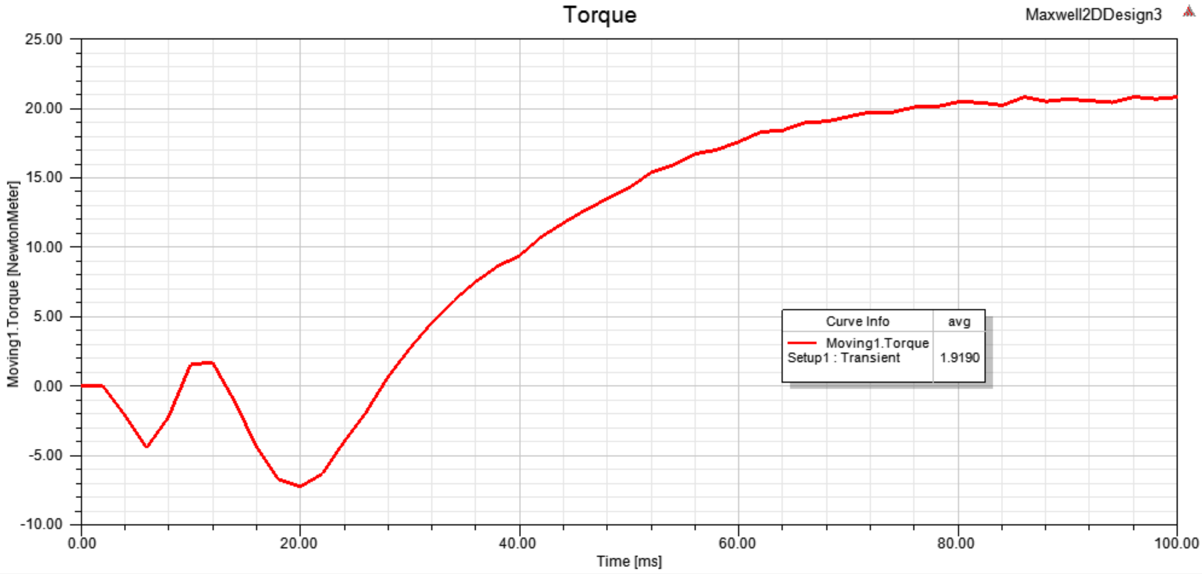


Figure 28 Torque vs Time 21
Figure 29 Power vs Time 21
Figure 30 Input Phase Currents 22
Figure 31 Flux Lines 22
Figure 32 Magnitude of Magnetic Flux Density 23
Figure 33 Magnetic Flux Density Vector........ 23

1. INTRODUCTION

The main purposes of project are to design three phase induction motor and then verify it in a FEA program.

2. WINDING DESIGN

Firstly, lamination 1 is chosen for induction motor design. All calculation methods can be seen in 'Winding Design' excel file.

Number of Poles	4				
Type of Winding	Integral, Double Layer, Distributed Winding	3. H	5. H	7. H	9. H
Winding Factors	0,9598	0,66667	0,21757	-0,1774	-0,3333
Number of Turns	180				
Wire Size	14AWG	<	2,177	(mm^2)	
Fill Factor	0,7				
Winding Connection	wye				
Voltage Rating (V)	380				
Current Rating (A)	4,6				

Output Power Rating (W)	3000				
Frequency	50				
Input Power Rating (W)	3308,15				

Table 1 Winding Design Parameters

Number of StatorSlots	36	
Slots per Pole	9	
Slot per Pole per Phase	3	
Slot Angle (degree)	20	0,34907
Conductors per Slot	30	
Nphase	180	

Table 2 Winding Design Calculations

A			C-			B		
a1	a2	a3	c10-	c11-	c12-	b1	b2	b3
a10	a11	a12	c7-	c8-	c9-	b10	b11	b12

A-			C			B-		
a4-	a5-	a6-	c1	c2	c3	b4-	b5-	b6-
a1-	a2-	a3-	c10	c11	c12	b1-	b2-	b3-

A			C-			B		
a7	a8	a9	c4-	c5-	c6-	b7	b8	b9
a4	a5	a6	c1-	c2-	c3-	b4	b5	b6

A-			C			B-		
a10-	a11-	a12-	c7	c8	c9	b10-	b11-	b12-
a7-	a8-	a9-	c4	c5	c6	b7-	b8-	b9-

Table 3 Winding Diagram

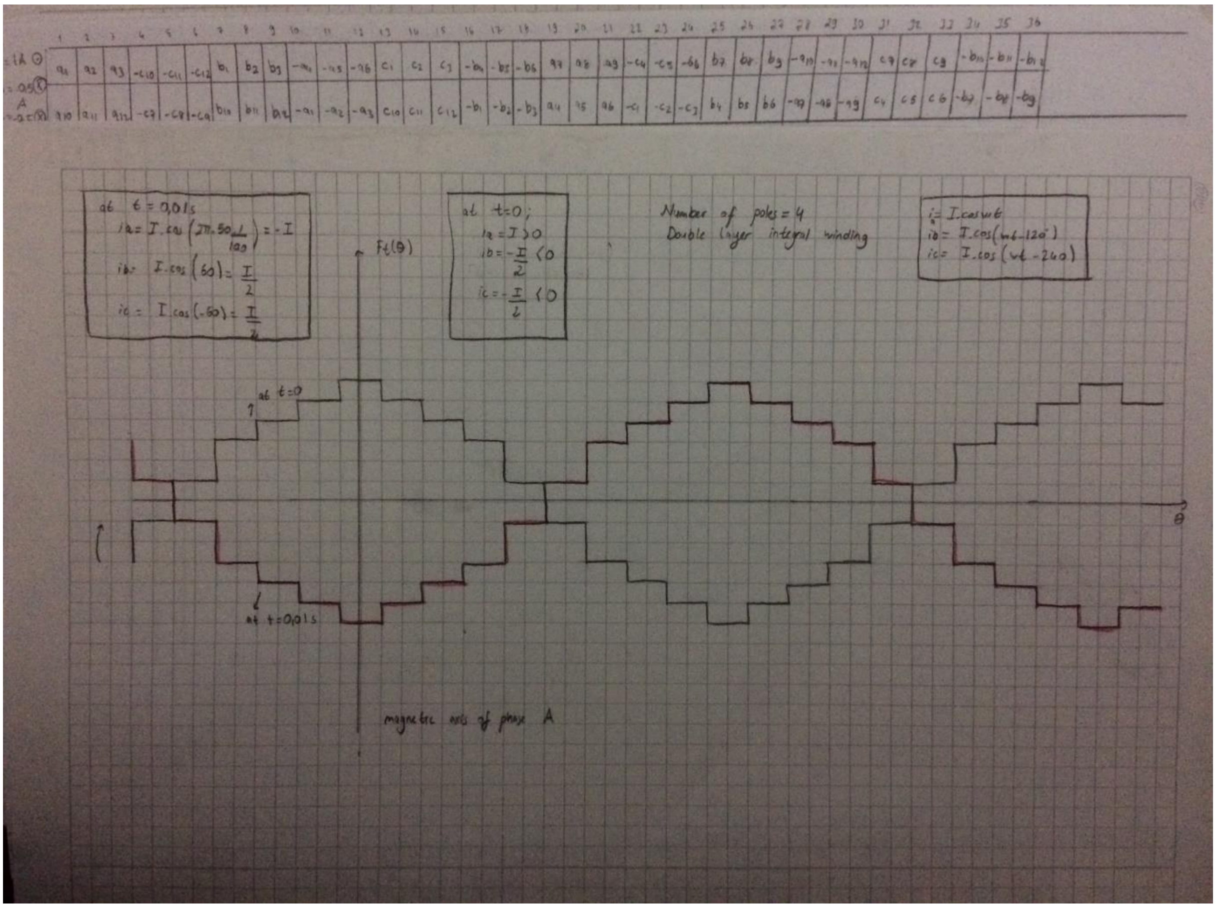


Figure 1 MMF Waveform

3. MOTOR PARAMETER ESTIMATION

Flux per Pole (Wb)	0,00572		
Bavg (T)	0,31667		
Airgap Clearance (m)	0,001		
Torque (N.m)	20,4628		
Speed (rad/s)	146,608	1400	rpm

Axial Length (m)	Di (m)	Do (m)	A (mm^2)
0,2	0,115	0,17	93,3

Specific Magnetic Loading (T)	Flux Density in Teeth (T)	Flux Density in Core (T)	Specific Electric Loading-q (A/m)
0,316665866	1,5	1,5	16962,62751

Full-Load Efficiency	Full-Load Power Factor	ns (rps)	Output Coefficient	D^2.L(m^3)
0,90685043	0,8	25	41,14255258	0,002645

Pole Pitch (m)	l_mt (m)	Phase Resistance (ohm)	Stator Copper Losses (W)
0,090320789	0,84774	3,081200902	195,5946332
		(17AWG-1,04mm^2)	

Phase Inductance (mH)	Leakage Inductance (mH)	Core Mass (kg)	Core Loss (W)
20,3575204	-	35,63587087	33,85407732

Table 4 Calculation Results

4. DETAILED ANALYSIS AND VERIFICATION

4.1 INPUTS

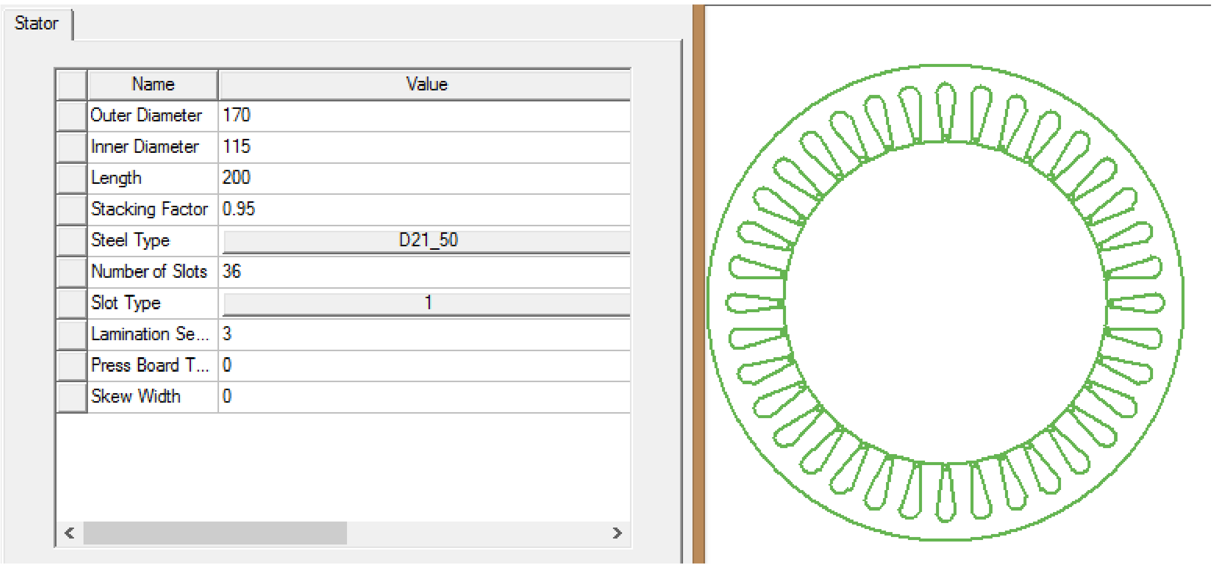


Figure 2 Stator Inputs

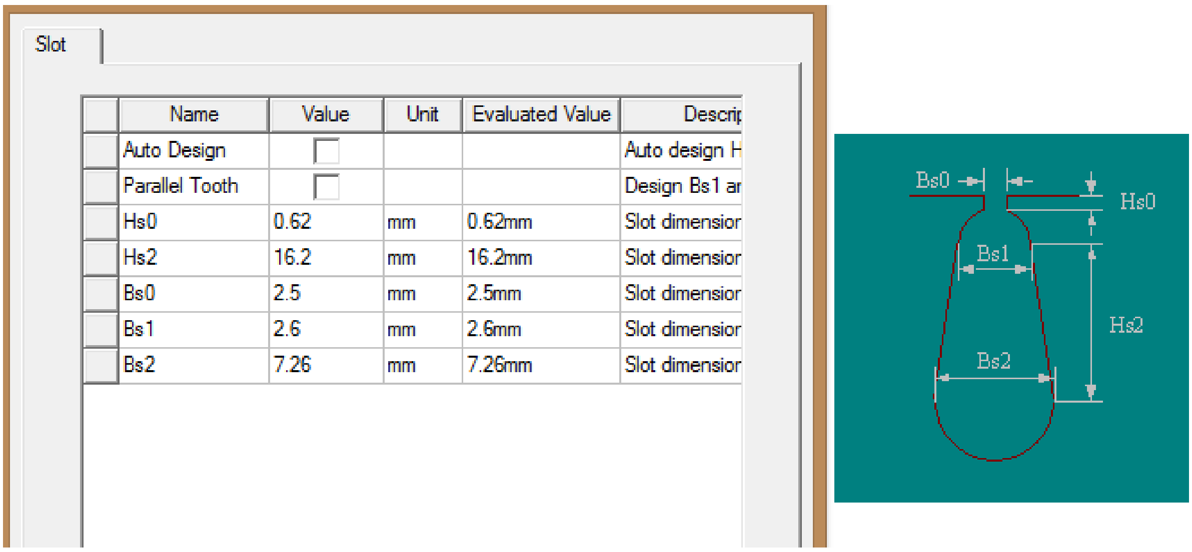


Figure 3 Stator Geometry

Winding | End/Insulation

Name	Value	Unit
Winding Layers	2	
Winding Type	Whole-Coiled	
Parallel Branches	1	
Conductors per Slot	30	
Coil Pitch	9	
Number of Strands	0	
Wire Wrap	0	mm
Wire Size	Diameter: 1.151mm	

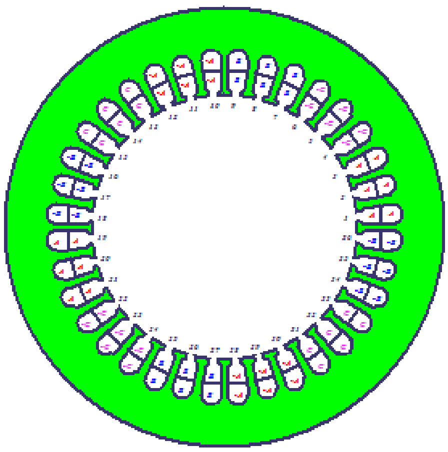


Figure 4 Stator Winding

Winding | End/Insulation

Name	Value	Unit	Evaluated
Input Half-turn Length	✔		
Half Turn Length	0	mm	0mm
Base Inner Radius	10	mm	
Tip Inner Diameter	2	mm	
End Clearance	1	mm	
Slot Liner	1	mm	
Wedge Thickness	1	mm	
Layer Insulation	0	mm	
Limited Fill Factor	0.7		

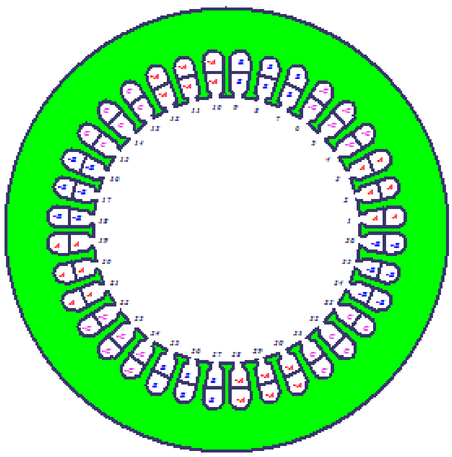


Figure 5 Stator Insulation

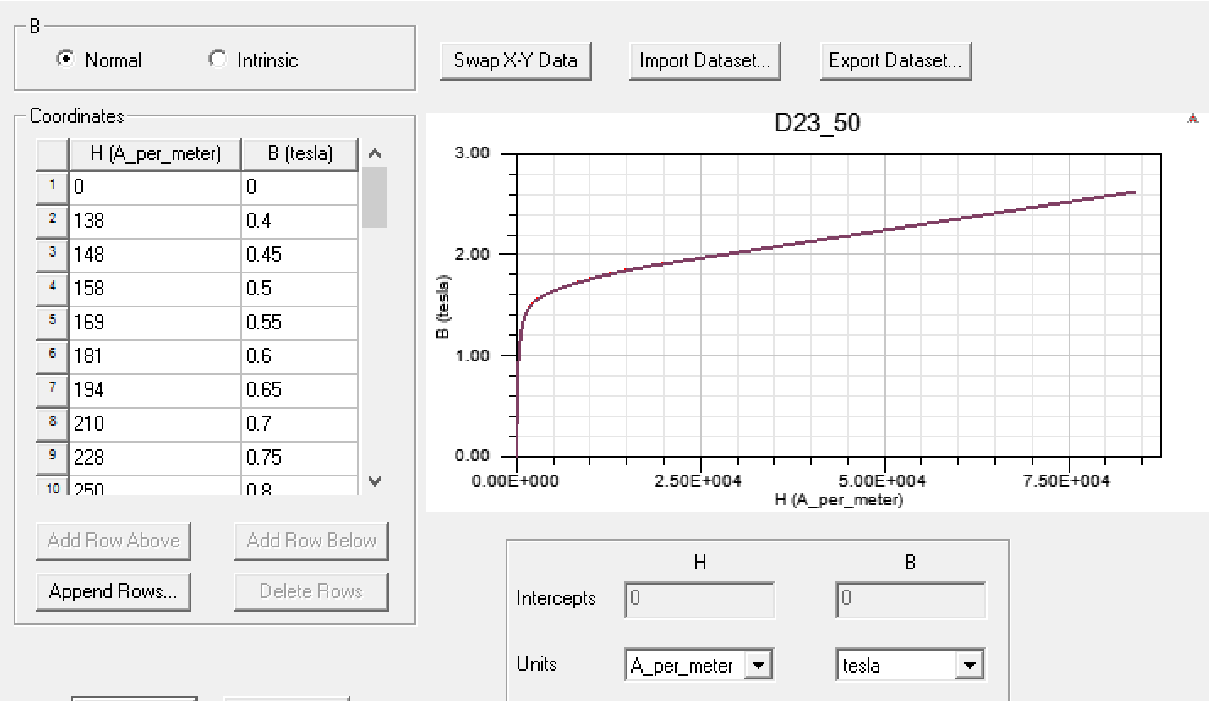


Figure 6 B-H Characteristics

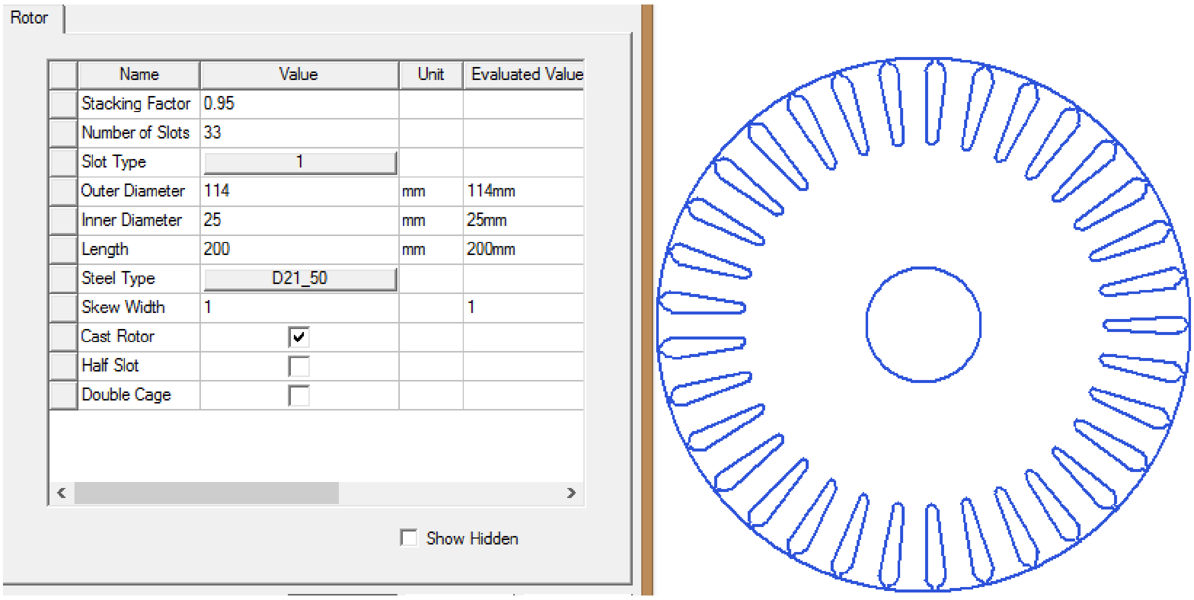


Figure 7 Rotor Structure

Slot

	Name	Value	Unit	Evaluated Value	Descrip
	Hs0	0.7	mm	0.7mm	Slot dimensior
	Hs01	0.1	mm	0.1mm	Slot dimensior
	Hs2	15	mm	15mm	Slot dimensior
	Bs0	1.1	mm	1.1mm	Slot dimensior
	Bs1	4.31	mm	4.31mm	Slot dimensior
	Bs2	2	mm	2mm	Slot dimensior

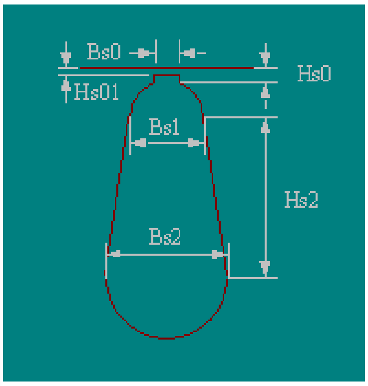


Figure 8 Rotor Geometry

Simulation: Setup1 Performance

Design Variation:

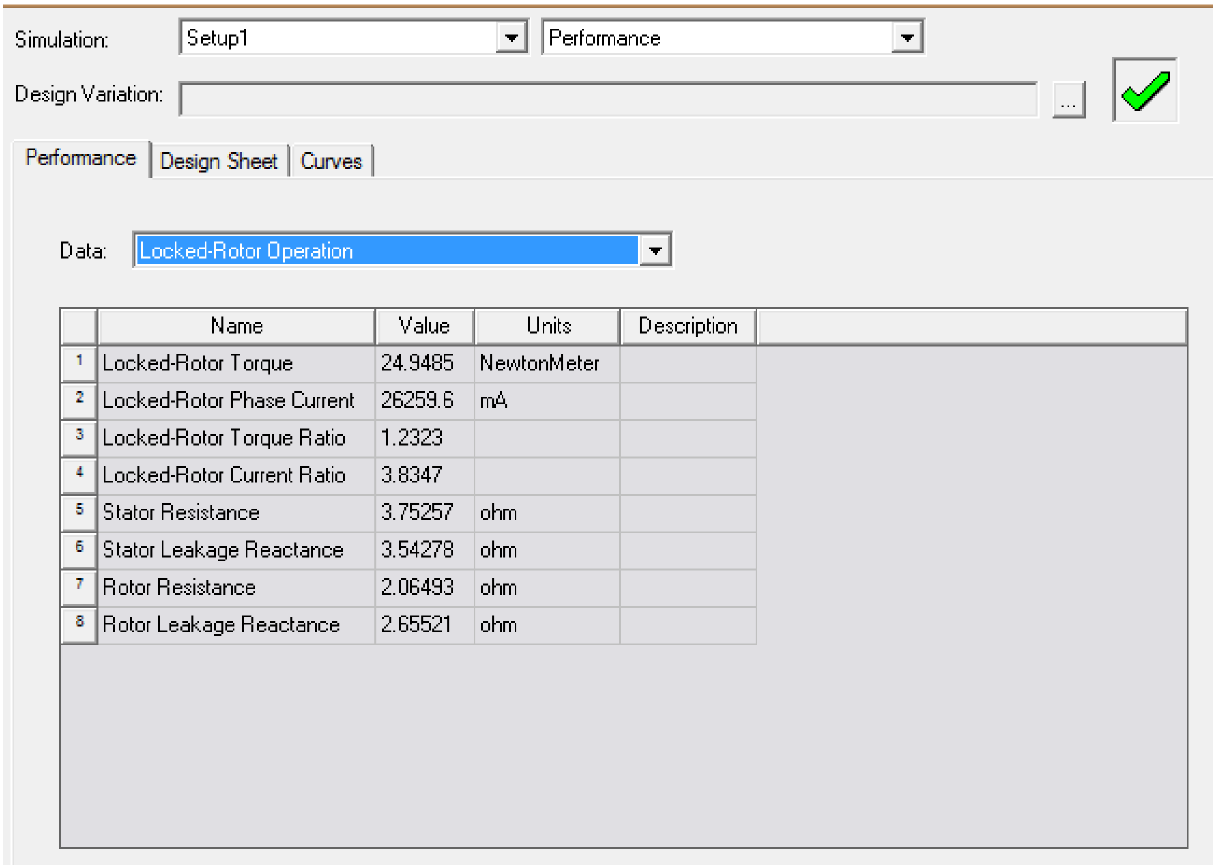
Performance | Design Sheet | Curves

Data: FEA Input Data

	Name	Value	Units	Description
1	Armature Parallel Branches	1		
2	Equivalent Model Depth	200	mm	
3	Equivalent Stator Stacking Factor	0.95		
4	Equivalent Rotor Stacking Factor	0.95		
5	Region Depth	351.326	mm	
6	Unit Fractions	1		

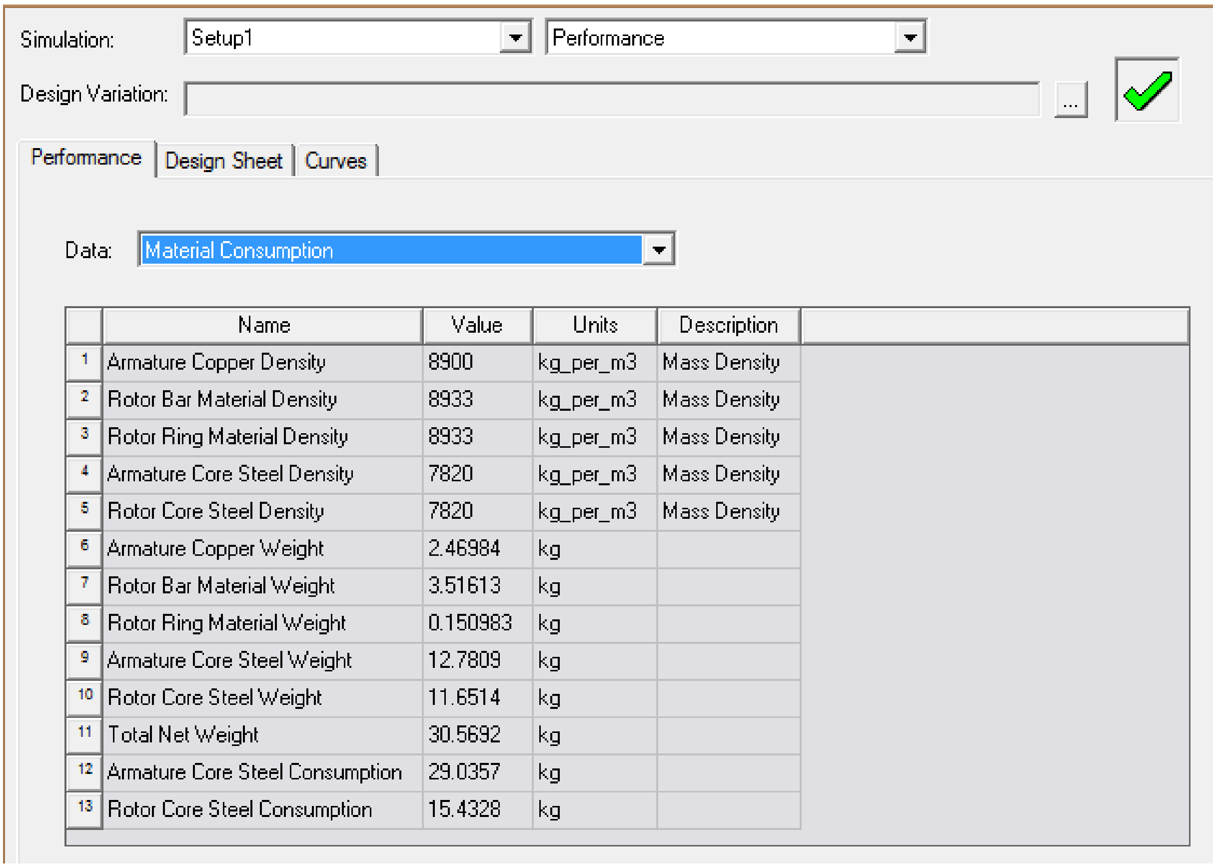
Figure 9 Input Data

4.2 OUTPUTS



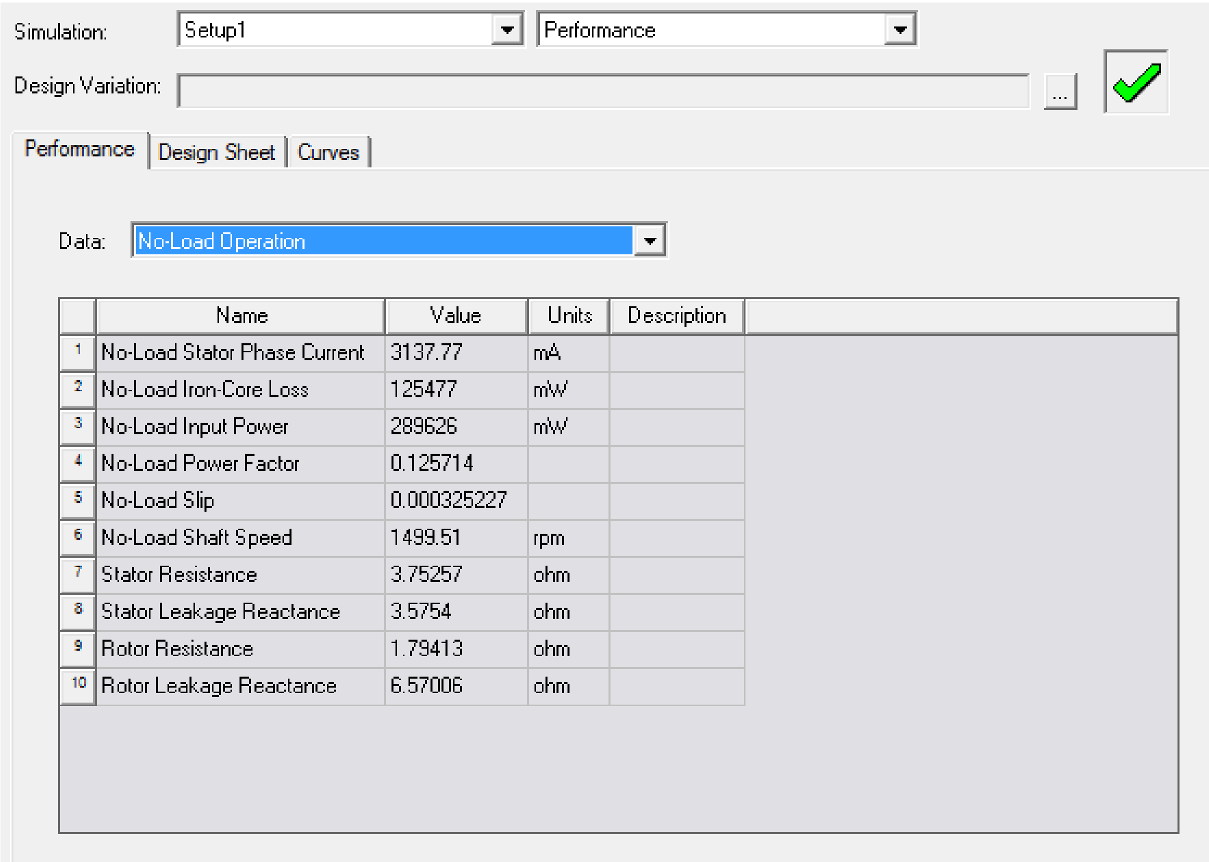
	Name	Value	Units	Description
1	Locked-Rotor Torque	24.9485	NewtonMeter	
2	Locked-Rotor Phase Current	26259.6	mA	
3	Locked-Rotor Torque Ratio	1.2323		
4	Locked-Rotor Current Ratio	3.8347		
5	Stator Resistance	3.75257	ohm	
6	Stator Leakage Reactance	3.54278	ohm	
7	Rotor Resistance	2.06493	ohm	
8	Rotor Leakage Reactance	2.65521	ohm	

Figure 10 Locked Rotor Operation



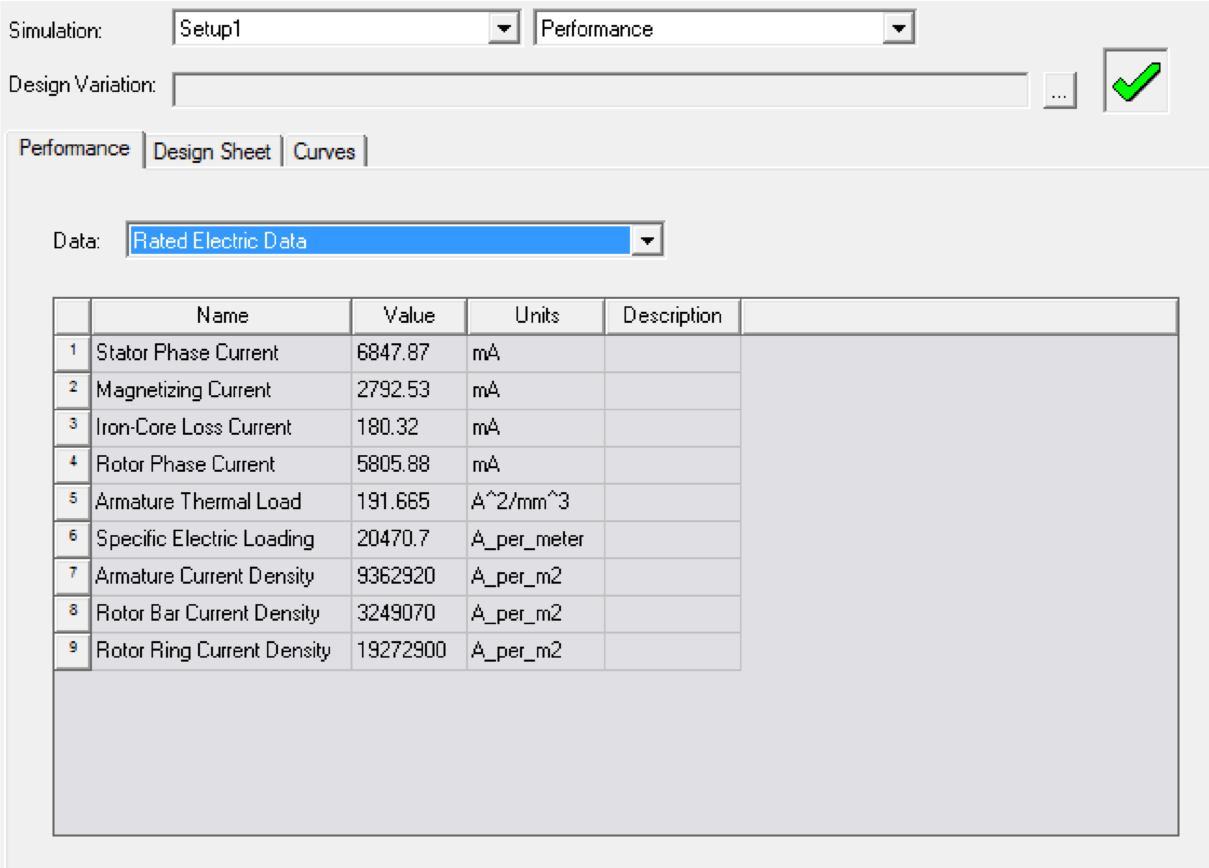
	Name	Value	Units	Description
1	Armature Copper Density	8900	kg_per_m3	Mass Density
2	Rotor Bar Material Density	8933	kg_per_m3	Mass Density
3	Rotor Ring Material Density	8933	kg_per_m3	Mass Density
4	Armature Core Steel Density	7820	kg_per_m3	Mass Density
5	Rotor Core Steel Density	7820	kg_per_m3	Mass Density
6	Armature Copper Weight	2.46984	kg	
7	Rotor Bar Material Weight	3.51613	kg	
8	Rotor Ring Material Weight	0.150983	kg	
9	Armature Core Steel Weight	12.7809	kg	
10	Rotor Core Steel Weight	11.6514	kg	
11	Total Net Weight	30.5692	kg	
12	Armature Core Steel Consumption	29.0357	kg	
13	Rotor Core Steel Consumption	15.4328	kg	

Figure 11 Material Consumption



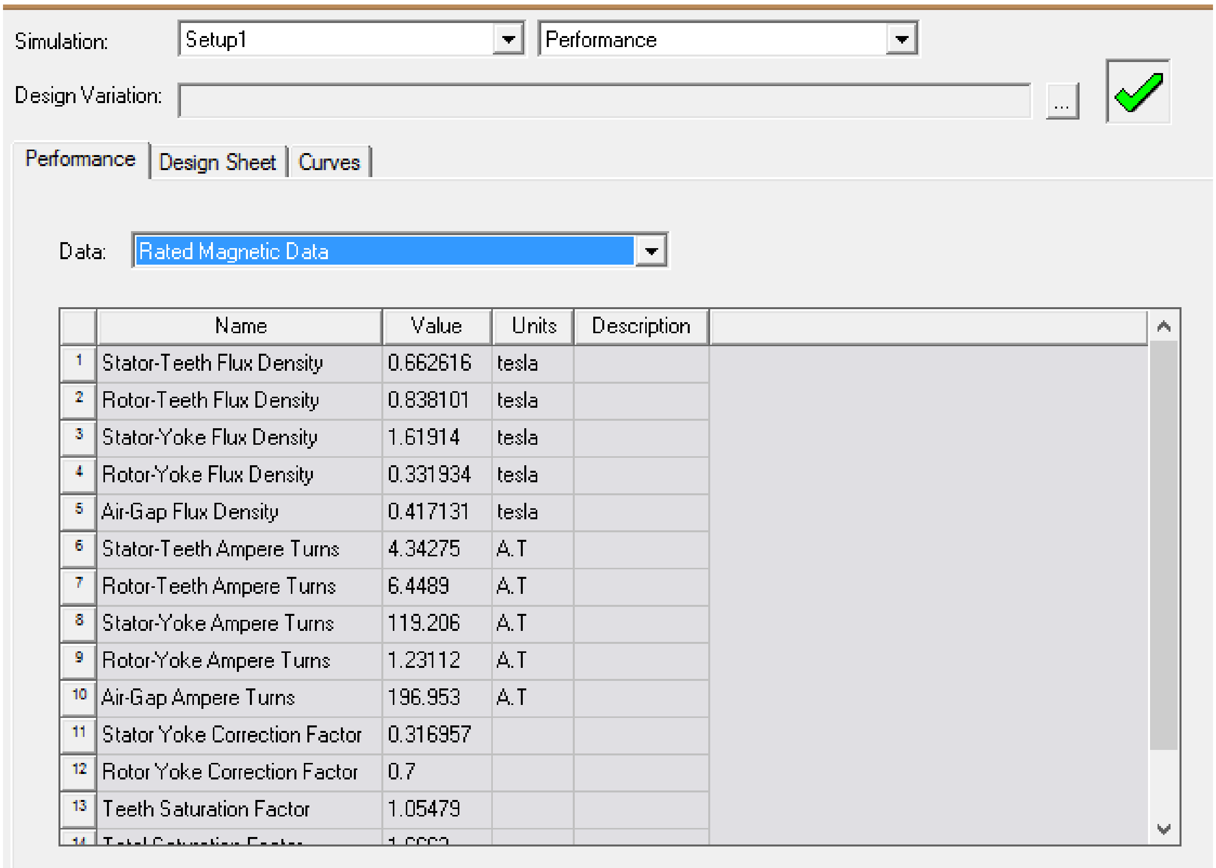
	Name	Value	Units	Description
1	No-Load Stator Phase Current	3137.77	mA	
2	No-Load Iron-Core Loss	125477	mW	
3	No-Load Input Power	289626	mW	
4	No-Load Power Factor	0.125714		
5	No-Load Slip	0.000325227		
6	No-Load Shaft Speed	1499.51	rpm	
7	Stator Resistance	3.75257	ohm	
8	Stator Leakage Reactance	3.5754	ohm	
9	Rotor Resistance	1.79413	ohm	
10	Rotor Leakage Reactance	6.57006	ohm	

Figure 12 No Load Operation



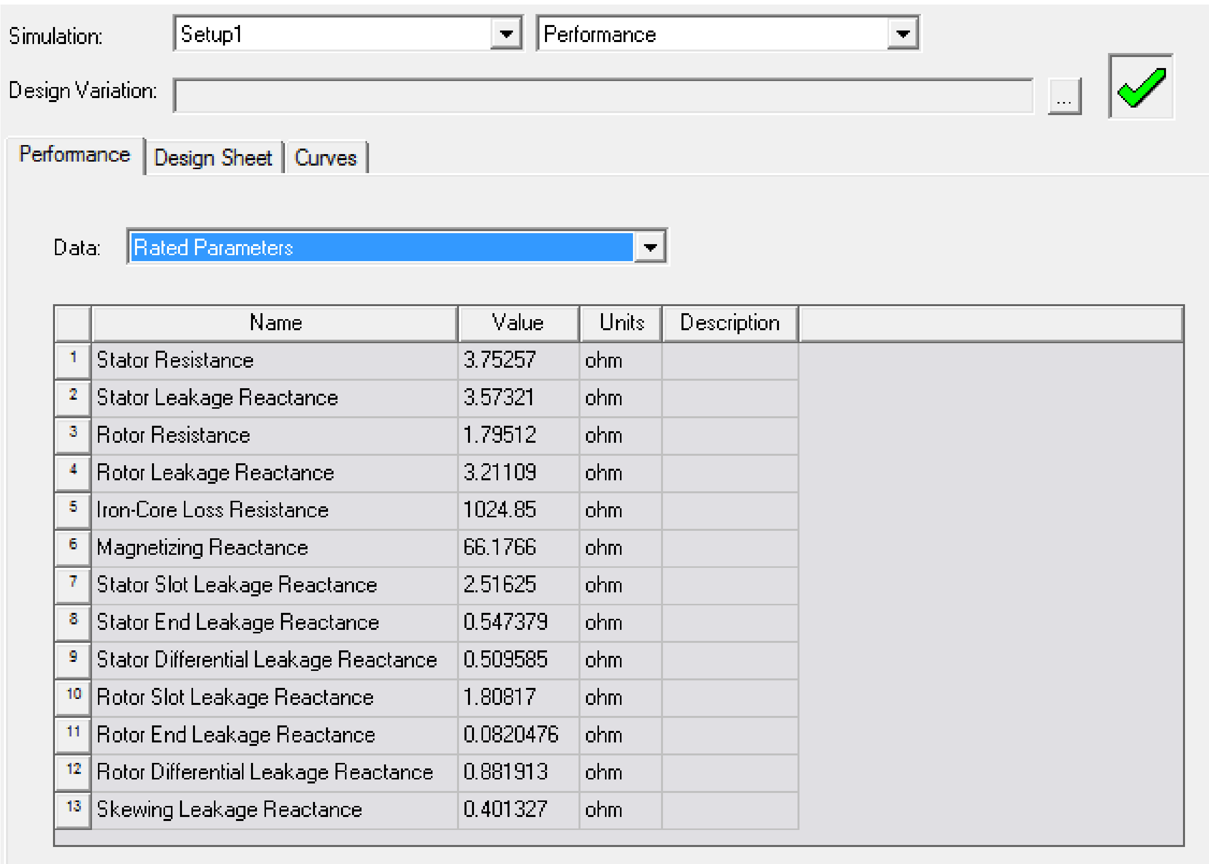
	Name	Value	Units	Description
1	Stator Phase Current	6847.87	mA	
2	Magnetizing Current	2792.53	mA	
3	Iron-Core Loss Current	180.32	mA	
4	Rotor Phase Current	5805.88	mA	
5	Armature Thermal Load	191.665	A^2/mm^3	
6	Specific Electric Loading	20470.7	A_per_meter	
7	Armature Current Density	9362920	A_per_m2	
8	Rotor Bar Current Density	3249070	A_per_m2	
9	Rotor Ring Current Density	19272900	A_per_m2	

Figure 13 Rated Electric Data



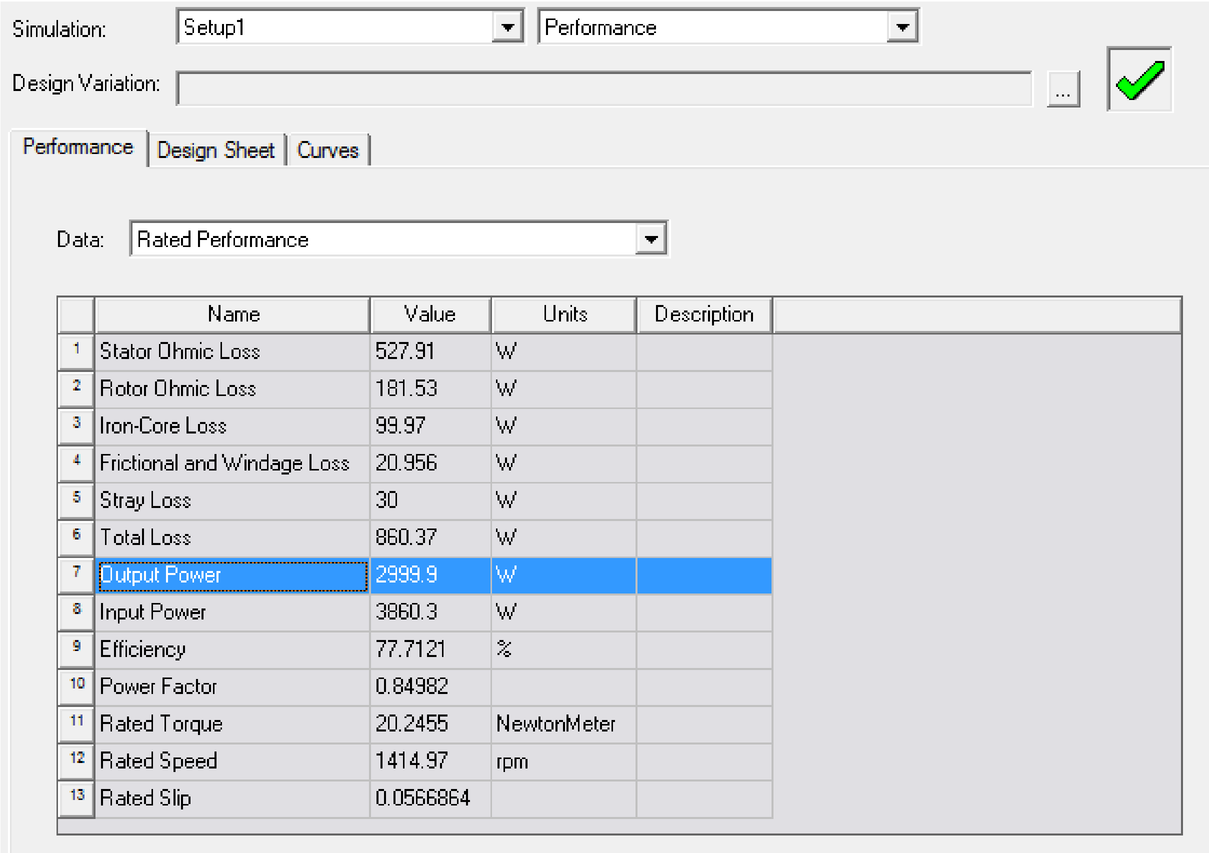
	Name	Value	Units	Description
1	Stator-Teeth Flux Density	0.662616	tesla	
2	Rotor-Teeth Flux Density	0.838101	tesla	
3	Stator-Yoke Flux Density	1.61914	tesla	
4	Rotor-Yoke Flux Density	0.331934	tesla	
5	Air-Gap Flux Density	0.417131	tesla	
6	Stator-Teeth Ampere Turns	4.34275	A.T	
7	Rotor-Teeth Ampere Turns	6.4489	A.T	
8	Stator-Yoke Ampere Turns	119.206	A.T	
9	Rotor-Yoke Ampere Turns	1.23112	A.T	
10	Air-Gap Ampere Turns	196.953	A.T	
11	Stator Yoke Correction Factor	0.316957		
12	Rotor Yoke Correction Factor	0.7		
13	Teeth Saturation Factor	1.05479		

Figure 14 Rated Magnetic Data



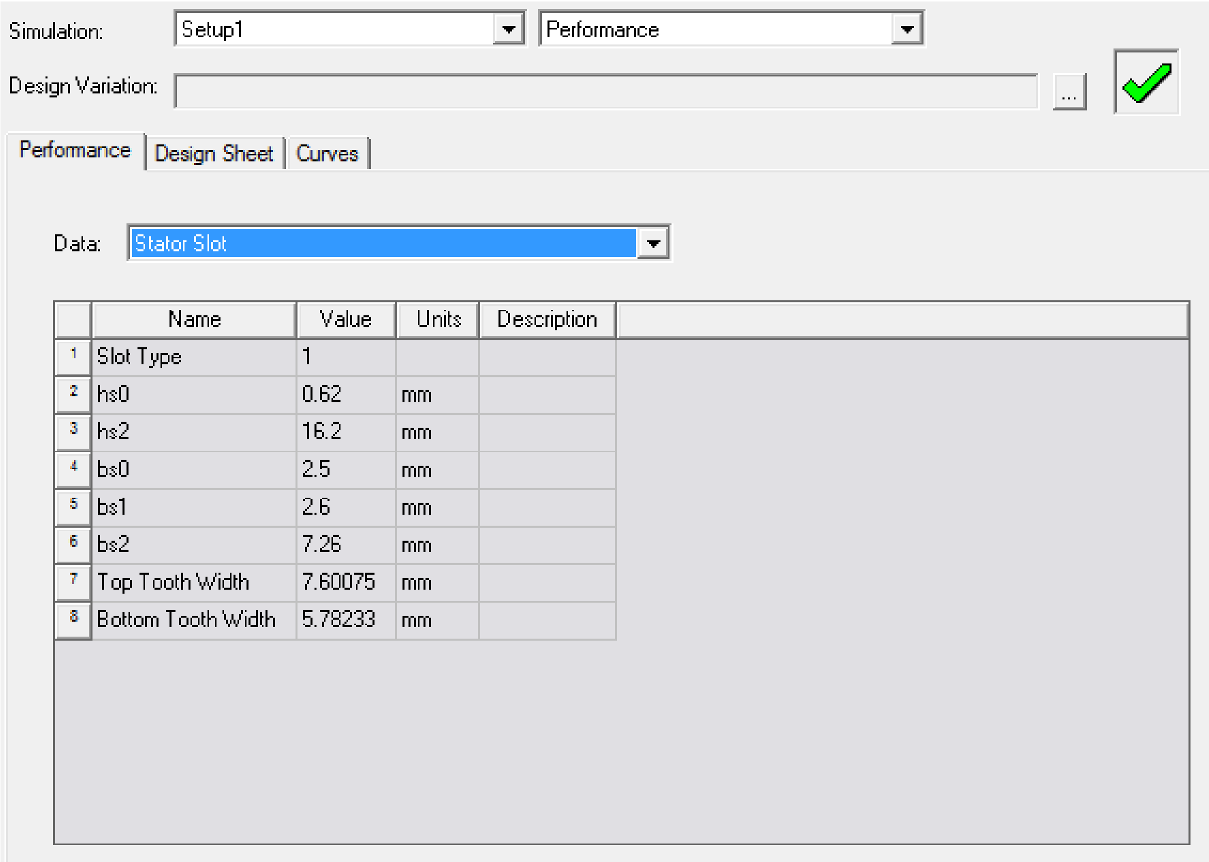
	Name	Value	Units	Description
1	Stator Resistance	3.75257	ohm	
2	Stator Leakage Reactance	3.57321	ohm	
3	Rotor Resistance	1.79512	ohm	
4	Rotor Leakage Reactance	3.21109	ohm	
5	Iron-Core Loss Resistance	1024.85	ohm	
6	Magnetizing Reactance	66.1766	ohm	
7	Stator Slot Leakage Reactance	2.51625	ohm	
8	Stator End Leakage Reactance	0.547379	ohm	
9	Stator Differential Leakage Reactance	0.509585	ohm	
10	Rotor Slot Leakage Reactance	1.80817	ohm	
11	Rotor End Leakage Reactance	0.0820476	ohm	
12	Rotor Differential Leakage Reactance	0.881913	ohm	
13	Skewing Leakage Reactance	0.401327	ohm	

Figure 15 Rated Parameters



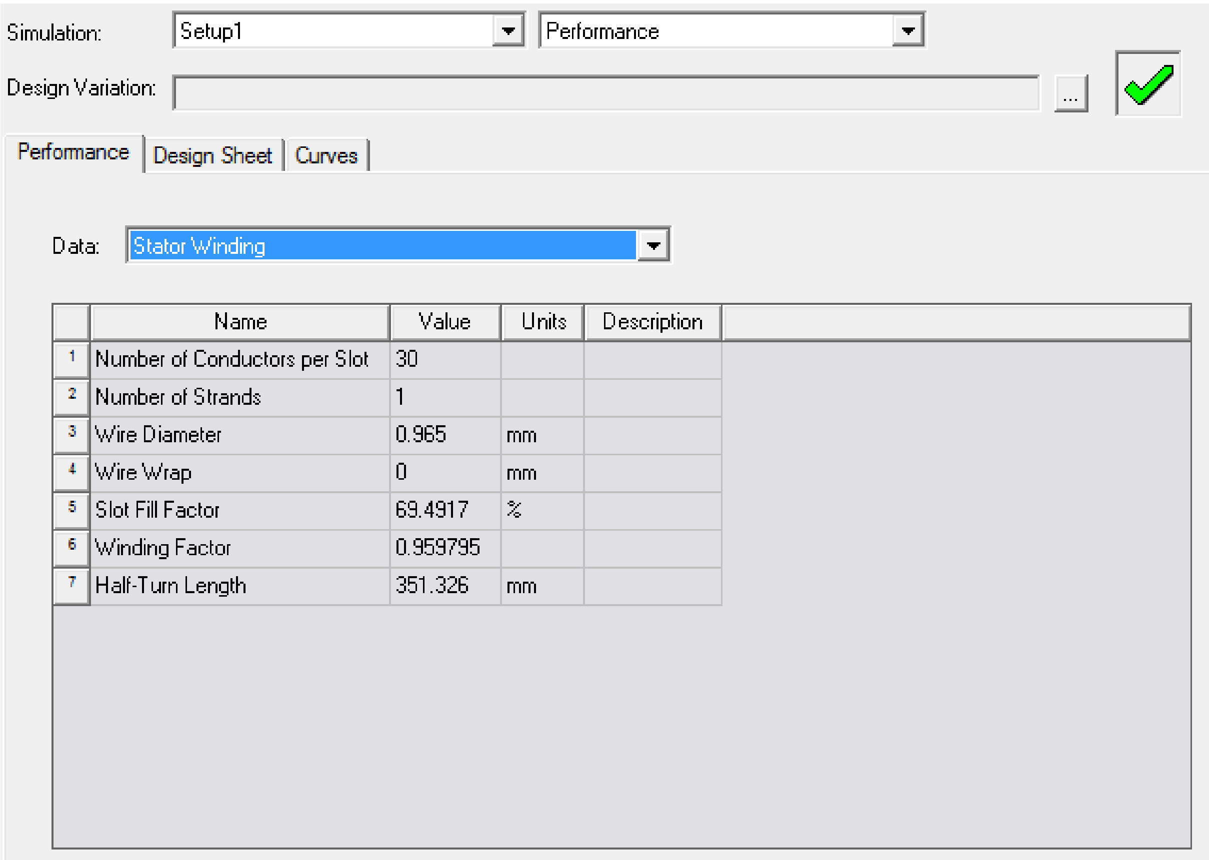
	Name	Value	Units	Description
1	Stator Ohmic Loss	527.91	W	
2	Rotor Ohmic Loss	181.53	W	
3	Iron-Core Loss	99.97	W	
4	Frictional and Windage Loss	20.956	W	
5	Stray Loss	30	W	
6	Total Loss	860.37	W	
7	Output Power	2999.9	W	
8	Input Power	3860.3	W	
9	Efficiency	77.7121	%	
10	Power Factor	0.84982		
11	Rated Torque	20.2455	NewtonMeter	
12	Rated Speed	1414.97	rpm	
13	Rated Slip	0.0566864		

Figure 16 Rated Performance



	Name	Value	Units	Description
1	Slot Type	1		
2	hs0	0.62	mm	
3	hs2	16.2	mm	
4	bs0	2.5	mm	
5	bs1	2.6	mm	
6	bs2	7.26	mm	
7	Top Tooth Width	7.60075	mm	
8	Bottom Tooth Width	5.78233	mm	

Figure 17 Stator Slot Geometry



	Name	Value	Units	Description
1	Number of Conductors per Slot	30		
2	Number of Strands	1		
3	Wire Diameter	0.965	mm	
4	Wire Wrap	0	mm	
5	Slot Fill Factor	69.4917	%	
6	Winding Factor	0.959795		
7	Half-Turn Length	351.326	mm	

Figure 18 Stator Winding

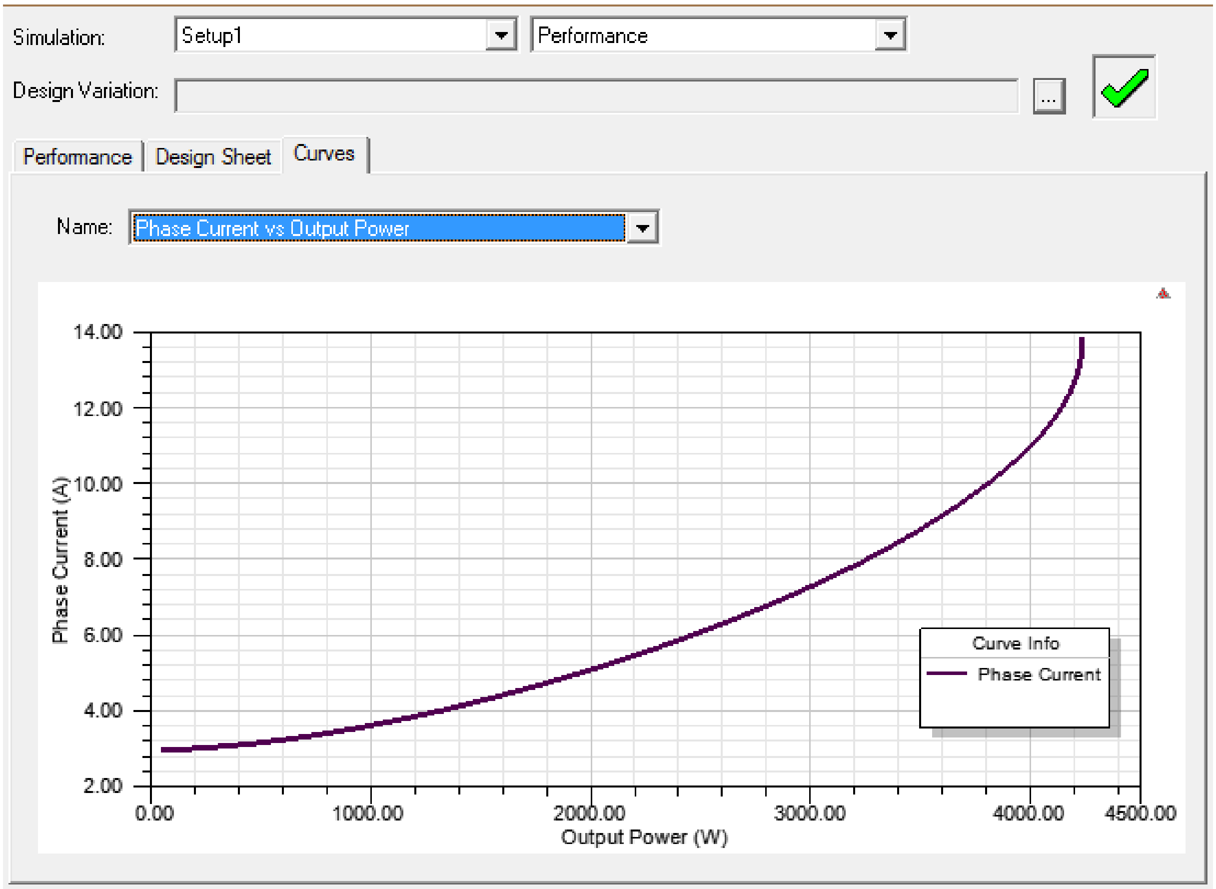


Figure 19 Phase Current vs Output Power

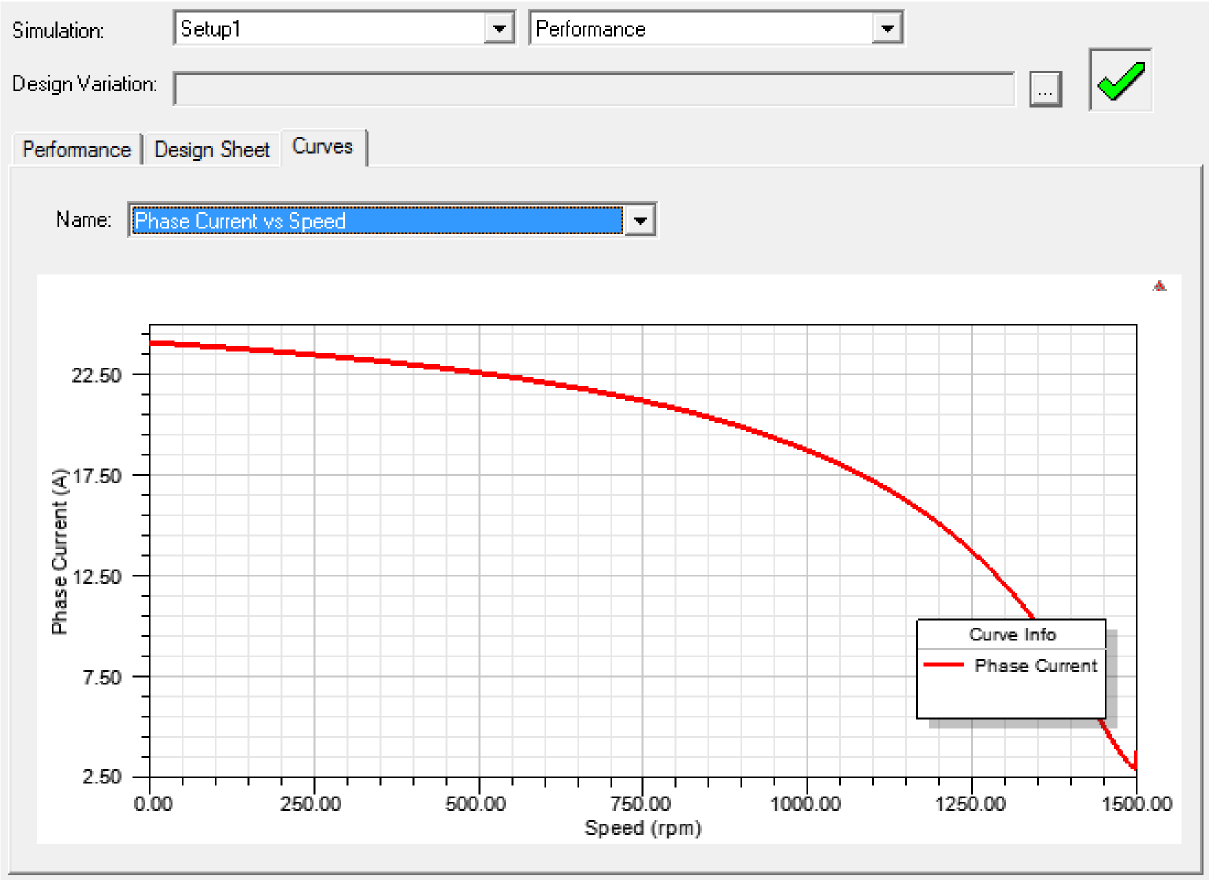


Figure 20 Phase Current vs Speed

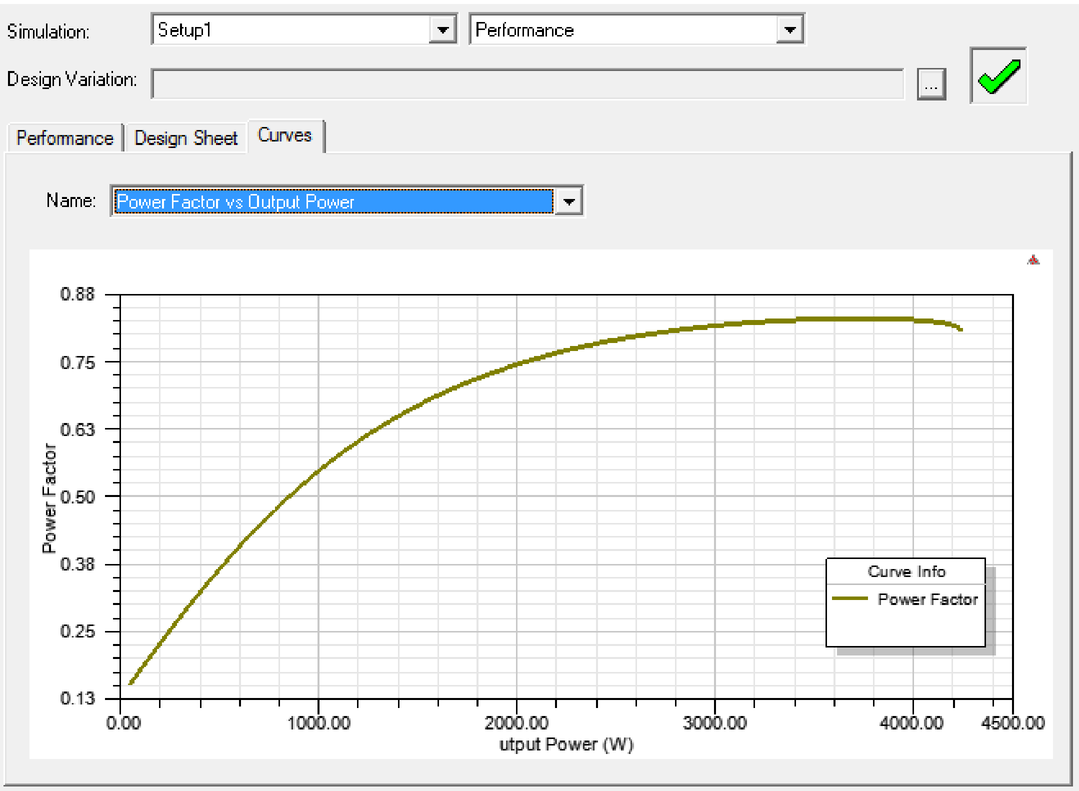


Figure 21 Power Factor vs Output Power

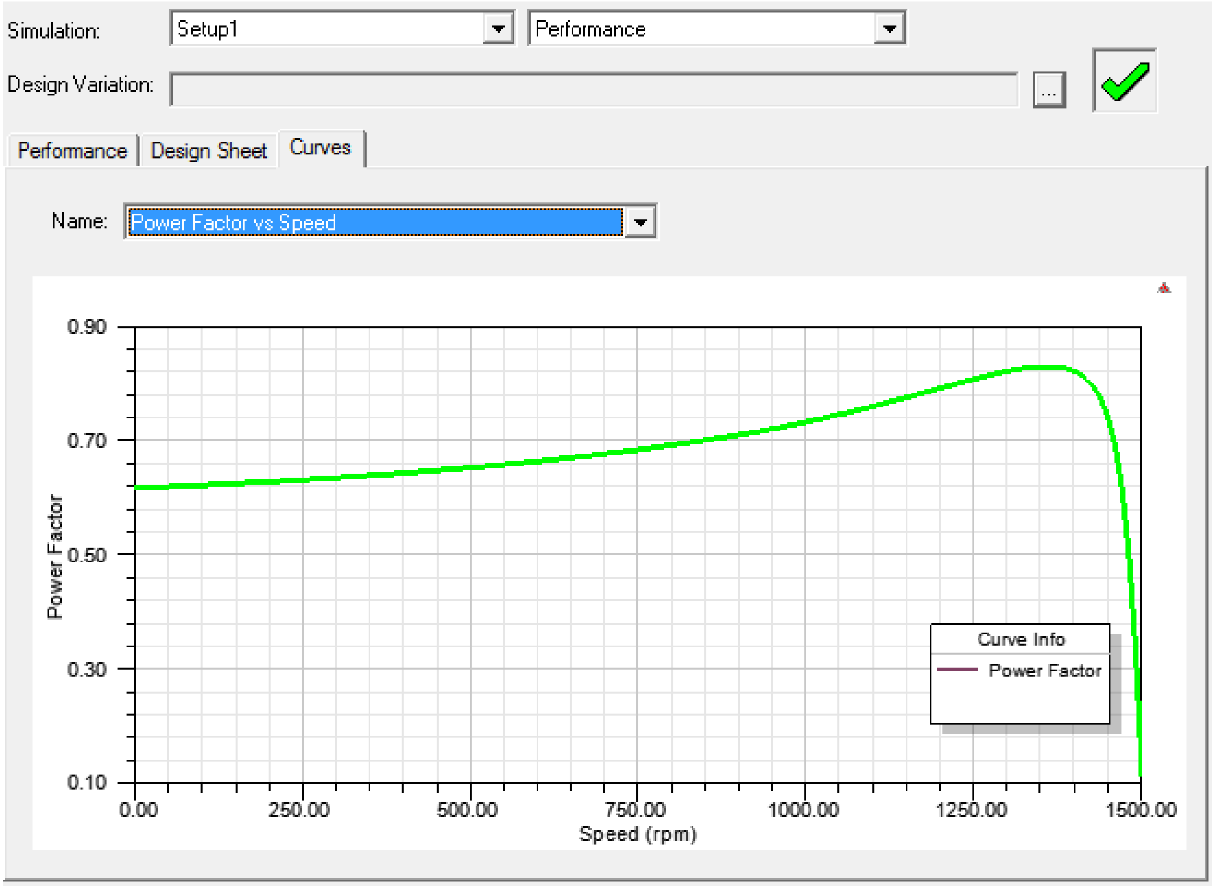


Figure 22 Power Factor vs Speed

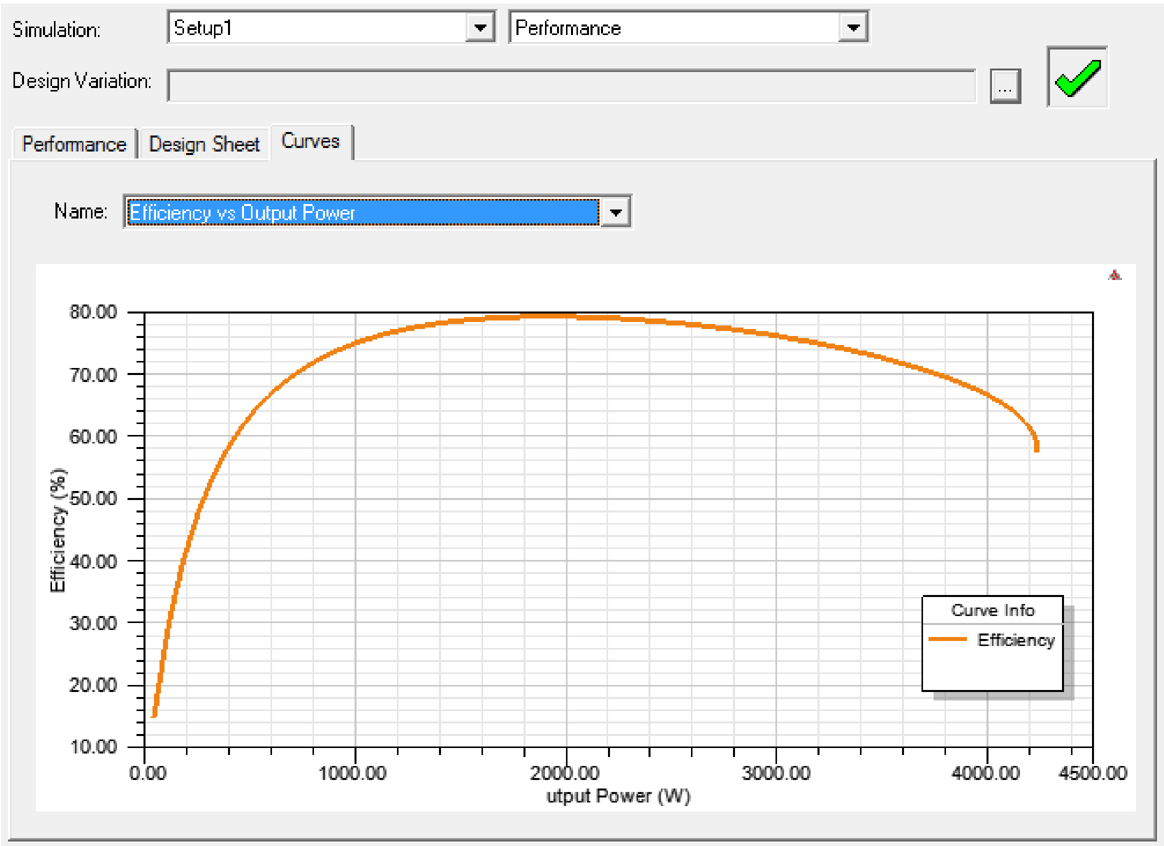


Figure 23 Efficiency vs Output Power

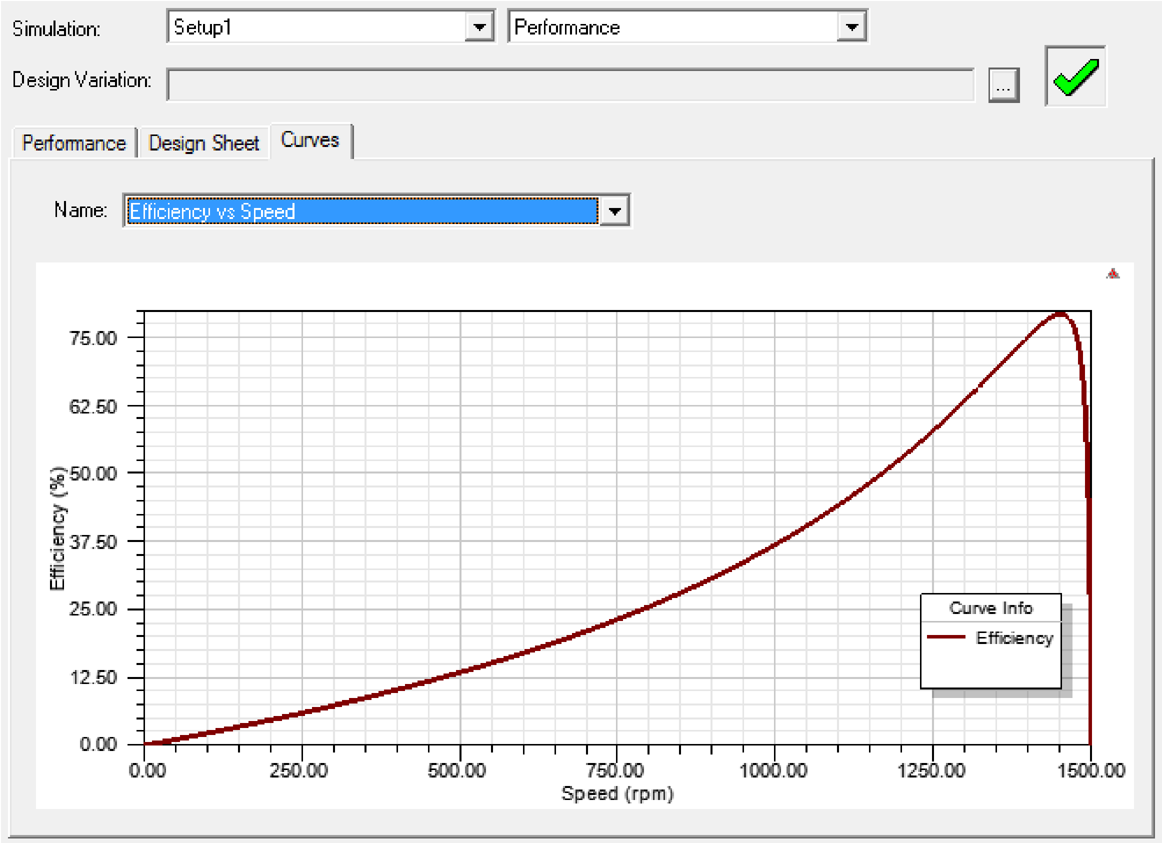


Figure 24 Efficiency vs Speed

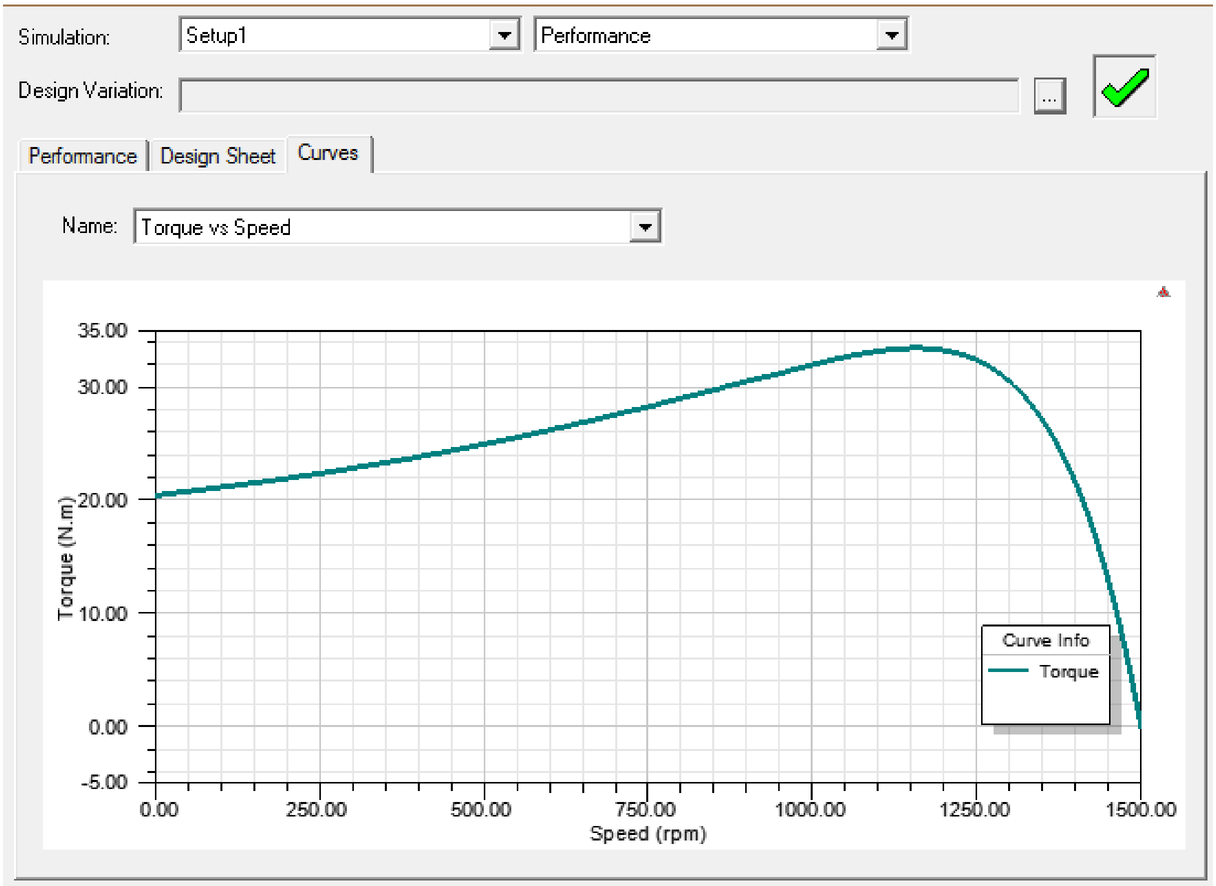


Figure 25 Torque vs Speed

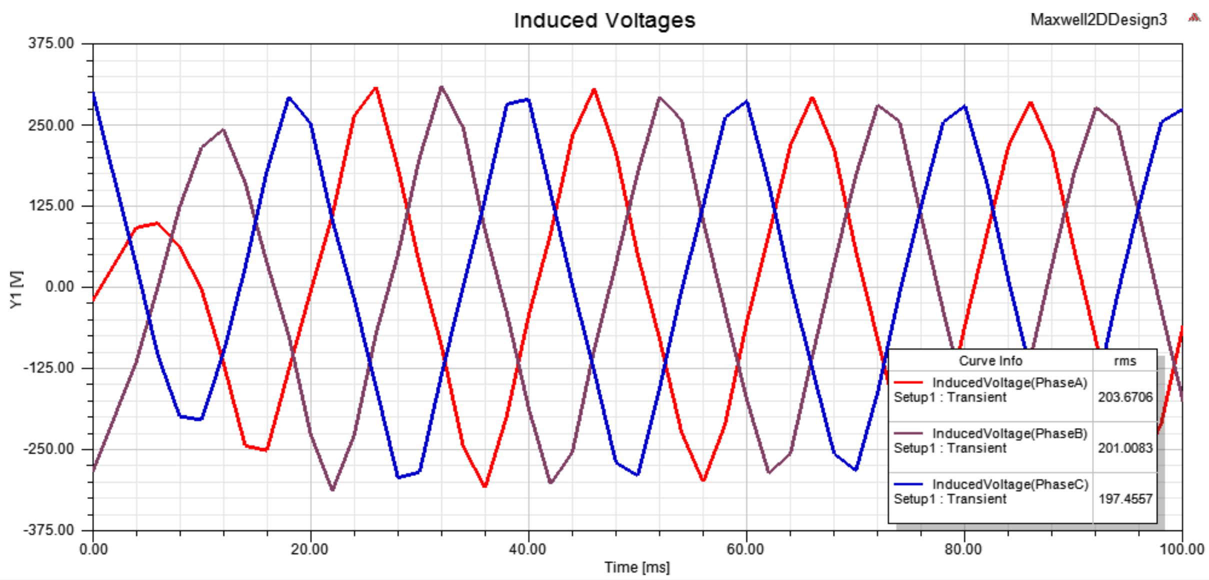


Figure 26 Induced Voltages vs Time

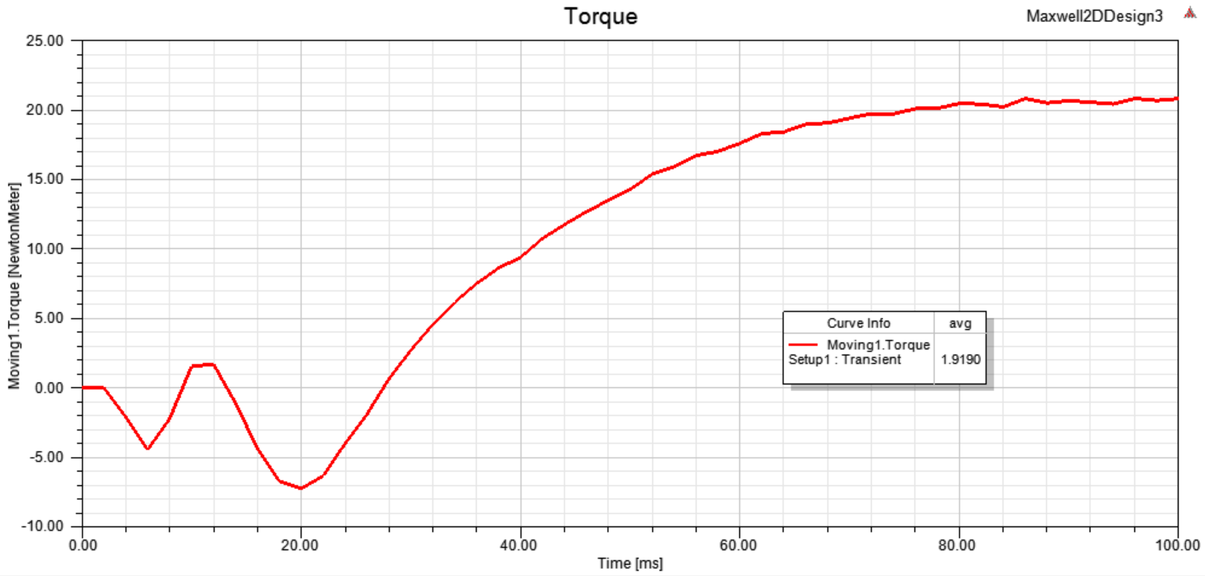


Figure 27 Torque vs Time

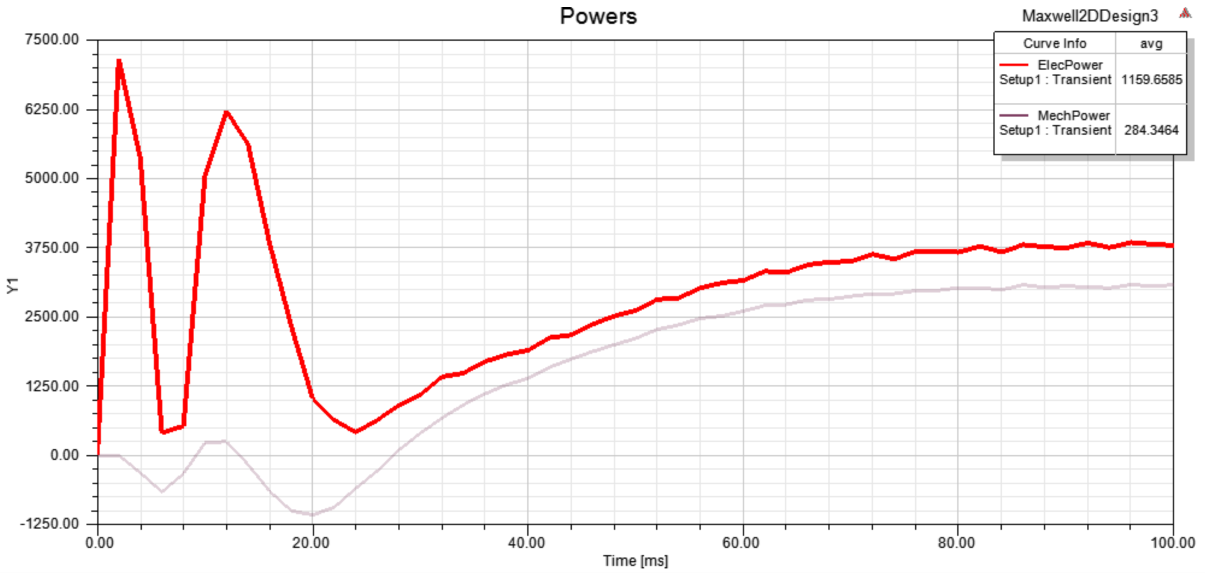


Figure 28 Power vs Time

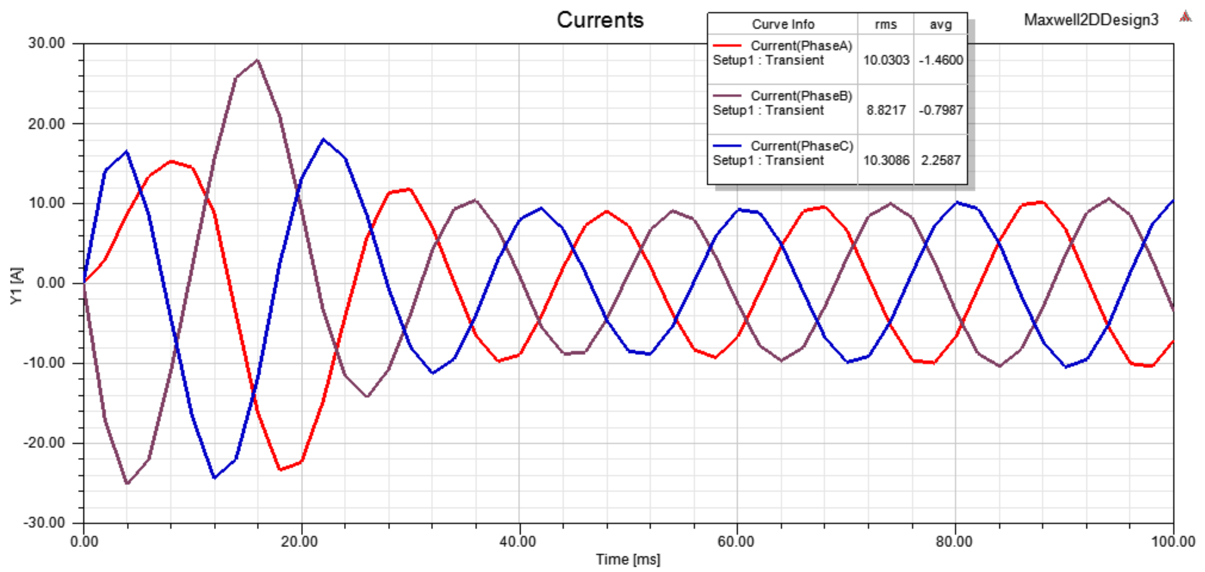


Figure 29 Input Phase Currents

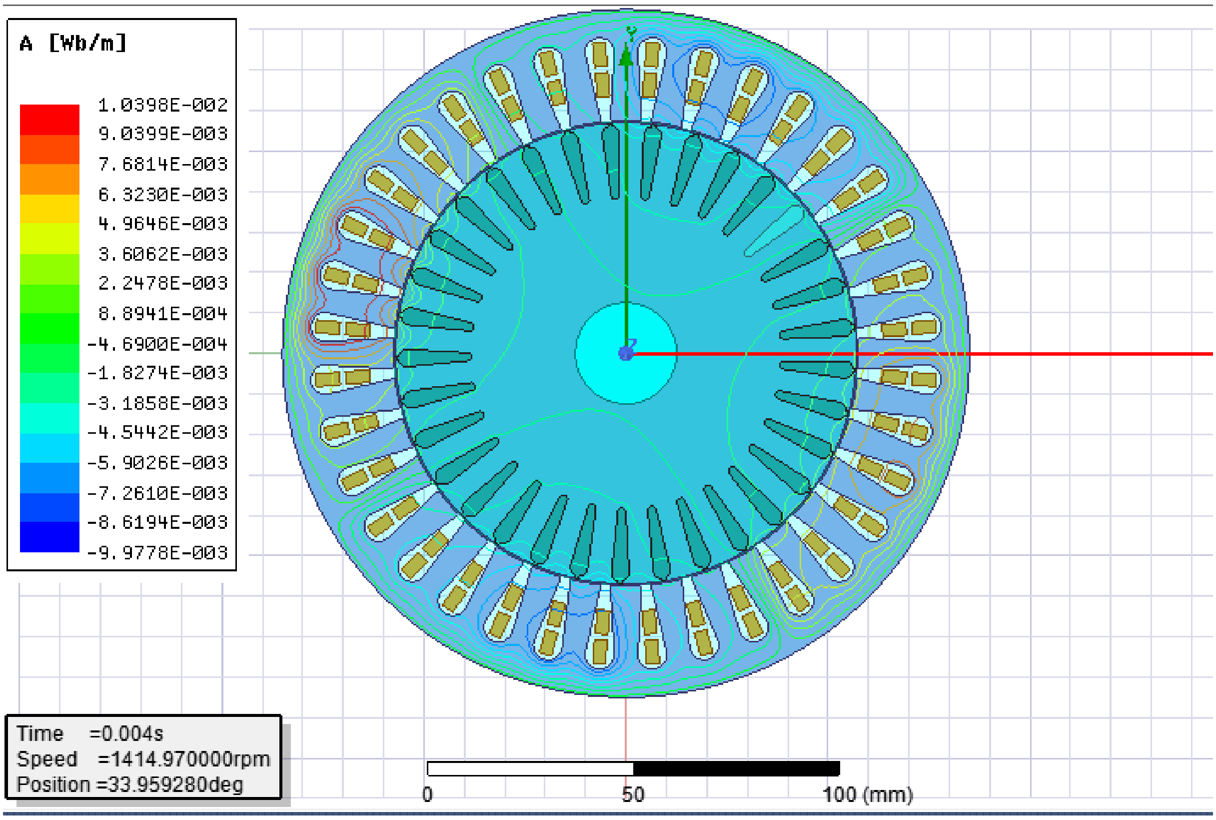


Figure 30 Flux Lines

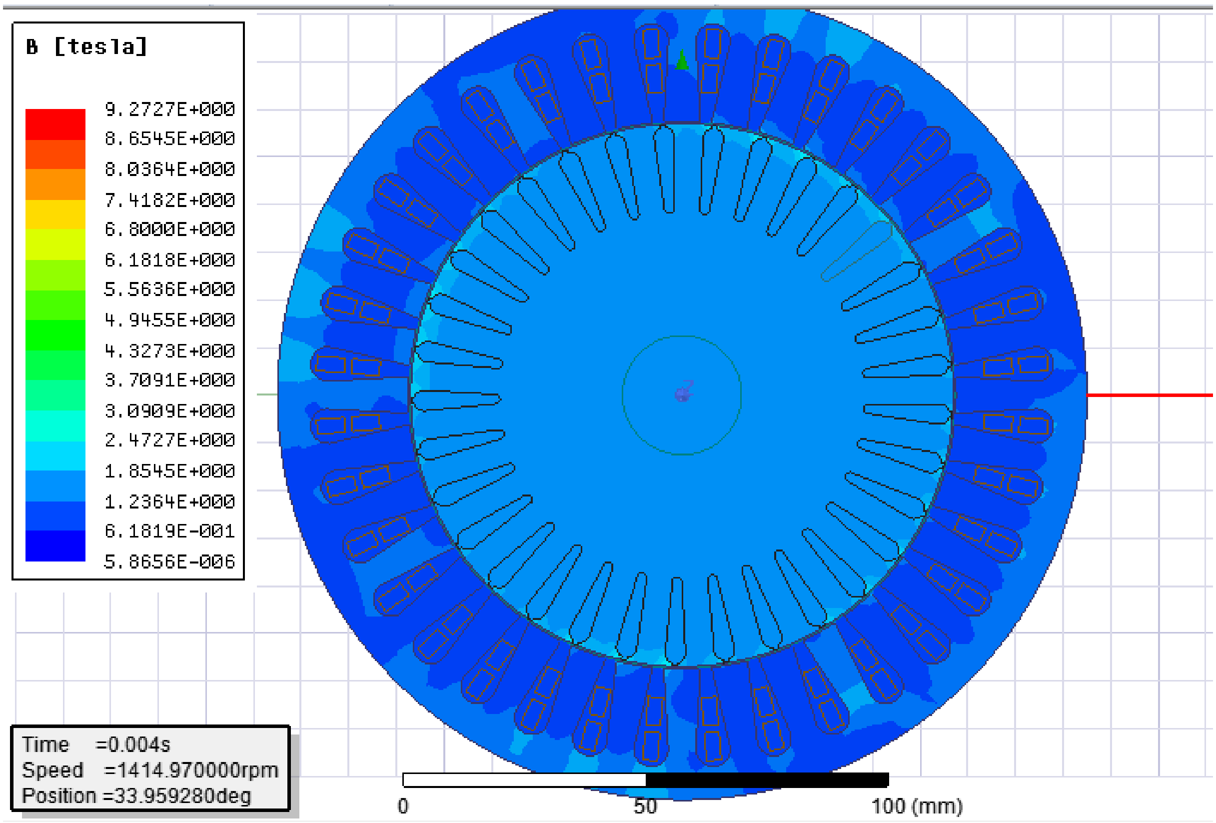


Figure 31 Magnitude of Magnetic Flux Density

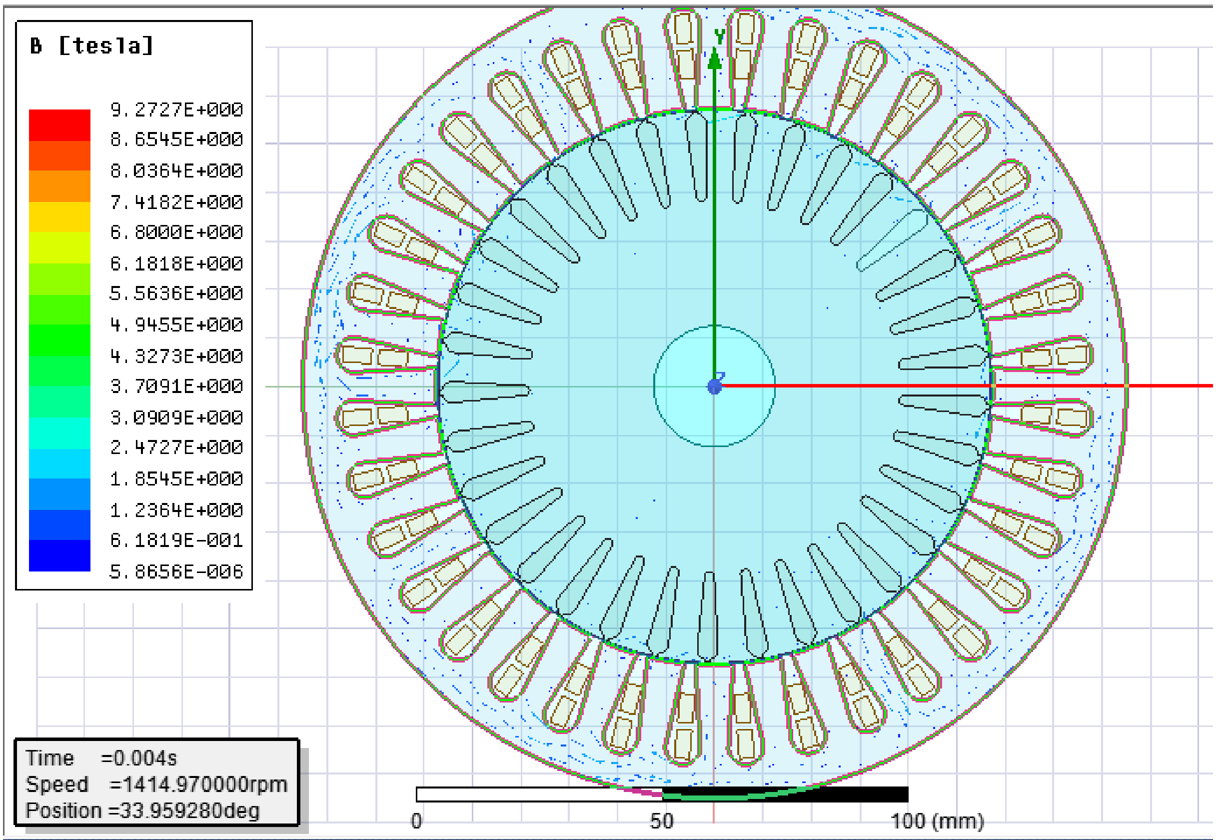


Figure 32 Magnetic Flux Density Vector

5. CONCLUSION

There are several significant design goals such as overall system efficiency, weight, cost, size. In order to achieve design optimization goal, the interaction between design parameters must be known well.

Best power factor with maximum efficiency is the main goal of design process. Geometry of the design is already chose. Design steps are based on following algorithm:

1. Calculate magnetic loading to get desired voltage
2. Determine rated torque and speed of induction motor
3. Calculate the approximate core and copper losses at the rated operating conditions by considering friction and windage losses
4. Calculate output coefficient based on geometry and desired output power Q
5. Calculate specific electrical loading

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). Design of Induction Motors: Received from http://keysan.me/ee564/