Tesla Model S Induction Motor

design by using Maxwell Ansoft

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Chapter 1. Design by Analytically

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Detailed analysis are given in 2nd project. By following chapters, basic machine parameters are calculated for Maxwell Ansoft.
The 2nd project is based on the The Induction Machine Handbook Chapter 14 & 15.
But in this project machine parameters are computed based on what we have learned during the semester.

Matlab Code (overall)

```
%given parameters
Pout = 215; %[kW]
Torque_rated = 220; %[Nm]
rated_speed = 6000; %[rpm]
m = 3; % [-] three phase
Is1 = 350; % [A] driver rated phase current
% assumed
neff = 0.96; %[-] efficiency
powerfactor = 0.88; %[-] power factor

%main dimensions
p1 = 2; %[-] pole pair
Pmech = Pout; %[kW] mechanical power
Pmech_pp = Pmech / (2*p1); %[kW] mechanical power per pole
Cmech = 220; %[kWs/m^3] from graph
f1 = rated_speed*2*p1/120; %[Hz] fund. freq.
nysn_mech = f1 / p1; % [Hz] synchronous mech. freq.
aspect_ratio = pi*p1^(1/3)/(2*p1); %[-] aspect ratio x = L / Dis
Dis = (Pmech/(Cmech*aspect_ratio*nysn_mech))^(1/3); %[m] inner stator diameter
L = aspect_ratio*Dis; %[m] length of the motor
Ftan = Torque_rated/(Dis/2); %[N] tangential force
stress_tan = Ftan / (pi*Dis*L); %[N/m^2] pascal tangential stress
out_in_ratio = 1.88; %[-] for 4pole m/c Dout/Dis
Dout = Dis*out_in_ratio; %[m] outer diameter of the stator
air_gap = 0.18+0.006*(Pmech*10^3)^0.4; %[mm]
safety_factor = 1.2;    %[-]
air_gap = air_gap*safety_factor; %[mm]

%stator winding
min_slot_pitch = 0.007; %[mm] recommended min. slot pitch for induction m/c
max_slot_pitch = 0.045; %[mm] recommended max. slot pitch for induction m/c
```

```
Qs_max = pi*Dis/(min_slot_pitch); %[-] max. possible stator number
Qs_min = pi*Dis/(max_slot_pitch); %[-] min. possible stator number
pitch_ratio = 5/6; %[-] pitch ratio to supress 5th and 7th harmonics
Qs = 48; %[-] stator slot number should be multiple of 2*p1*m
q = Qs / (2*p1*m); %[-] slots per pole per phase
lambda = pitch_ratio*180; %[°] pitch angle
kp1 = sind(lambda/2); %[-] pitch factor
alpha = 180/(Qs/(2*p1)); % [°] slot angle
kd1 = sind(q*alpha/2)/(q*sind(alpha/2)); %[°] distribution factors
kw1 = kp1*kd1; %[-] winding factor

Bg = 0.8; %[T] air gap initial set tesla peak value
fluxg_pp = Bg*(2/pi)*pi*Dis*L/(2*p1); %[weber] airgap flux per pole

Pin = Pout / neff; %[kW] input power
Vph = Pin*10^3 / (m*Is1*powerfactor); %[V] phase voltage in rms
Nph_req = sqrt(2)*Vph /(kw1*2*pi*f1*fluxg_pp); % [-] req. number of turn phase

turns_coil = 1; %[-] number of turns per coil
Nph = p1*q*turns_coil*2; %[-] min. turn per phase
Bg_res = Bg*Nph_req/Nph; %[T] air gap result with Nph
fluxg_pp_res = Bg_res*pi*Dis*L/(2*p1); %[weber] airgap flux per pole


J = 3.25; %[A/mm^2] current density
Ac = Is1/J; %[mm^2] copper area
dco = sqrt(4*Ac/pi); %[mm] diameter of the copper
ap = 4; % [-] number of strand
dco_ap = sqrt(4*Ac/(pi*ap));
% lets use AWG4 size where diameter is 5.19mm

% stator slot sizing
kfill = 0.4; %[-] slot fill factor
Aslot = pi*(dco_ap^2)*ap/4*turns_coil*2*(1/kfill); %[mm^2]requiered slot area

%stator tooth flux density
Bts = 1.625; %[Tesla] stator tooth flux density
slot_pitch = pi*Dis/Qs; %[m] slot pitch
L_eff = L + (2*air_gap*10^-3); %[m] effective air gap
kfe = 0.95; %[-] stacking factor
bts = Bg_res*slot_pitch*L_eff/(Bts*L*kfe); %[m] stator tooth width

%stator back core flux density
Bcs = 1.55; %[Tesla] stator back core flux density
hcs = (fluxg_pp_res/2)/(Bcs*kfe*L); %[m] stator back core height

%roughly estimate stator slot size
safety_back_core = 1.0;
hs = (Dout-Dis)/2 - hcs*safety_back_core; %[m] stator slot height
bs = (Dis/2+hs/2)*2*pi/Qs-bts; %[m] stator slot width (top+bottom/2, mid value)
As_res = hs*bs*10^6; %[mm^2] slot area result
kfill_res = Aslot/As_res*kfill; %[-]

%rotor slots
```

```
Qr = Qs + 2*2*p1; %[-] rotor slot number by assuming 1 skew slot at rotor
Ib = 2*m*Nph*kw1*Is1/Qr; %[A] bar current
Jb = 3.42; %[A/mm^2] current density of the bar
Ab = Ib/Jb; %[mm^2] bar area i.e. rotor slot area

%rotor tooth flux density
Btr = 1.675; %[Tesla] rotor tooth flux density
rotor_pitch = pi*(Dis-2*air_gap*10^-3)/Qr; %[m] rotor pitch
btr = Bg_res*rotor_pitch*L_eff/(Btr*kfe*L); %[m] rotor tooth width

%rotor back core flux density
Bcr = 1.5; %[Tesla]rotor back core flux density
hcr = (fluxg_pp_res/2)/(Bcr*kfe*L); %[m] rotor back core height

%roughly rotor slot sizes
safety_rotor_area = 1.0;
br = rotor_pitch - btr; %[m] rotor slot width
hr = Ab*safety_rotor_area*10^-6/br; % [m] rotor slot height

%shaft diameter
dshaft = Dis-(2*air_gap*10^-3)-(2*hr)-(2*hcr); %[m] shaft diameter

%end ring
Jer = 0.75*Jb; %[A/mm^2] end ring current density
Ier = Ib / (2*sind(180*p1/Qr)); %[A]end ring current
Aer = Ier / Jer; %[A/mm^2] end ring cross section
b = (hr+br)*10^3; %[mm] height of the Aer
a = Aer/b; %[mm] width of the Aer
```

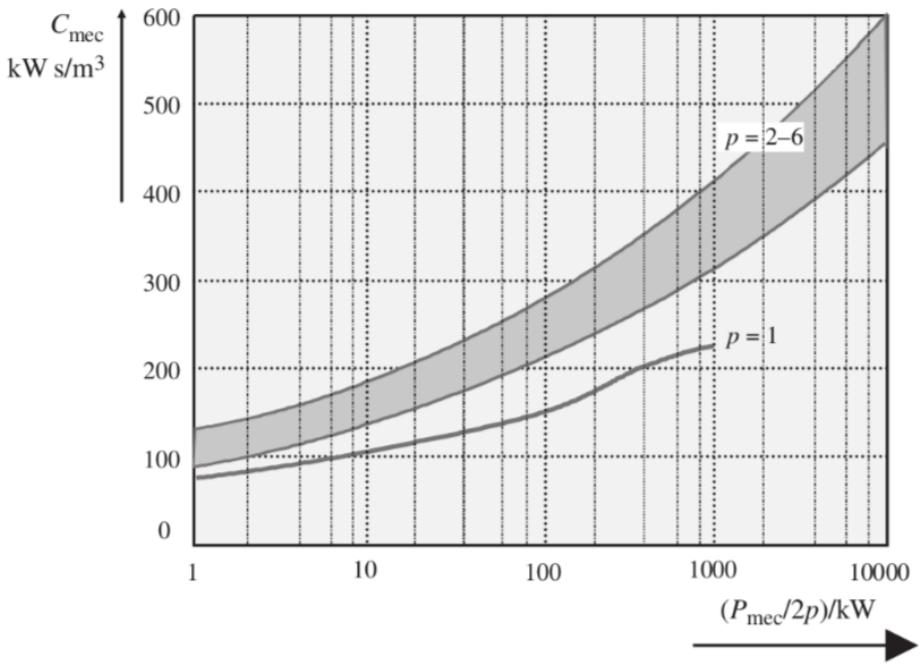
Given Parameters

```
Given and gathered parameters are summarized as follows:
power output rated  215 [kW]
torque rated 220 [Nm]
speed rated 6000 [rpm]
# of phase is 3
phase current rated 350 [A]

assuming;
efficiency is 0.9600
power factor is 0.8800

Note that details of the gathered parameters are given
in 2nd project.
```

Main Machine Parameters

```
chosen # of poles 4
mechanical power per pole 53.7500 [kW]
```

Figure 1.1. Cmech graph




```
Cmech value from graph 220 [kWs/m^3]
fundamental frequency 200 [Hz]
synchronus mechanical frequency 100 [Hz]
aspect ratiio X = Dis/L is 0.9895
inner diameter of the stator Dis 0.2145 [m]
stack length L 0.2123 [m]
```

Figure 1.2. typcial tangential stress values

Typical Tangential Stress Values

	Totally enclosed asynchronous machines	Sailent-pole synchronous machines or PMSMs	Nonsalient-pole synchronous machines			DC machines
			Indirect cooling		Direct water cooling	
			Air	Hydrogen		
A/kA/m, RMS	30–65	35–65	30–80	90–110	150–200	25–65
Air-gap flux density $\hat{B}_{\delta 1}$/T	0.7–0.9	0.85–1.05	0.8–1.05	0.8–1.05	0.8–1.05	0.6–1.1
Tangential stress $\sigma_{F\tan}$/Pa						
minimum	12 000*	21 000*	17 000*	51 000*	85 000*	12 000*
average	21 500*	33 500*	36 000*	65 500*	1,14 500*	29 000*
maximum	33 000*	48 000*	59 500*	81 500*	1,48 500*	47 500*
	*$\cos\varphi = 0.8$	*$\cos\varphi = 1$	*$\cos\varphi = 1$	*$\cos\varphi = 1$	*$\cos\varphi = 1$	*$\alpha_{DC} = 2/3$

```
tangential force Ftan 2.0508e+03 [N]
tangential stress 1.4331e+04 [N/m^2] in Pascal
note that it is the recommanded average value
```

Figure 1.3. stator outer to inner diameter ratio

N Poles	2	4	6	8	10	12
Do/Di	2	1.88	1.78	1.66	1.54	1.43

Source: T.Miller - Electric Machine Design Course, Lecture-5, Slide4

```
By using above table,
outer to inner diameter ratio is 1.8800
outer diameter of the stator Dout 0.4034

air gap 1.1939 [mm] with 1.2000 safety factor
```

Stator Winding

```
recommanded minimum and maximum slot pitch is 7
and 45 mm respectively.
by using these values min. stator slot is 14.9784 and max. is 96.2896.
chosen stator value is 48 which should be multiple of 12
pitch ratio is chosen as 5/6, for supress 5th and 7th harmonics
# of slots per pole per phase is 4
pitch angle 150 [°]
slot angle 15 [°]
fundamental pitch factor is 0.9659
distribution factor is 0.9577
fundamental winding factor is 0.9250
note that winding factors for 5th and 7th harmonics
are calculated in 2nd project.
```

Figure 1.4. typical flux density values

Typical Flux Density Values

Position	Typical flux density range (Ref. [3] Say)	Maximum flux density (Ref. [2] Lipo)
Airgap Bg	0.65 – 0.82 T (ave.)	
Stator yoke	1.1 – 1.45 T (peak)	1.7 T
Stator teeth	1.4 – 1.7 T	2.1 T
Rotor yoke	1.2 T	1.7 T
Rotor teeth	1.5 – 1.8 T	2.2 T

Source: Traditional Design of Electrical Machines, Slide-12

```
regarding the above table,
Selected peak air gap flux density is 0.8000 Tesla.
air gap flux avg. 0.0182 [Weber]

input power 223.9583 [kW]
phase voltage rms 242.3791 [V]
reqired # of turns per phase 16.1844

selected number of turns per coil is 1
# of turns per phase 16
resultant air gap flux density is 0.8092 Tesla

current density J is choosen as 3.2500
requirred copper area Ac 107.6923 [mm^2]
diameter of the copper dco 11.7097 [mm]
selected # of strand ap 4
requirred cable diameter is 5.8549 [mm]
AWG4 is used for this purpose which has the diameter 5.19mm
```

Stator Slot Sizing

```
selected fill factor is 0.4000
required slot area is Aslot 538.4615 [mm^2]

selected stator tooth flux density is 1.6250 Tesla
slot pitch is 0.0140 [mm]
stacking factor is taken as 0.9500
effective length is 0.2147 [m]
stator tooth width is bts 0.0074 [mm]

selected stator back core flux density is 1.5500 Tesla
stator back core height is hcs 0.0463 [mm]
```

```
Let's roughly estimate the stator slot size
stator slot height hs 0.0481 [mm]
stator slot width bs 0.0097 [mm]

resultant slot area 468.8194 [mm^2]
resultant fill factor is 0.4594
```

Rotor

```
selected rotor number is 56 by one slot skewing
bar current Ib 555.0184 [A]
current density Jb of the bar is 3.4200 [A/mm^2]
rotor slot area Ab 162.2861 [mm^2]

rotor tooth flux density is taken as 1.6750 Tesla
rotor pitch 0.0119 [mm]
rotor tooth width btr 0.0061 [mm]

rotor back core flux density is taken as 1.5000 Tesla
rotor back core height hcr 0.0478 [mm]

Let's roughly calculate rotor slot sizes
rotor slot width br 0.0058 [mm]
rotor slot height hr 0.0281 [mm]

shaft diameter is 0.0603

end ring current density Jer is taken as 2.5650 [A/mm^2]
end ring current Ier 2.4785e+03 [A]
end ring cross section Aer 966.2951 [mm^2]
height of the end ring b 33.8519 [mm]
width of the ring a 28.5448 [mm]
```

Chapter 2. RMxprtDesign

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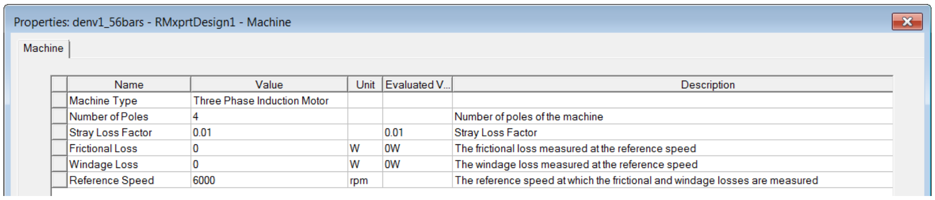
Machine parameters which are determined in the first chapter, are filled to corresponding parts in RMxprt as below.

Machine

Figure 2.1. RMxprtDesign Machine part

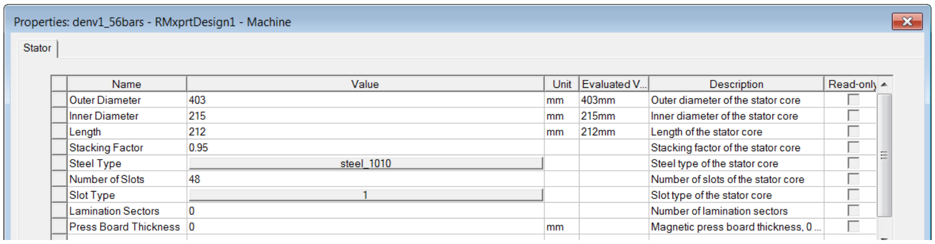


Properties: denv1_56bars - RMxprtDesign1 - Machine

Machine

Name	Value	Unit	Evaluated V...	Description
Machine Type	Three Phase Induction Motor			
Number of Poles	4			Number of poles of the machine
Stray Loss Factor	0.01		0.01	Stray Loss Factor
Frictional Loss	0	W	0W	The frictional loss measured at the reference speed
Windage Loss	0	W	0W	The windage loss measured at the reference speed
Reference Speed	6000	rpm		The reference speed at which the frictional and windage losses are measured

Figure 2.2. Rmxprt Stator

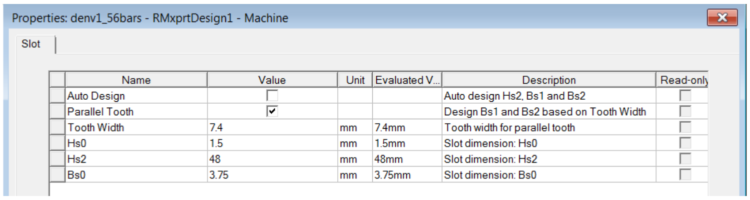


Properties: denv1_56bars - RMxprtDesign1 - Machine

Stator

Name	Value	Unit	Evaluated V...	Description	Read-only
Outer Diameter	403	mm	403mm	Outer diameter of the stator core	
Inner Diameter	215	mm	215mm	Inner diameter of the stator core	
Length	212	mm	212mm	Length of the stator core	
Stacking Factor	0.95			Stacking factor of the stator core	
Steel Type	steel_1010			Steel type of the stator core	
Number of Slots	48			Number of slots of the stator core	
Slot Type	1			Slot type of the stator core	
Lamination Sectors	0			Number of lamination sectors	
Press Board Thickness	0	mm		Magnetic press board thickness, 0 ...	

Figure 2.3. RMxprt Stator Slot



Properties: denv1_56bars - RMxprtDesign1 - Machine

Slot

Name	Value	Unit	Evaluated V...	Description	Read-only
Auto Design	☐			Auto design Hs2, Bs1 and Bs2	
Parallel Tooth	☑			Design Bs1 and Bs2 based on Tooth Width	
Tooth Width	7.4	mm	7.4mm	Tooth width for parallel tooth	
Hs0	1.5	mm	1.5mm	Slot dimension: Hs0	
Hs2	48	mm	48mm	Slot dimension: Hs2	
Bs0	3.75	mm	3.75mm	Slot dimension: Bs0	

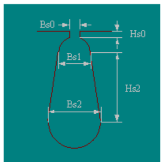
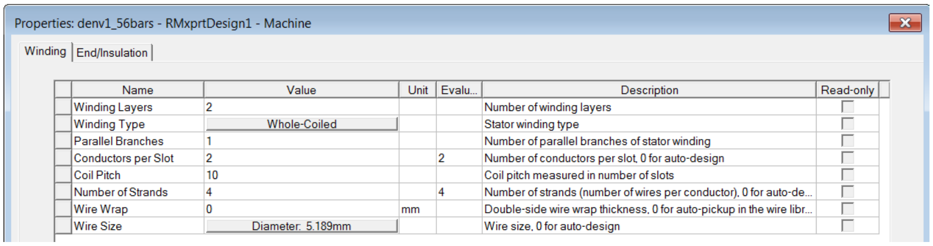


Figure 2.4. RMxprt Stator Winding



Properties: denv1_56bars - RMxprtDesign1 - Machine

Winding | End/Insulation

Name	Value	Unit	Evalu...	Description	Read-only
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-de...	
Wire Wrap	0	mm		Double-side wire wrap thickness, 0 for auto-pickup in the wire libr...	
Wire Size	Diameter: 5.189mm			Wire size, 0 for auto-design	

Figure 2.5. RMxprt stator winding coil

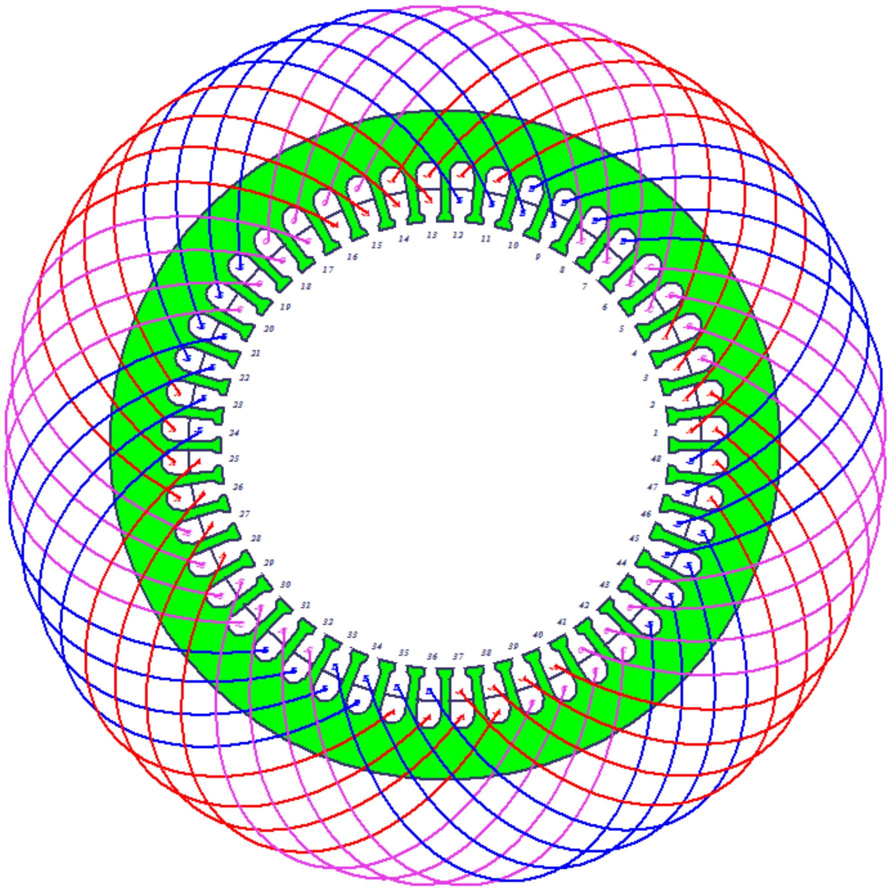


Figure 2.6. RMxprt stator overall

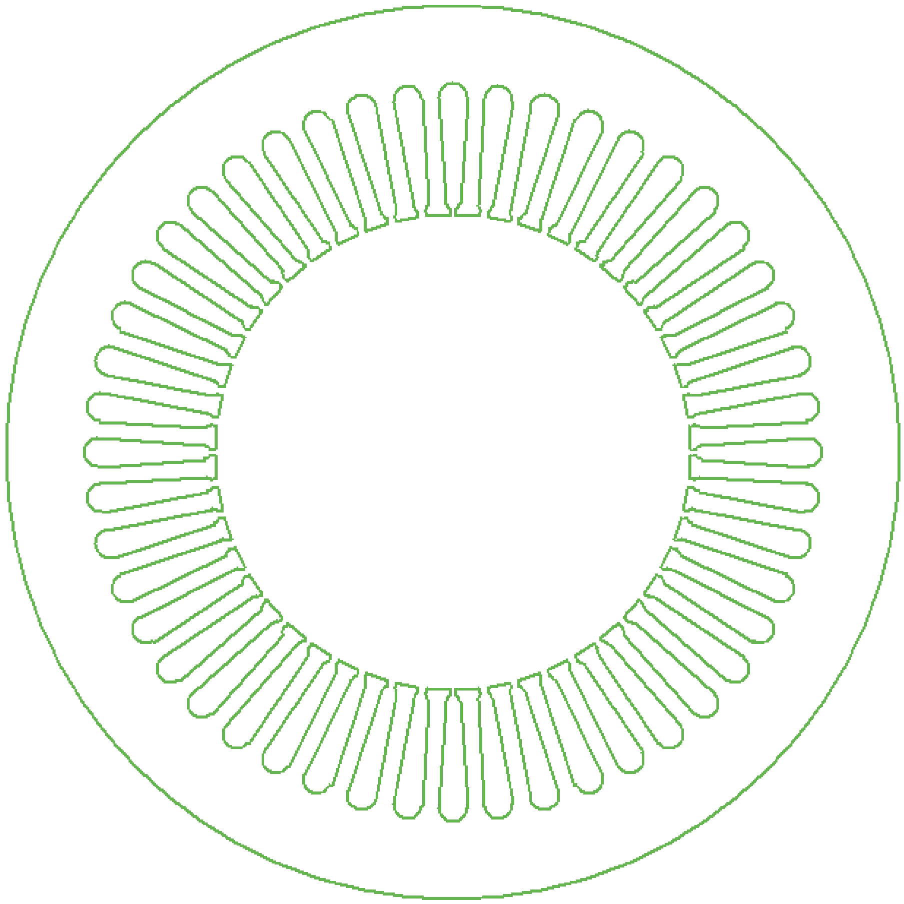
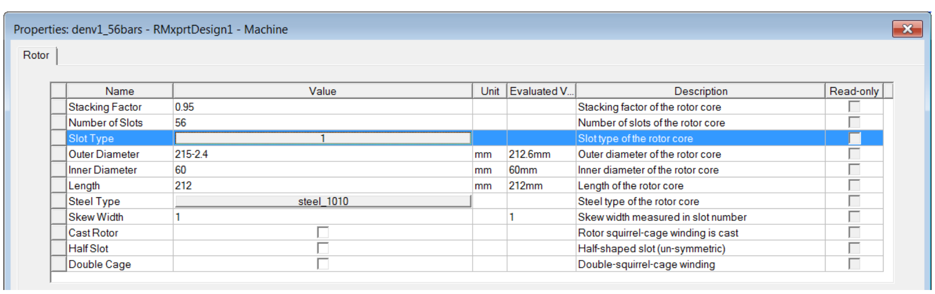


Figure 2.7. RMxprt rotor

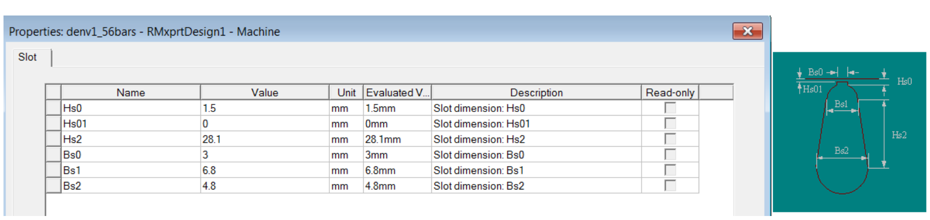


Properties: denv1_56bars - RMxprtDesign1 - Machine

Rotor

Name	Value	Unit	Evaluated V...	Description	Read-only
Stacking Factor	0.95			Stacking factor of the rotor core	
Number of Slots	56			Number of slots of the rotor core	
Slot Type	1			Slot type of the rotor core	
Outer Diameter	215-2.4	mm	212.6mm	Outer diameter of the rotor core	
Inner Diameter	60	mm	60mm	Inner diameter of the rotor core	
Length	212	mm	212mm	Length of the rotor core	
Steel Type	steel_1010			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 2.8. RMxprt rotor slot

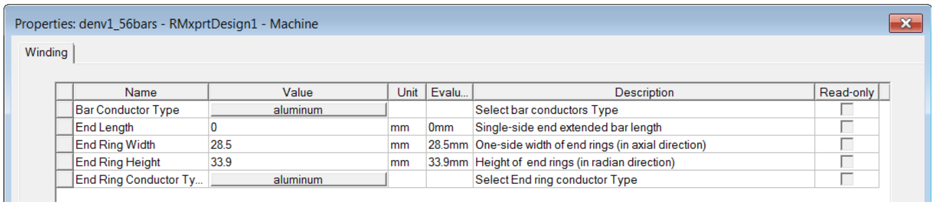


Properties: denv1_56bars - RMxprtDesign1 - Machine

Slot

Name	Value	Unit	Evaluated V...	Description	Read-only
Hs0	1.5	mm	1.5mm	Slot dimension: Hs0	
Hs01	0	mm	0mm	Slot dimension: Hs01	
Hs2	28.1	mm	28.1mm	Slot dimension: Hs2	
Bs0	3	mm	3mm	Slot dimension: Bs0	
Bs1	6.8	mm	6.8mm	Slot dimension: Bs1	
Bs2	4.8	mm	4.8mm	Slot dimension: Bs2	

Figure 2.9. RMxprt rotor winding


Properties: denv1_56bars - RMxprtDesign1 - Machine

Winding

Name	Value	Unit	Evalu...	Description	Read-only
Bar Conductor Type	aluminum			Select bar conductors Type	
End Length	0	mm	0mm	Single-side end extended bar length	
End Ring Width	28.5	mm	28.5mm	One-side width of end rings (in axial direction)	
End Ring Height	33.9	mm	33.9mm	Height of end rings (in radian direction)	
End Ring Conductor Ty...	aluminum			Select End ring conductor Type	

Figure 2.10. RMxprt rotor overall

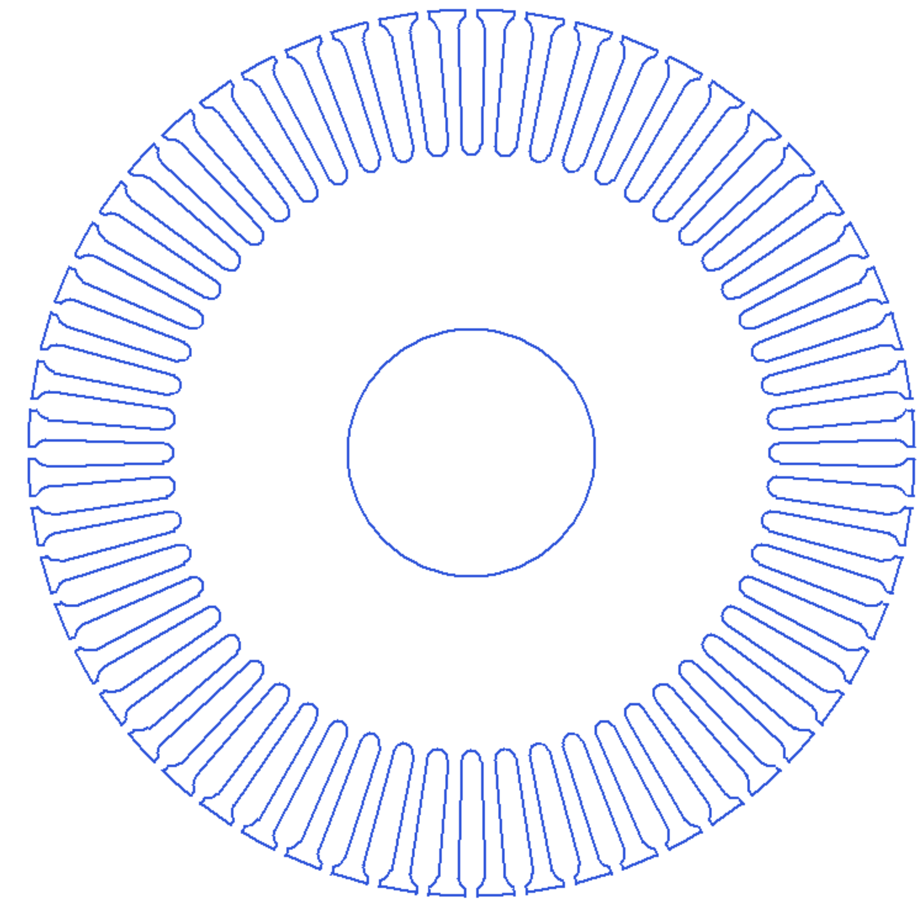
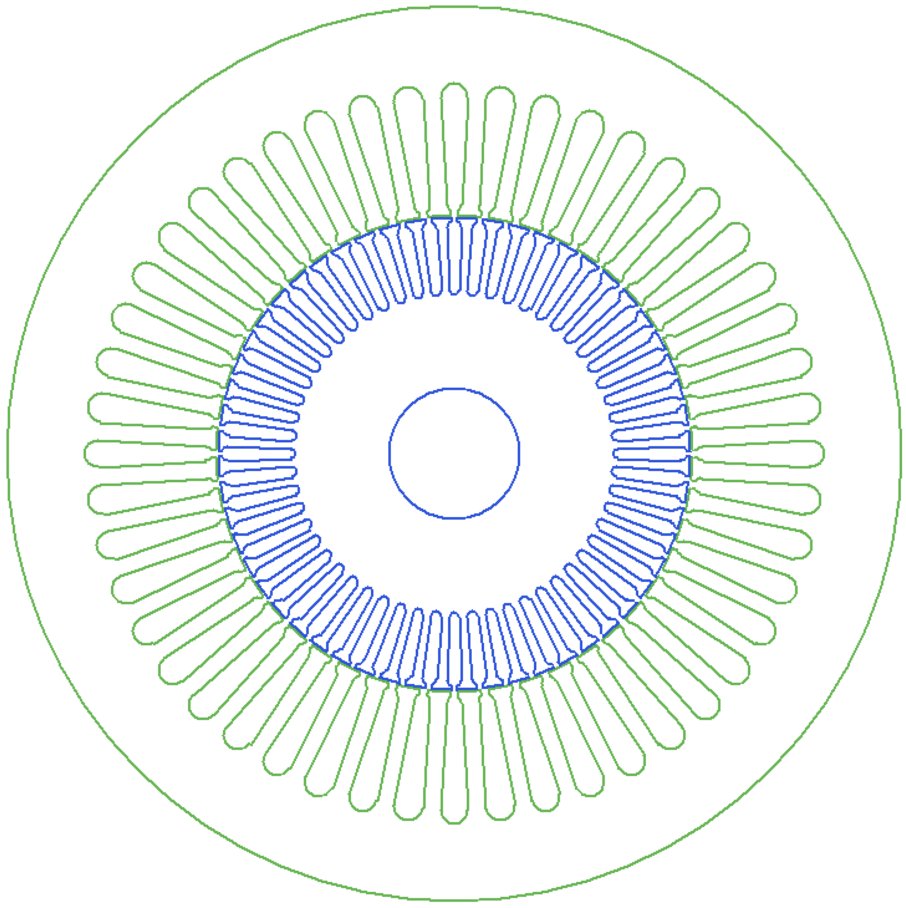
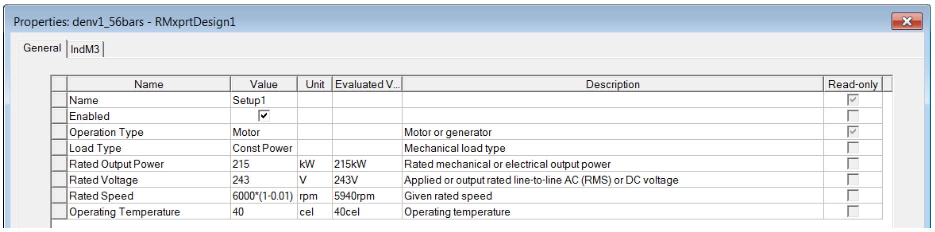


Figure 2.11. RMxprt machine overall



Analysis

Figure 2.12. RMxprt analysis

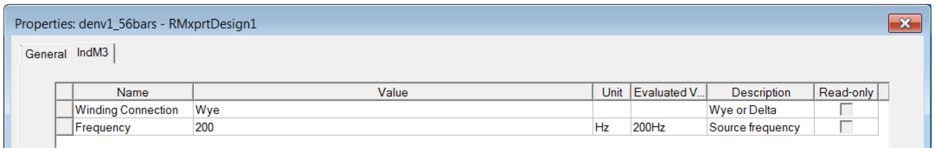


Properties: denv1_56bars - RMxprtDesign1

General | IndM3

Name	Value	Unit	Evaluated V...	Description	Read-only
Name	Setup1				☑
Enabled	☑				☐
Operation Type	Motor			Motor or generator	☑
Load Type	Const Power			Mechanical load type	☐
Rated Output Power	215	kW	215kW	Rated mechanical or electrical output power	☐
Rated Voltage	243	V	243V	Applied or output rated line-to-line AC (RMS) or DC voltage	☐
Rated Speed	6000*(1-0.01)	rpm	5940rpm	Given rated speed	☐
Operating Temperature	40	cel	40cel	Operating temperature	☐

Figure 2.13. RMxprt analysis setup indM3



Properties: denv1_56bars - RMxprtDesign1

General | IndM3

Name	Value	Unit	Evaluated V...	Description	Read-only
Winding Connection	Wye			Wye or Delta	☐
Frequency	200	Hz	200Hz	Source frequency	☐

Results

Figure 2.14. RMxprt torque speed graph

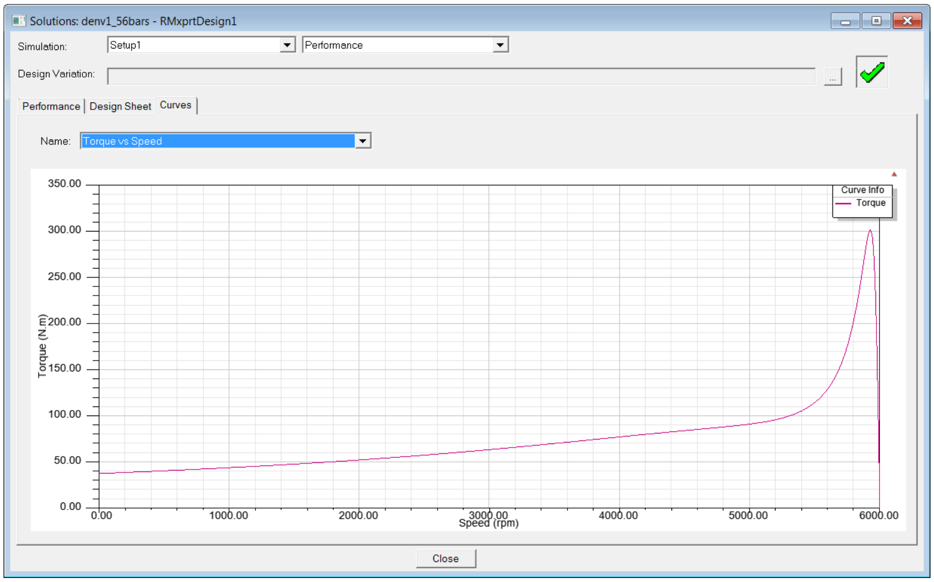
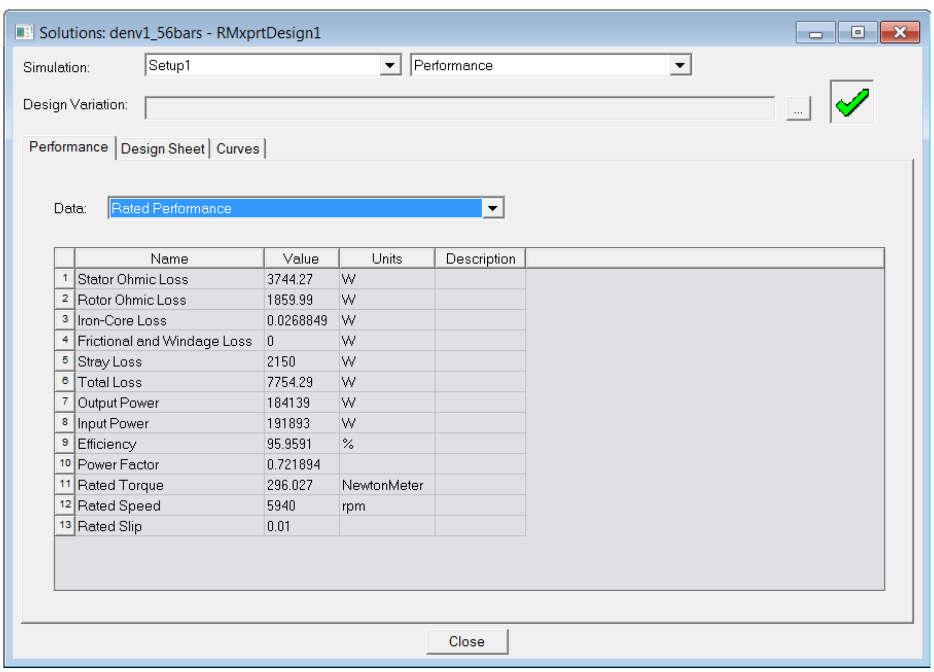


Figure 2.15. RMxprt rated performance



	Name	Value	Units	Description
1	Stator Ohmic Loss	3744.27	W	
2	Rotor Ohmic Loss	1859.99	W	
3	Iron-Core Loss	0.0268849	W	
4	Frictional and Windage Loss	0	W	
5	Stray Loss	2150	W	
6	Total Loss	7754.29	W	
7	Output Power	184139	W	
8	Input Power	191893	W	
9	Efficiency	95.9591	%	
10	Power Factor	0.721894		
11	Rated Torque	296.027	NewtonMeter	
12	Rated Speed	5940	rpm	
13	Rated Slip	0.01		

Figure 2.16. RMxprt rated magnetic data

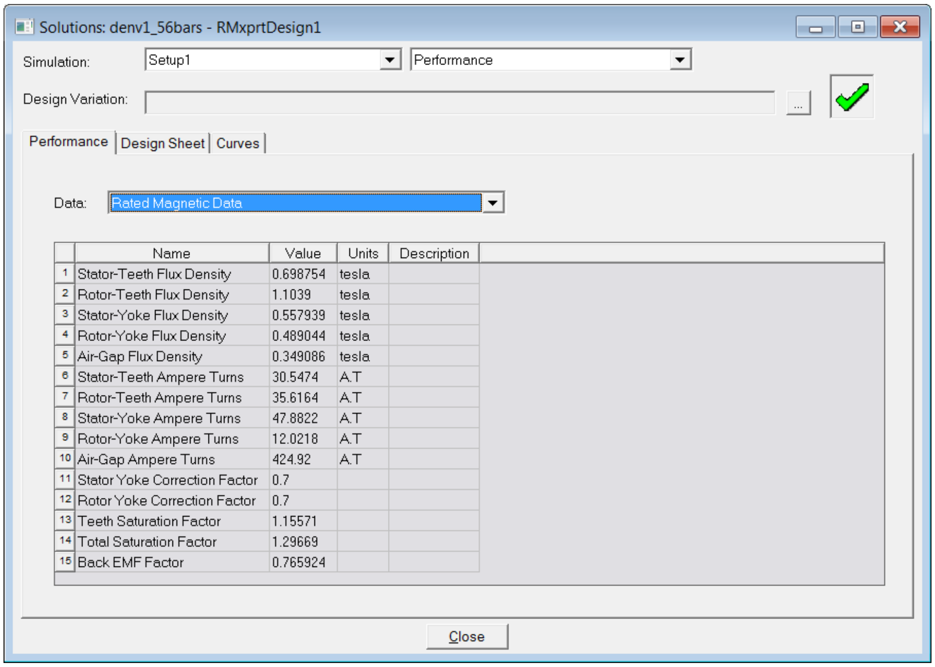


Figure 2.17. RMxprt rated electrical data

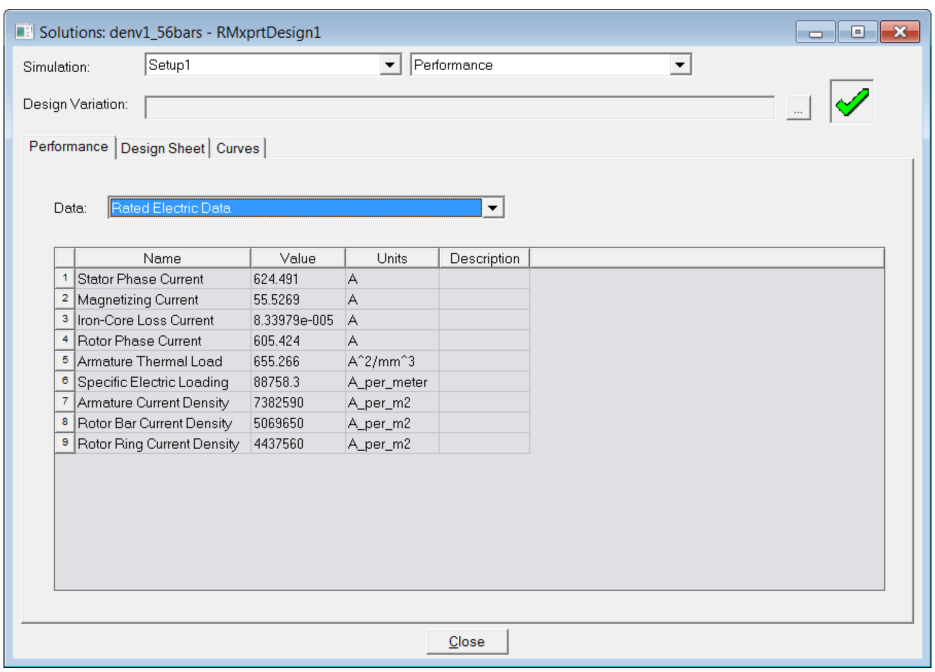
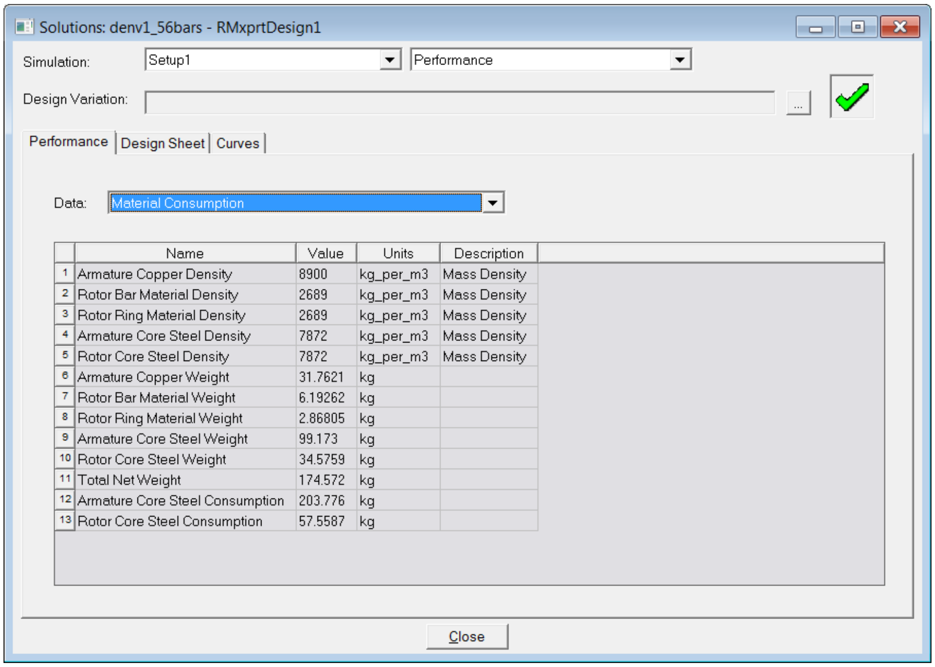
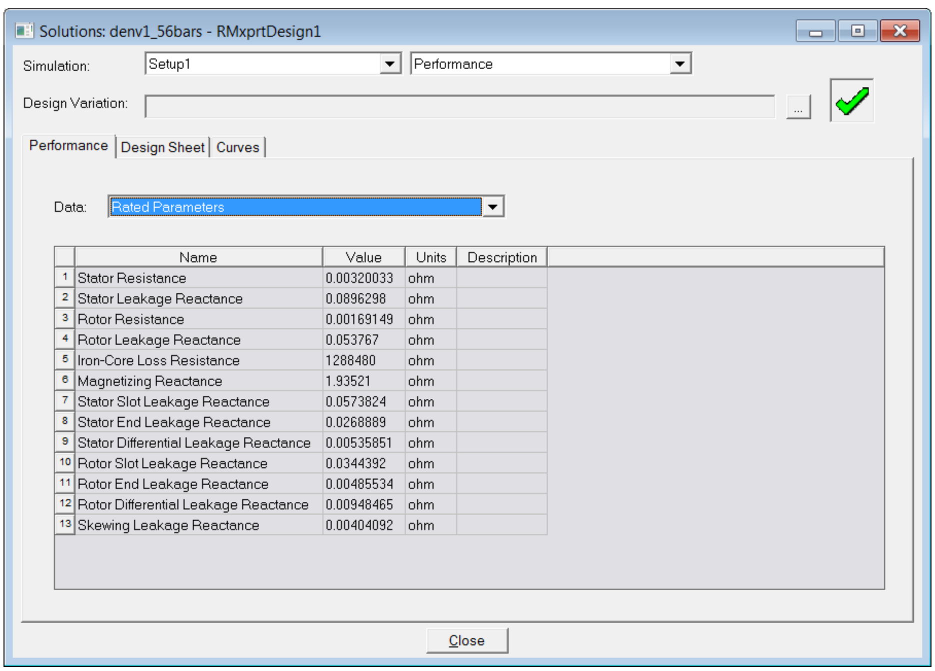


Figure 2.18. RMxprt material consumption



	Name	Value	Units	Description
1	Armature Copper Density	8900	kg_per_m3	Mass Density
2	Rotor Bar Material Density	2689	kg_per_m3	Mass Density
3	Rotor Ring Material Density	2689	kg_per_m3	Mass Density
4	Armature Core Steel Density	7872	kg_per_m3	Mass Density
5	Rotor Core Steel Density	7872	kg_per_m3	Mass Density
6	Armature Copper Weight	31.7621	kg	
7	Rotor Bar Material Weight	6.19262	kg	
8	Rotor Ring Material Weight	2.86805	kg	
9	Armature Core Steel Weight	99.173	kg	
10	Rotor Core Steel Weight	34.5759	kg	
11	Total Net Weight	174.572	kg	
12	Armature Core Steel Consumption	203.776	kg	
13	Rotor Core Steel Consumption	57.5587	kg	

Figure 2.19. RMxprt rated parameters



	Name	Value	Units	Description
1	Stator Resistance	0.00320033	ohm	
2	Stator Leakage Reactance	0.0896298	ohm	
3	Rotor Resistance	0.00169149	ohm	
4	Rotor Leakage Reactance	0.053767	ohm	
5	Iron-Core Loss Resistance	1288480	ohm	
6	Magnetizing Reactance	1.93521	ohm	
7	Stator Slot Leakage Reactance	0.0573824	ohm	
8	Stator End Leakage Reactance	0.0268889	ohm	
9	Stator Differential Leakage Reactance	0.00535851	ohm	
10	Rotor Slot Leakage Reactance	0.0344392	ohm	
11	Rotor End Leakage Reactance	0.00485534	ohm	
12	Rotor Differential Leakage Reactance	0.00948465	ohm	
13	Skewing Leakage Reactance	0.00404092	ohm	

Chapter 3. Maxwell2D Design

From RMxprt, 2DMaxwell design is created as below.

Figure 3.1. Maxwell2D one of the motor pole

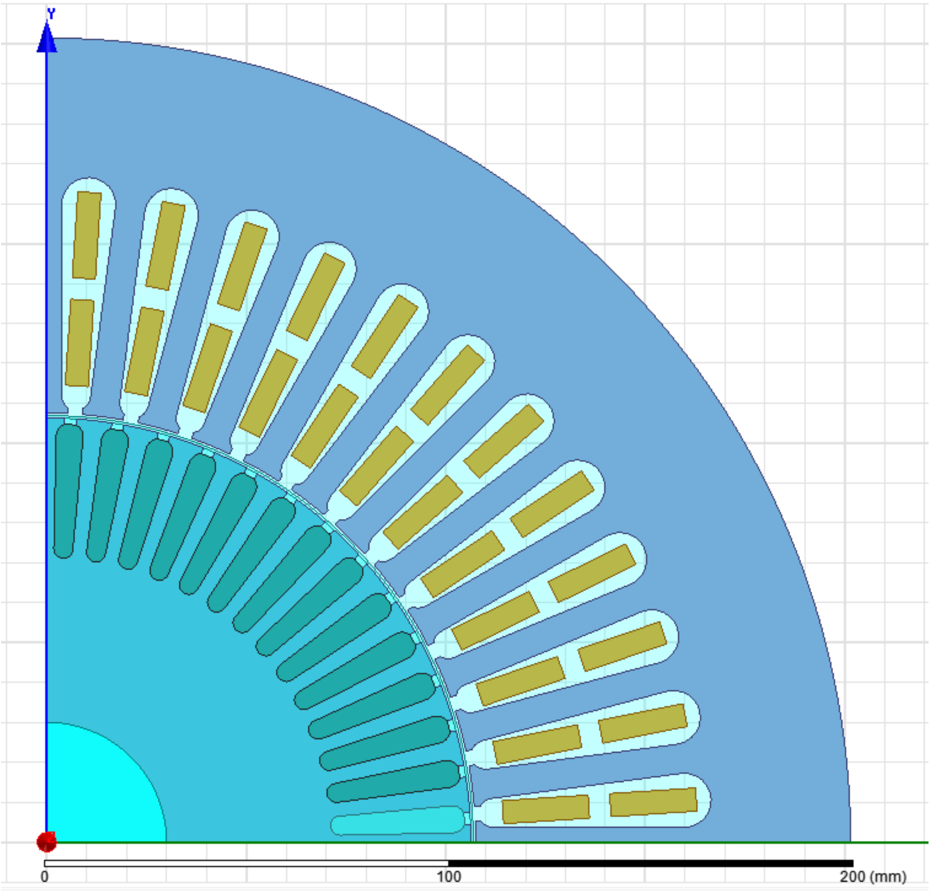


Figure 3.2. Maxwell2D motion setup

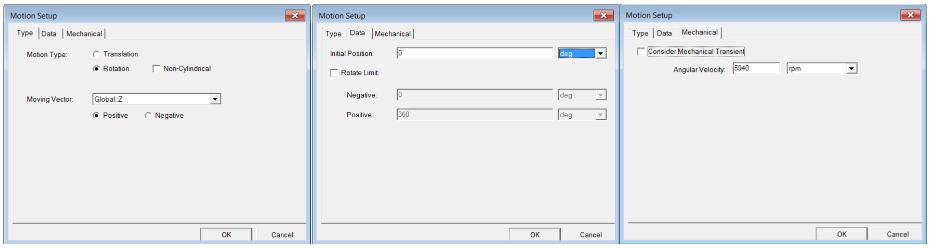


Figure 3.3. Maxwell2D boundaries

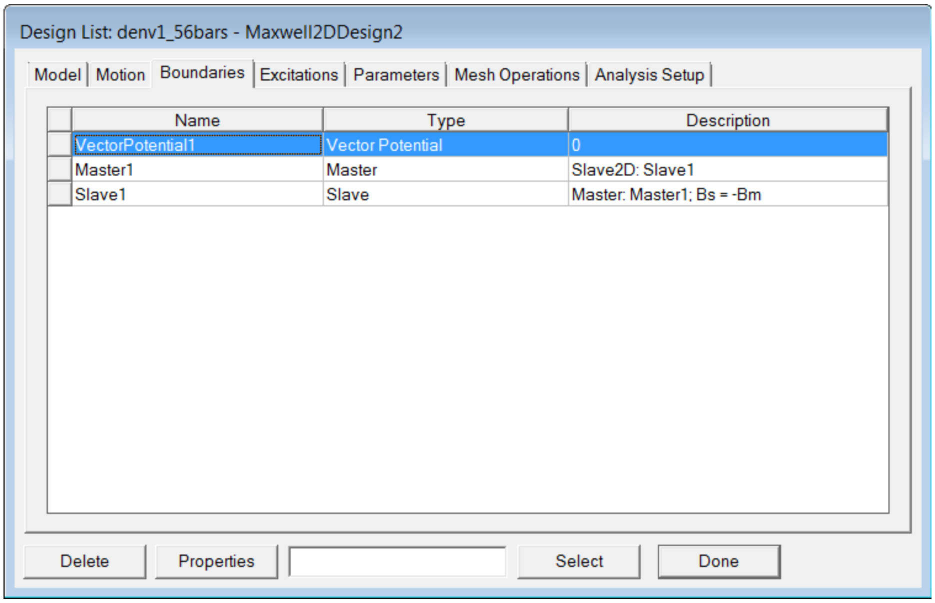


Figure 3.4. Maxwell2D excitation phase A

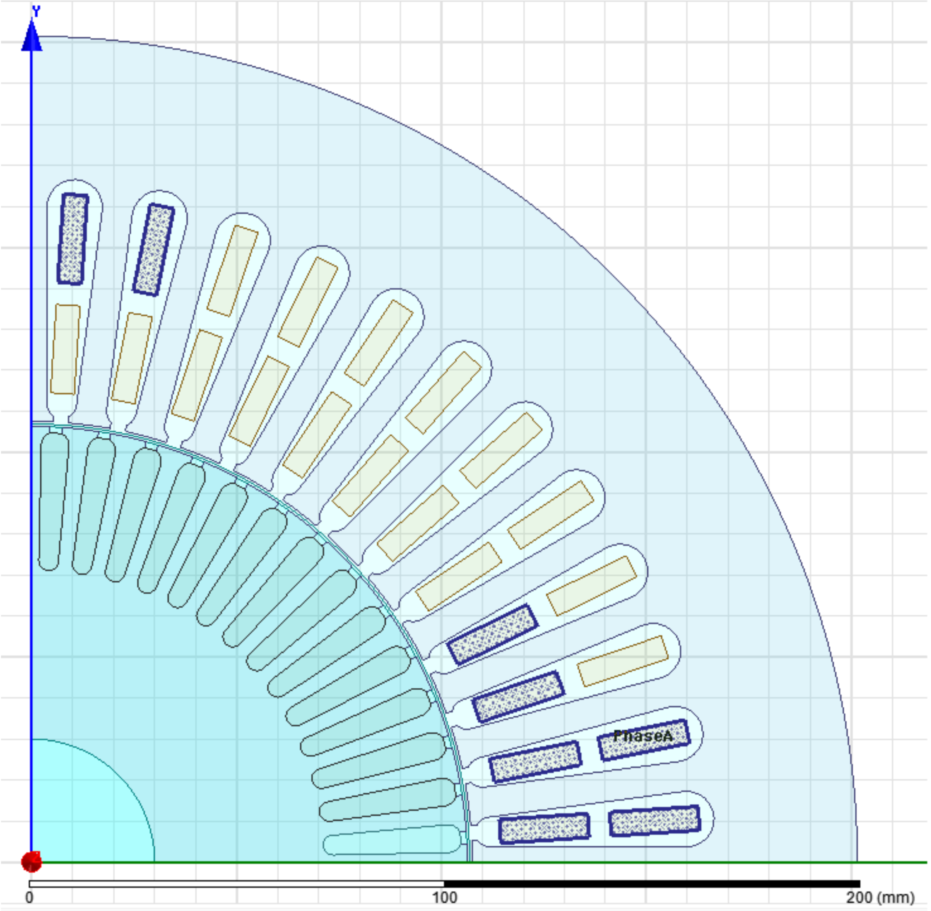


Figure 3.5. Maxwll2D excitation phaseB

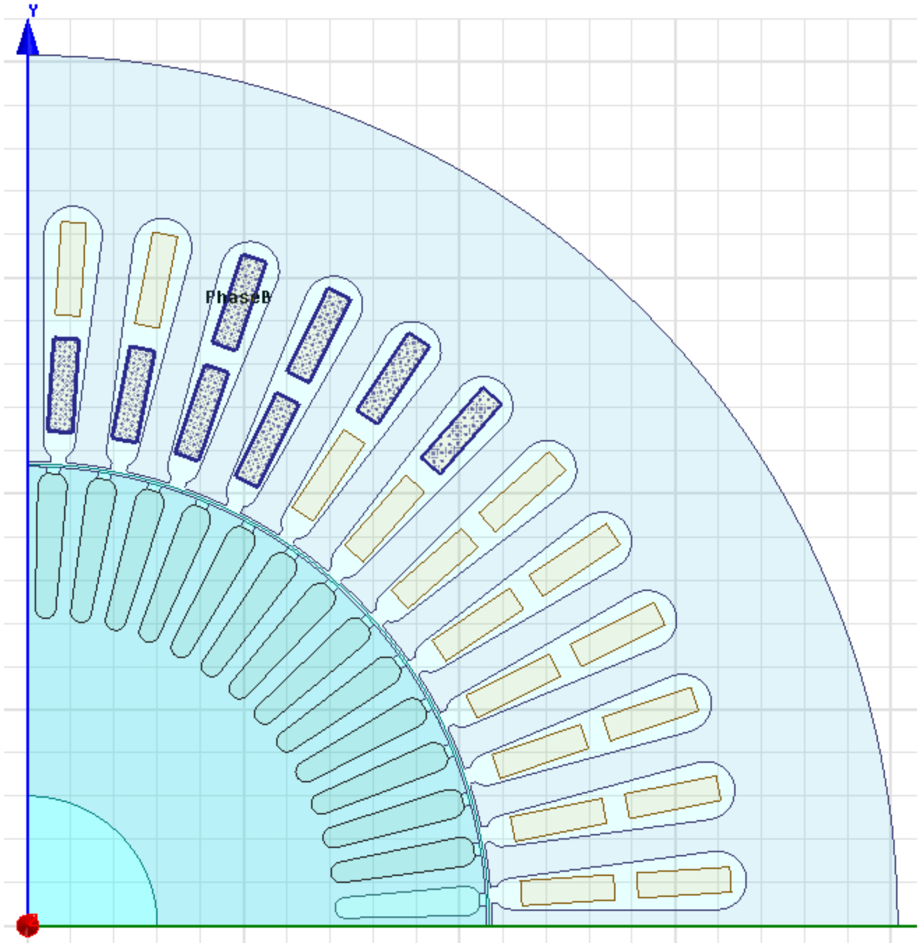


Figure 3.6. Maxwell2D excitation phaseC

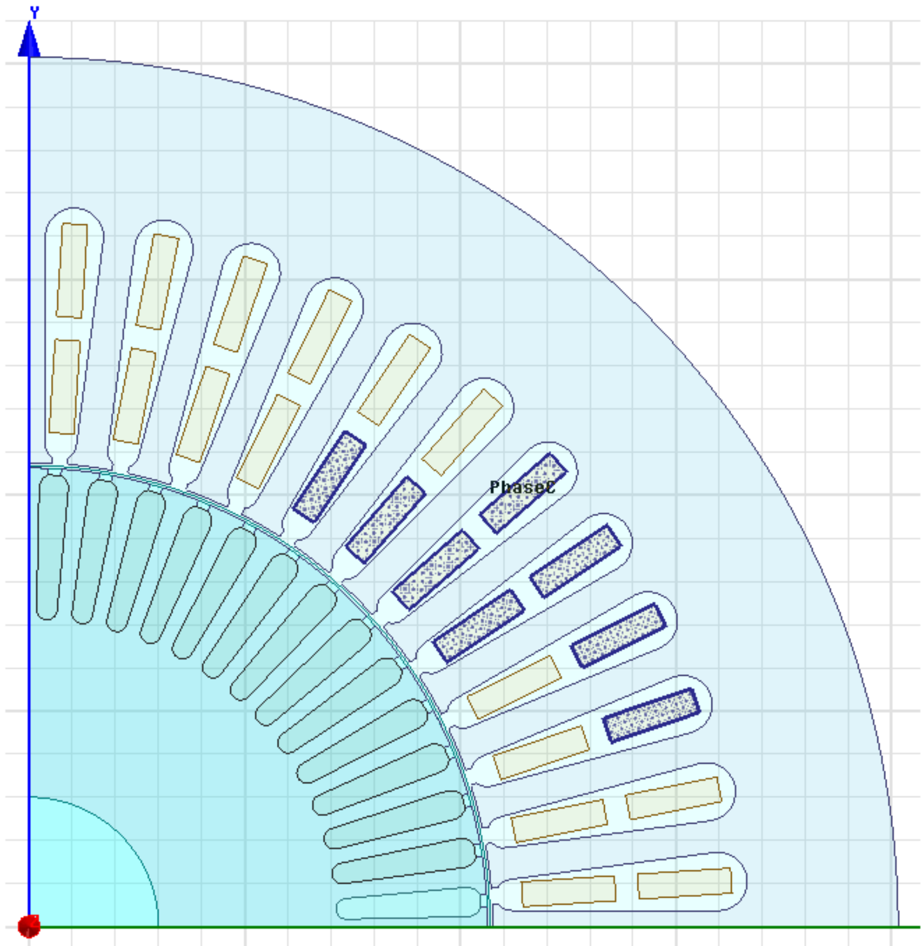


Figure 3.7. Maxwell2D excitation phaseA winding

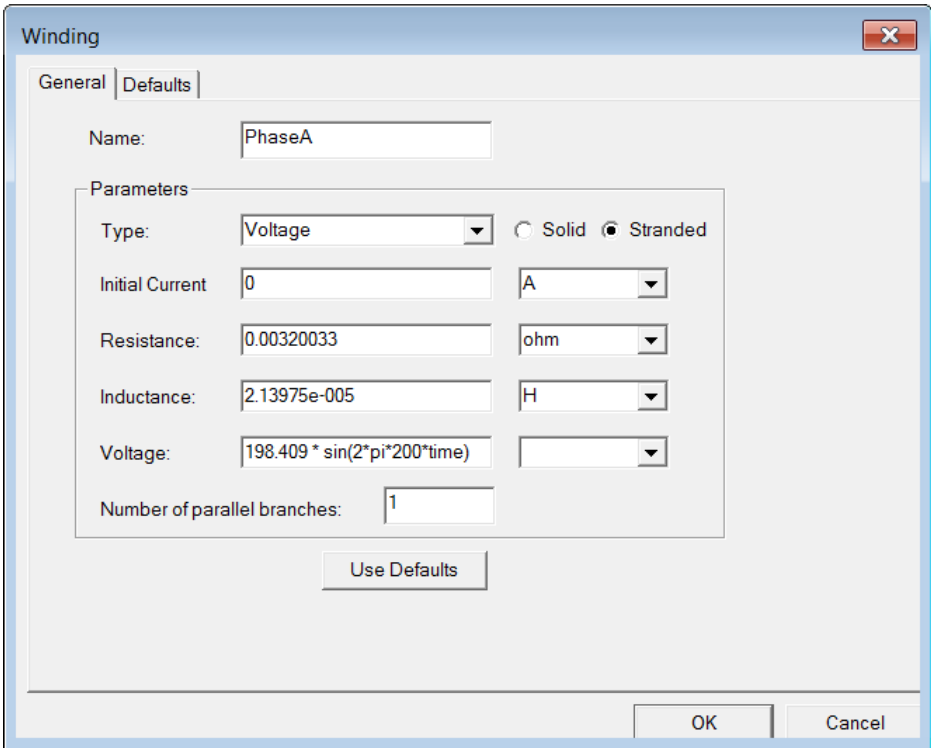


Figure 3.8. Maxwell2D mesh properties

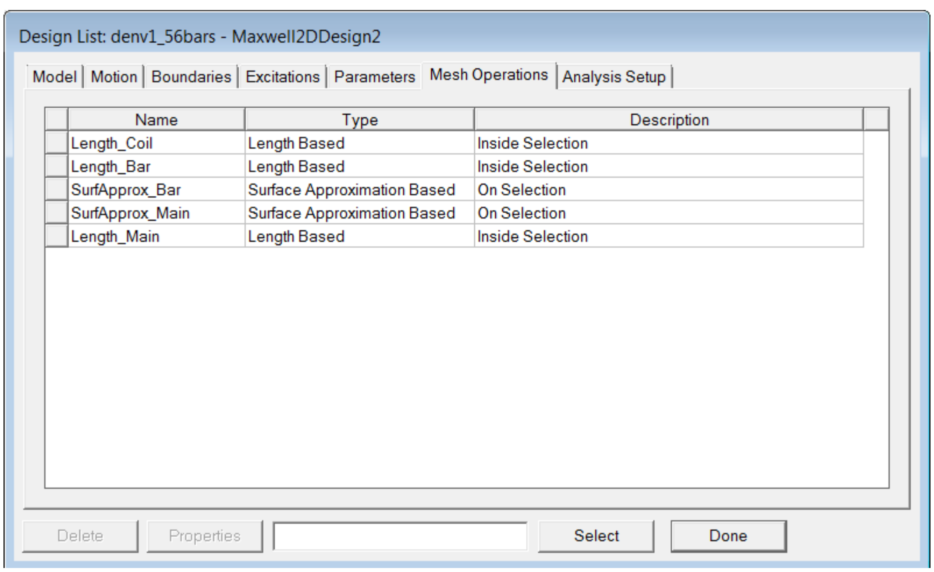


Figure 3.9. Maxwell2D solve setup

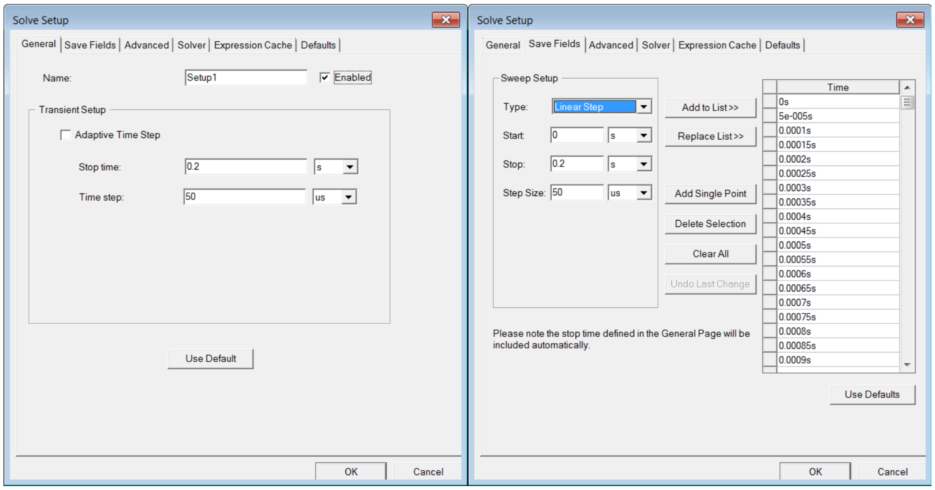


Figure 3.10. Maxwell2D torque result overall

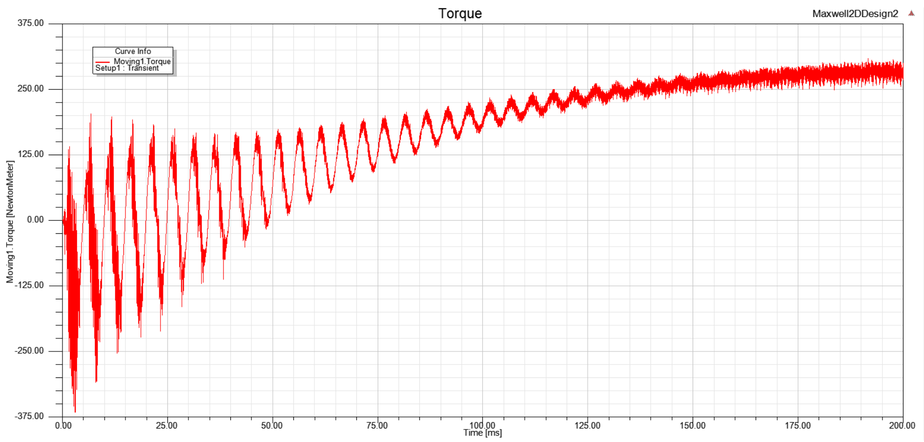


Figure 3.11. Maxwell2D winding phase currents overall

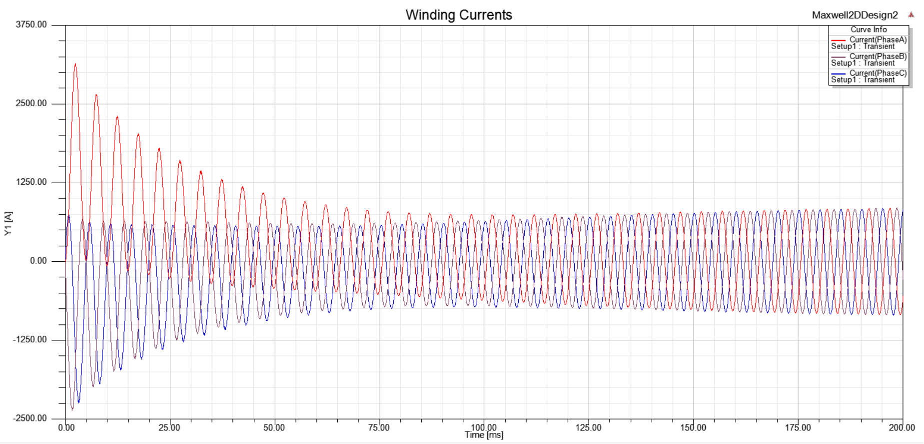


Figure 3.12. Maxwell2D torque result zoomed at steady state

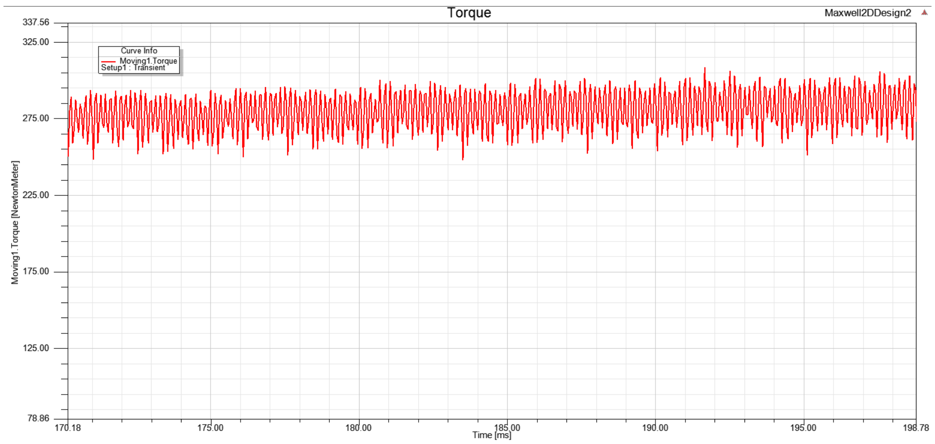


Figure 3.13. Maxwell2D winding phase currents zoomed at steady state

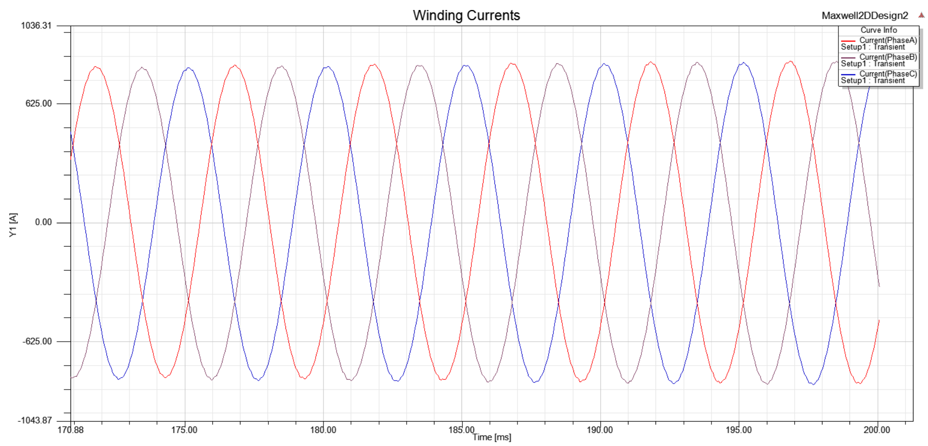


Figure 3.14. Maxwell2D induced voltages

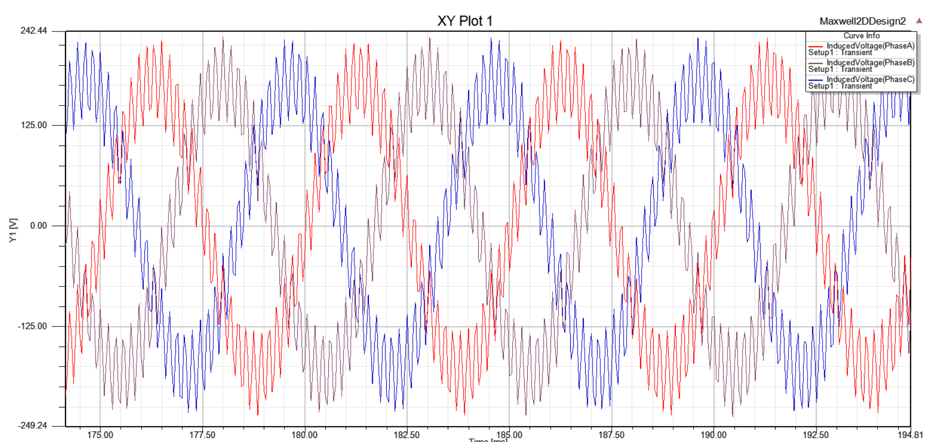


Figure 3.15. Maxwell2D created lines to measure flux density

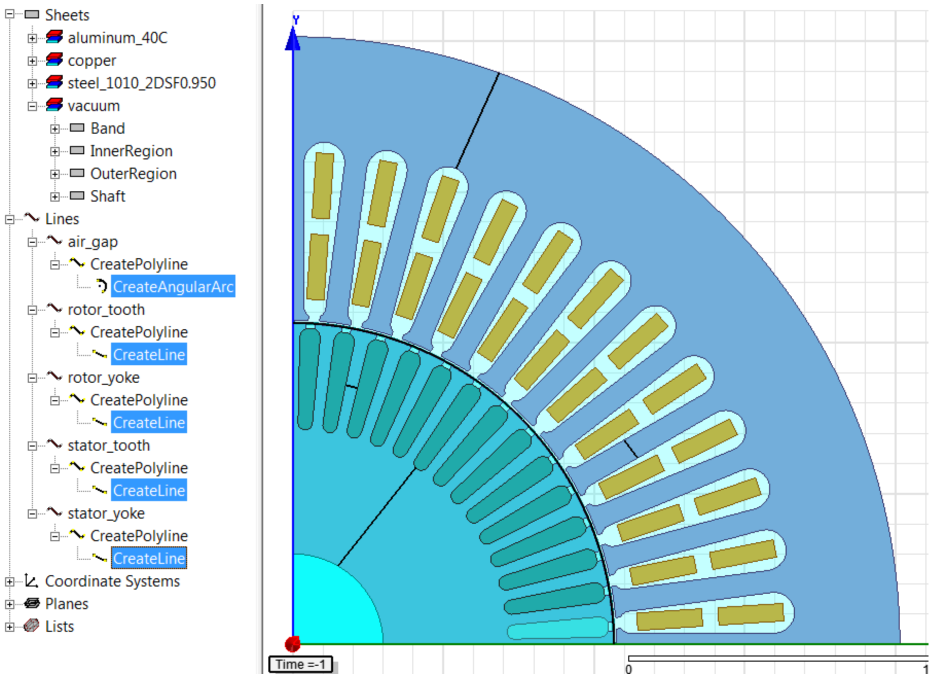


Figure 3.16. Maxwell2D airgap flux density

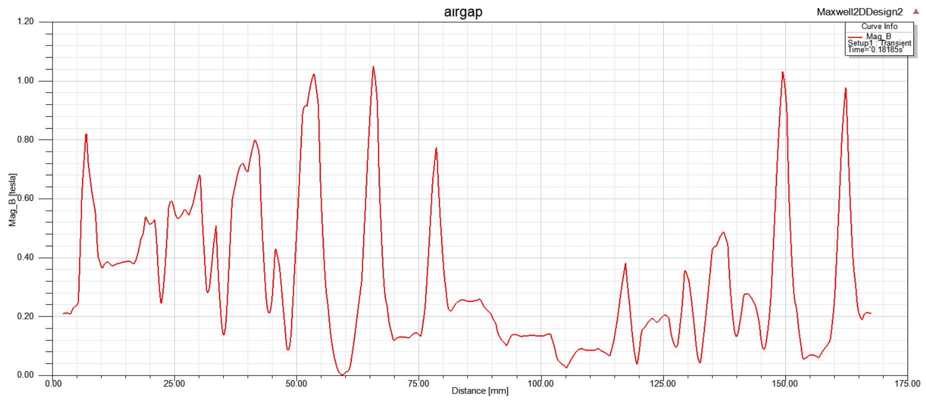


Figure 3.17. Maxwell2D rotor yoke flux density

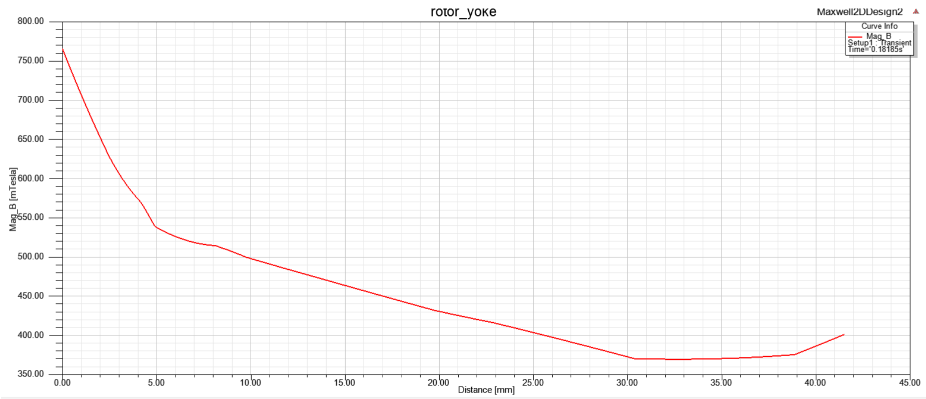


Figure 3.18. Maxwell2D stator yoke flux density

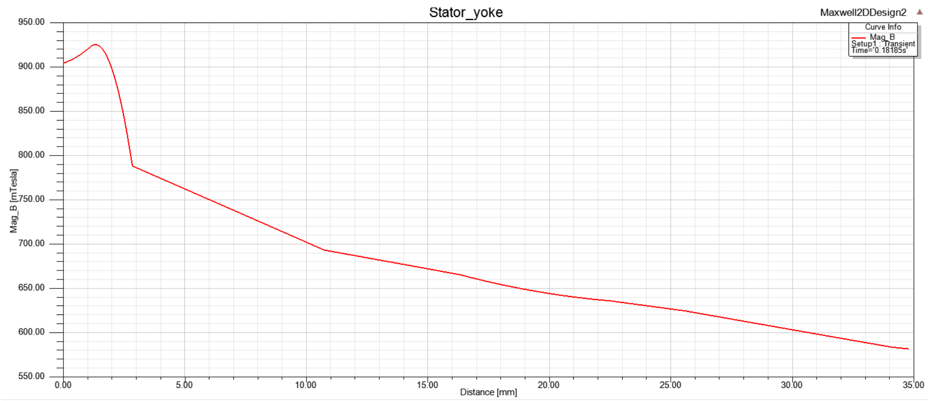


Figure 3.19. Maxwell2D stator tooth flux density

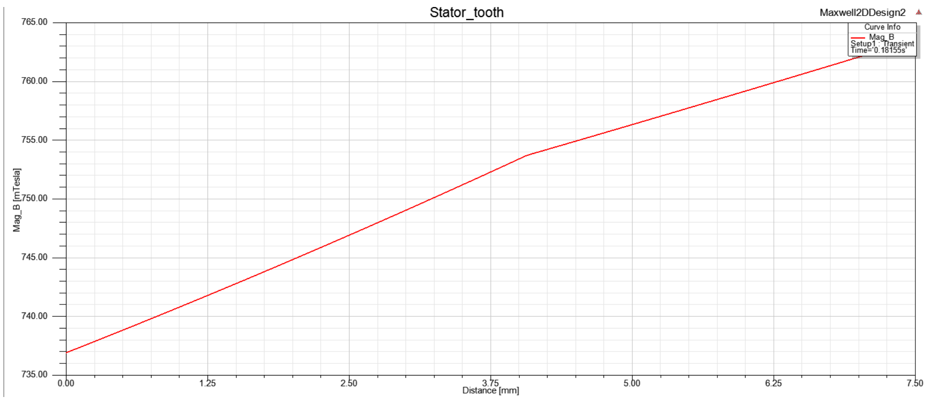


Figure 3.20. Maxwell2D magnetic flux density

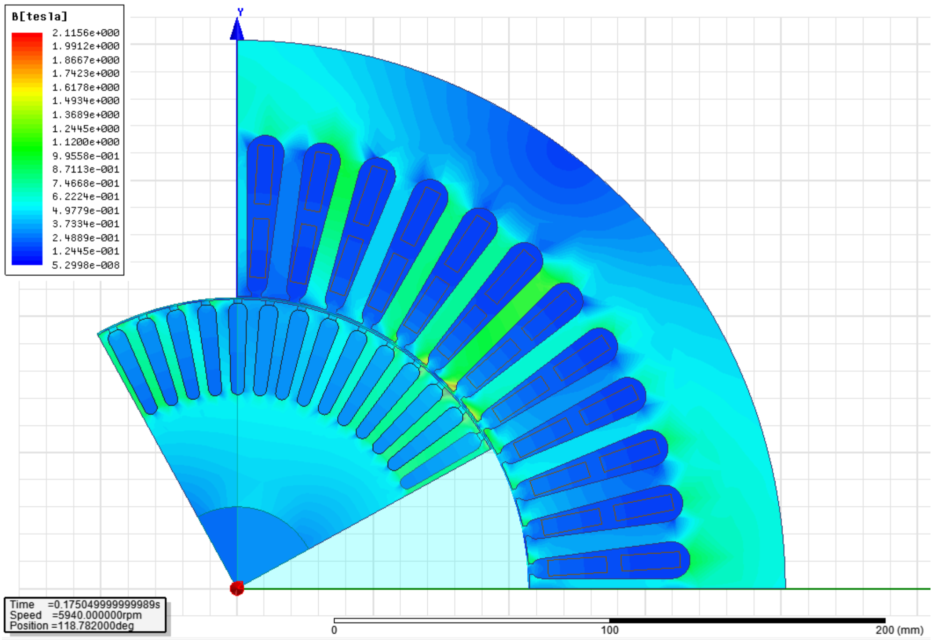


Figure 3.21. Maxwell2D magnetic flux density

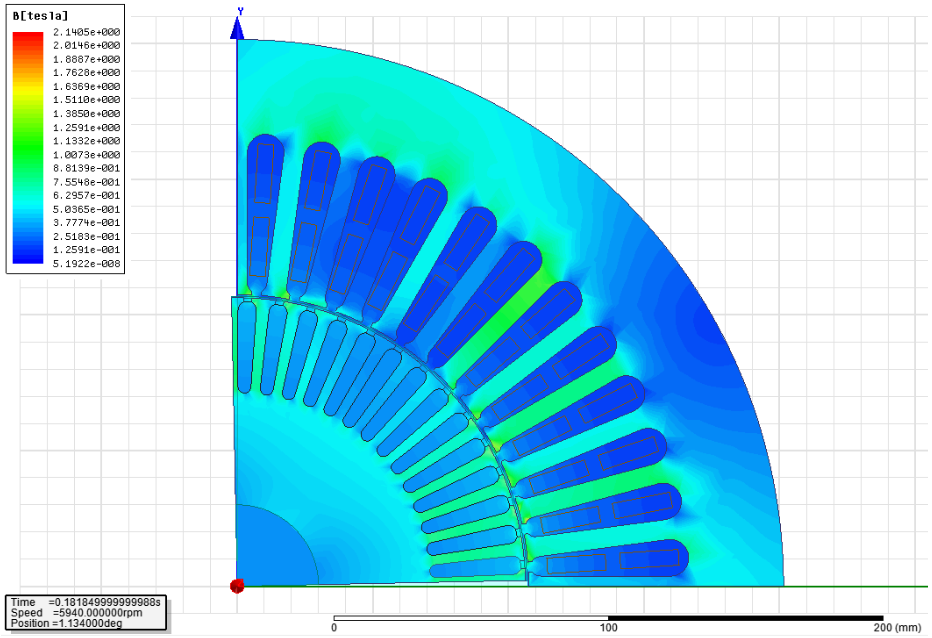


Figure 3.22. Maxwell2D magnetic fluxe lines

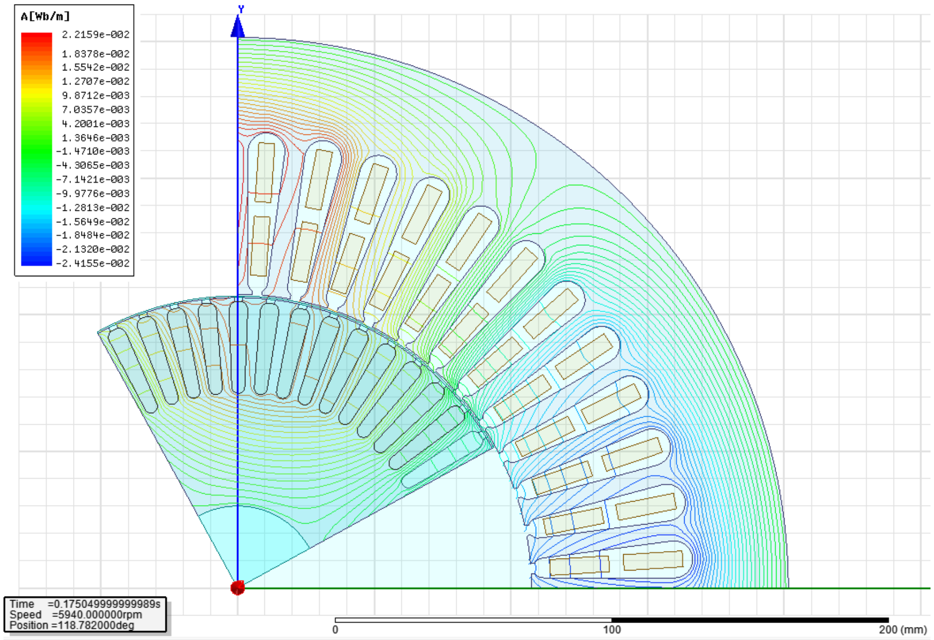


Figure 3.23. Maxwell2D magnetic flux lines

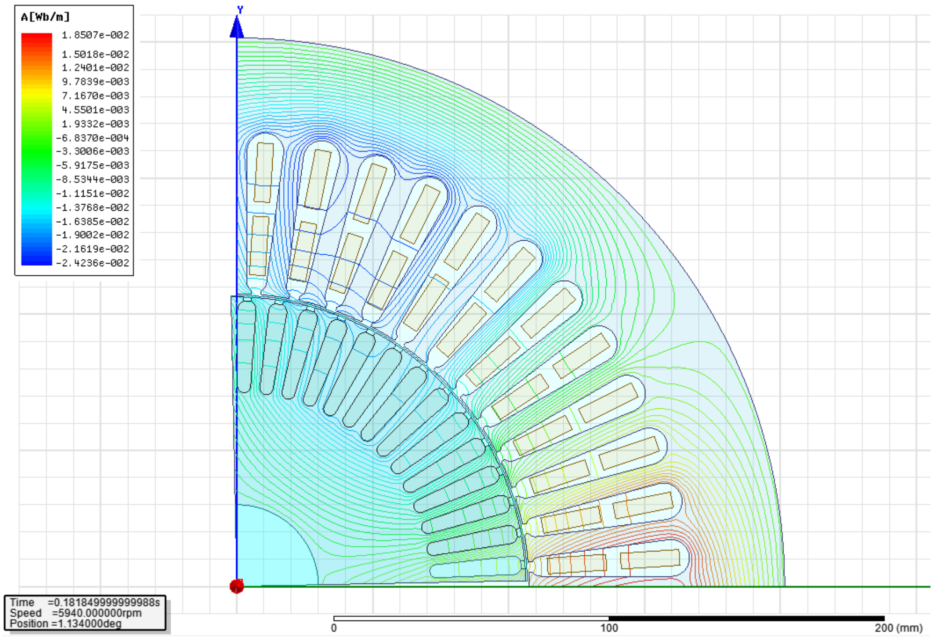


Figure 3.24. Maxwell2D magnetic flux density vector

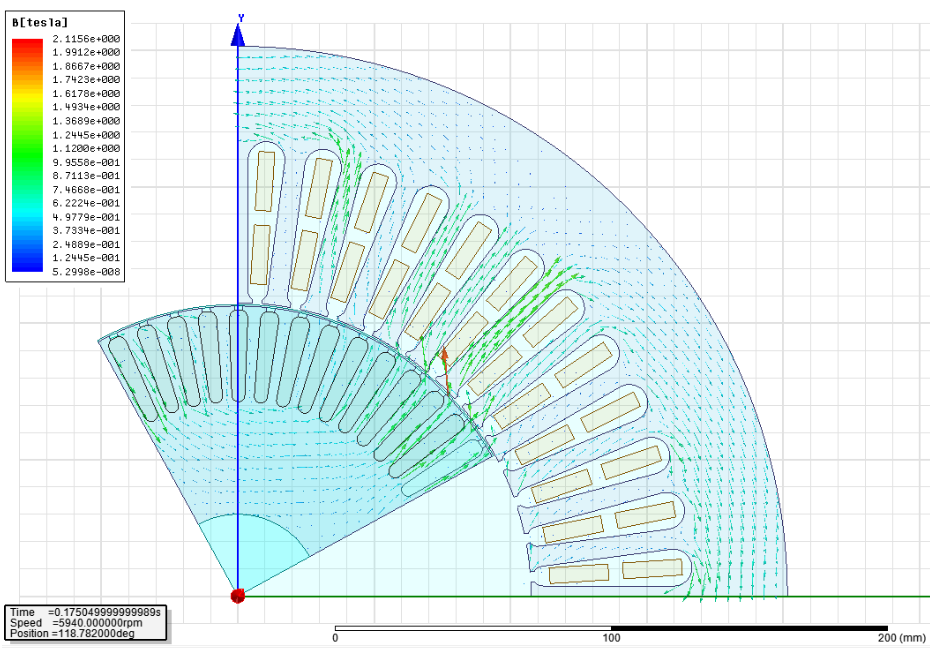
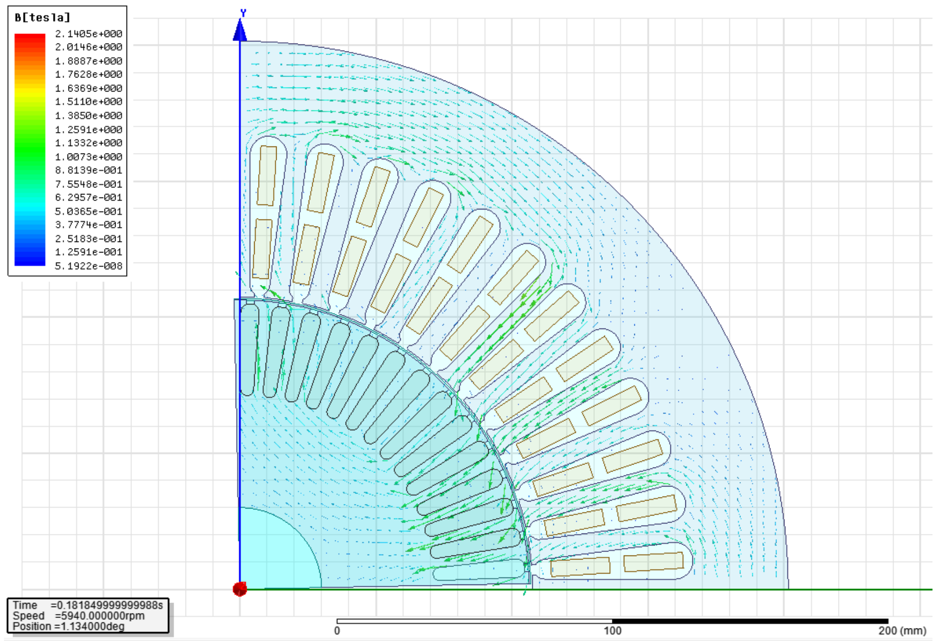


Figure 3.25. Maxwell2D magnetic flux density vector



Chapter 4. Conclusion

In this project Tesla Induction motor is designed. In the first chapter basic machine parameters are calculated. Followed steps to determine parameters are described corresponding chapter's subsections.
In chapter2, by using RMxprt Maxwell Ansoft program
three phase induction motor is designed with the machine parameters which are determined in chapter1.
Torque-speed characteristics, rated electrical data, magnetic data, rated performance, material consumption etc. are calculated with RMxprt and results are given in tables.
From RMxprt, 2D Maxwell design is created. A motion model is constructed and results like torque, phase winding currents, induced phase voltages, flux densities at airgap, stator tooth, stator yoke, rotor yoke, flux lines, flux density vectors are given in chapter3. By analysing flux densities especially in tooths of the satator and rotor, iterative slot size and shapes selection is done to avoid magnetic saturations.
By this project, a FEA software program is getting with familiar.