MIDDLE EAST TECHNICAL UNIVERSITY

ELECTRICAL AND ELECTRONICS ENGINEERING

EE564

DESIGN OF ELECTRICAL MACHINES

-PROJECT 3-

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EE564 DESIGN OF ELECTRICAL MACHINES

PROJECT 3

1. Introduction

In this project, squirrel cage induction generator will be designed for the Northel Energy's VIRA-250 wind turbine. Then, designed motor will be analyzed with FEM program. Specifications of the generator as follows,

- Rated Power: 250 kW
- Rated Wind Speed: 14 m/s
- Rated Turbine Speed: 24.3 rpm
- Gear Ratio: 31.2
- Number of Poles: 8
- Line to line voltage: 400 V
- Frequency: 50 Hz
- Rated Speed: 758 rpm
- Gearbox: (Coupled from wind turbine blade)
- Intended duty cycle :S1, direct on-line drive
- 3 phase

Design steps at below will be followed at this design.

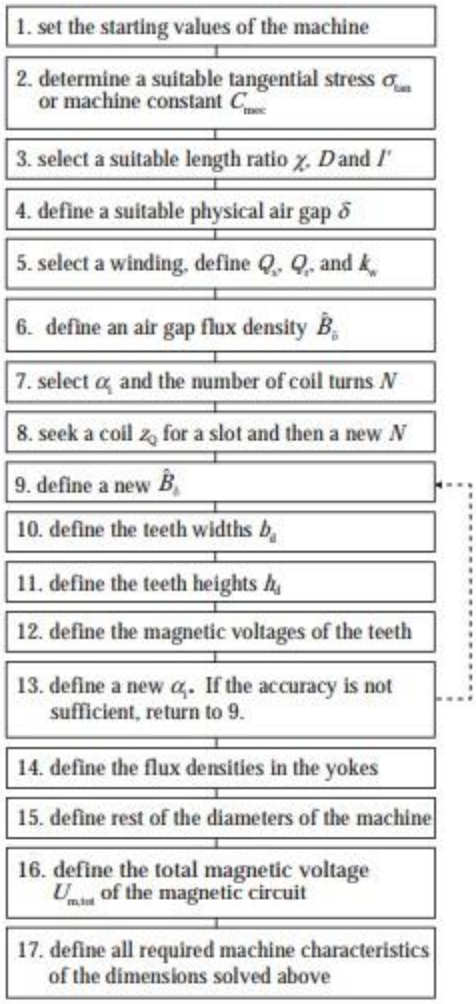


Figure Design process of a rotating electrical machine in brief. This chart was originally intended for induction motor design but may also be applied to other rotating-field machine types. The factor α_i behaves in a different way, especially in surface permanent magnet machines. The relative magnet width may be used as an initial value for α_i in PMSMs with rotor surface magnets of uniform thickness

Figure 1. Design procedure of machine

2. Starting Values

For this design, I aimed premium efficiency class because motor consumes high energy. It saturates %95,8 efficiency for high energy motors. Then, target efficiency is chosen %96.

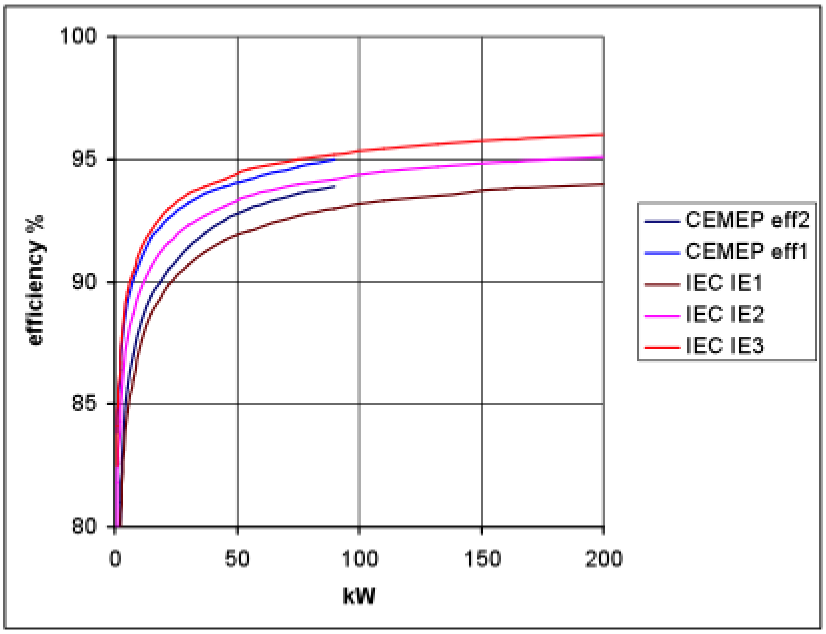


Figure 2. Efficiency class of machine

```
P_rated = 250000; %W
Vline = 400; %V
Npole = 8;
n_rated = 758; %rpm
w_rated = n_rated/60*2*pi;
T_rated = P_rated/w_rated; %Nm
f_rated = 50; %Hz
target_eff = 0.96; % %
target_pf = 0.87;
Vph = Vline/sqrt(3);
Pph = P_rated/3;

Npole_pair = Npole/2;

Iph = Pph/(Vph*target_eff*target_pf);% A

f_syn = f_rated/Npole_pair; %hz
n_syn = f_syn *60; %rpm
w_syn = n_syn*2*pi/60; % rad/sec

Number_of_ph = 3;

u0 = 4*pi*10e-7;
```

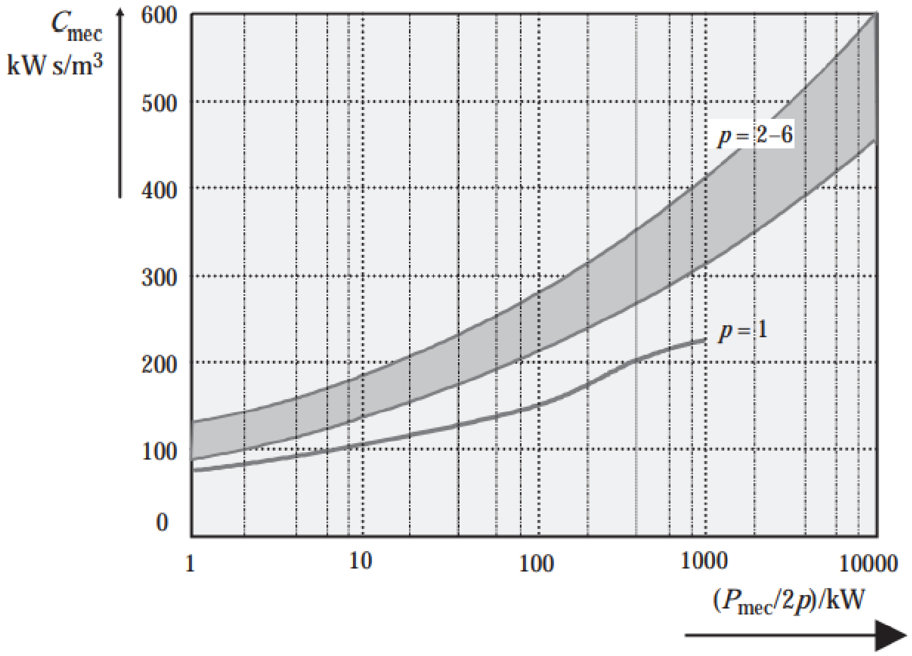
3. Main Dimensions

In this part, inner diameter and length of the machine will calculate. In order to achieve this Cmech(machine constant) should be detected according to calculated power per pole.

```
P_per_pole = P_rated/Npole;

fprintf('Power per pole is %g W.\n',P_per_pole);
```

```
Power per pole is 31250 W.
```



Machine constants of totally enclosed asynchronous and synchronous machines as a function of pole power

Figure 3. Cmech according to power

```
Cmech = 200000;
```

Product of inner_diameter^2 and length of the motor can be calculated from power and machine constant Cmech.

Pmech = Cmech*D^2*l'*fsync.

Also, aspect ratio should be calculated for decide dimensions. Aspect ratio can be calculated with following formula for asynchronous machines.

x = pi*(pole_pair^(1/3))/(2*pole_pair), x = L/D

```
D2L = P_rated/(Cmech* f_syn);

Aspect_Ratio= pi*(Npole_pair^(1/3))/(2*Npole_pair);
```

```
fprintf('di^2*L is %g\n',D2L);
fprintf('Aspect ratio is %g\n', Aspect_Ratio);
```

```
di^2*L is 0.1
Aspect ratio is 0.623371
```

L_machine = Aspect_Ratio * D_machine

Di^2*L is equal to the 1.66 . Also aspect ratio is equal to the 0.62. From previous parameters (D2L and aspect ratio), inner diameter and length of machine can be calculated. Moreover, outer diameter is calculated according to following table, which is generalized the outer diameter towards to the number of pole. Outer diameter coefficient is decreasing when number of pole increase because magnetic flux density at the yoke decreases proportionally.

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

Figure 4. General Do/Di value

```
M_inner_diameter = (D2L/Aspect_Ratio)^(1/3);
M_length = M_inner_diameter*Aspect_Ratio;
M_outer_diameter = 1.66*M_inner_diameter;

fprintf('Inner diameter is  %g m\n',M_inner_diameter);
fprintf('Outer diameter is  %g m\n',M_outer_diameter);


fprintf('Machine length is  %g m\n',M_length);
```

```
Inner diameter is  0.543356 m
Outer diameter is  0.901971 m
Machine length is  0.338712 m
```

After decide the main dimensions, we should check it with tangential (shear) stress. It should be in interval which is specified following table.

	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*
	*$\cos\varphi = 0.8$	*$\cos\varphi = 1$	*$\cos\varphi = 1$	*$\cos\varphi = 1$	*$\cos\varphi = 1$	*$\alpha_{DC} = 2/3$

Figure 5. Table of the electrical loading and tangential stress

```
M_inner_radius = M_inner_diameter/2;
F_tan = T_rated/M_inner_radius;
M_surface_area = M_inner_diameter*pi*M_length;

Shear_stress = F_tan/M_surface_area/1000; %Kpa

fprintf('Shear stress is  %g\n',Shear_stress);
```

```
Shear stress is  20.0504
```

Shear stress value is appropriate. So, dimensions are checked.

4. Air gap

After deciding main dimensions of the motor, air gap should be decided according to magnetic, electrical and mechanical properties. There is a trade-off between them. According to mechanical properties air gap should be maximize to rotate the machine smoothly. Therefore, according to electromagnetic properties, it should be minimize to make power transfer more.

Following figure shows that general air gap equations of asynchronous machines

$$\delta = 0.2 + 0.01P^{0.4} \text{mm when p=1}$$

$$\delta = 0.18 + 0.006P^{0.4} \text{mm when p > 1}$$

Smallest airgap is 0.2 mm

Figure 6. Air gap formula

```
airgap = (0.18 + 0.006*P_rated^0.4);

fprintf('Airgap is  %g mm\n',airgap);
```

```
Airgap is  1.04562 mm
```

5. Magnetic Parameters

Magnetic loading is specified previous part, which is equal to the 0.51T specified at below. Calculation details are made at the Project-2. Therefore, for this design, we do not know teeth dimensions yet, so that we have to decide either magnetic parameters or teeth dimensions, then calculate other one. At previous project, we selected lamination first, and then made a design. But, at this project, I would like to experience other way so that; I will specify magnetic parameters at desired intervals which are shown at following figure from textbook.

Table 6.1 Permitted flux densities of the magnetic circuit for various standard electrical machines

	Flux density B/T			
	Asynchronous machines	Salient-pole synchronous machines	Nonsalient-pole synchronous machines	DC machines
Air gap	0.7–0.90 ($\hat{B}_{\delta 1}$)	0.85–1.05 ($\hat{B}_{\delta 1}$)	0.8–1.05 ($\hat{B}_{\delta 1}$)	0.6–1.1 (B_{max})
Stator yoke	1.4–1.7 (2)	1.0–1.5	1.1–1.5	1.1–1.5
Tooth (apparent maximum value)	1.4–2.1 (stator) 1.5–2.2 (rotor)	1.6–2.0	1.5–2.0	1.6–2.0 (compensating winding) 1.8–2.2 (armature winding)
Rotor yoke	1–1.6 (1.9)	1.0–1.5	1.3–1.6	1.0–1.5
Pole core	—	1.3–1.8	1.1–1.7	1.2–1.7
Commutating poles	—	—	—	1.3

Figure 7. Magnetic loading formula

```
Bg_av = 0.51; %T
Bg = 0.8;    %T
Bs_yoke = 1.6;  %T
```

```
Bs_tooth = 1.9; %T
Br_yoke = 1.5;  %T
Br_tooth = 2.0;  %T

fprintf('Magnetic Loading is  %g T\n',Bg_av);
fprintf('Selected air gap flux density is  %g T\n',Bg);
fprintf('Selected stator yoke flux density is  %g T\n',Bs_yoke);
fprintf('Selected stator teeth flux density is  %g T\n',Bs_tooth);
fprintf('Selected rotor yoke flux density is  %g T\n',Br_yoke);
fprintf('Selected rotor teeth flux density is  %g T\n',Br_tooth);
```

```
Magnetic Loading is  0.51 T
Selected air gap flux density is  0.8 T
Selected stator yoke flux density is  1.6 T
Selected stator teeth flux density is  1.9 T
Selected rotor yoke flux density is  1.5 T
Selected rotor teeth flux density is  2 T
```

6. Electrical Parameters and Winding Selection

In this part of the project, number of slots of rotor and stator and winding factors of higher harmonics are calculated. For high pole machine, it is preferred to have Qr = Qs*1.2. In order to prevent cogging problem number of rotor and stator should be different and some combinations of these should be avoided as Qs = 2Qr, Qr = Qs +-2p, etc. Moreover, if Qr = 6pg +-2p+-1, g is an integer, mechanical noise and vibrations could be observed. Number of slots per pole per phase is decided 3.

```
qs = 3;
Qs = qs*Number_of_ph*Npole;
```

Qr = 1.2*Qs is nearly 86 and in general design, Qs/Qr = 72/88 is used.

```
Qr = 88;

fprintf('Number of stator slots are  %g\n',Qs);
fprintf('Number of rotor slots are  %g\n',Qr);
```

```
Number of stator slots are  72
Number of rotor slots are  88
```

In order to eliminate 5th harmonics of the machine, it is preferred to design double layer winding with 7/9 pitch factor. 3rd harmonics are eliminated because of line to line connection of phases.

```
pitch_factor = 7/9;
slot_angle = pi*Npole/Qs;
pitch_angle = pitch_factor*pi;
pole_pitch = pi*M_inner_diameter/Npole;

Kd_1 = sin(qs*slot_angle/2)/(qs*sin(slot_angle/2));
Kp_1 = sin(pitch_angle/2);
Kw_1 = Kd_1*Kp_1;
```

```
Kd_5 = sin(5*qs*slot_angle/2)/(qs*sin(5*slot_angle/2));
Kp_5 = sin(5*pitch_angle/2);
Kw_5 = Kd_5*Kp_5;

Kd_7 = sin(7*qs*slot_angle/2)/(qs*sin(7*slot_angle/2));
Kp_7 = sin(7*pitch_angle/2);
Kw_7 = Kd_7*Kp_7;

Kd_11 = sin(11*qs*slot_angle/2)/(qs*sin(11*slot_angle/2));
Kp_11 = sin(11*pitch_angle/2);
Kw_11 = Kd_11*Kp_11;


fprintf('Pitch factor is  %g\n',pitch_factor);
fprintf('Slot angle is  %g\n rad',slot_angle);
fprintf('Pitch angle is  %g\n rad',pitch_angle);



fprintf('Winding factor of fundemental harmonic is  %g\n',Kw_1);
fprintf('Winding factor of 5th harmonic is  %g\n',Kw_5);
fprintf('Winding factor of 7th harmonic is  %g\n',Kw_7);
fprintf('Winding factor of 11th harmonic is  %g\n',Kw_11);
```

```
Pitch factor is  0.777778
Slot angle is  0.349066 rad
Pitch angle is  2.44346 rad
Winding factor of fundemental harmonic is  0.901912
Winding factor of 5th harmonic is  -0.0377803
Winding factor of 7th harmonic is  -0.135868
Winding factor of 11th harmonic is  -0.135868
```

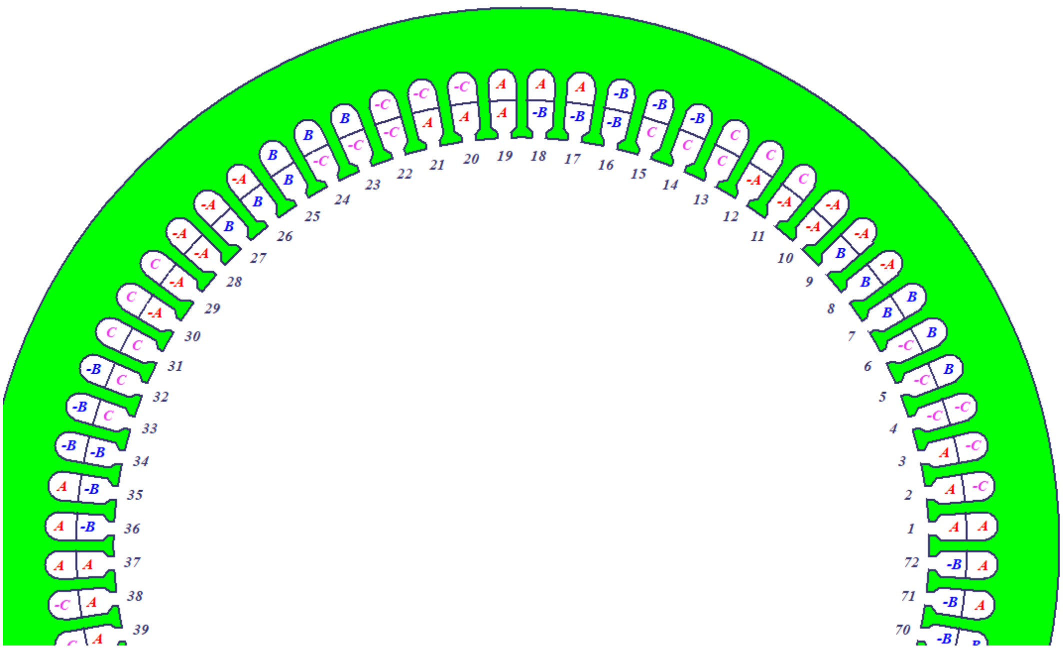


Figure 8. Winding diagram of the machine

Number of turns can be calculated induced EMF formula. Induced EMF is near to the phase voltage.

At the project-2, how I decide air gap average flux density is explained so that I have chosen peak of air gap magnetic flux density 0.8T, magnetic loading is nearly 0.51T.

```
Bg_av = 0.51;
magnetic_loading = 0.51;

Ind_emf = Vph;

flux_per_pole = Bg_av*pole_pitch*M_length;
Nph = Ind_emf/(4.44*f_rated*flux_per_pole*Kw_1);

Ns = Nph/(Npole_pair*qs);

fprintf('Calculated number of turns per phase is  %g\n',Nph);
fprintf('Calculated number of turns per slot is  %g\n',Ns);
```

```
Calculated number of turns per phase is  31.2922
Calculated number of turns per slot is  2.60769
```

To make number of turns integer Ns is taken 3.

```
Ns = 3;
Nph = Ns*(Npole_pair*qs);
fprintf('Number of turns per phase is  %g\n',Nph);
fprintf('Number of turns per slot is  %g\n',Ns);
```

```
Number of turns per phase is  36
Number of turns per slot is  3
```

Electrical loading is calculated as A = Ns*I*Qs/(pi*Di)

```
A = Shear_stress/magnetic_loading; %kA/m

fprintf('Magnetic loading is  %g T\n',magnetic_loading);
fprintf('Electrical loading is  %g kA/m\n',A);
```

```
Magnetic loading is  0.51 T
Electrical loading is  39.3144 kA/m
```

Electrical loading value is appropriate according to following figure from textbook.

In general, 7A/mm2 current density is used for 8 pole air cooling machines. Also skin depth should be considered at maximum frequency.

```
cu_resistivity = 1.7e-8; % Ohm*m
cu_permeability = 1.26e-6; % H/m
f_max = f_rated;
angular_frequency = 2*pi*f_max; % rad/sec
```

```
skin_depth = sqrt(cu_resistivity*2/(angular_frequency*cu_permeability));
copper_area = Iph/7;

fprintf('Phase current is  %g kA\n',Iph);
fprintf('skin depth is  %g mm\n',skin_depth*1000);
fprintf('Needed copper area is  %g mm2\n',copper_area);
```

```
Phase current is  432.045 kA
skin depth is  9.26786 mm
Needed copper area is  61.7207 mm2
```

According to the skin depth value cable can have maximum 20mm diameter. Phase current is calculated as 432Arms so that 5 parallel AWG4 cable can be used. Because desired current density of AWG4 is about 6A/mm2.

AWG gauge	Conductor Diameter Inches	Conductor Diameter mm	Conductor cross section in mm^2	Ohms per 1000 ft.	Ohms per km	Maximum amps for chassis wiring	Maximum amps for power transmission	Maximum frequency for 100% skin depth for solid conductor copper	Breaking force Soft Annealed Cu 37000 PSI
0000	0.46	11.684	107	0.049	0.16072	380	302	125 Hz	6120 lbs
000	0.4096	10.40384	84.9	0.0618	0.202704	328	239	160 Hz	4860 lbs
00	0.3648	9.26592	67.4	0.0779	0.255512	283	190	200 Hz	3860 lbs
0	0.3249	8.25246	53.5	0.0983	0.322424	245	150	250 Hz	3060 lbs
1	0.2893	7.34822	42.4	0.1239	0.406392	211	119	325 Hz	2430 lbs
2	0.2576	6.54304	33.6	0.1563	0.512664	181	94	410 Hz	1930 lbs
3	0.2294	5.82676	26.7	0.197	0.64616	158	75	500 Hz	1530 lbs
4	0.2043	5.18922	21.1	0.2485	0.81508	135	60	650 Hz	1210 lbs
5	0.1819	4.62026	16.8	0.3133	1.027624	118	47	810 Hz	960 lbs
6	0.162	4.1148	13.3	0.3951	1.295928	101	37	1100 Hz	760 lbs
7	0.1443	3.66522	10.6	0.4982	1.634096	89	30	1300 Hz	605 lbs
8	0.1285	3.2639	8.37	0.6282	2.060496	73	24	1650 Hz	480 lbs

Figure 9. Cable size table

```
awg4_cross_area = 21.1; %mm2
awg4_R_per_km = 0.081508; %ohm
cable_cross_area = 5*awg4_cross_area; %mm2
cable_R_per_km = awg4_R_per_km/5;  %@25 degree
```

I will make an approximation about copper length with following calculation.

```
one_turn_length = 2*M_length+2*M_inner_diameter;
total_copper_length = one_turn_length*Qs*Ns; %m
ph_stator_copper_resistance = cable_R_per_km*total_copper_length/3/1000;

fprintf('Total copper length is %g km\n',total_copper_length);
fprintf('Phase copper resistance is  %g ohm\n',ph_stator_copper_resistance);
```

```
Total copper length is 381.054 km
Phase copper resistance is  0.00207059 ohm
```

At high power motors, fill factor is important because heating and insulation are affected to it. In general, this kind of application %50 fill factor is applicable.

```
fill_factor = 0.5;
total_slot_area = 6*cable_cross_area/fill_factor; %mm^2
```

7. Stator Slot Dimensions

Teeth dimension will be calculated according to magnnetic flux densities. Moreover, slots will be design tapered type slots because I would like to make tooth width constant.

```
slot_pitch = pole_pitch/9;

fprintf('Pole pitch is  %g mm\n', pole_pitch*1000);
fprintf('Slot pitch is  %g mm\n', slot_pitch*1000);
fprintf('Needed slot area is %g mm2\n', total_slot_area);
```

```
Pole pitch is  213.375 mm
Slot pitch is  23.7084 mm
Needed slot area is 1266 mm2
```

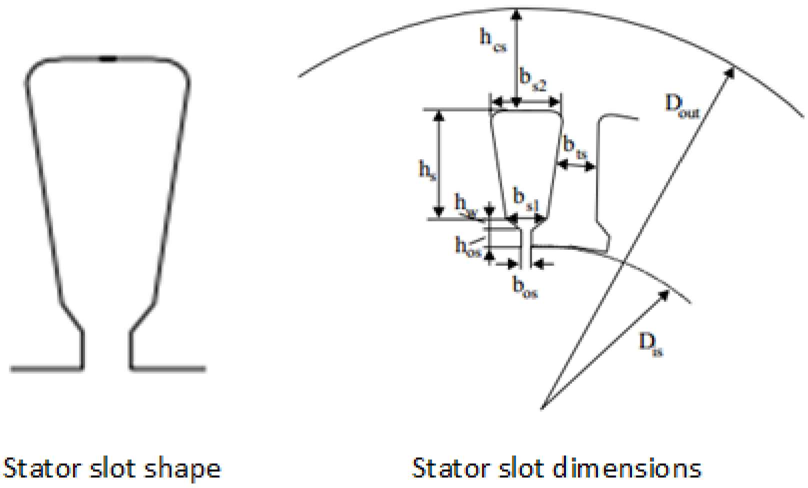


Figure 10. Stator slot illustration

All flux of air gap could not flux through to teeth because there is a leakage and fringing fluxes. So that, when I calculate teeth width, ı will take %95 of flux passes.

```
Kfe = 0.95;

b_ts= Bg_av*slot_pitch/(Kfe*Bs_tooth)*1000; %mm

fprintf('Stator slot tooth width (b_ts) is %g mm\n',b_ts);
```

```
Stator slot tooth width (b_ts) is 6.69877 mm
```

I will select slot opening according to the cable diameter to make producing easier.

```
b_os = 6; %mm
h_os = 2;
h_w = 2;
```

```
b_s1 = pi*(M_inner_diameter*1e3+2*h_os+2*h_w)/Qs-b_ts; % mm

fprintf('Stator slot opening width (b_os) is %g mm\n',b_os);
fprintf('Stator slot opening height (h_os) is %g mm\n',h_os);
fprintf('The bottom stator slot width (b_s1) is %g mm\n',b_s1);


b_s2 = sqrt(4*total_slot_area*tan(pi/Qs)+b_s1^2);

h_s = 2*total_slot_area/(b_s1+b_s2); % mm

fprintf('The top stator slot width (b_s2) is %g mm\n',b_s2);
fprintf('The useful stator slot height (hs) is %g mm\n',h_s);
```

```
Stator slot opening width (b_os) is 6 mm
Stator slot opening height (h_os) is 2 mm
The bottom stator slot width (b_s1) is 17.3587 mm
The top stator slot width (b_s2) is 22.8566 mm
The useful stator slot height (hs) is 62.9612 mm
```

Calculations are made by geometrical calculations.

```
h_cs = (1e3*M_outer_diameter-(1e3*M_inner_diameter+2*(h_os+h_w+h_s)))/2;

fprintf('The thickness of stator back iron(yoke) is (h_cs) is %g mm\n',h_cs);
```

```
The thickness of stator back iron(yoke) is (h_cs) is 112.346 mm
```

Check the yoke magnetic flux density.

```
B_cs = flux_per_pole/(2*M_length*h_cs*1e-3);

fprintf('Calculated Magnetic flux density at yoke is %g T\n',B_cs);
fprintf('Aimed Magnetic flux density at yoke is %g T\n',Bs_yoke);
```

```
Calculated Magnetic flux density at yoke is 0.484313 T
Aimed Magnetic flux density at yoke is 1.6 T
```

This value is smaller from saturation value of the iron so that, in order to decrease mass and cost of the motor outer diameter could decrease. I will increase B_cs value sligtly.

```
B_cs_aimed = 1.4; %T

h_cs_new = flux_per_pole/(2*M_length*B_cs_aimed*1e-3); % mm

M_outer_diameter_new = (2*h_cs_new+(1e3*M_inner_diameter+2*(h_os+h_w+h_s)))*1e-3; % m
```

```
fprintf('The decreased thickness of stator back iron(yoke) is (h_cs) is %g mm\n',h_cs_new);
fprintf('The decreased outer diameter is %g m\n',M_outer_diameter_new);
```

```
The decreased thickness of stator back iron(yoke) is (h_cs) is 38.8648 mm
The decreased outer diameter is 0.755008 m
```

8. Rotor Bar Dimensions

Rotor slots will fill aluminum so that fill factor is 1. Also, I will choose shape of the rotor teeth according to easy producing. Stacking factor is taken same as stator.

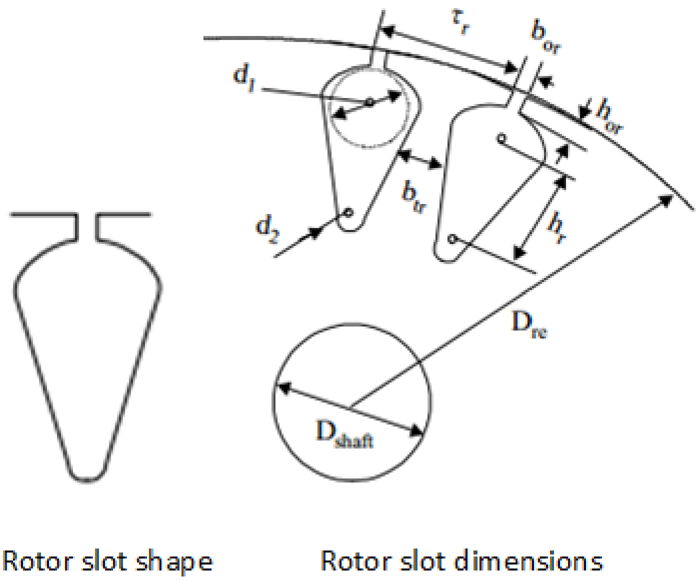


Figure 11. Rotor slot illustration

Equations are used in finding slot dimensions are given following table.

$$(1)\quad B_g \tau_s L \approx B_{ts} b_{ts} L K_{Fe}$$

$$(2)\quad B_g \tau_s L \approx B_{ts} b_{ts} L K_{Fe}$$

$$(3)\quad b_{s1} = \frac{\pi\left(D_{is} + 2h_{os} + 2h_w\right)}{N_s} - b_{ts}$$

$$(4)\quad A_{su} = h_s \frac{\left(b_{s1} + b_{s2}\right)}{2}$$

$$(5)\quad b_{s2} \approx b_{s1} + 2h_s \tan\frac{\pi}{N}$$

$$(6)\quad b_{s2} = \sqrt{4A_{su} \tan\frac{\pi}{N_s} + b_{s1}^{\,2}}$$

$$(7)\quad h_s = \frac{2A_{su}}{b_{s1} + b_{s2}}$$

$$(8)\quad h_{cs} = \frac{D_{out} - \left(D_{is} + 2\left(h_{os} + h_w + h_s\right)\right)}{2}$$

$$(9)\quad b_{tr} \approx \frac{B_g}{K_{Fe} B_{tr}} \cdot \tau_r$$

$$(10)\quad I_b = K_I \frac{2mW_1 K_{w1}}{N_r} I_{1n}$$

$$(11)\quad A_b = \frac{I_b}{J_b}$$

$$(12)\quad I_{cr} = \frac{I_b}{2\sin\frac{\pi p_1}{N_r}}$$

$$(13)\quad A_{cr} = \frac{I_{cr}}{J_{cr}}$$

$$(14)\quad d_1 = \frac{\pi\left(D_{re} - 2h_{or}\right) - N_r b_{tr}}{\pi + N_r}$$

$$(15)\quad A_b = \frac{\pi}{8}\left(d_1^{\,2} + d_2^{\,2}\right) + \frac{\left(d_1 + d_2\right)h_r}{2}$$

$$(16)\quad d_1 - d_2 = 2h_r \tan\frac{\pi}{N_r}$$

$$(17)\quad h_{cr} = \frac{\phi}{2}\frac{1}{L \cdot B_{cr}}$$

$$(18)\quad \left(D_{shaft}\right)_{max} \le D_{is} - 2g - 2\left(h_{or} + \frac{d_1 + d_2}{2} + h_r + h_{cr}\right) =$$

Figure 12. Equation table for rotor slot size

```
fprintf('Number of slot at the rotor is %g \n',Qr);
Rotor_slot_pitch = pi*(1e3*M_inner_diameter-2*airgap)/Qr; % mm
fprintf('Rotor slot pitch is %g mm\n',Rotor_slot_pitch);

b_tr = (Bg_av*Rotor_slot_pitch)/(Br_tooth*Kfe); % mm

h_or = 2; %mm
b_or = 3; %mm
```

```
Number of slot at the rotor is 88
Rotor slot pitch is 19.3231 mm
```

Rotor current should be calculated to calculate aluminum bar area. Chosen current density is decreased because of conductivity of the aluminum is smaller than copper.

```
J_rotor = 6; %A/mm2
KI = 0.8*target_pf +0.2;
I_rotor_bar = KI*2*Number_of_ph*Nph*Kw_1*Iph/Qr;
Rotor_al_area = I_rotor_bar/J_rotor;
I_rotor_ring = I_rotor_bar/(2*sin(2*pi/Qr)); % A
J_ring = 0.78*J_rotor; % A/mm^2
Rotor_ring_area = I_rotor_ring/J_ring; % mm^2
```

```
fprintf('Rotor slot current density is %g A/mm2\n',J_rotor);
fprintf('Rotor ring current density is %g A/mm2\n',J_ring);
fprintf('Rotor bar current is %g A\n',I_rotor_bar);
fprintf('Needed rotor aliminum area is %g mm2\n',Rotor_al_area);
fprintf('Rotor ring current is %g A\n',I_rotor_ring);
fprintf('Needen ring area is %g mm2\n',Rotor_ring_area);
```

```
Rotor slot current density is 6 A/mm2
Rotor ring current density is 4.68 A/mm2
Rotor bar current is 856.983 A
Needed rotor aliminum area is 142.831 mm2
Rotor ring current is 6006.4 A
Needen ring area is 1283.42 mm2
```

Then, we need to calculate rotor other rotor dimensions by using given equation 14,15,16,17 and 18 at previous equation table.

```
d_1 = (pi*(1e3*M_inner_diameter-2*airgap-2*h_or)-Qr*b_tr)/(pi+Qr); % mm

d_2 = 3; % mm
h_r = (d_1 - d_2)/(2*tan(pi/Qr)); % mm
rotor_slot_area = (pi/8)*(d_1^2+d_2^2)+(d_1+d_2)*h_r/2; % mm^2

h_cr = 1e3*flux_per_pole/(2*M_length*Br_yoke); % mm

Dshaftmax = M_inner_diameter*1e3-2*airgap-2*(h_or+h_r+h_cr+(d_1+d_2)/2); % mm
D_shaft = 100; % mm

fprintf('Tooth width of rotor slot (btr) is %g mm\n',b_tr);
fprintf('Opening width of rotor slot (bor) is %g mm\n',b_or);
fprintf('Opening height of rotor slot (hor) is %g mm\n',h_or);

fprintf('The top diameter of rotor bar (d1) is %g mm.\n',d_1);
fprintf('The bottom diameter of rotor bar (d2) %g mm.\n',d_2);
fprintf('The height of rotor bar (hr) %g mm.\n',h_r);
fprintf('Rotor slot area is %g mm^2.\n',rotor_slot_area);
fprintf('The height of the rotor back iron (hcr) is %g mm.\n',h_cr);
fprintf('Calculated maximum shaft diameter is %g mm.\n',Dshaftmax);
fprintf('Selected shaft diameter of rotor is %g mm.\n',D_shaft);
```

```
Tooth width of rotor slot (btr) is 5.18673 mm
Opening width of rotor slot (bor) is 3 mm
Opening height of rotor slot (hor) is 2 mm
The top diameter of rotor bar (d1) is 13.5112 mm.
The bottom diameter of rotor bar (d2) 3 mm.
The height of rotor bar (hr) 147.154 mm.
Rotor slot area is 1290.07 mm^2.
The height of the rotor back iron (hcr) is 36.2738 mm.
Calculated maximum shaft diameter is 153.898 mm.
Selected shaft diameter of rotor is 100 mm.
```

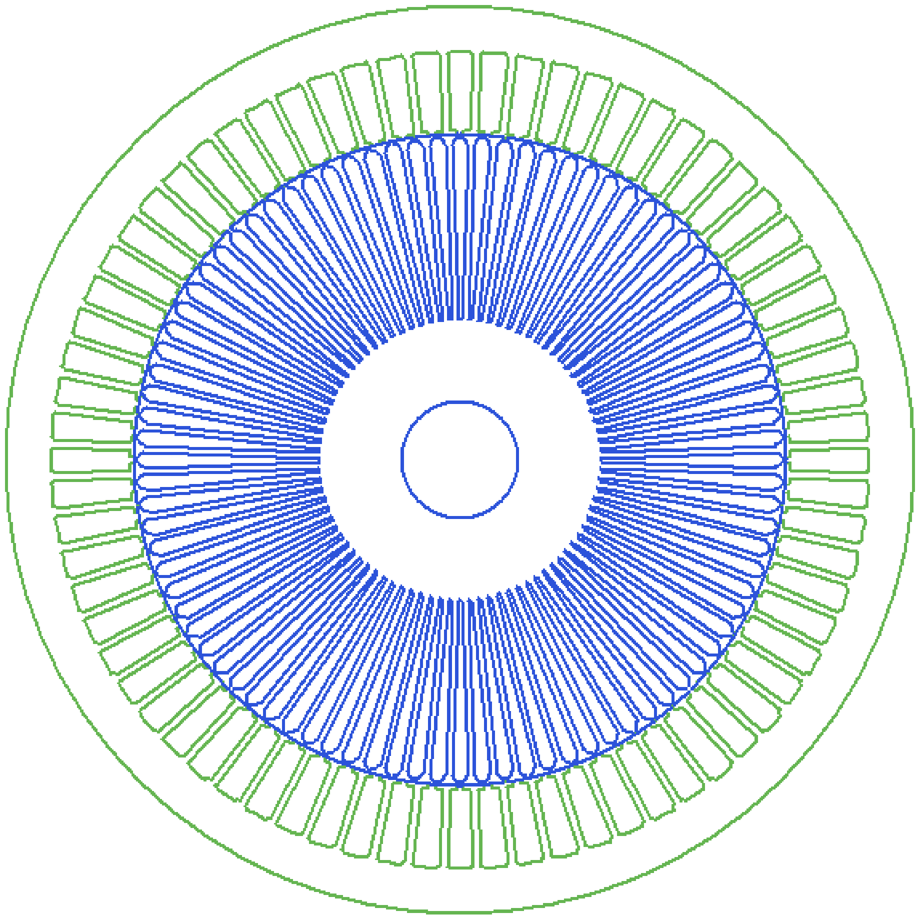


Figure 13. Machine stator and rotor

9. Effective Air gap

Flux density always decreases at the slot opening so that carter coefficient should be calculated and effective air gap distance estimate to calculate MMF and other dependent parameters. It will calculate after dimensions are decided.

```
K_s = (b_os/(airgap))/(5+(b_os/airgap));
k_cs = slot_pitch*1000/(slot_pitch*1000-K_s*b_os);

K_r = (b_or/(airgap))/(5+(b_or/airgap));
k_cr = Rotor_slot_pitch*1000/(Rotor_slot_pitch*1000-K_r*b_os);


eff_airgap = k_cs*k_cr*airgap;
fprintf('Carters coefficient of stator is %g.\n',k_cs);
fprintf('Carters coefficient of rotor is %g.\n',k_cr);
fprintf('Effective airgap is %g mm.\n',eff_airgap);
```

```
Carters coefficient of stator is 1.15639.
Carters coefficient of rotor is 1.00011.
Effective airgap is 1.20928 mm.
```

10. Thermal Calculations

Cooling ducts is added to keep cool the rotor.

- I will add 15 cooling ducts
- Air-forced convection cooling method is using at this machine
- Fan cooled machine

According to researched wind turbine datasheet, wind turbine machines are operating temperature between -40 to 85 degree.

```
N_ducts = 15;
L_ducts = 5; %mm

k = (L_ducts/eff_airgap)/(5+L_ducts/eff_airgap);

eff_L_ducts = k*L_ducts;

eqv_M_length = M_length-1e-3*N_ducts*eff_L_ducts+1e-3*2*eff_airgap; % m

fprintf('Number of cooling ducts is %g.\n',N_ducts);
fprintf('Length of a cooling duct is %g mm.\n',L_ducts);
fprintf('The equivalent core length with cooling ducts is %g m.\n',eqv_M_length);
```

```
Number of cooling ducts is 15.
Length of a cooling duct is 5 mm.
The equivalent core length with cooling ducts is 0.307183 m.
```

11. Inductances

In this part, leakage and magnetization inductances will be calculated. Formulations are derived in class. I have used them.

```
Lm =
(Number_of_ph/2)*M_inner_diameter*u0*eqv_M_length*(Kw_1*Nph)^2/(Npole_pair^2*eff_airgap*1e-3);
% Henries
Xm = 2*pi*f_rated*Lm; % Ohms

P_stator = u0*eqv_M_length*((h_os/b_os)+(h_s/(3*b_s2))); % permeance
Lph = P_stator*4*(Nph*Kw_1)^2*Number_of_ph/Qs; % Henries
Xs_ph = 2*pi*f_rated*Lph; % ohms
```

In order to calculate rotor permeance, we have to calculate both bar and ring permeance.

```
P_r1 = 0.66 + 2*h_r/(3*(d_1+d_2)) + h_or/b_or; % permeance
P_r2 = 0.9*Rotor_slot_pitch/(k_cs*eff_airgap)*1e-2; % permeance
Kx = 1; % skin effect coefficient
P_rotor = u0*eqv_M_length*(Kx*P_r1+P_r2); % permeance
Lrp = P_rotor*4*(Nph*Kw_1)^2*Number_of_ph/Qr; % Henries
Xrp = 2*pi*f_rated*Lrp; % ohms

Xph = Xs_ph+Xrp;

fprintf('The magnetizing inductance of the machine is %g mH.\n',Lm*1e3);
fprintf('The magnetizing reactance at 50Hz is %g Ohms.\n',Xm);
fprintf('leakage inductance of the stator is %g mH.\n',Lph*1e3);
fprintf('Leakage reactance of the stator at 50Hz is %g Ohms.\n',Xs_ph);
fprintf('Leakage inductance of the rotor referred to the stator side is %g mH.\n',Lrp*1e3);
fprintf('Leakage reactance of the rotor referred to the stator side is %g Ohms.\n',Xrp);
```

```
The magnetizing inductance of the machine is 171.424 mH.
The magnetizing reactance at 50Hz is 53.8544 Ohms.
leakage inductance of the stator is 0.848857 mH.
Leakage reactance of the stator at 50Hz is 0.266676 Ohms.
Leakage inductance of the rotor referred to the stator side is 4.10239 mH.
Leakage reactance of the rotor referred to the stator side is 1.2888 Ohms.
```

12. Resistances

Stator phase copper resistance is calculated previous part also. Also rotor resistance is calculated with rotor aluminum dimensions.

```
resistivity_al = 3.1*1e-8; % ohm*m %25 degree
Kr = 1.74;
Dre = M_inner_radius-1e-3*eff_airgap; % m
b = h_r+h_or+(d_1+d_2)/2; % mm
ler = 1e-3*pi*(Dre+b)/Qr; % m
Rbe = resistivity_al*((M_length*Kr/(rotor_slot_area*1e-6))+(ler/(2*Rotor_al_area*1e-
6*(sin(3*pi/Qr))^2))); %ohms
R2p = Rbe*4*Number_of_ph/Qr*(Nph*Kw_1)^2; % ohms

R1p = ph_stator_copper_resistance;

Rph = R1p+R2p;

fprintf('Length of rotor ring is  %g mm\n',ler*1000);

fprintf('Stator phase copper resistance is  %g ohm\n',R1p);
fprintf('Rotor phase resistance referred to stator side is  %g ohm\n',R2p);
```

```
Length of rotor ring is  5.62916 mm
Stator phase copper resistance is  0.00207059 ohm
Rotor phase resistance referred to stator side is  0.0097214 ohm
```

13. Mass Calculation

```
cu_density = 8.96; % gr/cm^3
al_density = 2.70; % gr/cm^3
fe_density = 7800; % kg/m^3
```

Copper mass;

```
copper_volume = cable_cross_area/100*total_copper_length*100; %cm3
copper_mass = copper_volume*cu_density/1000; %kg
```

Aluminum mass, bar and ring;

```
al_volume = Qr*(M_length*rotor_slot_area + ler* Rotor_al_area);%cm3
al_mass = al_volume*al_density/1000; %kg
```

Iron mass;

```
Stator_teeth_mass = fe_density*Qs*b_ts*1e-3*(h_s+h_w+h_os)*1e-3*M_length*Kfe; % kg
Stator_yoke_mass =  fe_density*pi/4*(M_outer_diameter_new^2-(M_outer_diameter_new-2*h_cs*1e-
3)^2)* M_length*Kfe; % kg

Rotor_teeth_mass = fe_density*Qr*b_tr*1e-3*(h_r+(d_1+d_2)/2)*1e-3*M_length*Kfe; % kg

iron_mass = Stator_teeth_mass+Stator_yoke_mass+Rotor_teeth_mass;
```

I increased the shaft length %20.

```
Shaft_mass = fe_density* pi/4*(D_shaft/1000)^2*M_length*1.2;


Total_mass = copper_mass+al_mass+iron_mass+Shaft_mass;

fprintf('Copper mass is  %g kg\n',copper_mass);
fprintf('Aliminum mass is  %g kg\n',al_mass);
fprintf('Iron mass is  %g kg\n',iron_mass);
fprintf('Shaft mass is  %g kg\n',Shaft_mass);
fprintf('Total mass is  %g kg\n',Total_mass);
```

```
Copper mass is  360.202 kg
Aliminum mass is  104.013 kg
Iron mass is  828.392 kg
Shaft mass is  24.8999 kg
Total mass is  1317.51 kg
```

14. Efficiency

In order to calculate efficiency, copper and core losses should be calculated.

```
Pcu_s = 3*Iph^2*(R1p);
Pcu_r = 3*Iph^2*(R2p);
Pcu = Pcu_s + Pcu_r;

K_core = 3.3;
Pcore = iron_mass*K_core;
```

Core loss resistance can be calculated for equivalent circuit.

```
Rc = Vph^2/(Pcore/3);
fprintf('Core loss resistance(Rc) is %g ohm\n',Rc);

Ploss = Pcore+Pcu;

fprintf('Stator copper conduction loss is  %g W\n',Pcu_s);
fprintf('Rotor aliminum conduction loss is  %g W\n',Pcu_r);
fprintf('Total conduction loss is  %g W\n',Pcu);
fprintf('Total core loss is  %g W\n',Pcore);
fprintf('Total loss is  %g W\n',Ploss);

Efficiency = P_rated/(P_rated+Ploss);

fprintf('Efficiency is %g percent\n',Efficiency*100);
```

```
Core loss resistance(Rc) is 58.5289 ohm
Stator copper conduction loss is  1159.51 W
Rotor aliminum conduction loss is  5443.87 W
Total conduction loss is  6603.38 W
Total core loss is  2733.69 W
Total loss is  9337.07 W
Efficiency is 96.3996 percent
```

15. Characteristics

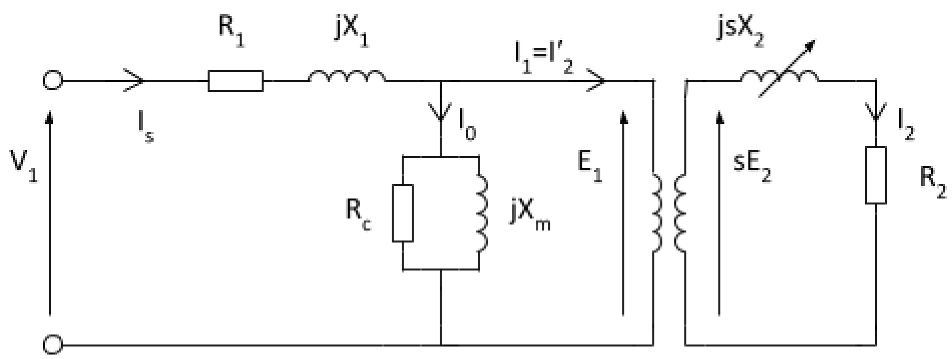


Figure 14. Equivalent circuit of machine

Thevenin variables and equivalent circuit parameters are calculated. Then using induction machine torque formula torque-speed characteristic is obtained.

```
Zm = (1j*Xm*Rc)/(1j*Xm+Rc); % ohms
Z1 = Rph+1j*Xph; % ohms
Vth = Vph*Zm/(Z1+Zm); % volts
Zth = Z1*Zm/(Z1+Zm); % ohms
Rth = real(Zth); % ohms
Xth = imag(Zth); % ohms

s = -1:0.001:2;
s = fliplr(s);
Nr = n_syn*(1-s); % rpm
wr = Nr*2*pi/60; % rad/sec
num = numel(s);
Tm = (3*abs(Vth)^2/w_syn)*(1./ ( (Rth+R2p./s).^2 + (Xth+Xrp)^2 ) )...
    .*(R2p./s); % Nm

Tm((s==0)) = 0; % Nm
figure;
plot(Nr,Tm,'k-','LineWidth',2.0);
xlabel('Rotor speed (rpm)','Fontweight','Bold');
ylabel('Torque (Nm)','Fontweight','Bold');
title ('Induction Generator Torque-Speed Characteristic','Fontweight','Bold');
grid on;

figure;
plot(Nr,Tm,'k-','LineWidth',2.0);
xlabel('Rotor speed (rpm)','Fontweight','Bold');
ylabel('Torque (Nm)','Fontweight','Bold');
title ('Induction Generator Torque-Speed Characteristic','Fontweight','Bold');
grid on;
xlim([650 850]);


Rated_slip = (n_syn-n_rated)/n_syn;
fprintf('The rated slip is %g.\n',Rated_slip);
Starting_torque = Tm((s==1)); % Nm
Max_torque = max(Tm); % Nm
slip_max_torque = s((Tm==Max_torque));
fprintf('The starting torque of this machine is %d Nm.\n', Starting_torque);
fprintf('The maximum torque of this machine is %d Nm.\n', Max_torque);
fprintf('The slip at maximum torque is %d.\n', slip_max_torque);
```

```
The rated slip is -0.0106667.
The starting torque of this machine is 2.384276e+00 Nm.
The maximum torque of this machine is 3.340213e+02 Nm.
The slip at maximum torque is 4.000000e-03.
```

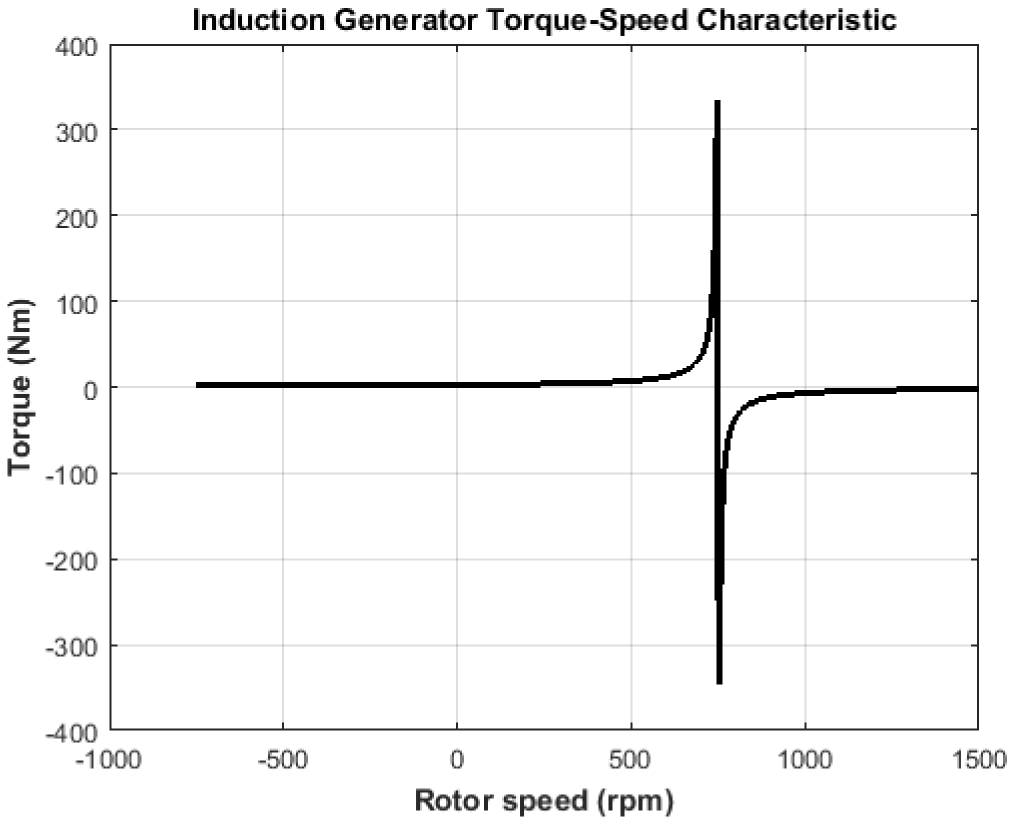


Figure 15. Torque-speed characteristic of the machine

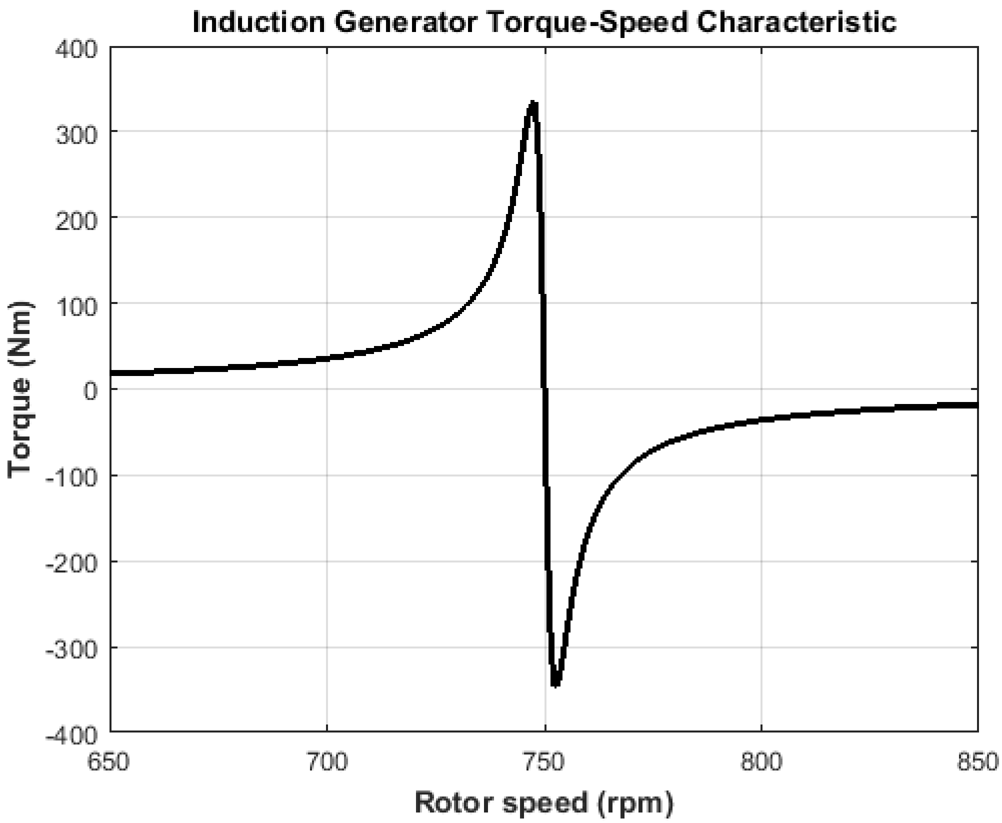


Figure 16. Torque-speed characteristic of the machine

According to my basic calculation torque-speed characteristic is as expected but I think that I have some mistake one of coefficient because torque value should be larger.

16. Finite Element Analysis

I have made FEA with Maxwell Rmxprt module. This machine operates as generator so that I put the graphs after rated speed first then I will put motor operation.

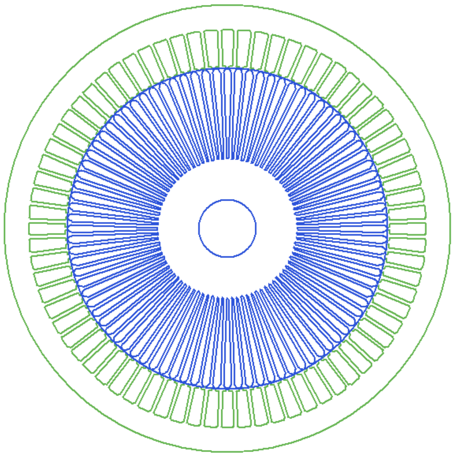


Figure 17. RMxpert design of machine

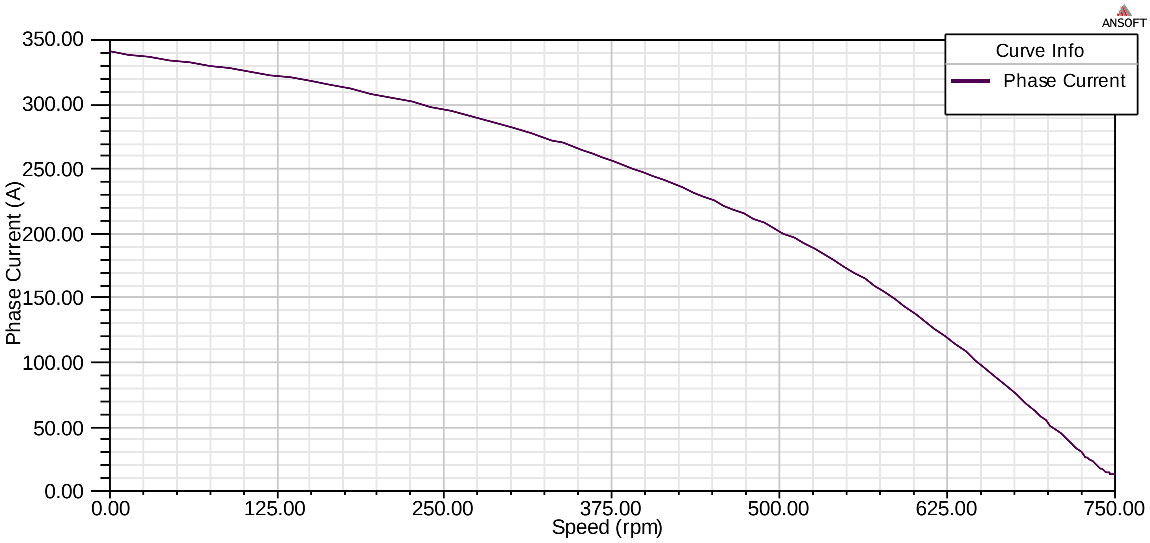


Figure 18. Phase current vs speed 1

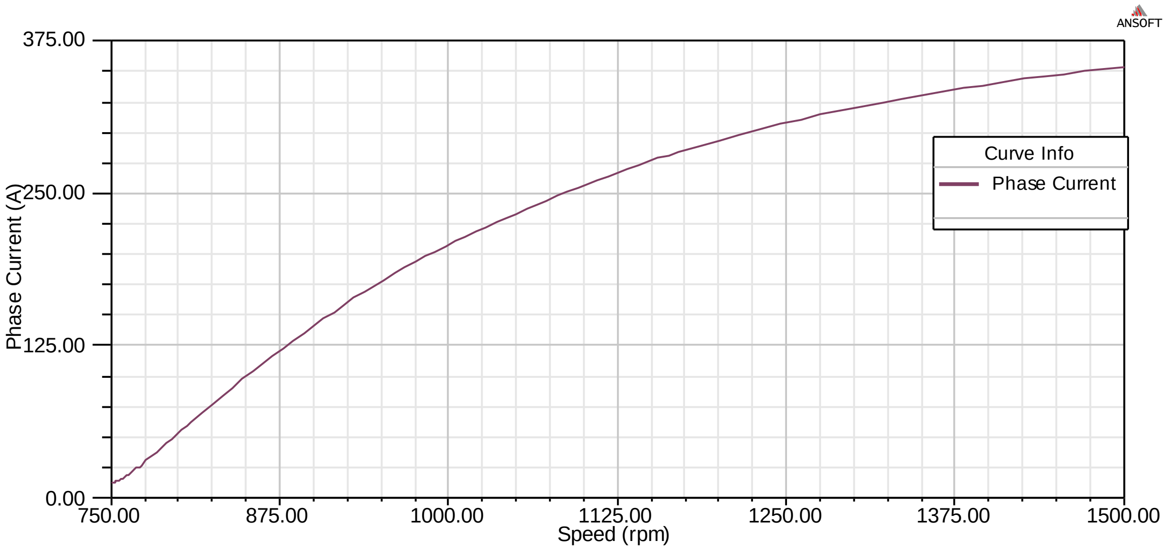


Figure 19. Phase current vs speed 2

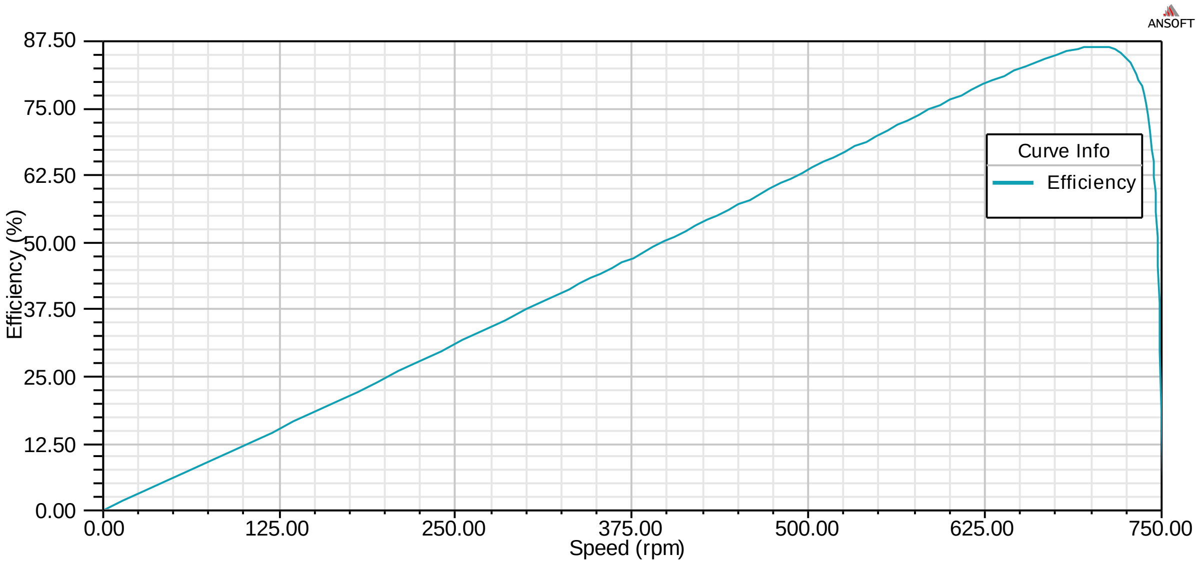


Figure 20. Efficiency vs speed 1

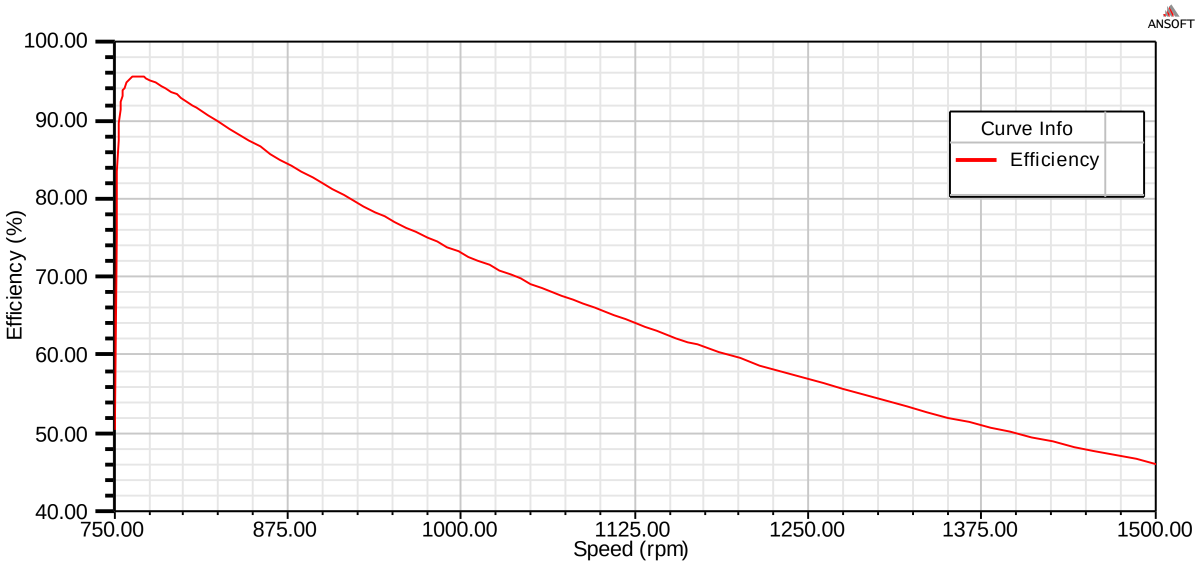


Figure 21. Efficiency vs speed 2

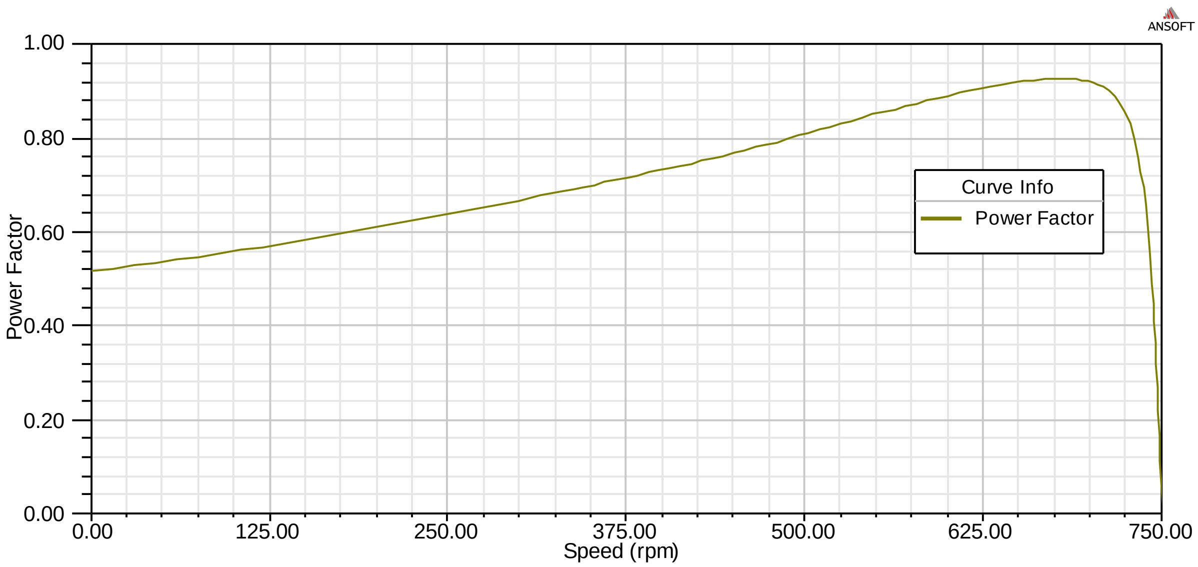


Figure 22. Power factor vs speed 1

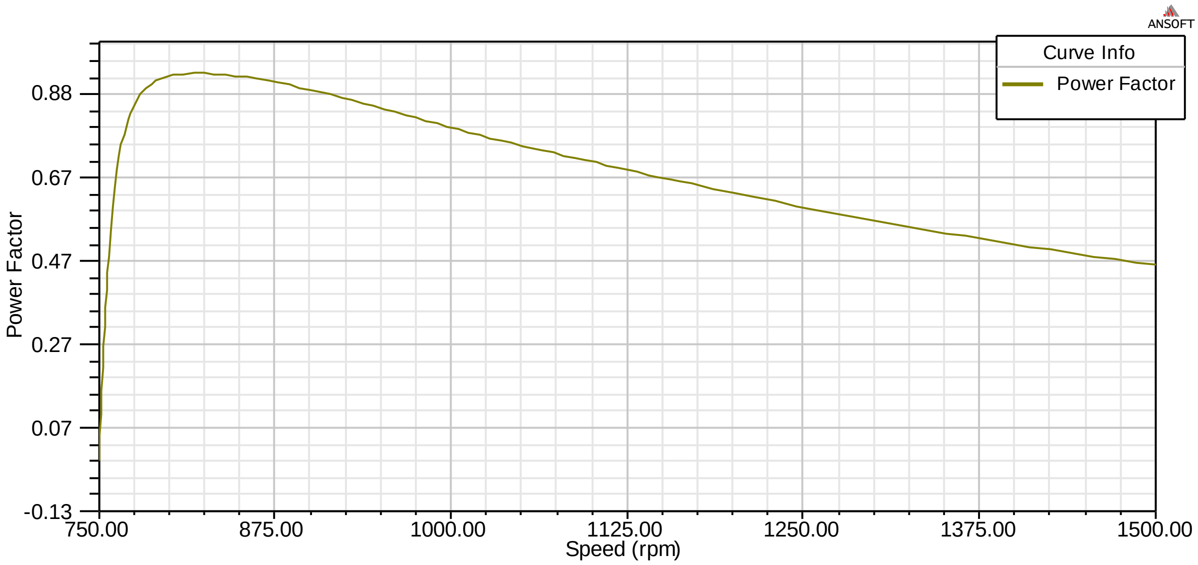


Figure 23. Power factor vs speed 1

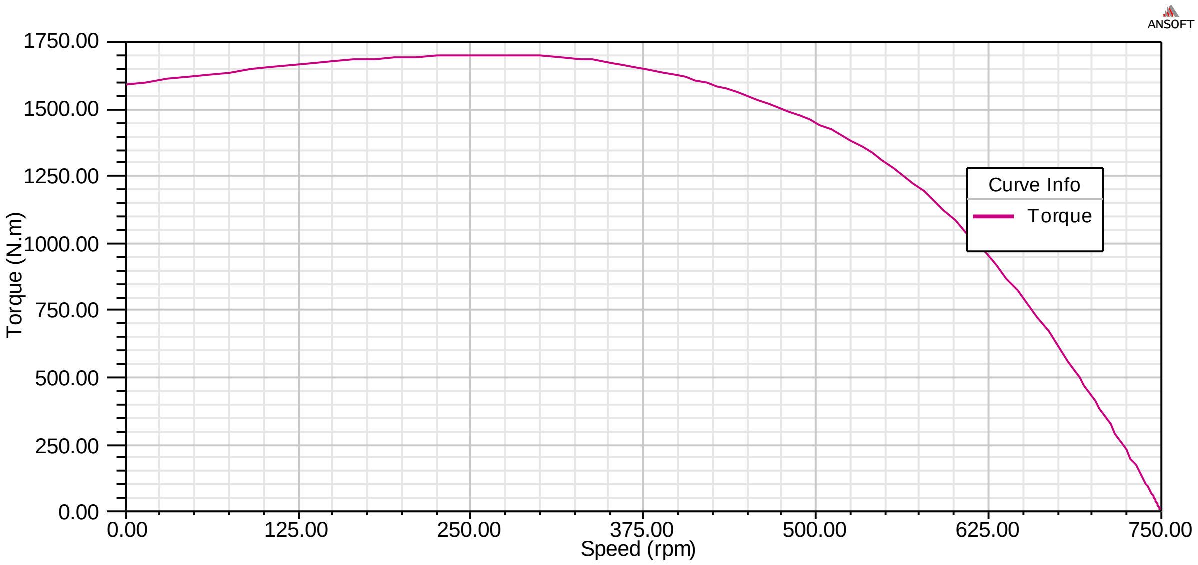


Figure 24. Torque vs speed 1

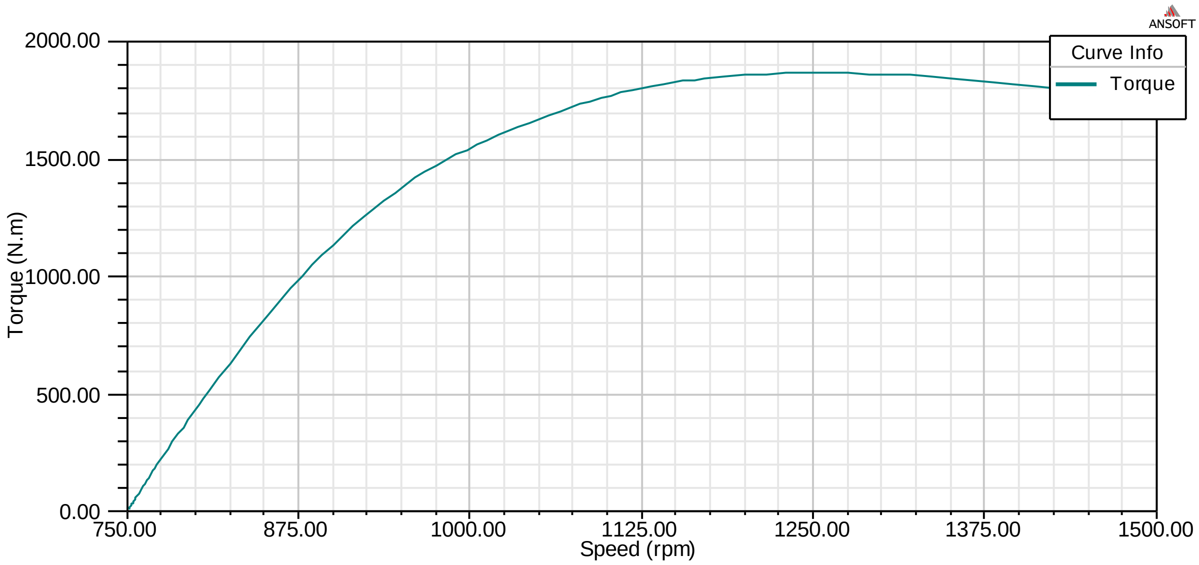


Figure 25. Torque vs speed 1

	Name	Value	Units	Description
1	Stator-Teeth Flux Density	1.26044	tesla	
2	Rotor-Teeth Flux Density	1.23605	tesla	
3	Stator-Yoke Flux Density	0.21556	tesla	
4	Rotor-Yoke Flux Density	0.36832	tesla	
5	Air-Gap Flux Density	0.325787	tesla	
6	Stator-Teeth Ampere Turns	15.2001		A.T.
7	Rotor-Teeth Ampere Turns	37.4193		A.T.
8	Stator-Yoke Ampere Turns	4.62687		A.T.
9	Rotor-Yoke Ampere Turns	1.68506		A.T.
10	Air-Gap Ampere Turns	221.04		A.T.

Figure 26. Table of flux densities

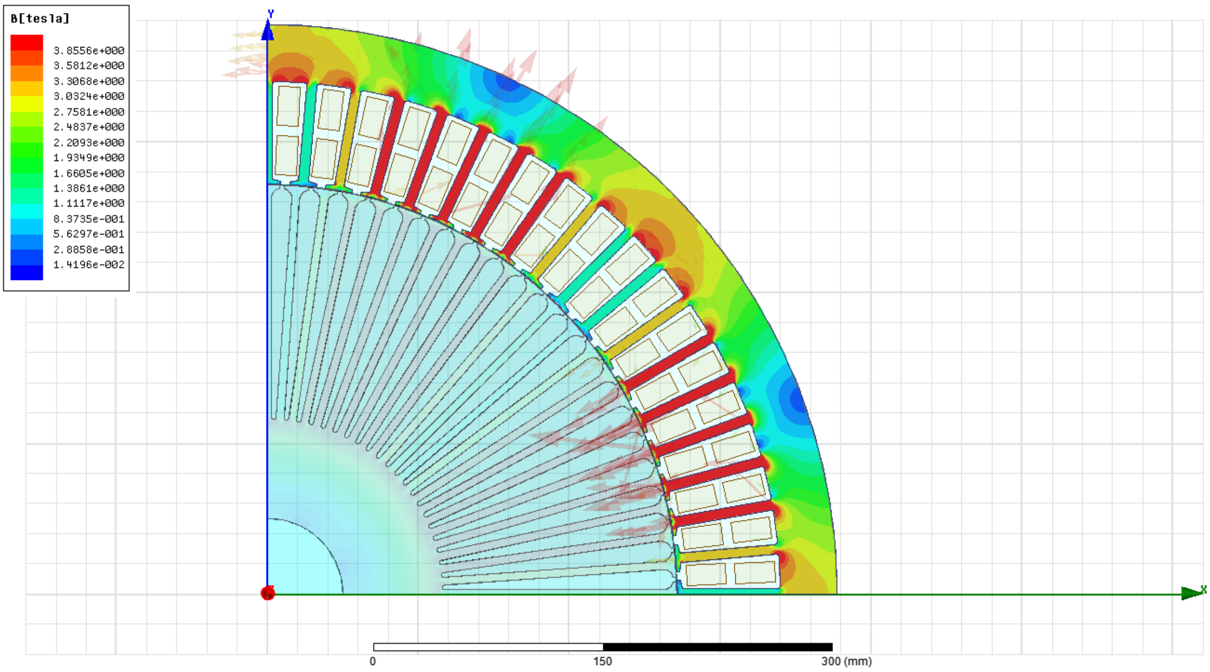


Figure 27. Magnitude of magnetic flux density of stator

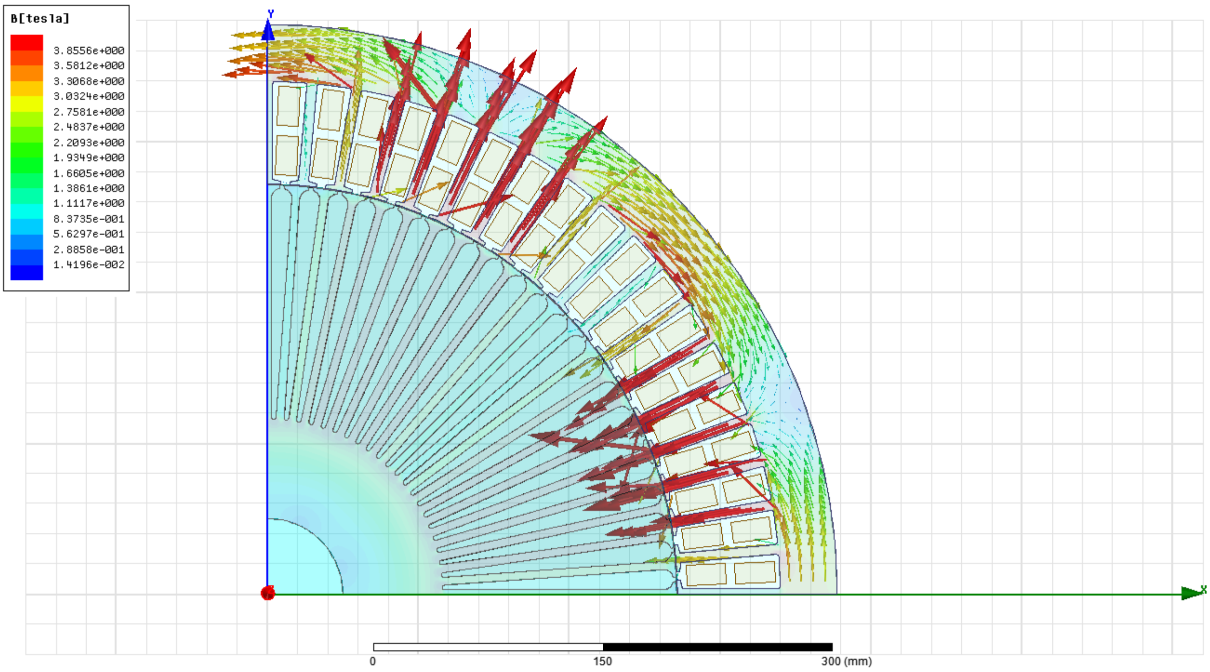


Figure 28.Vector of magnetic flux density of stator

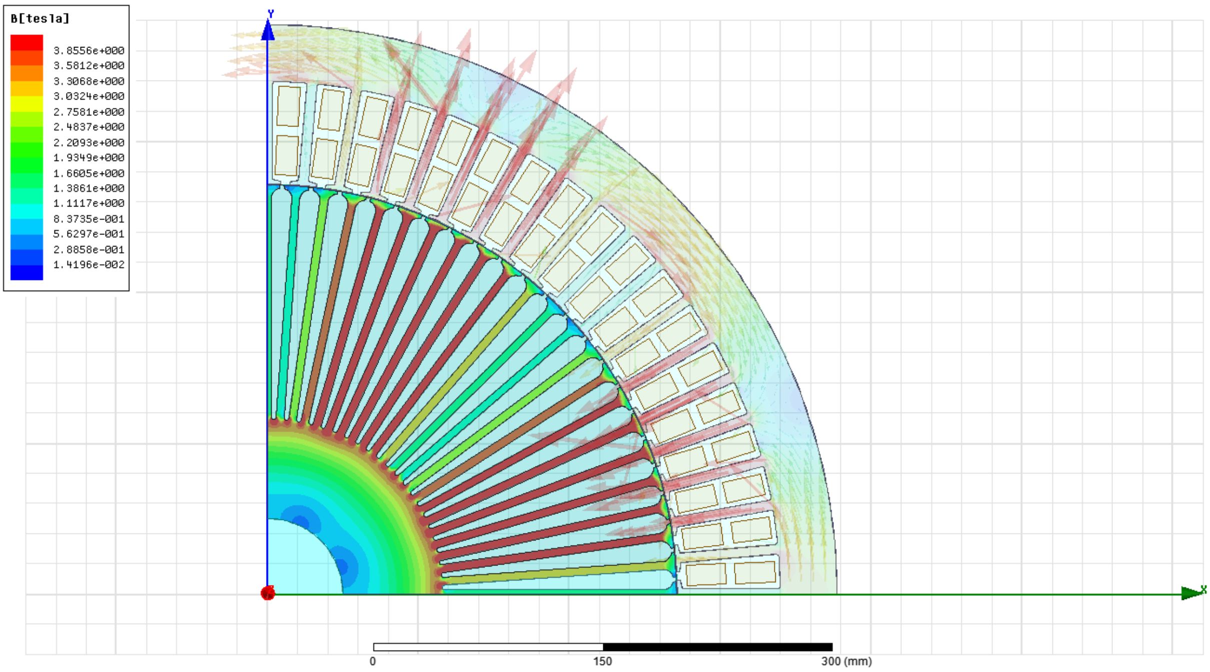


Figure 29. Magnitude of magnetic flux density of rotor

FEA results of my design conflict my calculation. I have make simulation with calculated phase current which is almost same as Rmexpert results and also flux densities are more reliable at Rmexpert value but I set this value by hand at the Maxwell 2D some parts are saturated. At the kinds of situation, all design should be repeated again and arrange mechanical dimensions again. Most probably, I have mistake at the stator slot and rotor slot winding or simulation inputs about these but I could not find the problem. If I have enough time, I redesign the mechanical dimensions. Also, efficiencies and phase current is almost same my analytical calculation. Cogging torque is not observed.

17. Conclusion

In this course, I have experienced machine design steps and important points. Kinds of design analytic calculation are most important step because we have to consider all parameters with detail. In general, design step is starting with deciding specification of machine like power, voltage rating, using area etc. Then we choose machine constant according to power rating to determine size of the machine. When we focus electrical and magnetic properties we have to calculate and determine electrical and magnetic loadings. One of the most important things of the design step is magnetic saturation specification. We have to avoid magnetic saturation at the stator and rotor. Moreover, efficiency is so important especially high power application. Also near to these heating and cooling is really important for the safety of the machine. Near to the electrical design steps, mechanical considerations are extremely important like a vibration. Our electrical winding design can affect these properties. Also, there is a lot of point to work hard when we design machines like leakage losses, cogging torques, harmonics, and skin effect, temperature effect on the winding, carter coefficient, stacking factor, slot dimensions, slot types, noise, and winding type and so on.

Moreover, simulation step also critical because we cannot calculate all points on the design but FEA can do. In order to do this we have to become an expert on the FEA program because there are many parameters we have to arrange carefully. Finally, this course taught us how we can learn machine design and where we start to design.