MIDDLE EAST TECHNICAL UNIVERSITY

ELECTRICAL AND ELECTRONICS ENGINEERING

EE564

DESIGN OF ELECTRICAL MACHINES

-PROJECT 2-

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1. Winding Design and Motor Parameter Estimation

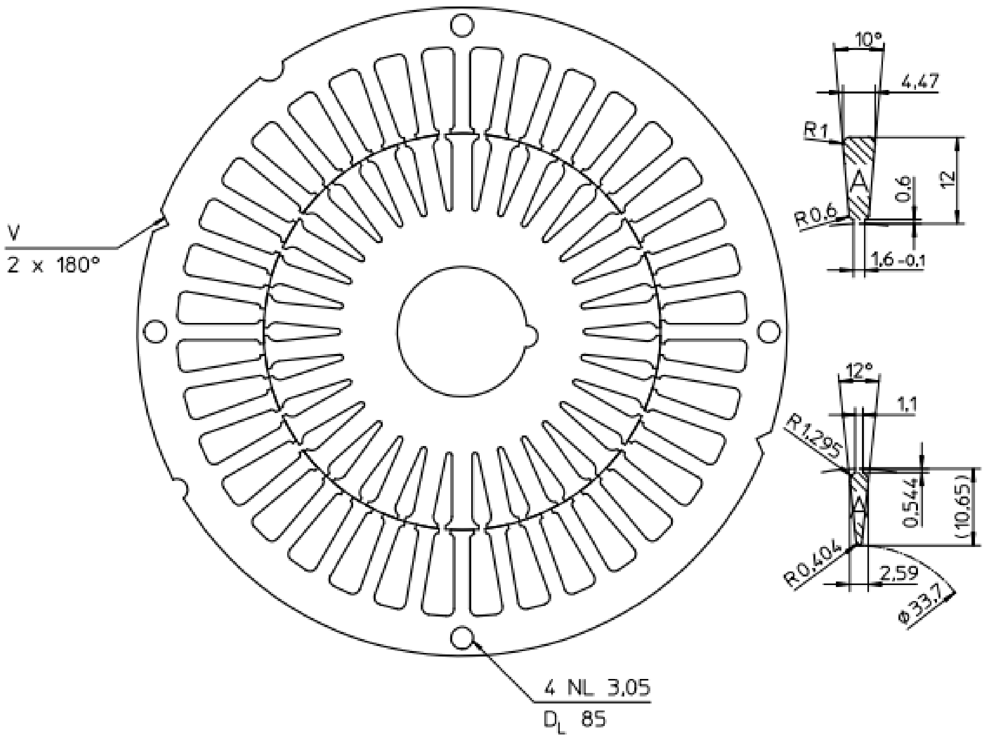

Figure 1. Chosen Lamination to Design Induction Motor

Chosen lamination has 90 mm outer diameter so that this type of lamination is available for high speed low torque and low power application, therefore I aimed that 1kW output power and 4 poles for this design. Then, synchronous speed becomes 1500 rpm.

Also, in order to eliminate 3rd harmonics on the MMF, I have chosen 220Vrms WYE connected input voltage which is equal to the 380Vrms per motor input phase. Moreover, with single layer stator winding; 5th, 7th and others except 3rd harmonics are effected so that in order to reduce 5th harmonic, I have designed double layer winding with 7/9*180 = 140 integral pitch factor.

1	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**	**16**	**17**	**18**
A_1	A_2	A_3	$-C_1$	$-C_2$	$-C_3$	B_1	B_2	B_3	$-A_4$	$-A_5$	$-A_6$	C_4	C_5	C_6	$-B_4$	$-B_5$	$-B_6$
A_{12}	$-C_{10}$	$-C_{11}$	$-C_{12}$	B_{10}	B_{11}	B_{12}	$-A_1$	$-A_2$	$-A_3$	C_1	C_2	C_3	$-B_1$	$-B_2$	$-B_3$	A_4	A_5

19	**20**	**21**	**22**	**23**	**24**	**25**	**26**	**27**	**28**	**29**	**30**	**31**	**32**	**33**	**34**	**35**	**36**
A_7	A_8	A_9	$-C_7$	$-C_8$	$-C_9$	B_7	B_8	B_9	$-A_{10}$	$-A_{11}$	$-A_{12}$	C_{10}	C_{11}	C_{12}	$-B_{10}$	$-B_{11}$	$-B_{12}$
A_6	$-C_4$	$-C_5$	$-C_6$	B_4	B_5	B_6	$-A_7$	$-A_8$	$-A_9$	C_7	C_8	C_9	$-B_7$	$-B_8$	$-B_9$	A_{10}	A_{11}

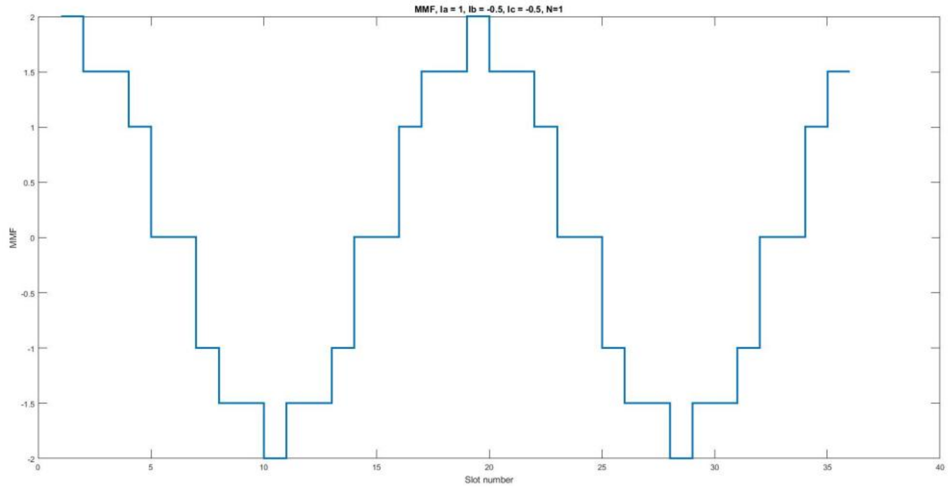

Figure 2. MMF values of Ia =1, Ib = -0.5, Ic = -0.5, N =1

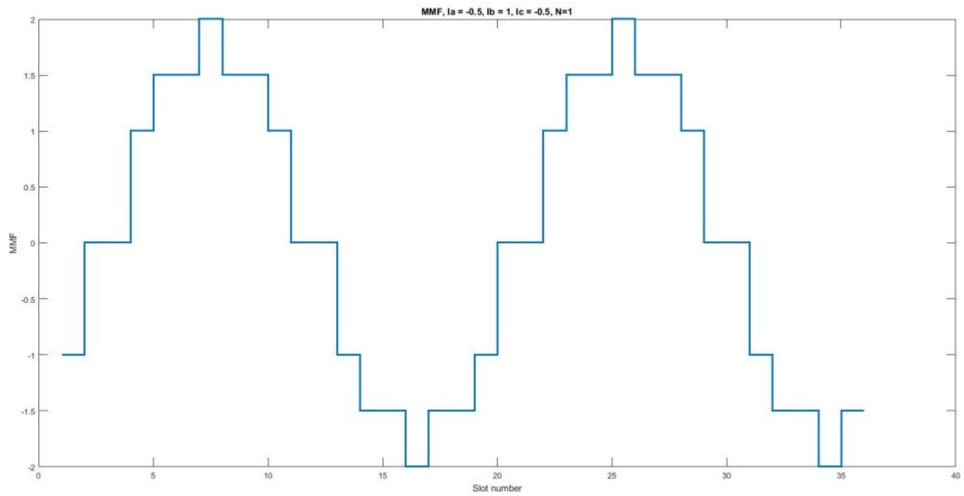

Figure 3. MMF values of Ia =-0.5 , Ib = 1, Ic = -0.5, N =1

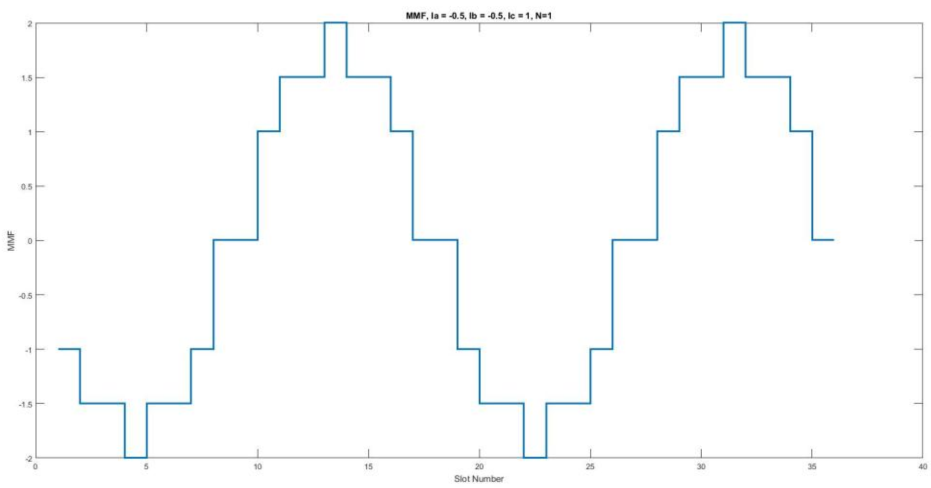

Figure 4. MMF values of Ia =1, Ib = -0.5, Ic = -0.5, N =1

Winding factors of fundamental and other harmonics are at below. Coil angle is 180/9 = 2 degree. Coil pitch degree is 7*20 = 140 degree. q is slot per pole per phase (q=36/4/3 = 3).

Distribution Factor

$$k_d = \frac{sin(q\frac{\alpha}{2})}{qsin(\frac{\alpha}{2})}$$

q: Number of coils

α: Angle between each coil

Pitch Factor

$$k_p = sin(\frac{\lambda}{2})$$

λ: Coil-pitch in electrical degrees

$$k_w = k_d \times k_p$$

Figure 5. Distribution, pitch and winding factors formulas

By using formulas at figure 5, following winding factors are calculated.

Kw_1= [sin(30) / (3*sin(10))]*sin(70) = 0.9

Kw_3 = [sin(3*30) / (3*sin(3*10))]*sin(3*70) = -0.33

Kw_5 = [sin(5*30) / (3*sin(5*10))]*sin(5*70) = -0.037

Kw_7 = [sin(7*30) / (3*sin(7*10))]*sin(7*70) = -0.135

Kw_9= [sin(9*30) / (3*sin(9*10))]*sin(9*70) = 0.33

Kw_{11}= [sin(11*30) / (3*sin(11*10))]*sin(11*70) = -0.135

Kw_{13}= [sin(13*30) / (3*sin(13*10))]*sin(13*70) = -0.037

In order to start decide specification of 3 phase induction motor, first of all, magnetic loading should be specified according to stator slot teeth magnetic saturation. In generally, at 50 Hz machine Bav can be selected between 0.35T and 0.6T. Stator is made from stainless steel in generally then, saturation point approximately 1.4T. Maximum stator slot teeth section and total slot section (with gap) is approximately 2. Instantaneous magnetic flux of teeth should be calculated to prevent saturation. Sinusoidal wave at figure 6 is represent air gap magnetic flux density then, maximum magnetic flux density can be take 0.9*pi/2*Bav. Which is equal to 1.4T/2 = 0.7 so Bav = 0.495.Becaıse of this result, I have taken magnetic loading 0.5T.

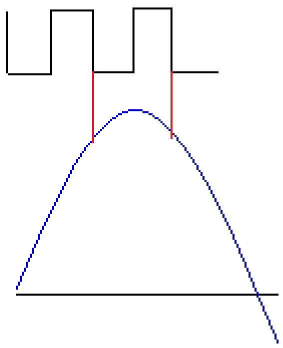

Figure 6. Illustration of air gap magnetic flux density on stator slot

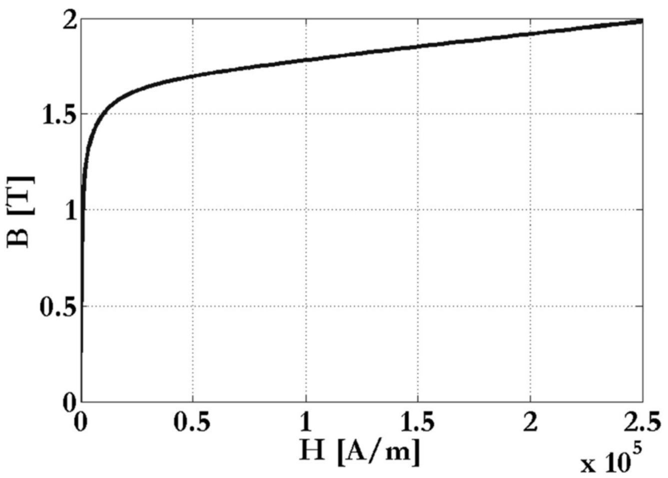

Figure 7. B-H curve of steel

$$t_y = \frac{B}{B_y}\frac{\pi D}{4p}$$

Figure 8. Yoke magnetic flux density formula

Moreover Byoke depends on yoke thickness with formula at figure 8. With this formula Byoke is calculated. D = 55m, p is pole pair which is equal to the 2 then ty is yoke thickness which is equal to (90-55)/2-12 = 5.5mm.

Bav = 0.5T

Bteeth=1.41T

Byoke = 0.98T

By using typical aspect ratio axial length of motor can be calculated but designed motor is small and high speed so aspect ratio can be between 0.4<x<2. So I take L = 110mm.

Therefore, when I increase length, efficiency increases because of increasing torque.

$$\chi \approx \frac{\pi}{2p}\sqrt[3]{p} \qquad \chi = \frac{L'}{D}$$

Figure 9. Aspect ratio formula

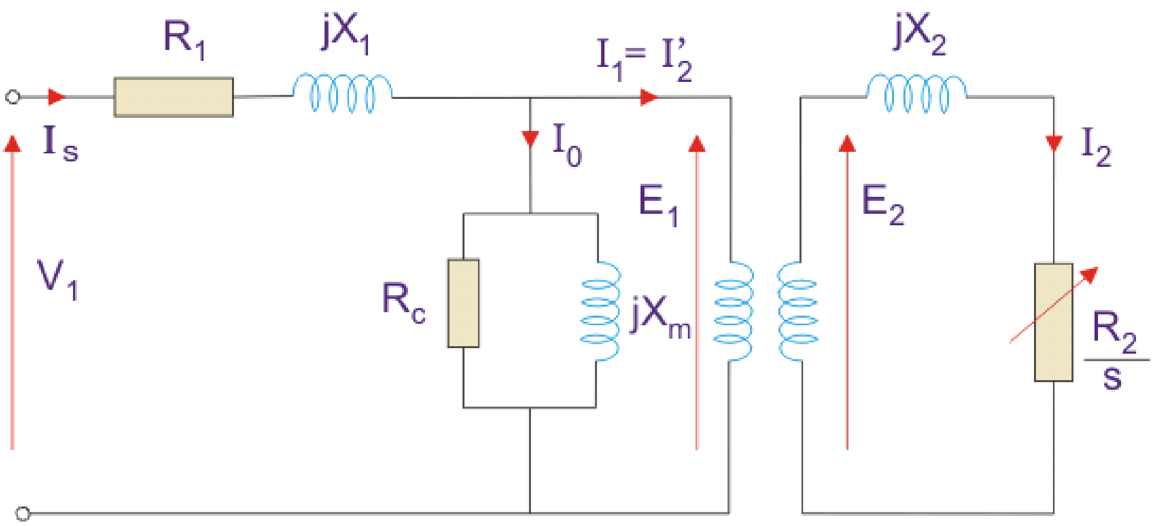

Figure 10. Equivalent circuit of induction motor

$$V_{rms(i)} = 4.44 f_i k_{w(i)} N_{ph} \Phi_{(i)}$$

Figure 11. Induced EMF formula

By using induced EMF formula as figure 11, we can calculate Nphase then we can specify slot current.

In order to specify number of turns and slot currents, induced emf(E1 on figure 10) formula can be used.

Assume E1 = V1 = 380, Flux = Bav*PoleArea, Pole area = Di*pi*L/4 = 4.7e-3 m^2

L =110mm, Nph = 809, N = 67

L =250mm, Nph = 353, N = 29.

$$N * Ipeak = Bpeak * A * R = Bpeak * A * \frac{lgap}{A * u0}$$

Also, air gap is calculated 0.27mm with following criterias.

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

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

Figure 12. Air gap area formula

Then, Is = Ipeak/sqrt(2) = 1.13 Arms for L=110

Electrical loading A = N*Is*Q/pi/Di = 15822 for L=110

Is = 2.7 Arms for L = 250mm

Electrical loading A = N*Is*Q/pi/Di = 15822 for L=250

Minimum diameter of wire for Is = 2.7Arms is 0.45mm, AWG25 wire. Slot are is 41mm^2, with %80 fill factor, each slot has 60 turns wire area should be smaller than 0.565mm^2, so that I have chosen AWG19, Dwire = 0.81mm, Awire = 0.515mm^2, rho = 26.40728 ohm/km

Fill factor is %72.

Minimum diameter of wire for Is = 1.13Arms is 0.287mm, AWG25 wire. Slot are is 41mm^2, with %80 fill factor, each slot has 134 turns wire area should be smaller than 0.244mm^2, so that I have chosen AWG24, Dwire = 0.51mm, Awire = 0.2mm^2, rho = 84.1976 ohm/km

Fill factor is %66.

Then, I will make calculations only L = 110mm case.

Torque = shear stress*Vr = A*Bav*2*pi*r_r^2*L = 16,5 Nm

Aprx. speed = 1100/16.5 = 66.66 => 1282 rpm

In order to calculate equivalent circuit of motor, I will made some assumptions. Using parameters below is referred figure 10.

Stator cable resistance is R1 = 2*(Dr/2+L)*Nphase*rho = 2*(55/2+110)*0.001*67*12*84.2e-3 = 33ohm.

Stator cable inductance is

L1 = Npole^2/R*pole/phase =Npole^2*u0*Apole/lgap = 600^2*4*pi*10^-7*0,00475/ (0.278*10^-3) = 7.72*4/3 = 10H, but this calculation is wrong most probably.

Rotor resistance can be calculated by thinking copper wires of each rotor slots are parallel connected which will so small.

Then leakage inductance could be modeled analytically but very complicated so using simulation tools is more appropriate to find it.

Core losses are modeled with datasheet parameter which gives losses per kg.

Copper loss of stator is approximately 1.13^2 * 66 = 84W

2. Detailed Analysis & Verification

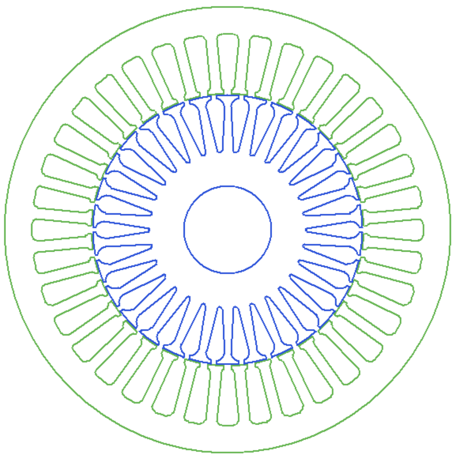

Figure 13. Rmxprt design of stator and rotor

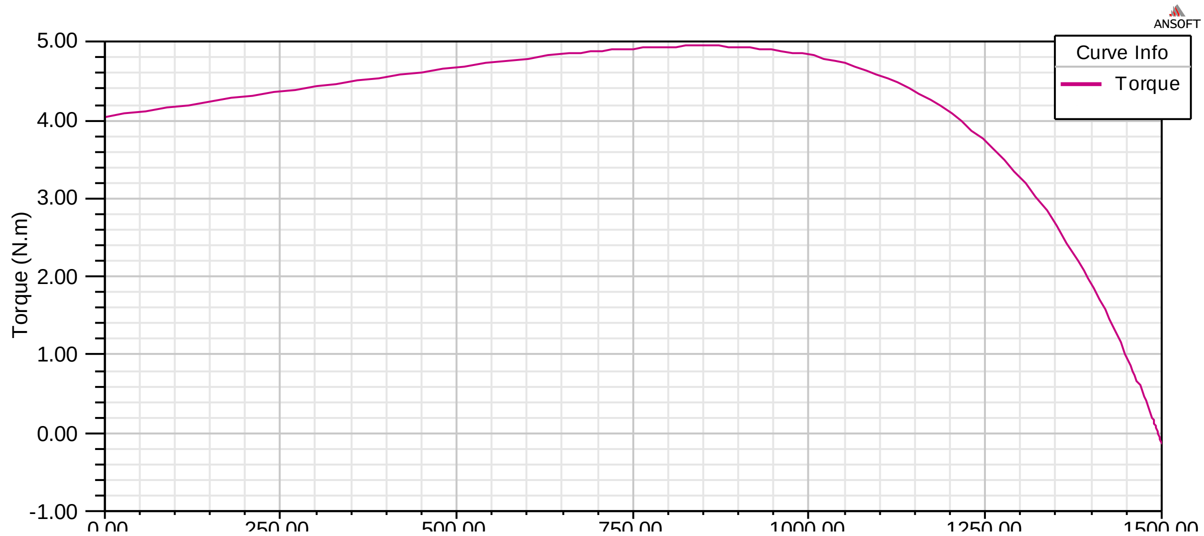

Figure 14. Torque-Speed Characteristic of Motor

As expected motor torque becomes zero at synchronous speed. In analytical solution maximum torque and power became differently. Reason of this difference could be unknown parameters of Maxwell design is arranged randomly then cause to decrease calculated magnetic flux density. At actual shape of this curve torque become peak at near to the rated speed which can obtain by reducing stator resistance. Starting torque of motor could be improved by skewing of rotor.

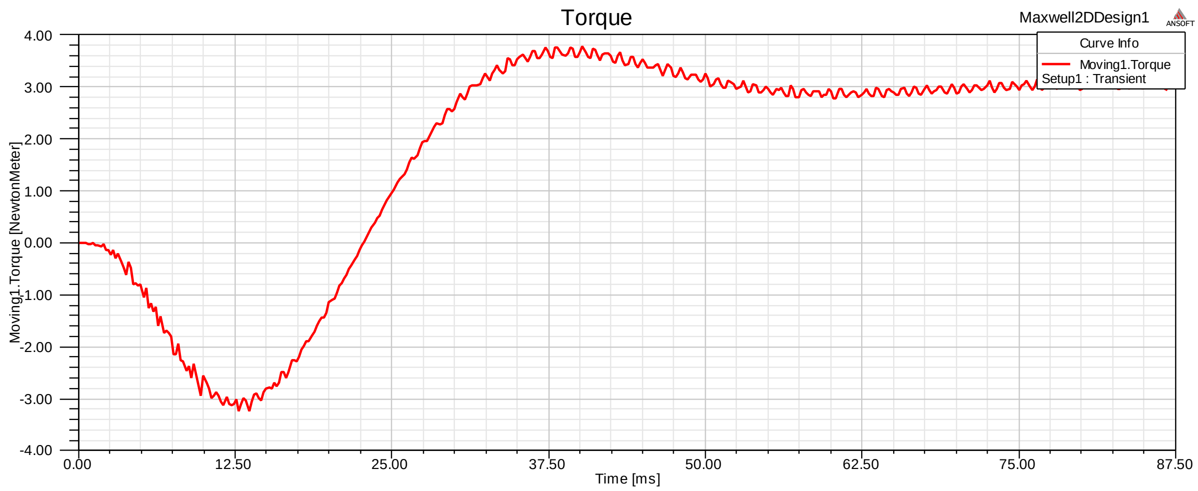

Figure 15. Torque-Time plot when Motion is starting

Because of starting torque is small, torque becomes negative at starting time instant.

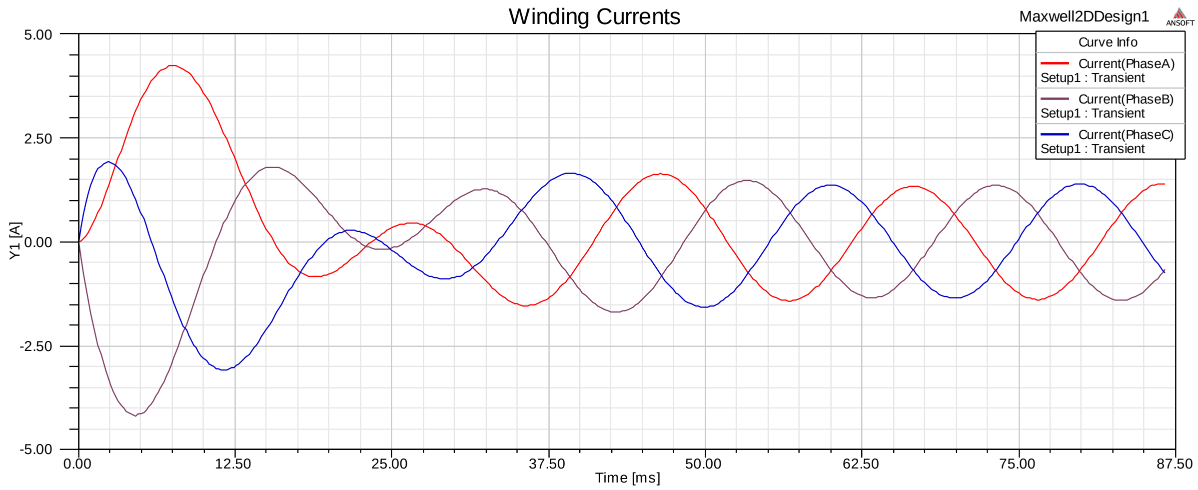

Figure 16. Stator wire currents per phase are shown

Simulation current is approximately near to the analytical solution. At starting time instant, because of torque became negative, motor behave as a generator so currents are higher.

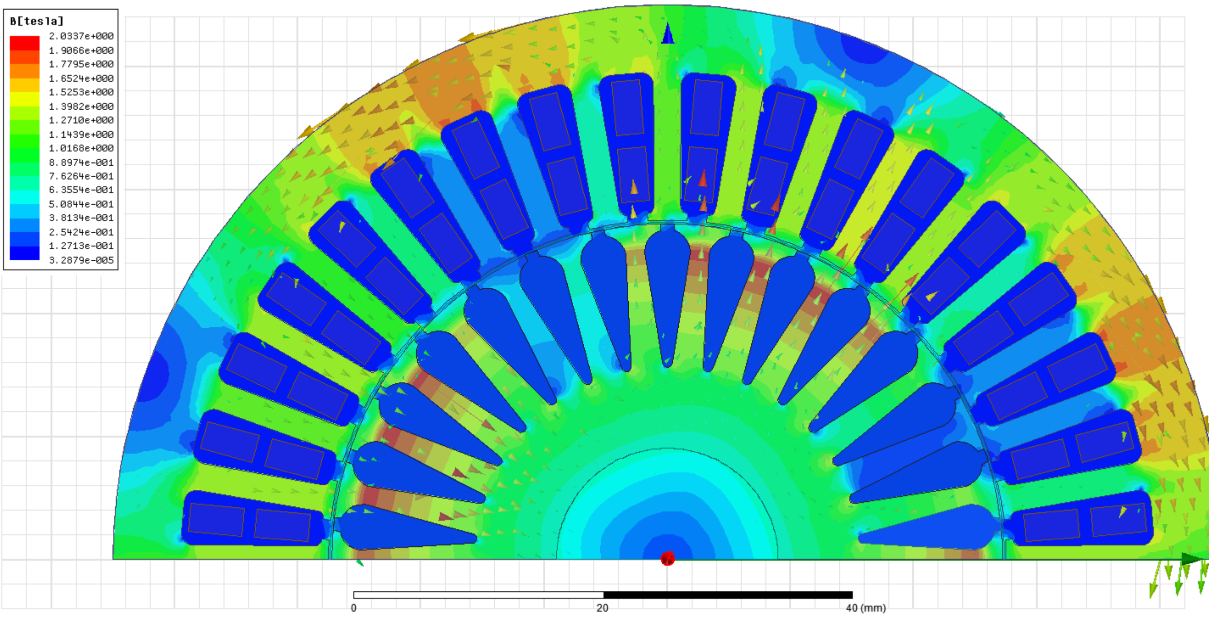

Figure 17. Instantaneously magnetic flux density at Ia = -0.7A , Ib = 1A, Ic = -0.7A

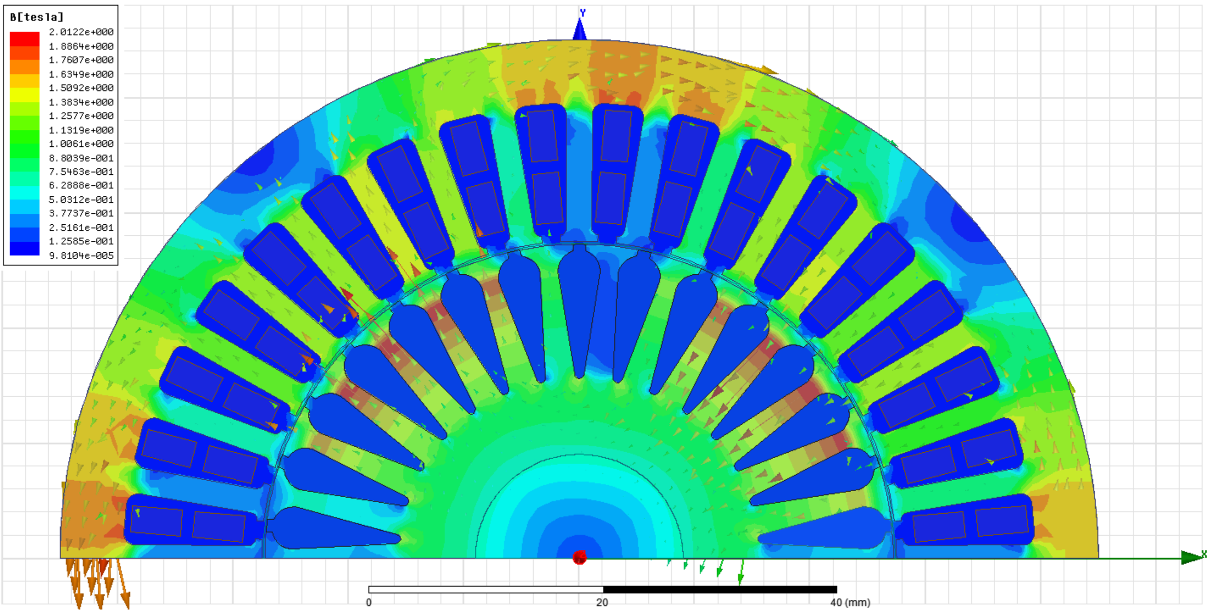

Figure 18. Instantaneously magnetic flux density at Ia = 1.4A , Ib = -0.7A, Ic = -0.7A

As figure 16 and 17 are shown magnetic flux density is moving according to current and cause to MMF. Then according to the phase sequence rotor is move clockwise direction. Also direction of yoke magnetic flux and flux density is change every time instant. Which can effect core loss of the motor.

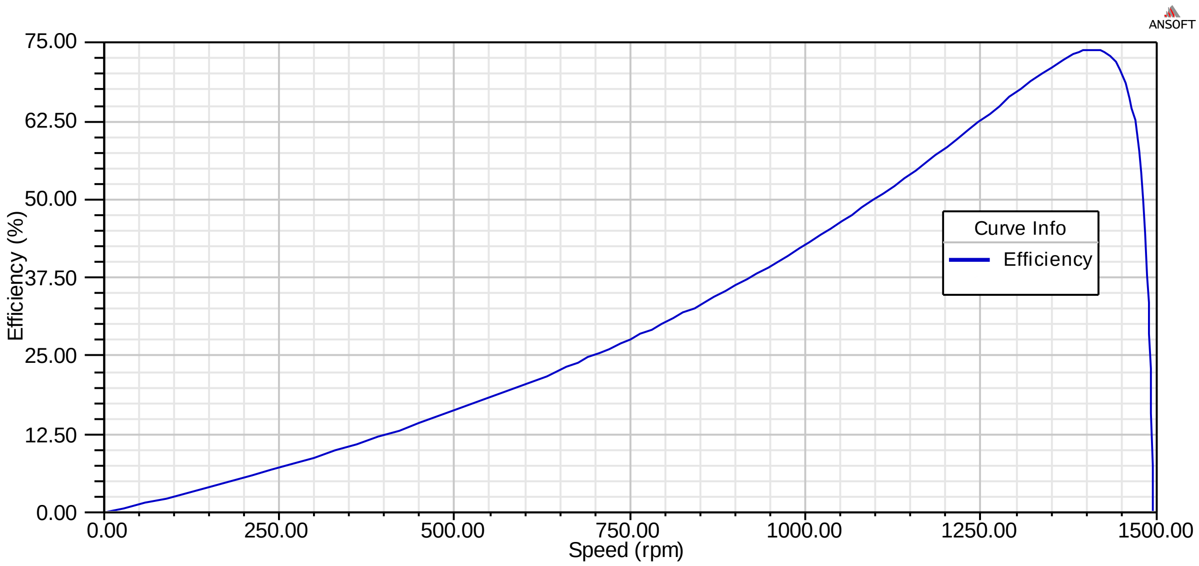

Figure 19. Efficiency vs. Speed characteristic with 20W frictional loss

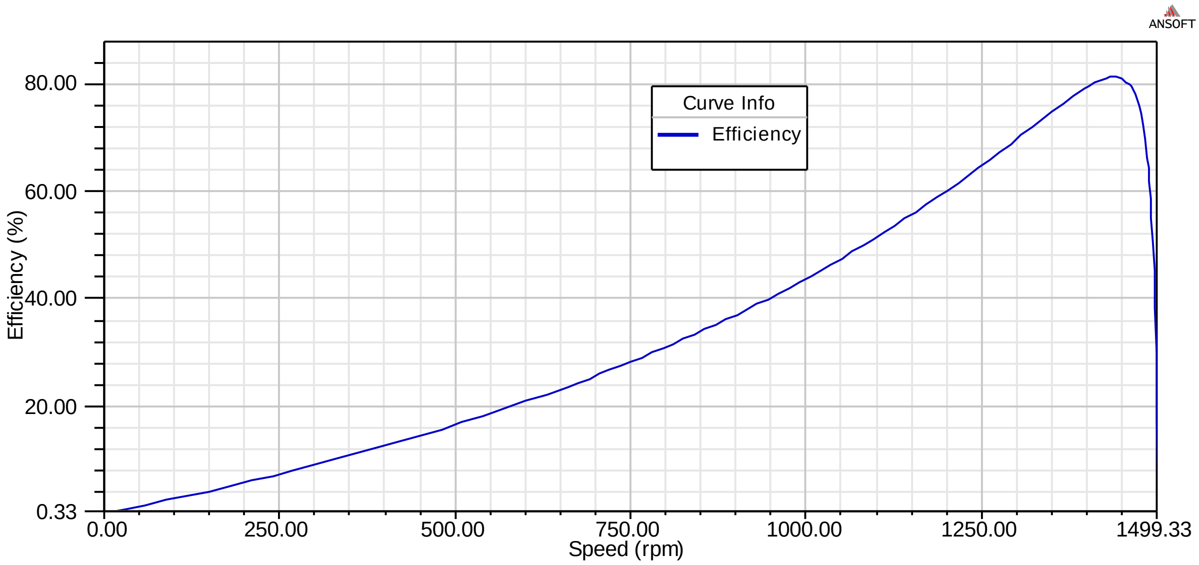

Figure 20. Efficiency vs. Speed characteristic without 20W frictional loss

In generally, induction motor efficiency should exceed %80, so that this design needs to optimization. In order to calculate exact value of efficiency we have to model frictional losses.

Note: all simulations are made with 20W frictional loss.

	Name	Value	Units	Description
1	Stator Resistance	32.1938	ohm	
2	Stator Leakage Reactance	18.1779	ohm	
3	Rotor Resistance	23.6865	ohm	
4	Rotor Leakage Reactance	28.1761	ohm	
5	Iron-Core Loss Resistance	480102000	ohm	
6	Magnetizing Reactance	521.059	ohm	
7	Stator Slot Leakage Reactance	13.6528	ohm	
8	Stator End Leakage Reactance	2.4014	ohm	
9	Stator Differential Leakage Reactance	2.12376	ohm	
10	Rotor Slot Leakage Reactance	16.5813	ohm	
11	Rotor End Leakage Reactance	0.703049	ohm	
12	Rotor Differential Leakage Reactance	9.46856	ohm	
13	Skewing Leakage Reactance	0.952945	ohm	

Figure 21. Rated Parameters

	Name	Value	Units	Description
1	No-Load Stator Phase Current	0.405874	A	
2	No-Load Iron-Core Loss	0.000276894	W	
3	No-Load Input Power	50.3134	W	
4	No-Load Power Factor	0.147165		
5	No-Load Slip	0.00416992		
6	No-Load Shaft Speed	1493.75	rpm	
7	Stator Resistance	32.1938	ohm	
8	Stator Leakage Reactance	18.1787	ohm	
9	Rotor Resistance	23.6862	ohm	
10	Rotor Leakage Reactance	28.1792	ohm	

Figure 22. No-load Operation Parameters

	Name	Value	Units	Description
1	Stator Phase Current	0.436306	A	
2	Magnetizing Current	0.395926	A	
3	Iron-Core Loss Current	4.29702e-007	A	
4	Rotor Phase Current	0.174144	A	
5	Armature Thermal Load	25.1411		A^2/mm^3.
6	Specific Electric Loading	11817.5	A_per_meter	
7	Armature Current Density	2.12745		A/mm^2.
8	Rotor Bar Current Density	0.93274		A/mm^2.
9	Rotor Ring Current Density	2.35694		A/mm^2.

Figure 23. Rated Electrical Data

Specific electrical loading is applicable for induction motor and which is as same as calculated value with approximately same error values at other parameters errors.

	X [mm]	AirGapFluxDensityParameter [mTesla] Setup1 : Performance
1	0.000000	422.004000

	X [mm]	StatorTeethFluxDensityParameter [mTesla] Setup1 : Performance
1	0.000000	965.428000

	X [mm]	StatorYokeFluxDensityParameter [tesla] Setup1 : Performance
1	0.000000	1.100740

Figure 24. Magnetic flux densities

Maxwell calculated flux densities but I guess that teeth density is calculated wider side of stator. Other values are expected.

3. Conclusion

Design of electrical machine is very complicated and important for industry, so that according to power rating and application efficiency, harmonics, cost, speed could be critical and design is made according to this parameter. Also, most important design parameter is magnetic loading dependently magnetic flux density. Because if magnetic flux densities is saturated anywhere, losses increase and controllability could be decrease. Also, after decide magnetic loading, electrical loading should be arranged. Stator wire current depends on magnetic flux density, number of turns, frequency, winding factor and dimensions. There is a lot of trade-offs so that according to design specification, we get an advantage with some parameters but some parameters will be worse. Actually, as other magnetic circuits, copper losses should be minimize unless increase core losses. Beside electrical parameters, we have to know mechanical parameters (like friction, flexibilty etc.) to better design.