MIDDLE EAST TECHNICAL UNIVERSITY

EE564

DESIGN OF ELECTRICAL MACHINES

Project-2 Motor Winding Design & Analysis

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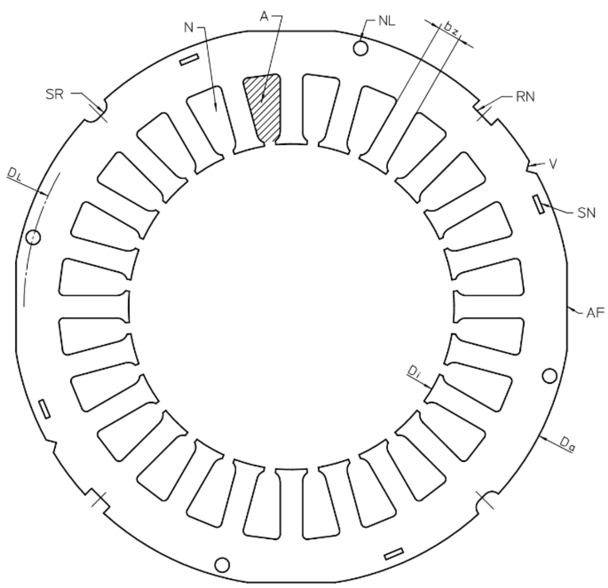
1 WINDING DESIGN

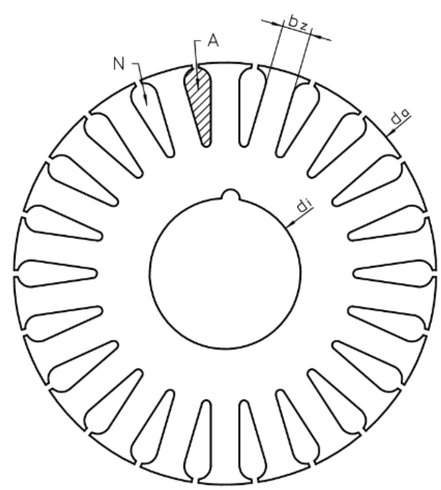
In this study, design and analysis of stator winding for a 400V(l-l), 50 Hz, three-phase, squirrel cage, four-pole induction motor built with IEC 63/6-8.55 laminations from Kienle Spiess. Thickness of the laminations is selected to be 0.5 mm and dimensions of the core material are given in Figure 1.1.

IEC 63/6-8.55	Maße und Varianten				
	D_a	D_i	N	A	b_z
SB 090.14.X00	90 +0,07	55±0,037	36	41	2,25
02 wie Abbildung		03 o NL			
RB 055.10.Y.00		d_a	N	A	b_z
d_i		55	30	17,3	2,8
01 18 +0,027 M					
Blechdicke SB und RB	0,35 / 0,5				

(a)



(b)



(c)

Figure 1.1 (a) properties of the selected lamination and dimension legend for (b) stator, (c) rotor

As it is given in Figure 1.1, selected stator lamination is constituted by 36 slots(Qs), as a starting point an four pole, integral slot, full-pitched, double layer stator winding has been constructed and corresponding winding diagram given with MMF waveforms are given for both Ia=1, Ib= -0.5 Ic=-0.5 and Ia=-0.5, Ib= 1, Ic=-0.5 in **Error! Reference source not found.**. It shows that the resulting MMF waveform has almost a sinusoid shape with a triangular appearance at the peaks indicating a 5th and/or 7th harmonic content.

As the number of slots per pole per phase (q) and slot angle(α) have already been set and which are given by:

$$q = \frac{\mathrm{Q}s}{2pm} = 3$$

$$\alpha = \frac{2\pi}{\mathrm{Q}s/p} = 20$$

distribution factor(kd) can be calculated by for nth harmonic order

$$k_d = \frac{\sin(qn\frac{\alpha}{2})}{\mathrm{q}\sin(n\frac{\alpha}{2})}$$

where p is the number of pole pairs, m is the number of phases and n is the harmonic order.

Table 1.1 Distribution factors for full-pitched winding

Harmonic order	Distribution factor (kd)
Fundemental	0.9598
3	0.6667
5	0.2176
7	-0.1774
9	-0.3333
11	-0.1774
13	0.2176

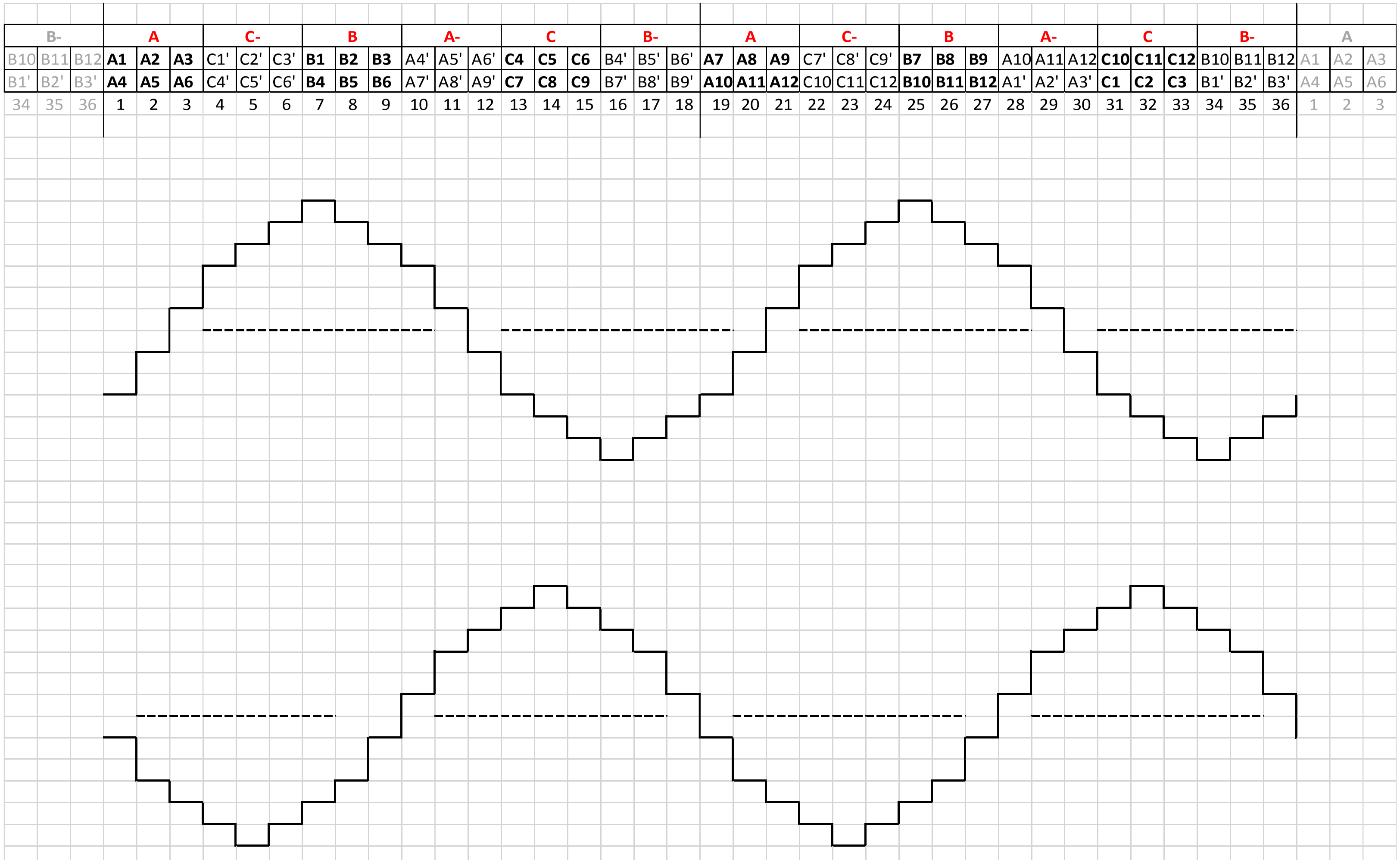


Figure 1.2 Full pitched, double layer stator winding diagram and corresponding MMF waveform for (top) Ia=1pu, Ib= -0.5pu Ic=-0.5pu, (bottom) Ia=-0.5pu, Ib= 1pu , Ic= -0.5pu

In order to minimize the harmonic content of the induced voltages and resulting harmonics in the current drawn from the supply network, winding factors for low order harmonics can be optimized by adjusting pitch factor k_p :

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

$$k_w = k_d * k_p$$

where λ is the coil pitch (electrical).

Using the software in [3], winding factors for various short pitched alternatives are calculated and depicted in Table 1.2, after evaluating the table 8/9 coil span is found to be optimal choice since it will provide a significant attenuation for low order harmonics of the induced voltages with a small sacrifice in the fundamental voltages. New winding diagram and MMF waveform is given for Ia=1, Ib= -0.5 Ic=-0.5 in Figure 1.2.

Table 1.2 Absolute values of winding factors for different coil spans

Winding Factor	Full Pitch	8/9	7/9	6/9
kw_1	0.960	0.945	0.902	0.831
kw_5	0.217	0.140	0.038	0.188
kw_7	0.177	0.060	0.136	0.154
kw_{11}	0.177	0.060	0.136	0.154
kw_{13}	0.217	0.140	0.038	0.189

Taking the machine aspect ratio (l'/D) as ~1, and taking $C_{mec} = 80$ kWs/m3

$$\mathrm{P}_{mec} = D^2 l' C_{mec} n_{syn}$$

expected mechanical power rating of this machine is found to be $\approx 300W$

For a four-pole machine at this power range, power factor is around 0.8 [2], taking %80 efficiency at full-load, rated rms current of the machine can be found by

$$\mathrm{I}_{rated} = \frac{\mathrm{P}_{mec}}{\sqrt{3}V_{rated} * \cos\Phi * \eta} = 0.59\mathrm{A}$$

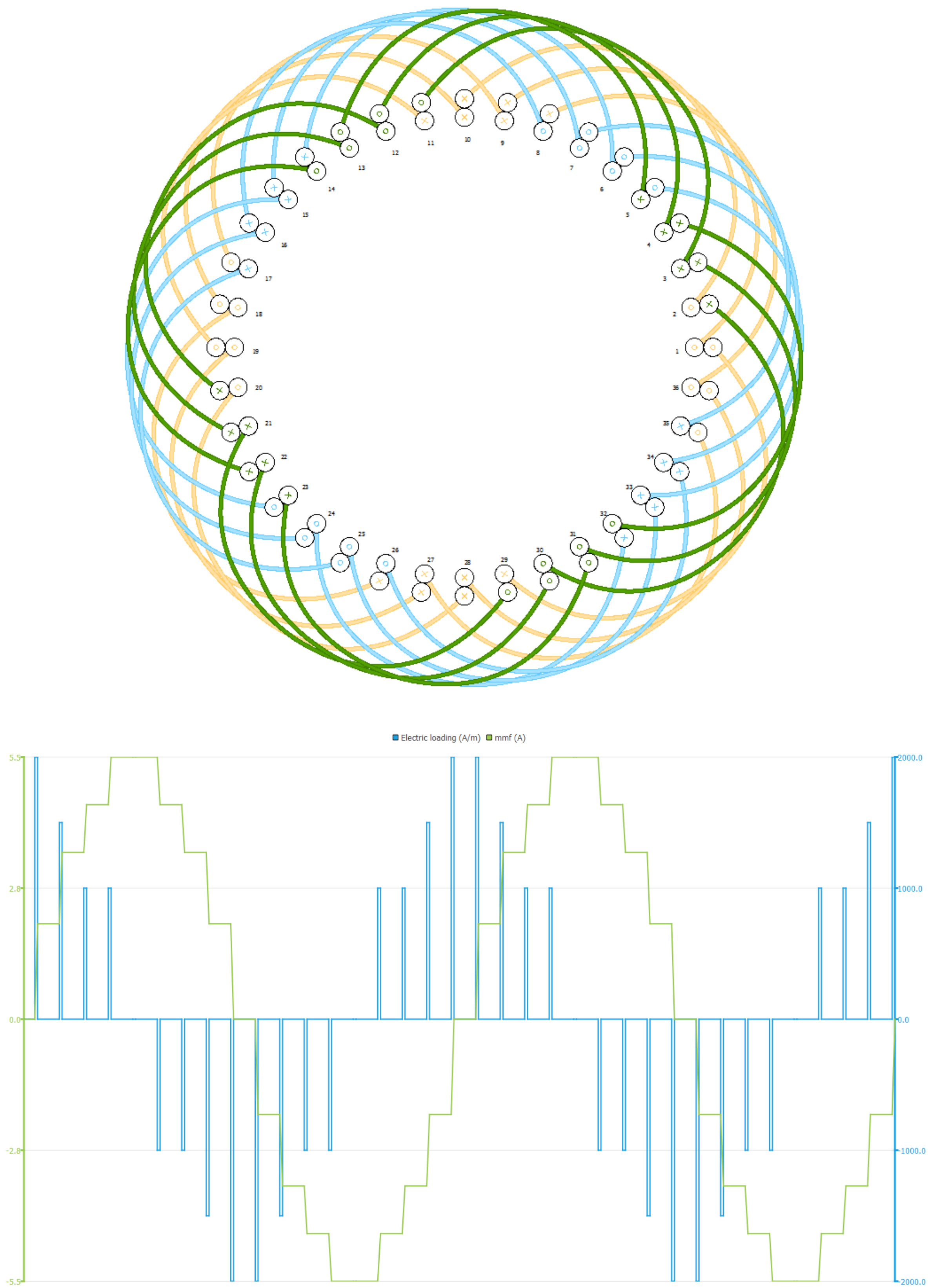


Figure 1.3 Winding diagram and corresponding MMF waveform for 8/9 coil span with Ia=1pu, Ib= -0.5pu Ic=-0.5pu

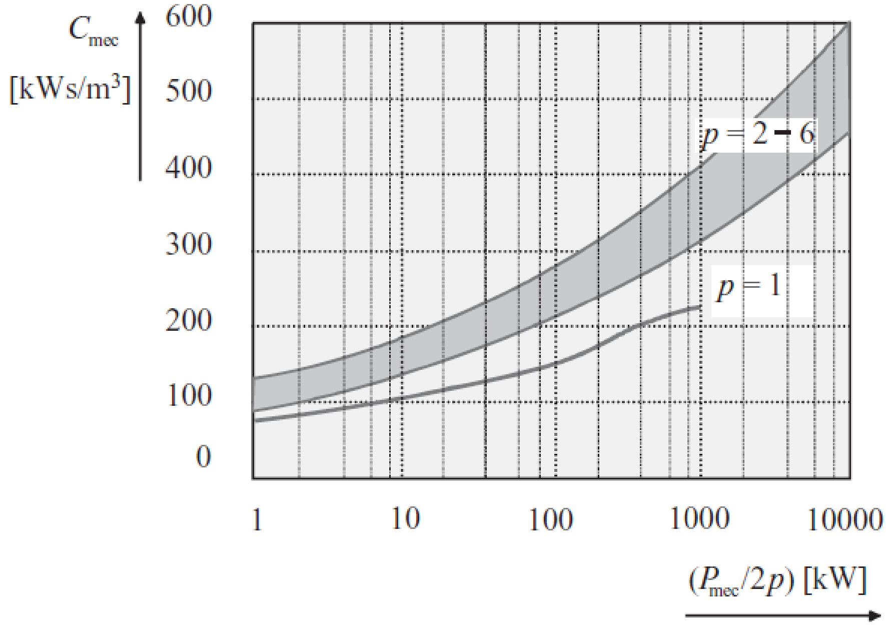


Figure 1.4 Machine constants of totally enclosed asynchronous and synchronous machines as a function of pole power [2]

If Y-connection is chosen, rated current of the coils are equal to the line currents. Then, taking current density, J as 4A/mm ^{2} (considering AC resistance) wire size (A_{cu}) can be found as

$$A_{cu} = \frac{I_{rated}}{J} = 0.148\, mm^2 \approx 0.15\, mm^2 \approx 25AWG$$

For a double-layer winding, fill factor/space factor of the stator will be limited to 0.6 [2]. Taking fill factor k_f as 0.5, and using slot area A_s (41mm^2 from Figure 1.1)

number of conductors in one slot, $z_Q = \frac{k_f A_s J}{A_c} \approx 136\ (must\ be\ even)$

Then using the equality $N_s = z_Q pq$, number of series turns in one phase, N_s is found to be 816.

Recommend air-gap for p>1, $\delta = \left(0.18 + 0.006{P_{mec,W}}^{0.4}\right) \approx 0.24mm$

2 MOTOR PARAMETER ESTIMATION

<u>Specific Magnetic Loading</u>

$$\boldsymbol{\Phi_p = \frac{V_{ph}}{4.44 N_s k_w f} = 0.0013} \text{ Wb}$$

$$\mathbf{B}_{\boldsymbol{g,av}} = \frac{\boldsymbol{\Phi_p}}{\boldsymbol{\pi DL/poles}} = 0.57\text{T}$$

Checking for the peak air-gap flux density, $\hat{\boldsymbol{B}} = \mathbf{B}_{\boldsymbol{g,av}} \frac{\boldsymbol{\pi}}{\mathbf{2}}$=0.901 T, slightly higher than recommended values for enclosed induction machines.

Mean flux density in stator teeth,

$$\mathbf{B}_{\boldsymbol{st,avg}} = \boldsymbol{\Phi_p / (TeethArea * no\ of\ teeth\ per\ pole)} = 1.22\text{T}$$

$$\widehat{\mathbf{B}_{\boldsymbol{st}}} = \mathbf{B}_{\boldsymbol{st,avg}} \frac{\boldsymbol{\pi}}{\mathbf{2}} = 1.92\text{T}$$

Taking Loos/kg=35W/kg for this lamination with 0.5mm thickness

$$\mathbf{P}_{\boldsymbol{iron,teeth}} = \boldsymbol{14.5W}$$

Mean flux density in stator core

Yoke cross section: $\mathbf{A}_{\boldsymbol{s,core}} = \boldsymbol{L * 0.5(\mathbf{D}_o - D - 2h_{teeth})}$

$$\mathbf{B}_{\boldsymbol{s,av}} = \frac{\boldsymbol{\Phi_p}}{\mathbf{2*A}_{\boldsymbol{s,core}}} = 2.2\text{T ! problem}$$

<u>Specific Electrical Loading</u>

$$\overline{\boldsymbol{A}} = \frac{\mathbf{N}_{\boldsymbol{slot}} \boldsymbol{I_{rms} Q}}{\boldsymbol{\pi D}} = 16.8 \text{ kA/m}$$

Quite smaller than recommended minimum value but for small machine it might be acceptable.

Rated Speed

Assuming 1% rated slip, $\mathbf{n}_{r} = (1 - s)\frac{60f}{p}$=1474 rpm

Rated Torque

$$T = \frac{P_{mec}}{2\pi(n_r/60)} = 2.1 \text{ Nm}$$

Stator Phase Resistance

$$l_{mt} = 2L + 2.3\tau_p + 0.08 = 28cm$$

Taking $\rho_{cu} = 21m\Omega mm^2/m$ for 80 C

$$R_S = \frac{\rho_{cu} l_{mt} N_s}{A_{cu}} = 4.75\Omega$$

Then approximate stator copper losses: $3R_S {I_{rated}}^2 = 5.04W$

Phase Inductance and Magnetizing Inductance

Taking δ_{ef}=1.05δ

$$L_{sp} = \frac{2}{\pi}\tau_p L \frac{\mu o}{\delta_{ef}} \frac{4q}{\pi} \frac{m}{Qs}(k_{w1}N_s)^2 = 1.4\ H$$

$$L_m = L_{sp} * \frac{m}{2} = 2.11H$$

Leakage Inductance

air-gap leakage inductance of the machine can be approximated as

$$\mathbf{L_{\delta}} = \boldsymbol{\sigma_{\delta}} \mathbf{L_m} = \boldsymbol{23mH}$$

taking $\boldsymbol{\sigma_{\delta}}$ as 0.011 from figure 4.12 in [2], for q=3 and 8/9 coil span

additionally, slot leakage inductance can be calculated using number of conductors in a slot and slot dimensions as:

3 SIMULATION RESULTS

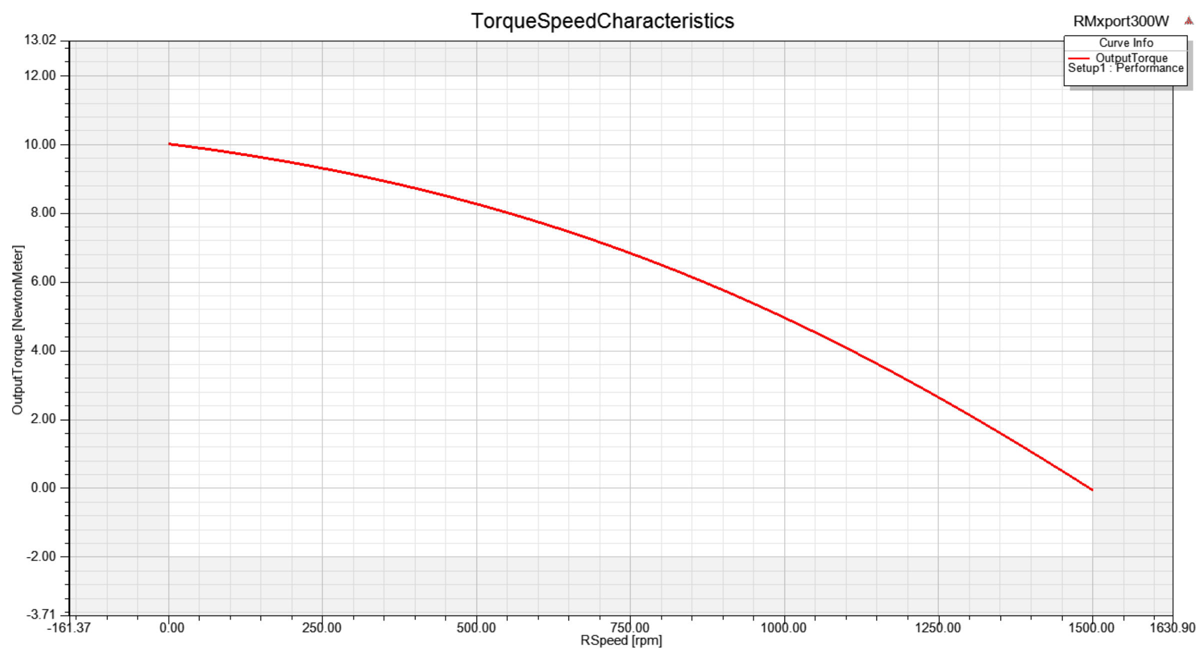


Figure 3.1 Torque-Speed characteristics of the designed machine

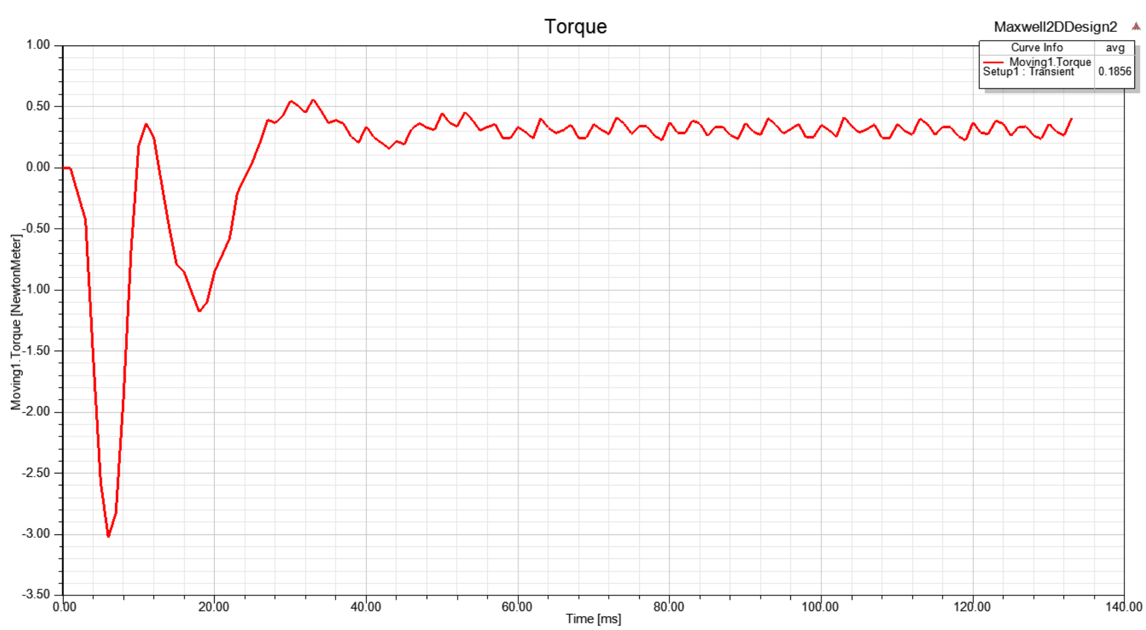


Figure 3.2 Machine Torque at 1474 rpm

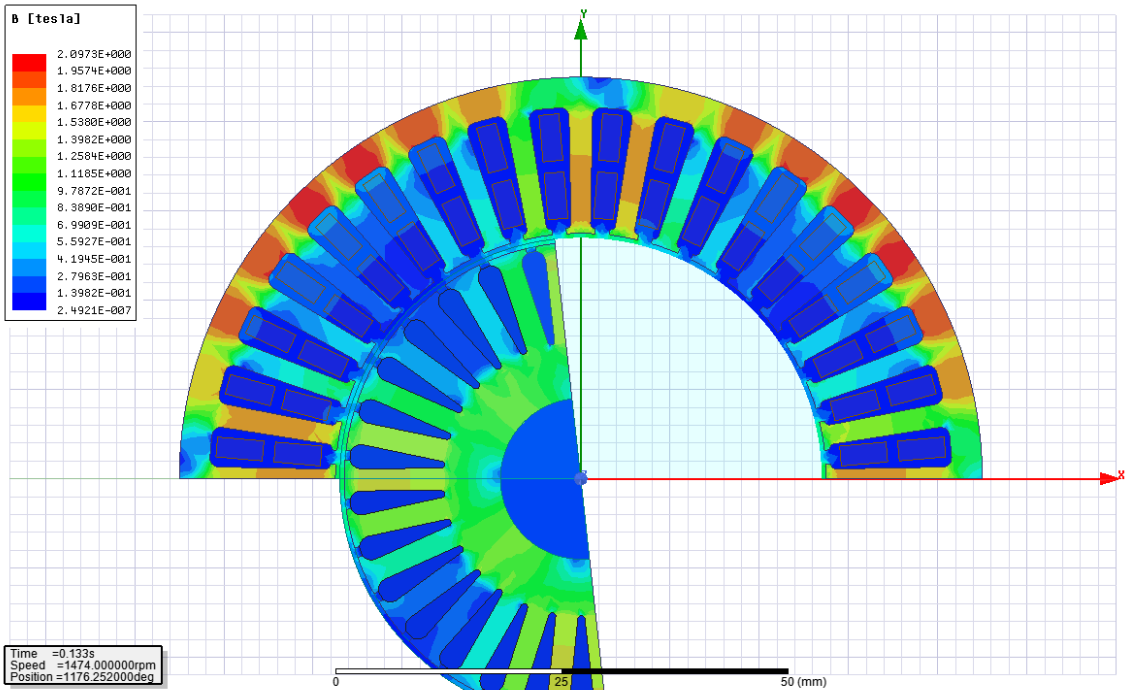
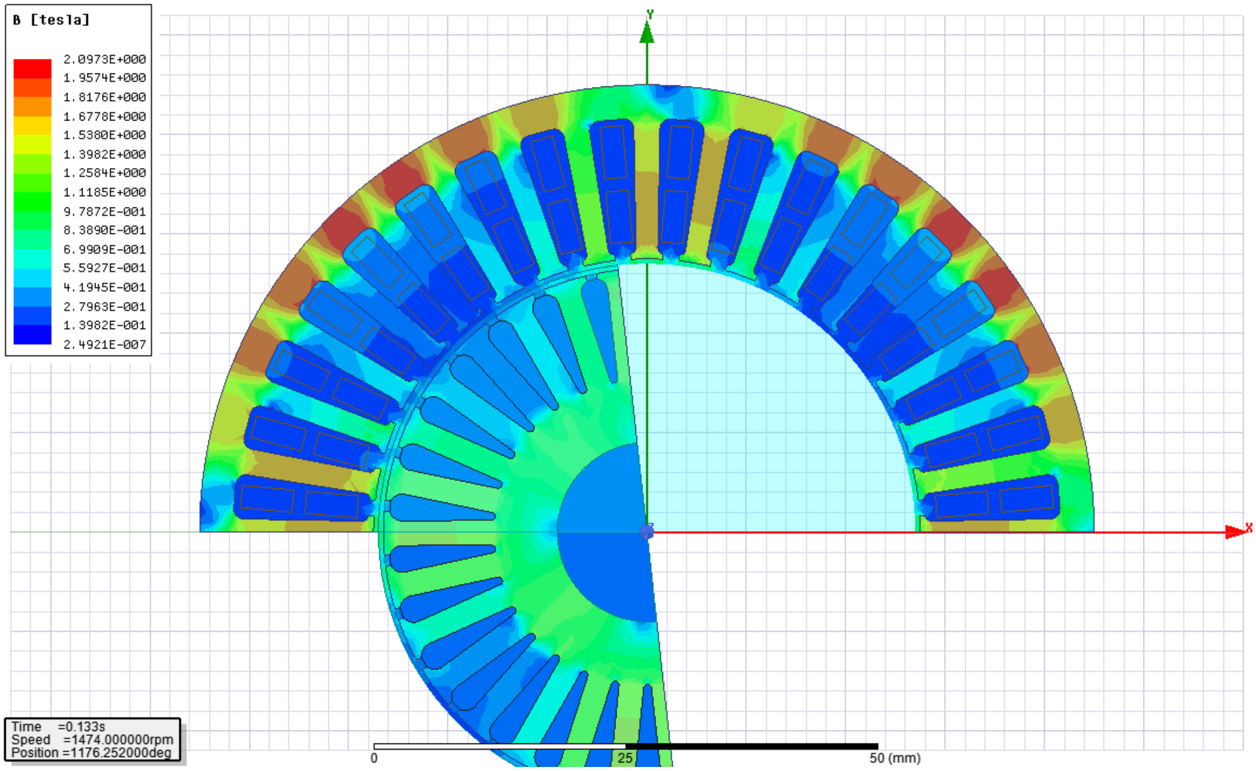


Figure 3.3 Flux Density Distribution for Ia=3.67, Ib=5.45, Ic=-9.1



B [tesla]
2.0973E+000
1.9574E+000
1.8176E+000
1.6778E+000
1.5380E+000
1.3982E+000
1.2584E+000
1.1185E+000
9.7872E-001
8.3890E-001
6.9909E-001
5.5927E-001
4.1945E-001
2.7963E-001
1.3982E-001
2.4921E-007
Y
X
Time =0.133s
Speed =1474.000000rpm
Position =1176.252000deg
0
25
50 (mm)

4 REFERENCES

[1] IEC 63/6-8.55 datasheet, online:. http://katalog.kienle-spiess.de

[2] Pyrhonen, J., Jokinen, T., & Hrabovcova, V. (2013). Design of rotating electrical machines. John Wiley & Sons.

[3] https://sourceforge.net/projects/dolomites/