Introductory Course on Design of Surface Permanent Magnet Motors

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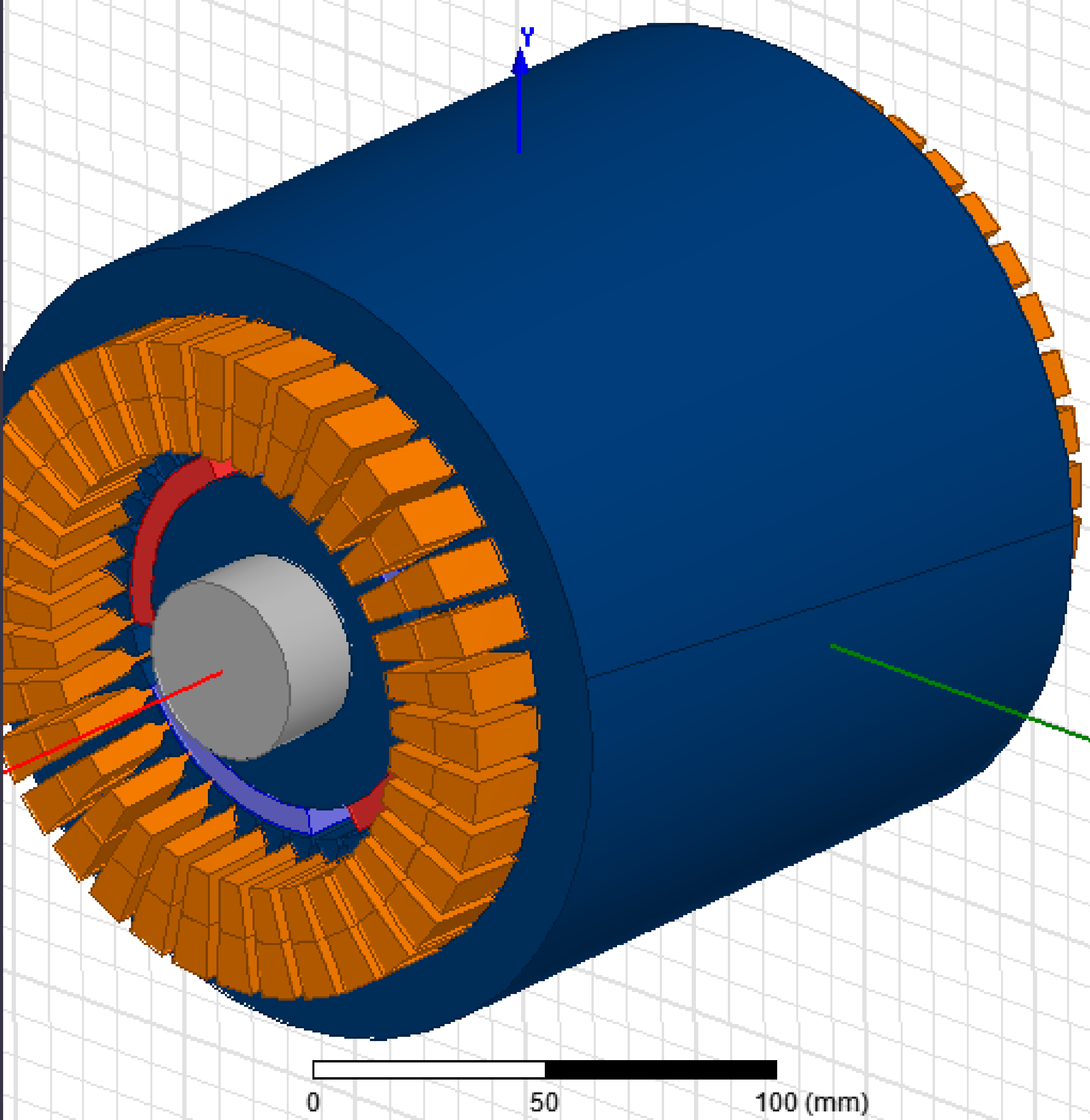
Objective

$$P_{out} = 20HP$$

$$Speed = 3600RPM$$

$$V_{t,L-L} = 415V$$



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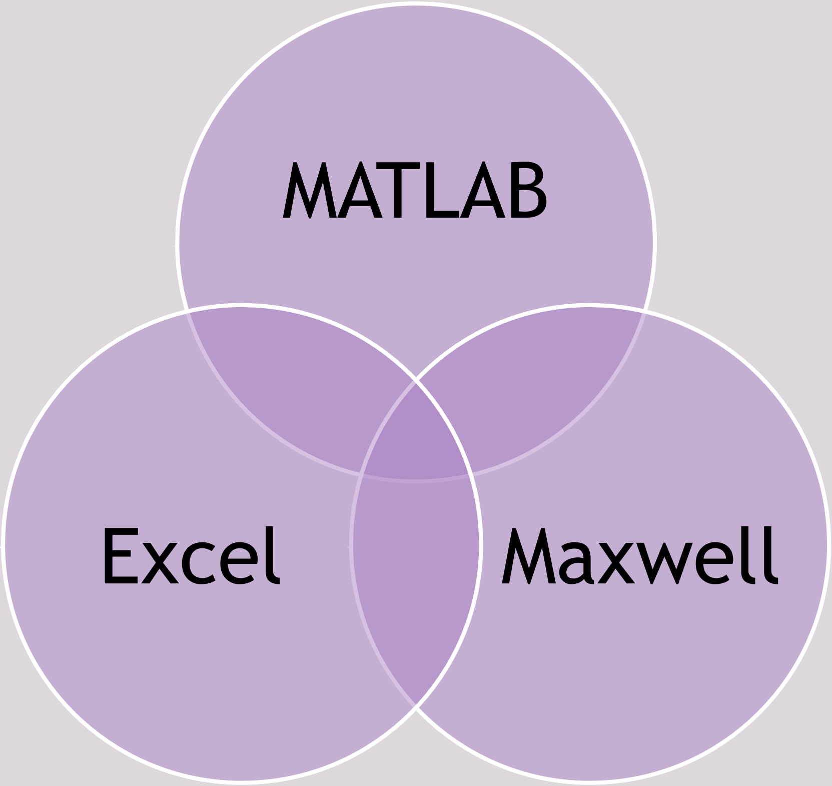
PRELIMINARY DESIGN

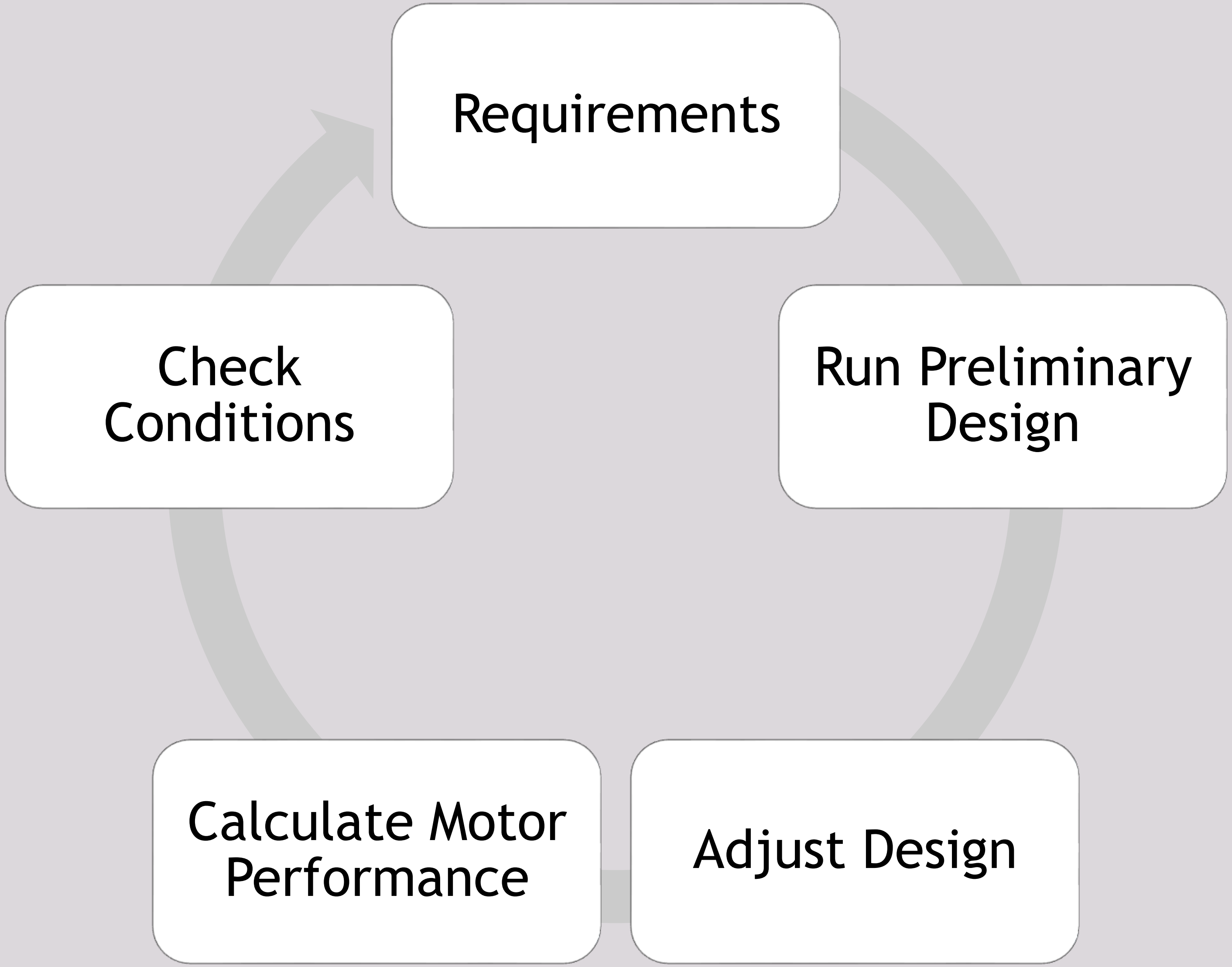
Calculation of main dimensions & parameters

Classification of variables

- Design Variables
  - Independent
    - Fixed: P_{out}, D_o
    - Adjusted by Designer: $B_{av}, ar = \frac{L_{stk}}{\tau_p}$
  - Dependent
    - Direct Dependent: $T_{out} = \frac{P_{out}}{\omega_m}$
    - Indirect Dependent: $w_{st}, N_{tc}, KgRotor$

Design workflow





Some direct dependents

$$T_{out} = \frac{P_{out}}{\omega_m}$$

Rated output torque

Rated frequency of supply

$$RPM = \frac{120 \times f}{p}$$

Number of poles

Calculation of input power (input VA)

$$P_{in} = \frac{P_{out}}{\eta_d}$$

$$Q_{in} = \frac{P_{out}}{\eta_d \times \cos(\varphi)}$$

Desired efficiency

Desired power factor

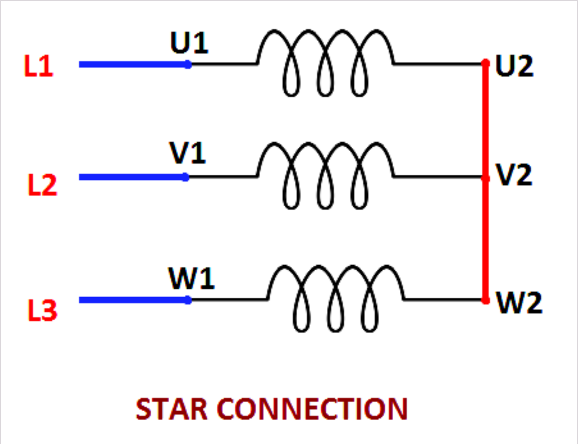
Calculation of terminal current

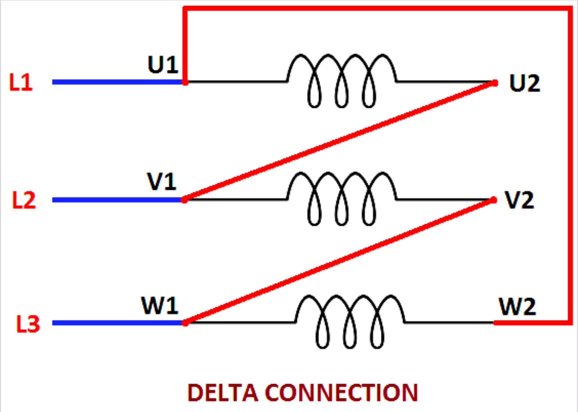
$$I_t = \frac{P_{in}}{\sqrt{3}V_t \cos(\varphi)}$$

We should assume a desired power factor

Calculation of phase voltage & current

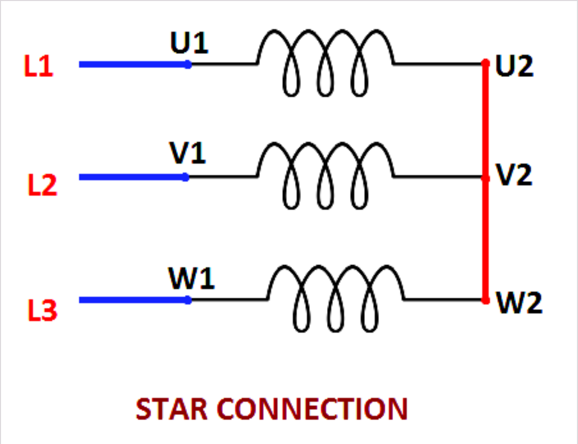
$$I_{ph} = \begin{cases} I_t \\ \dfrac{I_t}{\sqrt{3}} \end{cases}$$

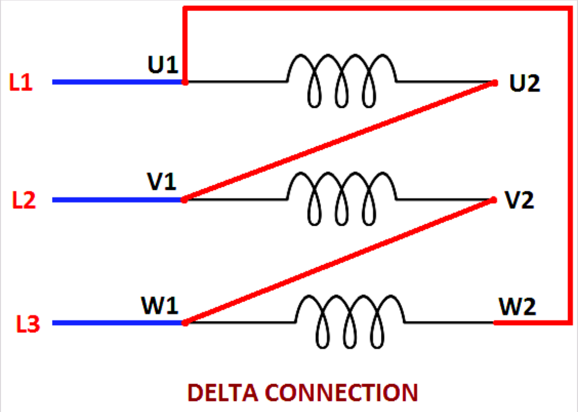




Calculation of phase voltage & current

$$V_{ph} = \begin{cases} \dfrac{V_t}{\sqrt{3}} \\ V_t \end{cases}$$





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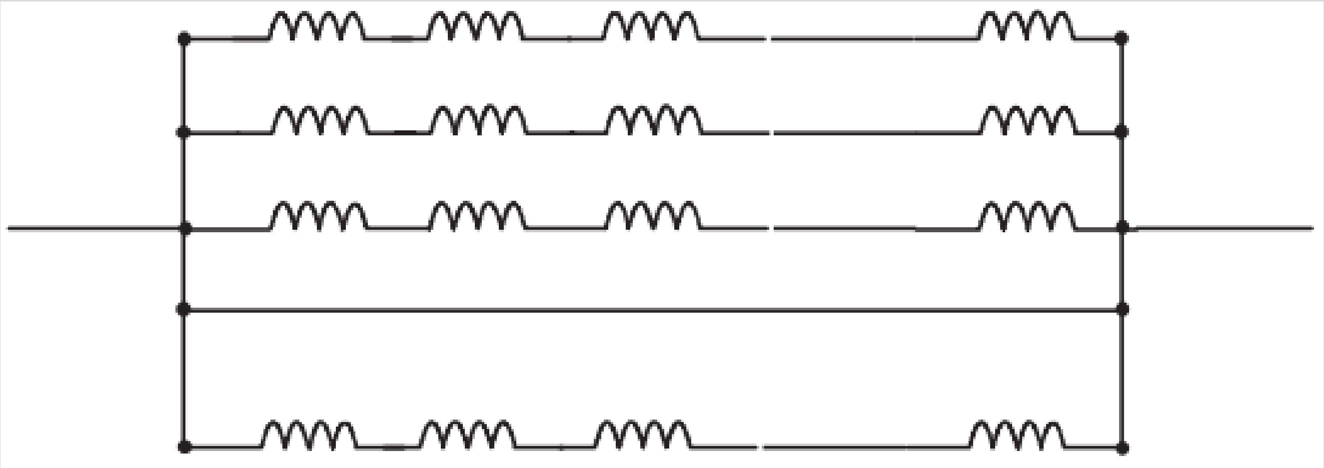
Calculation of coil voltage & current

$$I_c = \frac{I_{ph}}{N_p}$$



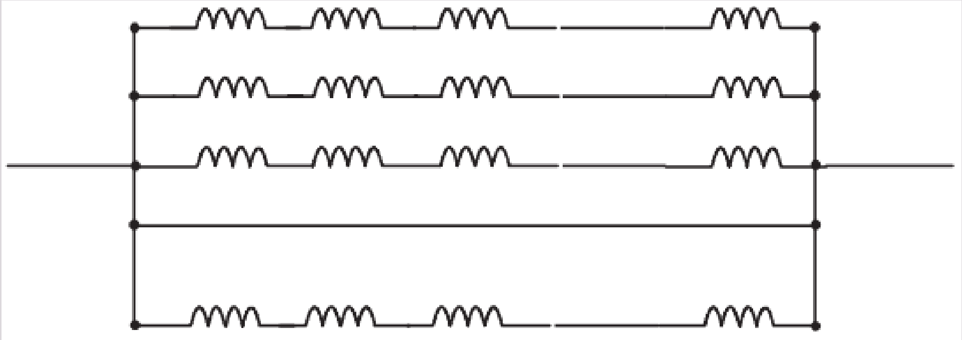
Number of parallel paths

Calculation of coil voltage & current

Number of stator slots

$$V_{ph} = \frac{V_c \times \dfrac{N_s}{m}}{N_p}$$

Number of phases



$\dfrac{N_s}{m}$ = Number of coils in each phase in double layer winding

Motor output equation

Rotor volume

$$P_{out}[kW] = G \times D^2 L \times rps$$

Output constant

Revolutions per second

Calculation of motor output constant

Ampere loading [kA/m]

$$G = 1.11 \times \pi^2 \times K_w \times B_{av} \times ac$$

Winding factor

Magnetic loading [Tesla]

Calculation of main dimensions

$$D^2 L = \frac{G}{P_{out} \times rps}$$

$$ar = \frac{L}{\tau_p}$$

$$\tau_p = \frac{\pi D}{p}$$

Pole pitch

Pole flux

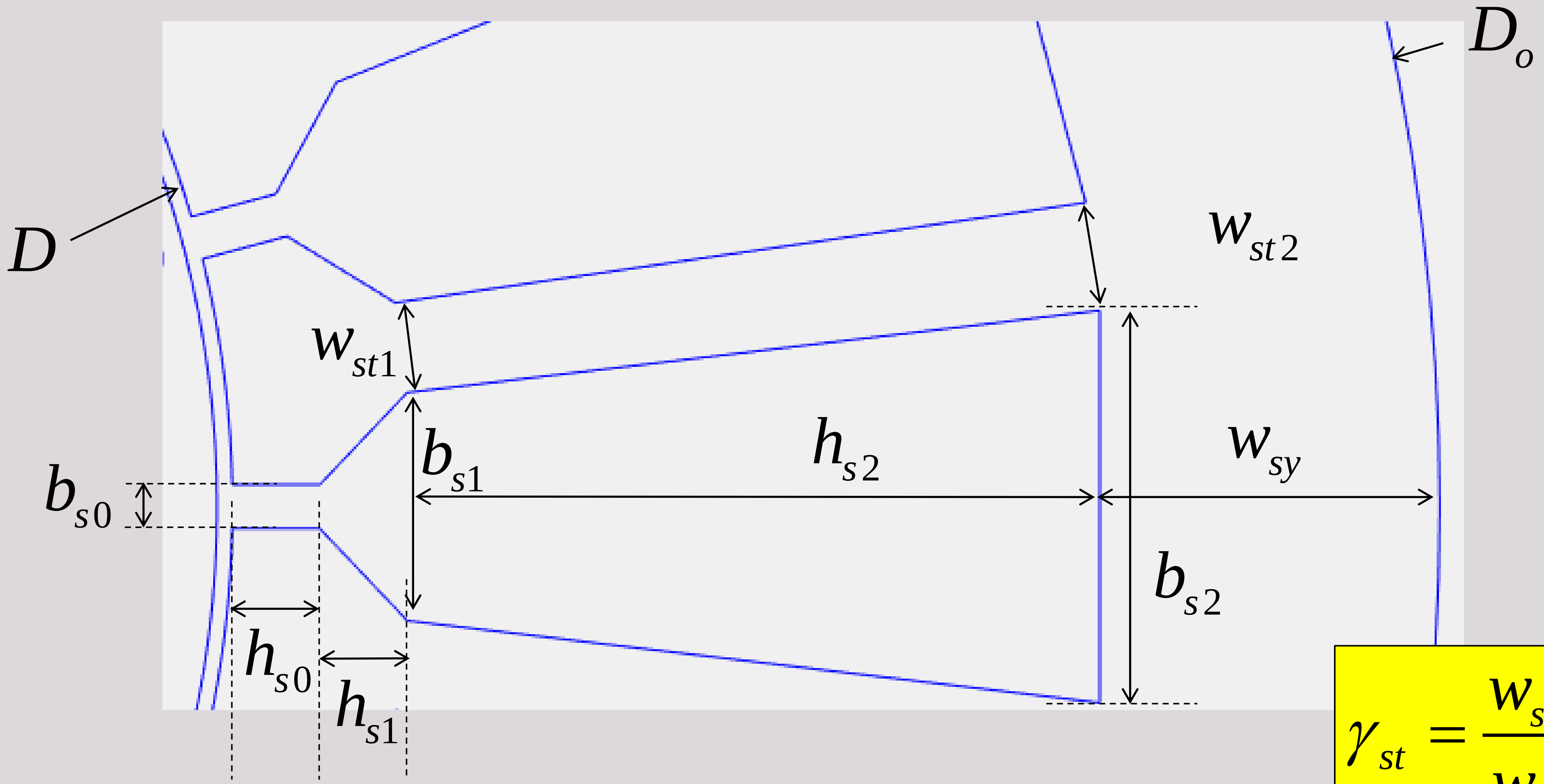
Total air gap flux

$$\varphi_{total} = B_{av} \times \pi DL$$

Flux under the pole

$$\varphi_p = \frac{\varphi_{total}}{p}$$

Stator slot dimensions



$$\gamma_{st} = \frac{w_{st2}}{w_{st1}}$$

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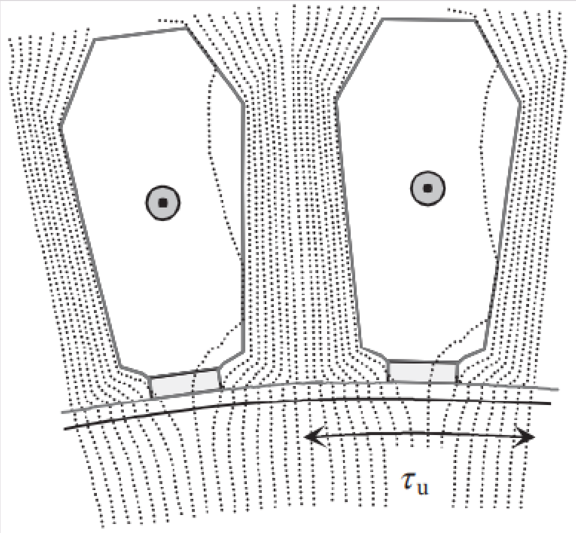
Calculation of width of stator tooth

Width of stator tooth at tip

$$\varphi_{st,\max} = B_{st} \times w_{st1} \times L \times k_i$$



$$w_{st2} = \gamma_{st} \times w_{st1}$$

Width of stator tooth at tail

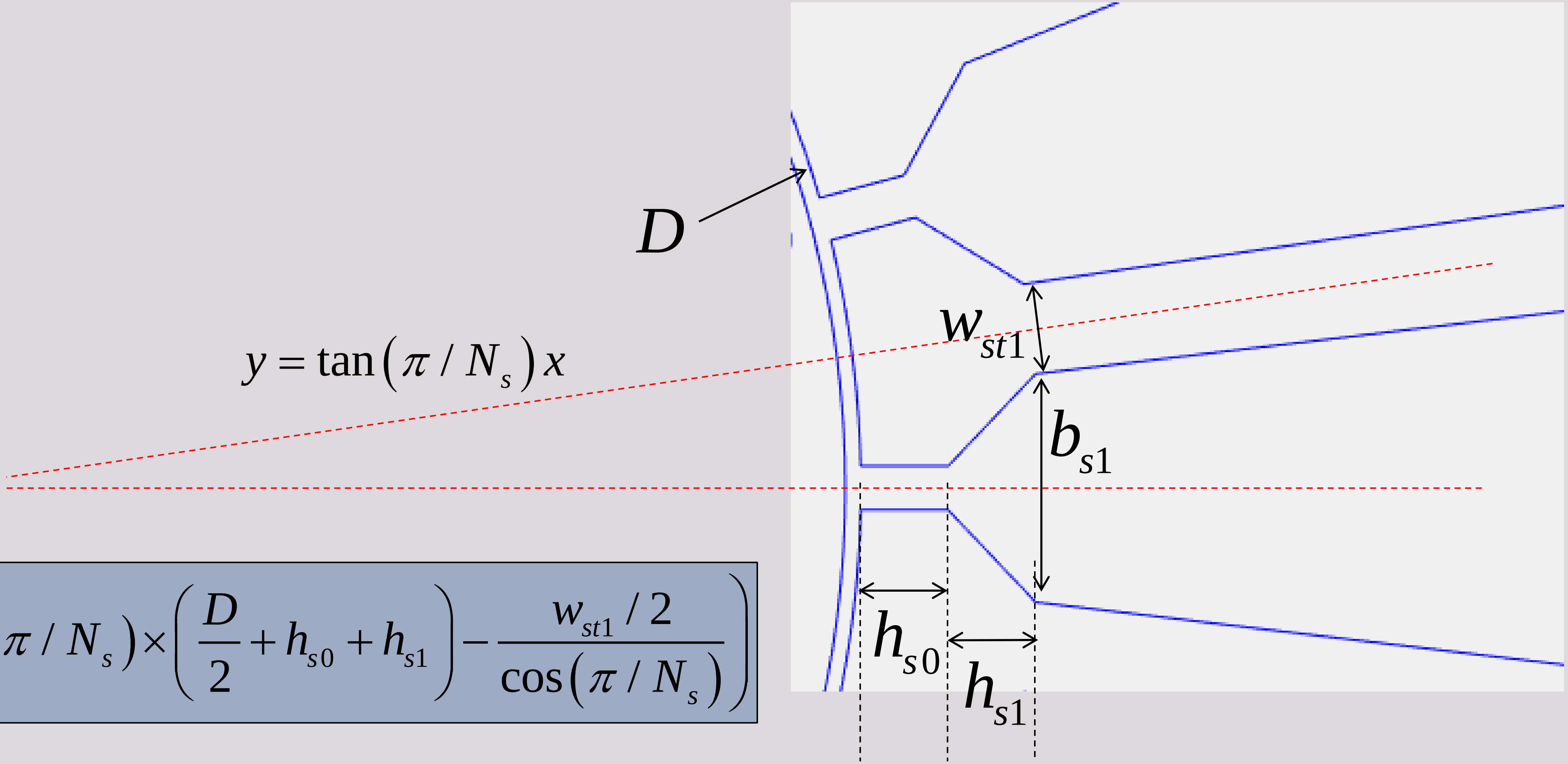
Stator tooth flux

$$\varphi_{st,\max} = \int B.ds = \int_{\frac{-\pi}{N_s}}^{\frac{\pi}{N_s}} B_r(\theta) \times \frac{D}{2} d\theta \times L$$

$$B_r(\theta) = B_m \cos(p\theta) = \frac{\pi}{2} B_{av} \cos(p\theta)$$

$$\varphi_{st,\max} = \frac{B_{av} \times \pi DL}{2p} \times \sin\left(\frac{\pi p}{N_s}\right) = \frac{\varphi_p}{2} \times \sin\left(\frac{\pi p}{N_s}\right)$$

Calculation of stator slot dimensions

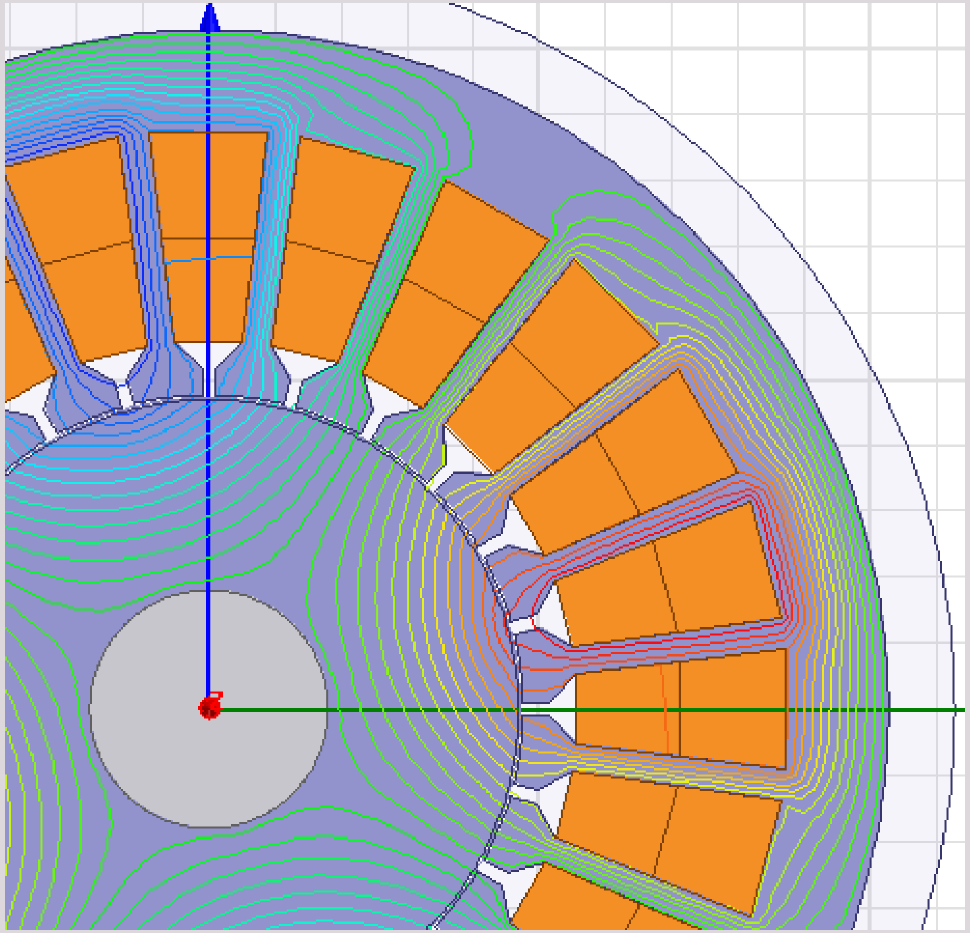


$$b_{s1} = 2\left(\tan(\pi / N_s) \times \left(\frac{D}{2} + h_{s0} + h_{s1} \right) - \frac{w_{st1}/2}{\cos(\pi / N_s)} \right)$$

Calculation of width of stator yoke

Width of stator yoke

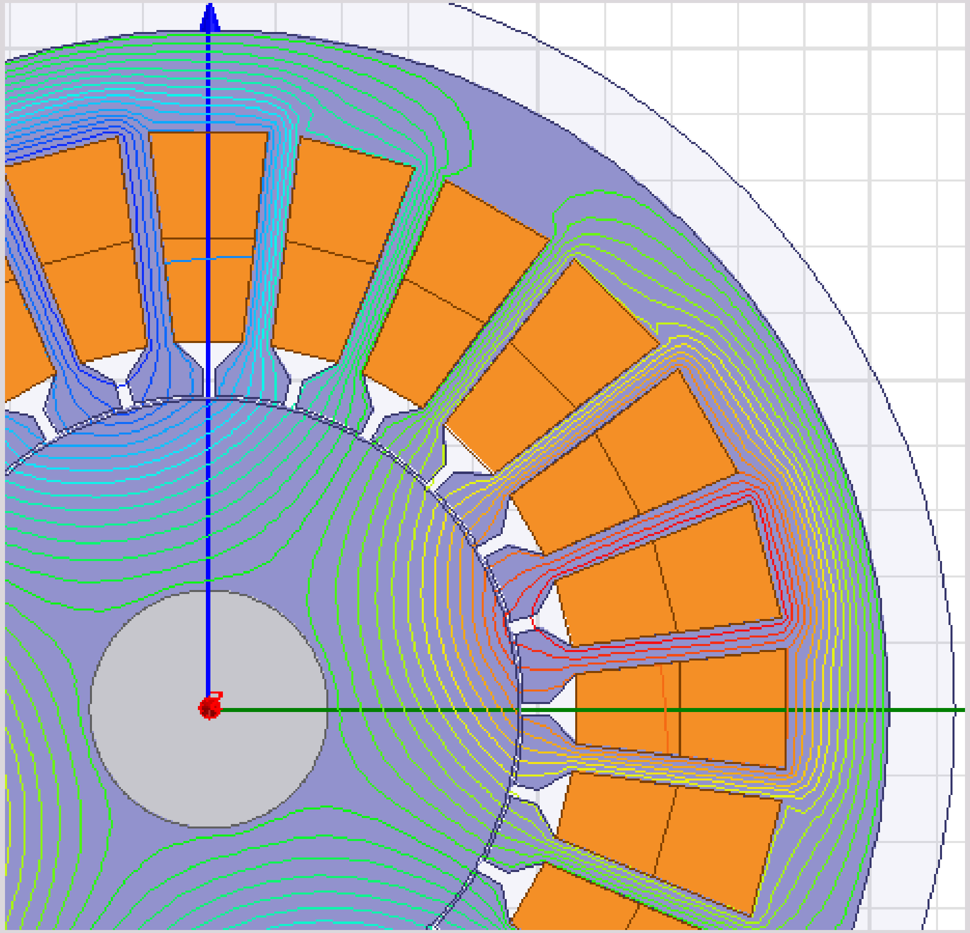
$$\frac{\varphi_p}{2} = B_{sy} \times w_{sy} \times L \times k_i$$



Calculation of width of rotor yoke

Width of rotor yoke

$$\frac{\varphi_p}{2} = B_{ry} \times w_{ry} \times L \times k_i$$



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Calculation of BEMF

Phase back EMF

$$\gamma_{emf} = \frac{E_{ph}}{V_{ph}}$$

Lower than 1: Motor operation

Grater than 1: Generator operation

Calculation of number of Ntph and Ntc (initial guess)

Number of turns per phase

$$E_{ph} = 4.44 \times f \times N_{tph} \times k_w \times \varphi_p$$

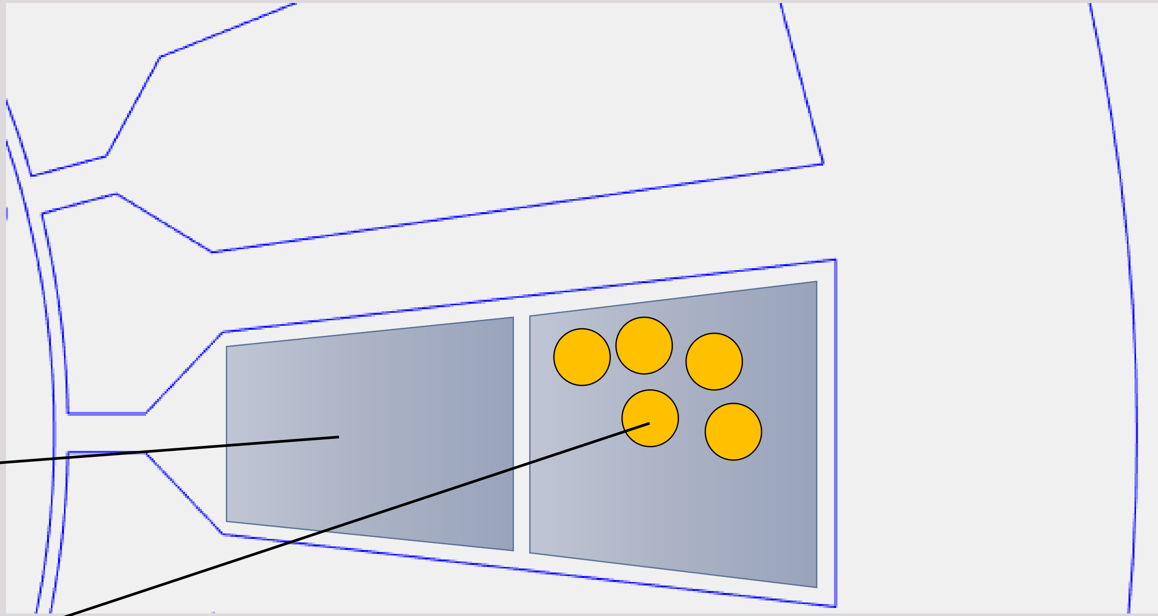
$$N_{tph} = N_{tc} \times \frac{N_s}{m} \times \frac{1}{N_p}$$

Number of turns per coil

Calculation of Slot Area

Gross area of coil arm

$$gAca$$



$$cAsc$$

Copper area of single conductor

$$cAca = N_{tc} \times cAsc$$

$$gAca = \frac{cAca}{Kf}$$

Fill factor

Calculation of cAsc (initial guess)

Coil current

$$cAsc = \frac{I_c}{J_{sw}}$$

Maximum current density in stator winding

After Calculation of cAsc we should update it with SWG or AWG table

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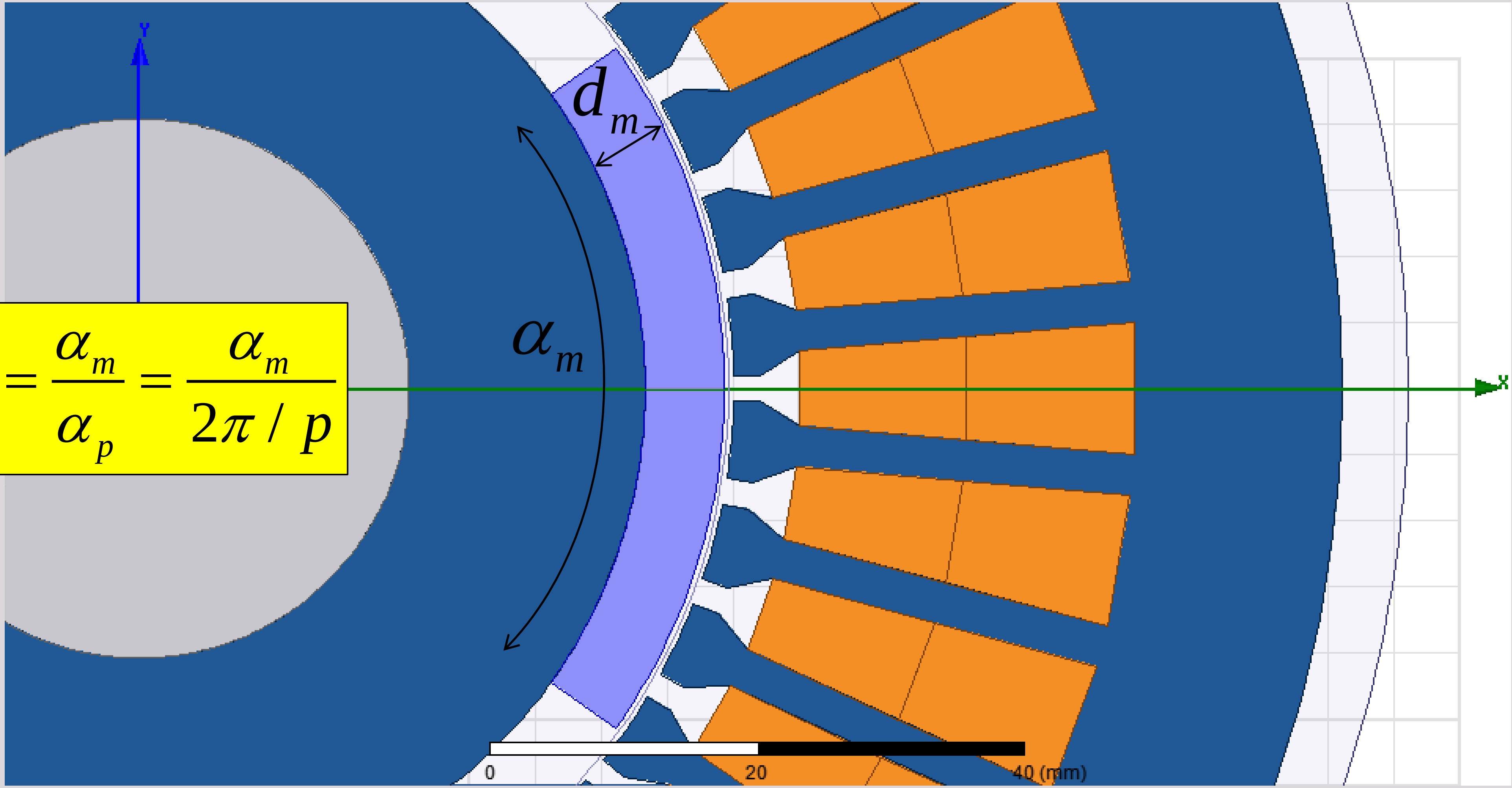
Calculation of stator slot dimensions

$$\begin{cases} \dfrac{(b_{s1}+b_{s2})}{4}\times h_{s2} = gAca \\ b_{s2} = 2\left(\tan\left(\pi / N_s\right)\times\left(\dfrac{D}{2}+h_{s0}+h_{s1}+h_{s2}\right) - \dfrac{w_{st2}/2}{\cos\left(\pi / N_s\right)} \right) \end{cases}$$

$$\boxed{a\times h_{s2}^{2} + b\times h_{s2} + c = 0}$$

Calculation of magnet dimensions



$$\gamma_m = \frac{\alpha_m}{\alpha_p} = \frac{\alpha_m}{2\pi / p}$$

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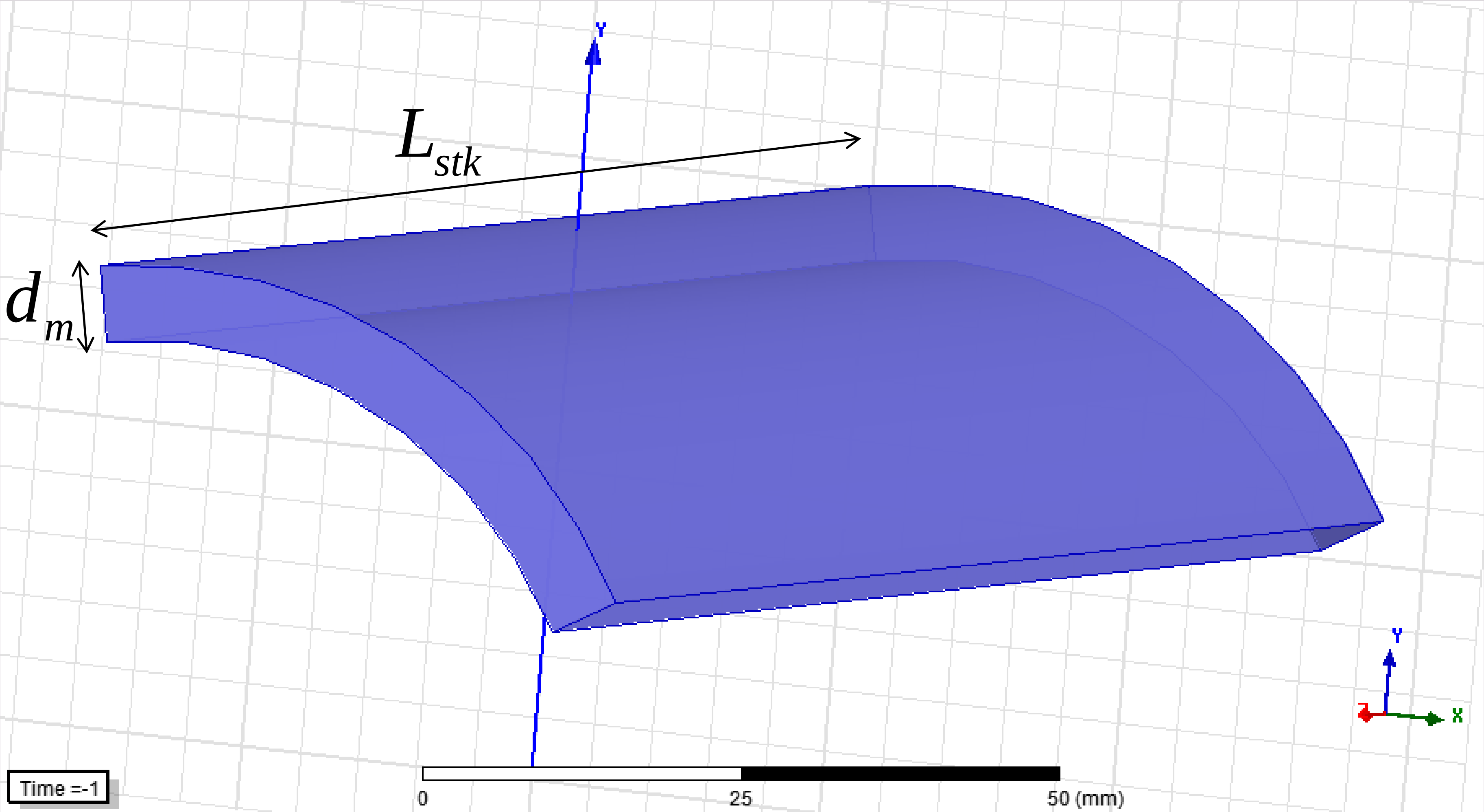
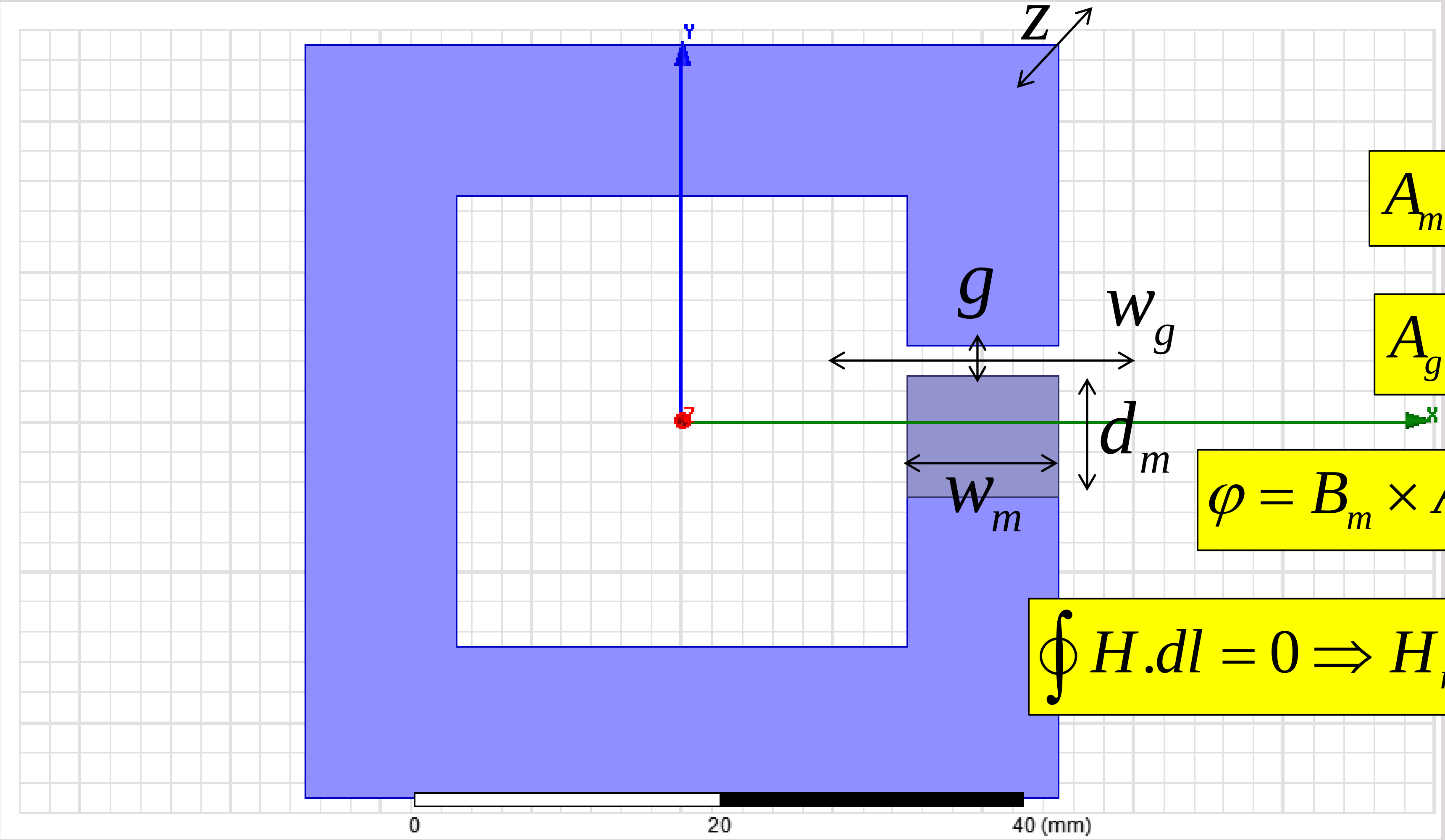
Calculation of magnet dimensions



Calculation of magnet dimensions, **ROUGH**



$$A_m = w_m \times z$$

$$A_g = w_g \times z$$

$$\varphi = B_m \times A_m \times k_l = B_g \times A_g$$

$$\oint H.dl = 0 \Rightarrow H_m \times d_m = H_g \times g \times k_r$$

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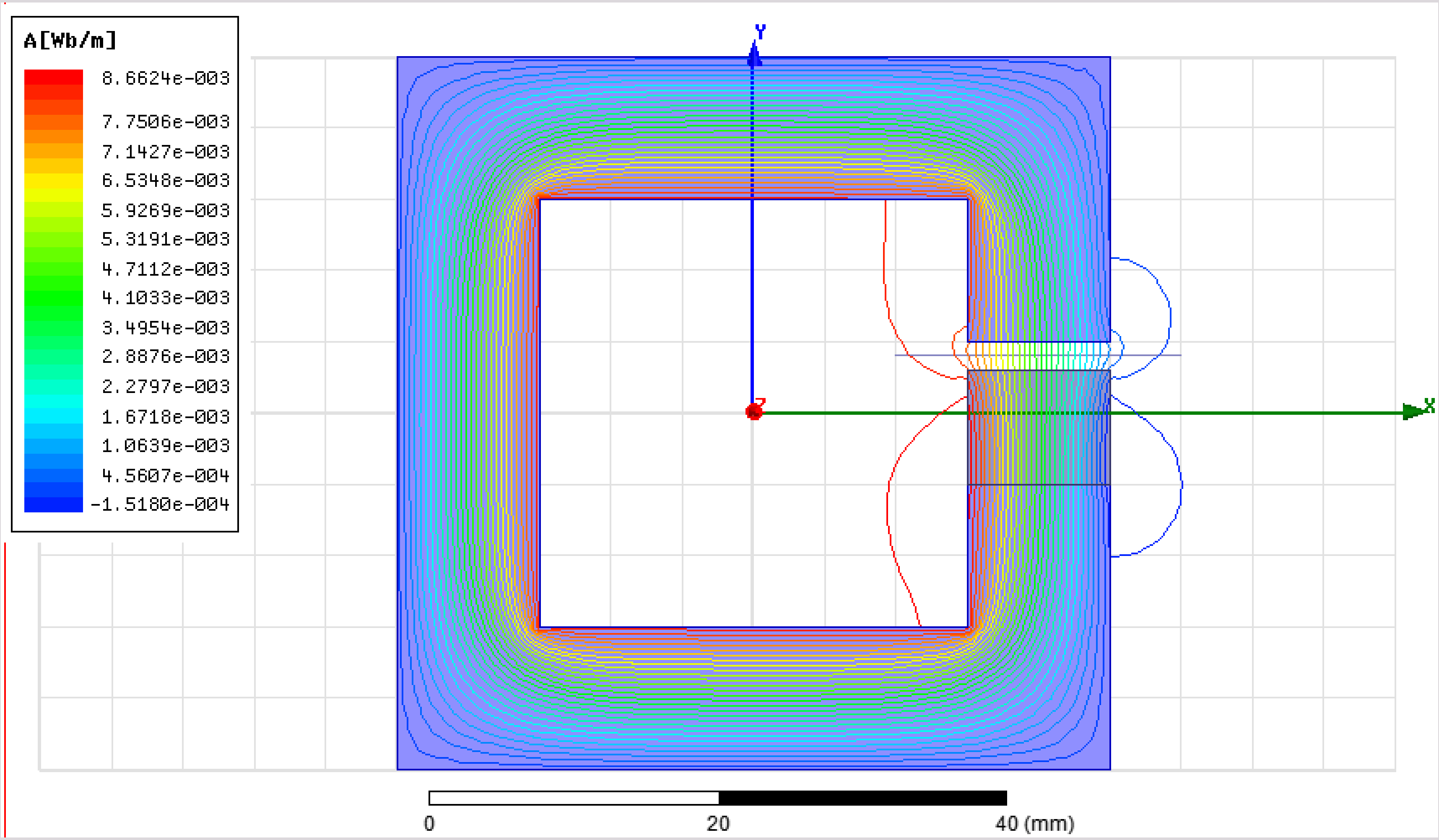
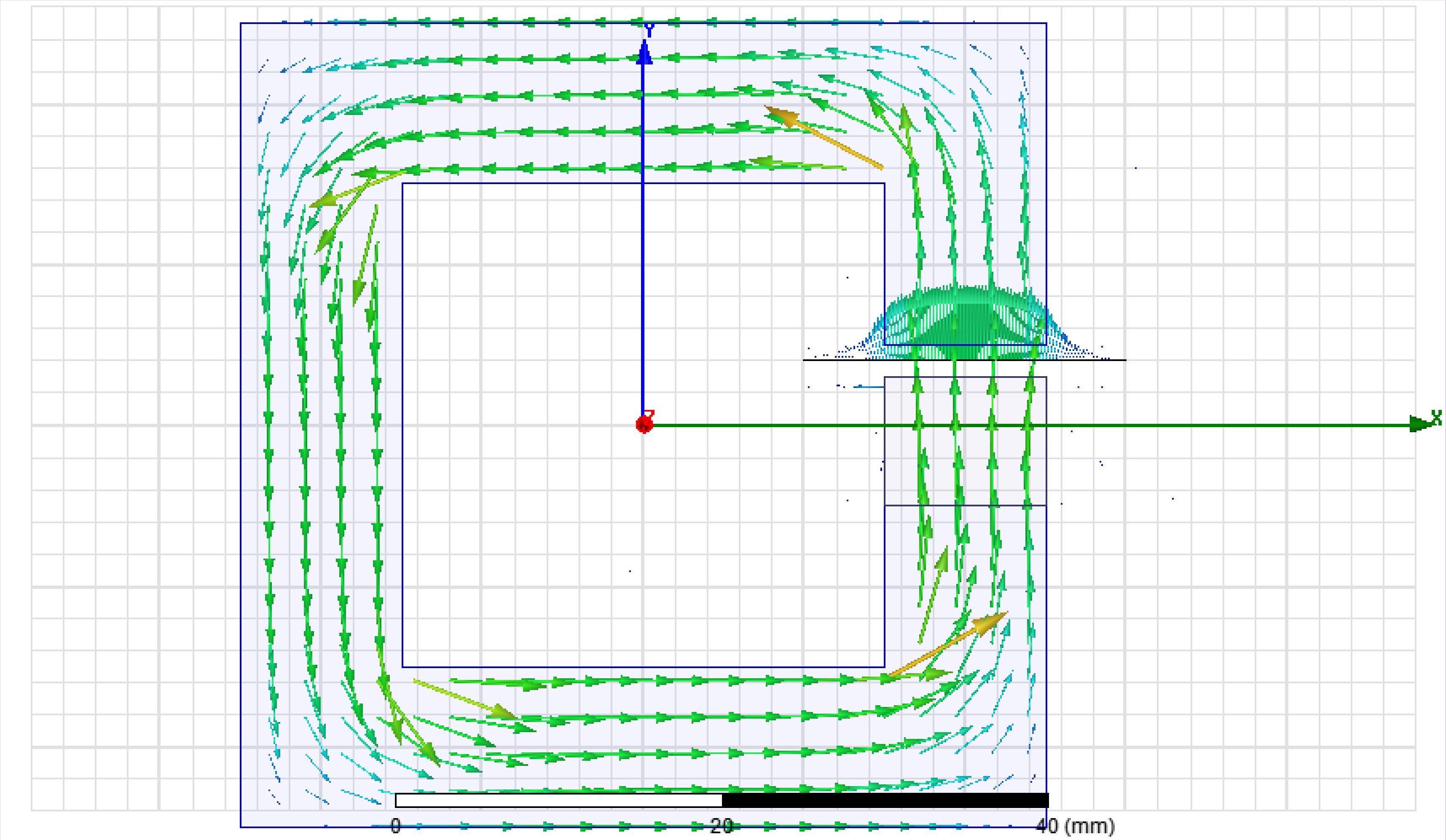
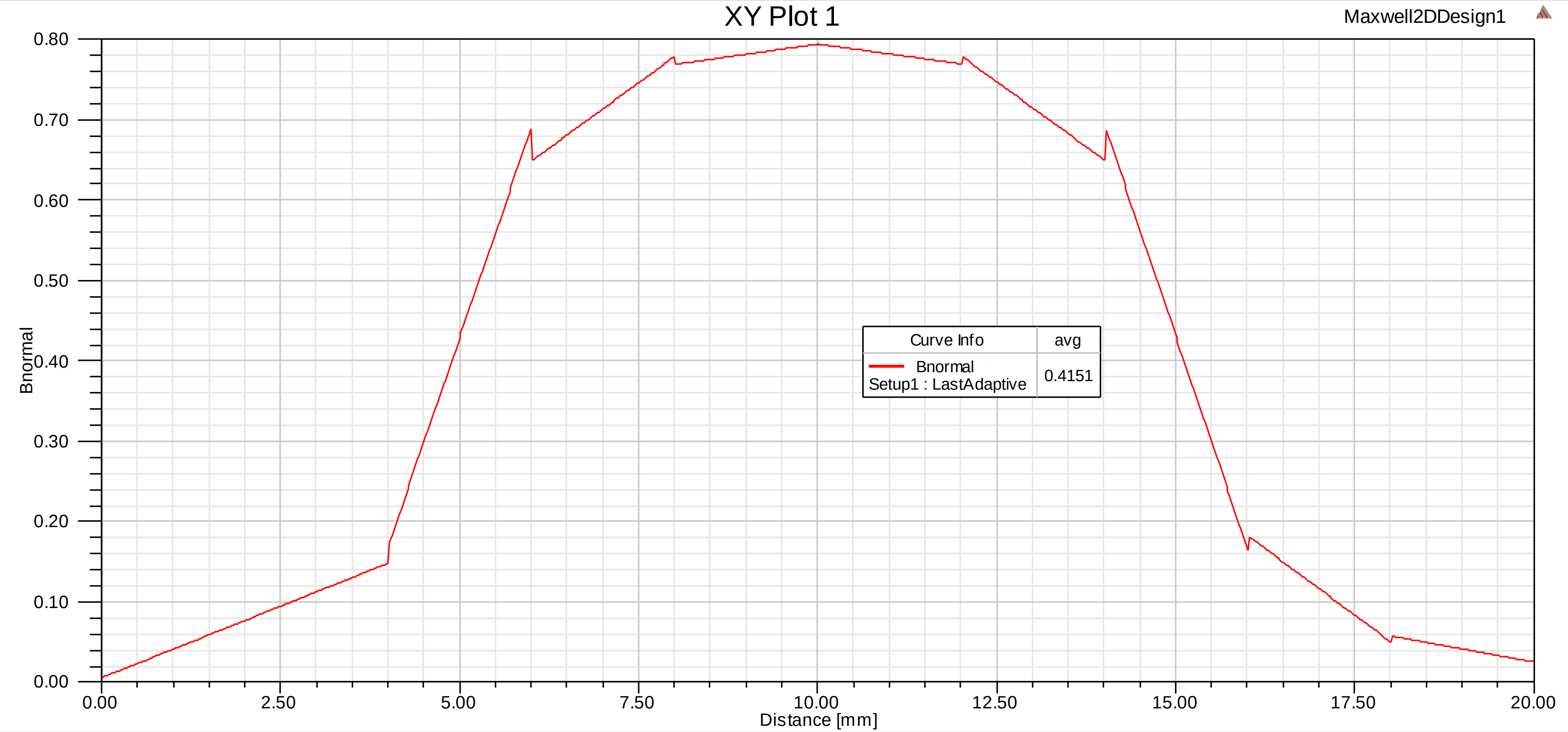
Calculation of Magnet Dimensions, <u>**ROUGH**</u>



Calculation of magnet dimensions, <u>ROUGH</u>

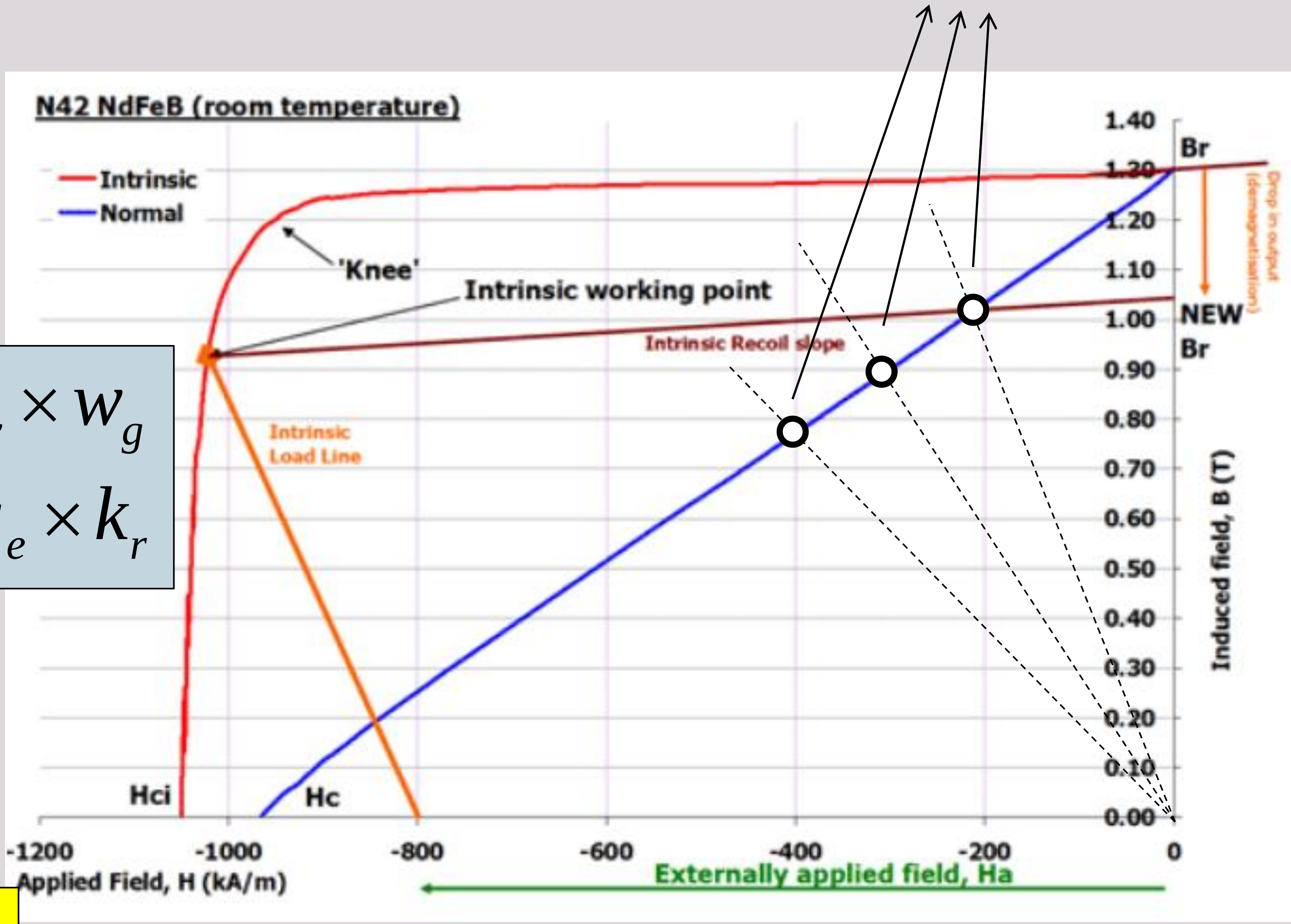


Calculation of magnet dimensions, **ROUGH**



Calculation of magnet dimensions, **ROUGH**

Operating point



$$
\begin{cases}
B_m \times w_m \times k_l = B_{av} \times w_g \\
H_m \times d_m = H_g \times g_e \times k_r
\end{cases}
$$

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Updating some parameters

$$N_{tc} \longrightarrow N_{tph} \longrightarrow \varphi_p \longrightarrow L$$

$$E_{ph} = 4.44 \times k_w \times f \times N_{tph} \times \varphi_p$$

$$\varphi_{p,new} = \frac{E_{ph}}{4.44 \times k_w \times f \times N_{tph,new}}$$

$$\varphi_p = B_{av} \times \frac{\pi D L}{p}$$

$$\frac{\varphi_{p,new}}{\varphi_{p,old}} = \frac{L_{new}}{L_{old}}$$

Calculation of phase resistance

Mean turn length

$$R_c = N_{tc} \times \rho \times \frac{L_{mt}}{cAsc}$$

$$L_{mt} = 2 \times L_{stk} + 4 \times L_{end} + 2 \times L_{span}$$

Number of stator slots

$$R_{ph} = R_c \times \left(\frac{N_s}{m} \right) \times \frac{1}{N_p^2}$$

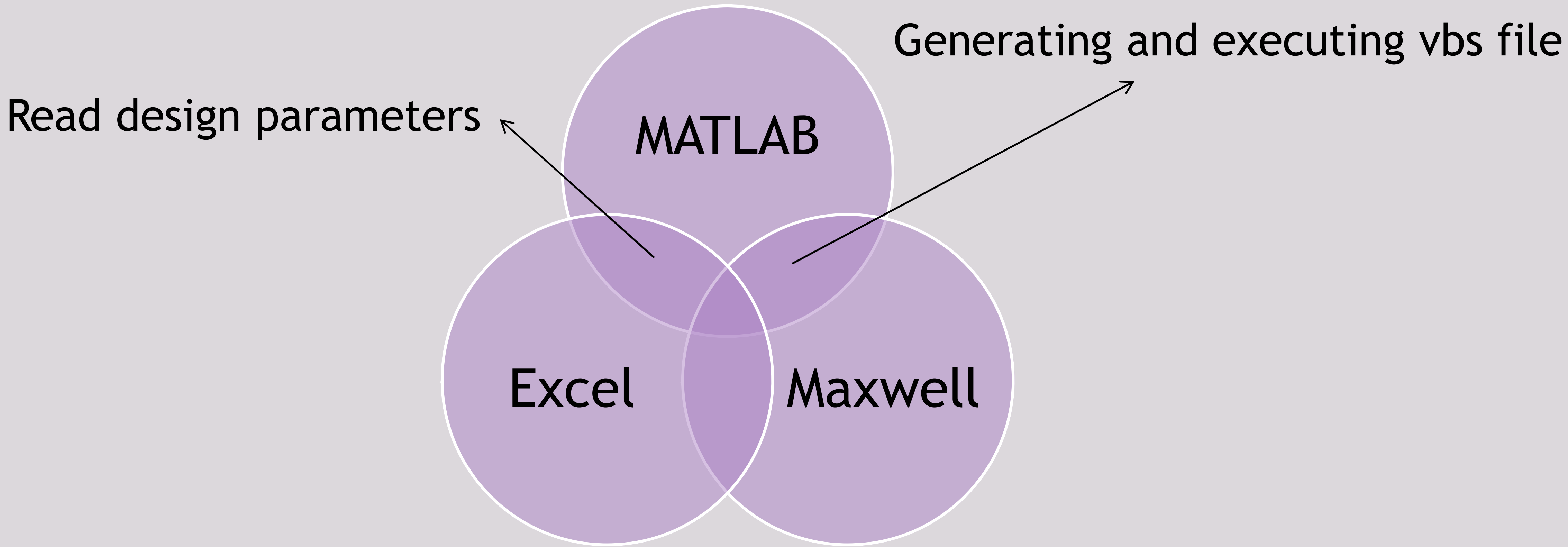
Number of parallel paths

Number of stator phases

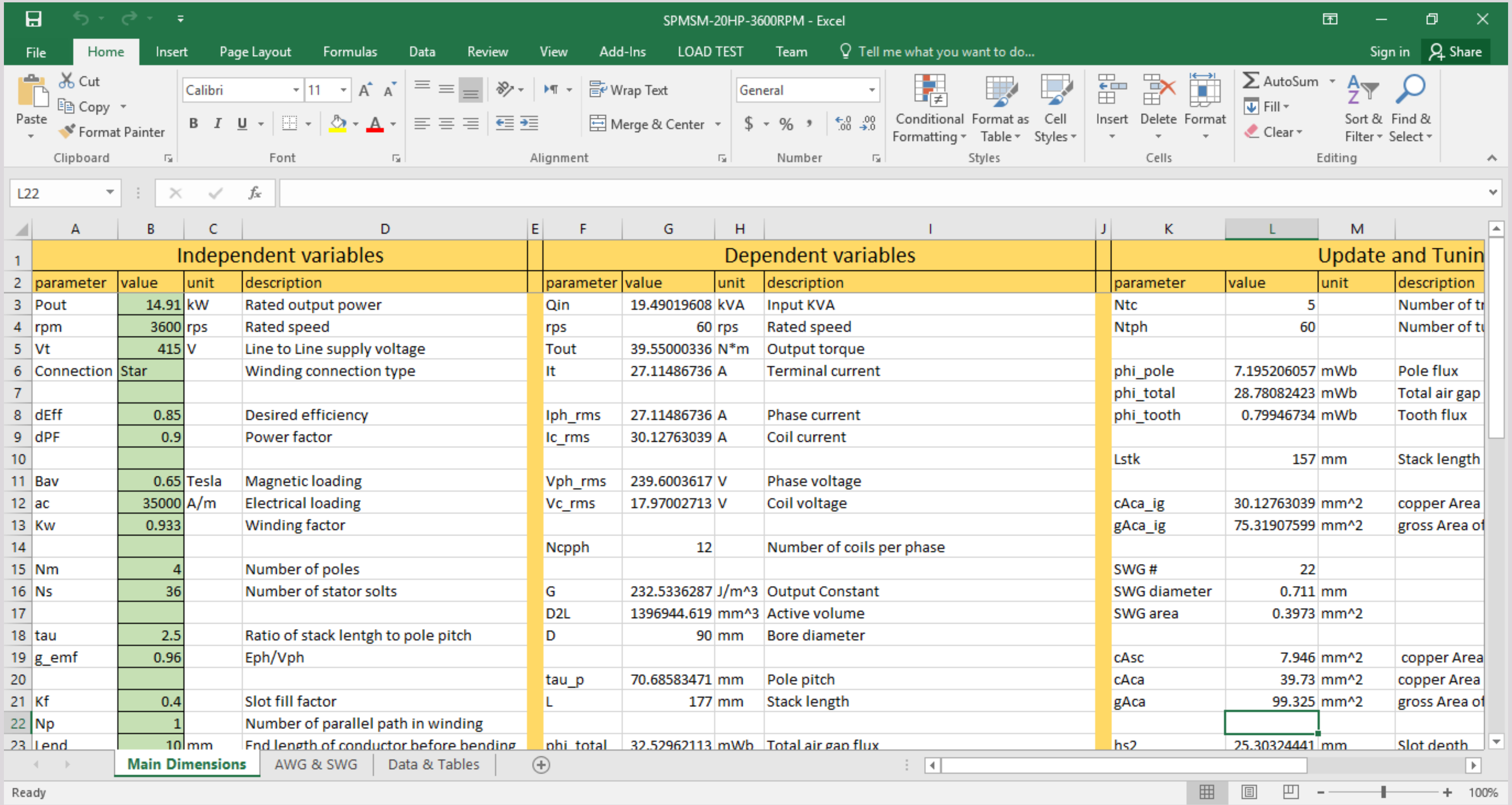
AUTOMATIC GENERATION OF FEA MODEL

Developing a MATLAB mfile for coupling excel file to ANSYS maxwell

Coupling Excel to ANSYS Maxwell



Developing Excel file



	A	B	C	D	F	G	H	I	K	L	M	N
1	Independent variables				Dependent variables				Update and Tunin			
2	parameter	value	unit	description	parameter	value	unit	description	parameter	value	unit	description
3	Pout	14.91	kW	Rated output power	Qin	19.49019608	kVA	Input KVA	Ntc	5		Number of tr
4	rpm	3600	rps	Rated speed	rps	60	rps	Rated speed	Ntph	60		Number of tu
5	Vt	415	V	Line to Line supply voltage	Tout	39.55000336	N*m	Output torque				
6	Connection	Star		Winding connection type	It	27.11486736	A	Terminal current	phi_pole	7.195206057	mWb	Pole flux
7									phi_total	28.78082423	mWb	Total air gap
8	dEff	0.85		Desired efficiency	Iph_rms	27.11486736	A	Phase current	phi_tooth	0.79946734	mWb	Tooth flux
9	dPF	0.9		Power factor	Ic_rms	30.12763039	A	Coil current				
10									Lstk	157	mm	Stack length
11	Bav	0.65	Tesla	Magnetic loading	Vph_rms	239.6003617	V	Phase voltage				
12	ac	35000	A/m	Electrical loading	Vc_rms	17.97002713	V	Coil voltage	cAca_ig	30.12763039	mm^2	copper Area
13	Kw	0.933		Winding factor					gAca_ig	75.31907599	mm^2	gross Area of
14					Ncpph	12		Number of coils per phase				
15	Nm	4		Number of poles					SWG #	22		
16	Ns	36		Number of stator solts	G	232.5336287	J/m^3	Output Constant	SWG diameter	0.711	mm	
17					D2L	1396944.619	mm^3	Active volume	SWG area	0.3973	mm^2	
18	tau	2.5		Ratio of stack lentgh to pole pitch	D	90	mm	Bore diameter				
19	g_emf	0.96		Eph/Vph					cAsc	7.946	mm^2	copper Area
20					tau_p	70.68583471	mm	Pole pitch	cAca	39.73	mm^2	copper Area
21	Kf	0.4		Slot fill factor	L	177	mm	Stack length	gAca	99.325	mm^2	gross Area of
22	Np	1		Number of parallel path in winding								
23	Lend	10	mm	End length of conductor before bending	phi_total	32.52962113	mWb	Total air gap flux	hs2	25.30324441	mm	Slot depth

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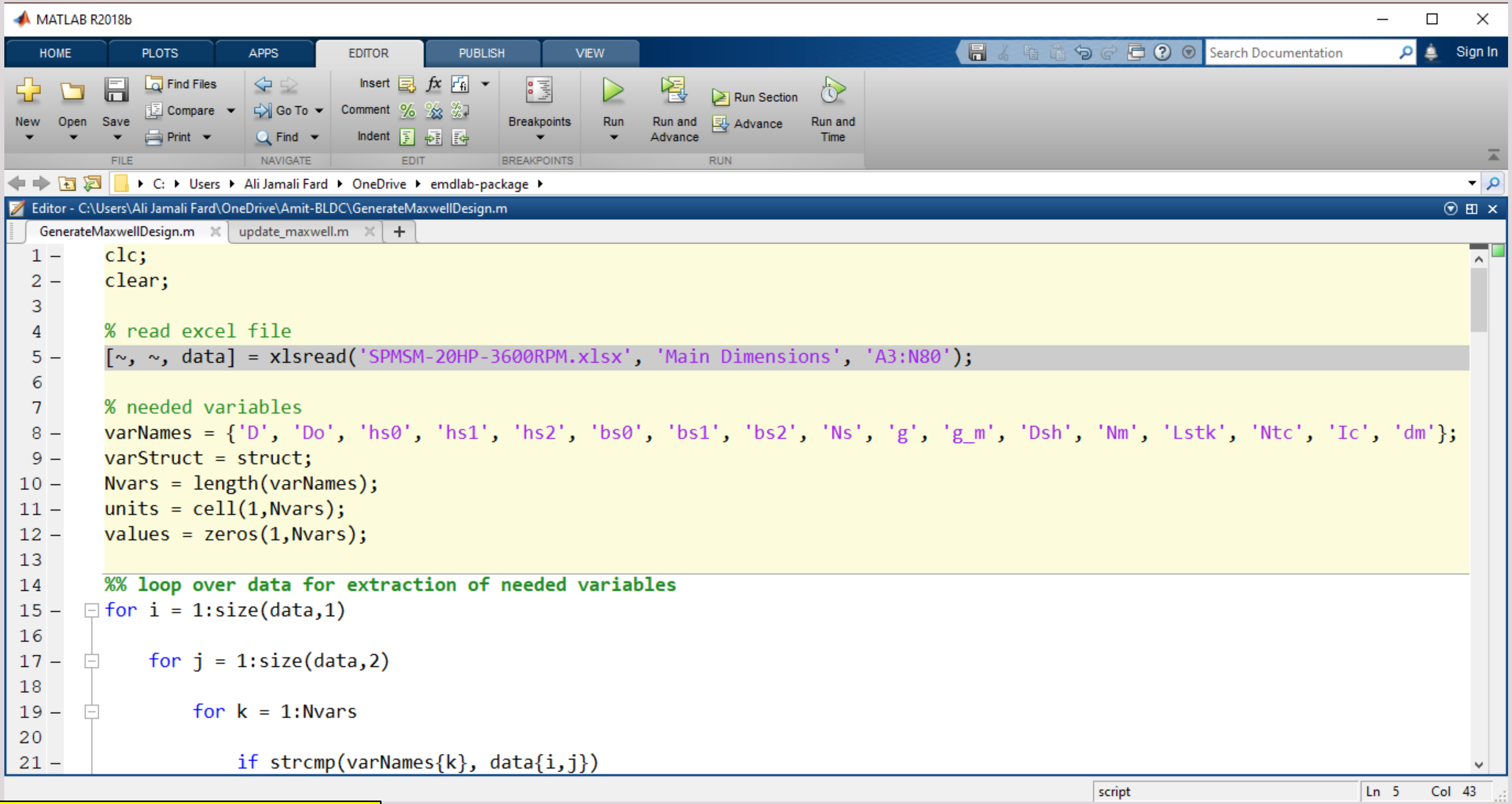
Developing Matlab script for auto generation of vbs file



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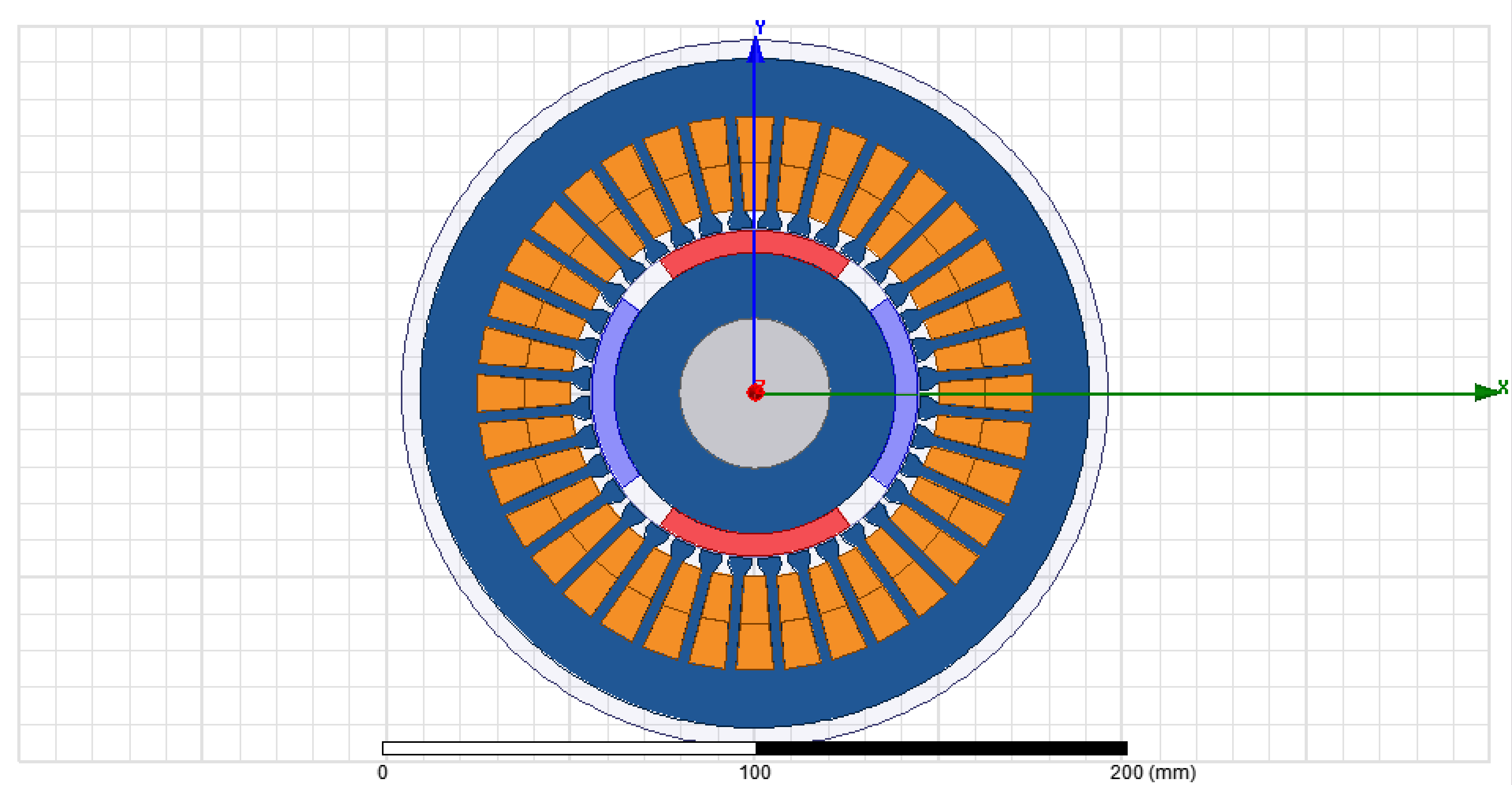
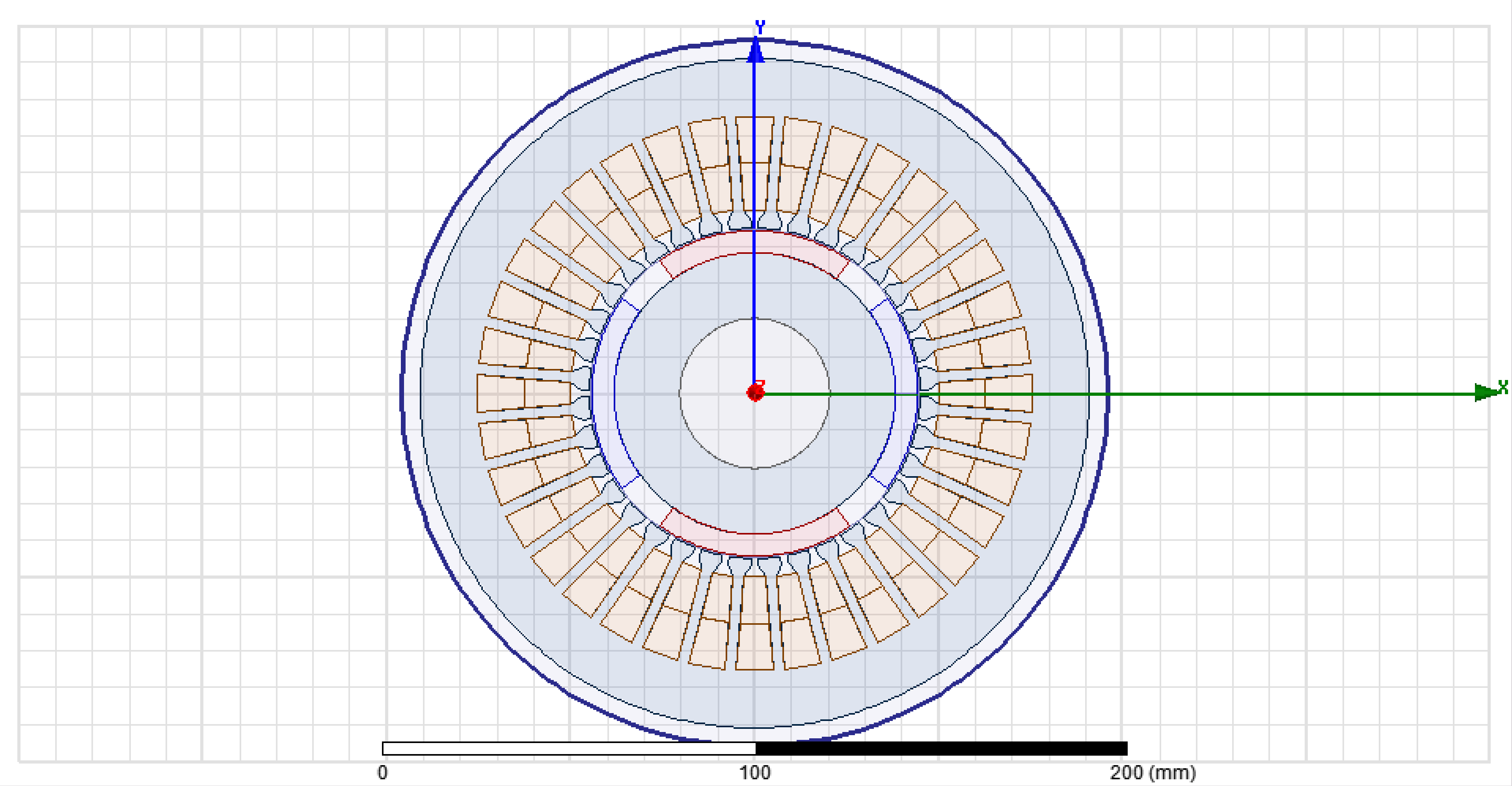
FINITE ELEMENT ANALYSIS

FEA of machine and derivation of main characteristics

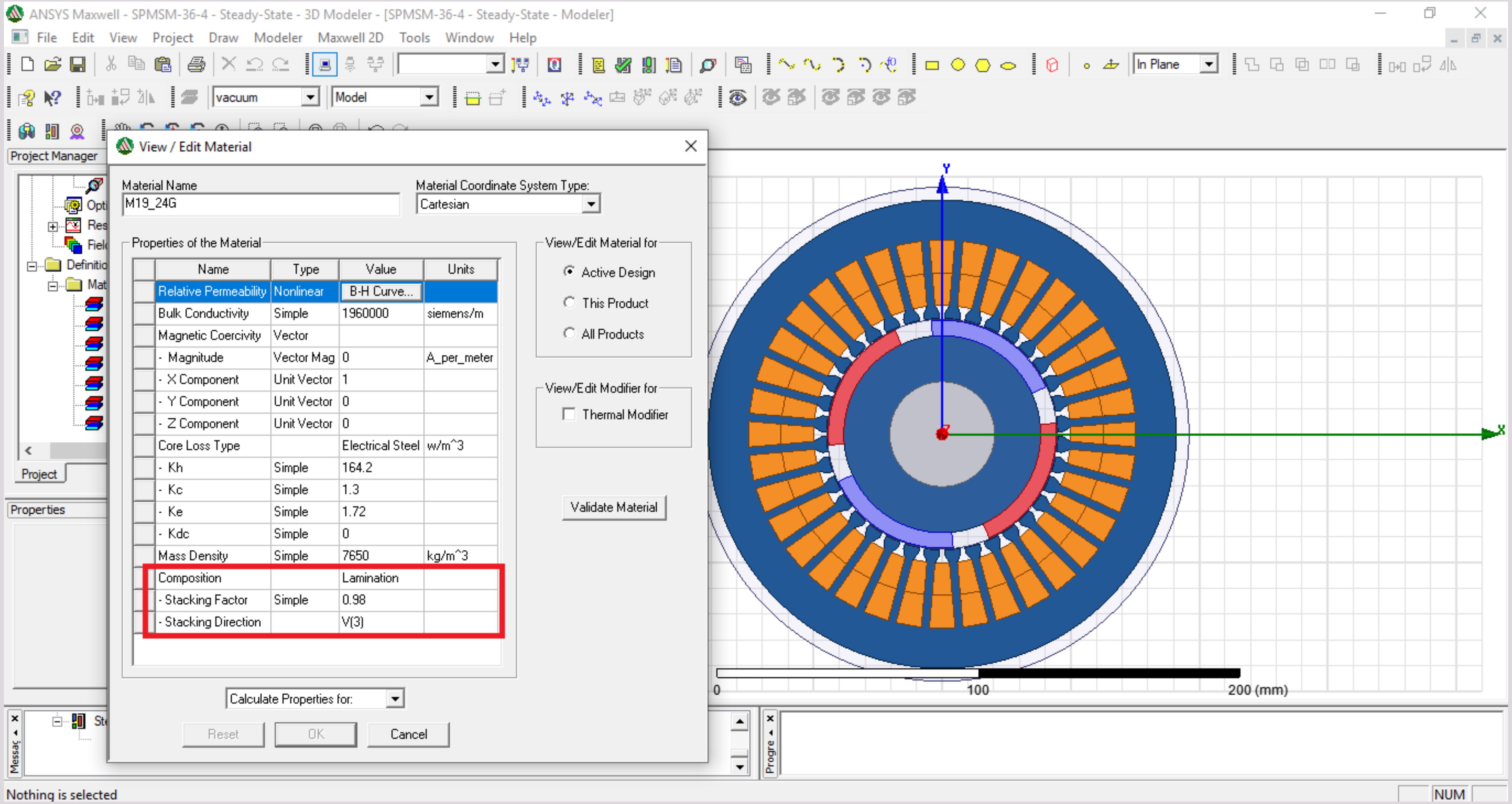
Motor sketch



Applying boundary condition (A=0)



Definition of steel material



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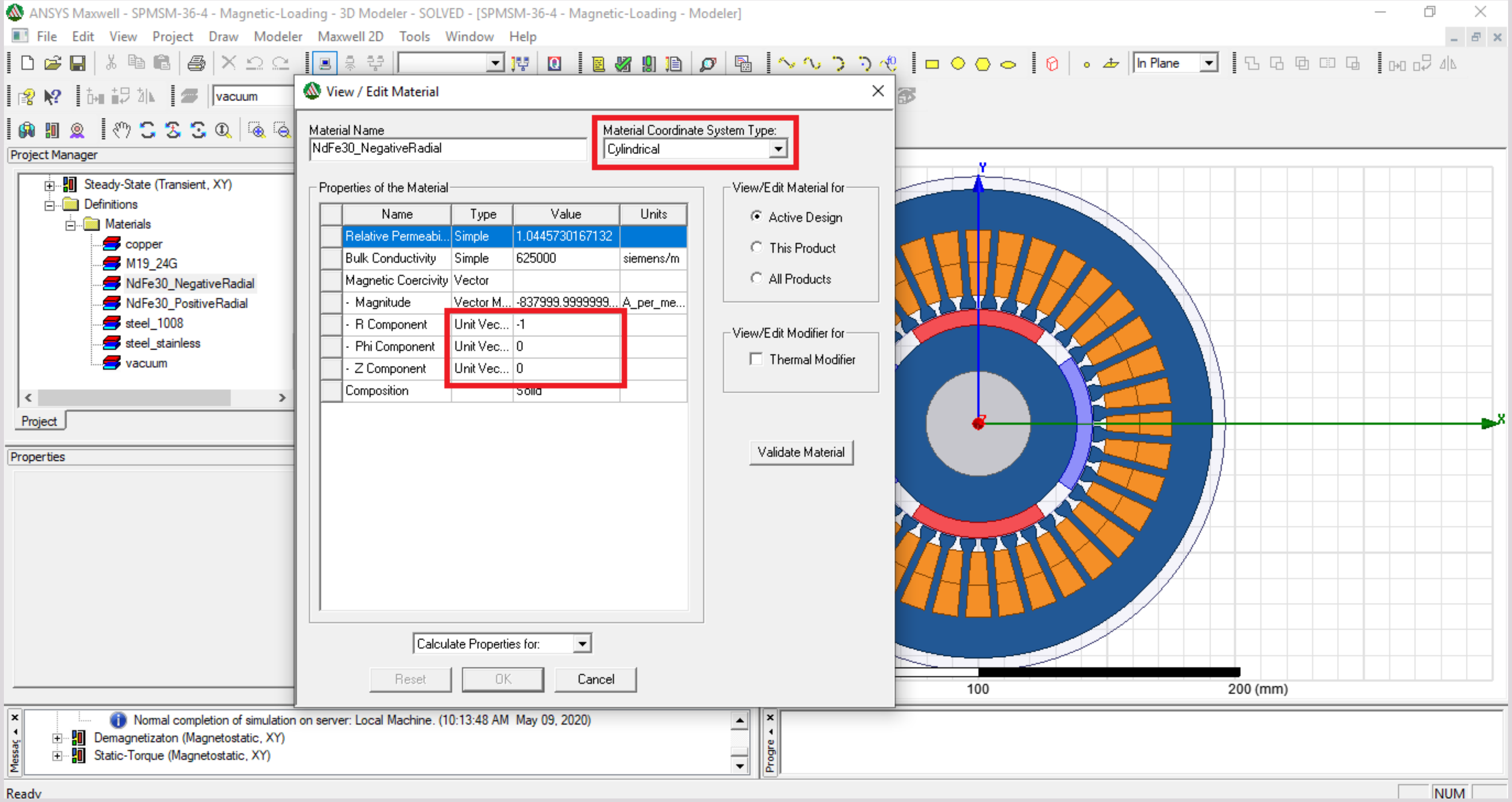
Definition of magnets



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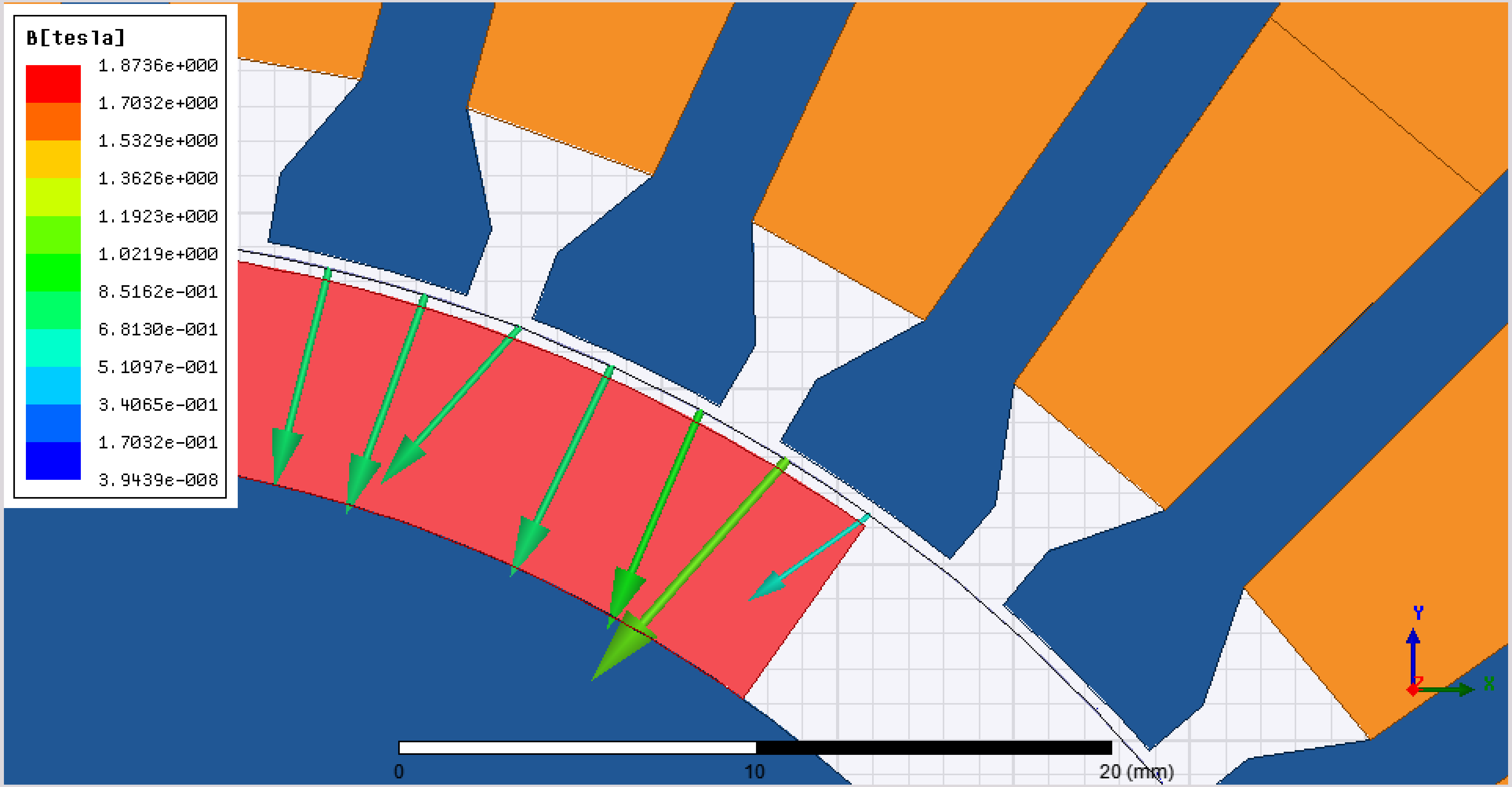
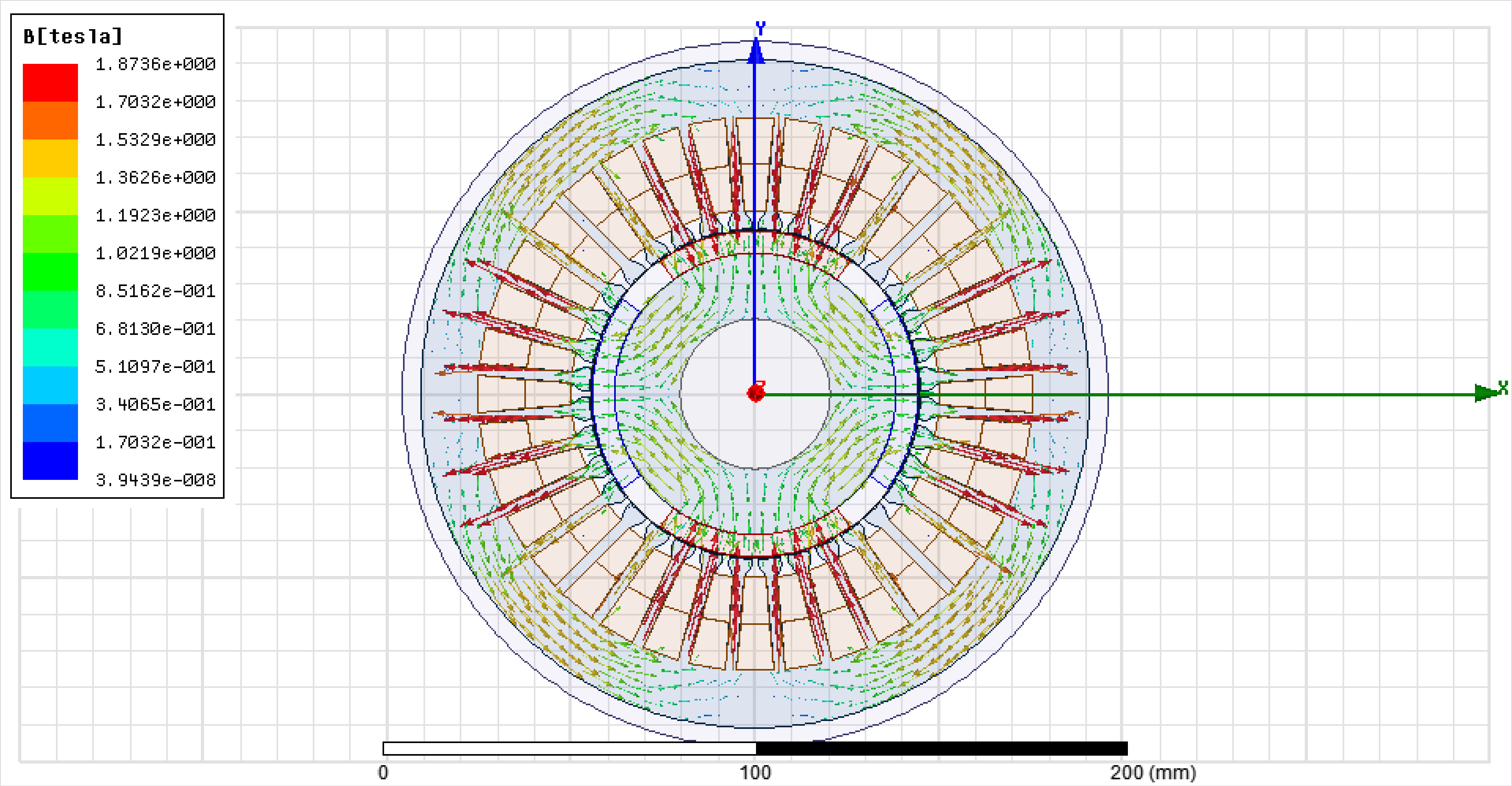
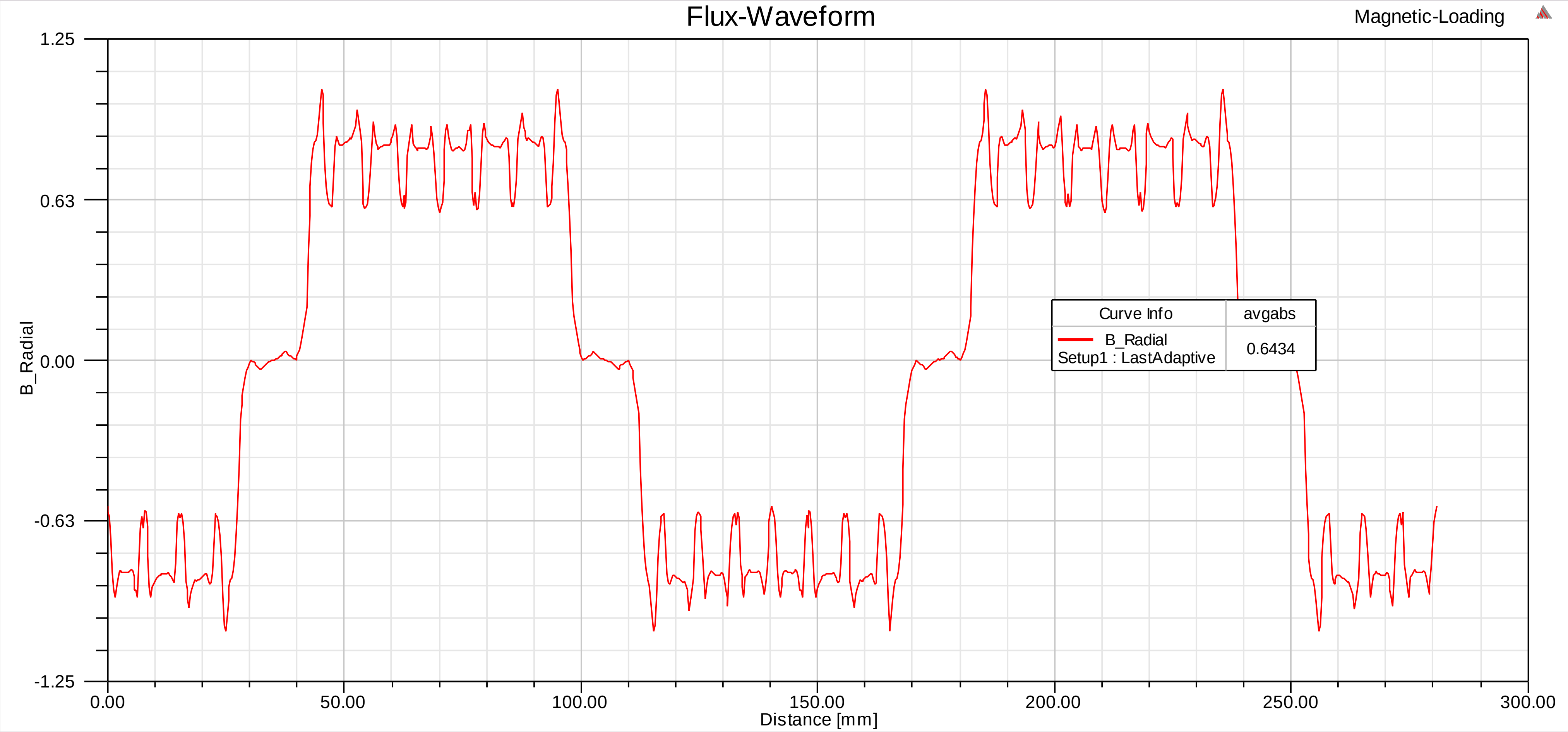
Calculation of magnetic loading (Bav)



Calculation of magnetic loading (finding proper magnet arc)



Calculation of magnetic loading (Bav)



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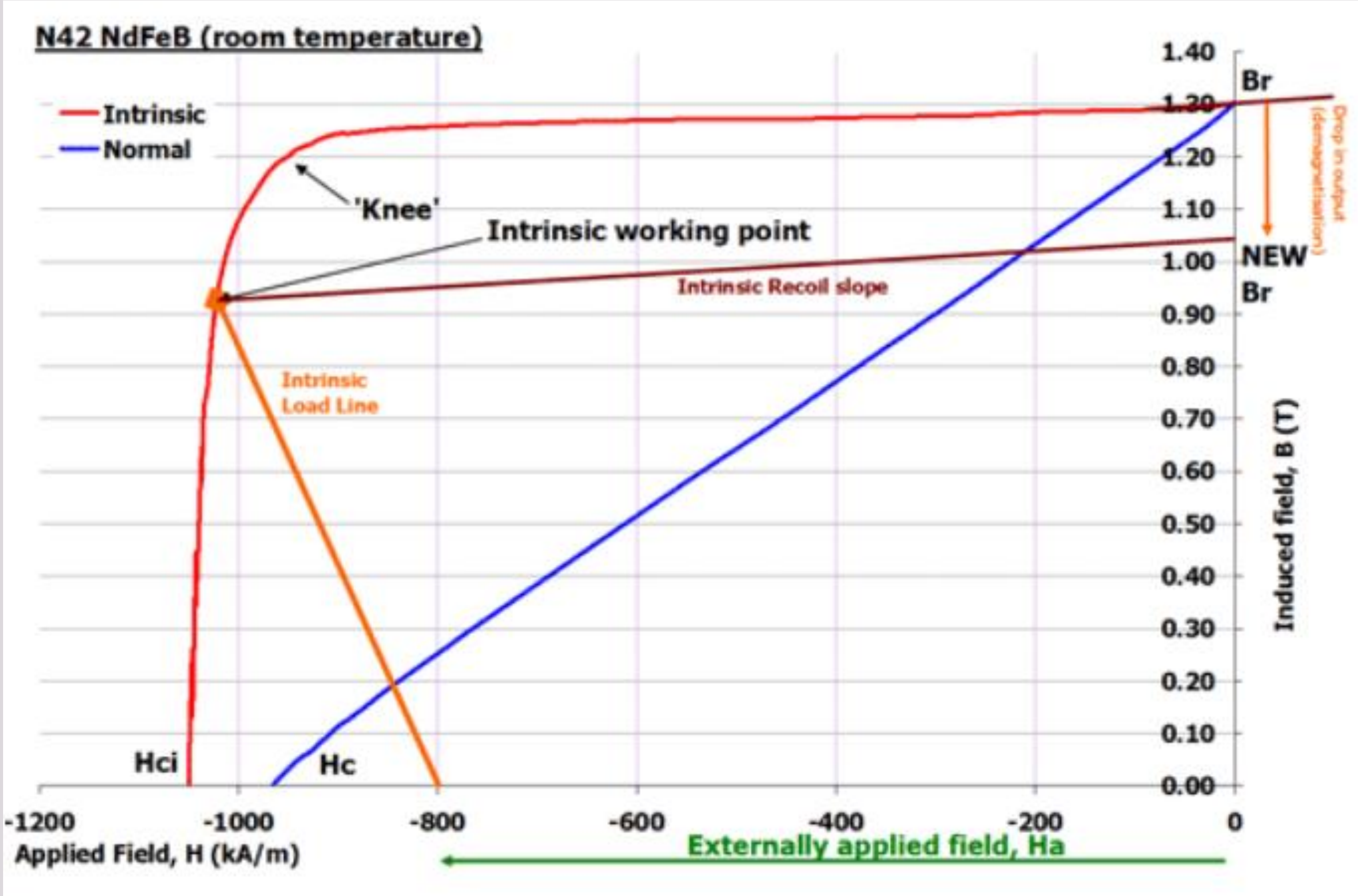
Demagnetization study (HB curve of magnet)



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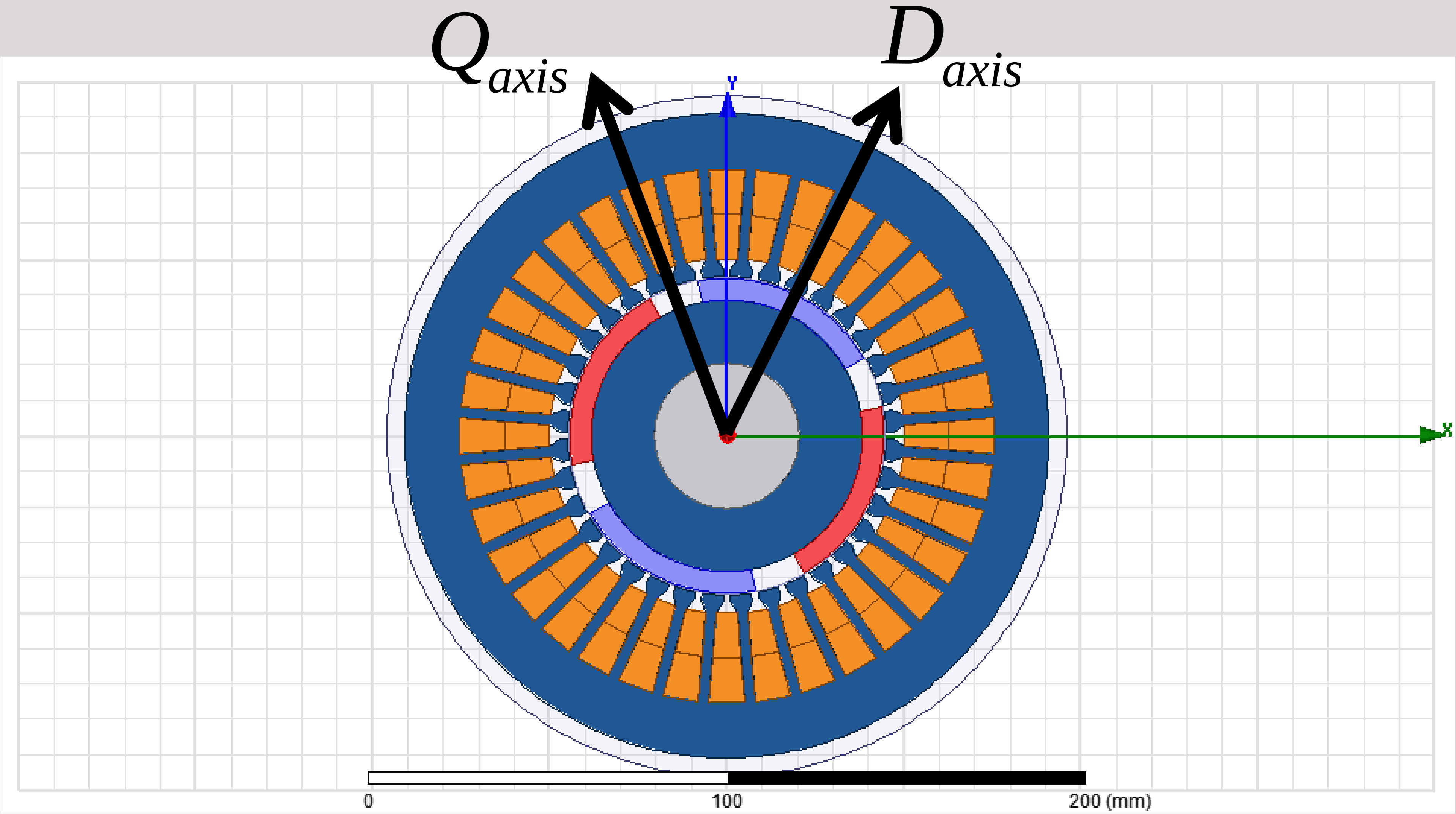
Demagnetization study (DQ reference frame of rotor)



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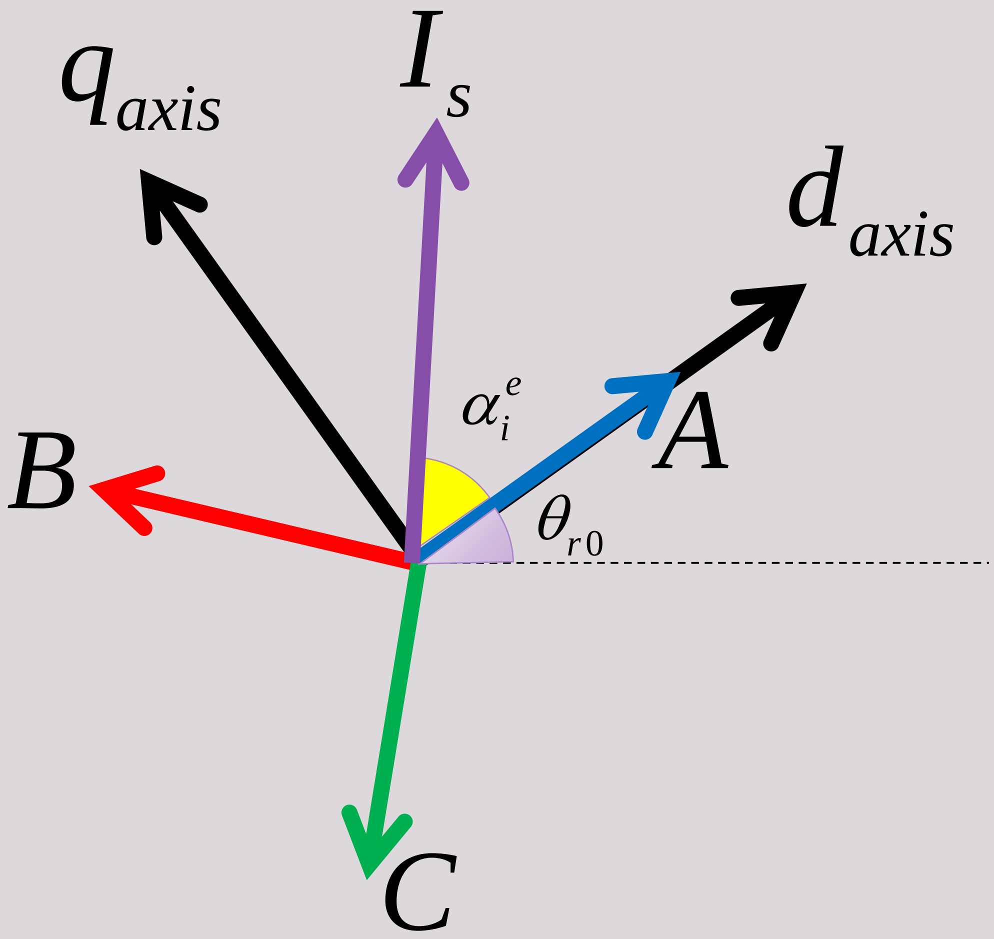
Demagnetization study (DQ reference frame of rotor)



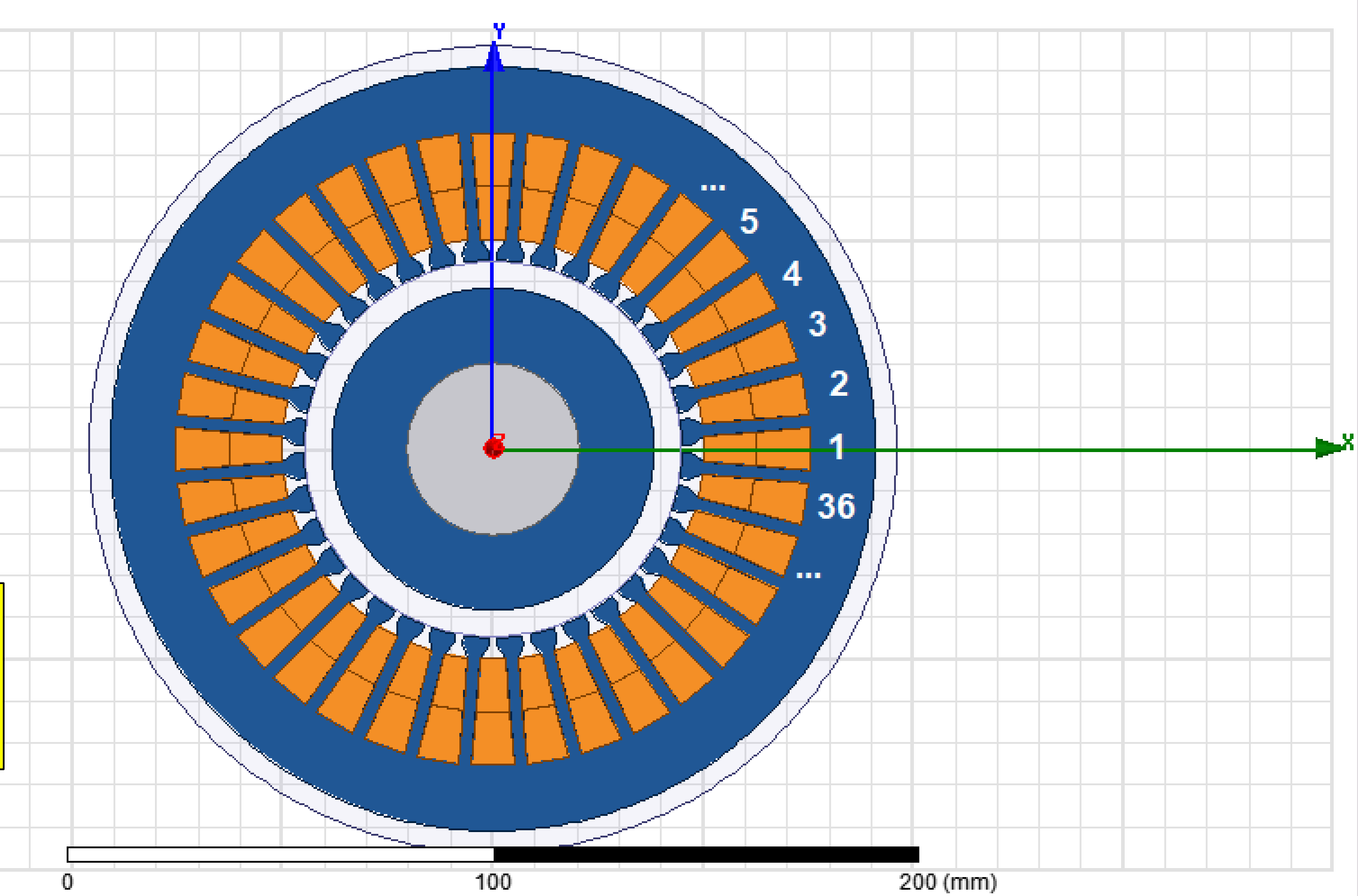
$$\begin{cases} i_{ds} = I_s \cos(\alpha_i^e) \\ i_{qs} = I_s \sin(\alpha_i^e) \end{cases}$$

$$\begin{cases} i_a = i_{ds} \\ i_b = -\dfrac{1}{2} i_{ds} + \dfrac{\sqrt{3}}{2} i_{qs} \\ i_c = -\dfrac{1}{2} i_{ds} - \dfrac{\sqrt{3}}{2} i_{qs} \end{cases}$$

Definition of stator winding

$$N_{cpph} = \frac{36}{3} = 12$$

$$q = \frac{N_s}{m \times p} = \frac{36}{3 \times 4} = 3$$



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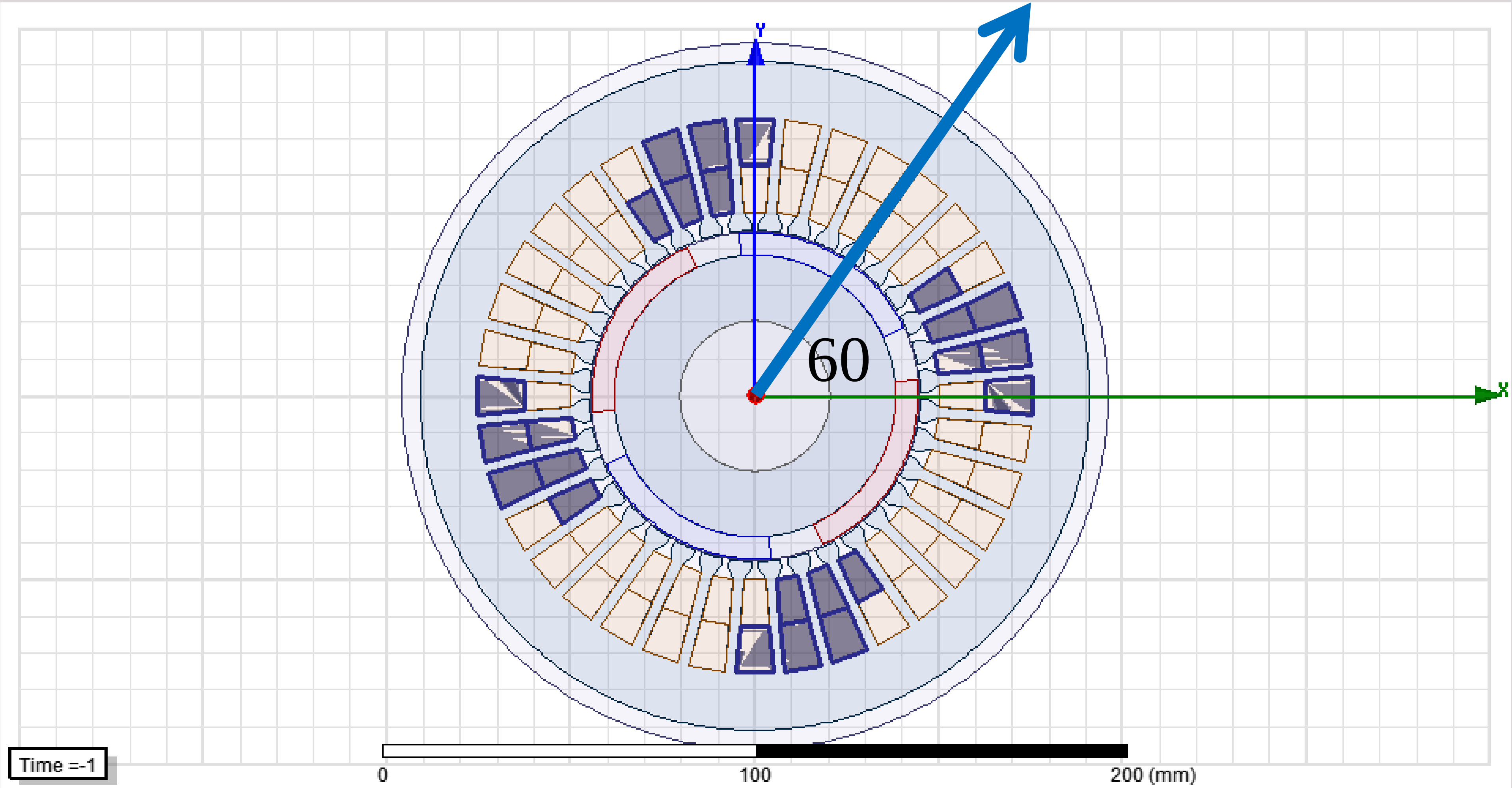
Finding magnetic axis of phase A



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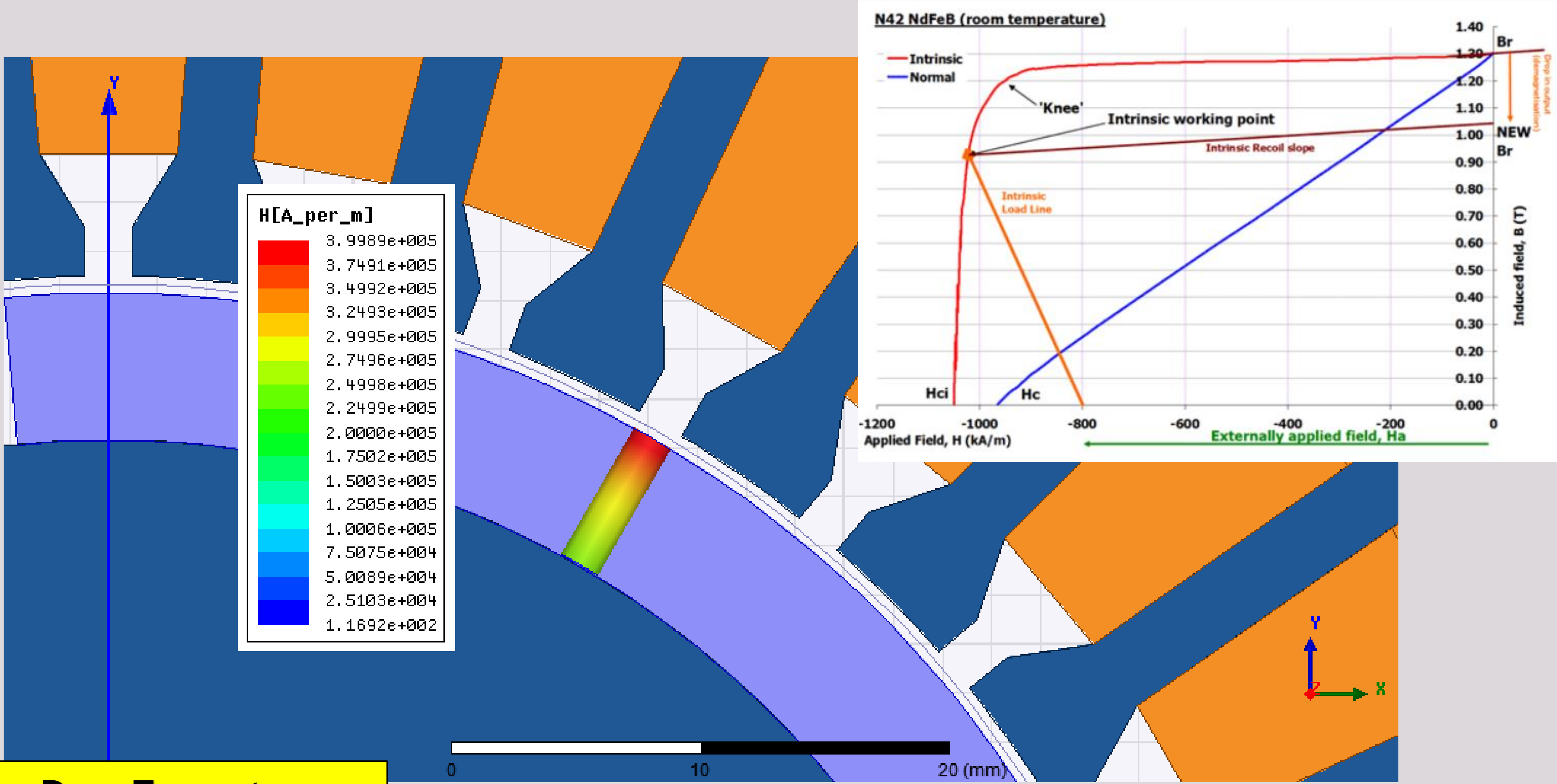
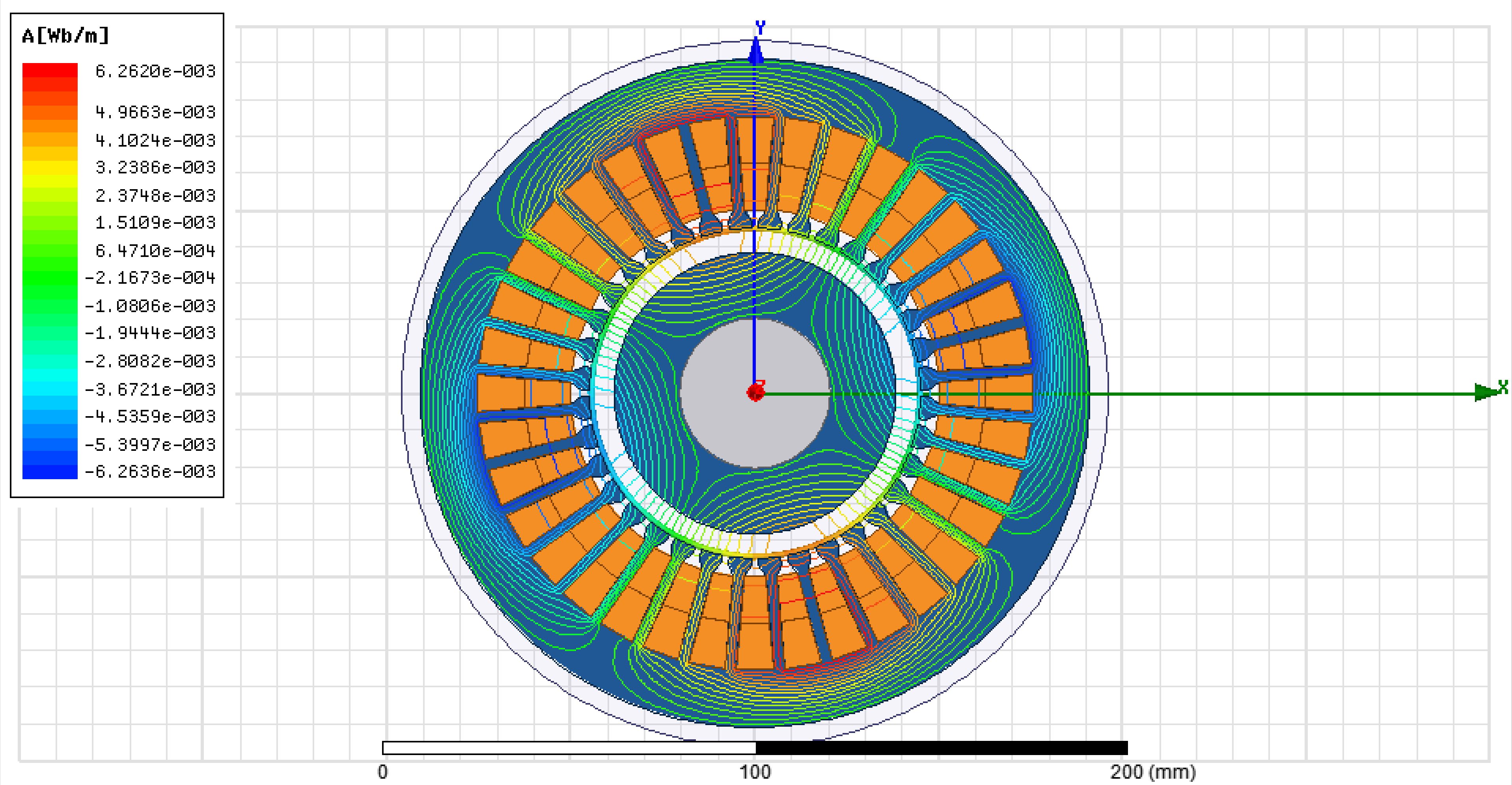
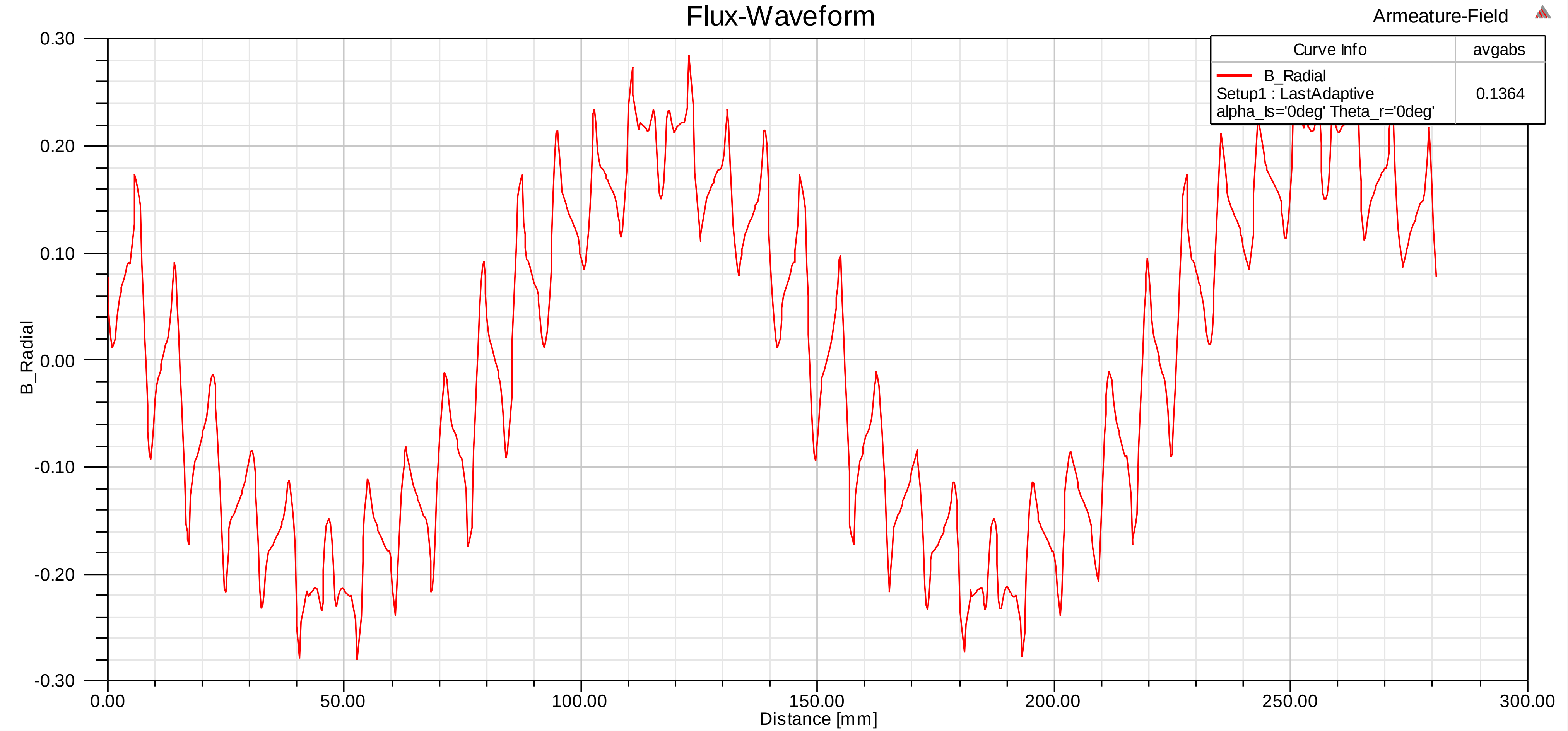
Demagnetization study



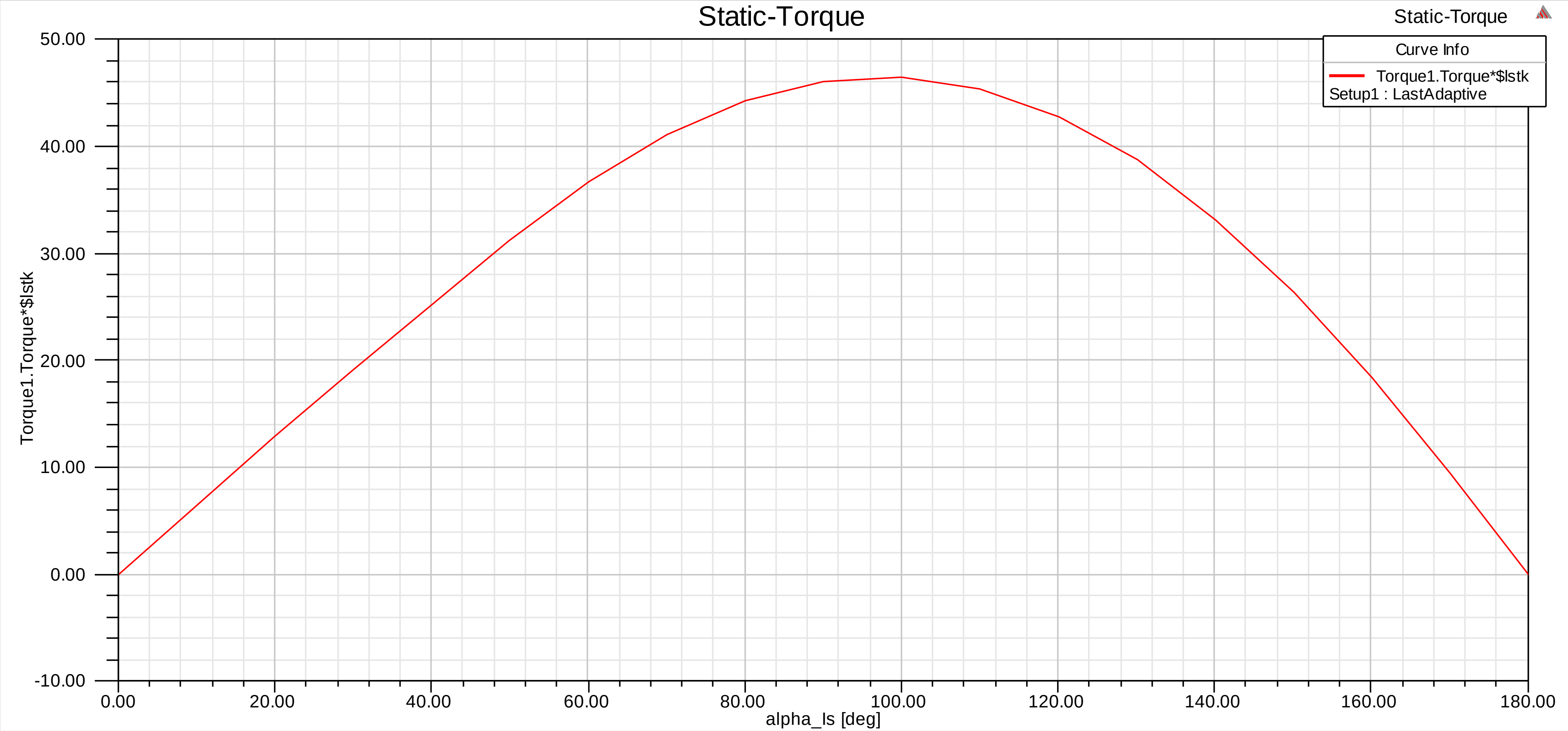
Calculation of armature field



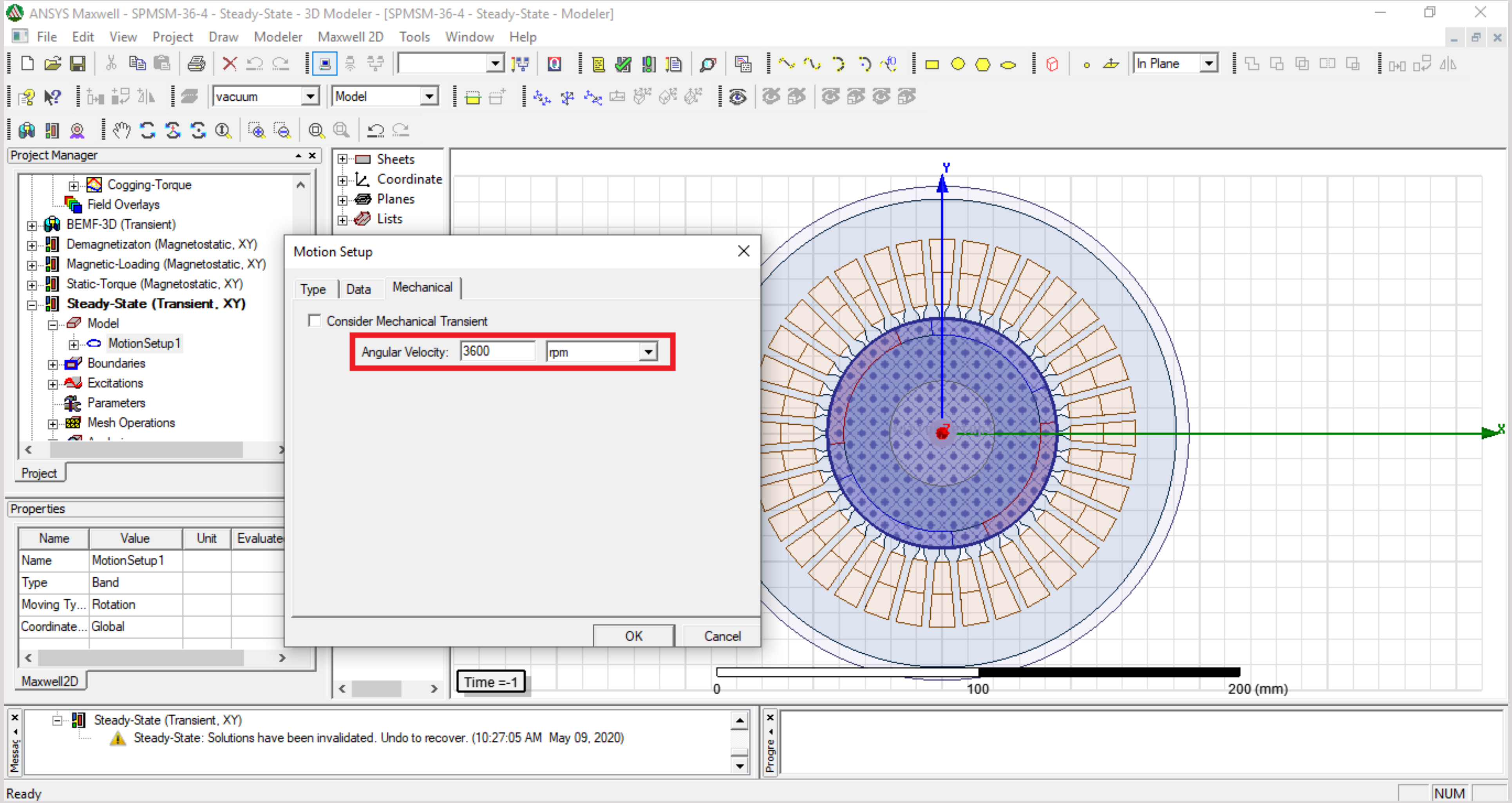
Calculation of armature field



Calculation of static torque



Calculation of BEMFs (motion setup)



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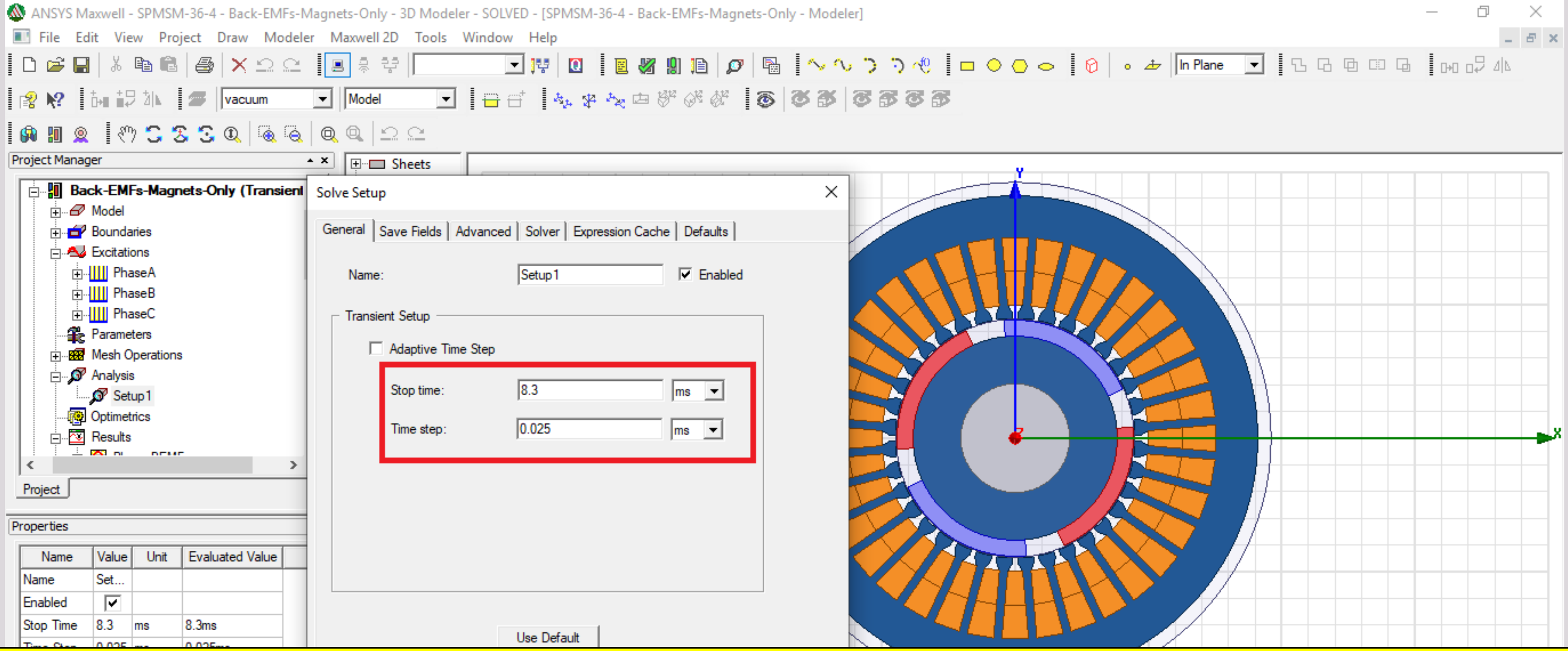
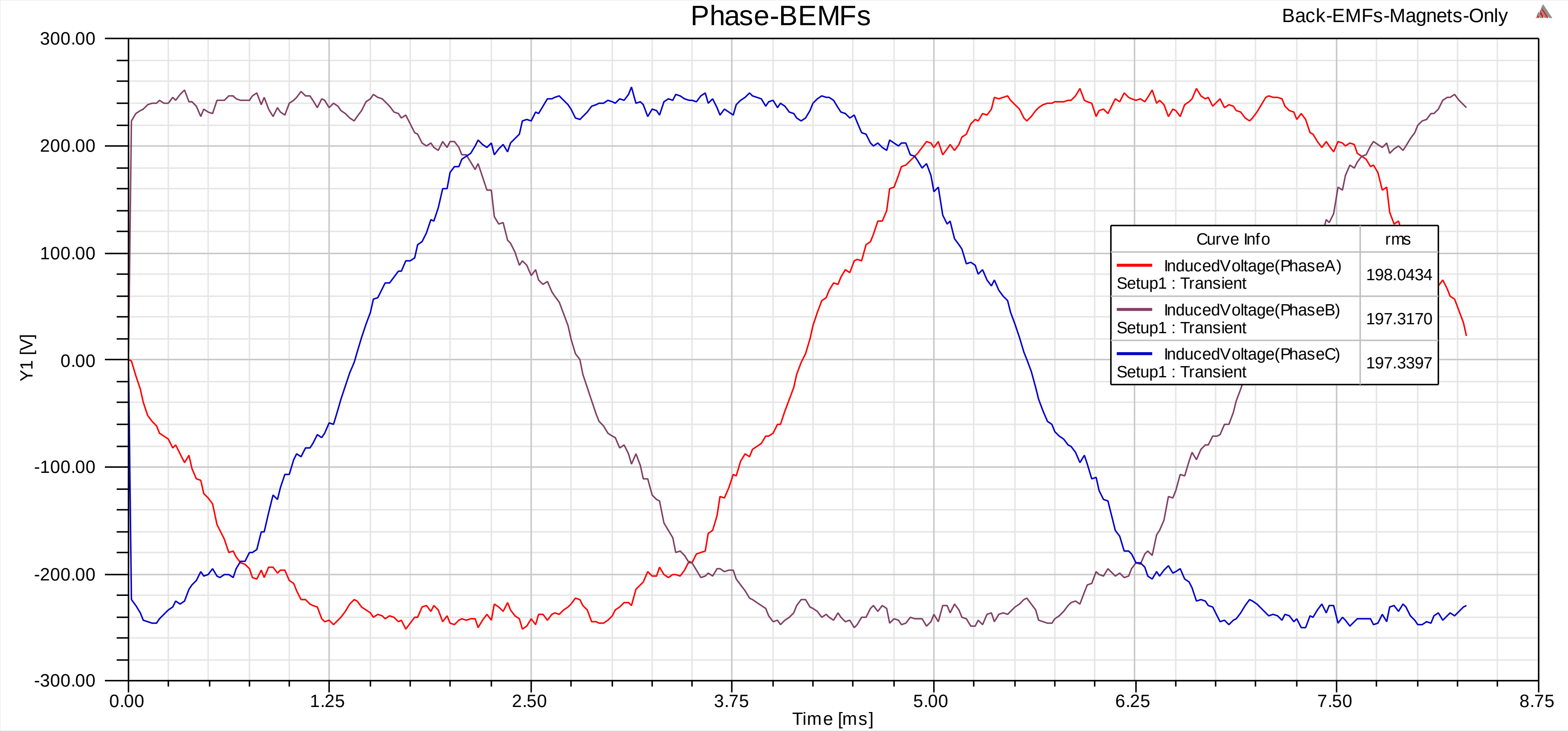
Calculation of BEMFs (setting of simulation time)



$$\theta_r = \omega_m t \Rightarrow t = \frac{\theta_r}{\omega_m} = \frac{2\times(2\pi / p)}{2\pi \times rps} = \frac{2\times 10^3}{p\times rps}[ms] = \frac{2\times 10^3}{4\times 60} \approx 8.3[ms]$$

https://ComProgExpert.com

Phase back EMFs



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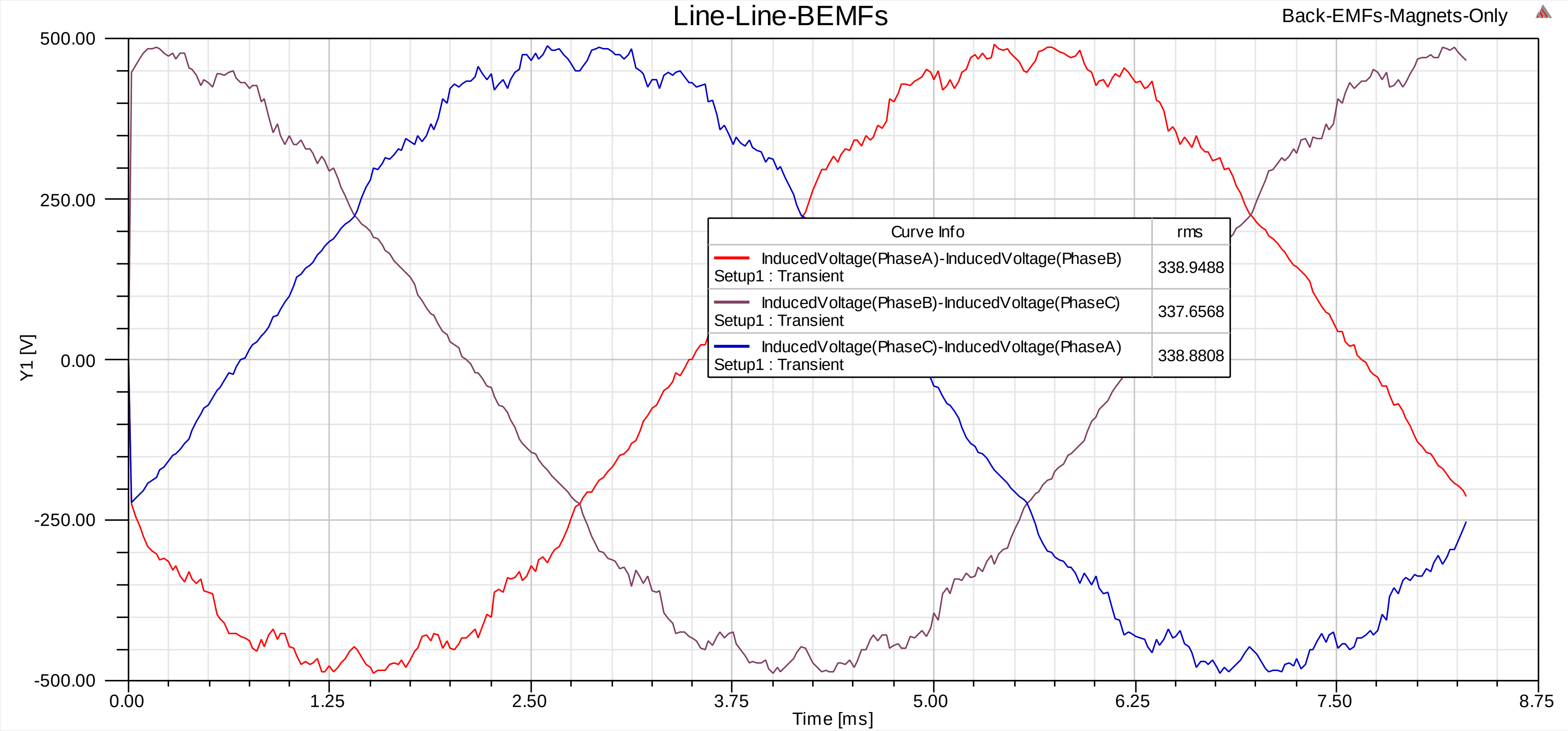
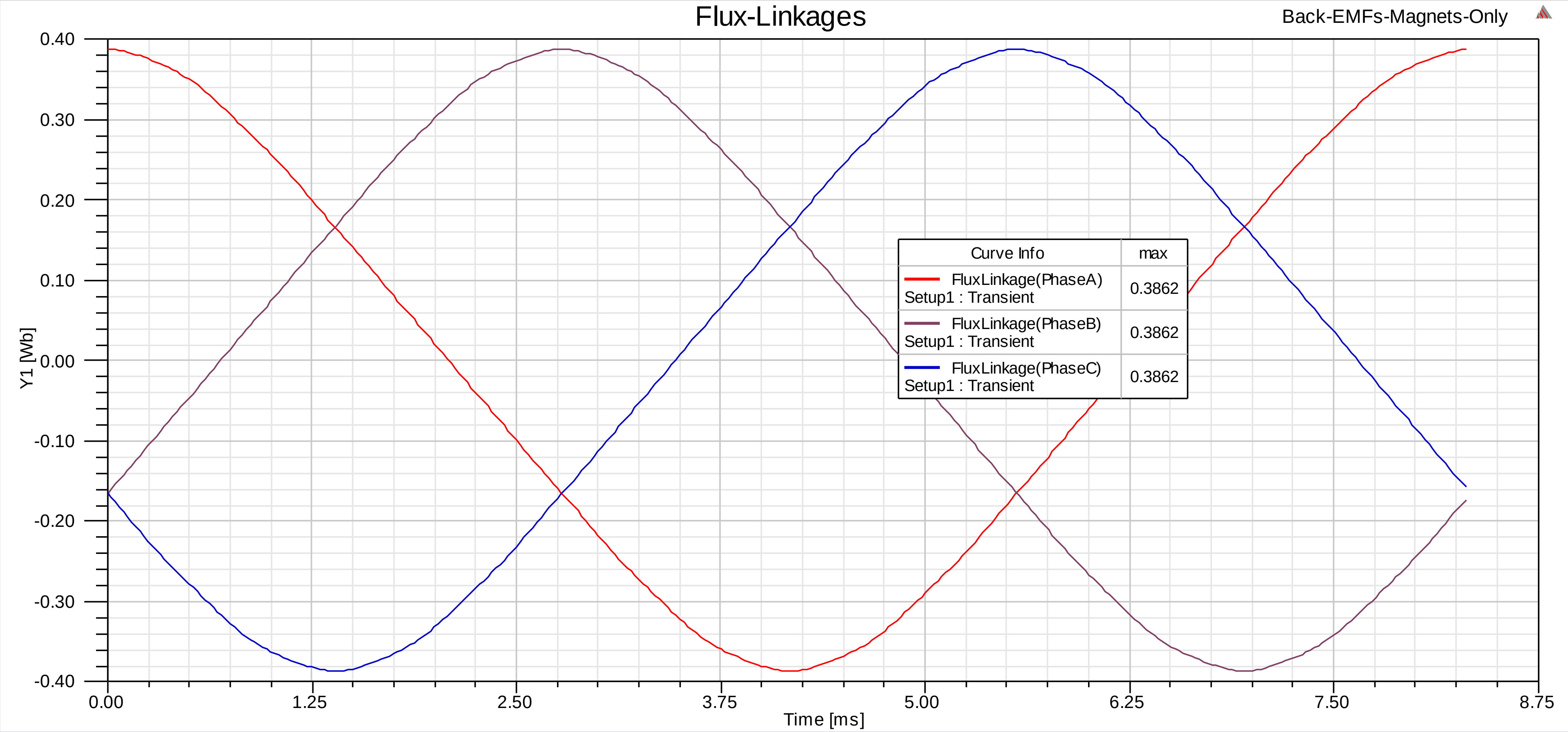
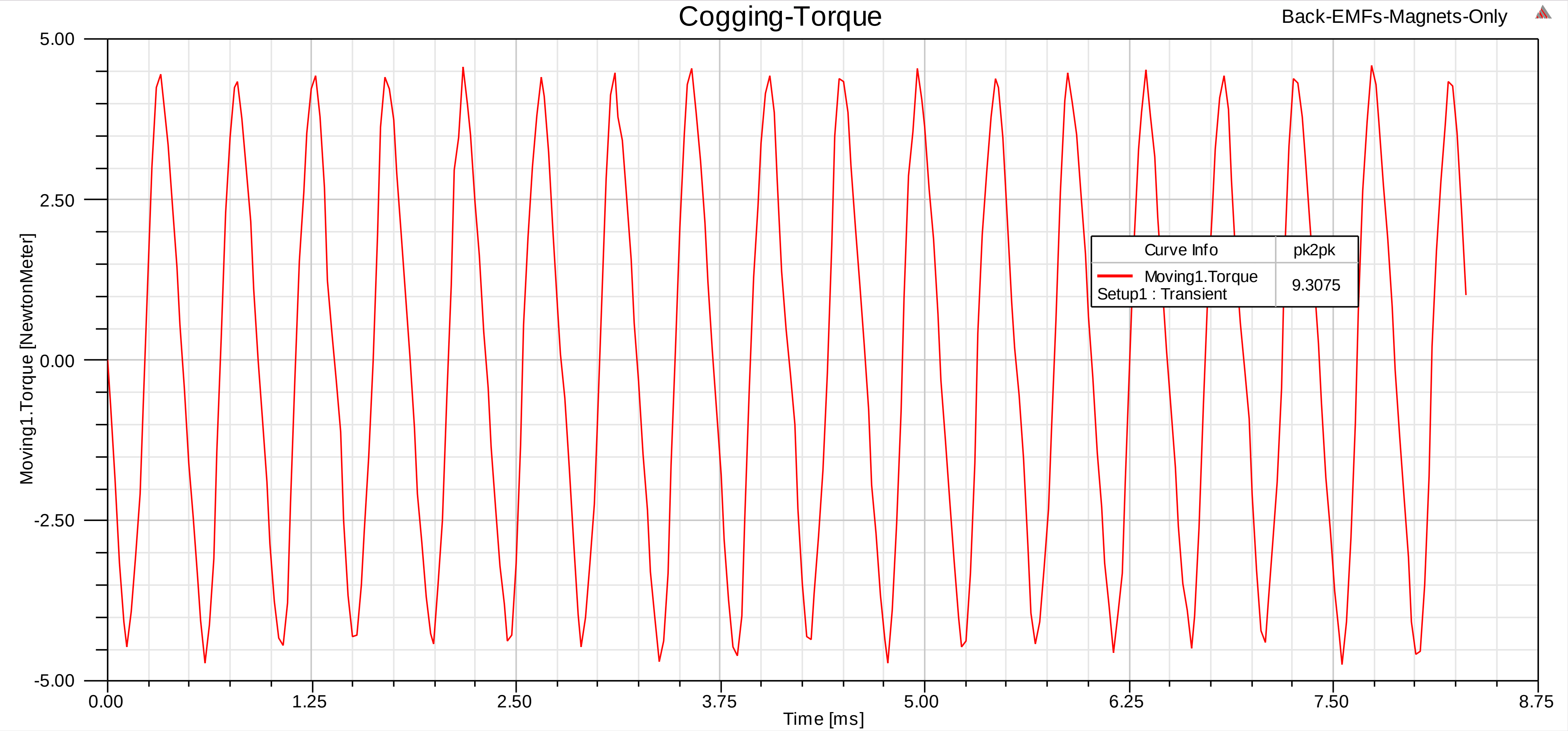
Line-to-Line back EMFs



Phase flux linkages



Cogging torque



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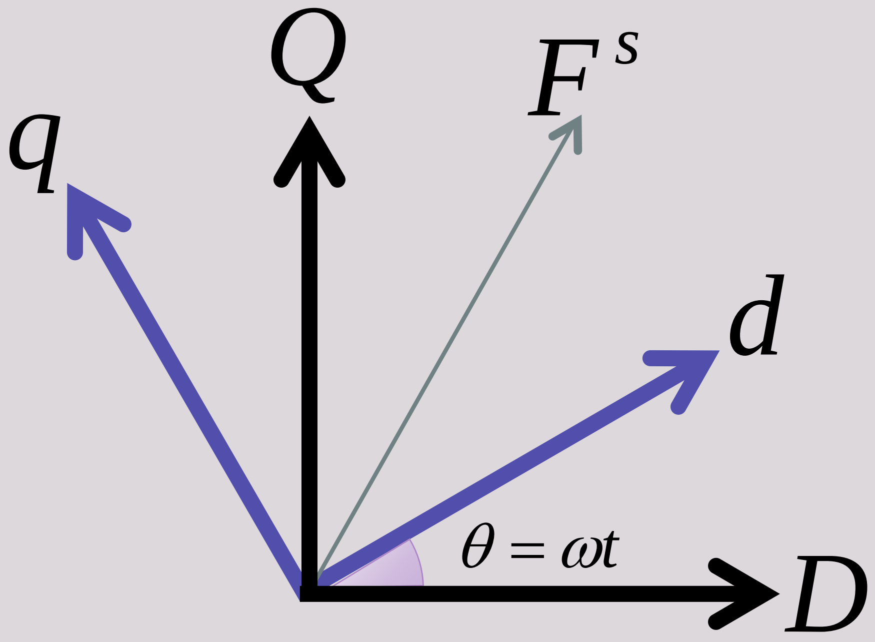
Rotor reference frame quantities



$$F^s = Fe^{j\theta_s}$$

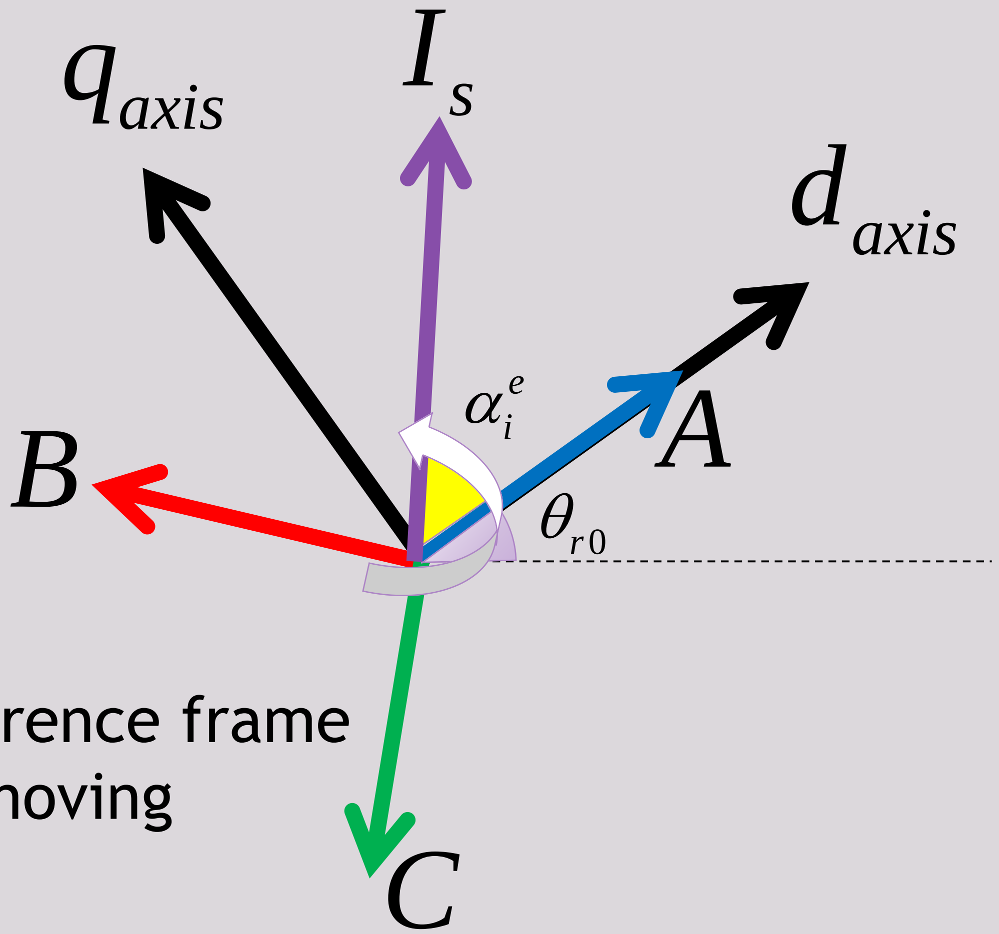
$$F^r = Fe^{j\theta_r} = Fe^{j(\theta_s - \omega t)}$$

$$F^r = F^s e^{-j\omega t}$$

$$F^r = \left(F_d^s + jF_q^s\right) \times \left(\cos\left(\omega t\right) - j\sin\left(\omega t\right)\right)$$

$$\boxed{\begin{cases} F_d^r = F_d^s \cos\left(\omega t\right) + F_q^s \sin\left(\omega t\right) \\ F_q^r = -F_d^s \sin\left(\omega t\right) + F_q^s \cos\left(\omega t\right) \end{cases}}$$

Steady state simulation



Rotor reference frame is moving

Is set for coinciding rotor Daxis and magnetic axis of phase A at start

Mechanical degree

$$\boxed{\theta_{rM} = \omega_m t + \theta_{r0}}$$

$$\omega_m = 2 \times \pi \times rps = 2 \times \pi \times 60$$

$$\boxed{\theta_{rE} = \frac{p}{2}\theta_{rM}}$$

$$\alpha_i^e = 80\deg + 2 \times \pi \times 60 \times \frac{4}{2} \times time$$

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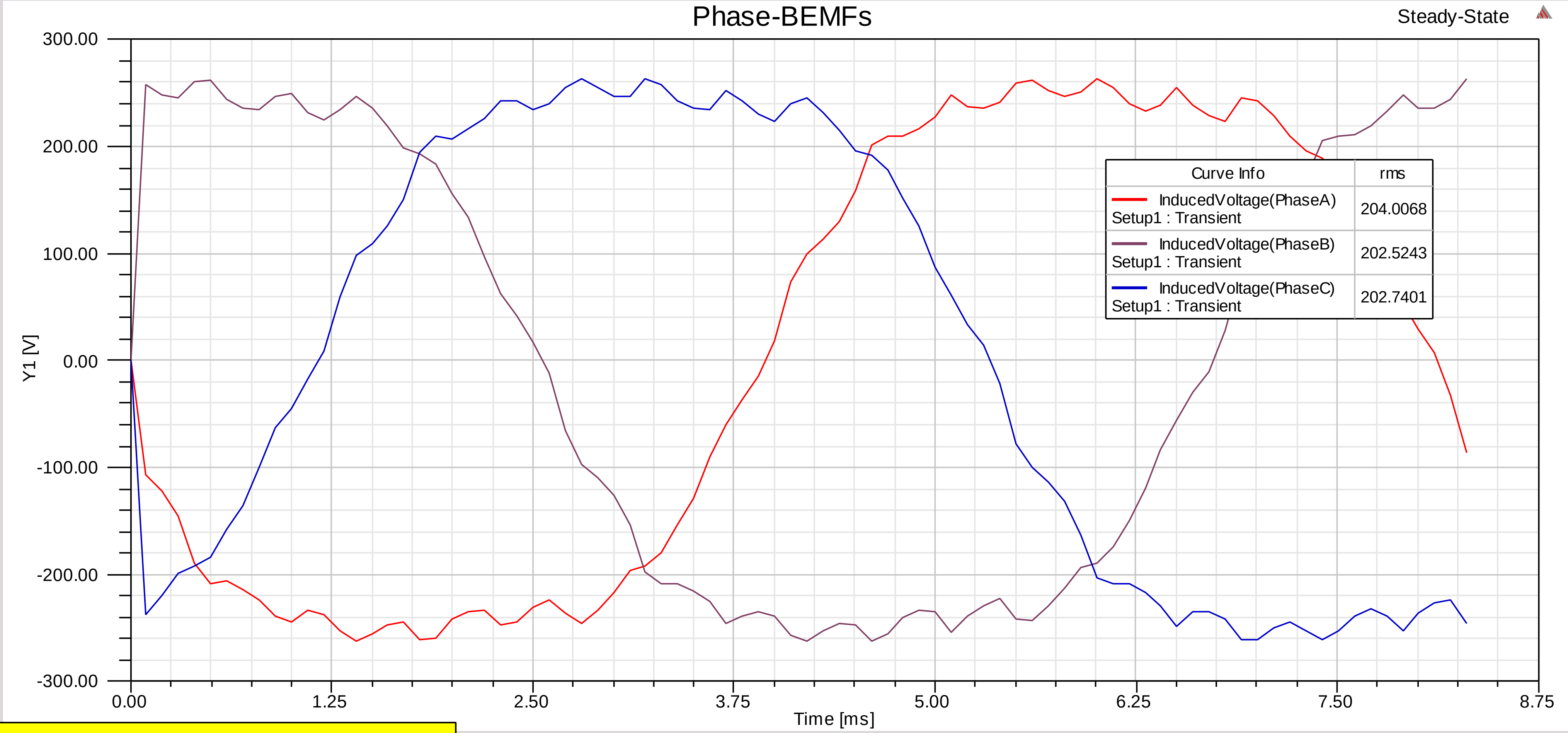
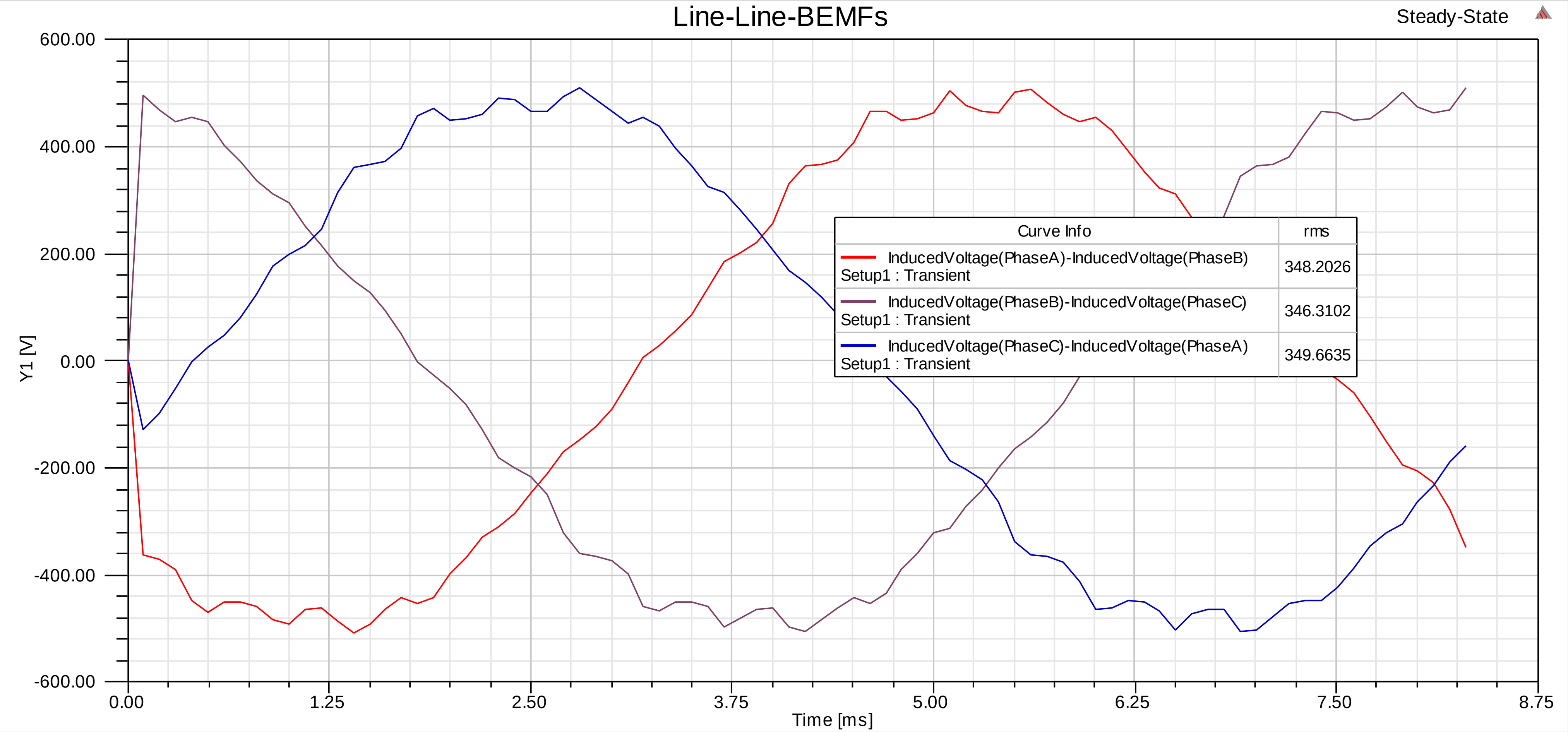
Phase induced voltage



Line-to-Line induced voltage



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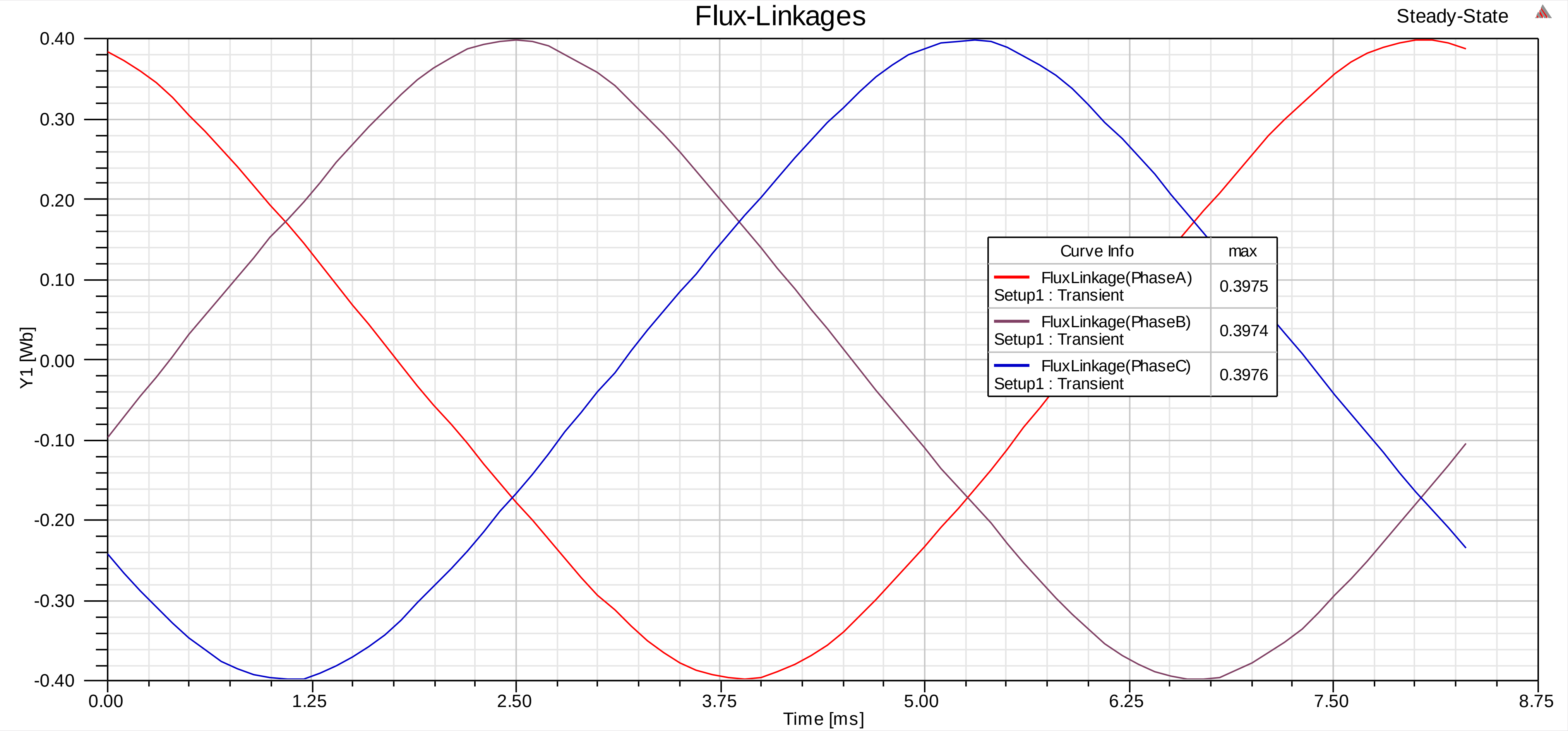
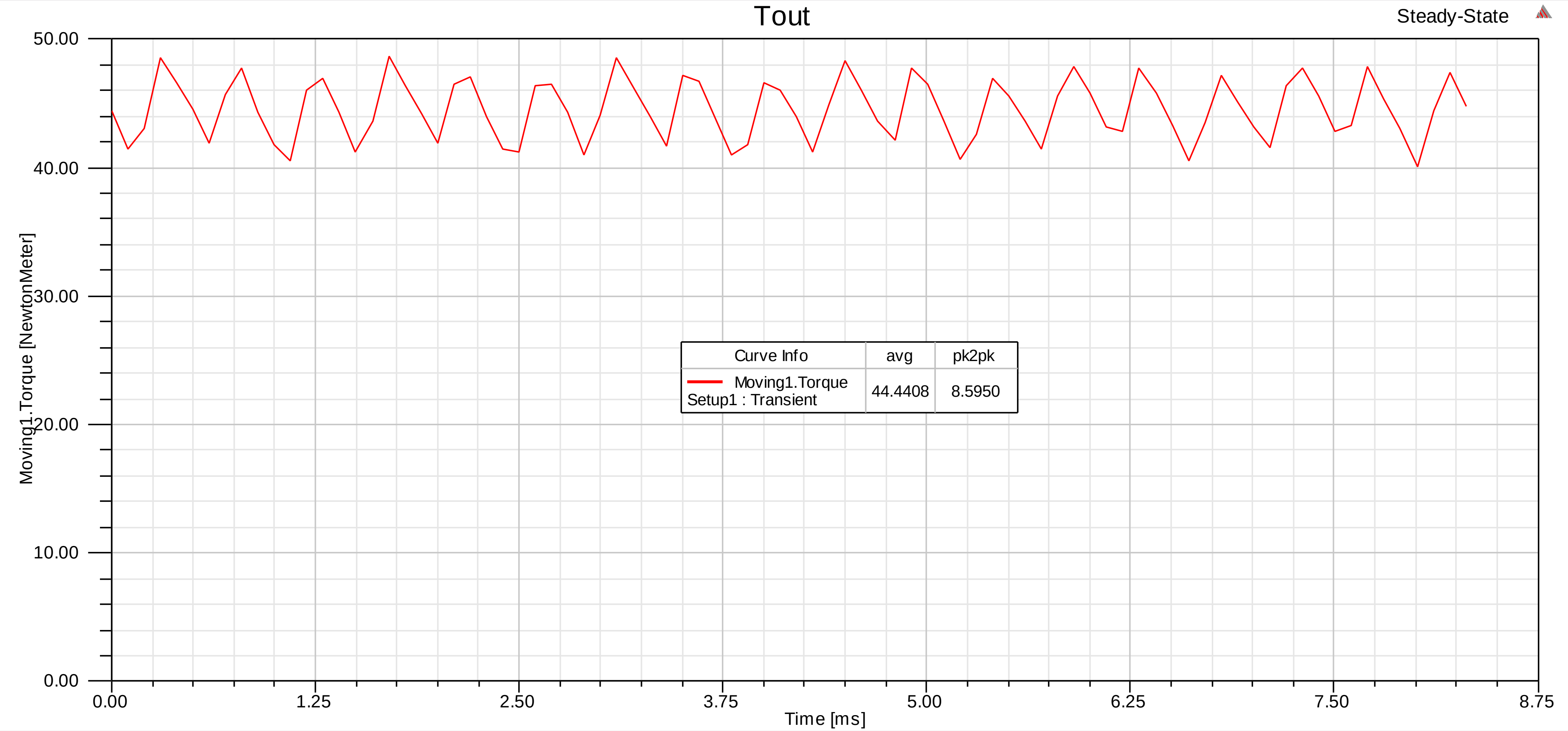
Phase Flux linkages



Steady state torque



3D Skew analysis for reduction of cogging torque

$$\theta_{skew} = 10\,\text{deg}$$