Created in COMSOL Multiphysics 6.0

Permanent Magnet Motor in 2D

Introduction

This tutorial model shows how to set up a 3-phase permanent magnet motor simulation in 2D, using motor parts that are available in the AC/DC Module Part Library. The model consists of three studies. First, a stationary study solves the problem at direct current, through the angular span of one pole pair, using Arkkio's method to calculate the rotor torque. Then, by specifying the initial mechanical angle to yield maximum torque, a transient study solves the time-dependent problem for a complete electrical period, and calculates the results for torque ripple and radial magnetic flux density. Finally, using the results from the transient study, the loss density in the stator iron is calculated with a frequency domain study.

Modeling

This model is set up in 2D and simulates the cross section on the rotational axis of the PM motor. The relevant equation is

$$\nabla \times \left(\frac{1}{\mu}\nabla \times \mathbf{A}\right) = \mathbf{J}$$

where $\mathbf{A}$ is the magnetic vector potential which defines the magnetic flux density $\mathbf{B} = \nabla \times \mathbf{A}$, $\mathbf{J}$ is the current density, and μ is the magnetic permeability. The equation is solved for the out-of-plane vector component only, which implies that in-plane currents and out-of-plane magnetic fields are neglected. This is a justified assumption for the 2D model which greatly simplifies and stabilizes the problem.

The separate rotor and stator objects are built as an assembly, and the relative rotation between rotor and stator is handled by the **Rotating Domain** node of the **Moving Mesh** feature, which includes all effects of relative motion between the parts. The domains are connected in the physics via boundary conditions on the continuity pair boundary, which resides in the air gap between them. This continuity pair allows for mesh discontinuities across the boundary where variables can be interpolated between the two independent meshes, ensuring continuity in the magnetic vector potential.

The torque is computed with the **Arkkio Torque Calculation** feature, which is automatically applied on the air gap domain adjacent to the continuity pair. The losses in the rotor and stator iron are calculated using a **Loss Calculation** subnode and a **Time to Frequency Losses** study. In the coils, the losses are Ohmic, while the losses in the iron are computed with the Steinmetz loss model.

Results and Discussion

The objective of the first study is to find the initial mechanical angle which produces the maximum torque on the rotor. As seen in Figure 1, the parametric sweep of the initial angle yields a curve displaying two extremes: one corresponding to accelerating torque, and the other corresponding to deceleration, in the direction of the prescribed counter-clockwise rotation. For the maximum accelerating torque, the former is chosen for the initial angle. The subsequent transient study solves the synchronous rotation of the stator field and the rotor. Figure 2 plots the rotor torque ripple as a function of time for one electrical period. Finally, a **Time to Frequency Losses** study calculates the loss density using the results of the previous transient study. Figure 4 shows the resulting loss density in the stator as well as the rotor iron.

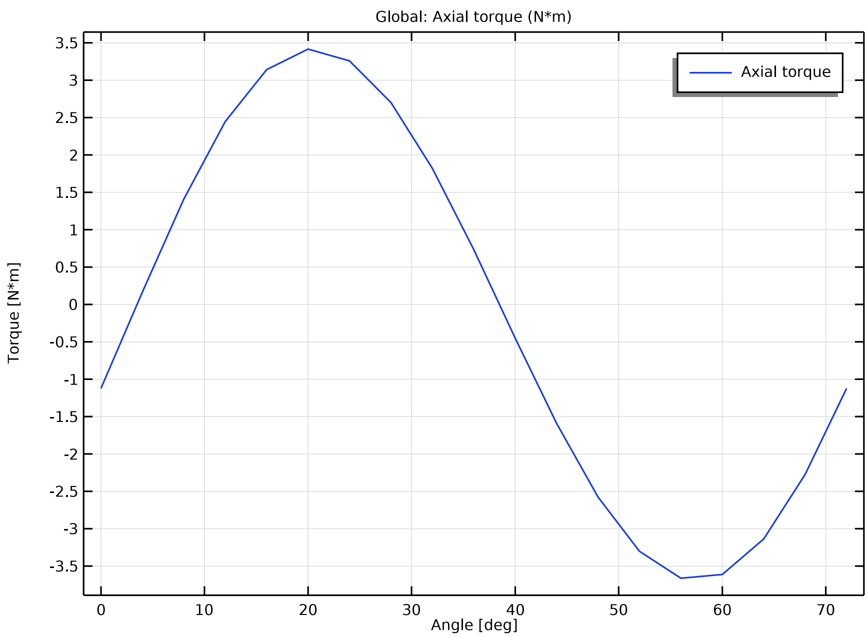


Figure 1: Rotor torque plotted as a function of the initial mechanical angle.

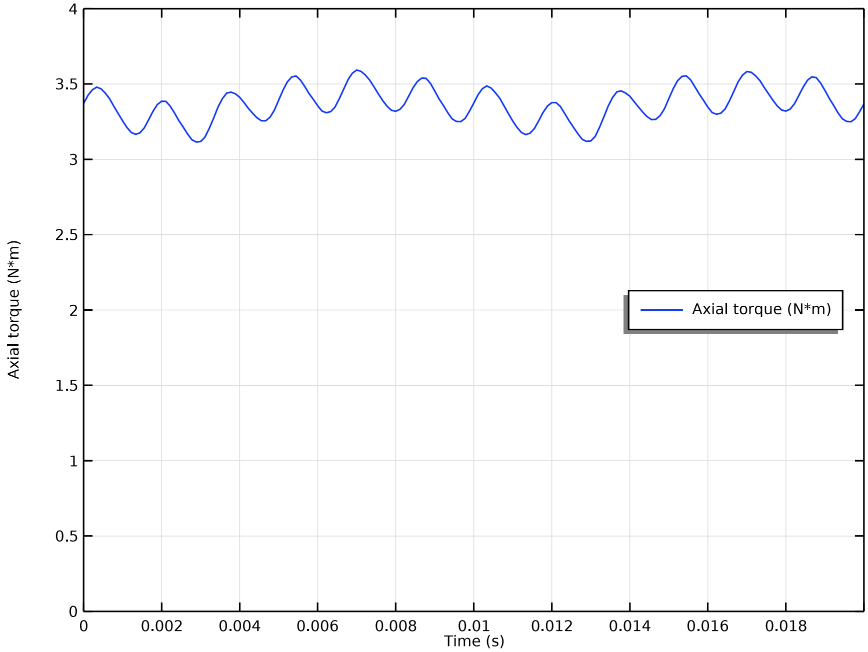


Figure 2: Rotor torque plotted as a function of time for a complete electrical period.

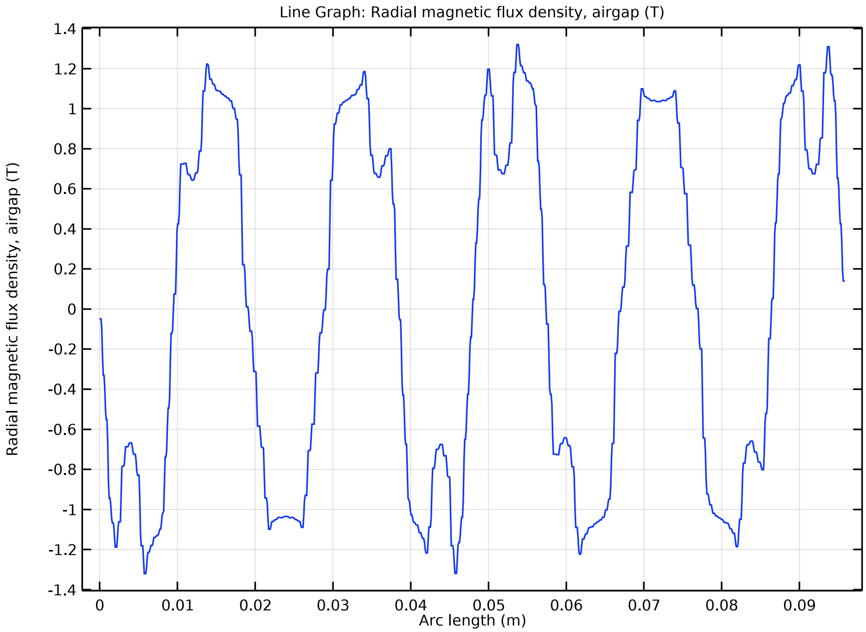


Figure 3: Radial magnetic flux density plotted versus the arc length of the continuity pair boundary, for time t = 0.

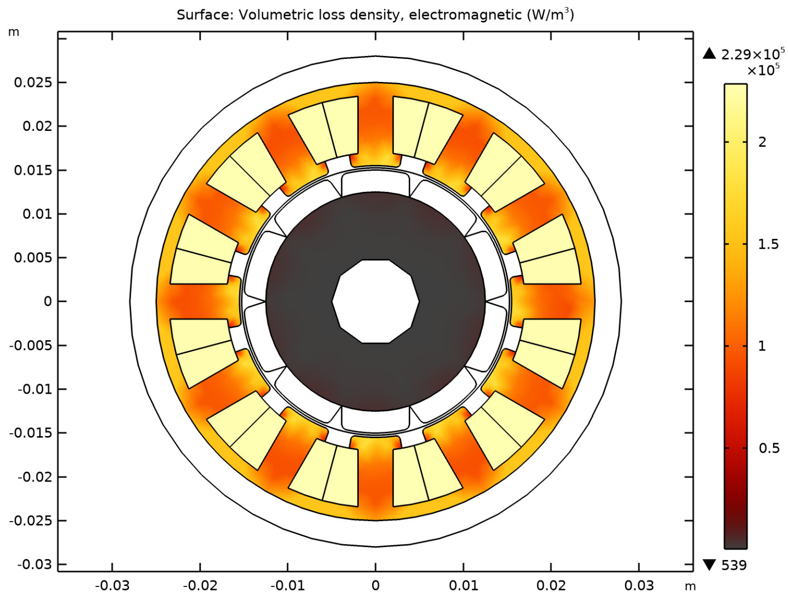


Figure 4: Loss density.

Application Library path: `ACDC_Module/Motors_and_Actuators/pm_motor_2d_introduction`

Modeling Instructions

From the **File** menu, choose **New**.

NEW

In the **New** window, click **Model Wizard**.

MODEL WIZARD

1 In the **Model Wizard** window, click **2D**.

2 In the **Select Physics** tree, select **AC/DC>Electromagnetics and Mechanics>Rotating Machinery, Magnetic (rmm)**.

3 Click **Add**.

4 Click **Study**.

5 In the **Select Study** tree, select **General Studies>Stationary**.

6 Click **Done**.

Begin by specifying a number of general parameters that will be used by the model.

GLOBAL DEFINITIONS

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

2 In the **Settings** window for **Parameters**, locate the **Parameters** section.

3 In the table, enter the following settings:

Name	Expression	Value	Description
L	200[mm]	0.2 m	Out-of-plane thickness of motor
init_ang	0[deg]	0 rad	Initial mechanical angle
Np	10	10	Number of poles
w_rot	600[rpm]	10 1/s	Rotational speed
f_el	w_rot*(Np/2)	50 1/s	Electrical frequency
I0	10[A]	10 A	Peak current
Nturn	10	10	Number of wire turns in slot
ff_slot	0.8	0.8	Slot filling factor

Next, build the motor using rotor and stator parts from the geometry part library. Initialize the parts, and tick the selections that are pre-defined to make it convenient to assign material properties and magnetization direction.

PART LIBRARIES

1 In the **Home** toolbar, click **Windows** and choose **Part Libraries**.

2 In the **Part Libraries** window, select **AC/DC Module>Rotating Machinery 2D>Rotors>Internal>surface_mounted_magnet_internal_rotor_2d** in the tree.

3 Click **Add to Geometry**.

GEOMETRY 1

Internal Rotor – Surface Mounted Magnets 1 (pi1)

1. In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** click **Internal Rotor – Surface Mounted Magnets 1 (pi1)**.
2. In the **Settings** window for **Part Instance**, locate the **Input Parameters** section.
3. In the table, enter the following settings:

Name	Expression	Value	Description
number_of_poles	Np	10	Number of magnetic poles in rotor
number_of_modeled_poles	Np	10	Number of magnetic poles included in the geometry

4. Click to expand the **Domain Selections** section. In the table, enter the following settings:

Name	Keep	Physics	Contribute to
Shaft	√	√	None
Rotor iron	√	√	None
Odd magnets	√	√	None
Even magnets	√	√	None
Rotor magnets	√	√	None
Rotor solid domains	√	√	None
Rotor air	√	√	None
All	√	√	None

PART LIBRARIES

1. In the **Home** toolbar, click **Windows** and choose **Part Libraries**.
2. In the **Model Builder** window, click **Geometry 1**.
3. In the **Part Libraries** window, select **AC/DC Module>Rotating Machinery 2D>Stators>External>slotted_external_stator_2d** in the tree.
4. Click **Add to Geometry**.

GEOMETRY 1

External Stator – Slotted 1 (pi2)

Select a radial partition for the slot winding type.

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** click **External Stator – Slotted 1 (pi2)**.

2 In the **Settings** window for **Part Instance**, locate the **Input Parameters** section.

3 In the table, enter the following settings:

Name	Expression	Value	Description
slot_winding_type	2	2	Slot winding type: 1-No partition, 2-Radial partition, 3-Azimuthal partition, 4-Radial and azimuthal partition.

4 Locate the **Domain Selections** section. In the table, enter the following settings:

Name	Keep	Physics	Contribute to
Stator iron	√	√	None
Stator slots	√	√	None
Stator air	√	√	None
All	√	√	None

Create an assembly from the two geometry objects, connected by a pair boundary.

Form Union (fin)

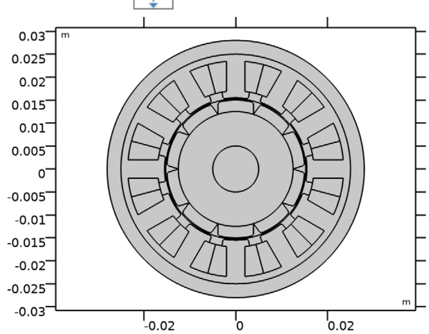
1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** click **Form Union (fin)**.

2 In the **Settings** window for **Form Union/Assembly**, locate the **Form Union/Assembly** section.

3 From the **Action** list, choose **Form an assembly**.

4 In the **Home** toolbar, click **Build All**.

5 Click the **Zoom Extents** button in the **Graphics** toolbar.



In order to follow the rotor poles, the stator field completes a period in the time it takes the rotor to move the angular span of two magnetic poles. Thus, the electrical frequency is scaled by Np/2 with respect to the rotor frequency. In the next step, define the time dependent angle, and the electrical and mechanical angle, where the latter are offset by the initial angle, init_ang, that you will choose to produce the maximum rotor torque.

DEFINITIONS

Electrical and Mechanical Angle

1 In the **Model Builder** window, expand the **Component 1 (comp1)>Definitions** node.

2 Right-click **Definitions** and choose **Variables**.

3 In the **Settings** window for **Variables**, type `Electrical and Mechanical Angle` in the **Label** text field.

4 Locate the **Variables** section. In the table, enter the following settings:

Name	Expression	Unit	Description
angle	2*pi*w_rot*if(isdefined(t),t,0[s])		Rotation angle
ang_e	Np/2*(angle-init_ang)	rad	Electrical angle
ang_m	angle		Mechanical angle

Next, define the cross section area of the slots, and the three phase currents of the stator coils.

Integration Over Half Slot

1 In the **Definitions** toolbar, click **Nonlocal Couplings** and choose **Integration**.

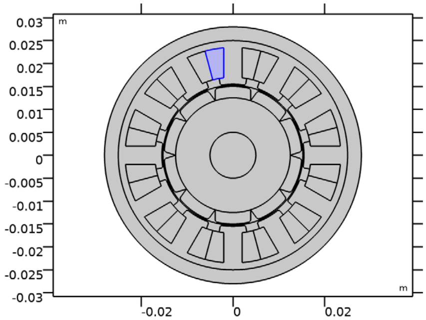
2 In the **Settings** window for **Integration**, type `Integration Over Half Slot` in the **Label** text field.

3 In the **Operator name** text field, type `halfslot_int`.

4 Locate the **Source Selection** section. Click **Paste Selection**.

5 In the **Paste Selection** dialog box, type `14` in the **Selection** text field.

6 Click **OK**.



Coil variables

1 Right-click **Definitions** and choose **Variables**.

2 In the **Settings** window for **Variables**, type `Coil variables` in the **Label** text field.

3 Locate the **Variables** section. In the table, enter the following settings:

Name	Expression	Unit	Description
`coil_area`	`halfslot_int(1)`	m^2	`Coil area`
`IA`	`I0*cos(ang_e)`	A	`Phase A current`
`IB`	`I0*cos(ang_e-120[deg])`	A	`Phase B current`
`IC`	`I0*cos(ang_e-240[deg])`	A	`Phase C current`
`wire_cross_section`	`halfslot_int(1)*ff_slot/Nturn`	m^2	`Coil wire cross section`

Now, define a cylindrical coordinate system in order to specify a radial direction for the remanent magnetic flux density of the rotor magnets.

Cylindrical System 2 (sys2)

In the **Definitions** toolbar, click **Coordinate Systems** and choose **Cylindrical System**.

Create union selections for the motor air and iron parts, respectively.

Air

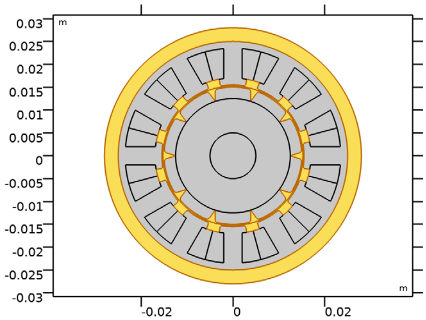
1 In the **Definitions** toolbar, click **Union**.

2 In the **Settings** window for **Union**, type `Air` in the **Label** text field.

3 Locate the **Input Entities** section. Under **Selections to add**, click **Add**.

4 In the **Add** dialog box, in the **Selections to add** list, choose **Rotor air (Internal Rotor – Surface Mounted Magnets 1)** and **Stator air (External Stator – Slotted 1)**.

5 Click **OK**.



Iron

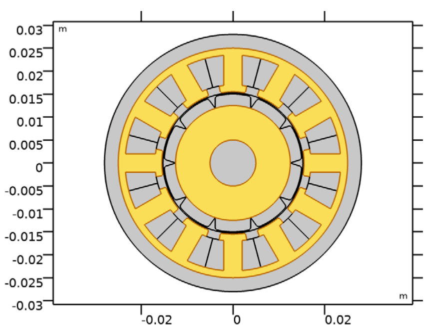
1 In the **Definitions** toolbar, click **Union**.

2 In the **Settings** window for **Union**, type `Iron` in the **Label** text field.

3 Locate the **Input Entities** section. Under **Selections to add**, click + **Add**.

4 In the **Add** dialog box, in the **Selections to add** list, choose **Rotor iron (Internal Rotor – Surface Mounted Magnets 1)** and **Stator iron (External Stator – Slotted 1)**.

5 Click **OK**.



Next, add materials and assign them to their appropriate domain selections.

ADD MATERIAL

1 In the **Home** toolbar, click **Add Material** to open the **Add Material** window.

2 Go to the **Add Material** window.

3 In the tree, select **Built-in>Air**.

4 Click **Add to Component** in the window toolbar.

5 In the tree, select **AC/DC>Soft Iron (Without Losses)**.

6 Click **Add to Component** in the window toolbar.

7 In the tree, select **AC/DC>Copper**.

8 Click **Add to Component** in the window toolbar.

9 In the tree, select **AC/DC>Hard Magnetic Materials> Sintered NdFeB Grades (Chinese Standard)>N54 (Sintered NdFeB)**.

10 Click **Add to Component** in the window toolbar.

11 In the tree, select **Built-in>Iron**.

12 Click **Add to Component** in the window toolbar.

13 In the **Home** toolbar, click **Add Material** to close the **Add Material** window.

MATERIALS

Soft Iron (Without Losses) (mat2)

1 In the **Model Builder** window, under **Component 1 (comp1)>Materials** click **Soft Iron (Without Losses) (mat2)**.

2 In the **Settings** window for **Material**, locate the **Geometric Entity Selection** section.

3 From the **Selection** list, choose **Iron**.

Iron (mat5)

1 In the **Model Builder** window, click **Iron (mat5)**.

2 In the **Settings** window for **Material**, locate the **Geometric Entity Selection** section.

3 From the **Selection** list, choose **Shaft (Internal Rotor – Surface Mounted Magnets 1)**.

4 Locate the **Material Contents** section. In the table, enter the following settings:

Property	Variable	Value	Unit	Property group
Relative permeability	mur_iso ; murii = mur_iso, murij = 0	4000	1	Basic
Electrical conductivity	sigma_iso ; sigmaii = sigma_iso, sigmaij = 0	0	S/m	Basic

Property	**Variable**	**Value**	**Unit**	**Property group**
Relative permittivity	epsilonr_iso ; epsilonrii = epsilonr_iso, epsilonrij = 0	1	1	Basic
Coefficient of thermal expansion	alpha_iso ; alphaii = alpha_iso, alphaij = 0	12.2e-6[1/K]	1/K	Basic
Heat capacity at constant pressure	Cp	440[J/(kg*K)]	J/(kg·K)	Basic
Density	rho	7870[kg/m^3]	kg/m^3	Basic
Thermal conductivity	k_iso ; kii = k_iso, kij = 0	76.2[W/(m*K)]	W/(m·K)	Basic
Young's modulus	E	200e9[Pa]	Pa	Young's modulus and Poisson's ratio
Poisson's ratio	nu	0.29	1	Young's modulus and Poisson's ratio

Copper (mat3)

1. In the **Model Builder** window, click **Copper (mat3)**.
2. In the **Settings** window for **Material**, locate the **Geometric Entity Selection** section.
3. From the **Selection** list, choose **Stator slots (External Stator – Slotted 1)**.

N54 (Sintered NdFeB) (mat4)

1. In the **Model Builder** window, click **N54 (Sintered NdFeB) (mat4)**.
2. In the **Settings** window for **Material**, locate the **Geometric Entity Selection** section.
3. From the **Selection** list, choose **Rotor magnets (Internal Rotor – Surface Mounted Magnets 1)**.

ROTATING MACHINERY, MAGNETIC (RMM)

In the **Definitions** toolbar, click **Moving Mesh** and choose **Domains>Rotating Domain**.

MOVING MESH

Rotating Domain 1

1 In the **Settings** window for **Rotating Domain**, locate the **Domain Selection** section.

2 From the **Selection** list, choose **All (Internal Rotor – Surface Mounted Magnets 1)**.

3 Locate the **Rotation** section. In the α text field, type `ang_m`.

ROTATING MACHINERY, MAGNETIC (RMM)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Rotating Machinery, Magnetic (rmm)**.

2 In the **Settings** window for **Rotating Machinery, Magnetic**, locate the **Thickness** section.

3 In the *d* text field, type `L`.

B-H Iron Regions

1 In the **Physics** toolbar, click **Domains** and choose **Ampère's Law**.

2 In the **Settings** window for **Ampère's Law**, type `B-H Iron Regions` in the **Label** text field.

3 Locate the **Domain Selection** section. From the **Selection** list, choose **Iron**.

4 Locate the **Constitutive Relation B-H** section. From the **Magnetization model** list, choose **B-H curve**.

Loss Calculation 1

1 In the **Physics** toolbar, click **Attributes** and choose **Loss Calculation**.

2 In the **Settings** window for **Loss Calculation**, locate the **Loss Model** section.

3 From the **Loss model** list, choose **Steinmetz**.

Odd Magnets

1 In the **Physics** toolbar, click **Domains** and choose **Ampère's Law**.

2 In the **Settings** window for **Ampère's Law**, type `Odd Magnets` in the **Label** text field.

3 Locate the **Domain Selection** section. From the **Selection** list, choose **Odd magnets (Internal Rotor – Surface Mounted Magnets 1)**.

4 Locate the **Coordinate System Selection** section. From the **Coordinate system** list, choose **Cylindrical System 2 (sys2)**.

5 Locate the **Constitutive Relation B-H** section. From the **Magnetization model** list, choose **Remanent flux density**.

6 Locate the **Constitutive Relation Jc-E** section. From the σ list, choose **User defined**.

Even Magnets

1 Right-click **Odd Magnets** and choose **Duplicate**.

2 In the **Settings** window for **Ampère's Law**, type `Even Magnets` in the **Label** text field.

3 Locate the **Domain Selection** section. From the **Selection** list, choose **Even magnets (Internal Rotor – Surface Mounted Magnets 1)**.

4 Locate the **Constitutive Relation B-H** section. Specify the **e** vector as

-1	r
0	phi
0	a

Phase A

1 In the **Physics** toolbar, click **Domains** and choose **Coil**.

2 In the **Settings** window for **Coil**, type `Phase A` in the **Label** text field.

3 Locate the **Domain Selection** section. Click **Paste Selection**.

4 In the **Paste Selection** dialog box, type `9,11,13-16,18,20` in the **Selection** text field.

5 Click **OK**.

6 In the **Settings** window for **Coil**, locate the **Coil** section.

7 From the **Conductor model** list, choose **Homogenized multiturn**.

8 Select the **Coil group** check box.

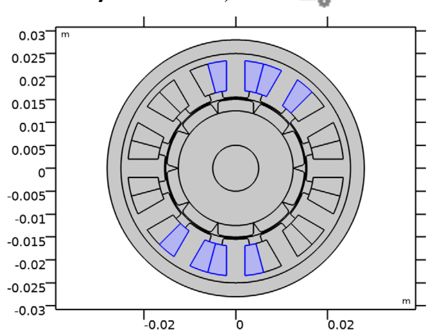
9 In the I_{coil} text field, type `IA`.

10 Locate the **Homogenized Multiturn Conductor** section. In the N text field, type `Nturn`.

11 In the a_{coil} text field, type `wire_cross_section`.

Loss Calculation 1

In the **Physics** toolbar, click **Attributes** and choose **Loss Calculation**.



Phase A

In the **Model Builder** window, click **Phase A**.

Reversed Current Direction 1

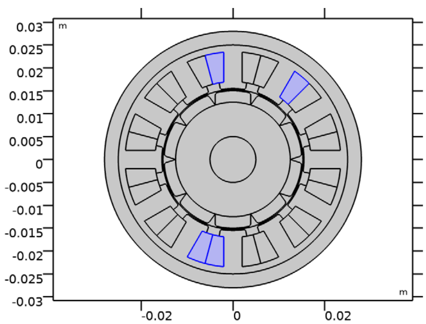
1 In the **Physics** toolbar, click **Attributes** and choose **Reversed Current Direction**.

2 In the **Settings** window for **Reversed Current Direction**, locate the **Domain Selection** section.

3 Click **Paste Selection**.

4 In the **Paste Selection** dialog box, type `11,13,14,20` in the **Selection** text field.

5 Click **OK**.



Phase B

1 Right-click **Phase A** and choose **Duplicate**.

2 In the **Settings** window for **Coil**, type `Phase B` in the **Label** text field.

3 Locate the **Domain Selection** section. Click **Clear Selection**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog box, type `5,7,10,12,17,19,21,23` in the **Selection** text field.

6 Click **OK**.

7 In the **Settings** window for **Coil**, locate the **Coil** section.

8 In the I_{coil} text field, type `IB`.

Reversed Current Direction 1

1 In the **Model Builder** window, expand the **Phase B** node, then click **Reversed Current Direction 1**.

2 In the **Settings** window for **Reversed Current Direction**, locate the **Domain Selection** section.

3 Click **Clear Selection**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog box, type `7,10,17,23` in the **Selection** text field.

6 Click **OK**.

Phase C

1 In the **Model Builder** window, right-click **Phase B** and choose **Duplicate**.

2 In the **Settings** window for **Coil**, type `Phase C` in the **Label** text field.

3 Locate the **Domain Selection** section. Click **Clear Selection**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog box, type `1,3,4,6,22,24-26` in the **Selection** text field.

6 Click **OK**.

7 In the **Settings** window for **Coil**, locate the **Coil** section.

8 In the I_{coil} text field, type `IC`.

Reversed Current Direction 1

1 In the **Model Builder** window, expand the **Phase C** node, then click **Reversed Current Direction 1**.

2 In the **Settings** window for **Reversed Current Direction**, locate the **Domain Selection** section.

3 Click **Clear Selection**.

4 Click **Paste Selection**.

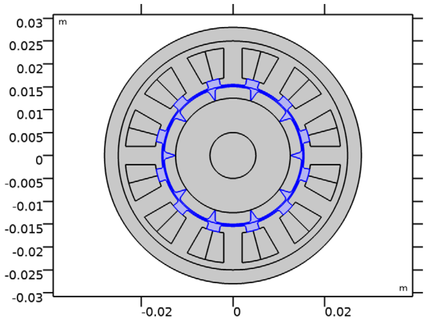
5 In the **Paste Selection** dialog box, type `3,6,24,26` in the **Selection** text field.

6 Click **OK**.

Next, implement the Arkkio Torque Calculation feature for calculating the torque on the rotor. The node is automatically applied to the air gap. The Arkkio force integrand is multiplied with a support function which is nonzero in the correct radial extent, between the rotor magnets and stator iron.

Arkkio Torque Calculation 1

In the **Physics** toolbar, click **Domains** and choose **Arkkio Torque Calculation**.



MESH 1

Free Triangular 1

In the **Mesh** toolbar, click **Free Triangular**.

Size

1. In the **Model Builder** window, click **Size**.
2. In the **Settings** window for **Size**, locate the **Element Size** section.
3. From the **Predefined** list, choose **Coarser**.
4. Click the **Custom** button.
5. Locate the **Element Size Parameters** section. In the **Maximum element size** text field, type `5[mm]`.
6. In the **Minimum element size** text field, type `0.5[mm]`.
7. In the **Model Builder** window, right-click **Mesh 1** and choose **Build All**.

STUDY 1: INITIAL ANGLE PARAMETRIC SWEEP AT DC CURRENT

1. In the **Model Builder** window, click **Study 1**.
2. In the **Settings** window for **Study**, type `Study 1: Initial angle parametric sweep at DC current` in the **Label** text field.

Step 1: Stationary

1. In the **Model Builder** window, under **Study 1: Initial angle parametric sweep at DC current** click **Step 1: Stationary**.
2. In the **Settings** window for **Stationary**, click to expand the **Results While Solving** section.
3. Select the **Plot** check box.

4 Click to expand the **Study Extensions** section. Select the **Auxiliary sweep** check box.

5 Click + **Add**.

6 In the table, enter the following settings:

Parameter name	Parameter value list	Parameter unit
init_ang (Initial mechanical angle)	`range(0,4[deg],360[deg]/(Np/2))`	`deg`

7 In the **Home** toolbar, click **Compute**.

RESULTS

Streamline 1

1 In the **Model Builder** window, expand the **Magnetic Flux Density Norm (rmm)** node.

2 Right-click **Streamline 1** and choose **Disable**.

Contour 1

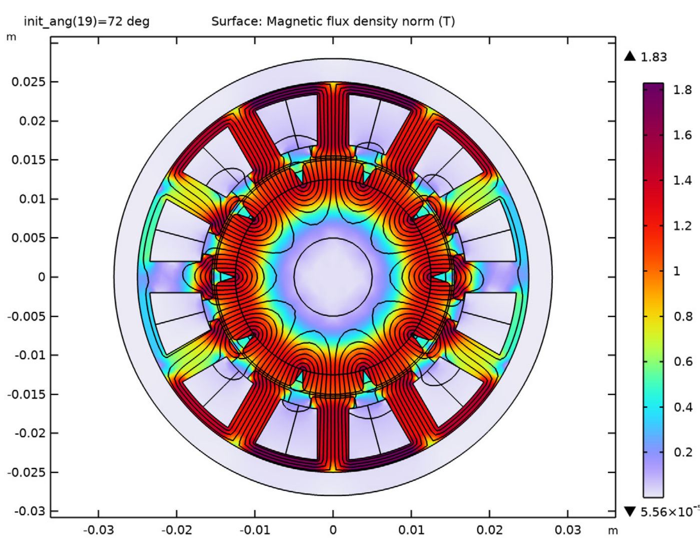
1 In the **Model Builder** window, click **Contour 1**.

2 In the **Settings** window for **Contour**, locate the **Levels** section.

3 In the **Total levels** text field, type `16`.

4 Locate the **Coloring and Style** section. From the **Color** list, choose **Black**.

5 In the **Magnetic Flux Density Norm (rmm)** toolbar, click **Plot**.



Torque

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `Torque` in the **Label** text field.

3 Locate the **Plot Settings** section. Select the **x-axis label** check box.

4 In the associated text field, type `Angle [deg]`.

5 Select the **y-axis label** check box.

6 In the associated text field, type `Torque [N*m]`.

Global 1

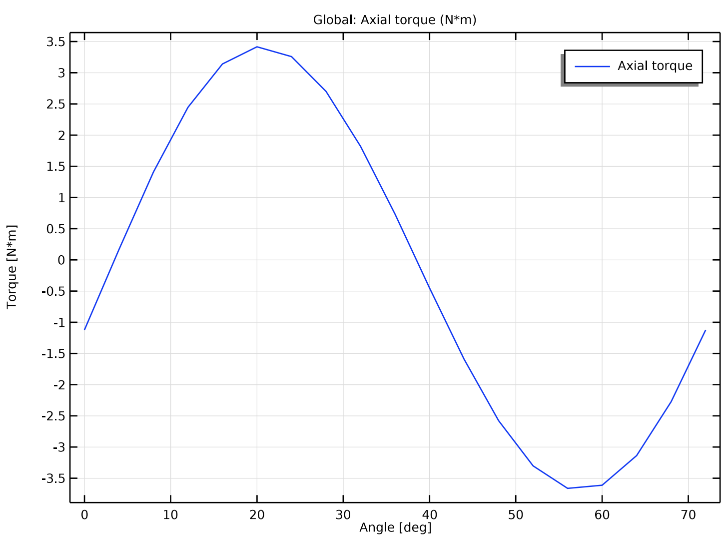
1 Right-click **Torque** and choose **Global**.

2 In the **Settings** window for **Global**, locate the **y-Axis Data** section.

3 In the table, enter the following settings:

Expression	Unit	Description
`rmm.Tark_1`	`N*m`	`Axial torque`

4 In the **Torque** toolbar, click **Plot**.



The maximum torque on the rotor is found at an initial angle offset of 20°. Select this angle for the parameter init_ang to start off the transient study.

GLOBAL DEFINITIONS

Parameters 1

1 In the **Model Builder** window, under **Global Definitions** click **Parameters 1**.

2 In the **Settings** window for **Parameters**, locate the **Parameters** section.

3 In the table, enter the following settings:

Name	Expression	Value	Description
init_ang	20[deg]	0.34907 rad	Initial mechanical angle

DEFINITIONS

Global Variable Probe 1 (var1)

1 In the **Definitions** toolbar, click **Probes** and choose **Global Variable Probe**.

2 In the **Settings** window for **Global Variable Probe**, locate the **Expression** section.

3 In the **Expression** text field, type `rmm.Tark_1`.

4 Select the **Description** check box.

ADD STUDY

1 In the **Home** toolbar, click **Add Study** to open the **Add Study** window.

2 Go to the **Add Study** window.

3 Find the **Studies** subsection. In the **Select Study** tree, select **General Studies>Stationary**.

4 Click **Add Study** in the window toolbar.

5 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 2: SYNCHRONOUS ROTATION

1 In the **Model Builder** window, click **Study 2**.

2 In the **Settings** window for **Study**, type `Study 2: Synchronous rotation` in the **Label** text field.

Time Dependent

1 In the **Study** toolbar, click **Study Steps** and choose **Time Dependent>Time Dependent**.

2 In the **Settings** window for **Time Dependent**, locate the **Study Settings** section.

3 In the **Output times** text field, type `range(0,2/Np/6/6,1)/f_el`.

In order for the transient solver to achieve a stable solution of the nonlinear problem, you need to apply two settings:

- setting **Update Jacobian** to **On every iteration**. This will make the convergence more robust within each time step.

- using **Linear** elements for the discretization. This will yield a more reliable solution near regions of magnetic saturation.

Solution 2 (sol2)

1 In the **Study** toolbar, click **Show Default Solver**.

2 In the **Model Builder** window, expand the **Solution 2 (sol2)** node.

3 In the **Model Builder** window, expand the **Study 2: Synchronous rotation>Solver Configurations>Solution 2 (sol2)>Time-Dependent Solver 1** node, then click **Fully Coupled 1**.

4 In the **Settings** window for **Fully Coupled**, click to expand the **Method and Termination** section.

5 From the **Jacobian update** list, choose **On every iteration**.

ROTATING MACHINERY, MAGNETIC (RMM)

1 In the **Model Builder** window, under **Component 1 (comp1)** click **Rotating Machinery, Magnetic (rmm)**.

2 In the **Settings** window for **Rotating Machinery, Magnetic**, click to expand the **Discretization** section.

3 From the **Magnetic vector potential** list, choose **Linear**.

4 From the **Magnetic scalar potential** list, choose **Linear**.

STUDY 2: SYNCHRONOUS ROTATION

In the **Study** toolbar, click **Compute**.

RESULTS

Torque ripple

1 In the **Model Builder** window, under **Results** click **Probe Plot Group 4**.

2 In the **Settings** window for **1D Plot Group**, type `Torque ripple` in the **Label** text field.

3 Locate the **Axis** section. Select the **Manual axis limits** check box.

4 In the **x minimum** text field, type `0`.

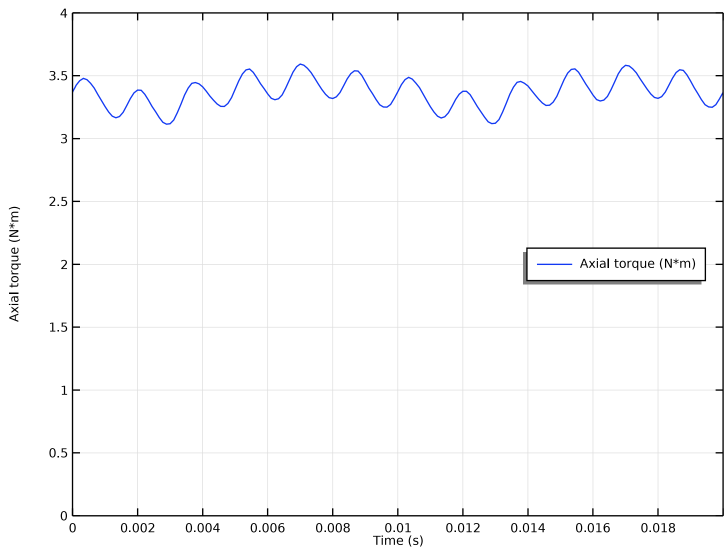
5 In the **x maximum** text field, type `0.02`.

6 In the **y minimum** text field, type `0`.

7 In the **y maximum** text field, type `4`.

8 Locate the **Legend** section. From the **Position** list, choose **Middle right**.

9 In the **Torque ripple** toolbar, click **Plot**.



Now plot the radial component of the magnetic flux density in the air gap. To do that, define a suitable boundary within the air gap, and plot the quantity along its arc length.

GEOMETRY 1

Internal Rotor – Surface Mounted Magnets 1 (pi1)

1 In the **Model Builder** window, under **Component 1 (comp1)>Geometry 1** click **Internal Rotor – Surface Mounted Magnets 1 (pi1)**.

2 In the **Settings** window for **Part Instance**, click to expand the **Boundary Selections** section.

3 In the table, enter the following settings:

Name	Keep	Physics	Contribute to
Exterior	√	√	None

4 In the **Home** toolbar, click **Build All**.

RESULTS

Air Gap Radial Magnetic Flux Density

1 In the **Home** toolbar, click **Add Plot Group** and choose **1D Plot Group**.

2 In the **Settings** window for **1D Plot Group**, type `Air Gap Radial Magnetic Flux Density` in the **Label** text field.

3 Locate the **Data** section. From the **Dataset** list, choose **Study 2: Synchronous rotation/ Solution 2 (sol2)**.

4 From the **Time selection** list, choose **First**.

Line Graph 1

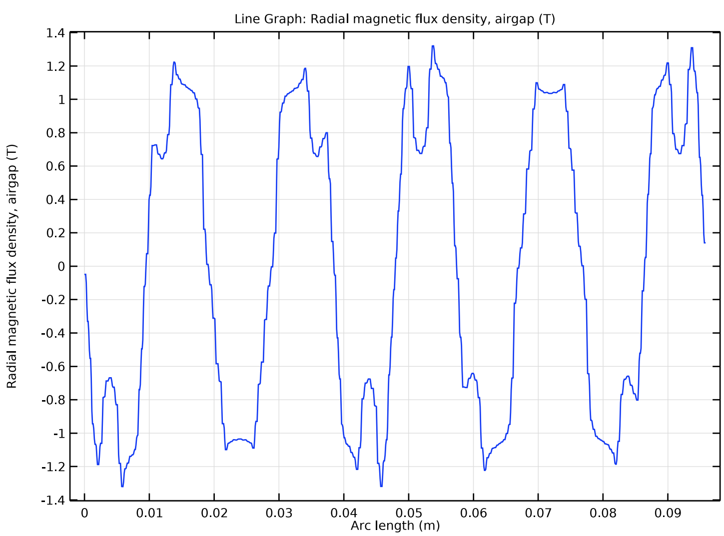
1 Right-click **Air Gap Radial Magnetic Flux Density** and choose **Line Graph**.

2 In the **Settings** window for **Line Graph**, locate the **Selection** section.

3 From the **Selection** list, choose **Exterior (Internal Rotor – Surface Mounted Magnets 1)**.

4 Locate the **y-Axis Data** section. In the **Expression** text field, type `rmm.ark1.Brad`.

5 In the **Air Gap Radial Magnetic Flux Density** toolbar, click **Plot**.



ADD STUDY

1 In the **Home** toolbar, click **Add Study** to open the **Add Study** window.

2 Go to the **Add Study** window.

3 Find the **Studies** subsection. In the **Select Study** tree, select **Preset Studies for Selected Physics Interfaces>Time to Frequency Losses**.

4 Click **Add Study** in the window toolbar.

5 In the **Home** toolbar, click **Add Study** to close the **Add Study** window.

STUDY 3: LOSS CALCULATION OVER FULL ROTATION

1 In the **Model Builder** window, click **Study 3**.

2 In the **Settings** window for **Study**, type `Study 3: Loss calculation over full rotation` in the **Label** text field.

Step 1: Time to Frequency Losses

1 In the **Model Builder** window, under **Study 3: Loss calculation over full rotation** click **Step 1: Time to Frequency Losses**.

2 In the **Settings** window for **Time to Frequency Losses**, locate the **Study Settings** section.

3 From the **Input study** list, choose **Study 2: Synchronous rotation, Time Dependent**.

4 In the **Electrical period** text field, type `1/f_el`.

5 In the **Home** toolbar, click **Compute**.

RESULTS

Cycle Averaged Losses (rmm)