Model created in COMSOL Multiphysics 6.4

Permanent Magnet Motor in Steady State

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Introduction

This tutorial covers the fundamentals of modeling an electrical machine with the Magnetic Machinery, Rotating, Time Periodic (MMTP) interface. MMTP solves for the steady-state operation directly while fully including the effects of nonlinear materials and induced currents. Concepts for determining the minimum temporal and spatial periodicities are discussed.

The geometry of a distributed wound interior permanent magnet machine is imported and configured with materials and winding layout before finding the current angle which gives peak torque production. Following this, overall results such as shaft power, loss per component and efficiency are evaluated together with plots of magnetic flux density, torque, voltages, and electromagnetic loss distribution.

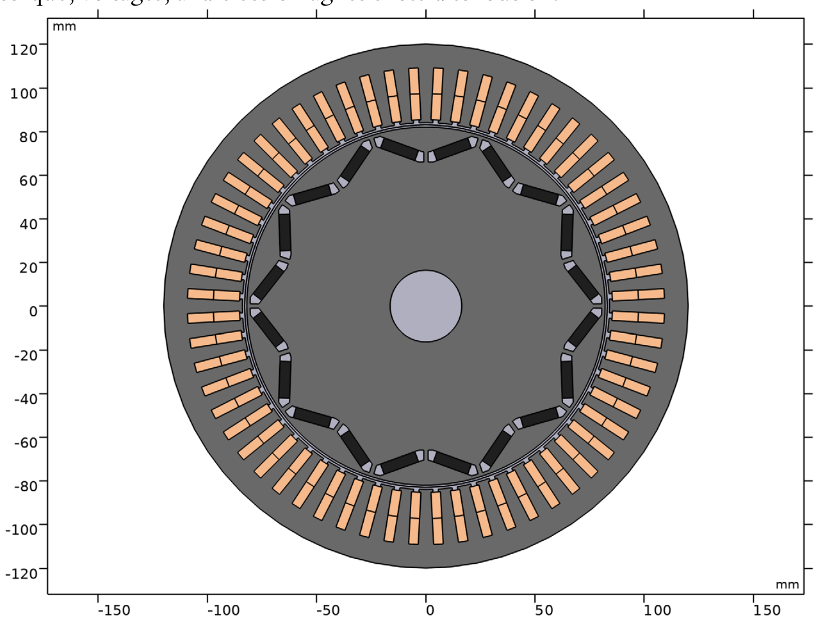


Figure 1: Complete geometry of motor design.

Model Definition

The Magnetic Machinery, Rotating, Time Periodic (MMTP) interface solves for a time period with the condition that field variations are periodic, or will repeat in subsequent time periods. The time period is the reciprocal of the **Time periodic electrical frequency** which is specified in the MMTP interface. The handle for time in this framework is the phase angle which always spans from 0 to 2π.

When modeling an electrical machine it can be beneficial to determine some aspects of the design a priori to conserve computational resources. Evaluation of a few expressions gives an understanding of the minimum spatial and temporal extents necessary for a reduced model to produce the same result as a full model.

SPATIAL PERIODICITY

The motor topology is a 10 pole 60 slot distributed wound interior permanent magnet synchronous machine. For most motor designs the spatial periodicity of the electromagnetic field can be found by evaluating $N_{\text{sec}} = \text{gcd}(N_p, N_s)$, where N_p and N_s are the number of poles and stator slots, and where gcd() finds the greatest common divisor of these integers. In this case, $N_{\text{sec}} = 10$ and hence it is sufficient to represent one tenth of the geometry to capture all spatial field variations. Field variations in neighboring sectors are identical although perhaps with an opposite polarity depending on the periodicity type.

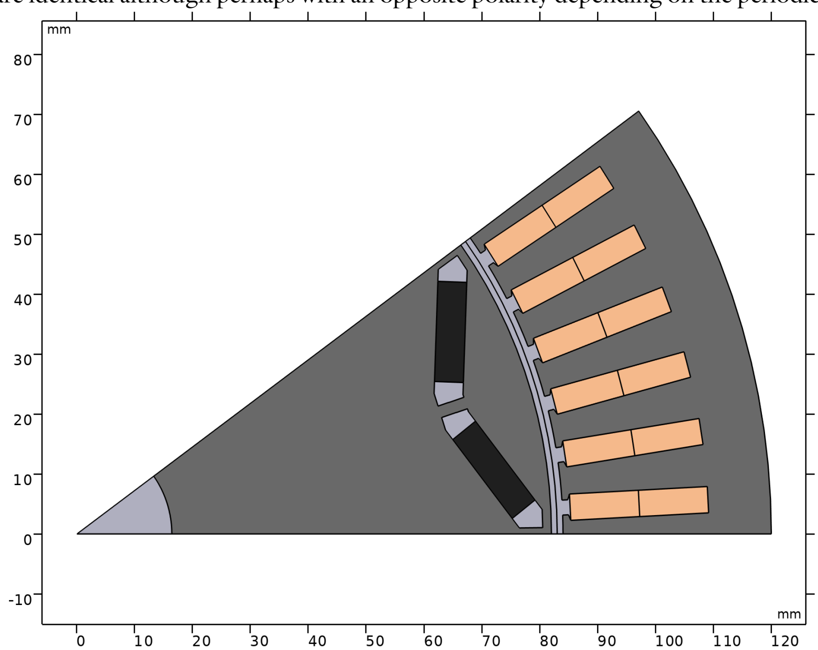


Figure 2: Sector symmetric geometry of motor design.

As a rule of thumb when there is an odd number of poles inside the modeled sector the periodicity type is antiperiodic, meaning the field variations in adjacent sectors have opposite sign. With an even number of poles in the sector the periodicity is symmetric. In this case there are two magnets arranged in a v-shape making out a single pole and hence the periodicity is antiperiodic.

Having created a sector symmetric geometry and specified the number of poles, the periodicity type and necessary rotational boundary features can be automatically configured by MMTP.

TEMPORAL PERIODICITY

The MMTP interface solves directly for the steady-state operation without resolving any startup transients. For most synchronous machines the time period in which fields are periodic is equivalent to the electrical excitation period.

It is not always however the rotor eddy currents will have the same time periodicity as the excitation even for a synchronous machine. A rather safe assumption is that the eddy currents are periodic with the spatial periodicity, meaning they will at least repeat after rotation has completed an angle of $360°/N_{\mathrm{sec}}$.

Generally, the MMTP time period should be the least common multiple of the periods of all fields being modeled. In this case the temporal periodicity of any induced currents will be at least twice that of the excitation period, since $360°/N_{\mathrm{sec}} \cdot N_p/2 = 180°\mathrm{E}$ (electrical degrees). Hence, setting the time periodic frequency equal to the excitation frequency will capture all field oscillations correctly.

TEMPORAL RESOLUTION

The cogging torque or torque due to reluctance variations as the rotor magnets are passing by stator teeth, will in this design occur on the 12'th harmonic of the fundamental electrical frequency according to the formula;

$$n_{\mathrm{cog}} = \frac{N_s}{\gcd(N_s, N_p)} \cdot 2$$

To obtain data for consistent analysis of the torque output it is a good idea to ensure the cogging torque is sufficiently resolved. With, for example, six frames per cogging period this will result in 72 time frames per excitation period. The software will calculate the solution to all time frames simultaneously while including effects of time derivatives.

INITIAL ELECTRICAL ANGLE

The default behavior of the MMTP interface assumes rotational synchronization between the **Rotating Domain** and the field excited by the **Multiphase Winding**. To obtain peak torque production however a specific angle offset between the rotating magnetic field and the rotor has to be found.

The optimal angle offset, or **Initial electrical angle** in MMTP, depends on several factors such as geometry, electrical steel grade or magnet strength, any of which will alter the magnetic reluctance of the design. While there are many motor control strategies deducing this offset analytically, the initial electrical angle can also be determined rather easily by letting the rotor remain stationary while stator field is rotating. The resulting torque output will resemble a sine curve where the maximum corresponds to peak torque in motoring mode, and the minimum to peak torque in generating mode.

TORQUE ACCURACY

The same result yielding initial angle for peak torque production can also be used to evaluate the accuracy of torque calculation. If no induced currents are present, the net torque experienced by a locked rotor when stator field is revolved exactly one electrical period should be zero. Hence calculating the average torque from this result and comparing it with the peak torque gives an idea of the torque accuracy in the model.

Results and Discussion

The first simulation is run with stationary rotor and no induced currents to determine the initial electrical angle giving peak torque as shown in Figure 3.

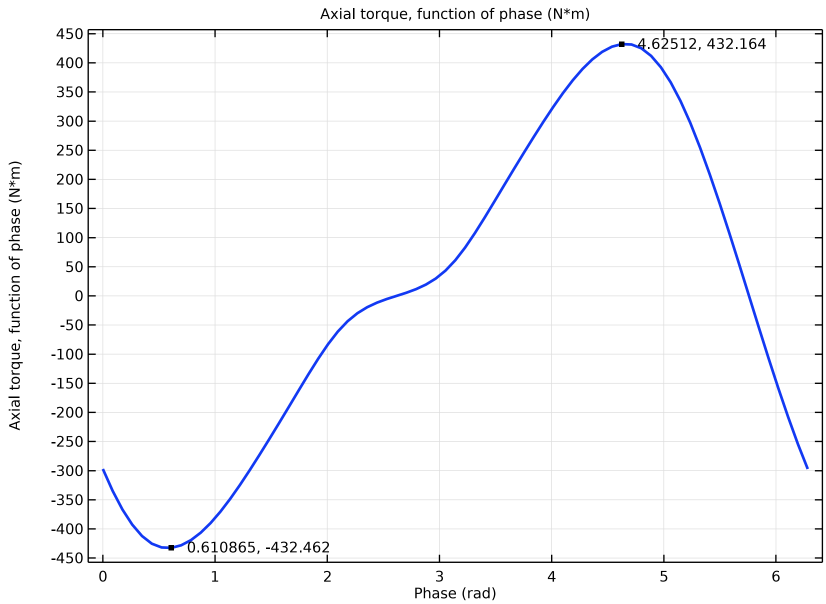


Figure 3: Torque curve with locked rotor.

Evaluating the average torque and dividing it by the peak value shows that the error in torque calculation is less than 0.1%.

Having updated the initial electrical angle, a second simulation with rotation produces steady-state torque as shown in Figure 4 and magnetic flux density distributions as shown in Figure 5 and Figure 6.

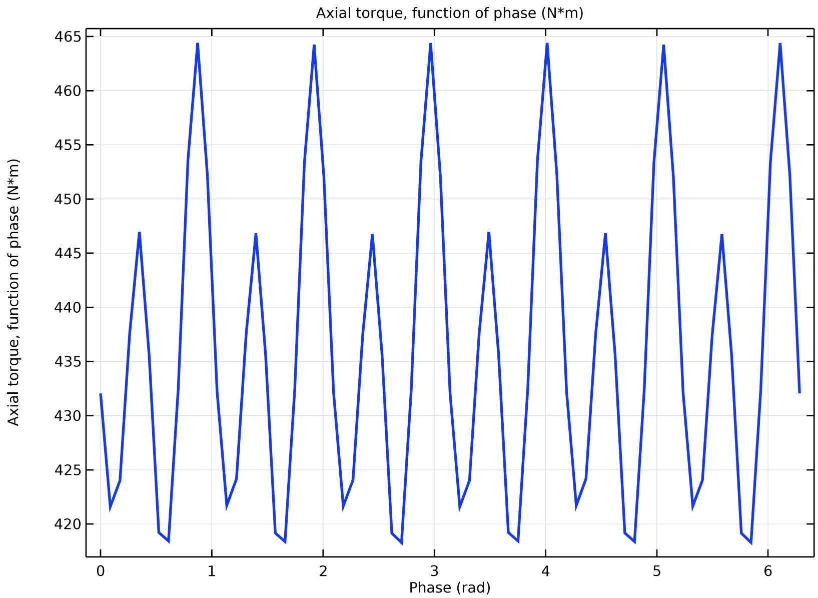


Figure 4: Steady-state torque.

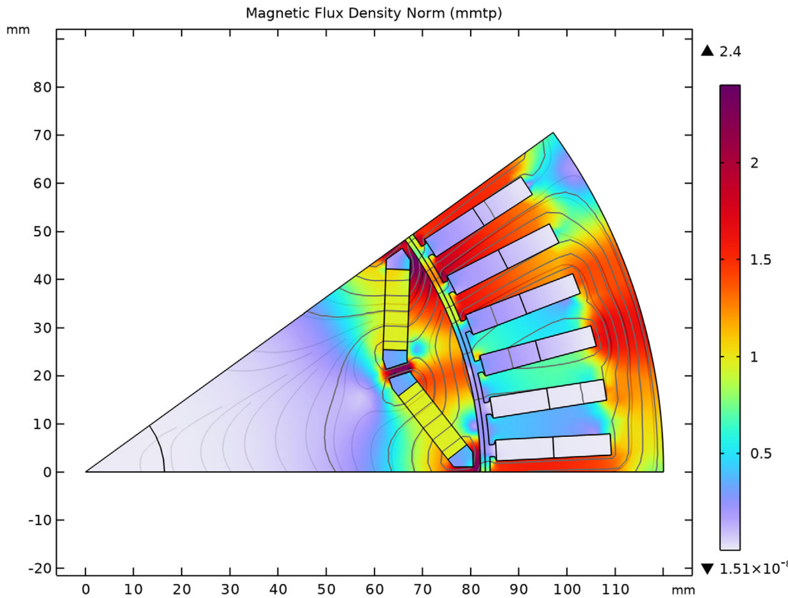


Figure 5: Magnetic flux density distribution at phase angle 0°E.

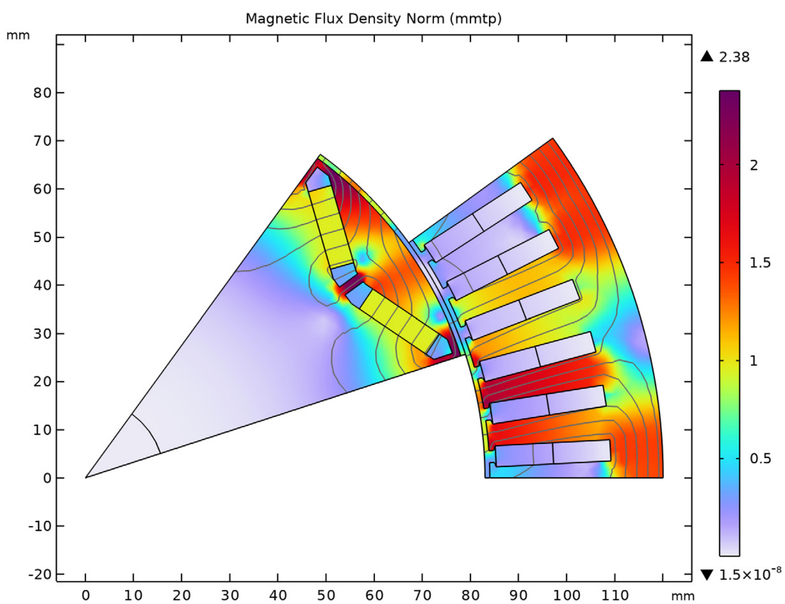


Figure 6: Magnetic flux density distribution at phase angle 90°E.

While the temporal variation of electromagnetic loss typically is not relevant in a thermal time scale, the spatial distribution can be of significance. Figure 7 shows this distribution across all motor components.

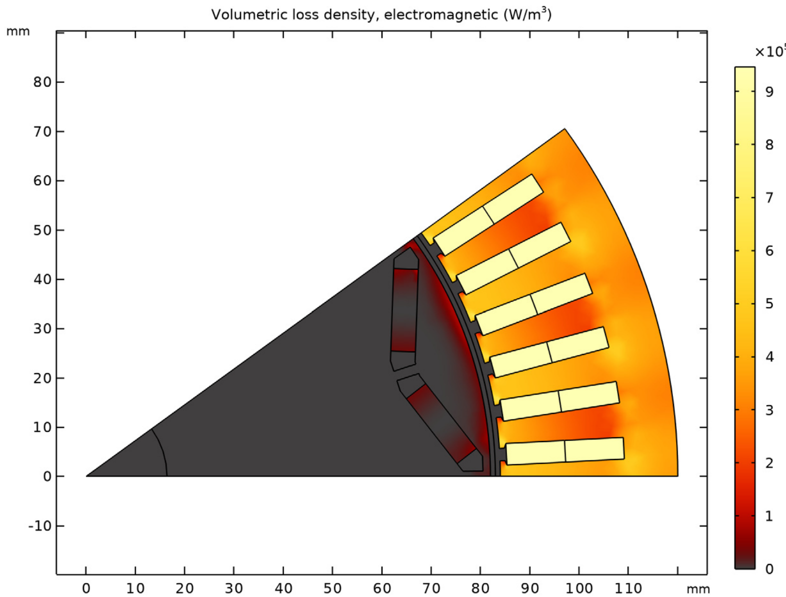


Figure 7: Distribution of time averaged electromagnetic loss.

To verify assumptions on the temporal periodicity of induced currents the plot in Figure 8 can be examined. Here the induced current density evaluated at a point in the magnet is scaled up and plotted together with the excitation current density of phase 1. The two vertical lines indicate half an electrical period, which corresponds with the spatial periodicity.

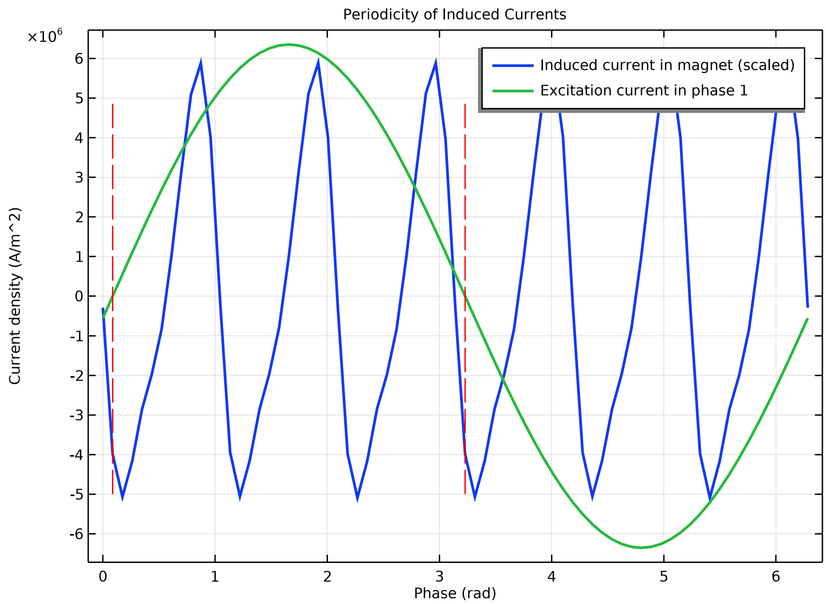


Figure 8: Induced current at a point in magnet and current excitation in phase 1.

By inspection it is seen that the induced currents are periodic with half the electrical period and completes six cycles in the span of the full period.

The overall results — such as shaft power, average torque, total losses, and electromagnetic efficiency — are calculated and tabulated in an **Evaluation Group** at the end of the Modeling Instructions. They can also be inspected by opening the model from the Application Library and selecting the **General Results** node under the **Results** branch in the **Model Builder**.

Application Library path: `ACDC_Module/Devices,_Motors_and_Generators/pmm_steady_state`

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** > **Magnetic Machinery, Rotating, Time Periodic (mmtp)**.

3 Click **Add**.

4 Click **Done**.

GEOMETRY 1

Insert the geometry sequence from the `pmm_steady_state_geom_sequence.mph` file.

1 In the **Geometry** toolbar, click **Insert Sequence** and choose **Insert Sequence**.

2 Browse to the model's Application Libraries folder and double-click the file `pmm_steady_state_geom_sequence.mph`.

3 In the **Geometry** toolbar, click **Build All**.

GLOBAL DEFINITIONS

Parameters 1 - Main

Move all geometry parameters to a new node to separate them from the main parameters.

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

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

3 Click on the first row, then Shift-click on the last nonempty row to select all rows in the table.

4 Click **Move to New Parameters**.

5 In the **Model Builder** window, click **Parameters 1**.

6 In the **Label** text field, type `Parameters 1 - Main`.

7 Locate the **Parameters** section. In the table, enter the following settings:

Name	Expression	Value	Description
speed	5000[rpm]	83.333 1/s	Shaft speed
f_el	speed*Np/2	416.67 1/s	Electrical excitation frequency
Ipk	50[A]	50 A	Phase current peak

Name	Expression	Value	Description
init_ang	0[rad]	0 rad	Initial current angle
n_cog	Ns/gcd(Np,Ns)*2	12	Cogging torque harmonic order
Nframes	n_cog*6	72	Number of frames
L	250[mm]	0.25 m	Motor axial length

Parameters 2 - Geometry

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

2 In the **Settings** window for **Parameters**, type `Parameters 2 - Geometry` in the **Label** text field.

ADD MATERIAL

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

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

Add magnet and electrical steel materials only. The default **Free Space** node specifies the magnetic properties of air for remaining domains.

3 In the tree, select **AC/DC** > **Hard Magnetic Materials** > **Sintered NdFeB Grades (Chinese Standard)** > **N42 (Sintered NdFeB)**.

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

5 In the tree, select **Nonlinear Magnetic** > **Silicon Steel NGO** > **Silicon Steel NGO 35PN270**.

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

MATERIALS

Silicon Steel NGO 35PN270 (mat2)

1 In the **Materials** toolbar, click **Add Material** to close the **Add Material** window.

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

3 From the **Selection** list, choose **Stator and rotor cores**.

N42 (Sintered NdFeB) (mat1)

1 In the **Model Builder** window, click **N42 (Sintered NdFeB) (mat1)**.

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

3 From the **Selection** list, choose **Rotor Magnets (Internal Rotor – V-shaped Embedded Magnets 1)**.

MAGNETIC MACHINERY, ROTATING, TIME PERIODIC (MMTP)

In the settings of **Magnetic Machinery, Rotating, Time Periodic (mmtp)** enter key parameters which defines the temporal periodicity and resolution, and which allows for automatic configuration of the spatial periodicity.

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

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

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

4 Locate the **Time Periodic Settings** section. In the f_{TP} text field, type `f_el`.

5 In the n_{TP} text field, type `Nframes`.

6 Locate the **Motion Settings** section. In the n_{poles} text field, type `Np`.

7 Click **Add Rotational Boundary Features**.

Multiphase Winding 1

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

2 In the **Settings** window for **Multiphase Winding**, locate the **Domain Selection** section.

3 From the **Selection** list, choose **All coils**.

4 Locate the **Multiphase Winding** section. In the I_{pk} text field, type `Ipk`.

5 In the α_{i} text field, type `init_ang`.

6 From the **Winding layout configuration** list, choose **Automatic three phase**.

7 In the n_{slots} text field, type `Ns`.

8 Click **Add Phases**.

Laminated Core 1

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

2 In the **Settings** window for **Laminated Core**, locate the **Domain Selection** section.

3 From the **Selection** list, choose **Stator and rotor cores**.

4 Locate the **Steinmetz** section. In the α text field, type `1.45`.

5 In the β text field, type `2.06`.

Magnet 1

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

2 In the **Settings** window for **Magnet**, locate the **Domain Selection** section.

3 From the **Selection** list, choose **Rotor Magnets (Internal Rotor – V-shaped Embedded Magnets 1)**.

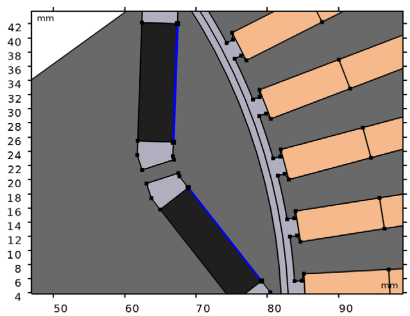
For the initial locked rotor simulation disable the magnet electric conductivity in order to evaluate torque accuracy.

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

North 1

1 In the **Model Builder** window, expand the **Magnet 1** node, then click **North 1**.

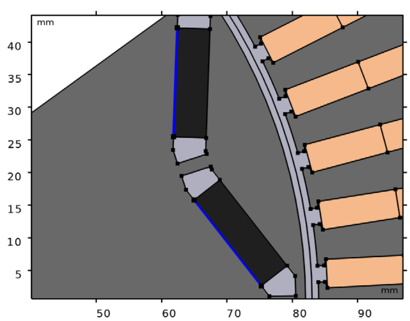
2 Select Boundaries 22 and 26 only.



South 1

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

2 Select Boundaries 7 and 17 only.



Rotating Domain 1

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

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

3 From the **Selection** list, choose **All domains (Internal Rotor – V-shaped Embedded Magnets 1)**.

4 Locate the **Rotating Domain** section. From the **Time periodic rotation** list, choose **Nonrotating**.

Refine the default mesh in domains with electrical steel and in the airgap region.

MESH 1

In the **Model Builder** window, under **Component 1 (comp1)** right-click **Mesh 1** and choose **Edit Physics-Induced Sequence**.

Size 1

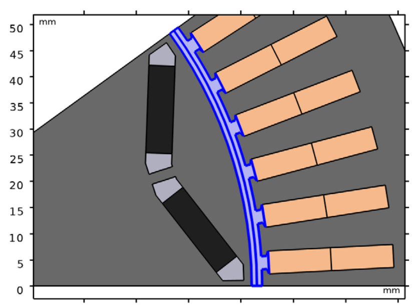
1. In the **Mesh** toolbar, click **Sizing** and choose **Size**.
2. Drag and drop below **Size**.
3. In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.
4. From the **Geometric entity level** list, choose **Domain**.
5. From the **Selection** list, choose **Stator and rotor cores**.
6. Locate the **Element Size** section. Click the **Custom** button.
7. Locate the **Element Size Parameters** section.
8. Select the **Maximum element size** checkbox. In the associated text field, type 3.

Size 2

1. Right-click **Size 1** and choose **Duplicate**.

   To achieve reasonable torque accuracy ensure there are at least two elements between the **Rotational Magnetic Continuity** boundaries and the nearest magnetic material such as the electrical steel or magnet.

2. In the **Settings** window for **Size**, locate the **Geometric Entity Selection** section.
3. Click **Clear Selection**.
4. Select Domains 8 and 10 only.



5 Locate the **Element Size Parameters** section. In the **Maximum element size** text field, type `airgap/3`.

6 Click **Build All**.

ADD STUDY

1 In the **Study** 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 the **Add Study** button in the window toolbar.

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

STUDY 1

Step 1: Stationary

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

RESULTS

Torque

1 In the **Results** toolbar, click **1D Plot Group**.

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

3 Locate the **Legend** section. Clear the **Show legends** checkbox.

Global 1

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

2 In the **Settings** window for **Global**, click **Add Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)** > **Magnetic Machinery, Rotating, Time Periodic** > **Mechanical** > **mmtp.drcon1.Tax_tpph - Axial torque, function of phase - N·m**.

3 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Phase**.

4 In the **Phase** text field, type `range(0,1/Nframes,1)*2*pi`.

5 Click to expand the **Coloring and Style** section. From the **Width** list, choose **2**.

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

Graph Marker 1

1 Right-click **Global 1** and choose **Graph Marker**.

2 In the **Settings** window for **Graph Marker**, locate the **Text Format** section.

3 Select the **Show x-coordinate** checkbox.

4 Click to expand the **Coloring and Style** section. From the **Anchor point** list, choose **Middle left**.

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

Main Results

1 In the **Results** toolbar, click **Evaluation Group**.

2 In the **Settings** window for **Evaluation Group**, type `Main Results` in the **Label** text field.

Global Evaluation 1

1 Right-click **Results** and choose **Global Evaluation**.

2 In the **Settings** window for **Global Evaluation**, click **Add Expression** in the upper-right corner of the **Expressions** section. From the menu, choose **Component 1 (comp1)** > **Magnetic Machinery, Rotating, Time Periodic** > **Mechanical** > **mmtp.drcon1.Tax_tpavg - Axial torque, time periodic average - N·m**.

3 In the **Main Results** toolbar, click **Evaluate**.

Update the `init_ang` variable and compute results with rotation and full torque.

GLOBAL DEFINITIONS

Parameters 1 - Main

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

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	4.625[rad]	4.625 rad	Initial current angle

MAGNETIC MACHINERY, ROTATING, TIME PERIODIC (MMTP)

Rotating Domain 1

1 In the **Model Builder** window, under **Component 1 (comp1)** > **Magnetic Machinery, Rotating, Time Periodic (mmtp)** click **Rotating Domain 1**.

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

3 From the **Time periodic rotation** list, choose **Synchronous (pole pair)**.

Magnet 1

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

2 In the **Settings** window for **Magnet**, locate the **Constitutive Relation Jc-E** section.

3 From the σ list, choose **From material**.

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

RESULTS

Magnetic Flux Density Norm (mmtp)

To plot the magnetic field at a different phase angle, update the dataset settings.

Study 1/Solution 1 (sol1)

1 In the **Model Builder** window, expand the **Results** > **Datasets** node, then click **Study 1/ Solution 1 (sol1)**.

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

3 In the **Solution at angle (phase)** text field, type 90.

Magnetic Flux Density Norm (mmtp)

1 In the **Model Builder** window, under **Results** click **Magnetic Flux Density Norm (mmtp)**.

2 In the **Magnetic Flux Density Norm (mmtp)** toolbar, click **Plot**.

Voltages

1 In the **Results** toolbar, click **1D Plot Group**.

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

Global 1

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

2 In the **Settings** window for **Global**, click **Add Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)** > **Magnetic Machinery, Rotating, Time Periodic** > **Winding** > **Voltage** > **mmtp.wnd1.aPh1.V_tpph - Winding phase voltage, function of phase - V**.

3 Locate the **y-Axis Data** section. In the table, enter the following settings:

Expression	Unit	Description
mmtp.wnd1.aPh2.V_tpph	V	Winding phase voltage, function of phase
mmtp.wnd1.aPh3.V_tpph	V	Winding phase voltage, function of phase

4 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Phase**.

5 In the **Phase** text field, type range(0,1/Nframes,1)*2*pi.

6 In the **Voltages** toolbar, click **Plot**.

Electromagnetic Loss

1 In the **Results** toolbar, click **2D Plot Group**.

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

Surface 1

1 Right-click **Electromagnetic Loss** and choose **Surface**.

2 In the **Settings** window for **Surface**, click **Replace Expression** in the upper-right corner of the **Expression** section. From the menu, choose **Component 1 (comp1)** > **Magnetic Machinery, Rotating, Time Periodic** > **Heating and losses** > **mmtp.Qh - Volumetric loss density, electromagnetic - W/m³**.

3 Locate the **Coloring and Style** section. From the **Color table** list, choose **GrayBody**.

Adjust the color table to make loss distribution in rotor more visible.

4 From the **Color table transformation** list, choose **Nonlinear**.

5 Set the **Color calibration parameter** value to **-0.8**.

6 In the **Electromagnetic Loss** toolbar, click **Plot**.

Magnetic Flux Density Norm (mmtp)

Add more evaluation features to the **Main Results** node to gather key results from the simulation.

Global Evaluation 2

1 In the **Model Builder** window, under **Results** > **Main Results** right-click **Global Evaluation 1** and choose **Duplicate**.

2 In the **Settings** window for **Global Evaluation**, locate the **Expressions** section.

3 In the table, enter the following settings:

Expression	Unit	Description
mmtp.drcon1.Tax_tpavg*2*pi*speed	kW	Shaft power

Main Results

In the **Model Builder** window, click **Main Results**.

Surface Integration 1

1 In the **Main Results** toolbar, click **Integration** and choose **Surface Integration**.

2 In the **Settings** window for **Surface Integration**, locate the **Selection** section.

3 From the **Selection** list, choose **All coils**.

4 Click **Add Expression** in the upper-right corner of the **Expressions** section. From the menu, choose **Component 1 (comp1)** > **Magnetic Machinery, Rotating, Time Periodic** > **Heating and losses** > **mmtp.Qh - Volumetric loss density, electromagnetic - W/m³**.

Multiply the loss density variable with the number of sectors and axial length of motor to get the total loss.

5 Locate the **Expressions** section. In the table, enter the following settings:

Expression	Unit	Description
mmtp.Qh*L*Nsec	kW	Winding loss

Surface Integration 2

1 Right-click **Surface Integration 1** and choose **Duplicate**.

2 In the **Settings** window for **Surface Integration**, locate the **Selection** section.

3 From the **Selection** list, choose **Stator core**.

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

Expression	Unit	Description
mmtp.Qh*L*Nsec	kW	Stator core loss

Surface Integration 3

1 Right-click **Surface Integration 2** and choose **Duplicate**.

2 In the **Settings** window for **Surface Integration**, locate the **Selection** section.

3 From the **Selection** list, choose **Rotor iron (Internal Rotor – V-shaped Embedded Magnets 1)**.

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

Expression	Unit	Description
mmtp.Qh*L*Nsec	kW	Rotor core loss

Surface Integration 4

1 Right-click **Surface Integration 3** and choose **Duplicate**.

2 In the **Settings** window for **Surface Integration**, locate the **Selection** section.

3 From the **Selection** list, choose **Rotor Magnets (Internal Rotor – V-shaped Embedded Magnets 1)**.

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

Expression	Unit	Description
mmtp.Qh*L*Nsec	kW	Magnet loss

Main Results

1. In the **Model Builder** window, click **Main Results**.
2. In the **Settings** window for **Evaluation Group**, locate the **Transformation** section.
3. Select the **Transpose** checkbox.
4. From the **Transformation type** list, choose **General**.
5. Select the **Keep child nodes** checkbox.
6. In the **Expression** text field, type `gev2/(gev2+int1+int2+int3+int4)*100`.
7. In the **Row header** text field, type `Efficiency (%)`.
8. In the **Main Results** toolbar, click **Evaluate**.

The remaining steps describe how to reproduce Figure 8.

Periodicity of Induced Currents

1. In the **Results** toolbar, click **1D Plot Group**.
2. In the **Settings** window for **1D Plot Group**, type `Periodicity of Induced Currents` in the **Label** text field.
3. Click to expand the **Title** section. From the **Title type** list, choose **Label**.
4. Locate the **Plot Settings** section.
5. Select the **y-axis label** checkbox. In the associated text field, type `Current density (A/m^2)`.

Point Graph 1

1. In the **Periodicity of Induced Currents** toolbar, click **Point Graph**.
2. In the **Settings** window for **Point Graph**, locate the **Selection** section.
3. Click **Paste Selection**.
4. In the **Paste Selection** dialog, type `25` in the **Selection** text field.
5. Click **OK**.
6. In the **Settings** window for **Point Graph**, click **Replace Expression** in the upper-right corner of the **y-Axis Data** section. From the menu, choose **Component 1 (comp1)** > **Magnetic Machinery, Rotating, Time Periodic** > **Currents and charge** > **mmtp.JZ_tpph - Current density out of plane, function of phase - A/m²**.

7 Locate the **y-Axis Data** section. In the **Expression** text field, type `mmtp.JZ_tpph*50`.

8 Select the **Description** checkbox. In the associated text field, type `Induced current in magnet (scaled)`.

9 Locate the **x-Axis Data** section. From the **Parameter** list, choose **Phase**.

10 In the **Phase** text field, type `range(0,1/Nframes,1)*2*pi`.

11 Click to expand the **Coloring and Style** section. From the **Width** list, choose **2**.

12 Click to expand the **Legends** section. Select the **Show legends** checkbox.

13 Find the **Include** subsection. Clear the **Point** checkbox.

14 Clear the **Solution** checkbox.

15 Select the **Description** checkbox.

Point Graph 2

1 Right-click **Point Graph 1** and choose **Duplicate**.

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

3 Click **Clear Selection**.

4 Click **Paste Selection**.

5 In the **Paste Selection** dialog, type `83` in the **Selection** text field.

6 Click **OK**.

7 In the **Settings** window for **Point Graph**, locate the **y-Axis Data** section.

8 In the **Expression** text field, type `mmtp.JZ_tpph`.

9 In the **Description** text field, type `Excitation current in phase 1`.

Periodicity of Induced Currents

In the **Periodicity of Induced Currents** toolbar, click **Line Segments**.

Line Segments 1

Add vertical line segments marking the zero crossing of first half period of the excitation current of phase 1.

1 In the **Settings** window for **Line Segments**, locate the **x-Coordinates** section.

2 In the table, enter the following settings:

Expression	Unit	Description
0.0873	1	
0.0873	1	

3 Locate the **y-Coordinates** section. In the table, enter the following settings:

Expression	Unit	Description
-5e6	1	
5e6	1	

4 Click to expand the **Coloring and Style** section. From the **Color** list, choose **Red**.

5 Find the **Line style** subsection. From the **Line** list, choose **Dashed**.

Line Segments 2

1 Right-click **Results** > **Periodicity of Induced Currents** > **Line Segments 1** and choose **Duplicate**.

2 In the **Settings** window for **Line Segments**, locate the **x-Coordinates** section.

3 In the table, enter the following settings:

Expression	Unit	Description
0.0873+pi		
0.0873+pi		

4 In the **Periodicity of Induced Currents** toolbar, click **Plot**.