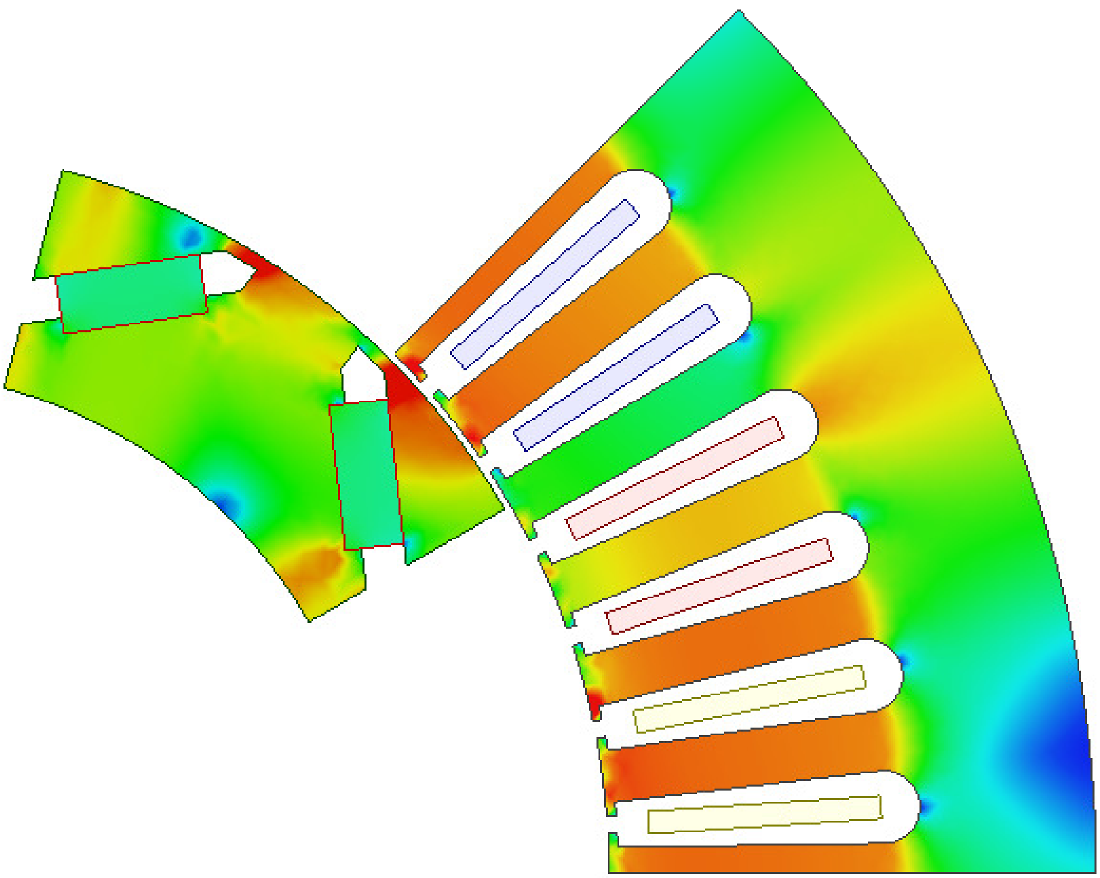
Study of a Permanent Magnet Motor with MAXWELL 2D: Example of the 2004 Prius IPM Motor

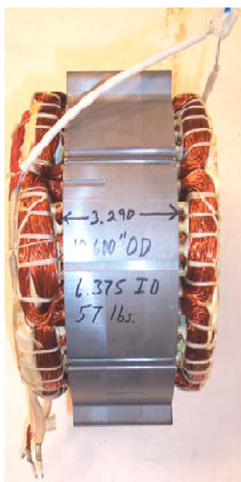


Motors - Permanent Magnet Motor (Prius IPM)

Study of an electrical machine

- The Electro Mechanical software package provided by Ansoft enables extensive electrical malchinesimulation. This application note details the simulaton of an electrical machine with Maxwel2D. We will cover static and transient simulations.
- This application note will use the 2004 Toyota Prius motor as basis. It is a 8-pole permanent magnet motor with embedded magnets. The single layer windings are made of 3 phases. The stator has 48 slots. This motor is public, we therefore have the full set of parameters. We will also use Oak Ridge National Laboratory testing results in this note.

> Note: This application has not been done with the collaboration of Toyota



- References:
  - **Report on Toyota/Prius Motor Torque Capability, Torque Property, No-Load Back EMF, and Mechanical Losses,**
    - J. S. Hsu, Ph.D., C. W. Ayers, C. L. Coomer, R. H. Wiles
    - Oak Ridge National Laboratory
  - **Report on Toyota/Prius Motor Design and manufacturing Assessment**
    - J. S. Hsu, C. W. Ayers, C. L. Coomer
    - Oak Ridge National Laboratory
  - **Evaluation of 2004 Toyota Prius Hybrid Electric Drive System Interim Report**
    - C. W. Ayers, J. S. Hsu, L. D. Marlino, C. W. Miller,G. W. Ott, Jr.,C. B. Oland
    - Oak Ridge National Laboratory

Overview of the Study:

- GETTING STARTED
  - Creating the 3D Model
  - Reducing the size of the 3D Model
  - Material properties of the machine
  - Applying Master/Slave Boundary Condition
- STATIC ANALYSIS
- DYNAMIC ANALYSIS
- COGGING TORQUE

Launching Maxwell

- **To access Maxwell:**
  1. Click the Microsoft **Start** button, select **Programs**, and select **Ansoft > Maxwell 15.0** and select **Maxwell 15.0**

Setting Tool Options

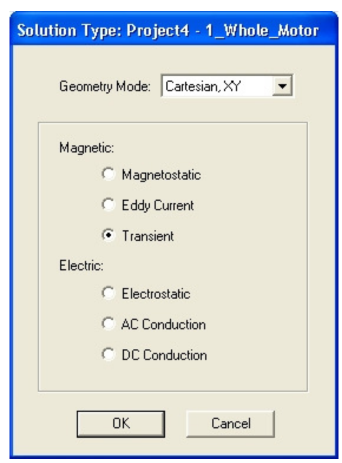
- **To set the tool options:**
  - **Note:** In order to follow the steps outlined in this example, verify that the following tool options are set :
  - Select the menu item *Tools > Options > Maxwell 2D Options*
    - Maxwell Options Window:
      1. Click the **General Options** tab
         - Use Wizards for data input when creating new boundaries: ☑ **Checked**
         - Duplicate boundaries/mesh operations with geometry: ☑ **Checked**
      2. Click the **OK** button
  - Select the menu item *Tools > Options > Modeler Options.*
    - Modeler Options Window:
      1. Click the **Operation** tab
         - Automatically cover closed polylines: ☑ **Checked**
      2. Click the **Display** tab
         - Default transparency = 0.8
      3. Click the **Drawing** tab
         - Edit property of new primitives: ☑ **Checked**
      4. Click the **OK** button

Opening a New Project

- **To open a new project:**
  - After launching Maxwell, a project will be automatically created. You can also create a new project using below options.
    1. In an Maxwell window, click the 🗋 On the Standard toolbar, or select the menu item ***File > New***.
  - Select the menu item ***Project > Insert Maxwell 2D Design***, or click on the icon
- **Rename Design**
  - Right click on the design Maxwell2D Design1 and select **Rename**
  - Change the name of the design to **"1_Whole_Motor"**

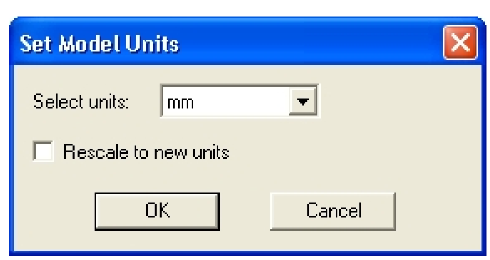
Set Solution Type

- **To set the Solution Type:**
  - Select the menu item ***Maxwell 2D > Solution Type***
  - Solution Type Window:
    1. Geometry Mode: **Cartesian, XY**
    2. Choose **Magnetic > Transient**
    3. Click the **OK** button



Set Default Units

- **To Set Default Units**
  - Select the menu item ***Modeler > Units***
  - In Units window,
    - Select units: **mm**
    - Press **OK**



Creating the 2D Model

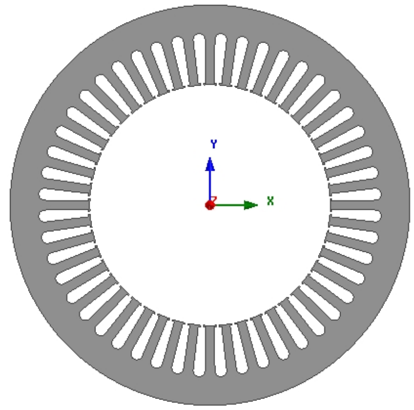
- Maxwell has number of **User Defined Primitives** for motor parts. These primitives can describe all the main parts of motors.
- **Create the Stator:**
  - A User Defined Primitive will be used to create the stator
  - Select the menu item ***Draw > User Defined Primitive > Syslib > Rmxprt > SlotCore***
  - Use the values given in the panel below to create the stator

Parameters | Info

Name	Value	Unit	Evaluated Value	Description
DiaGap	161.9	mm	161.9mm	Core diameter on gap si...
DiaYoke	269.24	mm	269.24mm	Core diameter on yoke ...
Length	0	mm	0mm	Core length
Skew	0	deg	0deg	Skew angle in core len...
Slots	48		48	Number of slots
SlotType	2		2	Slot type: 1 to 6
Hs0	1.03	mm	1.03mm	Slot opening height
Hs01	0	mm	0mm	Slot closed bridge height
Hs1	0	mm	0mm	Slot wedge height
Hs2	29.5	mm	29.5mm	Slot body height
Bs0	1.93	mm	1.93mm	Slot opening width
Bs1	5	mm	5mm	Slot wedge maximum w...
Bs2	8	mm	8mm	Slot body bottom width,...
Rs	5	mm	5mm	Slot body bottom fillet
FilletType	0		0	0: a quarter circle; 1: ta...
HalfSlot	0		0	0 for symmetric slot, 1 f...
SegAngle	0	deg	0deg	Deviation angle for slot ...
LenRegion	200	mm	200mm	Region length
InfoCore	0		0	0: core; 100: region.

Show Hidden

- **Change Attributes**
  - Change the name of the sheet to **Stator**
  - Change the color of the sheet to **Gray**



- **Create the Rotor**
  - A User Defined Primitive will be used to create the rotor
  - Select the menu item ***Draw > User Defined Primitive > Syslib > Rmxprt > IPMCore***
  - Use the values given in the below to create the rotor

Parameters | Info

Name	Value	Unit	Evaluated Value	Description
DiaGap	160.4	mm	160.4mm	Core diameter on gap sid...
DiaYoke	110.64	mm	110.64mm	Core diameter on yoke sid...
Length	0	mm	0mm	Core length
Poles	8		8	Number of poles
PoleType	3		3	Pole type: 1 to 6.
D1	157.44	mm	157.44mm	Limited diameter of PM du...
O1	0	mm	0mm	Bottom width for separate...
O2	7.28	mm	7.28mm	Distance from duct botto...
B1	4.7	mm	4.7mm	Duct thickness
Rib	14	mm	14mm	Rib width
HRib	3	mm	3mm	Rib height (for types 3~5)
DminMag	4.5	mm	4.5mm	Minimum distance betwee...
ThickMag	6.48	mm	6.48mm	Magnet thickness
WidthMag	32	mm	32mm	Total width of all magnet ...
LenRegion	200	mm	200mm	Region length
InfoCore	0		0	0: core; 1: magnets; 2: du...

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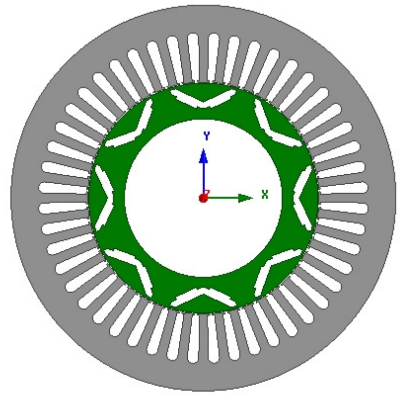
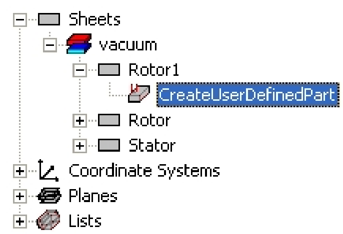
- **Change Attributes**
  - Change the name of the sheet to **Rotor**
  - Change the color of the sheet to **Green**

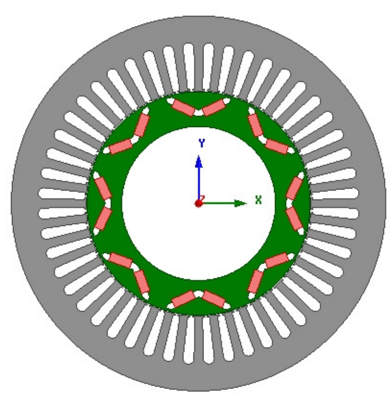


- **Create the Magnets**
  - Select the sheet **Rotor** from history tree
  - Select the menu item ***Edit > Copy***
  - Select the menu item ***Edit > Paste***
  - New sheet named **Rotor1** is created
  - Expand the history tree for **Roto1**
  - Double click on the command **CreateUserDefinedPart** to edit properties
  - In Properties window,
    - Change the value for InfoCore to **1** (magnets)
    - Press **OK**



HRib	3	mm	3mm	Rib height
DminMag	4.5	mm	4.5mm	Minimum distance bet
ThickMag	6.48	mm	6.48mm	Magnet thickness
WidthMag	32	mm	32mm	Total width of all magı
LenRegion	200	mm	200mm	Region length
InfoCore	1		1	0: core; 1: magnets; 2

- **Change Attributes**
  - Change the name of the sheet to **Magnet**
  - Change the color of the sheet to **Light Red**



Motors - Permanent Magnet Motor (Prius IPM)

- **Create Windings**
  - A User Defined Primitive will be used to create the windings.
  - Select the menu item ***Draw > User Defined Primitive > Syslib > Rmxprt > LapCoil***
  - Use the values given in the panel below to create the coil

Parameters | Info

Name	Value	Unit	Evaluated Value	Description
DiaGap	161.9	mm	161.9mm	Core diameter on gap si...
DiaYoke	269.24	mm	269.24mm	Core diameter on yoke ...
Length	0	mm	0mm	Core length
Skew	0	deg	0deg	Skew angle in core len...
Slots	48		48	Number of slots
SlotType	2		2	Slot type: 1 to 7
Hs0	1.28	mm	1.28mm	Slot opening height
Hs1	0.1	mm	0.1mm	Slot wedge height
Hs2	29.7	mm	29.7mm	Slot body height
Bs0	2.11	mm	2.11mm	Slot opening width
Bs1	3.14	mm	3.14mm	Slot wedge maximum w...
Bs2	5.65	mm	5.65mm	Slot body bottom width,...
Rs	2.5	mm	2.5mm	Slot body bottom fillet
FilletType	0		0	0: a quarter circle; 1: ta...
Layers	1		1	Number of winding layers
CoilPitch	5		5	Coil pitch measured in s...
EndExt	5	mm	5mm	One-side end extended...
SpanExt	18	mm	18mm	Axial length of end spa...
SegAngle	10	deg	10deg	Deviation angle for end...
LenRegion	200	mm	200mm	Region length
InfoCoil	1		1	0: winding; 1: coil; 2: te...

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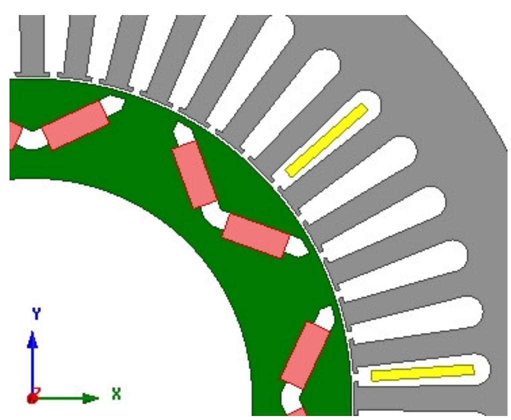
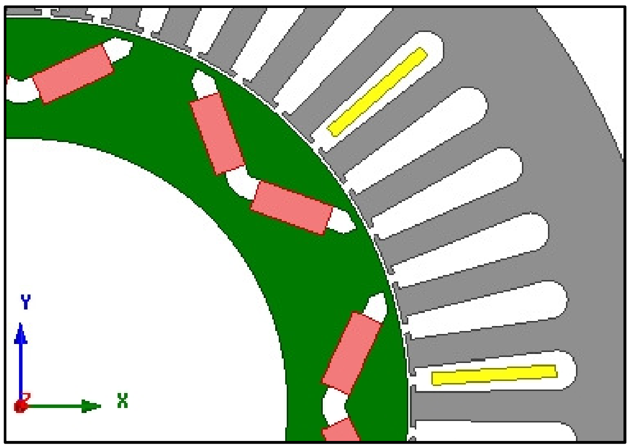
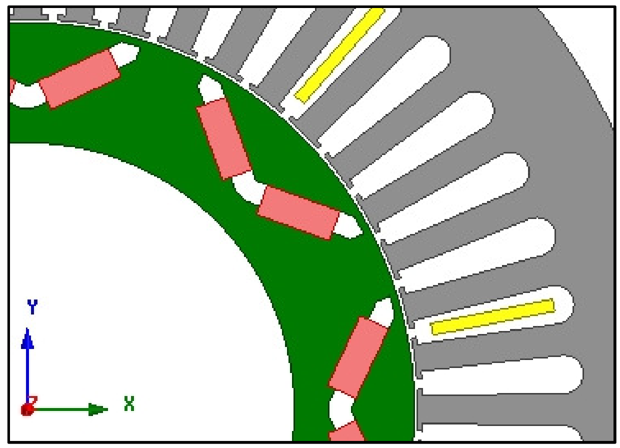
- **Change Attributes**
  - Change the material of the sheet to **Copper**
  - Change the color of the sheet to **Yellow**



- Rotate Coil
  - Select the sheet **LapCoil1** from the history tree
  - Select the menu item ***Edit > Arrange > Rotate***
  - In Rotate window,
    1. Axis: **Z**
    2. Angle: **7.5 deg**
    3. Press **OK**

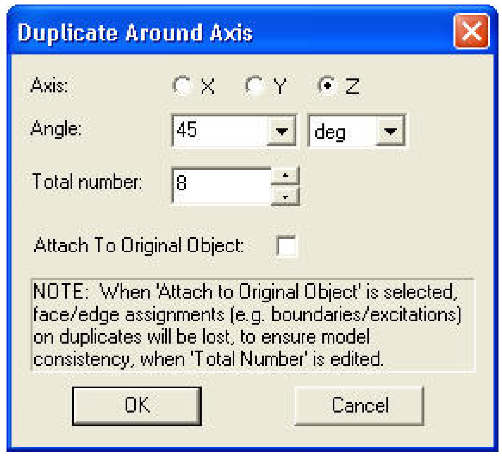




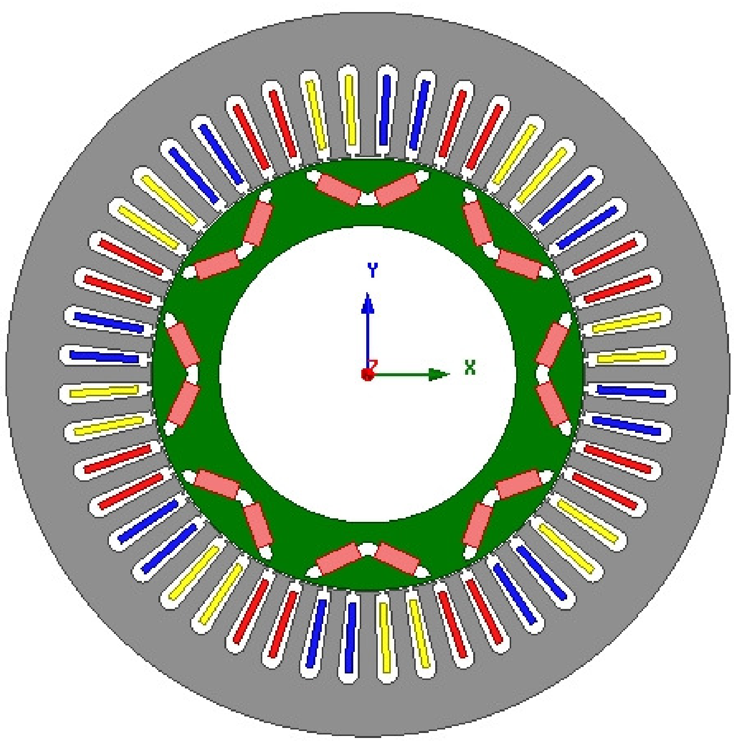
- Duplicate Coil
  - Select the sheet **LapCoil1** from the history tree
  - Select the menu item ***Edit > Duplicate > Around Axis***
  - In Duplicate Around Axis window,
    1. Axis: **Z**
    2. Angle : **15 deg**
    3. Total Number: **3**
    4. Press **OK**

- Change Attributes
  - Change the name of the sheets LapCoil1, LapCoil1_1 and LapCoil1_2 to **PhaseA, PhaseC,** and **PhaseB** respectively
  - Change the color of the sheets PhaseB and Phase C to **Blue** and **Red**

- Duplicate Coils
  - Press **Ctrl** and select the sheets **PhaseA, PhaseB** and **PhaseC** from the history tree
  - Select the menu item ***Edit > Duplicate > Around Axis***
  - In Duplicate Around Axis window,
    1. Axis: **Z**
    2. Angle : **45 deg**
    3. Total Number: **8**
    4. Press **OK**

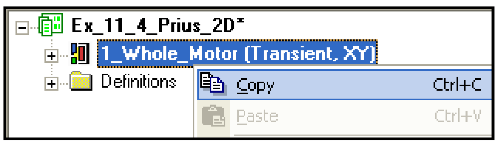


- Motor geometry is complete



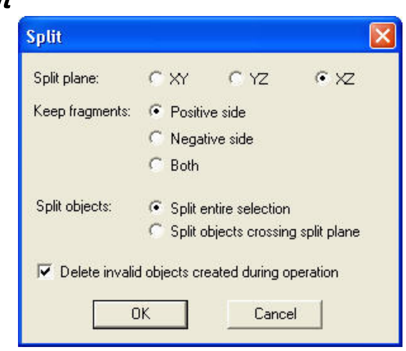
Copy Design

- To Copy Design
  - Select the Maxwell design **“1_Whole_Motor”** from the Project Manager tree, right click and select **“Copy”**
  - Select the project name from the Project manager tree, right click and select **“Paste”**
  - Change the name of the design to **“2_Partial_Motor”**

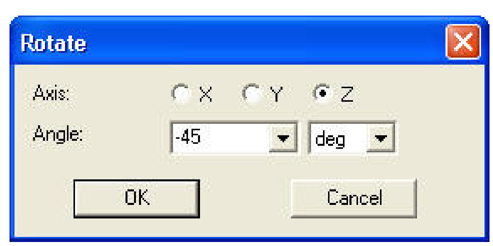


Reduce Model Size

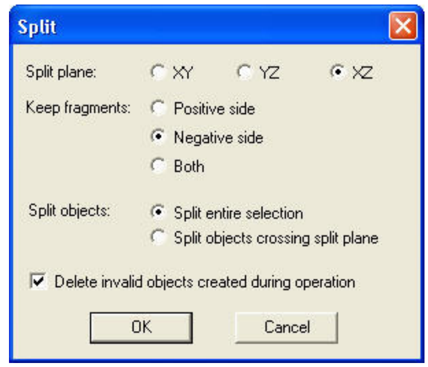
- We can take advantage of the topology of the motor to reduce the size of the problem. This motor has 8 pair of poles. We can only use one height of the motor. This is valid because the stator has:
  - 48 slots (8 is a divider of 48).
  - The 3-phase winding has also a periodicity of 45 degrees.
- From now on, the Maxwelldesign ‘**2_Partial_Motor**’ will be used. We have saved a copy of the whole geometry as it will be used later for other studies.
- **Split Model by XZ**
  - Select the menu item ***Edit > Select All***
  - Select the menu item ***Modeler > Boolean > Split***
  - In Split window,
    1. Split Plane: **XZ**
    2. Keep fragments: **Positive Side**
    3. Split Objects: **Split entire Selection**
    4. Press **OK**



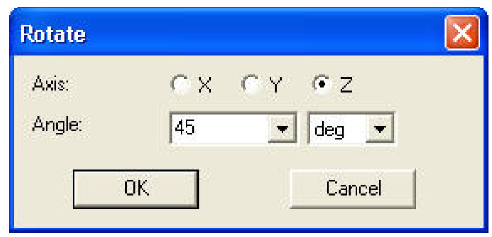
- **Rotate Model**
  - We have achieved half model now
  - Select the menu item ***Edit > Select All***
  - Select the menu item ***Edit > Arrange > Rotate***
  - In Rotate window,
    1. Axis: **Z**
    2. Angle: **-45 deg**
    3. Press **OK**



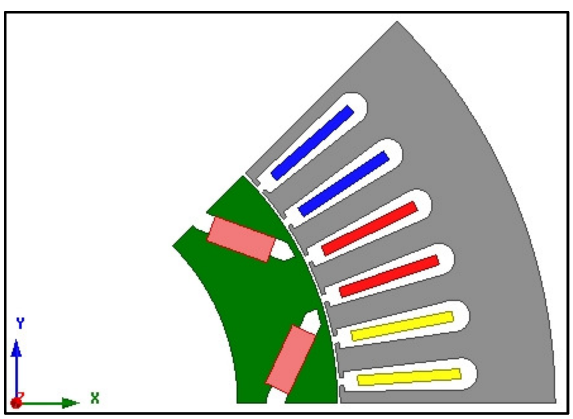
- Split Model by XZ
  - Select the menu item *Edit > Select All*
  - Select the menu item *Modeler > Boolean > Split*
  - In Split window,
    1. Split Plane: **XZ**
    2. Keep fragments: **Negative Side**
    3. Split Objects: **Split entire Selection**
    4. Press **OK**



- Rotate Model
  - Select the menu item *Edit > Select All*
  - Select the menu item *Edit > Arrange > Rotate*
  - In Rotate window,
    1. Axis: **Z**
    2. Angle: **45 deg**
    3. Press **OK**



- Reduced Model
  - The 3D model now looks like below

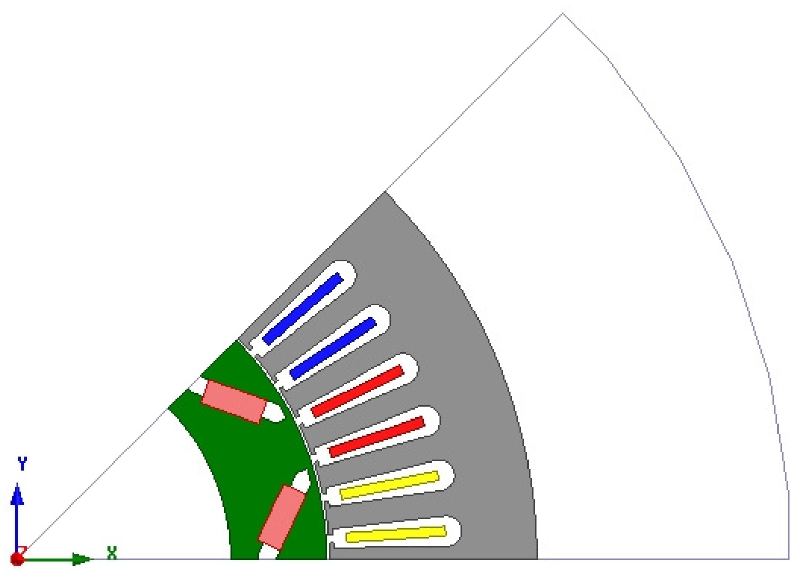


- Change Attributes
  - Change the name of the sheets PhaseA and PhaseA_7 to **PhaseA1** and **PhaseA2**
  - Change the name of the sheets PhaseB and PhaseB_7 to **PhaseB1** and **PhaseB2**
  - Change the name of the object PhaseC and PhaseC_7 to **PhaseC1** and **PhaseC2**

Create Region

- **Create Rectangle**
  - Select the menu item ***Draw > Line***
    1. Using the coordinate entry field, enter the first vertex
       - **X: 0.0, Y: 0.0, Z: 0.0**, Press the **Enter** key
    2. Using the coordinate entry field, enter the second vertex
       - **X: 200.0, Y: 0.0, Z: 0.0**, Press the **Enter** key
    3. Press **Enter** a second time to finish the drawing
- **Sweep Line**
  - Select the line **Polyline1** from history tree
  - Select the menu item ***Draw > Sweep > Around Axis***
  - In Sweep Around Axis window,
    1. Axis: **Z**
    2. Angle of sweep: **45**
    3. Number of segments: **5**
    4. Press **OK**

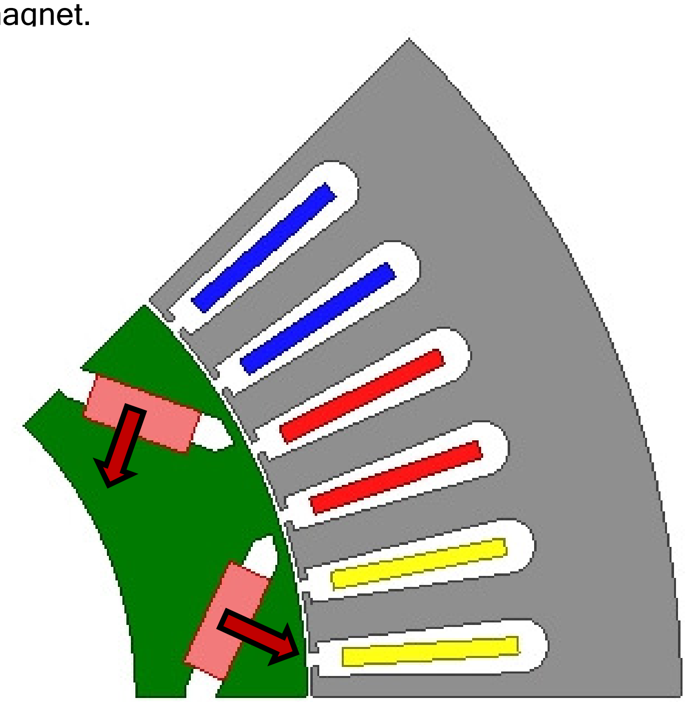
- **Change Attributes**
  - Change the name of the resulting sheet to **Region**
  - Select Display Wireframe: ☑ **Checked**



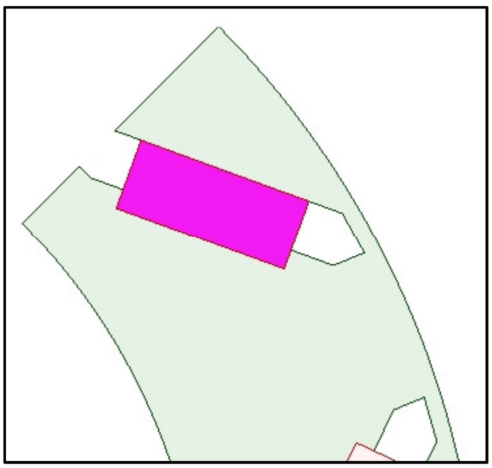
Material Properties for the Motor

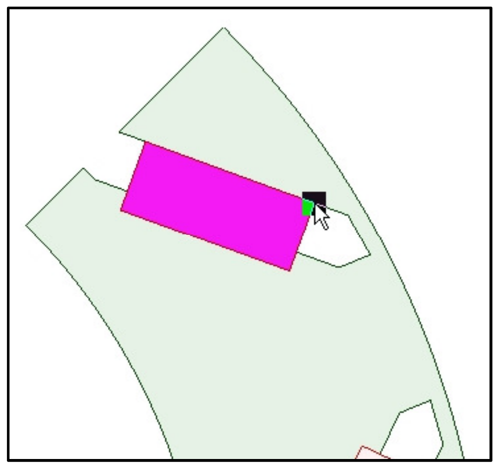
Permanent Magnet Characterization

- The Prius Permanent Magnets (PMs) are high-strength magnets.
- In order to define PMs magnetization orientation, we need to create separate objects for each magnet.
- **Separate Objects**
  - Select the object **Magnets** from the history tree
  - Select the menu item ***Modeler > Boolean > Separate Bodies***
- **Change Attributes**
  - Change the name of the object Magnets to **PM1**
  - Change the name of the object Magnets_Separate1 to **PM2**
- Since the magnets will rotate, the orientation cannot be given through fixed coordinate systems (CS). The use of face CS is required. Face CS are CS that are attached to the face of an object. When the object moves, the Face CS also moves along with the object.
- The Prius's PMs are oriented as shown below. Therefore, we will create a face CS for each magnet.

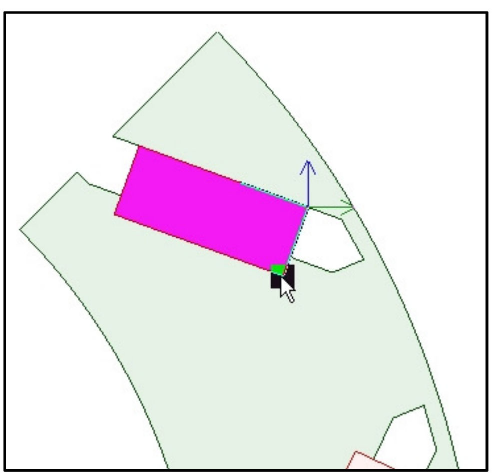


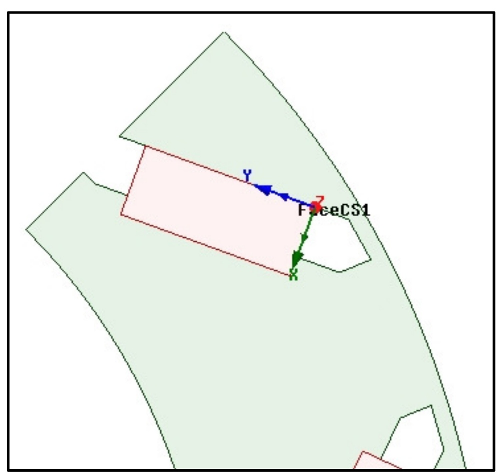
- **Hide All other Objects**
  - Select the menu item ***View > Active View Visibility***
  - In the window,
    1. Disable the visibility for all objects except **Rotor, PM1** and **PM2**
    2. Press **Done**
- **To Create Face Coordinate System**
  - Select the menu item ***Edit > Select > Faces*** or press **"f"** from keyboard
  - Select the face of the sheet **PM1** as shown in below image
  - Select the menu item ***Modeler > Coordinate System > Create > Face CS***
  - Select the vertex on the face of PM1 to define origin





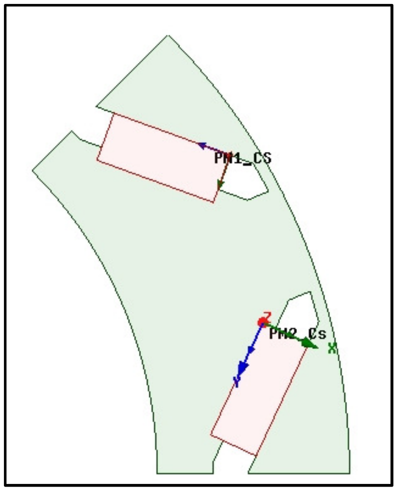
  - Select the vertex of the magnet as shown in below image to define X axis
  - A Face coordinate system will be created as shown in below image
  - Rename the FaceCS1 to **PM1_CS**





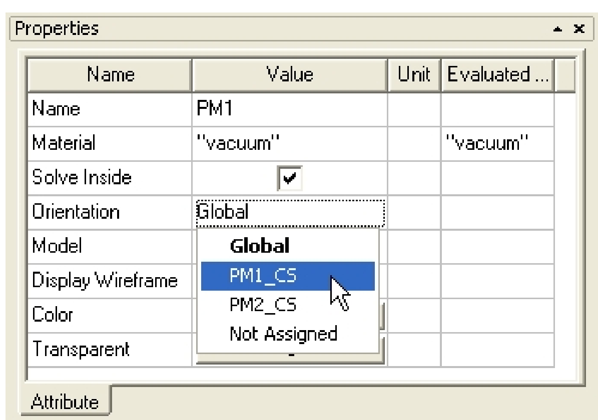
Motors - Permanent Magnet Motor (Prius IPM)

- Similarly Create a Face coordinate system for PM2 and name it as **PM2_CS.**
- Make sure to have the X axis looking toward the air gap



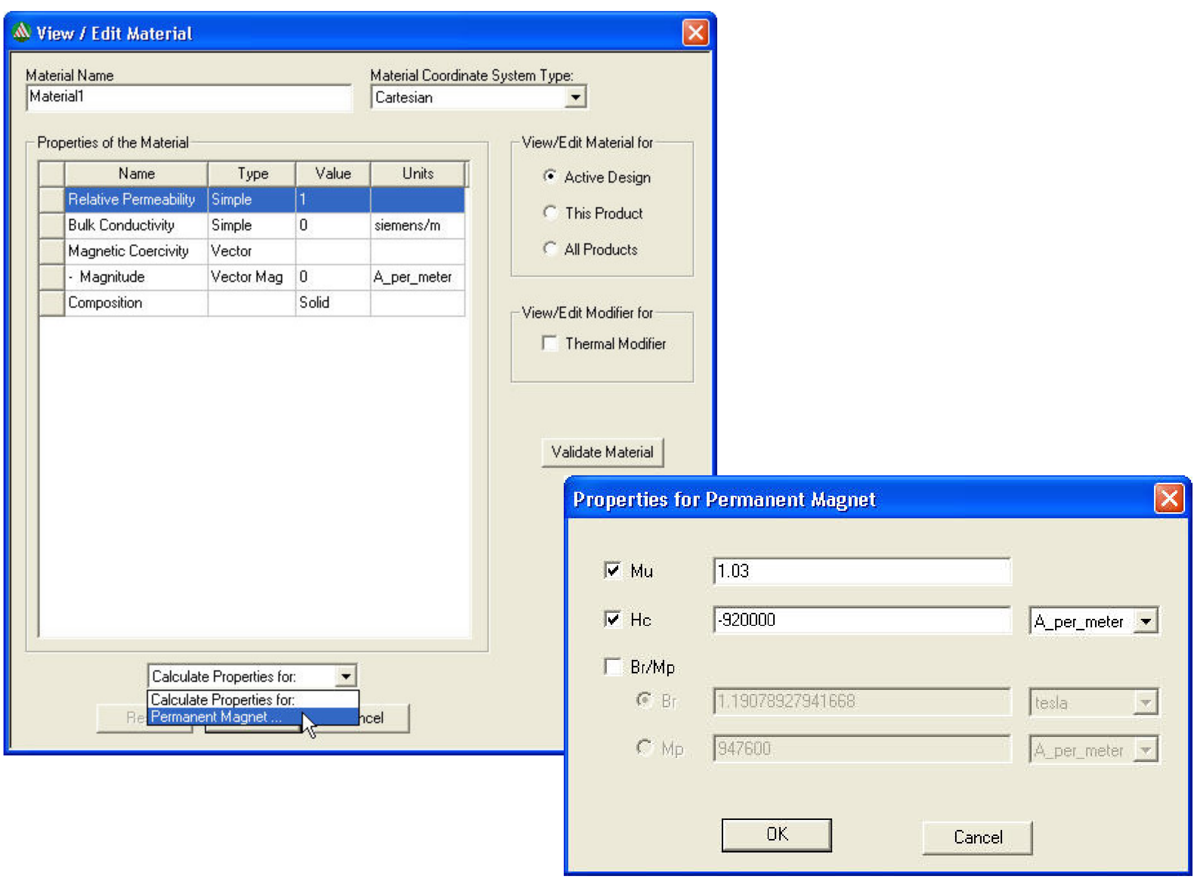
- Select the menu item ***Modeler > Coordinate System > Set Work CS***
  1. Select **Global**

- **Set Magnet Orientations**
  - Select the sheet **PM1** and goto the Properties window,
  - Change the orientation coordinate system from Global to **PM1_CS**

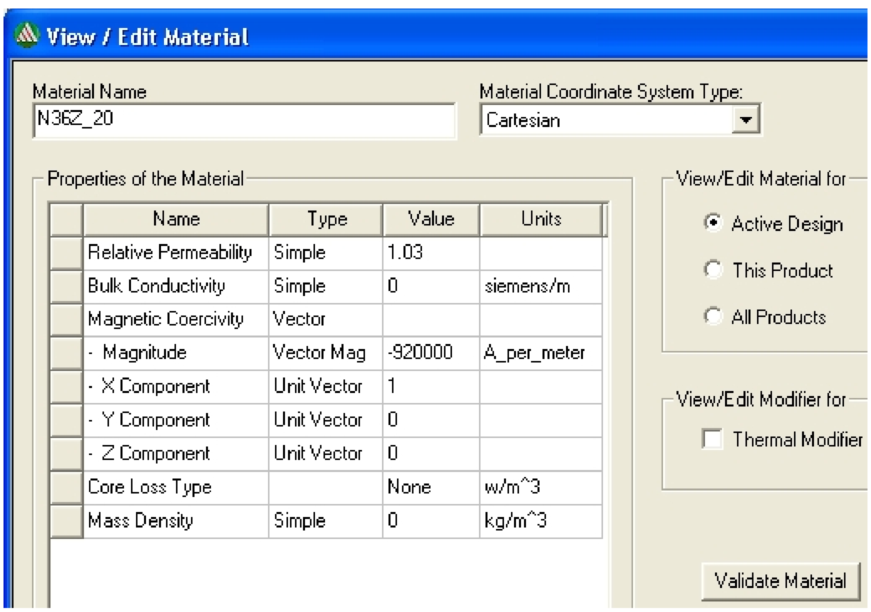


- Similarly change the orientation coordinate system for **PM2** to **PM2_CS**
- Select the menu item ***View > Show All > Active View***
- Select the menu item ***Edit > Select > Objects*** or press **"o"** from keyboard

- Create Material for PM1
  - Select the sheet **PM1** from the history tree, right click and select **Assign Material**
  - In Select definition window, press the button **Add Material** to add new material
  - In View/Edit Material window,
    - A separate menu is available at the bottom of window to assign Magnet Properties
    - Set the option at the bottom Calculate Properties for **Permanent Magnet**
    - In Properties for Permanent Magnet window,
      1. Mu: **1.03**
      2. Hc: **-920000 A_per_meter**
      3. Press **OK**



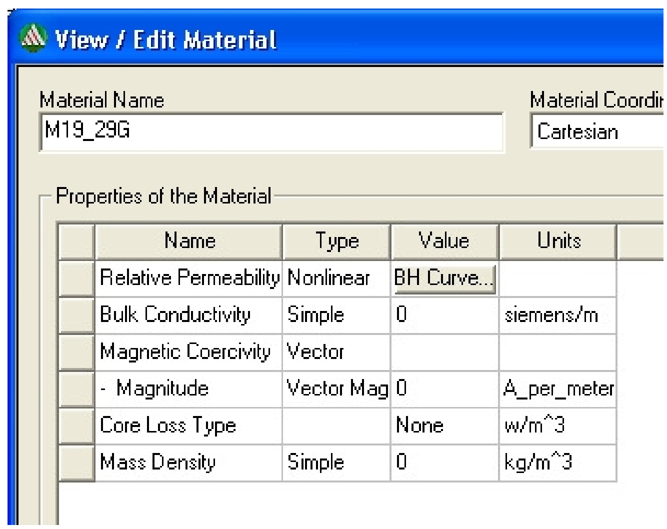
- In View/Edit Material window,
  1. Material Name: **N36Z_20**
     - If the coordinate system *PM1_CS* is such that the **X axis** goes in the opposite direction of the air gap accordingly to the image below, leave the X orientation to **1** and 0 for the Y and Z components. If the X axis was in the opposite direction, you would need to enter -1 for the X component.
  2. Select **Validate Material**
  3. Press **OK**



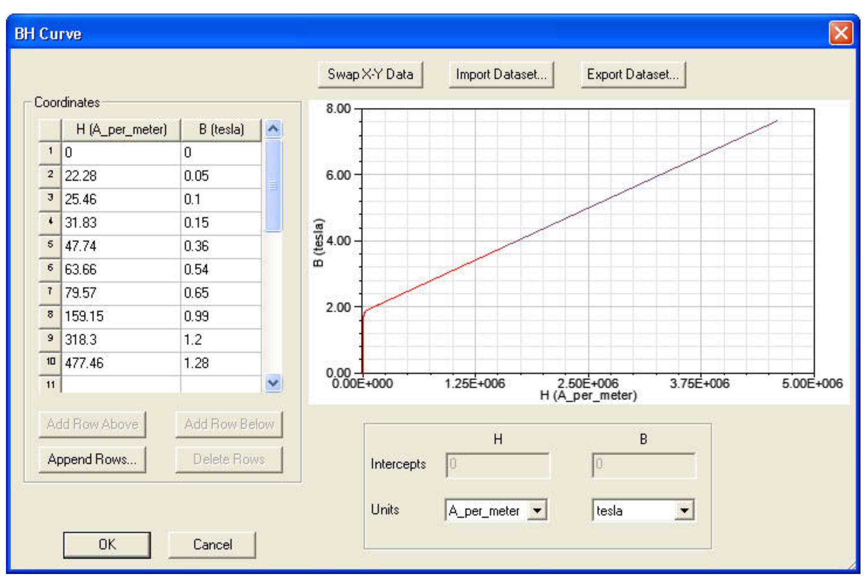
- **Material for PM2**
  - If the definition of *PM2_CS* is opposite with *PM1_CS* (X axis in the direction of the air gap), you can use the same material for *N36Z_20* for *PM2*. If it is not the case, you can clone the material *N36Z_20* and change the orientation to be consistent with the *PM2_CS* axis.
  - Since we created PM2_CS in opposite to PM1_CS, we will use same material
  - Right click on the object **PM2** and select **Assign Material**
  - In Select Definition window,
    - Type **N36Z_20** in Search by Name field
    - Press **OK**

Motors - Permanent Magnet Motor (Prius IPM)

- **Material for Stator and Rotor**
  - Press **Ctrl** and select the sheets **Stator** and **Rotor,** right click and select **Assign Material**
  - In Select Definition window, select **Add Material**
  - In View/Edit Material window,
    1. Material Name: **M19_29G**
    2. Relative Permeability
       - Type: **Nonlinear**
       - Press the button **BH Curve** that appears in Value field
       - In **BH Curve** window, enter that values for **B** and **H** as given in below table
       - Press **OK**

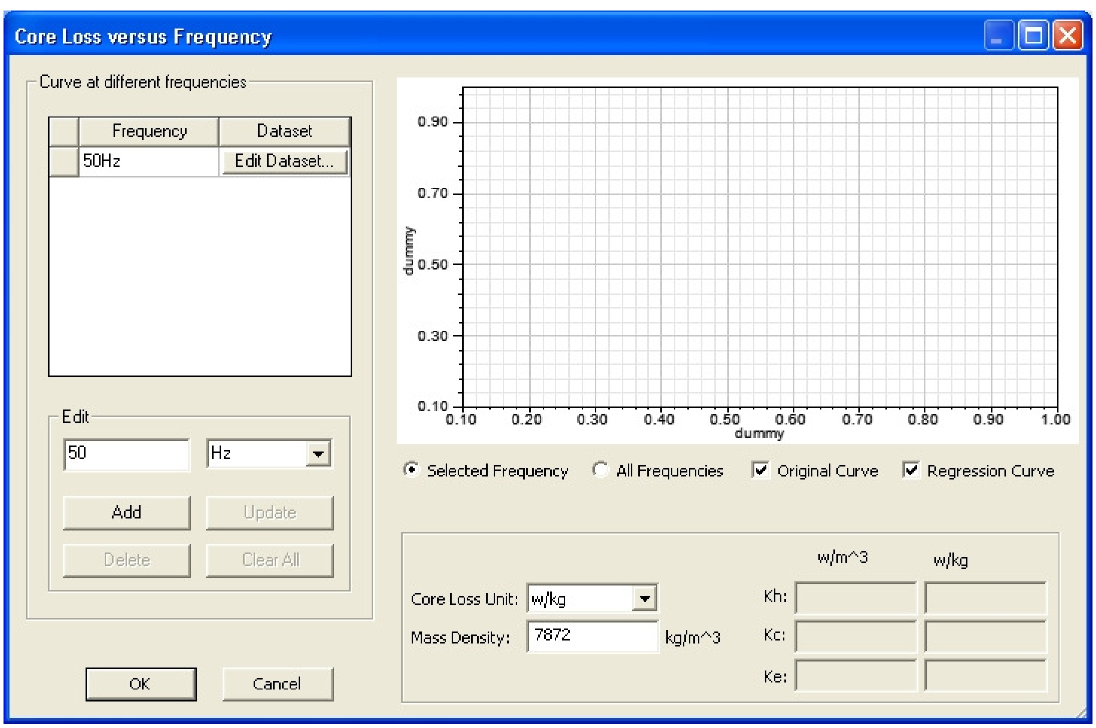


H	B
0	0
22.28	0.05
25.46	0.1
31.83	0.15
47.74	0.36
63.66	0.54
79.57	0.65
159.15	0.99
318.3	1.2
477.46	1.28
636.61	1.33
795.77	1.36
1591.5	1.44
3183	1.52
4774.6	1.58
6366.1	1.63
7957.7	1.67
15915	1.8
31830	1.9
111407	2
190984	2.1
350138	2.3
509252	2.5
560177.2	2.563994494
1527756	3.779889874



- **Material Properties for Core Loss calculations**
  - This section is only necessary if you wish to compute the coreloss of the motor.
  - In the Transient solver, we are able to compute coreloss (or hystereris loss), stranded loss and eddy current loss (or proximity loss). We will only consider coreloss in this document.
  - In View/Edit Material window,
    - Set Core Loss Type to **Electrical Steel**
    - Set the option at the bottom Calculate Properties for **Core Loss versus Frequency**

    - In Core Loss versus Frequency window,
      - Set Core Loss units to **W/kg**
      - Set Mass Density to **7872 kg/m^3**
      - In Edit window, set **50 Hz** and select the button **Add**
      - Select the button **Edit Dataset** to open dataset window

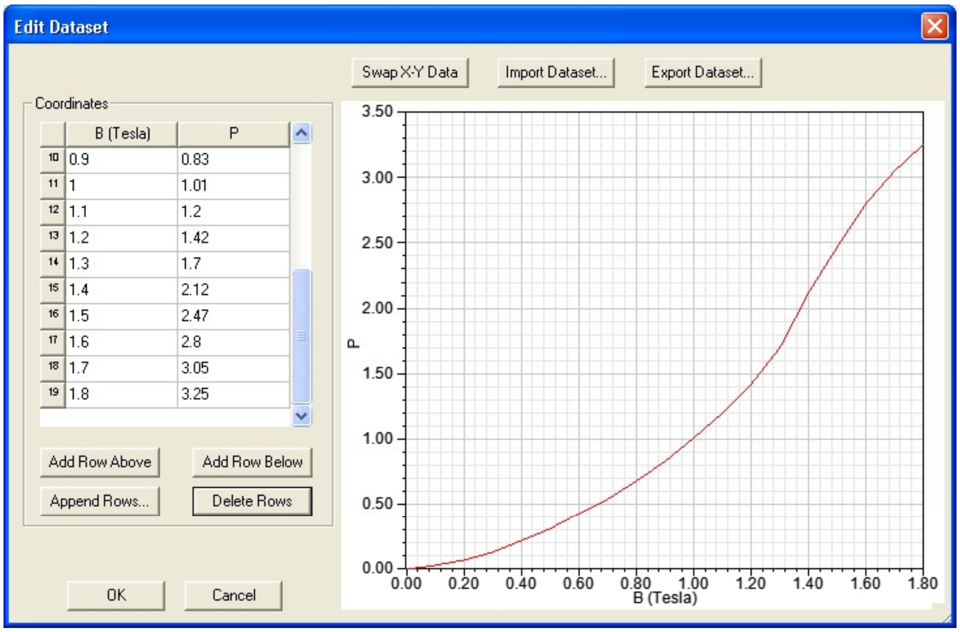


Motors - Permanent Magnet Motor (Prius IPM)

- In Edit Dataset window,
  - Enter the values as shown in below table
  - Press **OK**

50 Hz

B	P
0	0
0.1	0.03
0.2	0.07
0.3	0.13
0.4	0.22
0.5	0.31
0.6	0.43
0.7	0.54
0.8	0.68
0.9	0.83
1	1.01
1.1	1.2
1.2	1.42
1.3	1.7
1.4	2.12
1.5	2.47
1.6	2.8
1.7	3.05
1.8	3.25



- Similarly add more datasets for frequencies of **100, 200, 400** and **1000 Hz**

100Hz

B	P
0	0
0.1	0.04
0.2	0.16
0.3	0.34
0.4	0.55
0.5	0.8
0.6	1.08
0.7	1.38
0.8	1.73
0.9	2.1
1	2.51
1.1	2.98
1.2	3.51
1.3	4.15
1.4	4.97
1.5	5.92

200Hz

B	P
0	0
0.1	0.09
0.2	0.37
0.3	0.79
0.4	1.31
0.5	1.91
0.6	2.61
0.7	3.39
0.8	4.26
0.9	5.23
1	6.3
1.1	7.51
1.2	8.88
1.3	10.5
1.4	12.5
1.5	14.9

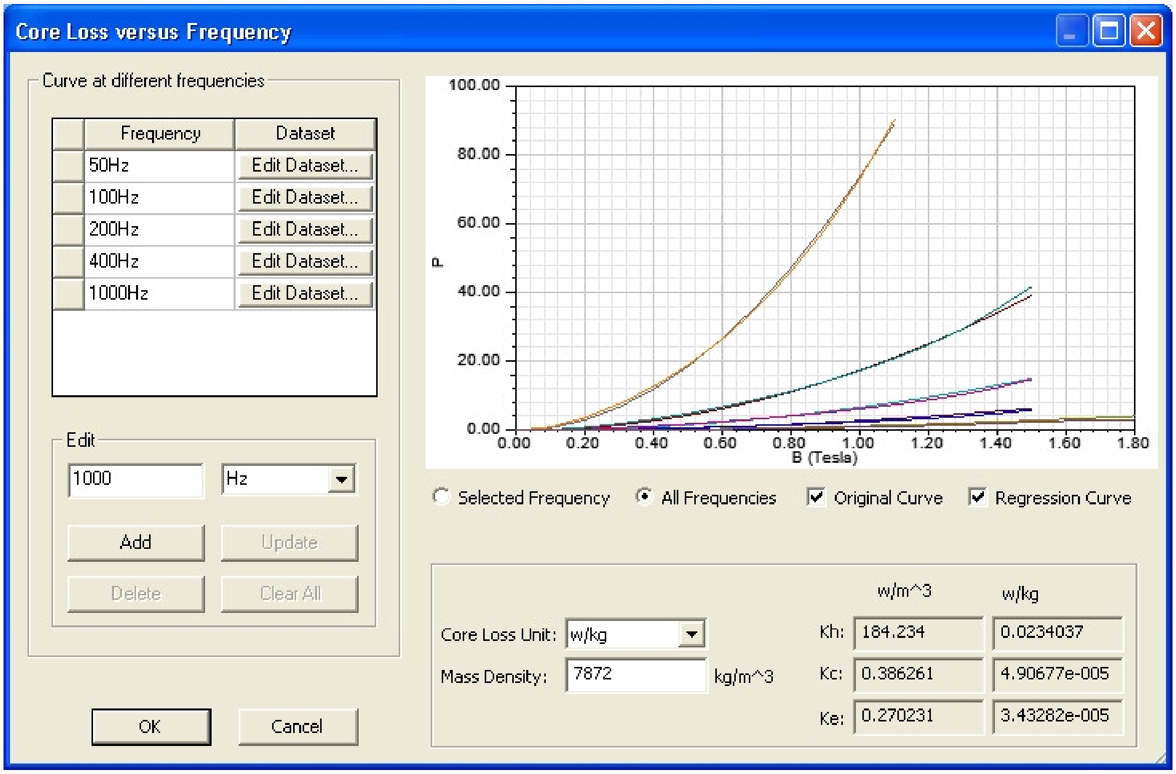
400Hz

B	P
0	0
0.1	0.21
0.2	0.92
0.3	1.99
0.4	3.33
0.5	4.94
0.6	6.84
0.7	9
0.8	11.4
0.9	14.2
1	17.3
1.1	20.9
1.2	24.9
1.3	29.5
1.4	35.4
1.5	41.8

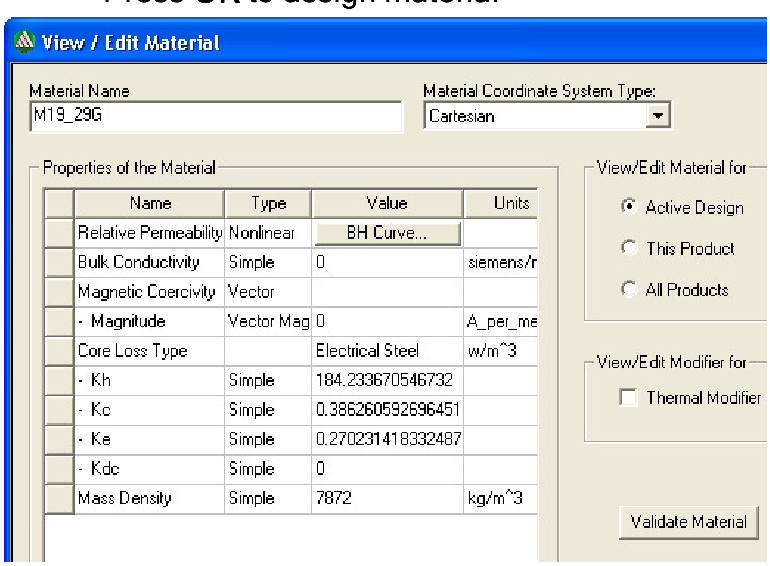
1000Hz

B	P
0	0
0.1	0.99
0.2	3.67
0.3	7.63
0.4	12.7
0.5	18.9
0.6	26.4
0.7	35.4
0.8	46
0.9	58.4
1	73
1.1	90.1

- The coreloss coefficient are automatically calculated

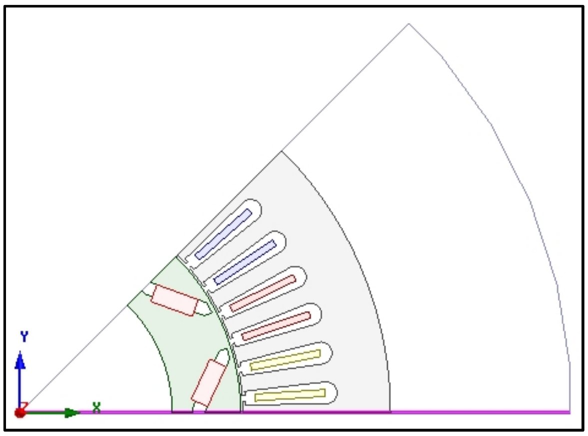


- Press **OK** to accept the setings
- In View/Edit Materials window,
  - Press **OK** to assign material

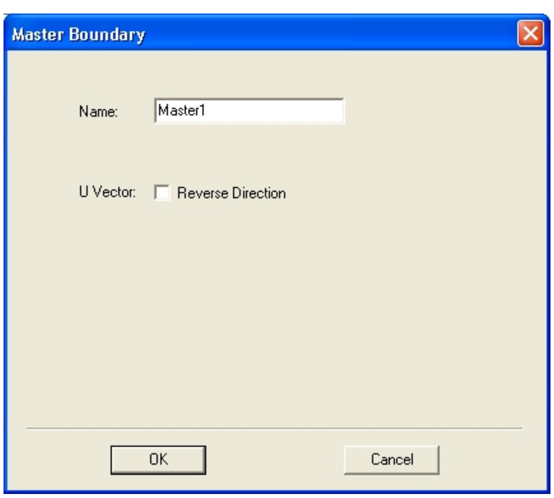


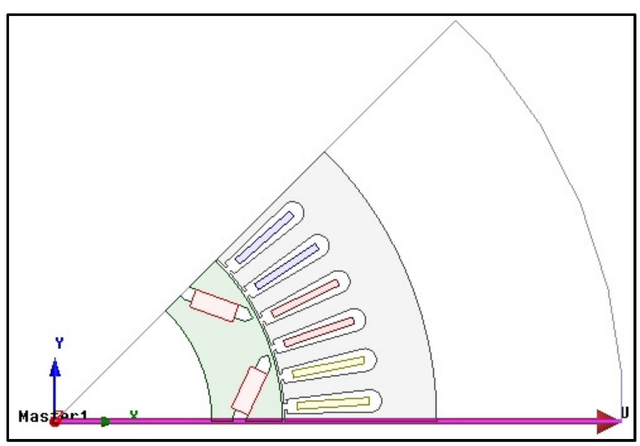
Applying Master / Slave Boundary

- The Master and Slave boundary condition takes advantage of the periodicity of the motor. Two planes are to be defined: the master and slave planes. The H-field at every point on the slave surface matches the (plus or minus) H-field at every point on the master surface.
- **To Assign Master Boundary**
  - Select the menu item *Edit > Select > Edges*
  - Select the edge of the region that coincides with Global X axis

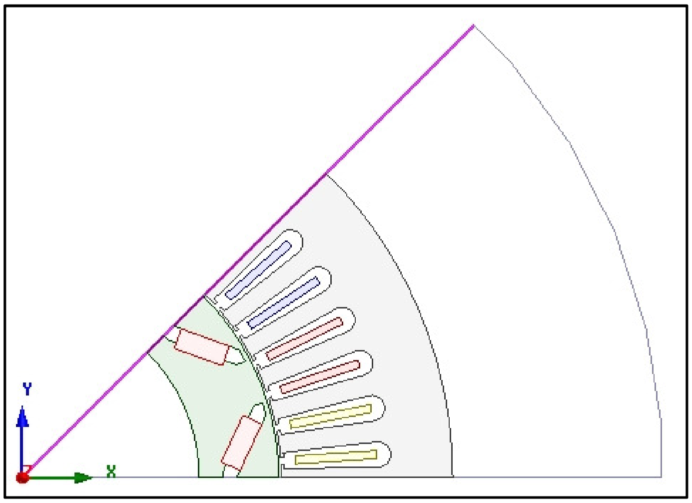


  - Select the menu item *Maxwell 2D > Boundaries > Assign > Master*
  - In Master Boundary window,
    1. Check the direction of U Vector shown in Graphic window
    2. If the direction is pointing away from the origin, use Reverse Direction
    3. Press **OK** to accept the settings

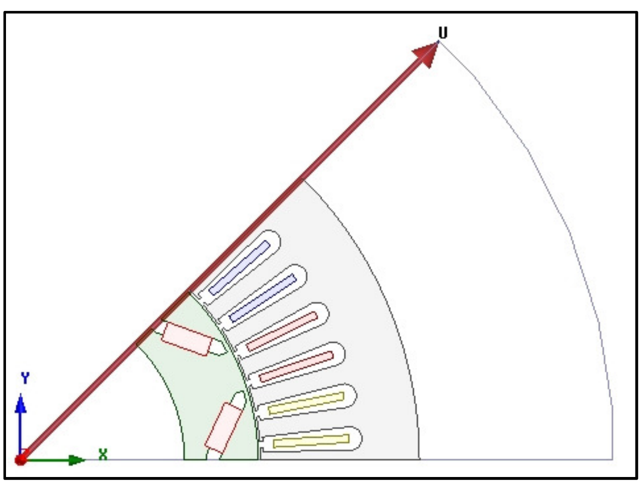


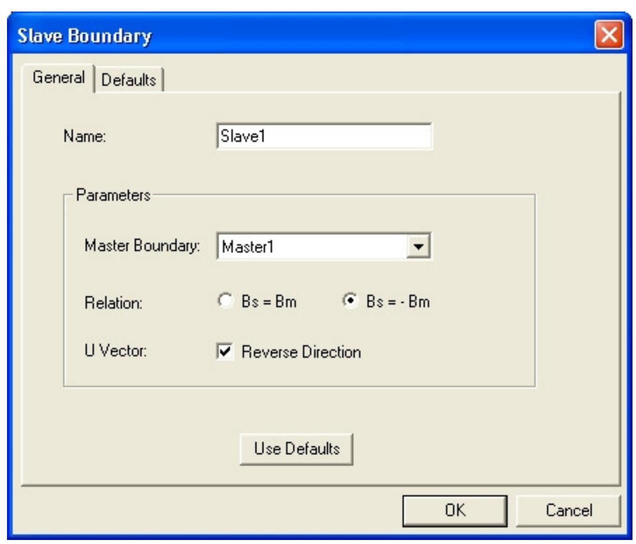


- **To Define Slave Boundary**
  - Select opposite edge of the region as shown in below image



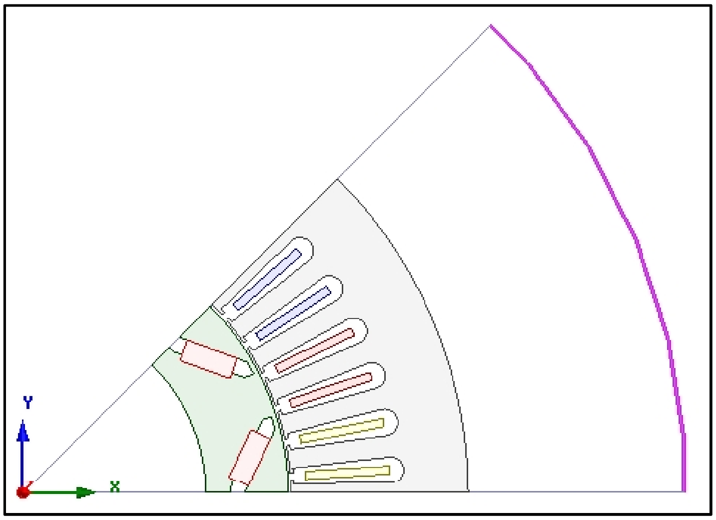
  - Select the menu item ***Maxwell 2D > Boundaries > Assign > Slave***
  - In Slave Boundary window,
    1. Master Boundary: **Master1**
    2. Relation: select **Hs = -Hm**
    3. Use **Reverse Direction** if U vector direction is not consistent with Master
    4. Press **OK**



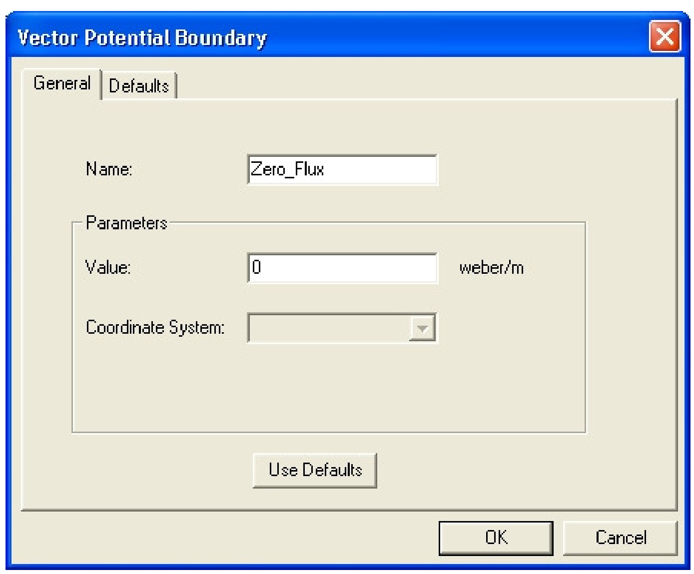


Assign Vector Potential Boundary

- **To Assign Vector Potential Boundary to region**
  - Select the menu item ***Edit > Select > Edges***
  - Select the edges of the Region as shown in below image



  - Select the menu item ***Maxwell 2D > Boundaries > Assign > Vector Potential***
  - In Vector Potential Boundary window,
    - Name: **Zero_Flux**
    - Set the value to **0 weber/m**
    - Select **OK**



Static Analysis

- We will study the different static parameters of the motor.

Copy Design

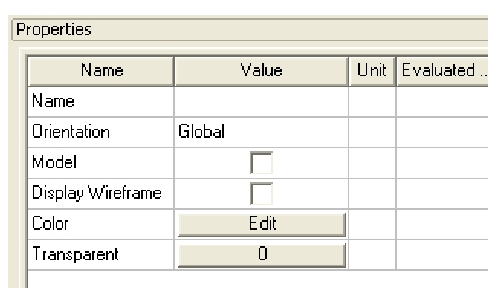
- **To Copy Design**
  - Select the Maxwell Design “ **2_Partial_Motor”** from the Project Manager tree, right click and select **Copy**
  - Right click on Project Name and select **Paste**
  - Rename the newly created design to **“3_Partial_Motor_MS”**

Set Static Analysis

- **To Set Static Analysis**
  - Select the menu item ***Maxwell 2D > Solution Type***
    - Change solution type to **Magnetic > Magnetostatic**
    - Press **OK**

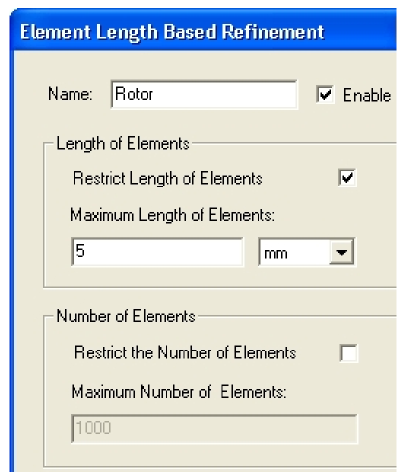
No Load Study

- The first analysis that will be performed consists in computing the fields due to the permanent magnets.
- The Coils are not needed in the model since no current is defined.
- **To Deactivate Coils**
  - Press **Ctrl** and select all coils from history tree
  - Goto the Properties window for selected sheets
  - Uncheck the box **Model** from Properties window to neglect the coils for simulation
  - Keep all the coils selected and select the menu item ***View > Hide Selection > Active View***

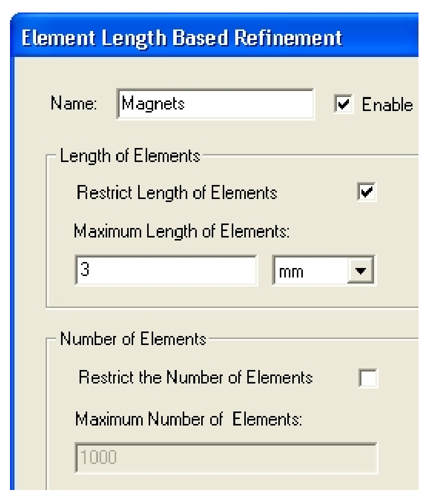


Apply Mesh Operations

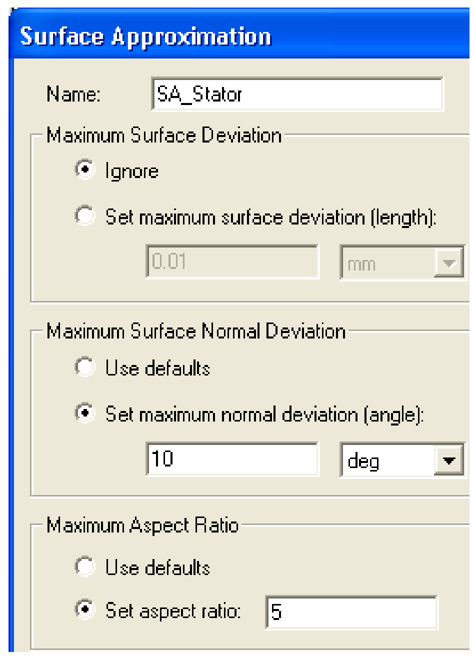
- The adaptive meshing is very effective, so it is not necessary to enter dedicated mesh operations. However, it is always a good idea to start with a decent initial mesh in order to reduce time computation since we know where the mesh needs to be refined for a motor. The non linear resolution will be faster with a small aspect ratios for the elements in the steel.
- To Apply Mesh Operations for Rotor
  - Select the sheet **Rotor** from history tree
  - Select the menu item ***Maxwell 2D > Mesh Operations > Assign > Inside Selection > Length Based***
  - In Element Length Based Refinement window,
    1. Name: **Rotor**
    2. Restrict length of Elements: ☑ **Checked**
    3. Maximum Length of Elements: **5 mm**
    4. Press **OK**



- To Apply Mesh Operations for Magnets
  - Press **Ctrl** and select the sheets **PM1** and **PM2**
  - Select the menu item ***Maxwell 2D > Mesh Operations > Assign > Inside Selection > Length Based***
  - In Element Length Based Refinement window,
    1. Name: **Magnets**
    2. Restrict length of Elements: ☑ **Checked**
    3. Maximum Length of Elements: **3 mm**
    4. Press **OK**



- **To Apply Mesh Operation for Stator**
  - Select the sheet **Stator** from history tree
  - Select the menu item *Maxwell 2D > Mesh Operations > Assign > Surface Approximation*
  - In Surface Approximation window,
    - Name: **SA_Stator**
    - Set maximum normal deviation (angle) : **30 deg**
    - Set aspect ratio: **5**
    - Press **OK**

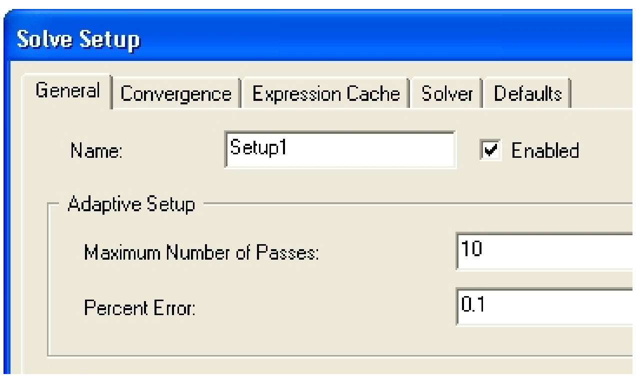


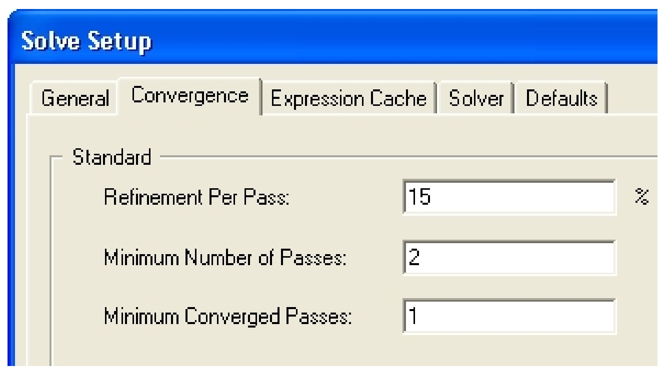
Set Torque Parameter

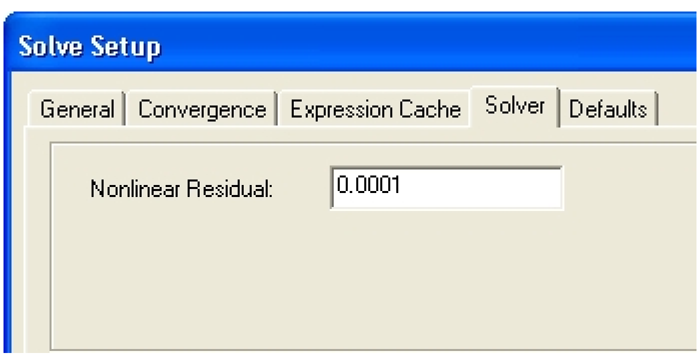
- **To Set Torque Calculation**
  - Press **Ctrl** and select the sheets **PM1, PM2** and **Rotor**
  - Select the menu item *Maxwell 2D > Parameters > Assign > Torque*
  - In Torque window,
    - Press **OK** to accept default settings

Analysis Setup

- To Create Analysis Setup
  - Select the menu item *Maxwell 2D > Analysis Setup > Add Solution Setup*
  - In Solve Setup Window,
    1. **General** Tab
       - Percentage Error: **0.1**
    2. **Convergence** tab
       - Refinement Per pass: **15 %**
    3. **Solver** Tab
       - Non-linear Residuals: **0.0001**
    4. Press **OK**







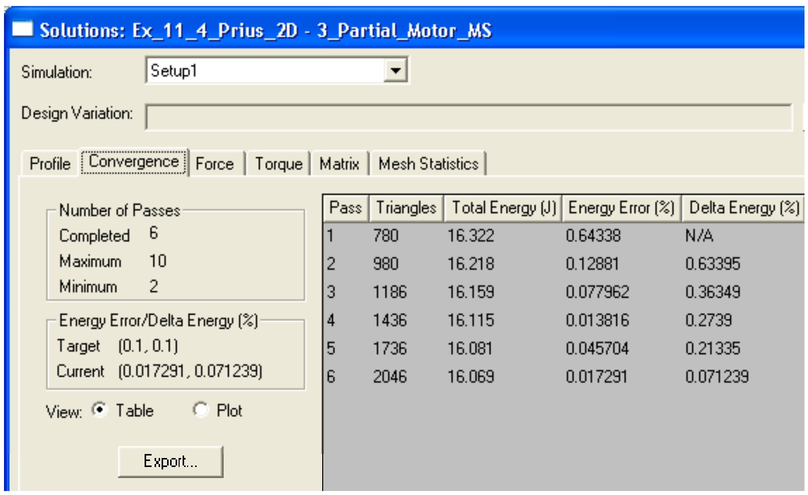
Analyze

- To Run the Solution
  - Select the menu item *Maxwell 3D > Analyze All*

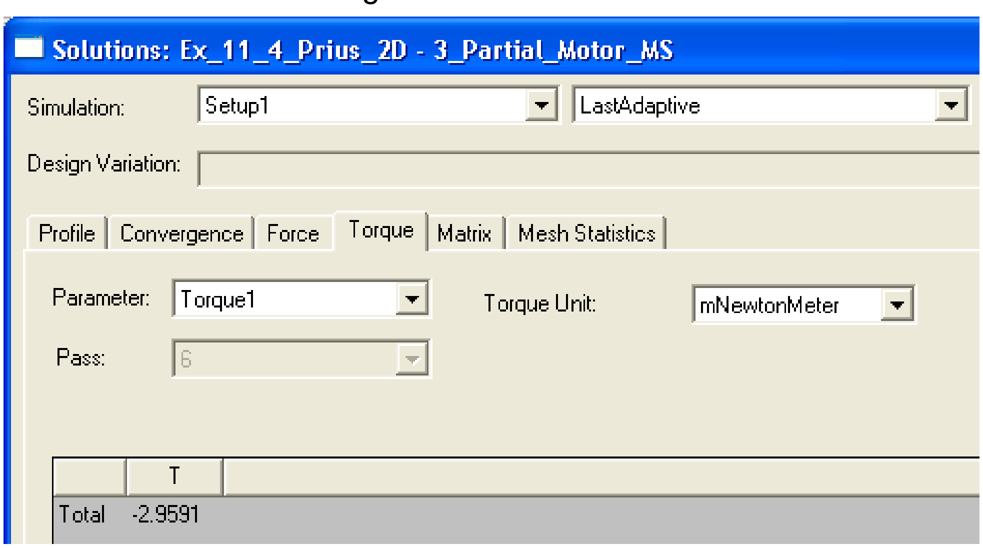
Post Processing

Solution Data

- Select the menu item ***Maxwell 3D > Results > Solution Data***
- To View Convergence
  1. Select **Convergence** tab

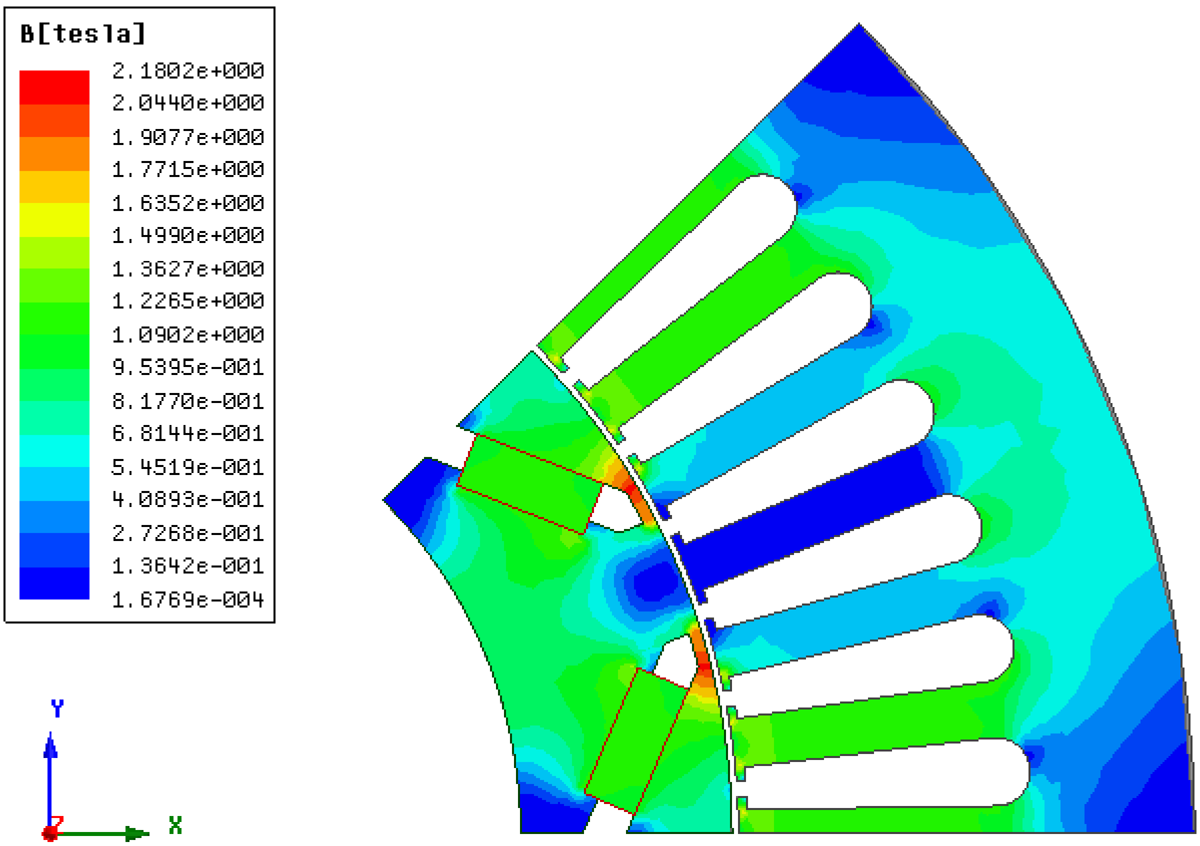


- To View Torque Values
  1. Select the **Torque** tab
     - The torque for the full motor needs to be multiplied by 8 (symmetry factor), then by 0.082 (to account for the motor length). The value is very small in regards to the full load operation. Different angles between the rotor and the stator would give different values.



Field Plots

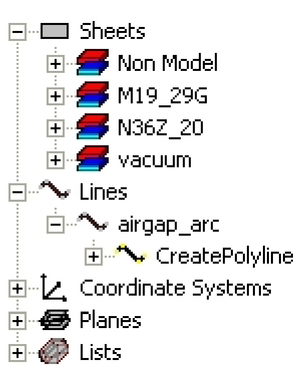
- Plot Magnetic Flux Density
  - Press **Ctrl** and select the sheets **PM1, PM2, Stator** and **Rotor**
  - Select the menu item ***Maxwell 2D > Fields > Fields > B > Mag_B***
  - In Create Field Plot window,
    1. Press **Done**
  - The steel is highly saturated close to the magnets as expected. This saturations appears just because of the magnets strengths.

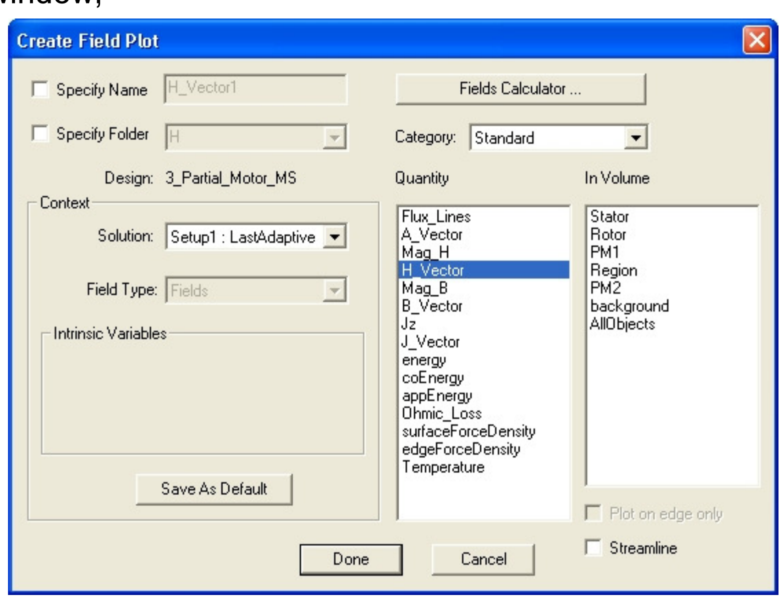


Vector Plot in Airgap

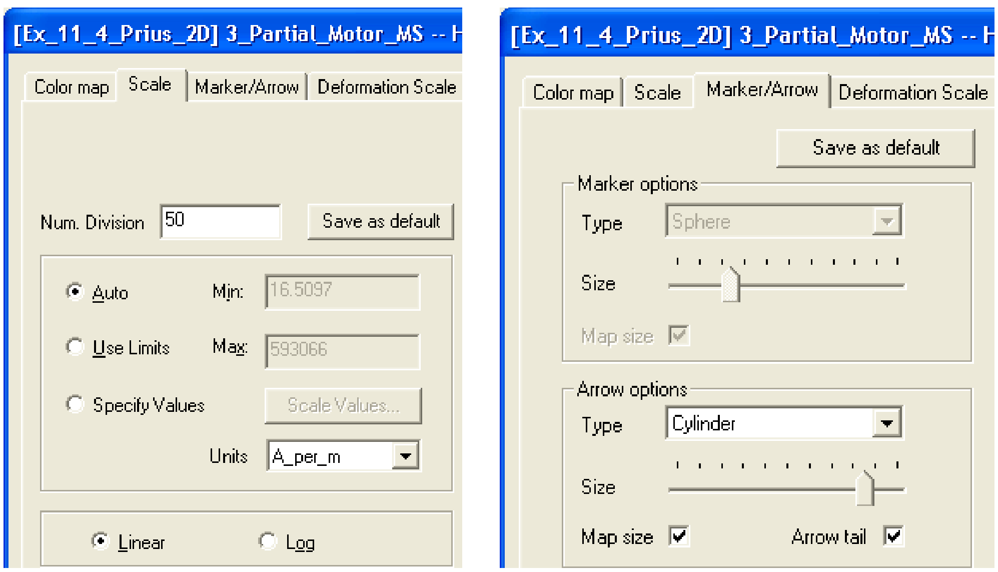
- Create an Arc for Vector Plot
  - Select the menu item *Draw > Arc > Center Point*
  - A massage box appears asking if Geometry needs to be create d as a Non-model object. Press **Yes** to it
    1. Using Coordinate entry field, enter the center of arc
       - **X: 0, Y :0, Z: 0,** Press the **Enter** Key
    2. Change the definition coordinate system of the coordinate entry field to Cylindrical

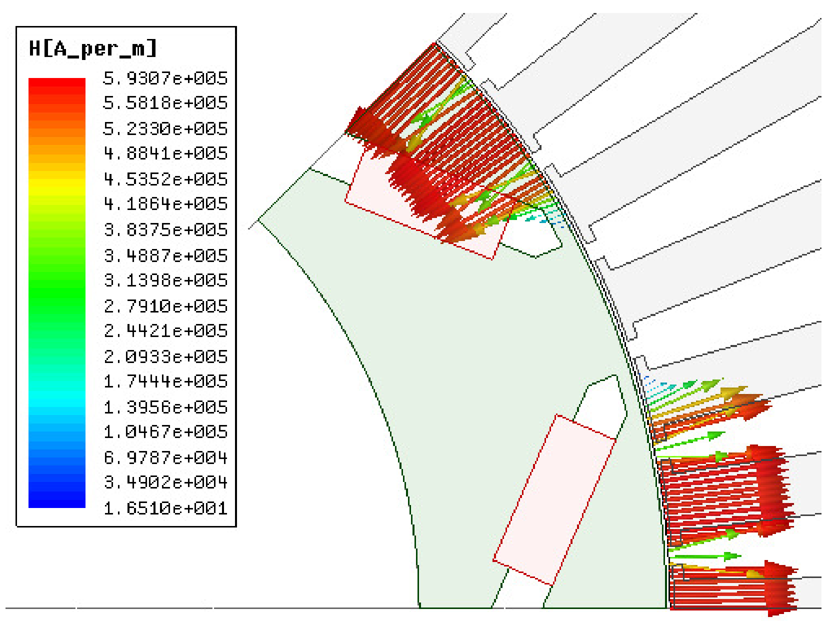
    3. Using Coordinate entry field, enter the first point of arc
       - **R: 80.575, Phi :0, Z: 0,** Press the **Enter** Key
    4. Using Coordinate entry field, enter the first point of arc
       - **R: 80.575, Phi : 45, Z: 0,** Press the **Enter** Key
    5. To finish the arc, move the mouse on the drawing area, right mouse click, and select the menu entry **Done**
  - Rename the created Polyline to **airgap_arc**
- Plot H_Vector on Arc
  - Select the line **airgap_arc** from the history tree
  - Select the menu item *Maxwell 2D > Fields > Fields > H > H_Vector*
  - In Create Field Plot window,
    1. Press **Done**





- **Modify Plot Attributes**
  - Double click on the plot Legend to modify its attributes
  - In the window,
    1. **Scale** Tab
       - Num. Division: **50**
    2. **Marker/Arrow** Tab
       - Size: **Set to appropriate value**
    3. Press **Apply** and **Close**





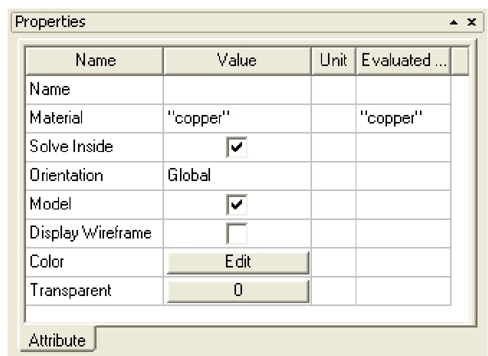
Full Load Study

Copy Design

- **To Copy Design**
  - Select the Maxwell Design “ **3_Partial_Motor_MS”** from the Project Manager tree, right click and select **Copy**
  - Right click on Project Name and select **Paste**
  - Rename the newly created design to **“4_Partial_Motor_MS2”**
  - In this design, we apply current in the coils

Activate Coils

- **To Activate Coils**
  - Press **Ctrl** and select all coils from history tree
  - Goto the Properties window for selected object
  - Check the button **Model** to activate all coils

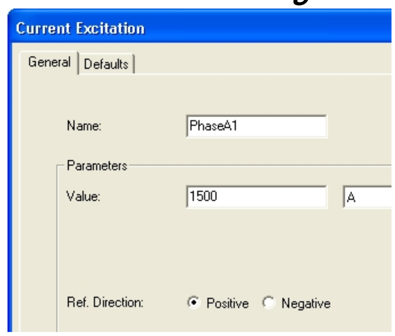


Apply Excitations

- The coils are partially represented in the model. We need to enter the current that flows in and out inside each coil. The excitation is realized through a balanced three phase system. For instance, in our example, we apply:
  - 1500 A to PhaseA
  - -750 A to PhaseB
  - -750 A to PhaseC.
- In the Magnetosatic solver, the sources are given in terms of currents. We do not need to model each turn at this stage; therefore we only enter the total current in each phase. The number of turns and the electrical topology are only taken into account for the inductances calculation.

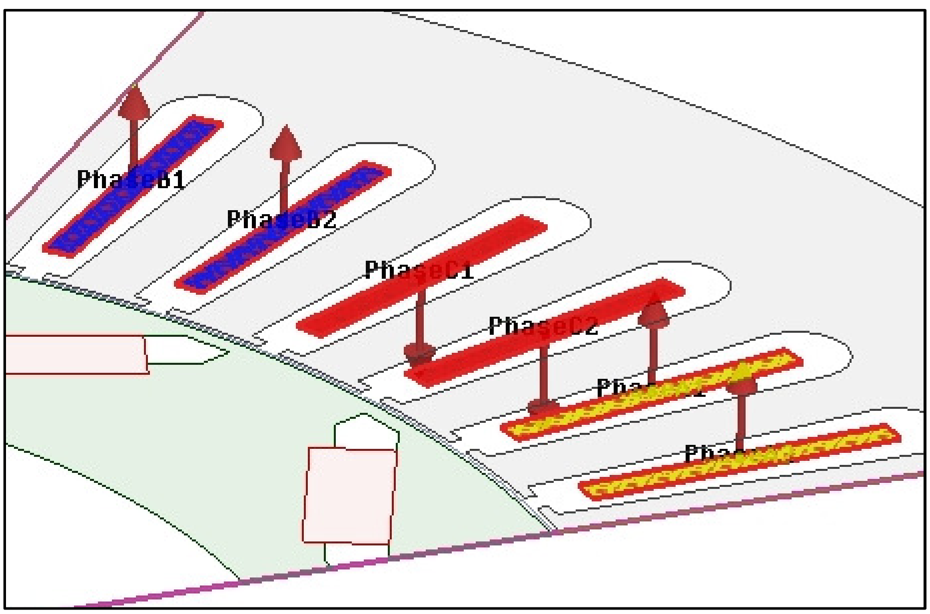
Motors - Permanent Magnet Motor (Prius IPM)

- Assign Excitations for Phase A
  - Select the sheet **PhaseA1** from history tree
  - Select the menu item ***Maxwell 2D > Excitations > Assign > Current***
  - In Current Excitation window,
    1. Name: **PhaseA1**
    2. Value: **1500 A**
    3. Ref. Direction: **Positive**
    4. Press **OK**



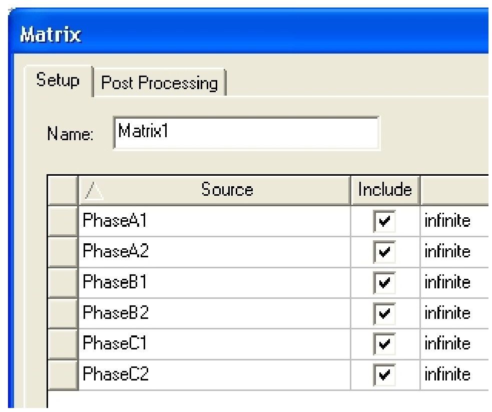
  - Similarly select the sheet **PhaseA 2** from history tree
  - Select the menu item ***Maxwell 2D > Excitations > Assign > Current***
  - In Current Excitation window,
    1. Name: **PhaseA2**
    2. Value: **1500 A**
    3. Ref. Direction: **Positive**
    4. Press **OK**
- Assign Excitations for PhaseC
  - Select the sheet **PhaseC1** from history tree
  - Select the menu item ***Maxwell 2D > Excitations > Assign > Current***
  - In Current Excitation window,
    1. Name: **PhaseC1**
    2. Value: **-750 A**
    3. Ref. Direction: **Negative**
    4. Press **OK**
  - Similarly select the sheet **PhaseC2** from history tree
  - Select the menu item ***Maxwell 2D > Excitations > Assign > Current***
  - In Current Excitation window,
    1. Name: **PhaseC2**
    2. Value: **-750 A**
    3. Ref. Direction: **Negative**
    4. Press **OK**

- **Assign Excitations for PhaseB**
  - Select the sheet **PhaseB1** from history tree
  - Select the menu item ***Maxwell 2D > Excitations > Assign > Current***
  - In Current Excitation window,
    1. Name: **PhaseB1**
    2. Value: **-750 A**
    3. Ref. Direction: **Positive**
    4. Press **OK**
  - Similarly select the sheet **PhaseC2** from history tree
  - Select the menu item ***Maxwell 2D > Excitations > Assign > Current***
  - In Current Excitation window,
    1. Name: **PhaseB2**
    2. Value: **-750 A**
    3. Ref. Direction: **Positive**
    4. Press **OK**

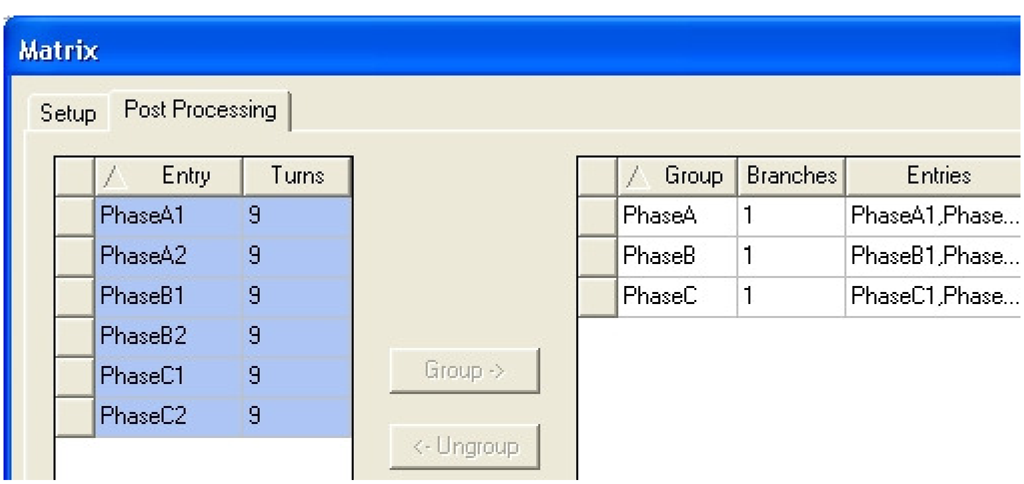


Set Parameters

- We are interested by the inductances computation. The source set up is independent from the winding arrangement: we have only entered the corresponding amp-turns for each terminal. When looking at the inductances, we obviously need to enter the number of turns for the coils and also how the coils are electrically organized.
- **To Sect Inductance Calculations**
  - Select the menu item *Maxwell 2D > Parameters > Assign > Matrix*
  - In Matrix window,
    1. Setup Tab
       - For all sources:
         1. Include : ☑ **Checked**



    2. Post Processing Tab
       - Set Turns for all phases to **9**
       - Press **Ctrl** and select the sources **PhaseA1** and **PhaseA2**
       - Select the button **Group**
       - Rename the group as **PhaseA**
       - Similarly create the groups **PhaseB** (using PhaseB1 and PhaseB2) and **PhaseC** (using PhaseC1 and PhaseC2)



Analyze

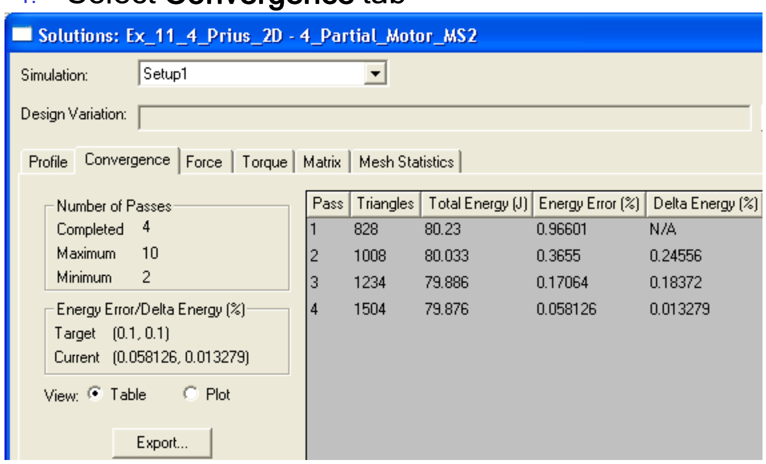
To Run the Solution

- Select the menu item ***Maxwell 2D > Analyze All***

Post Processing

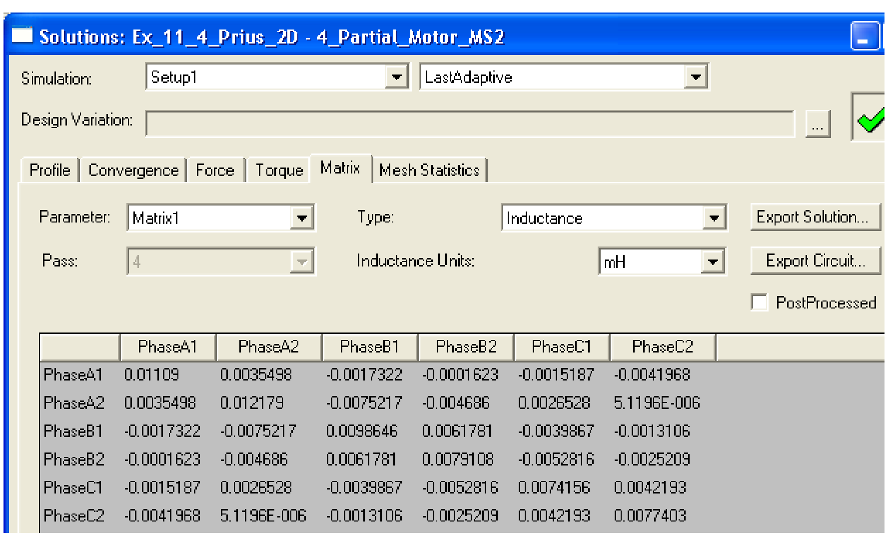
Solution Data

- Select the menu item ***Maxwell 2D > Results > Solution Data***
- To View Convergence
  1. Select **Convergence** tab



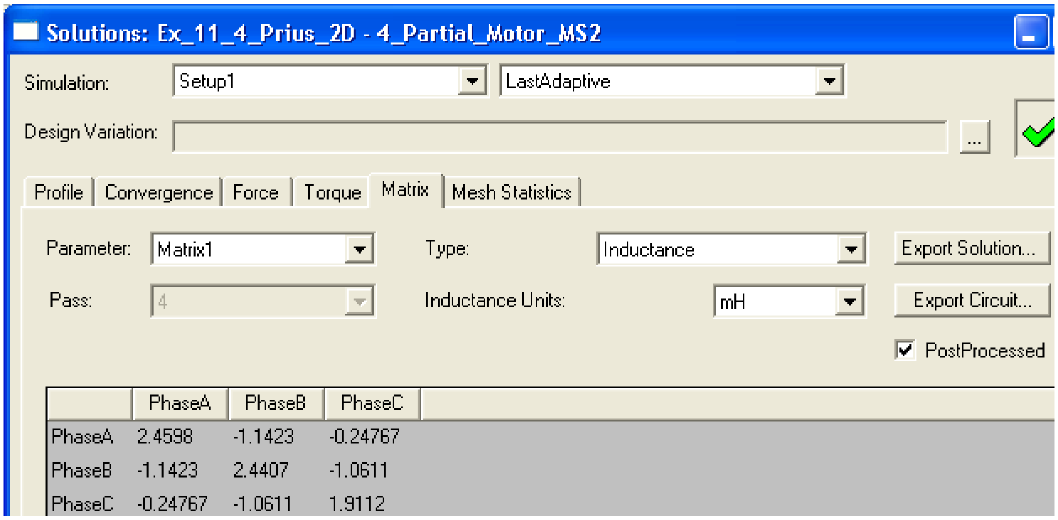
Pass	Triangles	Total Energy (J)	Energy Error (%)	Delta Energy (%)
1	828	80.23	0.96601	N/A
2	1008	80.033	0.3655	0.24556
3	1234	79.886	0.17064	0.18372
4	1504	79.876	0.058126	0.013279

- To View Inductance Values
  1. Select the **Matrix** tab



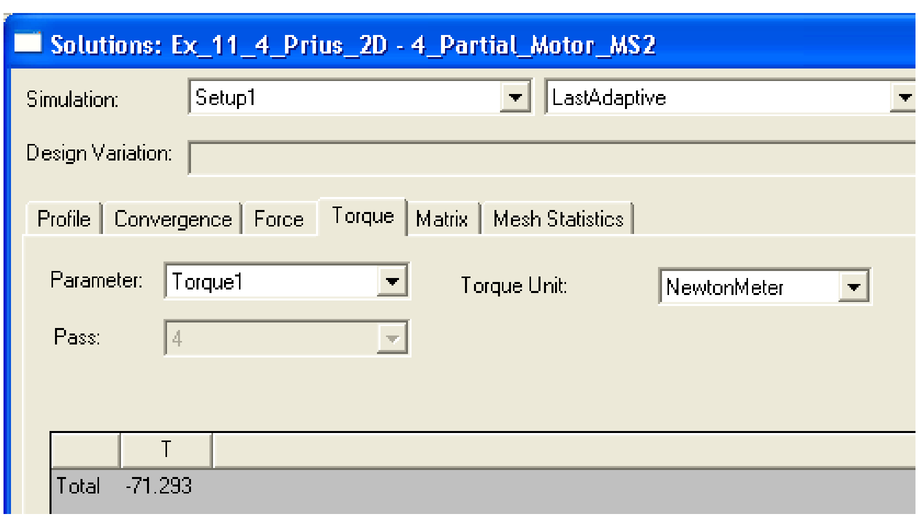
	PhaseA1	PhaseA2	PhaseB1	PhaseB2	PhaseC1	PhaseC2
PhaseA1	0.01109	0.0035498	-0.0017322	-0.0001623	-0.0015187	-0.0041968
PhaseA2	0.0035498	0.012179	-0.0075217	-0.004686	0.0026528	5.1196E-006
PhaseB1	-0.0017322	-0.0075217	0.0098646	0.0061781	-0.0039867	-0.0013106
PhaseB2	-0.0001623	-0.004686	0.0061781	0.0079108	-0.0052816	-0.0025209
PhaseC1	-0.0015187	0.0026528	-0.0039867	-0.0052816	0.0074156	0.0042193
PhaseC2	-0.0041968	5.1196E-006	-0.0013106	-0.0025209	0.0042193	0.0077403

- The Values shown are Per Turn Values
- To View Total inductance, check the button **PostProcessed**



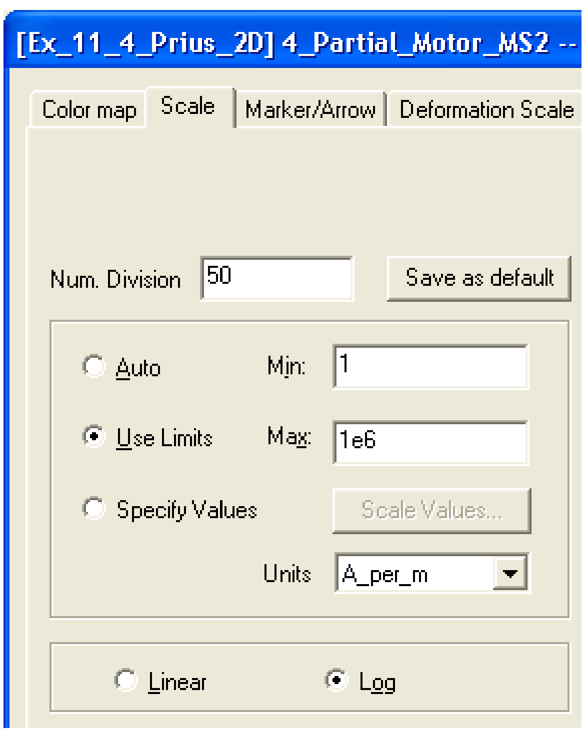
- **Note:** it is possible to export the inductance matrix to Simplorer using the ***Export Circuit*** button

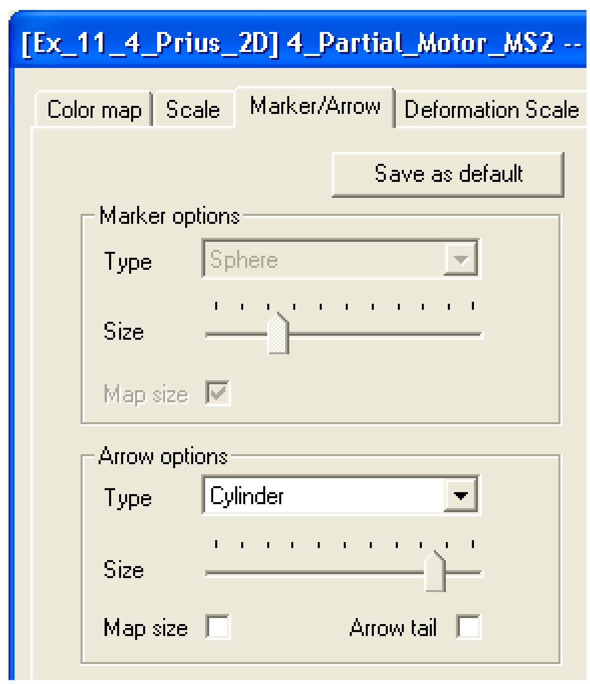
- To View Torque Values
  1. Select the **Torque** tab
  2. The torque for the full motor needs to be multiplied by 8 (symmetry factor), then multiplied by 0.083 (length of the motor). This gives around 47N.m. In this case, we have not synchronized the position of the rotor poles with the winding currents, so we are far from the optimized excitation value to obtain a maximum torque. Different angles between the rotor and the stator would give different values.



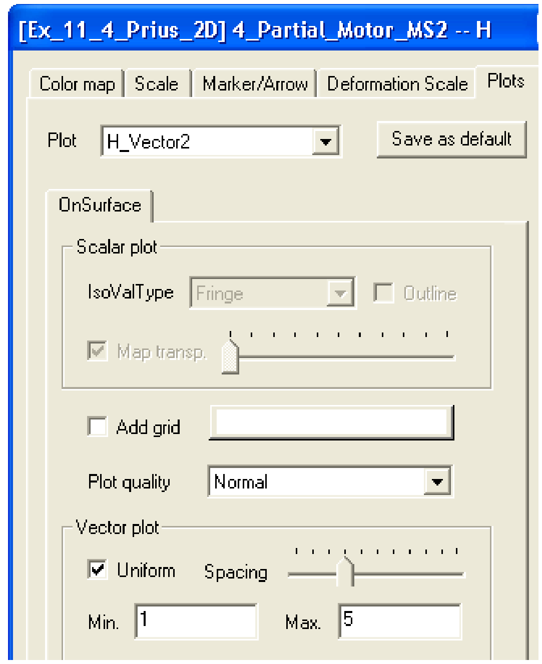
H Vector Plot

- **Plot H_Vector on XY Plane**
  - Select the Plane **Global:XY** from history tree
  - Select the menu item ***Maxwell 2D > Fields > Fields > H > H_Vector***
  - Press **Done**
- **Modify Plot Attributes**
  - In the window,
    1. **Scale** Tab
       - Select **User Limits**
         - Min: **1**
         - Max: **1e6**
       - Select **Log**
    2. **Marker/Arrow** Tab
       - Map Size: ☐ **Unchecked**
       - Arrow Tail: ☐ **Unchecked**

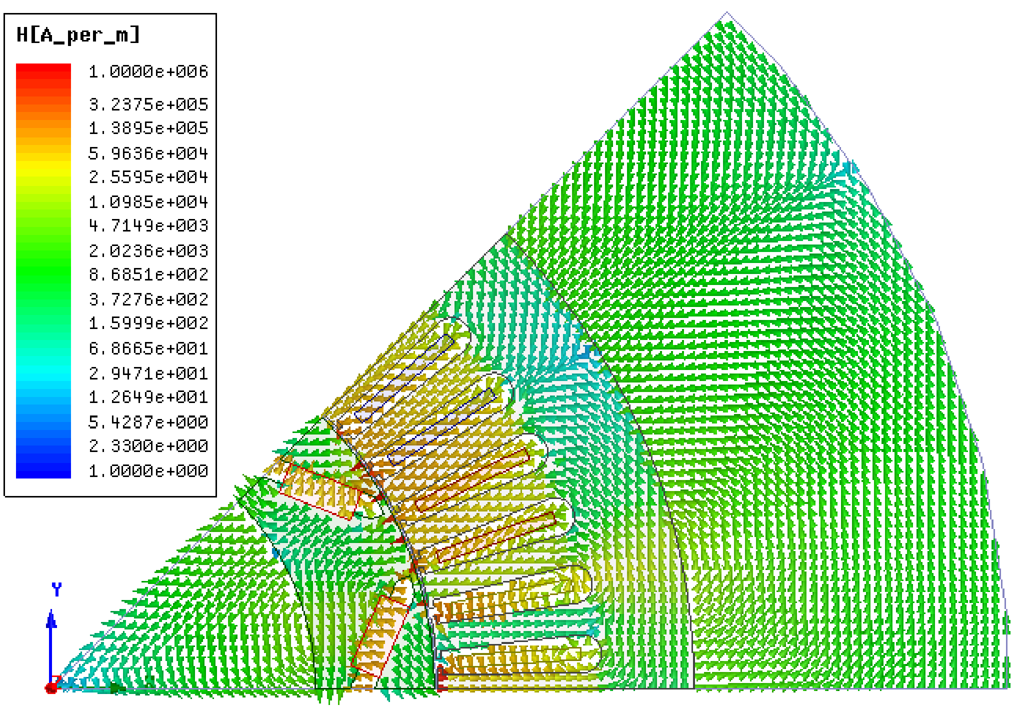




1. **Plots** Tab
   - Plot: **H_Vector2**
   - Spacing: **Four Spaces from Left**
     - Min: **1**
     - Max: **5**
2. Press **Apply** and **Close**



- Plot should look as below



Dynamic Analysis

- We will study the transient characteristic of the motor.

Copy Design

- **To Copy Design**
  - Select the Maxwell Design " **2_Partial_Motor"** from the Project Manager tree, right click and select **Copy**
  - Right click on Project Name and select **Paste**
  - Change the name of the design to **"5_Partial_Motor_TR"**

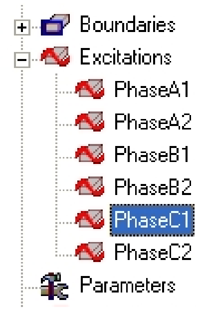
About Transient Solver

- The transient solver acts differently from the Magnetostatic solver mainly because:
  - There is not adaptive meshing. Since the relative position of objects changes at every time step, Maxwell does not re-mesh adaptively for obvious time saving. In transient analysis, we will build a good mesh valid for all the rotor positions.
  - The sources definition is different. In Magnetostatic, we were only interested in the total current flowing into conductor. In Transient, we use stranded conductors (the exact number of conductors is required for each winding) as the current or voltage can be an arbitrary time function. We need to create dedicated current terminals and windings.

Create Coils

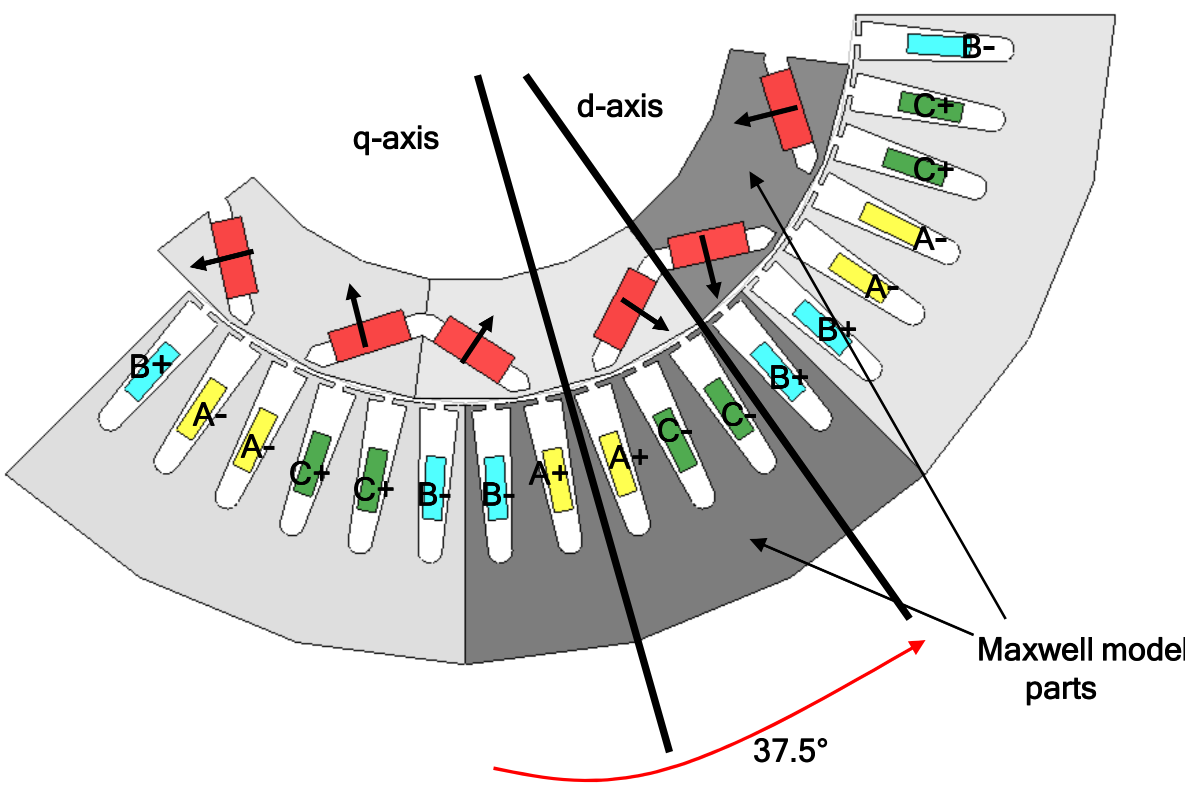
- **To Create Coils**
  - Press **Ctrl** and select all coils from history tree
  - Select the menu item ***Maxwell 2D > Excitations > Assign > Coil***
  - In Coil Excitation window,
    - Base Name: Leave default name as object names will be used automatically
    - Number of Conductors: **9**
    - Polarity: **Positive**
    - Press **OK**

- **Modify Excitation Direction**
  - Direction of excitation for PhaseC needs to be reverses
  - Expand the Project Manager tree to view **Excitations**
  - Double click on the tab **PhaseC1** to modify it
  - In Coil Excitation window,
    - Change Polarity to **Negative**
  - Similarly change the polarity of **PhaseC2** to **Negative**



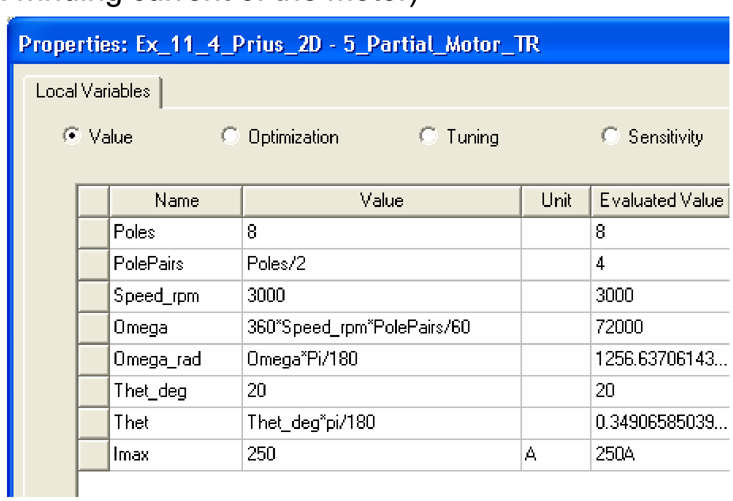
Motor excitation

- The IPM motor is such that the rotor is in synchronism with the phase excitation. The excitation is such that the flux due to the permanent magnet is maximized in synchronization with the rotor movement.
- The excitation is a 3 phase balanced current. The phase sequence is A+C-B+
- At t=0, the A-phase has to be in the opposite axis to the d-axis. Therefore we have to move the initial position of the rotor by 30 deg such that the pole be aligned at the middle of A+A-



Create Parameters for excitations

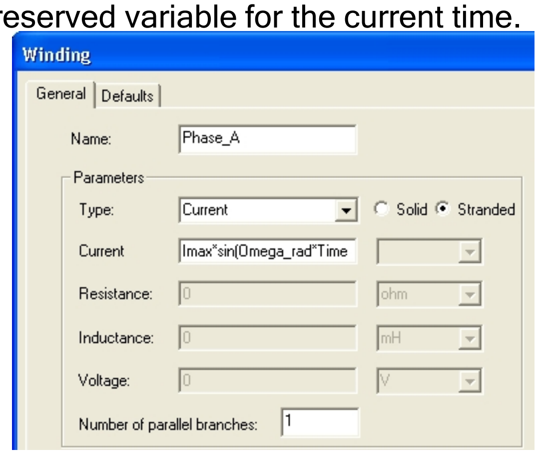
- **To Create Parameters**
  - Select the menu item *Maxwell 2D > Design Properties*
  - In Properties window, select **Add**
  - In Add Property window,
    - Name: **Poles** (number of poles of the motor)
    - Value: **8**
    - Press **OK**
  - Similarly add more properties as below
    1. Name: **PolePairs** (number of pair of poles)
       - Value: **Poles/2**
    2. Name: **Speed_rpm** (speed of the motor in rpm)
       - Value: **3000**
    3. Name: **Omega** (pulsation of the excitation in degrees/s)
       - Value: **360*Speed_rpm*PolePairs/60**
    4. Name: **Omega_rad** (pulsation in rad/s)
       - Value: **Omega * pi / 180**
    5. Name: **Thet_deg** (load angle of the motor)
       - Value: **20**
    6. Name: **Thet** (load angle in radian)
       - Value: **Thet_deg * pi /180**
    - **Note:** Do not specify unit to any of the above parameters
    7. Name: **Imax** (peak winding current of the motor)
       - Value: **250**
       - Unit: **A**



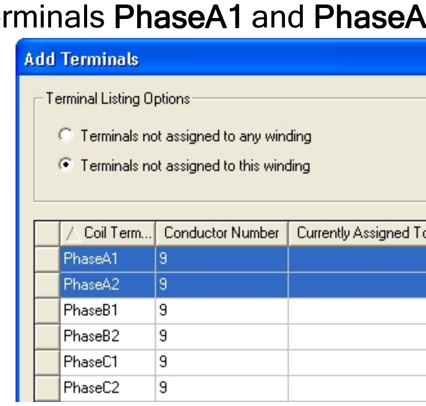
Name	Value	Unit	Evaluated Value
Poles	8		8
PolePairs	Poles/2		4
Speed_rpm	3000		3000
Omega	360*Speed_rpm*PolePairs/60		72000
Omega_rad	Omega*Pi/180		1256.63706143...
Thet_deg	20		20
Thet	Thet_deg*pi/180		0.34906585039...
Imax	250	A	250A

Create Windings

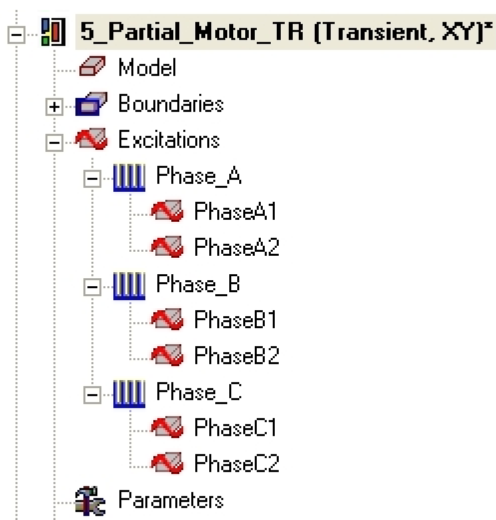
- The terminals are meant to define the excitation paths in and out of the model. The actual excitation is defined through the definition of windings. A winding needs to be defined for each parallel electrical excitation of the motor.
- The motor is excited with a balanced three phase connection. A sinusoidal excitation is applied. At each time step, the phases have a 120 degree shift. The load angle is also added.
- **To Create Winding for Phase A**
  - Select the menu item ***Maxwell 2D > Excitation > Add Winding***
  - In Winding window,
    1. Name: **Phase_A**
    2. Type: **Current**
    3. Check **Stranded**
    4. Current: **Imax*sin(Omega_rad*Time+Thet)**
       - **Time** is internally reserved variable for the current time.
    5. Press **OK**



- **To Add Terminal to Winding**
  - Expand the Project Manager tree to view Excitations
  - Right click on winding **Phase_A** and select **Add Coils**
  - Press **Ctrl** and select the terminals **PhaseA1** and **PhaseA2**
  - Press **OK**

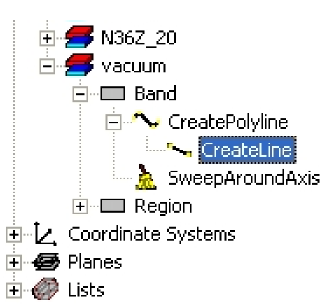


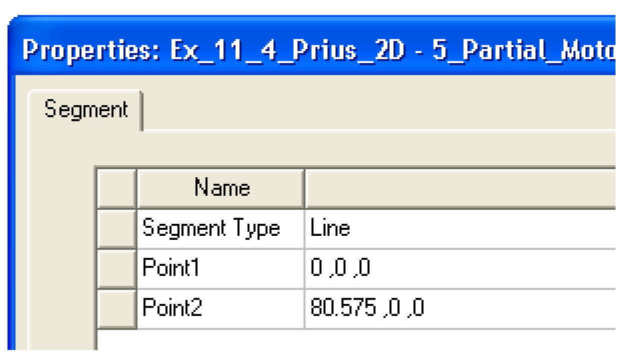
- **Add Winding for Phase B and Phase C**
  - Similarly add Windings for Phase B and Phase C
  - Phase B
    1. Name: **Phase_B**
    2. Type: **Current**
    3. Check **Stranded**
    4. Current: **Imax*sin(Omega_rad*Time-2*pi/3+Thet)**
       - It is shift by -120 degrees from PhaseA.
    5. Press **OK**
    6. Add terminals **PhaseB1** and **PhaseB2** to this winding
  - Phase C
    1. Name: **Phase_C**
    2. Type: **Current**
    3. Check **Stranded**
    4. Current: **Imax*sin(Omega_rad*Time+2*pi/3+Thet)**
       - It is shift by +120 degrees from PhaseA.
    5. Press **OK**
    6. Add terminals **PhaseC1** and **PhaseC2** to this winding



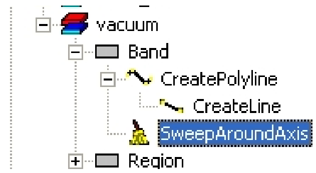
Create Band Object

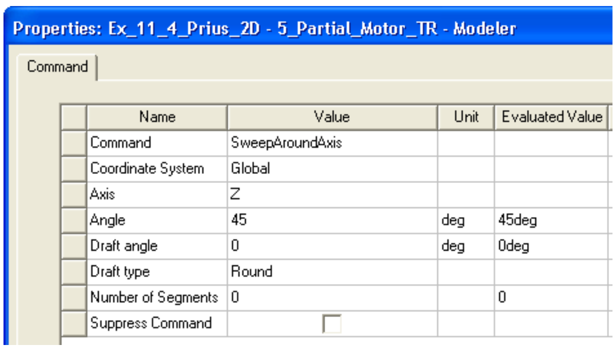
- The moving parts (rotor and permanent magnets) need to be enclosed in an air object, the band. This will separated the moving part from the fixed part of the project. Some rules apply for the definition of the band object for motor applications:
  - The band object must be somewhat larger than the rotating parts in all directions (except at the boundaries)
  - The band object should be a facetted type cylinder of wedge
  - It is very advisable to have an air object that encloses all the moving object inside the band object. This will facilitate the mesh handling around the air gap
- To create the Band object, we will clone the region and adapt the parameters
- **To Duplicate Region**
  - Select the sheet **Region** from history tree
  - Select the menu item ***Edit > Copy***
  - Select the menu item ***Edit > Paste***
  - Change the name of the sheet Region1 to **Band**
- The rotor radius is 80.2mm. The inner diameter of the stator 80.95mm. We pick the middle for Band object .
- **To Edit Band Object**
  - Expand the history tree for the sheet **Band**
  - Double click on the command **CreateLine** to open its properties
  - In Properties window,
    - Change Point2 position to **80.575,0,0**
    - Press **OK**





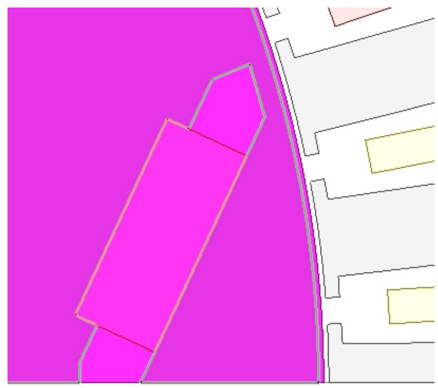
- Double click on the command **SweepAroundAxis** to open its properties
- In Properties window,
  - Change Number of Segments to **0**
  - Press **OK**




Properties: Ex_11_4_Prius_2D - 5_Partial_Motor_TR - Modeler

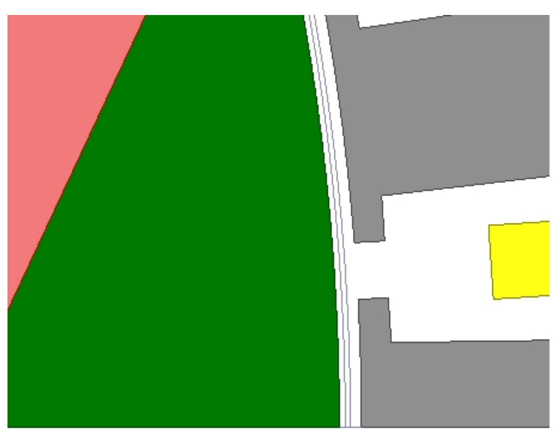
Command

Name	Value	Unit	Evaluated Value
Command	SweepAroundAxis		
Coordinate System	Global		
Axis	Z		
Angle	45	deg	45deg
Draft angle	0	deg	0deg
Draft type	Round		
Number of Segments	0		0
Suppress Command	☐		



Create Inner Band

- We now create an object that enclosed the moving objects inside the ***Band***.
- **Copy Band**
  - Select the sheet **Band** from history tree
  - Select the menu item ***Edit > Copy***
  - Select the menu item ***Edit > Paste***
  - Change the name of the sheet to **Band_in**
- **To Edit Band_in Object**
  - Expand the history tree for the sheet **Band_in**
  - Double click on the command **CreateLine** to open its properties
  - In Properties window,
    - Change Point2 position to **80.4,0,0**
    - Press **OK**

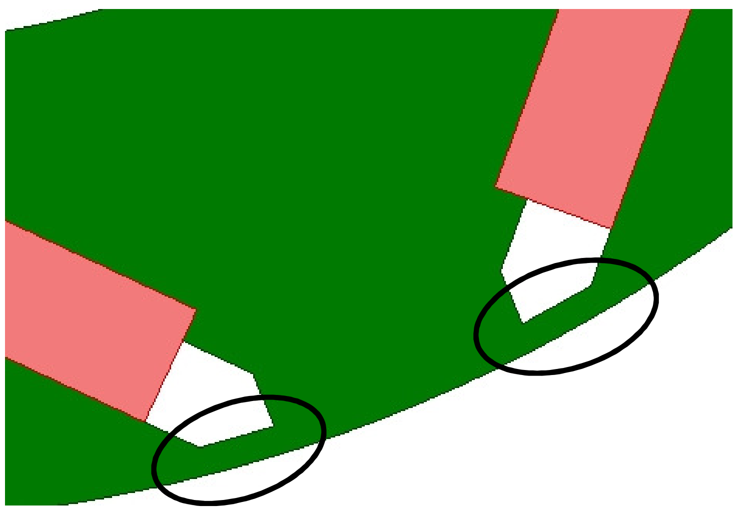


Mesh Operations

- The transient solver does not use adaptive meshing because this would require to refine the mesh at every time steps, leading to very high computation time. Using Mesh operations, we will define a decent mesh for the full transient simulation.

Mesh Operation for Rotor

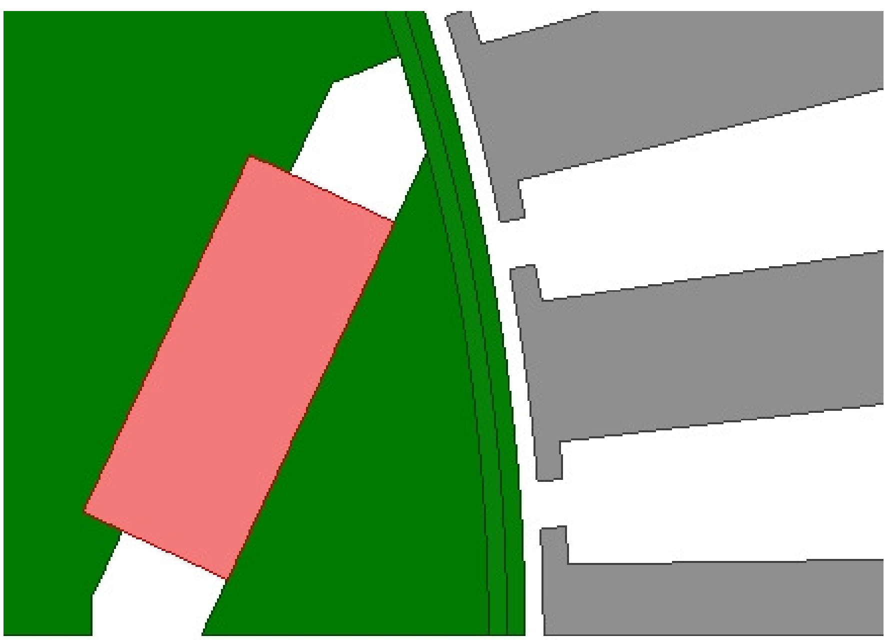
- The Rotor is designed to be highly saturated around the permanent magnets, close to the air gap. It is required to have a good mesh density around this area.
- To achieve this requirement, we create a couple of objects inside the rotor; then mesh operations will be applied to these objects in order to have a nice mesh around the ducts.



Highly saturated zones

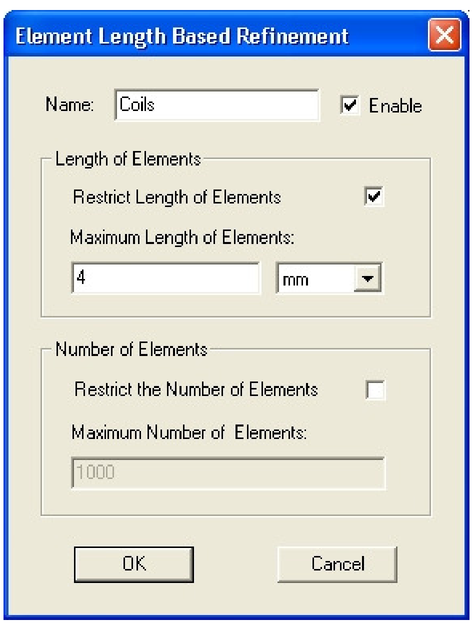
- **Create Line**
  - Select the menu item ***Draw > Line***
    1. Using the coordinate entry field, enter the first vertex
       - **X: 78.72, Y: 0.0, Z: 0.0**, Press the **Enter** key
    2. Using the coordinate entry field, enter the second vertex
       - **X: 80.2, Y: 0.0, Z: 0.0**, Press the **Enter** key
    - Press **Enter** again to end drawing
    - Change the name of the resulting line to **Rotor2**

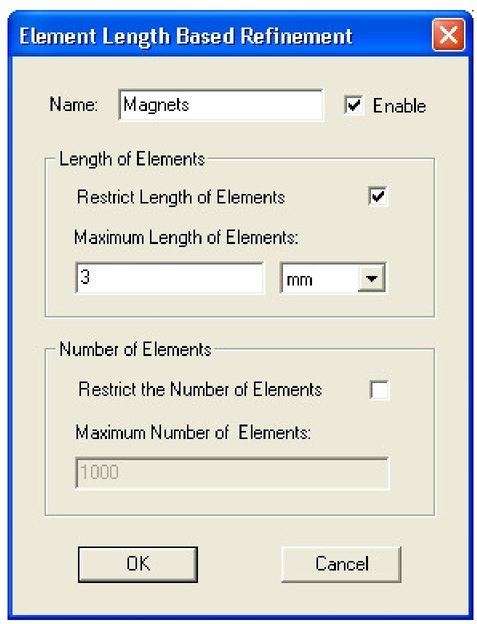
- **To Sweep Line**
  - Select the line **Rotor2** from the history tree
  - Select the menu item ***Draw > Sweep > Around Axis***
  - In Sweep Around Axis window,
    1. Axis: **Z**
    2. Angle of sweep: **45**
    3. Number of segments: **0**
    4. Press **OK**
  - Change the material property of **Rotor2** to **M19_29G**. Also, assign the same color and transparency as the object Rotor.
- **Create Rotor3**
  - Using same process as for Rotor2, create Rotor3
  - Use line coordinates as mentioned below to create line
    - **X: 78.72, Y: 0.0, Z: 0.0**
    - **X: 79.46, Y: 0.0, Z: 0.0**
  - Change the material property of **Rotor3** to **M19_29G**. Also, assign the same color and transparency as the object Rotor.



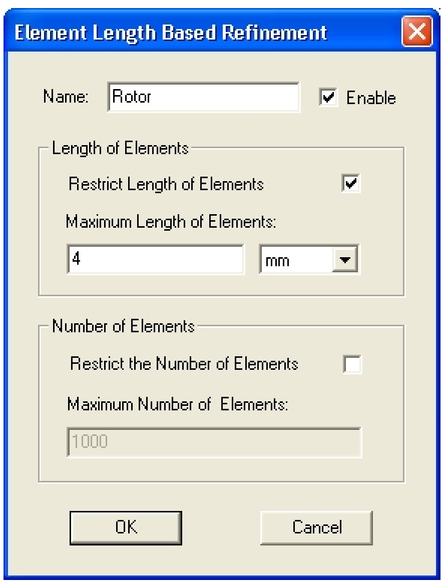
Mesh Operations for Rest

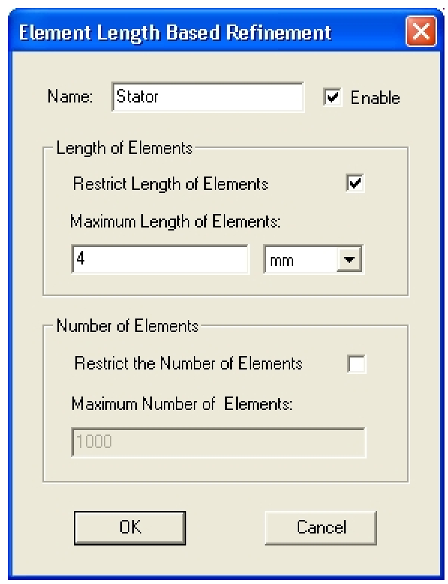
- **Assign Mesh Operation for Coils**
  - Press **Ctrl** and select all **Coils** from history tree
  - Select the mesh item ***Maxwell 2D > Mesh Operations > Assign > Inside Selection > Length Based***
  - In Element Length based Refinement window,
    1. Name: **Coils**
    2. Restrict the Length of Elements: ☑ **Checked**
    3. Maximum Length of Elements: **4 mm**
    4. Restrict the Number of Elements: ☐ **Unchecked**
    5. Press **OK**
- **Mesh Operation for Magnets**
  - Press **Ctrl** and select the sheets **PM1** and **PM2** from history tree
  - Select the menu item ***Maxwell 2D > Mesh Operations > Assign > Inside Selection > Length Based***
  - In Element Length based Refinement window,
    1. Name: **Magnets**
    2. Restrict the Length of Elements: ☑ **Checked**
    3. Maximum Length of Elements: **3 mm**
    4. Restrict the Number of Elements: ☐ **Unchecked**
    5. Press **OK**





- **Mesh Operation for Rotor**
  - Press **Ctrl** and select the sheets **Rotor, Rotor2** and **Rotor3** from history tree
  - Select the menu item ***Maxwell 2D > Mesh Operations > Assign > Inside Selection > Length Based***
  - In Element Length based Refinement window,
    1. Name: **Rotor**
    2. Restrict the Length of Elements: ☑ **Checked**
    3. Maximum Length of Elements: **4 mm**
    4. Restrict the Number of Elements: ☐ **Unchecked**
    5. Press **OK**

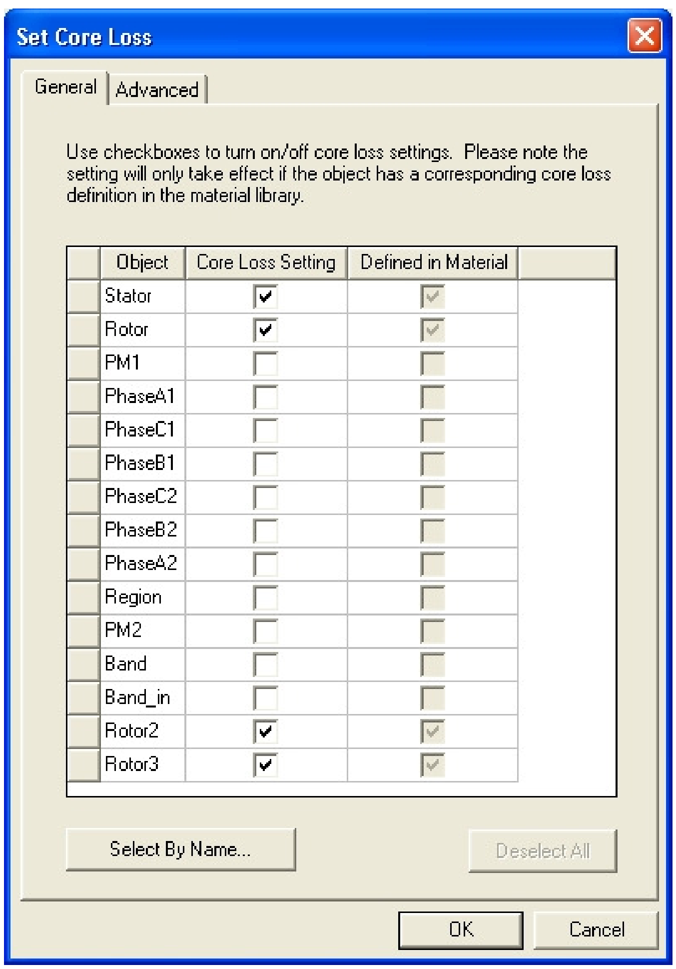




- **Mesh Operation for Stator**
  - Select the sheet **Stator** from history tree
  - Select the menu item ***Maxwell 2D > Mesh Operations > Assign > Inside Selection > Length Based***
  - In Element Length based Refinement window,
    1. Name: **Stator**
    2. Restrict the Length of Elements: ☑ **Checked**
    3. Maximum Length of Elements: **4 mm**
    4. Restrict the Number of Elements: ☐ **Unchecked**
    5. Press **OK**

Set Core Loss

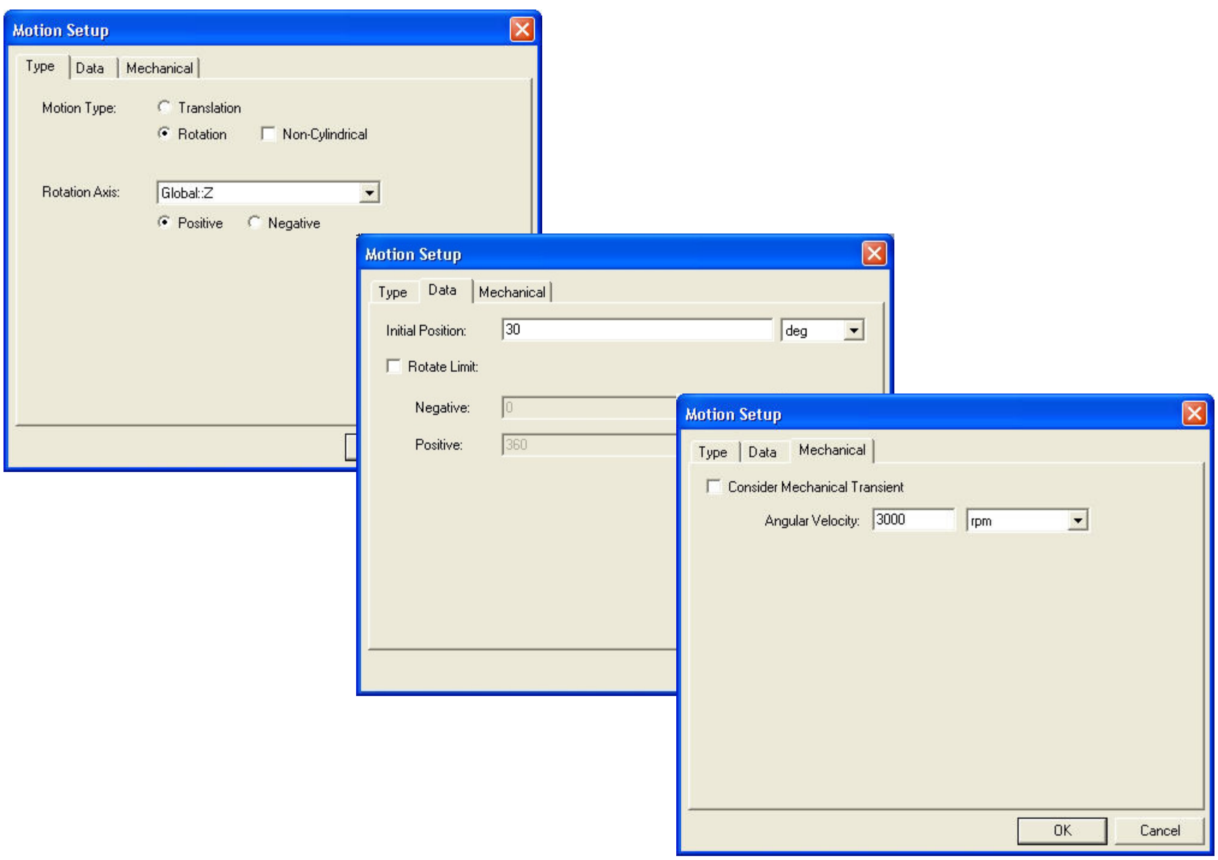
- The coreloss are not activated by default.
- Core Loss parameters must be defined to all objects in which core loss is to be calculated
- Since we have already defined core loss parameters in material definition, we can set core loss calculation for all those objects
- **To Set Core Loss Calculations**
  - Select the menu item *Maxwell 2D > Excitations > Set Core Loss*
  - In Set Core Loss window,
    - Enable Core Loss Settings for **Stator, Rotor, Rotor2** and **Rotor3**
    - Press **OK**



Assign Motion

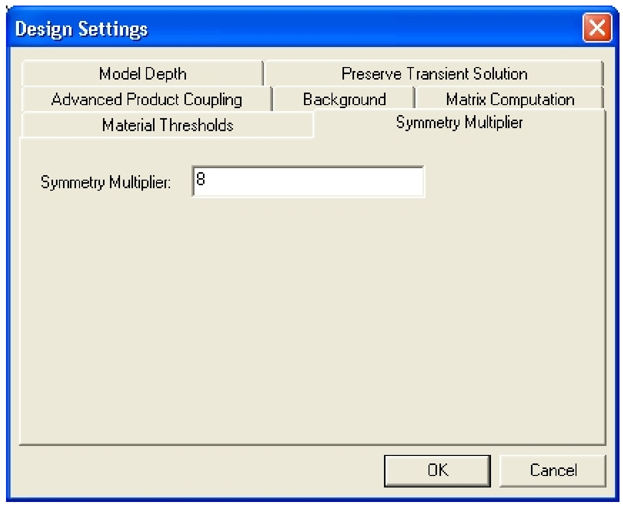
To Assign Motion

- Select the sheet **Band** from the history tree
- Select the menu item ***Maxwell 2D > Model > Motion Setup > Assign Band***
- In Motion Setup window,
  1. **Type** Tab
     - Motion Type: **Rotation**
     - Rotation Axis: **Global:Z**
     - Select **Positive**
  2. **Data** Tab
     - Initial Position: **30 deg**
     - The initial position of this synchronous motor is such that the A phase is opposite to the d-axis.
  3. **Mechanical** Tab
     - Angular Velocity: **3000 rpm**
  4. Press **OK**

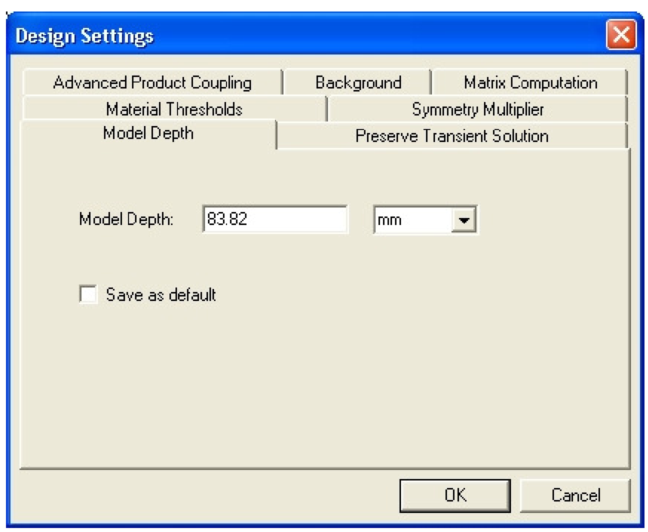


Set Symmetry Multiplier and Model Depth

- **To Set Symmetry Multiplier**
  - Select the menu item *Maxwell 2D > Design Settings*
  - In Design Settings window,
    1. **Symmetry Multiplier** tab
       - Symmetry Multiplier: **8**
       - Since we model 1/8th of the motor (our model spans on 45°), The force, torque will be rescaled to take into account the full model.

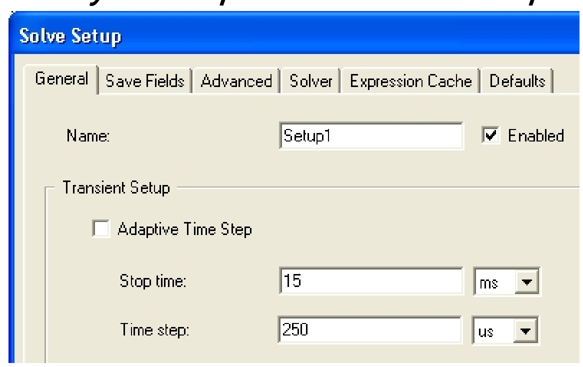


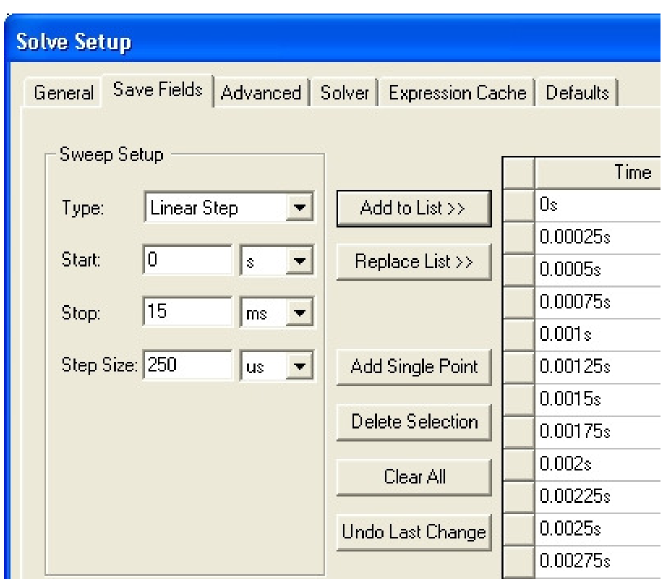
- **To Set Model Depth**
  - In Design Settings window,
    2. Select **Model Depth** tab
       - Model Depth: **83.82 mm**
    - Press **OK**

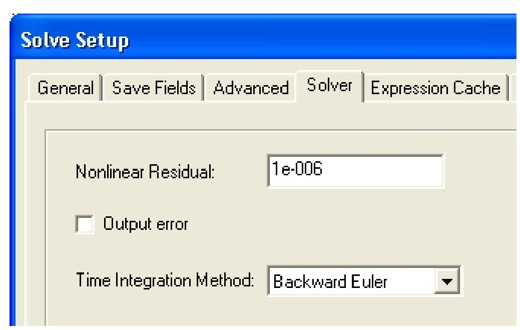


Solution Setup

- **To Create Solution Setup**
  - At 3000 rpm, a revolution takes 20ms (3000 rpm means 50 revolutions per second or 1/50 s for one revolution) . To achieve reasonable accuracy, we want to have a time step every 1 or 2 degrees. In this study, to have faster results, we use a time step of 250 us (thus every 4.5 degrees).
  - Select the menu item *Maxwell 2D > Analysis Setup > Add Solution Setup*
  - In Solve Setup window,
    1. **General** tab
       - Stop Time: **15 ms**
       - Time Step: **250 us**
    2. **Save Fields** tab
       - Type : **Linear Step**
       - Start: **0 s**
       - Stop: **15 ms**
       - Step Size: **250 us**
       - Select **Add to List**
    3. **Solver** tab
       - Non-linear Residuals: **1e-6**
    4. Press **OK**

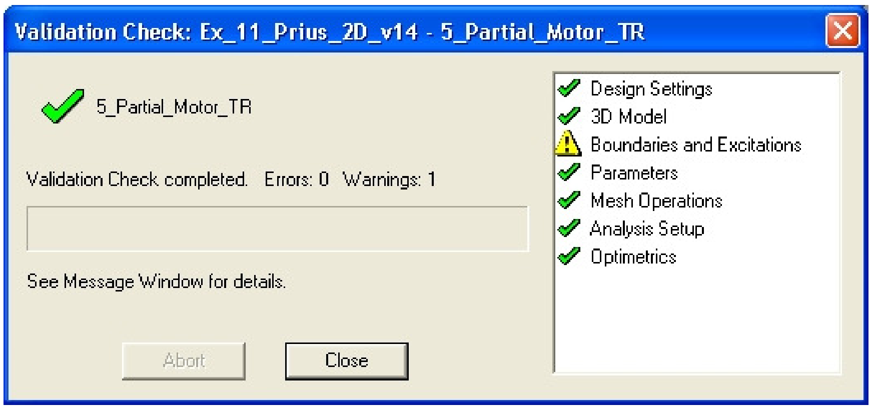






Validation Check

- **To Check the Validity of the Setup**
  - Select the menu item *Maxwell 2D > Validation Check*



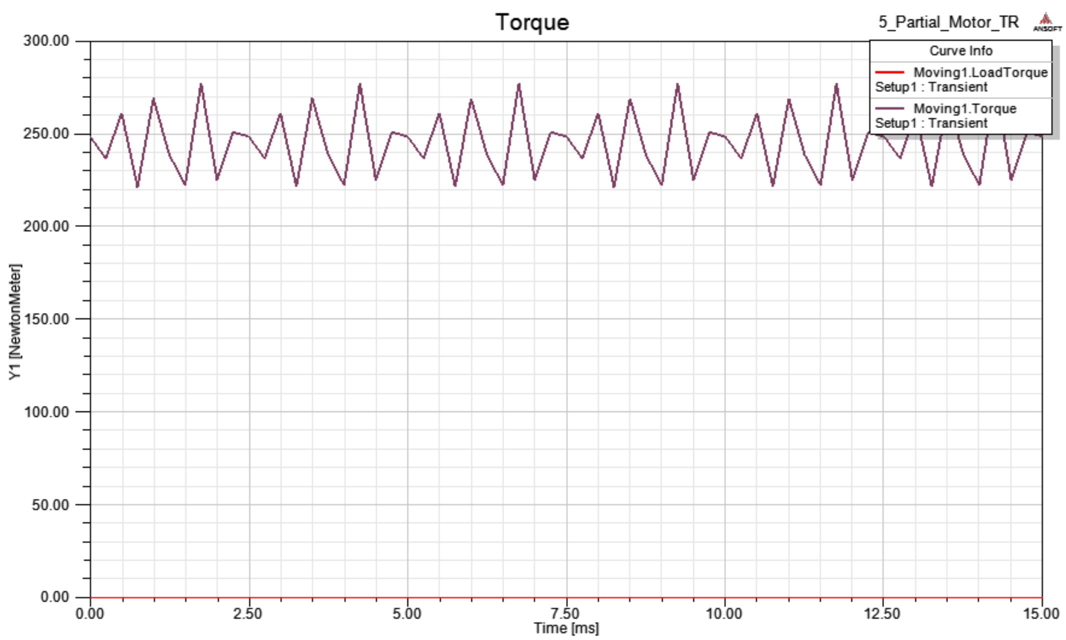
  - Maxwell checks the geometry, excitation definitions, mesh operations and so one. The model is validated but some Warnings are displayed in the message box:
    1. Eddy effect are not taken into account in our design which is what we decided

Solve

- **To Run Solution**
  - Select the menu item *Maxwell 2D > Analyze All*

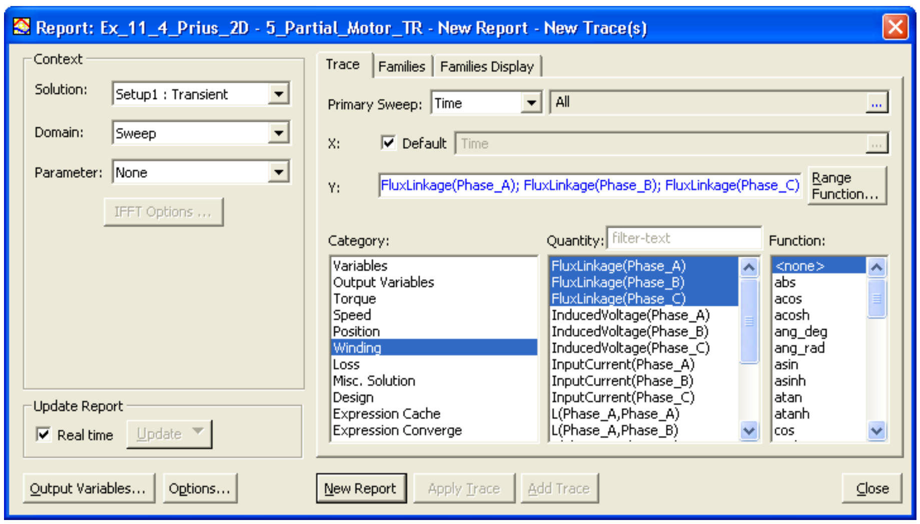
Postprocessing

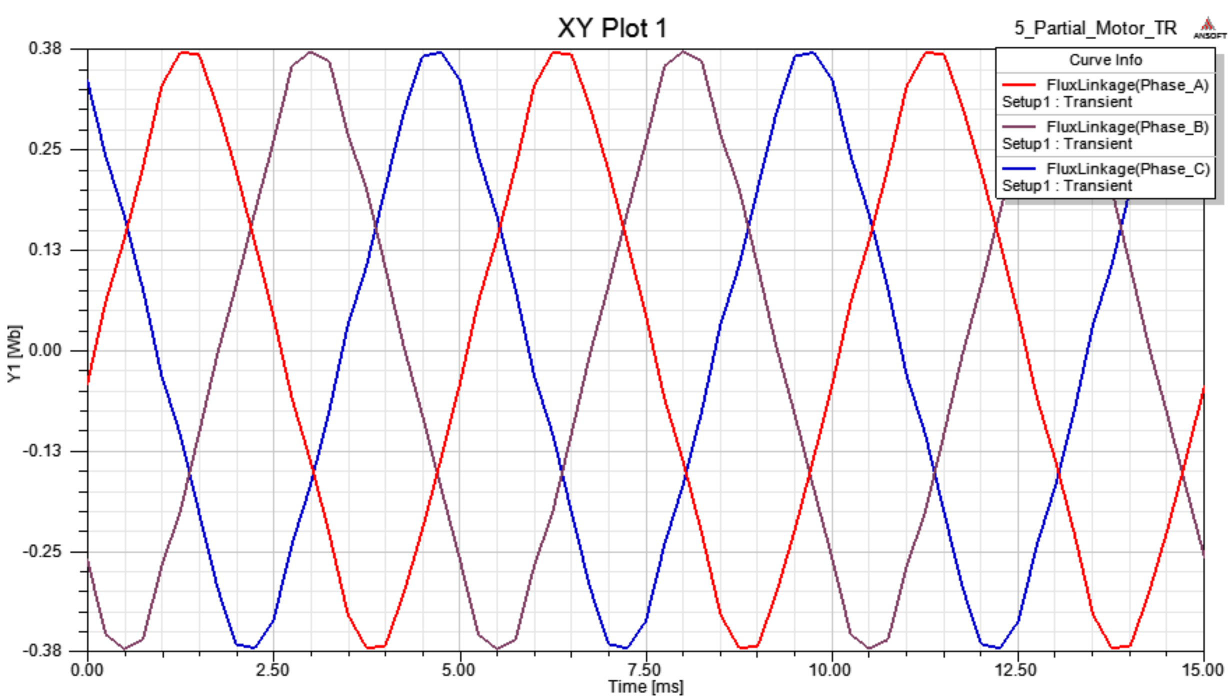
- Solve information appear in the profile of simulation
- **To View Solution Data**
  - Select the menu item *Maxwell 2D > Results > Solution Data*
- Performance curves can be displayed during the simulation. They are updated at the end of each time steps.
- **To Create Torque Vs Time Plot**
  - Select the menu item *Maxwell 2D > Results > Create Quick Reports*
  - In Quick report window,
    1. Select **Torque**
    2. Press **OK**



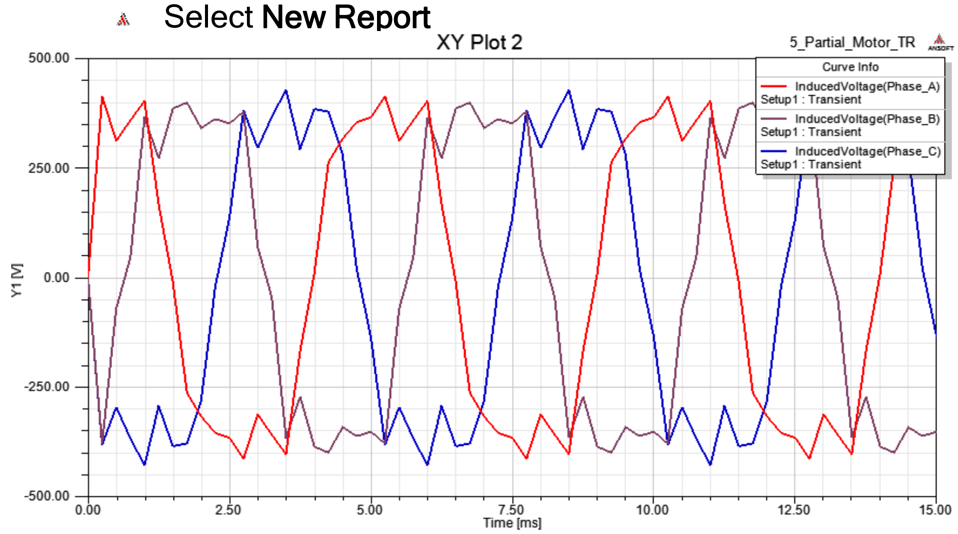
- The *LoadTorque* (in red) is zero as we are in motor mode.
- We can see that there are a lot of ripples in the Torque. The ratio between the torque and the torque ripples is almost 10 percent. This is due to the unique structure of the IPM motor (Internal Permanent Magnets). To limit the ripple, some manufacturers modify slightly the rotor shape around the magnets or add a second layer of internal magnets. Also the control strategy plays a big role into preventing the ripples.
- The torque value is around 240 N.m. This value is compatible with measurement.

- Plot Flux Linkages Vs Time
  - Select the menu item *Maxwell 2D > Results > Create Transient Report > Rectangular Plot*
  - In report window,
    - Category: **Winding**
    - Quantity: Press **Ctrl** and select **FluxLinkage(Phase_A), FluxLinkage(Phase_B)** and **FluxLinkage(Phase_C)**
    - Select **New Report**

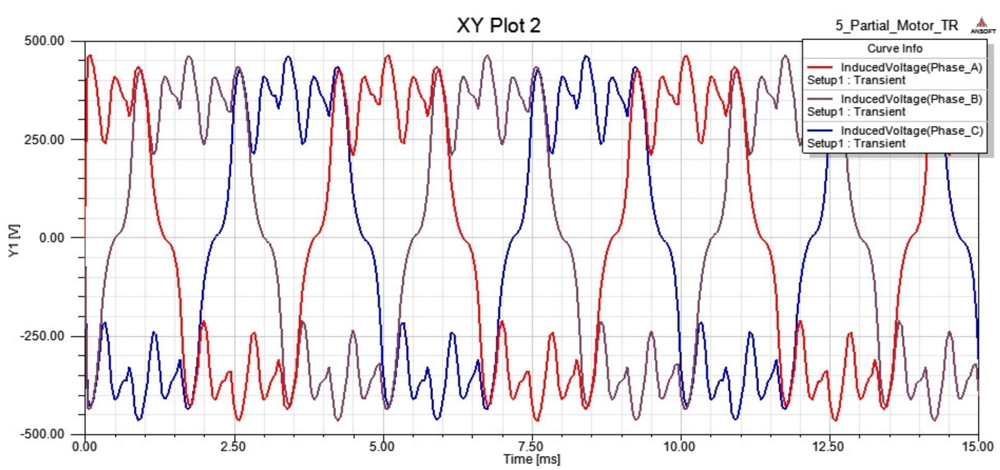




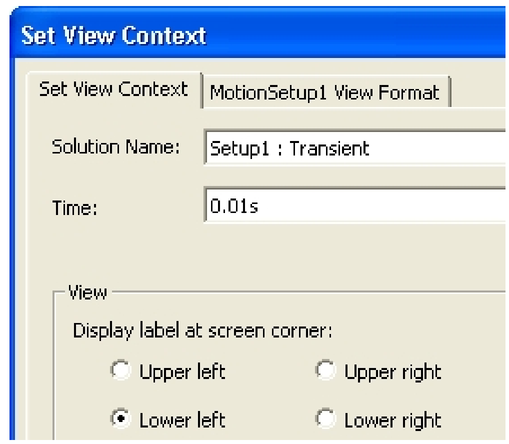
- **Plot Induced Voltages Vs Time**
  - Select the menu item ***Maxwell 2D > Results > Create Transient Report > Rectangular Plot***
  - In report window,
    - Category: **Winding**
    - Quantity: Press **Ctrl** and select **InducedVoltage(Phase_A), InducedVoltage(Phase_B)** and **InducedVoltage (Phase_C)**
    - Select **New Report**



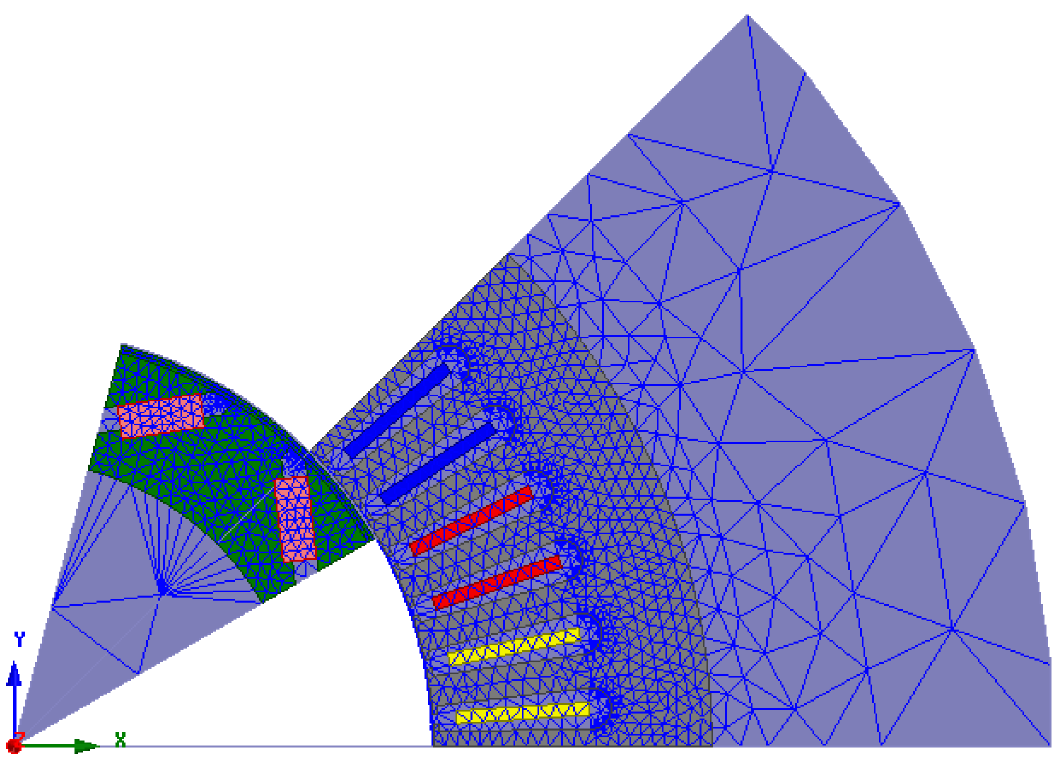
  - The curves are not really smooth. The reason is that the time step is too high. As the induced voltage is a derived quantity, Maxwell needs to derive the total flux ; the time steps is way to high to have accurate Induced Voltage. If you re run the simulation with a time steps of 50us (instead of 250 us), the Induced Voltage will have a more realistic shape:



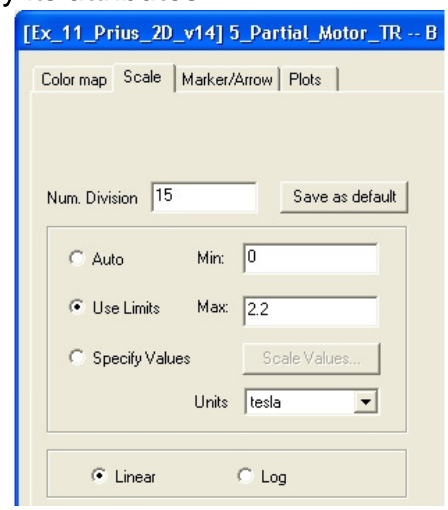
- **Plot Mesh**
  - Select the menu item ***View > Set Solution Context***
  - In Set View Context window,
    1. Set Time to **0.01 s**
    2. Select **OK**

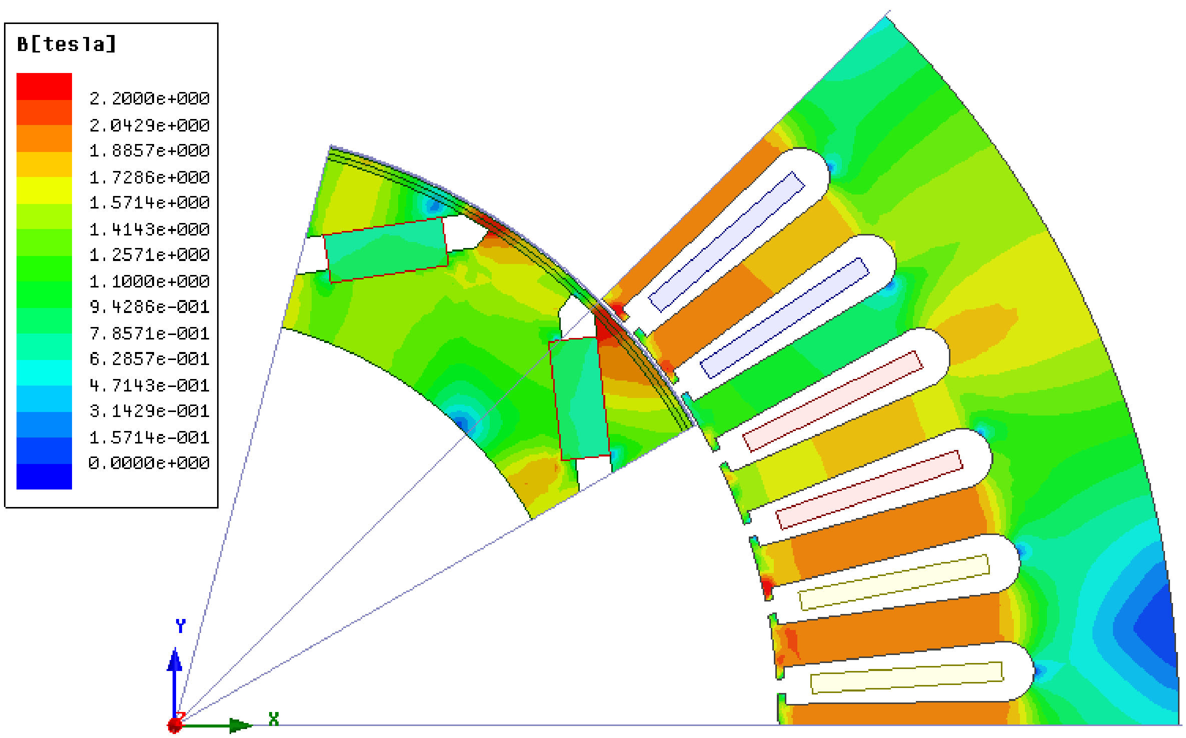


  - Select the menu item ***Edit > Select All***
  - Select the menu item ***Maxwell 2D > Fields > Plot Mesh***
  - In Create Mesh Plot window,
    - Press **Done**



- Plot Flux Density
  - Press **Ctrl** and select the objects **Rotor, Rotor1, Rotor2, PM1, PM2** and **Stator**
  - Select the menu item ***Maxwell 2D > Fields > Fields > B > Mag_B***
  - In Create Field Plot window,
    - Press **Done**
  - Double click on the legend to modify its attributes
  - In the window,
    - **Scale** tab
      - Select **User Limits**
        - Min: **0**
        - Max: **2.2**
    - Press **Apply** and **Close**

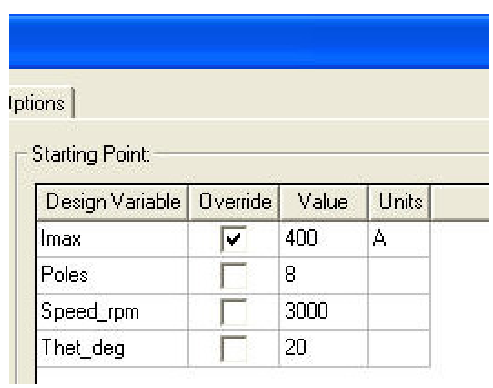




Parametric Study

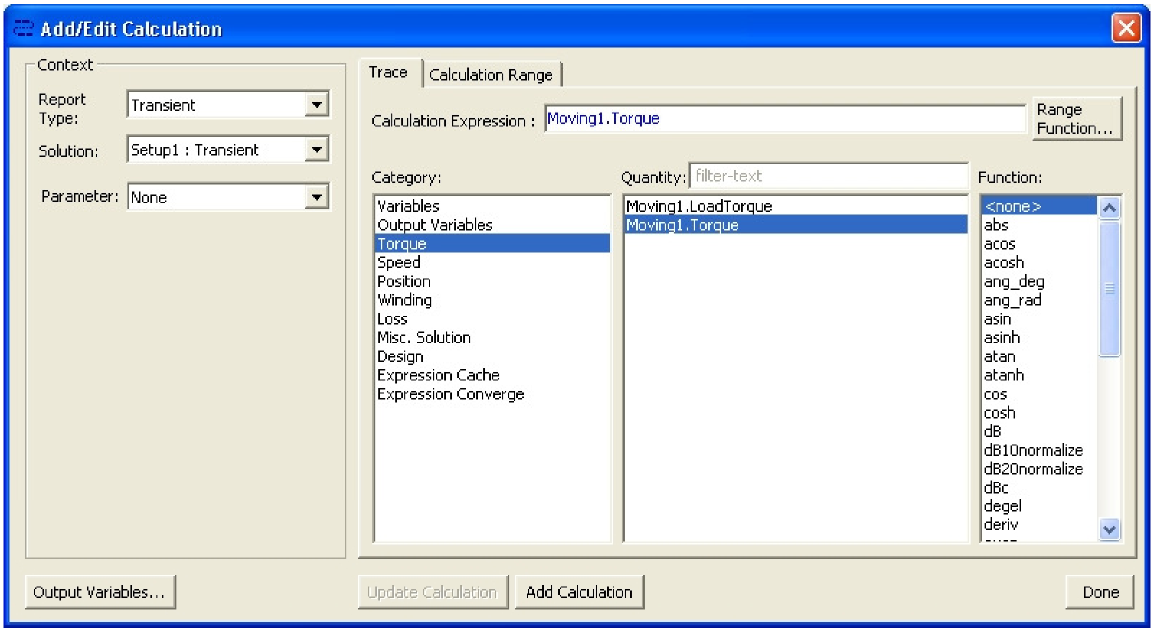
- The setup that has been solved was with a load angle of 20 deg. If the load angle is modified, the simulation has to be restarted.
- A parametric sweep will therefore take a very long time. We can propose two approaches:
  - Realize a Equivalent Circuit Extraction of the motor. This method requires the combination of parametric sweeps in magneto-static and the circuit simulator Simplorer. We will not discuss this method in this write-up.
  - Realize a parametric transient simulation. To cut the simulation time, the use of the Distributive Solve is necessary. This is the chosen method.
- **To Create a Parametric Analysis**
  - Select the menu item ***Maxwell 2D > Optimetrics Analysis > Add Parametric***
  - In Setup Sweep Analysis window, select **Add**
  - In Add/Edit window,
    1. Variable: **Thet_deg**
    2. Select **Linear Step**
    3. Start: **0**
    4. Stop: **60**
    5. Step: **15**
    6. Select **Add**

  - In Setup Sweep Analysis window, **General** Tab
    - This panel enables the user to change a design variable. For instance, if you wish to run the parametric sweep with a peak winding current of **400 A**, select the ***Override*** button, and change the current value.

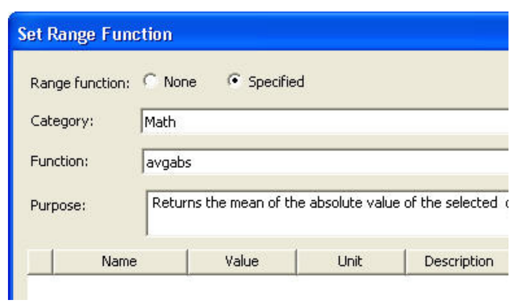


Motors - Permanent Magnet Motor (Prius IPM)

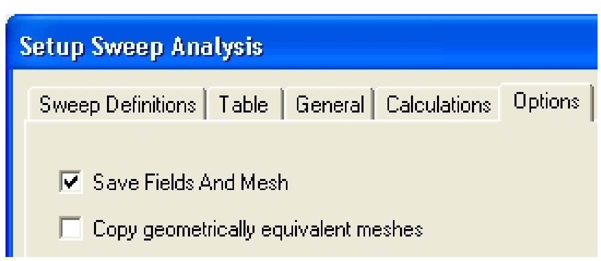
- **Calculation** tab, Select **Setup calculation**
- In Add/Edit Calculation window,
  - Category: **Torque**
  - Quantity: **Moving1.Torque**



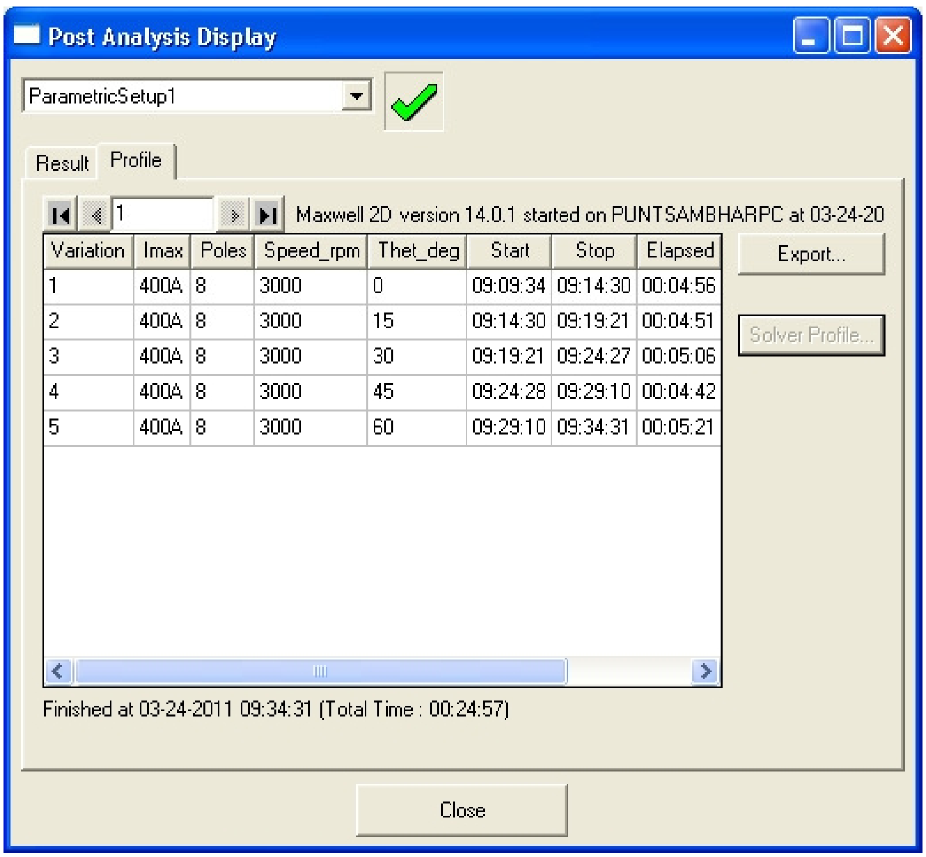
- Select the button **Range Function**
- In Set Range Function window,
  - Category: **Math**
  - Function: **avgabs**
  - Press **OK**
- Select **Add Calculation**
- Press **Done**



- In Setup Sweep Analysis window, select **Options** tab
  - Save Fields And Mesh: ☑ **Checked**
  - Press **OK**



- **Run Parametric Solution**
  - Expand the Project Manager tree to view **Optimetrics**
  - Right click on the tab **ParametricSetup1** and select **Analyze**
  - The Calculation Process will be done for all variations
- **View Results**
  - Select the menu item ***Maxwell 2D > Optimetrics Analysis > Optimetrics Results***
  - The results can also be monitored while solution is running



Variation	Imax	Poles	Speed_rpm	Thet_deg	Start	Stop	Elapsed
1	400A	8	3000	0	09:09:34	09:14:30	00:04:56
2	400A	8	3000	15	09:14:30	09:19:21	00:04:51
3	400A	8	3000	30	09:19:21	09:24:27	00:05:06
4	400A	8	3000	45	09:24:28	09:29:10	00:04:42
5	400A	8	3000	60	09:29:10	09:34:31	00:05:21

- All the plots are now available for any variation

Cogging Torque

- The Cogging Torque corresponds to the torque due to the shape of the teeth and the permanent magnets, when all the coils excitations are 0. The torque is a very small value in regard to the full load torque. Its computation is very sensitive to the mesh, as its value is in the same order of magnitude of the mesh noise.
- To compute accurately the cogging Torque, one could solve a parametric sweep in Magnetostatic (the input parameter being the angle between rotor and stator). This method will not lead to excellent results as the error due to the mesh will be different for each position (the mesh will change for every row).
- The preferred method is the use of the transient solver with motion:
  - We will move the rotor at the speed of 1 deg/s
  - The mesh will remain unchanged for all the positions thanks to the Band object : the mesh inside the Band object will rotate with the rotor
  - Each time step will be independent of the other
  - The adaptive mesh will not be used therefore the simulation time will be shorter

Copy Design

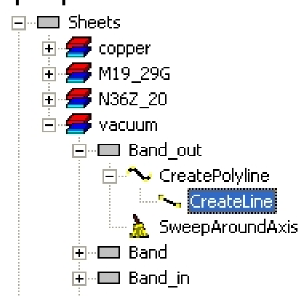
- **To Copy Design**
  - Select the Maxwell Design **“5_Partial_Motor_TR”** from the Project Manager tree, right click and select **Copy**
  - Right click on Project Name and select **Paste**
  - Change the name of the design to **“6_Partial_Motor_CT”**

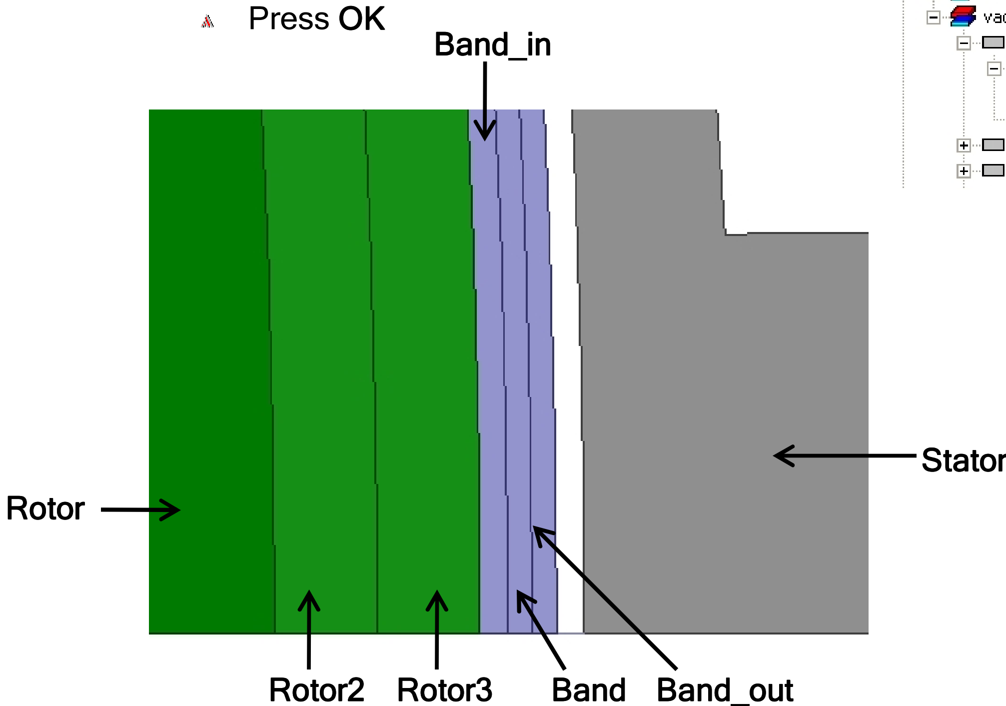
Create Outer Band

- We derive the set up for the cogging torque calculation from the Full load setup. We will change the speed, the excitations and some meshing operations.
- Since the mesh has to be well defined in the air gap, we will add an object so that we have enough layers of element:
- **Copy Band**
  - Select the sheet **Band** from history tree
  - Select the menu item ***Edit > Copy***
  - Select the menu item ***Edit > Paste***
  - Change the name of the sheet to **Band_out**

Motors - Permanent Magnet Motor (Prius IPM)

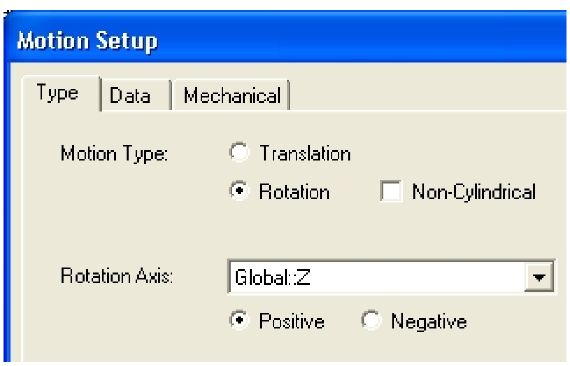
- **To Edit Band_out Object**
  - Expand the history tree for the sheet **Band_out**
  - Double click on the command **CreateLine** to open its properties
  - In Properties window,
    - Change Point2 position to **80.75,0,0**
    - Press **OK**

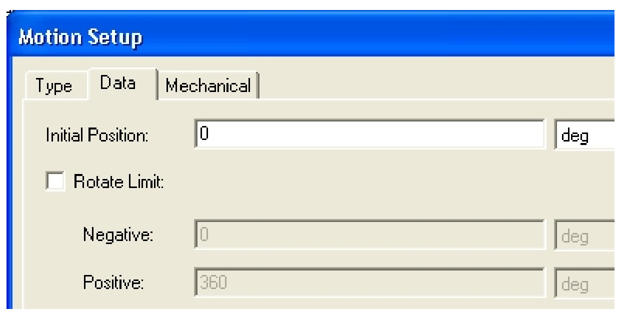


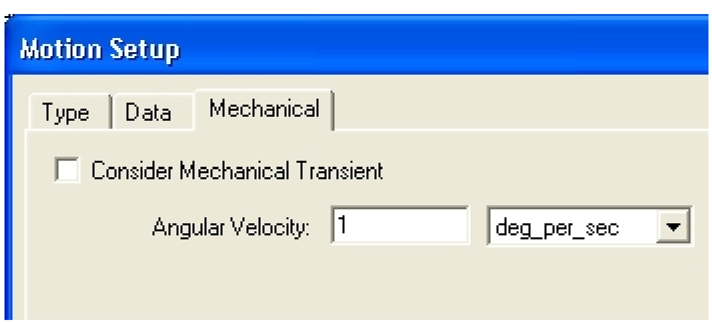


Modify Motion Setup

- **Delete Existing Motion Setup**
  - Select the menu item ***Maxwell 2D > Model > Motion Setup > Delete All***
- **Assign Motion**
  - Select the sheet **Band** from the history tree
  - Select the menu item ***Maxwell 2D > Model > Motion Setup > Assign Band***
  - In Motion Setup window,
    1. **Type** Tab
       - Motion Type: **Rotation**
       - Rotation Axis: **Global:Z**
       - Select **Positive**
    2. **Data** Tab
       - Leave it unchanged
    3. **Mechanical** Tab
       - Angular Velocity: **1 deg_per_sec**
    4. Press **OK**

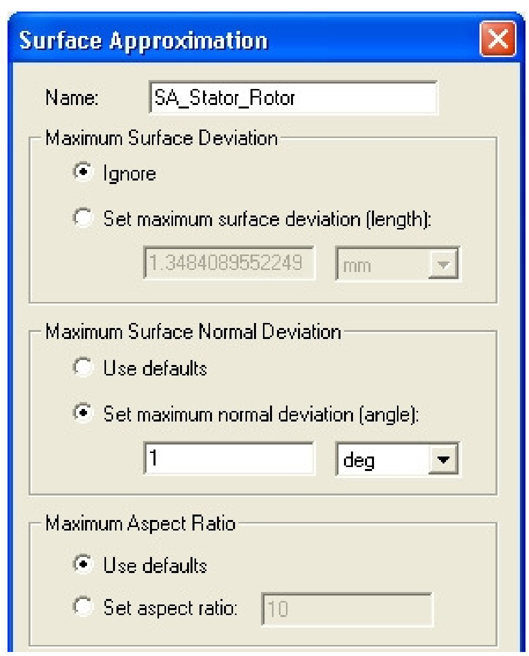






Edit Mesh Operations

- We also need to change the meshing operations. The mesh density that was good enough to compute the full load torque won't be accurate enough for the cogging torque
- **To Edit Mesh Operations**
  - Expand the Project Manager tree to view **Mesh Operations**
  - Double click on the mesh operation **Stator** to change its parameters
  - In Element Length Based Refinement window,
    - Change Maximum Length of Elements to **3mm**
  - Similarly change Maximum Length of Elements for operation **Rotor** to **3mm**
- **Add New Mesh Operation**
  - Press **Ctrl** and select the sheets **Stator, Rotor, Rotor2** and **Rotor3** from history tree
  - Select the menu item ***Maxwell 2D > Mesh Operations > Assign > Surface Approximation***
  - In Surface Approximation window,
    - Name: **SA_Stator_Rotor**
    - Set Maximum Normal Deviation (angle): **1 deg**
    - Press **OK**



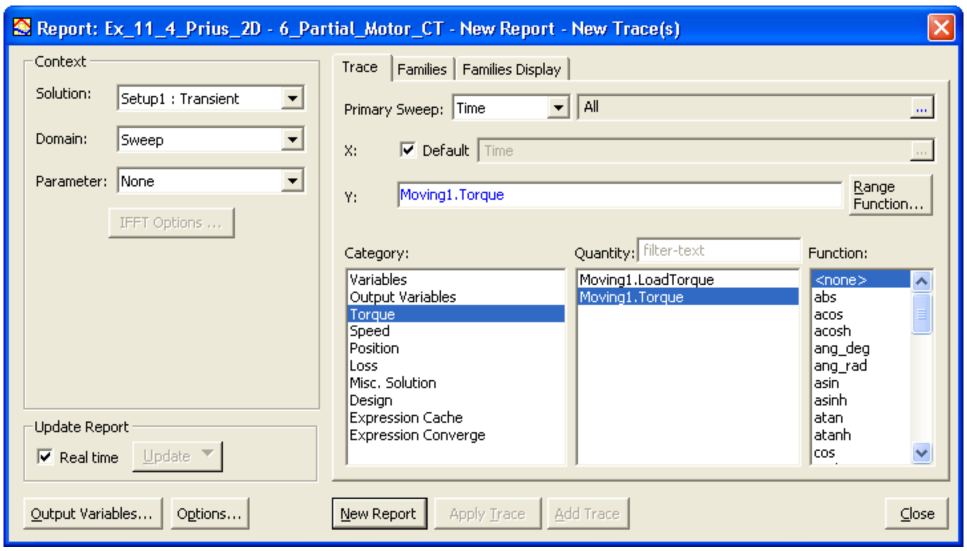
- ## Remove Coils
  - We can delete the coils as they are not needed in the cogging torque simulation
  - **To Delete Coils**
    - Press **Ctrl** and select all coils from history tree
    - Select the menu item ***Edit > Delete*** or press **Delete** button from keyboard
    - Select the menu item ***Maxwell 2D > Excitations > Delete All***

- ## Modify Analysis Setup
  - One pole pair takes 7.5 mech degrees. We will solve over ***15 s*** in order to have two periods (remember: the speed is 1 deg/s)
  - We set the time step to ***0.125 s*** to have a very smooth curve. An higher time step is still valid if you want a faster result.
  - **To Modify Analysis Setup**
    - Expand the Project Manager tree to view **Analysis**
    - Double click on the tab **Setup1** to modify its parameters
    - In Solve Setup window,
      - **General** tab
        - Stop Time: **15 s**
        - Time Step: **0.125 s**
      - **Save Fields** tab
        - Select the button **Clear All**
      - **Solver** tab
        - Nonlinear Residuals: **1e-4**
      - Press **OK**

- ## Solve
  - **To Run Solution**
    - Expand the Project Manager tree to view **Analysis**
    - Right click on the tab **Setup1** and select **Analyze**

PostProcess

- Plot Torque Vs Time
  - Select the menu item *Maxwell 2D > Results > Create Transient Report > Rectangular Plot*
  - In Report window,
    - Category: **Torque**
    - Quantity: **Moving1.Torque**
    - Select **New Report**



- The Torque trace appears. As expected, the cogging torque is periodical. The peak value is about *1.75 N.m*.