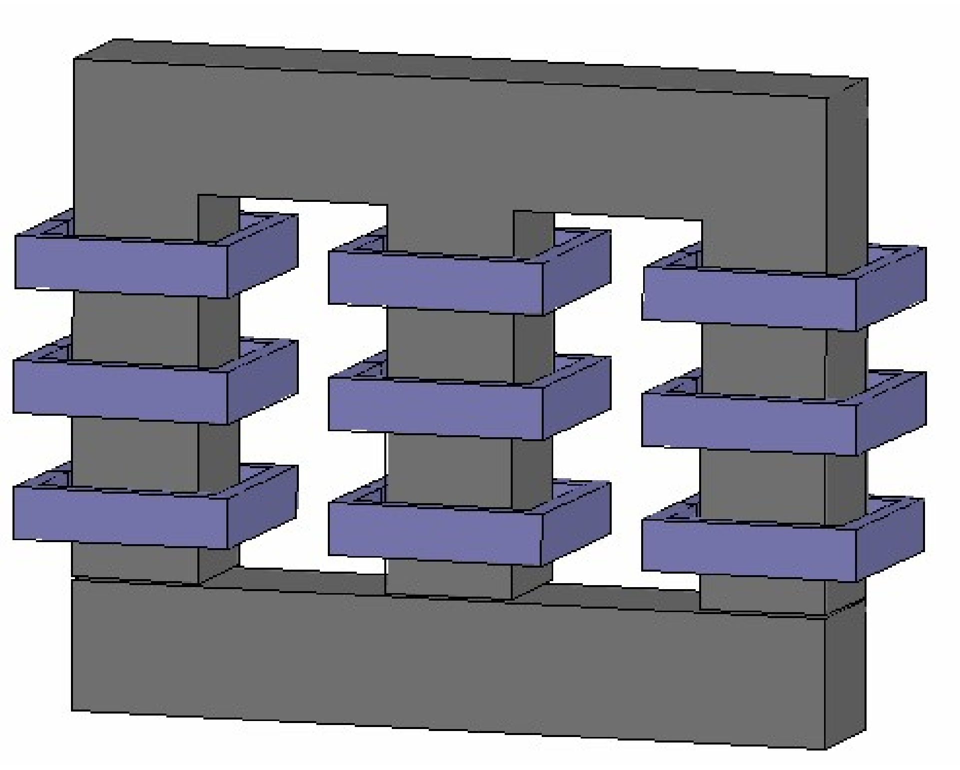
Example (Magnetostatic) - Inductance Calculation

- The implementation and application of a 3-phase Inductor using the Magnetostatic Solver to calculate the nonlinear inductance
  - The inductance calculation is an important part of a magnetostatic simulation. The inductive properties will, of course, change with the nonlinearities of the problem. The properties and concepts of the inductance calculation are described in this example.
  - This example uses a 3-phase, 3-coil-per-phase inductor to demonstrate how the inductance calculation produces meaningful results. The setup is scrutinized and the results are examined. Then a half-symmetry model is examined to familiarize the user with a half-symmetry setup.



Ansoft Maxwell Design Environment

- The following features of the Ansoft Maxwell Design Environment are used to create the models covered in this topic
  - 3D Solid Modeling
    - Primitives: **Box, Rectangle, Region**
    - Surface Operations: **Section**
    - Boolean Operations: **Subtract, Separate Bodies, Split**
    - 3D Modeler: **Delete Last Operation**
    - Sweep: **Along Path**
    - Duplicate: **Along Line**
  - Boundaries/Excitations
    - Current: **Stranded**
  - Analysis
    - **Magnetostatic**
  - Results
    - **Inductance Matrix**

Getting Started

Launching Maxwell

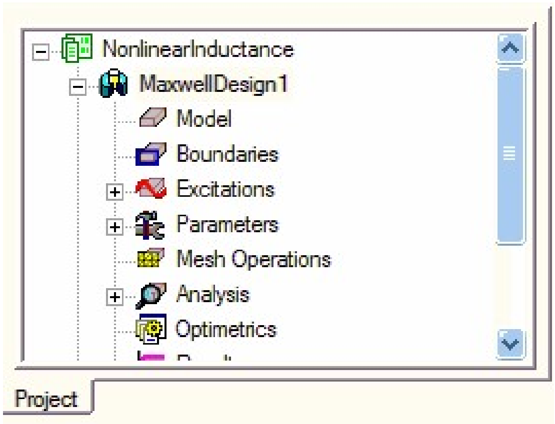
1. To access Maxwell, click the Microsoft **Start** button, select **Programs**, and select **Ansoft** and then **Maxwell 11.**

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 :
  1. Select the menu item ***Tools > Options > Maxwell Options***
  2. Maxwell Options Window:
     1. Click the **General Options** tab
        - Use Wizards for data entry when creating new boundaries: ☑ **Checked**
        - Duplicate boundaries with geometry: ☑ **Checked**
     2. Click the **OK** button
  3. Select the menu item ***Tools > Options > 3D Modeler Options.***
  4. 3D Modeler Options Window:
     1. Click the **Operation** tab
        - Automatically cover closed polylines: ☑ **Checked**
     2. Click the **Drawing** tab
        - Edit property of new primitives: ☑ **Checked**
     3. Click the **OK** button

Opening a New Project

- **To open a new project:**
  1. In an Maxwell window, click the 🗋 On the Standard toolbar, or select the menu item *File > New*.
  2. Select the menu item *Project > Insert Maxwell Design*, or click on the icon



Set Solution Type

- Select the menu item: *Maxwell > Solution Type > Magnetostatic*, or right mouse click on MaxwellDesign1 and select *Solution Type …*

Creating the 3D Model of a Nonlinear Inductor

- The example that will be used to demonstrate the inductance calculation is that of a 3-phase transformer with multiple windings in series for each phase.

Set Model Units

- Select the menu item *3D Modeler > Units >* Select Units*: in (inches)*

Create the Core

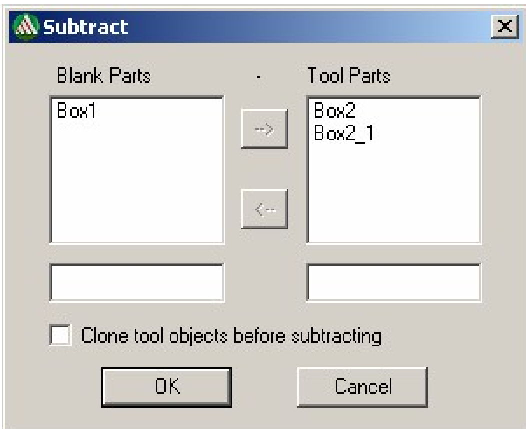
1. Select ***Draw > Box*** to start the drawing procedure:
   1. Enter -1, -6, 0 as the starting point of the box
   2. Enter 2, 12, 10 to define the dimensions of the box
   3. A Properties dialog appears:
      1. Select ***OK***
   4. Hold down **Ctrl+D** or click the button to view the entire geometry.

2. Select ***Draw > Box*** to start drawing the window.
   1. Enter -1, 1, 2 as the starting point of the box
   2. Enter 2, 3, 6 to define the dimensions of the box
   3. A Properties dialog appears:
      1. Select ***OK***

3. Select **Box2** from the object tree (selected by default after creating it in step 2).
4. Select ***Edit > Duplicate > Around Axis*** to create a second window.
   1. Axis: **Z**
   2. Angle: **180 deg**
   3. Total number: **2**
   4. Select ***OK***
5. Select ***OK***

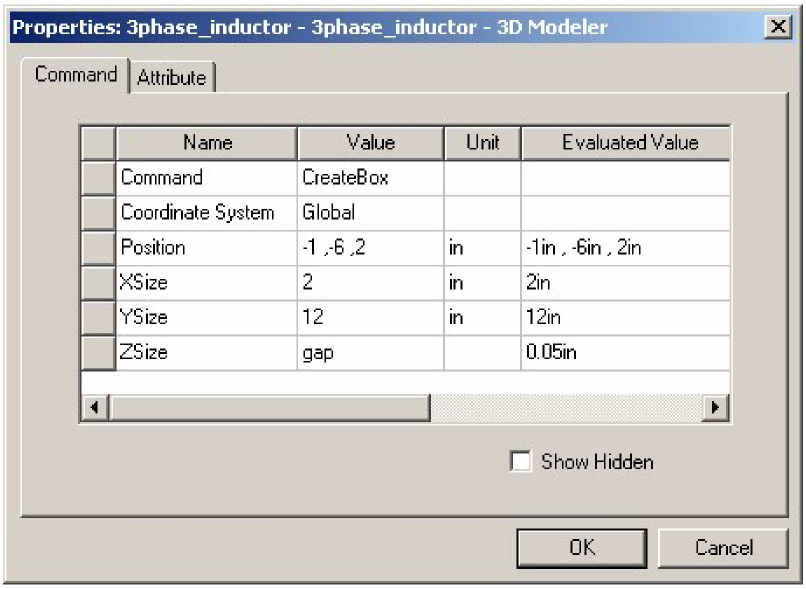
6. Select **Box1**, and then select **Box2** and **Box2_1** from the object tree.
   Use **Ctrl** or **Shift** to select multiple items throughout this example.

7. Select ***3D Modeler > Boolean > Subtract***
   1. Make sure that **Box1** is in the Blank Parts box and that **Box2** and **Box2_1** are in the Tool Parts box (this is true if **Box1** is selected first).
   2. Make sure that **Clone tool objects before subtracting** is deselected.
   3. Select ***OK***



Create the Core (continued)

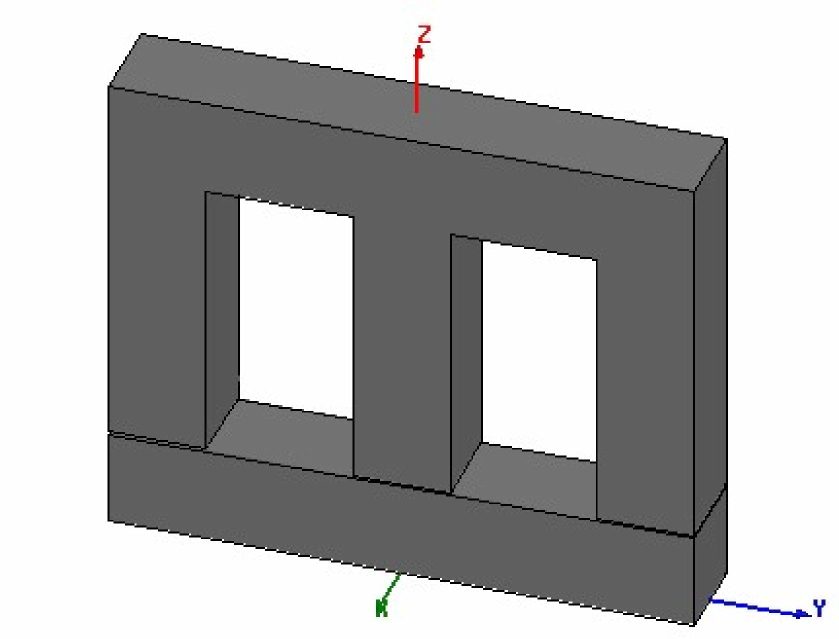
8. Select *Draw > Box* to start drawing the gap:
   1. Enter -1, -6, 2 as the starting point of the box
   2. Enter 2, 12, 0.05 to define the dimensions of the box
   3. A Properties dialog appears:
      1. In the value box of Zsize, enter **gap** and type Enter to accept this value.
         1. In the **Add Variable** box that appears, enter 0.05in for the value.
         2. Select *OK*
      2. Select *OK*



9. Select **Box1** and then **Box3** from the Object Tree.
   (Use **Ctrl** or **Shift** to select multiple items.)
10. Select *3D Modeler > Boolean > Subtract.*
    1. Make sure that **Box1** is in the Blank Parts box and that **Box2** and **Box2_1** are in the Tool Parts box (this is true if **Box1** is selected first).
    2. Make sure that **Clone tool objects before subtracting** is deselected.
    3. Select *OK*

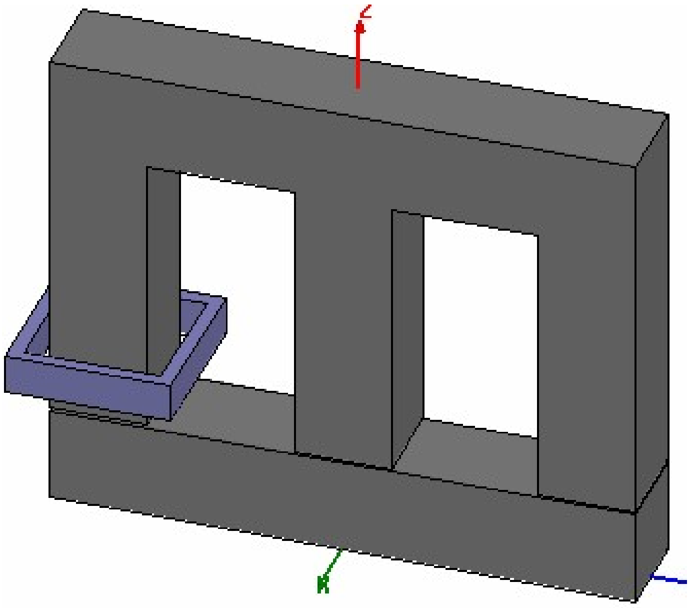
Create the Core (continued)

11. Select **Box1.**
12. Select ***3D Modeler > Boolean > Separate Bodies*** (the E and I parts of the core are now separate).
13. Double-click on **Box1** in the object tree (a Properties window pops up).
    1. Change the name from **Box1** to **Core_E**.
    2. Select **OK.**
14. Double-click on **Box1_1** in the object tree (a Properties window pops up).
    1. Change the name from **Box1_1** to **Core_I**.
    2. Select **OK.**
15. Select both **Core_E** and **Core_I** from the object tree.
    1. Find the Attribute window (on the left side, under the project tree by default).
    2. Click on the Material Value **vacuum** (a Materials list appears).
        1. Find **steel_1008** and double-click on this material to accept it (or single-click and select **OK**).
16. The cores are now completely defined.



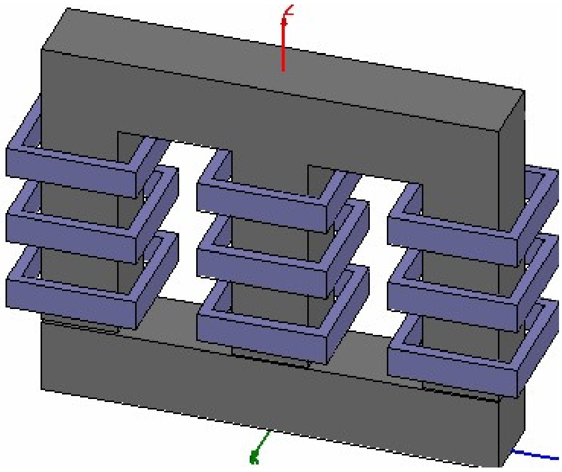
Create the Coils

1. Select *3D Modeler > Grid Plane > YZ*
2. Select *Draw > Rectangle*.
    1. Enter 0, -3.6, 3.5 as the starting point of the rectangle
    2. Enter 0, 0.3, -0.8 to define the dimensions of the rectangle
    3. A Properties dialog appears:
        1. Select *OK*
3. Select *3D Modeler > Grid Plane > XY*
4. Select *Draw Rectangle*.
    1. Enter 1.5, -6.5, 3 as the starting point of the rectangle
    2. Enter -3, 3, 0 to define the dimensions of the rectangle
    3. A Properties dialog appears:
        1. Select *OK*
5. Select **Rectangle2** from the object tree.
6. Select *3D Modeler > Delete Last Operation* to produce a line.
7. Select **Rectangle1** and **Rectangle2** from the object tree.
8. Select *Draw > Sweep > Along Path*
    1. A **Sweep along path** window pops up:
        1. Angle of twist: 0deg
        2. Draft Angle: 0deg
        3. Draft type: Round
        4. Select **OK**
    2. Select **OK**



Create the Coils (continued)

9. Select **Rectangle1** from the object tree.
10. Select ***Edit > Duplicate > Along Line***
    1. Enter 0, 0, 0.
    2. Enter 0, 0, 1.925.
        1. Total Number: 3
        2. Select **OK.**
    3. Select **OK.**



11. Select **Rectangle1**, **Rectangle1_1**, and **Rectangle1_2** from the object tree. (Use **Ctrl** or **Shift** to select multiple items.)
12. Select ***Edit > Duplicate > Along Line***
    1. Enter 0, 0, 0.
    2. Enter 0, 5, 0.
        1. Total Number: 3
        2. Select **OK.**
    3. Select **OK.**

13. Select **Rectangle1**, **Rectangle1_1**, and **Rectangle1_2** from the object tree.
14. In the Attribute window, type **Coil_left** in the Name Value.

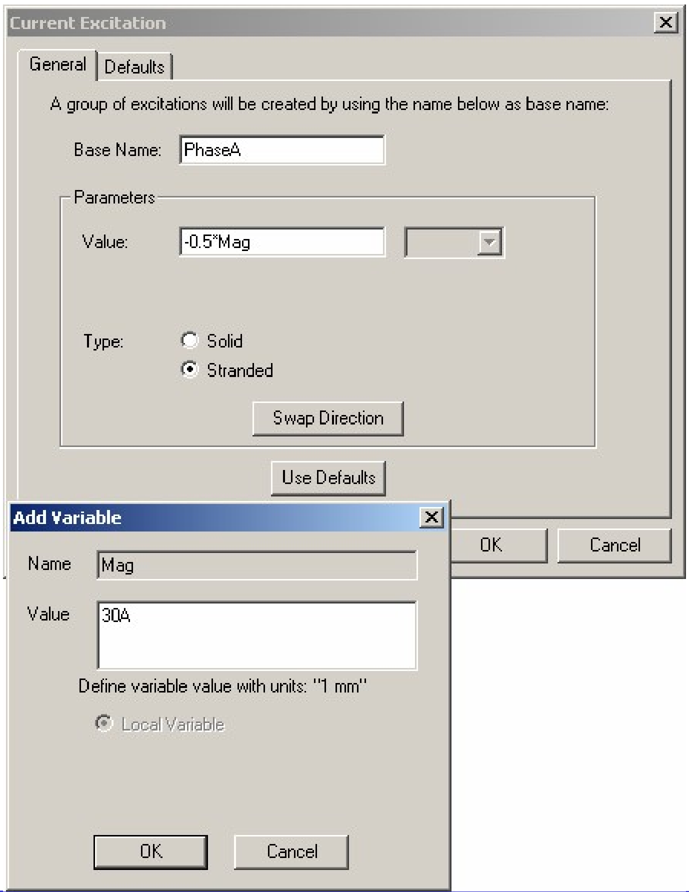
15. Select **Rectangle1_3**, **Rectangle1_1_1**, and **Rectangle1_2_1** from the object tree.
16. In the Attribute window, type **Coil_mid** in the Name Value.

17. Select **Rectangle1_4**, **Rectangle1_1_2**, and **Rectangle1_2_2** from the object tree.
18. In the Attribute window, type **Coil_right** in the Name Value.

19. Select all **Coil** objects from the object tree.
20. In the Attribute window, click on the Material Value **vacuum** (a Materials list appears).
    1. Find **copper** and double-click on this material to accept it (or single-click and select **OK**).

Create the Terminals and Define the Sources:

1. Select all the **Coil** objects from the object tree.
2. Select ***3D Modeler > Surface > Section…***
    1. Select **YZ**
    2. Select **OK**
3. Select all the **Section** sheets (selected by default after the last operation).
4. Select ***3D Modeler > Boolean > Separate Bodies***
5. Select the extra Sections (1_1 through 9_1) and delete them (by using Delete on the keyboard or ***Edit > Delete*** from the command menu).
6. Select the sheets **Section1**, **Section2**, **Section3** from the object tree.
7. Select ***Maxwell > Excitations > Assign > Current…***
8. The Current Excitation dialog appears.
    1. Base Name: **PhaseA**
    2. Value: **-0.5*Mag**
    3. Type: **Stranded**
9. Select **OK**
10. An Add Variable dialog appears
    1. For the Variable **Mag:**
       Value: **30A**
11. Select **OK**
12. Select the sheets **Section4, Section5, Section6** from the object tree.
13. Select ***Maxwell > Excitations > Assign > Current…***
    1. Base Name: **PhaseB**
    2. Value: **Mag**
    3. Type: **Stranded**
14. Select **OK**

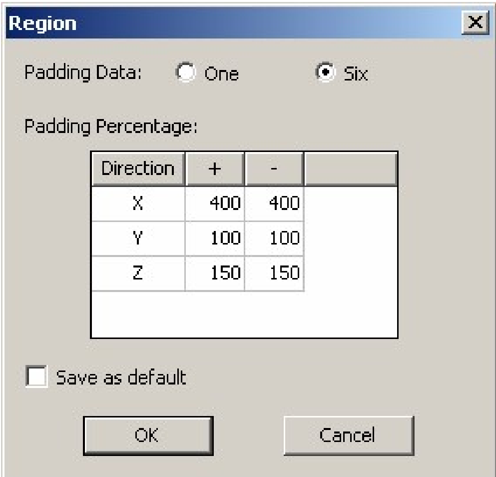


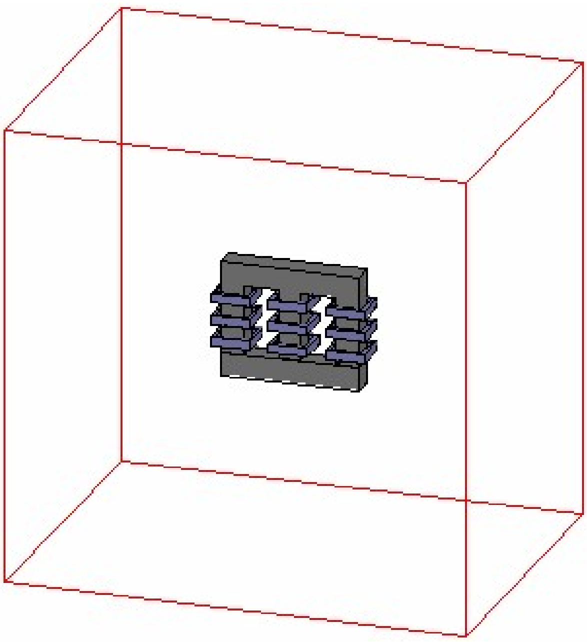
Create the Terminals and Define the Sources (continued):

15. Select the sheets **Section7**, **Section8**, **Section9** from the object tree.
16. Select ***Maxwell > Excitations > Assign > Current…***
17. The Current Excitation dialog appears.
    1. Base Name: **PhaseC**
    2. Value: **-0.5*Mag**
    3. Type: **Stranded**
18. Select **OK**

Create the Region Object

1. Select ***Draw > Region***
    1. A Region dialog box opens up.
    2. Fill in the information as follows:
       Padding Data: **Six**
       X: **400, 400**
       Y: **100, 100**
       Z: **150, 150**
    3. Select **OK**
2. Select **OK**





Inductance Calculation Defining Equations

- Inductance in a magnetostatic simulation can be defined as

$$\lambda_1 = L_{11} I_1 + L_{12} I_2 + \cdots$$
$$\lambda_2 = L_{21} I_1 + L_{22} I_2 + \cdots$$
$$\cdots$$

  where λ is the flux linkage for an individual coil, and I is the current.

- This inductance is the apparent inductance - it defines the ratio of flux linkage to current in one coil.

- The inductance of a coil can also be defined by the energy storage as

$$L = 2 \times W / I^2$$
$$= \int \vec{B} \cdot \vec{H} d\Omega / I^2$$

  where the energy is determined by the magnetic flux density and field intensity in the solution space.

- This energy storage calculation is what determines the inductance values in the matrix. The on-diagonal elements (L_{11}, L_{22}, etc.) are determined by exciting the coils individually and finding the energy from the B and H fields for each individual case. The off-diagonal elements (L_{12}, L_{21}, L_{13}, etc.) are determined from a combination of the B and H fields from the individually excited cases. The following is the exact defining equation for the inductance calculation

$$L_{ij} = \int \vec{B}_i \cdot \vec{H}_j d\Omega$$

  where it is assumed that one ampere is flowing through the respective coils.

- For nonlinear materials, the value of the inductance obtained from these calculations is only valid for the specific source currents. If any of the source currents change, the characteristics of the field solution will change as well as the inductance of each coil (less change when in a linear region, greatest change when moving from the linear region to a saturated region).

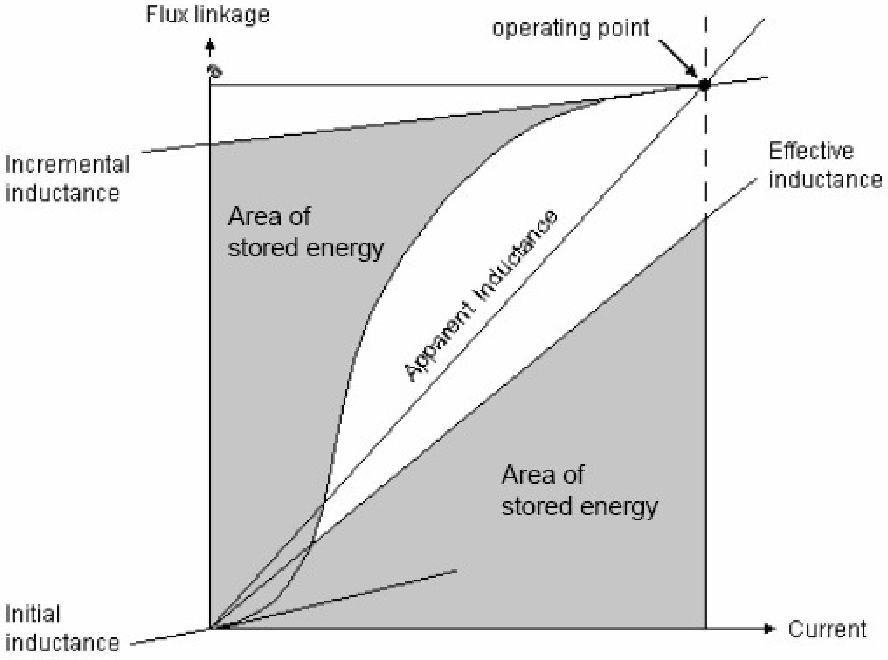
- If only linear materials are used, the value of the inductance will be valid for any value of source currents.

Inductance Calculation Methodology

- The inductance calculation is performed after the field solution and depends on the values of the field solution at every point in the solution space because it requires an energy integral in the entire solution space.

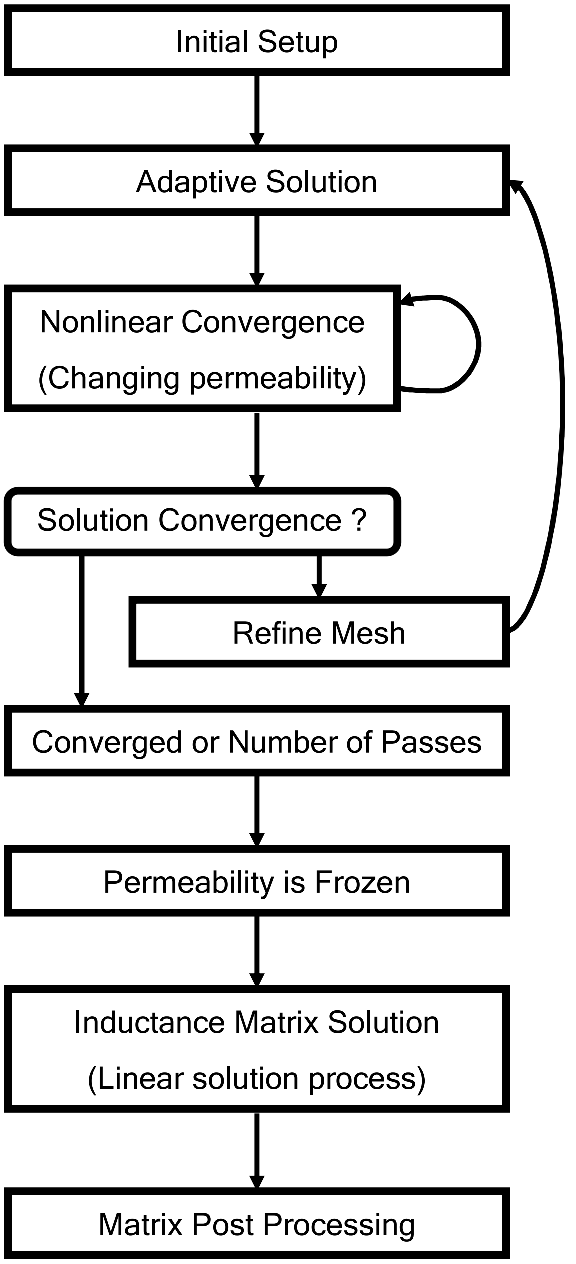
- After the field solution is completed, the relative permeability values are “frozen”. Then, one ampere is sequentially excited in each coil, and a field solution is performed with the frozen permeabilities. With these field solutions, the energy integral is performed and the inductance is obtained as described previously.

- The inductance obtained in this manner is the inductance per turn^2 (referred to as the nominal inductance in the software) and is the apparent inductance (determined by the flux linkage/current operating point in the graphic below).



- Incremental inductance can be obtained by performing energy perturbation techniques (changing the source currents and finding the slope).

Inductance Calculation Process



Inductance Calculation Post Processing

- The nominal inductances that are computed by the solver are returned in units of Henries/turns^2. In order to return each inductance in units of Henries, the number of turns for each coil must be specified at some point. Also, the inductance matrix can be grouped to represent windings in series, and a factor can be included if the winding is made up of parallel branches. These are all considered post-processing, and they can help to return meaningful quantities.

- The post processed inductances are calculated as follows:

$$L_{ij} = N_i N_j L_{ij\_nom}$$

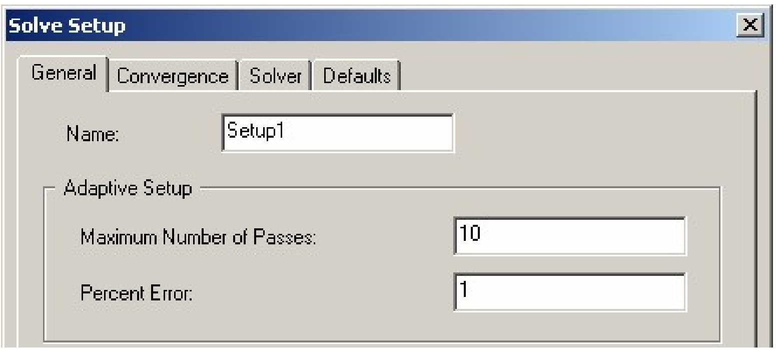
$$L_{group} = \sum_{i\_group} \sum_{j\_group} L_{ij}$$

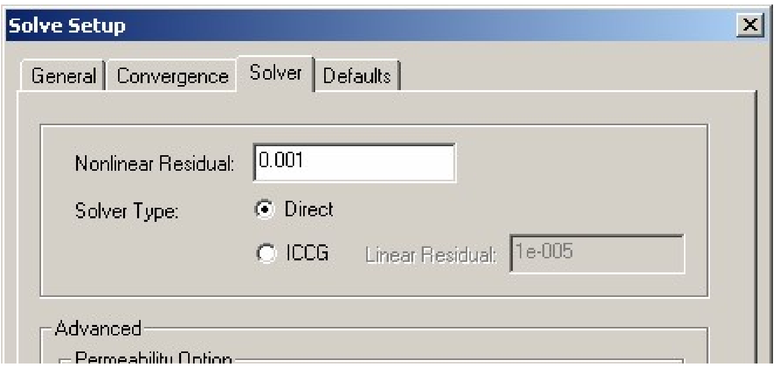
$$L_{branched} = L_{group} / b$$

- The first step is to find the coil inductances from the nominal inductances by multiplying by the number of turns in each coil (or number of turns squared for self inductances).
- The next step is to group the series inductances by adding up all the inductances in the block (i.e. if conductors 1 through N are grouped, then add up the N by N block of inductances to obtain the grouped self inductance – the same process is followed for grouped mutual inductances).
- The final step is to take into account parallel branches by dividing by the number of branches squared. The inductance decreases with parallel branches because of the reduced number of turns per branch.

Create a Solution Setup

1. Select *Maxwell > Analysis Setup > Add Solution Setup …*
   1. In the General tab:
      1. Set Maximum Number of Passes to 10
      2. Set Percent Error to 1
   2. In the Solver tab:
      1. Set Nonlinear Residual to 0.001
   3. Select **OK**

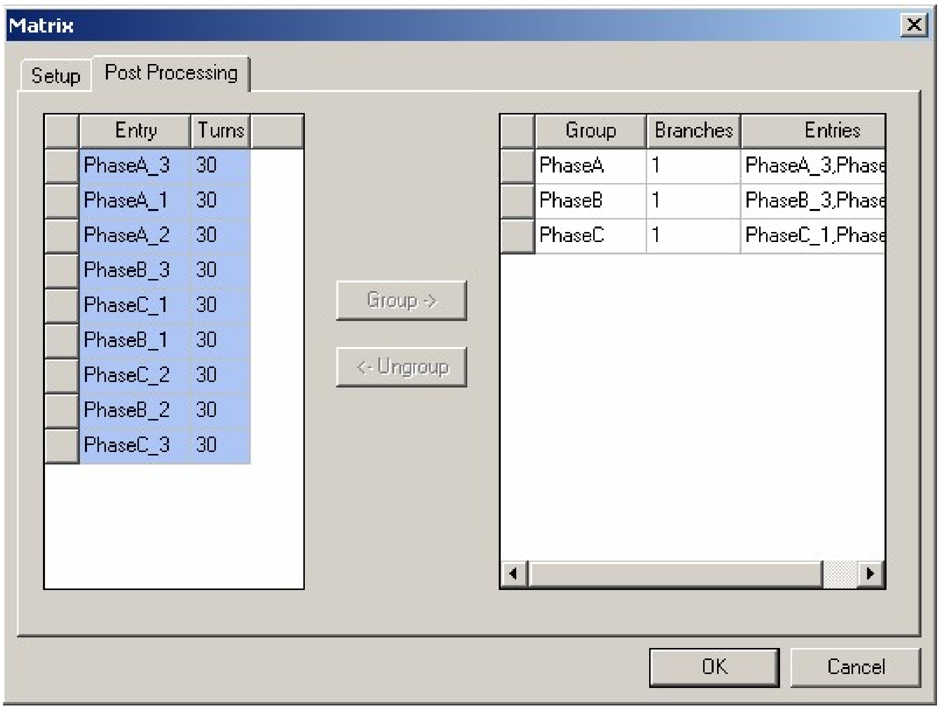




- The Nonlinear Residual is important in simulations with nonlinear materials that operate outside of the linear region. Increasing the number will make the simulation run faster, decreasing the number will force the nonlinear solver to more precisely find the nonlinear B-H operating points within the steel (or other nonlinear magnetic material).
- **It is often the case with saturated nonlinear materials that the Nonlinear Residual will need to be reduced to obtain accurate results.**

Create Matrix Parameters

1. Select ***Maxwell > Parameters > Assign > Matrix…***
    1. In the Setup tab, check the boxes to Include all the Sources (or click on the word Include to automatically check all the boxes).
    2. In the Post Processing tab, set the turns for each source to **30**
    3. Select **PhaseA_1, PhaseA_2,** and **PhaseA_3** and select **Group ->** (Use **Ctrl** or **Shift** to select multiple items.)
    4. Select **PhaseB_1, PhaseB_2,** and **PhaseB_3** and select **Group ->**
    5. Select **PhaseC_1, PhaseC_2,** and **PhaseC_3** and select **Group ->**
    6. Rename Group1 to **PhaseA**
    7. Rename Group2 to **PhaseB**
    8. Rename Group3 to **PhaseC**
    9. Leave Branches set to 1 for each Group

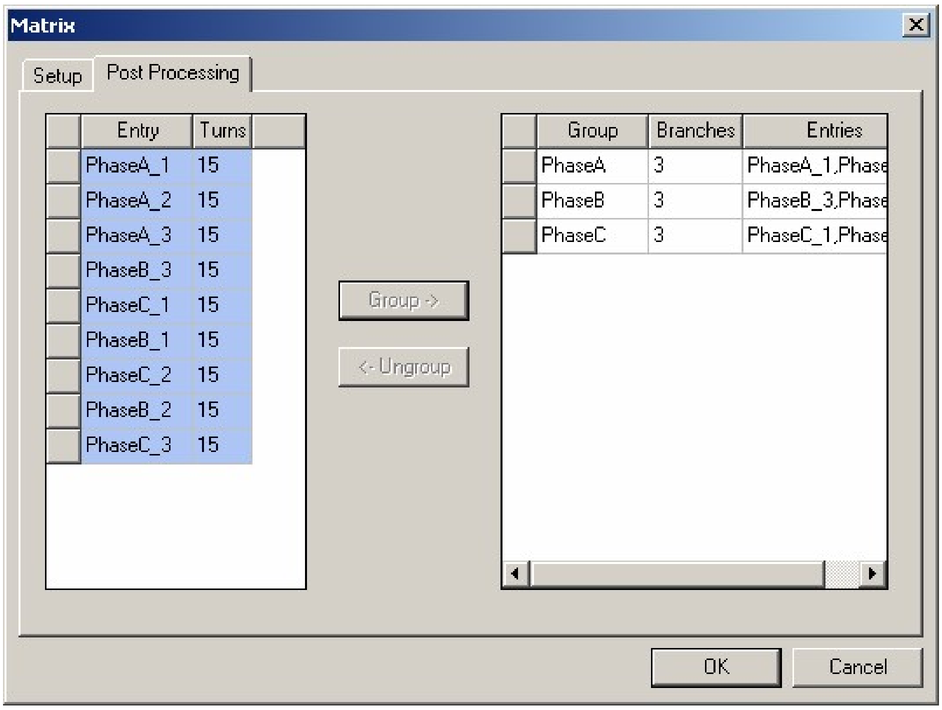


- This setup says that each source has 30 turns and that the sources on each leg are connected in series (as far as the post-processing is concerned).

Create Matrix Parameters (continued)

- We will create a second Matrix Parameter to show what the settings signify.

2. Select *Maxwell > Parameters > Assign > Matrix…*
   1. In the Setup tab, check the boxes to Include all the Sources (or click on the word Include to automatically check all the boxes).
   2. In the Post Processing tab, set the turns for each source to **15**
   3. Select **PhaseA_1, PhaseA_2,** and **PhaseA_3** and select **Group ->**
   4. Select **PhaseB_1, PhaseB_2,** and **PhaseB_3** and select **Group ->**
   5. Select **PhaseC_1, PhaseC_2,** and **PhaseC_3** and select **Group ->**
   6. Rename Group1 to **PhaseA**
   7. Rename Group2 to **PhaseB**
   8. Rename Group3 to **PhaseC**
   9. Set Branches to 3 for each Group



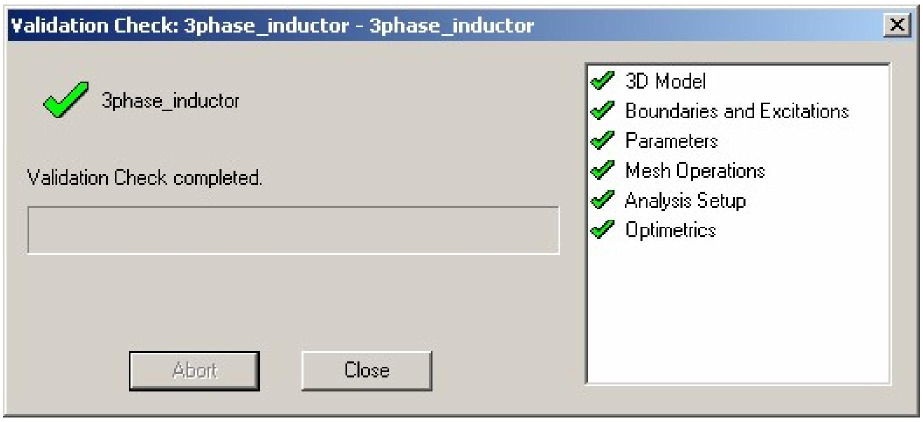
- This setup says that each source has 15 turns in 3 branches of 5 turns each (with twice the current in each turn as for the 30 turn case) and that the sources on each leg are connected in series (as far as the post-processing is concerned).

Save the Project

1. Select the menu item ***File > Save As***
2. From the Save As window, type in **3phase_inductor**
3. Click on the **Save** button

Check the Validity of the Model

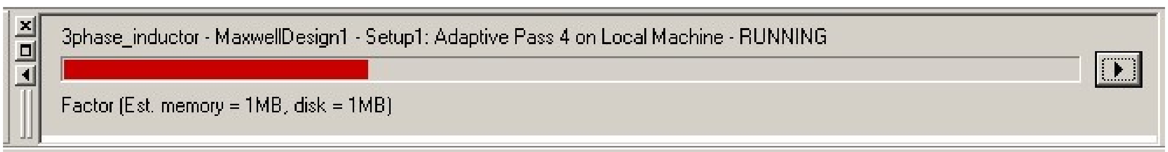
- Select the menu item ***Maxwell > Validation Check***, or click on the icon



- The problem won't solve if there are errors (errors are denoted by a red X), but it will solve if all the validations return a green check or a warning (warnings are denoted by a yellow triangle, and should be noted, but can often be safely ignored).

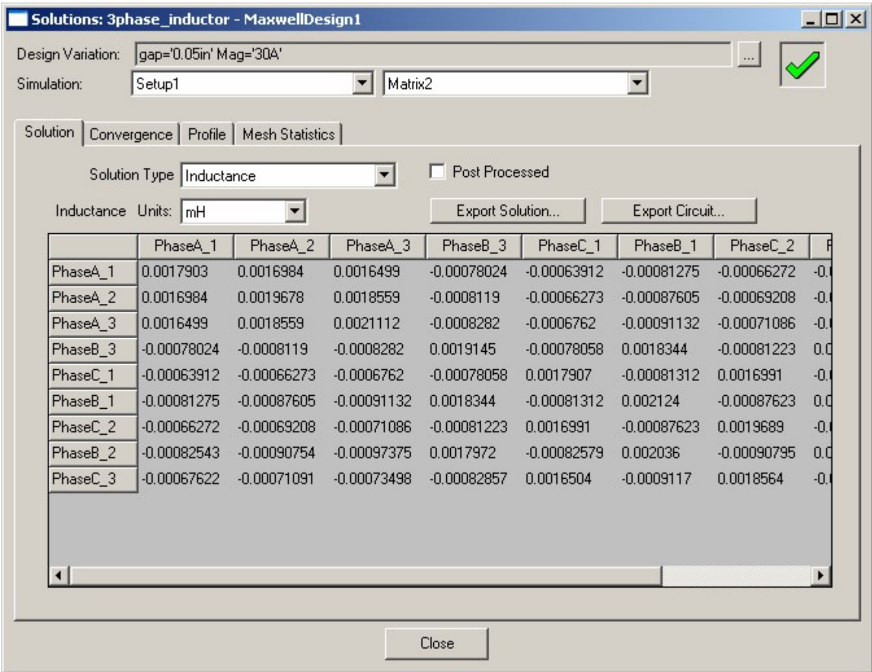
Analyze

- Select the menu item ***Maxwell > Analyze***, or click on the icon
- This should take about 10 minutes to solve on a standard computer (such as a fast laptop or standard desktop), and about 5 minutes on a fast computer.



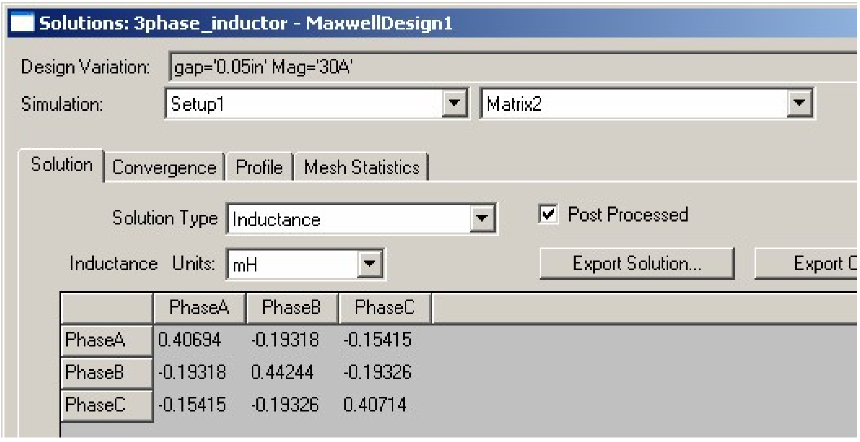
Inductance Matrix Solutions

- Open up the matrix solution data by selecting ***Maxwell > Results > Solution Data***
- The first display that appears (by default) is the non-post processed data for Matrix2



	PhaseA_1	PhaseA_2	PhaseA_3	PhaseB_3	PhaseC_1	PhaseB_1	PhaseC_2
PhaseA_1	0.0017903	0.0016984	0.0016499	-0.00078024	-0.00063912	-0.00081275	-0.00066272
PhaseA_2	0.0016984	0.0019678	0.0018559	-0.0008119	-0.00066273	-0.00087605	-0.00069208
PhaseA_3	0.0016499	0.0018559	0.0021112	-0.0008282	-0.0006762	-0.00091132	-0.00071086
PhaseB_3	-0.00078024	-0.0008119	-0.0008282	0.0019145	-0.00078058	0.0018344	-0.00081223
PhaseC_1	-0.00063912	-0.00066273	-0.0006762	-0.00078058	0.0017907	-0.00081312	0.0016991
PhaseB_1	-0.00081275	-0.00087605	-0.00091132	0.0018344	-0.00081312	0.002124	-0.00087623
PhaseC_2	-0.00066272	-0.00069208	-0.00071086	-0.00081223	0.0016991	-0.00087623	0.0019689
PhaseB_2	-0.00082543	-0.00090754	-0.00097375	0.0017972	-0.00082579	0.002036	-0.00090795
PhaseC_3	-0.00067622	-0.00071091	-0.00073498	-0.00082857	0.0016504	-0.0009117	0.0018564

- Check the box marked **Post Processed** to see the results.

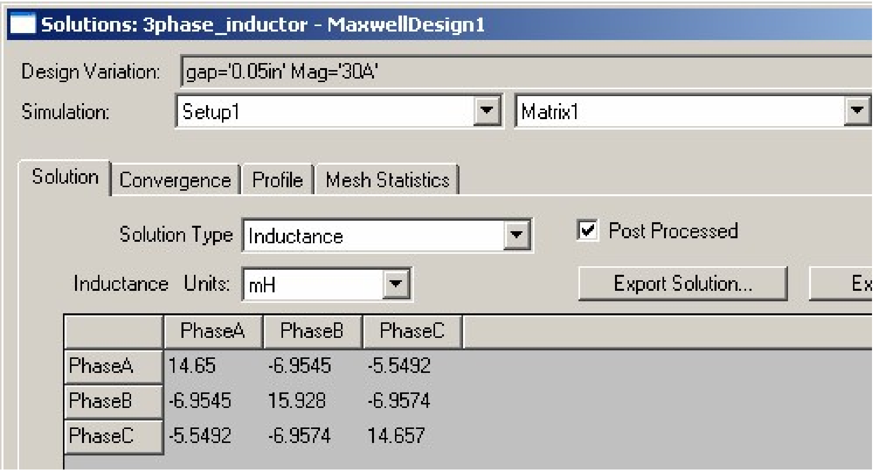


	PhaseA	PhaseB	PhaseC
PhaseA	0.40694	-0.19318	-0.15415
PhaseB	-0.19318	0.44244	-0.19326
PhaseC	-0.15415	-0.19326	0.40714

- Notice that the results are symmetric in both axes as we would expect.
- Notice that the mutual inductances are negative. It is important to note that the direction of the current used for the mutual inductances is determined by the direction of the arrow for each excitation.

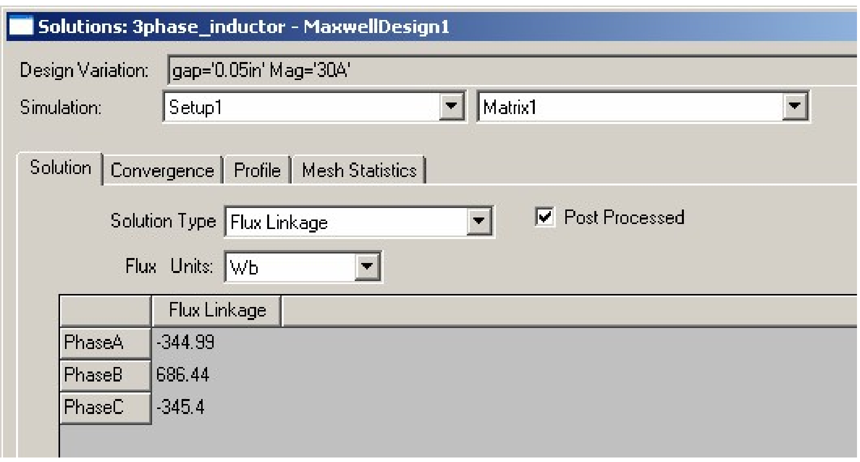
Inductance Matrix Solutions (continued)

- Change to **Matrix1** solutions by clicking on the pull-down menu with Matrix2.



- Notice that the results change to reflect twice the turns and one-third the branches (2^2 * 3^2 = 36 times the previous inductance value).
- Remember that by increasing the turns, the current in each turn is decreased to keep the total ampere-turns constant - this is very important for nonlinear materials. The solutions apply only for this value of current.
- If you were to compare the non-post processed results for both matrices, you would see that these values are the same.

- Change the Solution Type from Inductance to Flux Linkage to see either the Post Processed or nominal flux linkage values.



Results and Interpretations

- These results are being obtained from a magnetostatic simulation with arbitrary constant current inputs defined for each leg. The notation used was in terms of 3 phases, which might imply that this is an AC inductor of some sort. The modeling of AC currents in a magnetostatic simulation can sometimes be valid for instantaneous values (of force and inductance), but the requirements are that eddy currents do not effect the solution (either a low frequency source or low loss materials). The other two options available in the Maxwell software are eddy current simulations (which allows AC sources, but does not allow nonlinear materials), and transient simulations (which allows the study of nonlinear and AC phenomena).

- This type of magnetostatic simulation would also be valuable for an Equivalent Circuit Extraction (again, eddy currents should be negligible) - this would require each phase to be excited as a variable, and run as a full parametric simulation including all phases across all possible current values (at least 5^3 variations to see any nonlinear behavior). Notice that if you do an equivalent circuit extraction of the inductance, the flux values automatically take into account the grouping and other post-processing values specified in the matrix parameter.

- Other magnetostatic results can be obtained from this simulation, such as force on the Core_I object and magnetic field in the steel (is it saturating?).

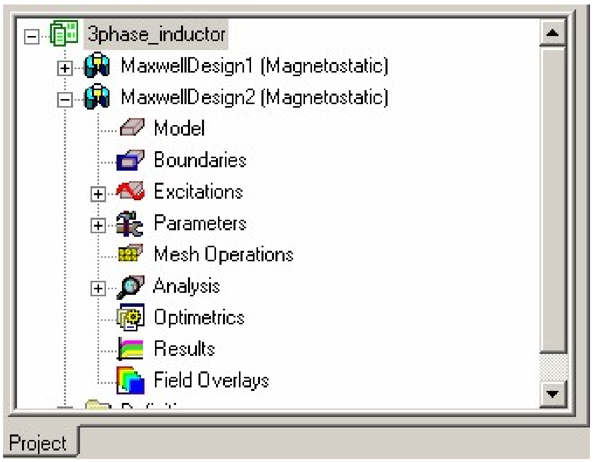
- Remember that this simulation uses nonlinear materials, so all of the solutions are only valid for this specific set of excitations. If you were to change the input currents, then you will have to solve again to see how the inductance and other results change.

- **Another important note is that although we included 2 matrix parameters, this is not necessary to see differently post-processed results.** You can edit the post-processing characteristics of the matrix after having solved the problem, and the results will adjust to reflect the changes without needing to resolve. The only time that you would need multiple matrices is if one matrix or the other did not include all the coils. **By using two matrices, the inductance calculation was performed twice, lengthening the simulation.** The point of this example was to show that multiple matrix parameters can be defined - not to suggest using multiple matrix parameters.

Create a Symmetry Model

1. Right-click on **MaxwellDesign1** in the project tree (this is the design name).
2. Choose **Copy** from the menu.
3. Right-click on **3phase_inductor** in the project tree (this is the project name).
4. Choose **Paste** from the menu.
5. You now have a new design in your project that has the same setup as the first design.

   Remember to double-click on the design name to switch from one design to the other!



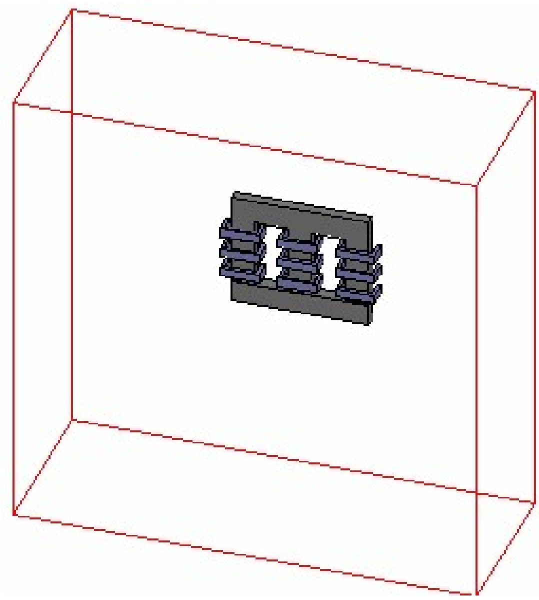
6. Select all the visible objects (except the Region) by typing **Ctrl + A** when within the 3D modeler window (or select them all in the object tree).
7. Select ***3D Modeler > Boolean > Split…*** to split the model at the YZ plane.
   1. In the Split window that appears, choose the following:
      1. Split Plane : **YZ**
      2. Keep Fragments: **Positive side**
      3. Split Objects: **Split entire selection**
   2. Select OK
8. Expect to see some errors and warnings that the sheet objects were deleted. There are options in the Split command to keep the sheet objects when splitting the solids, but we will not need the sheets for a symmetry simulation.

Create a Symmetry Model (continued)

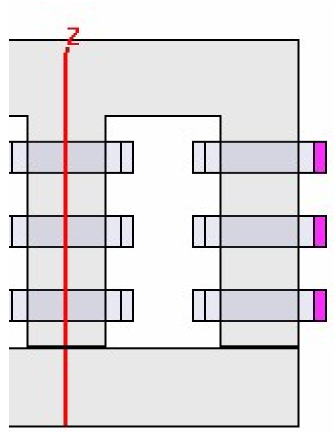
9. Select ***Draw > Region*** to edit the region object.
    1. Change the padding percents as follows:

       +X: 800

       -X: 0
    2. Select **OK** to accept.
10. The entire geometry is now on the positive side of the YZ plane.



11. Adjust the visibility by going to ***View > Active View Visibility…***
12. In the 3D Modeler tab, find the **Region** object and deselect Visibility.
13. Choose **OK** to accept.
14. Rotate the geometry to look at the split plane of the core and coils.
15. Type **f** in the 3D modeler to switch to face selection mode (type **o** to switch back to object selection) - face selection can also be found in ***Edit > Select > Faces***.

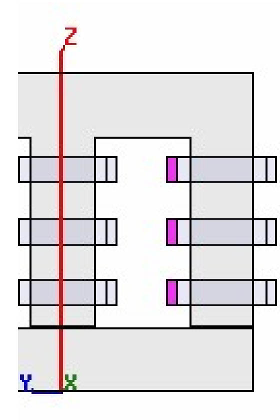


16. Select the right-most coil faces on the YZ plane.

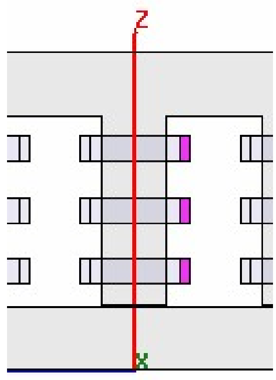
    (Use **Ctrl** to select multiple items graphically.)
17. Select ***Maxwell > Excitations > Assign > Current…***
18. In the Current Excitation dialog, enter the following:
    1. Base Name: **PhaseA_in**
    2. Value: **-0.5*Mag**
    3. Type: **Stranded**
19. Select **OK** to accept the excitation.

Create a Symmetry Model (continued)

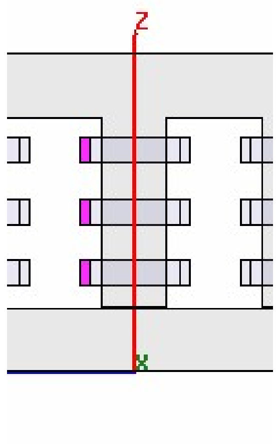
20. Select the next right-most coil faces on the YZ plane.
    (Use **Ctrl** to select multiple items graphically.)
21. Select ***Maxwell > Excitations > Assign > Current…***
22. In the Current Excitation dialog, enter the following:
    1. Base Name: **PhaseA_out**
    2. Value: **-0.5*Mag**
    3. Type: **Stranded**
    4. Click **Swap Direction** so that the arrow is pointing in the negative X direction.
23. Select **OK** to accept the excitation.



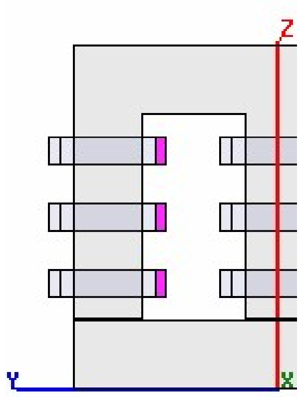
24. Continue with the next leg by selecting the next 3 coil faces on the YZ plane.
25. Select ***Maxwell > Excitations > Assign > Current…***
26. In the Current Excitation dialog, enter the following:
    1. Base Name: **PhaseB_in**
    2. Value: **Mag**
    3. Type: **Stranded**
27. Select **OK** to accept the excitation.



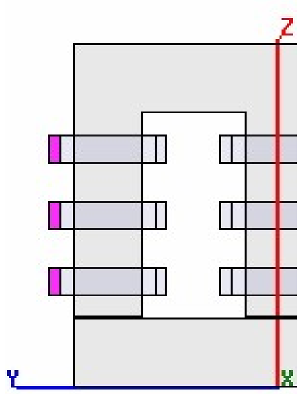
28. Now select the 3 return faces of the middle coil.
29. Select ***Maxwell > Excitations > Assign > Current…***
30. In the Current Excitation dialog, enter the following:
    1. Base Name: **PhaseB_out**
    2. Value: **Mag**
    3. Type: **Stranded**
    4. Click **Swap Direction** so that the arrow is pointing in the negative X direction.
31. Select **OK** to accept the excitation.



Create a Symmetry Model (continued)



32. Continue to the last leg by selecting the next 3 coil faces on the YZ plane.
33. Select *Maxwell > Excitations > Assign > Current…*
34. In the Current Excitation dialog, enter the following:
    1. Base Name: **PhaseC_in**
    2. Value: **-0.5*Mag**
    3. Type: **Stranded**
35. Select **OK** to accept the excitation.



36. Finish by selecting the 3 return faces of the last coil.
37. Select *Maxwell > Excitations > Assign > Current…*
38. In the Current Excitation dialog, enter the following:
    1. Base Name: **PhaseC_out**
    2. Value: **-0.5*Mag**
    3. Type: **Stranded**
    4. Click **Swap Direction** so that the arrow is pointing in the negative X direction.
39. Select **OK** to accept the excitation.

Creating Matrix Parameters

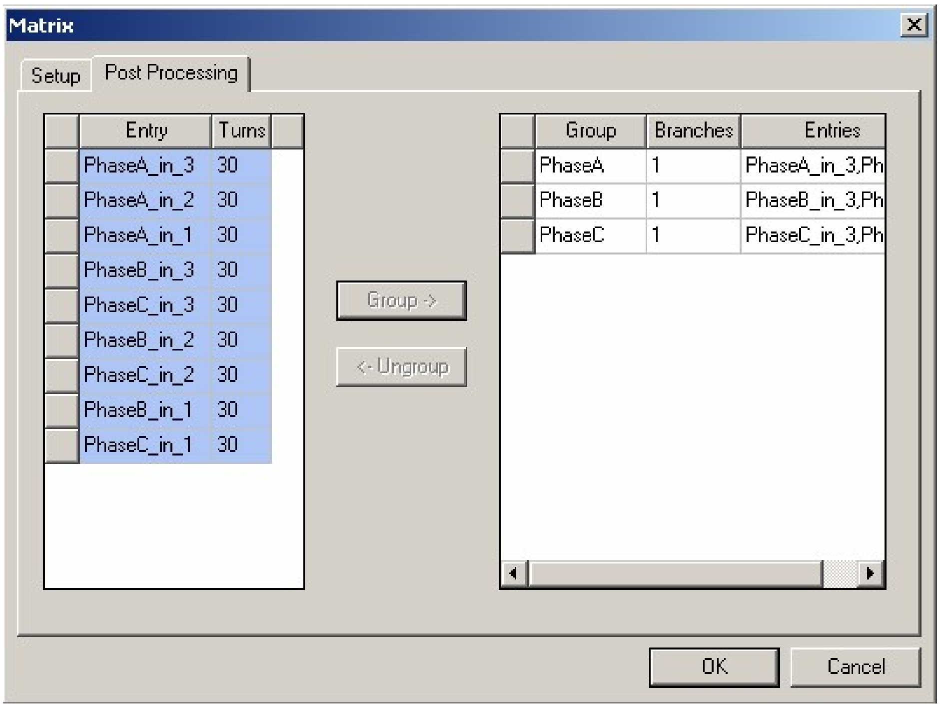
- Now that the excitations are redefined, the matrix has to be redefined. The matrices were deleted when the old excitations were deleted (which were deleted when the sheet objects were deleted during the split operation).

- When matrix parameters are defined, a check will be performed for proper conduction paths and for terminals correctly defined across a cross-section of the conduction paths. Several errors can appear when defining a matrix, and these often have to do with the definition of the conducting objects or the excitation.

- The excitations that appear in the matrix setup, are those excitations that are pointing into the conductor. So, for a symmetry model that requires two excitations per conductor, only one excitation per conductor will be listed in the matrix setup - this excitation will be the one pointing into the modeled conductor.

Create Matrix Parameters

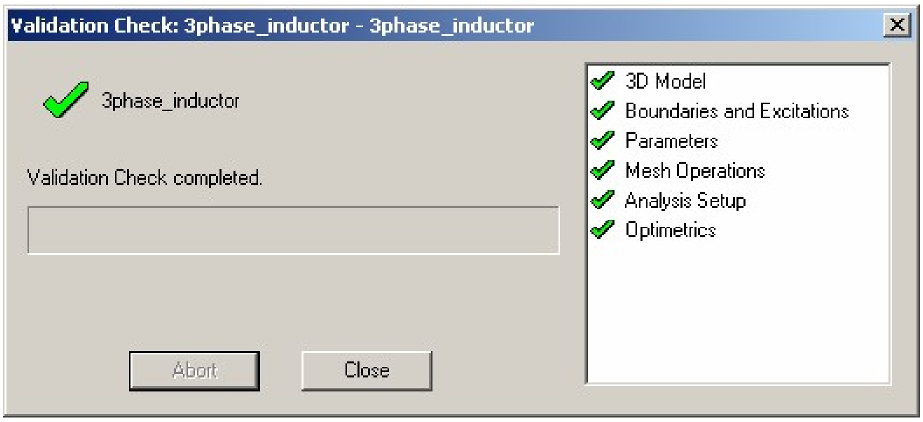
1. Select ***Maxwell > Parameters > Assign > Matrix…***
   1. In the Setup tab, check the boxes to Include all the Sources (or click on the word Include to automatically check all the boxes).
   2. In the Post Processing tab, set the turns for each source to **30**
   3. Select **PhaseA_in_1, PhaseA_in_2,** and **PhaseA_in_3** and select **Group ->** (Use **Ctrl** or **Shift** to select multiple items.)
   4. Select **PhaseB_in_1, PhaseB_in_2,** and **PhaseB_in_3** and select **Group ->**
   5. Select **PhaseC_in_1, PhaseC_in_2,** and **PhaseC_in_3** and select **Group ->**
   6. Rename Group1 to **PhaseA**
   7. Rename Group2 to **PhaseB**
   8. Rename Group3 to **PhaseC**
   9. Leave Branches set to 1 for each Group



- This setup says that each source has 30 turns and that the sources on each leg are connected in series (as far as the post-processing is concerned).

Check the Validity of the Model

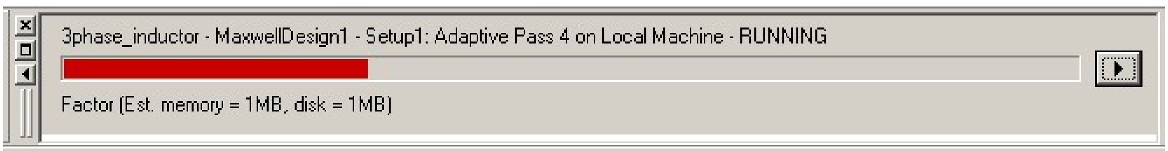
- Select the menu item ***Maxwell > Validation Check***, or click on the icon



- The problem won't solve if there are errors (errors are denoted by a red X), but it will solve if all the validations return a green check or a warning (warnings are denoted by a yellow triangle, and should be noted, but can often be safely ignored).

Analyze

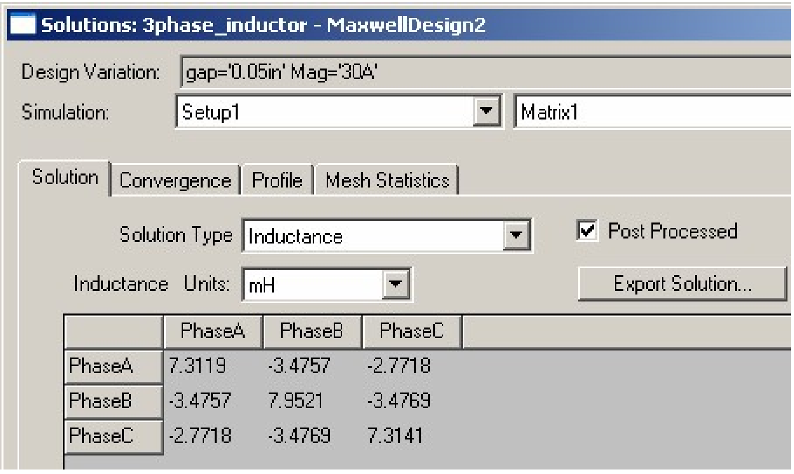
- Select the menu item ***Maxwell > Analyze***, or click on the icon
- This should take about 5 minutes to solve on a standard computer (such as a fast laptop or standard desktop), and about 3 minutes on a fast computer (half the time!).



- This half model runs twice as fast – taking advantage of symmetries can have an even greater effect on larger models!

Inductance Matrix Solutions

1. Open up the matrix solution data by selecting ***Maxwell > Results > Solution Data***
2. Check the box marked **Post Processed** to see the results.



- Notice that the results are half the value that we obtained for the full model. This is very important to remember when using these values. The halved results are consistent for other parameters and properties as well (i.e. torque, total energy, etc.)
- If these values are used to create an Equivalent Circuit Extraction, remember to use a scaling factor of 2 to account for the symmetry.

3. Change the Solution Type from Inductance to Flux Linkage.
   - Notice that these numbers are halved as well.