A Switched Reluctance Motor Problem

This application note describes how to set up, solve, and analyze the results of a four-phase switched reluctance motor using RMxpert and EMpulse, the transient solver in Maxwell 2D.

RMxpert uses a combination of analytical and magnetic circuit equations to predict the performance of this motor problem. The transient solver of Maxwell 2D uses the time domain finite element method, coupled with the electrical equations of the drive circuit and the motion problem, to predict the dynamic and transient behavior of the switched reluctance motor.

You can create the RMxpert project from scratch or open the pre-solved project srm.pjt, located in the /ansoft/examples/rmxprt/ directory. You can create the finite element project from scratch or download srm_fea.pjt from the Technical Support page for EM products on the Ansoft web site at www.ansoft.com. If you are creating the project from scratch, select Switched Reluctance Motors as the motor type in RMxpert.

These projects were created using version 3.0 of RMxpert and version 8.0 of Maxwell 2D. If any of the definitions within this application note seem unclear, refer to the online documentation for additional information.
Motor Characteristics

The operating principle of the switched reluctance motor is as follows: Motion is produced as a result of the variable reluctance in the air gap between the rotor and the stator. When a stator winding is energized, reluctance torque is produced by the tendency of the rotor to move to its minimum reluctance position. The direction of the torque generated is a function of the rotor position with respect to the energized phase, and is independent of the direction of current flow through the phase winding. Continuous torque can be produced by intelligently synchronizing each phase’s excitation with the rotor position.

The following table displays the characteristics of the SRM used in this application note:

<table>
<thead>
<tr>
<th>Characteristic</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Number of phases</td>
<td>4</td>
</tr>
<tr>
<td>Number of stator poles</td>
<td>8</td>
</tr>
<tr>
<td>Number of rotor poles</td>
<td>6</td>
</tr>
<tr>
<td>Stator outer diameter (mm)</td>
<td>120</td>
</tr>
<tr>
<td>Rotor outer diameter (mm)</td>
<td>74</td>
</tr>
<tr>
<td>Shaft diameter (mm)</td>
<td>30</td>
</tr>
<tr>
<td>Airgap (mm)</td>
<td>0.5</td>
</tr>
<tr>
<td>Stack length (mm)</td>
<td>65</td>
</tr>
<tr>
<td>Winding turns per pole</td>
<td>142</td>
</tr>
</tbody>
</table>

The following figure shows the geometry used in this example (a 4-phase SRM with 8 rotor poles and 6 stator poles):
Switched Reluctance Motor Analysis

RMxprt assumes the switched reluctance motor operates with shaft position feedback to synchronize the commutation of the phase currents with precise rotor position.

Two modes of operations are supported: the single pulse operation, and the chopping current strategy. In the single pulse operation, each phase is energized at the turn-on angle and switched off at the turn-off angle. The difference between the turn-off and the turn-on angle is called the *dwell angle*. The chopping current strategy is a hysteresis-type current regulator in which the power transistors are switched off and on according to whether the current is greater or less than a reference current.

RMxprt supports only switched reluctance motors in which the number of stator poles is greater than the number of rotor poles. The number of phases in the stator winding is the number of stator poles divided by the smallest common denominator of the number of stator poles and the number of rotor poles.

The lead angle, which is positive if the phase is triggered before the aligned position between the phase-axis and the rotor pole, should be constant over the entire range of speed.

General Data

Use the General window to specify the motor characteristics.

- Before generating the model, select metric units and the American wire setting:
  1. Choose Tools/Options, and make certain the Wire Setting is American (AWG).
  2. Choose OK to accept the wire gauge settings.
  3. Choose Tools/Model Units, and select Metric Unit.

- Now define the general data:
  1. Choose the General tab.
  2. Enter 0.55 kW in the Rated Output Power field. This is the mechanical power developed at the shaft.
  3. Enter 300 V in the DC Rated Voltage field.
  4. Enter 1500 rpm in the Rated Speed field. The operating point is defined by the rated output power and the nearest speed value from the rated output speed. If the auto-design mode for the stator coils is enabled, the load point is defined by the output power and the rated speed.
  5. Enter 12 W in the Friction Loss field. This is the mechanical loss due to bearing friction and air resistance at the given speed.
  6. Enter 0 in the Lead Angle of Trigger field. An angle of 0 means that each phase is triggered when its axis is aligned with the rotor pole axis.
  7. Enter 84 in the Trigger Pulse Width field. This value is the period for the “on” status of the transistors. The maximum “on” period is given by 360 degrees divided by the number of stator phases.
  8. Enter 2 V in the Transistor Drop field. This value is the voltage drop on all the transistors in one conduction path.
  9. Enter 2 V in the Diode Drop field. This is the voltage drop on all the diodes in one discharge path (anti-parallel diodes).
  10. Enter 75 degrees in the Operating Temperature field. The temperature has a direct influence on the stator winding resistance.
  11. Select Full-Voltage as the Circuit Type.
  12. Leave the Chopped Current Control box deselected. If you want to use the chopping current strategy, select the Chopped Current Control box, and define the maximum and minimum currents.
The general data for the motor is now defined.
Stator Data

Use the Stator Core and Stator Coil windows to define the stator characteristics.

Define the Stator Dimensions

Use the Stator Core window to define the stator dimensions.

1. Enter 8 in the Number of Poles field to specify the number of poles in the stator. This is the total number of poles, or the number of pole pairs multiplies by two.
2. Enter 120 mm in the Outer Diameter field to specify the outer diameter of the stator.
3. Enter 75 mm in the Inner Diameter field to specify the inner diameter of the stator.
4. Enter 9 mm in the Yoke Thickness field. This value refers to the thickness of the stator core.
5. Enter 0.5 in the Pole Embrace field. The pole embrace is defined as the ratio of the actual pole arc to the maximum pole angle. (The maximum pole angle is 90 mechanical degrees for a four pole motor. If the actual pole arc is 45 mechanical degrees, the ratio is 0.5). The pole embrace ranges from between 0 and 1.
6. Enter 65 mm in the Length of Stator field. This value is the effective magnetic length of the core, defined as the total iron length minus the total insulation length between the laminations. The value (usually between 0.93 and 1) is defined as a ratio from the total core length.
7. Enter 0.95 in the Stacking Factor field. This gives a value of 61.75 mm as the net length of the steel, after taking lamination into account.
8. Select GBA3 as the Steel Type to specify the steel type used in manufacturing the stator lamination.

The stator core of the motor is now defined.
Define the Stator Winding

Use the Stator Coil window to define the stator winding.

Define the stator coils:

1. Enter 0.3 mm in the Slot Insulation field. This value is the thickness of the slot insulation in the stator coil.
2. Enter 0 mm in the End Adjustment field. This value refers to the distance from the end of the stator to the stator coil.
3. Enter 1 in the Parallel Branches field. This value indicates the number of parallel branches in the stator coil per phase.
4. Enter 142 in the number of Turns per Pole field. This value is the number of turns for each stator pole.
5. Enter 1 in the number of Wires per Conductor field.
6. Enter 0.08 mm in the Wire Wrap field.
7. Enter 0 in the Wire Diameter field.
8. Select AUTO as the wire Gauge. AUTO allows the software to calculate the optimal value of the wire diameter, while USER allows you to specify a diameter that does not correspond to a particular gauge.

The stator winding coils are now defined.
The following diagrams show the end adjustment and the wire wrap for the stator coil:
Rotor Data

Use the Rotor Core window to define the rotor characteristics.

➤ Define the rotor core dimensions:
   1. Enter 6 in the Number of Poles field to specify the number of poles in the rotor. This number differs from the number of stator poles.
   2. Enter 0.5 mm in the Air Gap field. This defines the width of the air gap between the rotor and the stator.
   3. Enter 30 mm in the Inner Diameter field to specify the inner diameter of the rotor.
   4. Enter 9 mm in the Yoke Thickness field. This value refers to the thickness of the rotor core.
   5. Enter 0.5 in the Pole Embrace field. This value is the ratio of the actual pole angle to the maximum possible pole angle. The range falls between 0 and 1.
   6. Enter 65 mm in the Length of Rotor field.
   7. Enter 0.95 in the Stacking Factor field. This gives a value of 61.75 mm as the net length of the steel, after taking lamination into account.
   8. Select GBA3 as the Steel Type to specify the steel type used in manufacturing the rotor lamination.

The rotor core of the motor is now defined.

<table>
<thead>
<tr>
<th>General</th>
<th>Stator Core</th>
<th>Stator Coil</th>
<th>Rotor Core</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td></td>
<td>Number of Poles: 6</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Air Gap (mm): 0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Inner Diameter (mm): 30</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Yoke Thickness (mm): 9</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Pole Embrace: 0.5</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Length of Rotor (mm): 65</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Stacking Factor: 0.95</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Steel Type: GBA3</td>
</tr>
</tbody>
</table>
Process the Analytical Design

Once the data for the model has been specified, generate the motor design.

➤ Generate the design:
  ■ Choose Analysis/Analytical Design. RMxpert calculates the motor performance parameters.

Check the Lamination

Once the analysis is complete, observe the laminations on the objects.

➤ Check the lamination:
  1. Choose Tools/Options, and make certain that Lamination is on for all of the items.
  2. Choose OK to accept the lamination settings and close the window.
  3. Choose Post/Process/View Lamination. A cross-section of the motor appears, displaying the laminations.
  4. Choose File/Exit when you have finished viewing the laminations.

Design Output

Choose Post Process/Design Output to examine the motor’s parameters. The Design Output window is broken down into the following sections: General Data, Stator Core Data, Stator Coil Data, Rotor Core Data, Full-Load Operation Data, No-Load Operation Data, Start Operation Data, and Transient FEA Input Data.

GENERAL DATA

This information is the same as the data you entered in the General window.

STATOR CORE DATA

This information is the same as the data you entered in the Stator Core window.

STATOR COIL DATA

This information is generally the same as the data you entered in the Stator Coil window, except for the wire information, which was computed during the design phase (because you selected AUTO as the Gauge).

RMxpert calculated the wire diameter to be 0.5733 mm.

ROTOR CORE DATA

This information is the same as the data you entered in the Rotor Core window.
FULL-LOAD OPERATION DATA

The following motor performance parameters are calculated at the rated output power:

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Description</th>
</tr>
</thead>
<tbody>
<tr>
<td>Input DC Current (A)</td>
<td>The DC value of the current at the input DC source.</td>
</tr>
<tr>
<td>Phase RMS Current (A)</td>
<td>The RMS value for the phase current.</td>
</tr>
<tr>
<td>Phase Current Density ( (A^2/mm^3) )</td>
<td>The current density through the cross-section of one stator winding.</td>
</tr>
<tr>
<td>Frictional and Wind Loss (W)</td>
<td>The mechanical loss due to bearing friction and air resistance at the operation speed.</td>
</tr>
<tr>
<td>Iron-Core Loss (W)</td>
<td>The total core loss in the stator and rotor based on loss curve or constant loss.</td>
</tr>
<tr>
<td>Winding Copper Loss (W)</td>
<td>The power loss due to the resistance of the stator winding. This is the total copper loss.</td>
</tr>
<tr>
<td>Diode Loss (W)</td>
<td>The power loss based on the operation of the diodes.</td>
</tr>
<tr>
<td>Transistor Loss (W)</td>
<td>The power loss based on the operation of the switching transistors.</td>
</tr>
<tr>
<td>Total Loss (W)</td>
<td>The total power loss is equal to the combined losses of the friction and wind loss, the iron core loss, the copper loss, the transistor loss, and the diode loss.</td>
</tr>
<tr>
<td>Output Power (W)</td>
<td>The mechanical power at the shaft.</td>
</tr>
<tr>
<td>Input Power (W)</td>
<td>The rated DC voltage multiplied by the DC Input Current.</td>
</tr>
<tr>
<td>Efficiency (%)</td>
<td>The output power divided by the input power.</td>
</tr>
<tr>
<td>Rated Speed (rpm)</td>
<td>The running speed at the specified rated output power.</td>
</tr>
<tr>
<td>Rated Torque (N.m)</td>
<td>The mechanical torque available at the rated output power.</td>
</tr>
<tr>
<td>Flux Linkage (Wb)</td>
<td>The total flux linkage seen by one phase.</td>
</tr>
<tr>
<td>Stator-Pole Flux Density</td>
<td>The maximum flux density in the stator pole.</td>
</tr>
<tr>
<td>Stator-Yoke Flux Density</td>
<td>The maximum flux density in the stator yoke.</td>
</tr>
<tr>
<td>Rotor-Pole Flux Density</td>
<td>The maximum flux density in the rotor pole.</td>
</tr>
<tr>
<td>Rotor-Yoke Flux Density</td>
<td>The maximum flux density in the rotor yoke.</td>
</tr>
<tr>
<td>Coil Length per Turn (mm)</td>
<td>The length of one turn.</td>
</tr>
<tr>
<td>Winding Resistance in Phase (ohm)</td>
<td>The resistance per phase at the operating temperature fixed in the General window.</td>
</tr>
<tr>
<td>Winding Leakage Inductance (mH)</td>
<td>The leakage inductance per phase.</td>
</tr>
<tr>
<td>Iron-Core-Loss Resistance</td>
<td>The equivalent resistance based on the input voltage and the core-loss.</td>
</tr>
<tr>
<td>Frequency of Phase Current (Hz):</td>
<td>The frequency of the phase current.</td>
</tr>
<tr>
<td>Maximum Output Power (W)</td>
<td>The maximum output power for the motor.</td>
</tr>
</tbody>
</table>

**NO-LOAD OPERATION DATA**

This section displays the speed, DC current, and input power, assuming only friction loss.

**START OPERATION DATA**

This section displays the estimated start torque, DC current, and maximum start current.

**TRANSIENT FEA INPUT DATA**

This information is used when calculating the motor performance using the 2D time transient finite element field solver, EMpulse.

For the armature winding, this section displays:

- the number of turns, as seen from the terminal.
- the number of parallel branches.
- the terminal resistance.
- the end leakage inductance.

This section also displays the 2D equivalent values for the air-gap and the stacking factors, to be used in the finite element calculation. If the length of the stator equals the length of the rotor, then the problem is an exact 2D configuration, and the 2D equivalent length is given by the input data.

This section also displays the estimated rotor inertia, without taking into account any mechanical load attached on the shaft.

When you have reviewed the output data, choose Exit to exit the Design Output window.
Plot the Performance Curves

Examine the performance curves for the model.

- Plot the performance curves:
  1. Choose **Post Process/Performance Curves**. The **PlotData** window appears, with an **Open** window visible. The following plot titles are available to open:

     - **flxlinks.dat**: Family of Flux Linkage vs Current for different currents and positions
     - **n_curr.dat**: Input DC Current vs Speed
     - **n_effi.dat**: Efficiency vs Speed
     - **n_pow2.dat**: Output Power vs Speed
     - **n_torq.dat**: Output Torque vs Speed
     - **wv_curm.dat**: Maximum Phase Current vs Position in electrical degrees
     - **wv_curr.dat**: Rated Phase Current vs Position in electrical degrees
     - **wv_flux.dat**: Flux Linkage vs Position in electrical degrees
     - **wv_indc.dat**: Air-Gap Inductance vs Position in electrical degrees
     - **wv_volt.dat**: Phase Voltage vs Position in electrical degrees

  2. Select the name of the plot to view.
  3. Choose **OK**. The plot appears in the **PlotData** window. After you’ve opened one plot, choose **Plot/Open** to open a different plot.
The following two figures show the performance plots for the rated phase current (wv_curr.dat) and the linkage flux (wv_flux.dat):

4. When you have finished viewing the performance curves, choose File/Exit to exit PlotData.
Analyse the Geometry

Now that the motor design is complete, examine the geometry, and define the options to be used for the time transient finite element analysis (FEA).

➤ Analyse the geometry:
1. Choose Tools/Options, and make certain the Maxwell Path is set to the directory where the Maxwell software is installed. There are three check boxes in the Field section of this window. Make certain that they are all deselected. Choose OK to exit this window.
2. Choose Analysis/View Geometry. A full cut-away cross-section of the motor appears in the Maxwell 2D Modeler. Since the model has four poles and the windings are symmetrical, you can reduce this model from 360 to 180 degrees. Choose File/Exit to exit the Maxwell 2D Modeler.
3. Again, choose Tools/Options. In the Field section, select Periodic, and leave the value set to 1. Choose OK to exit this window.
4. Choose Analysis/View Geometry to view the model again. Notice that only half (180 degrees) of the motor is modeled. If the Periodic field in the Options window was set to two, the full motor geometry would be created. Choose File/Exit to exit the Maxwell 2D Modeler again and examine some other options for creating the geometry.
5. Choose Tools/Options. Notice the check boxes for Difference and Teeth-Teeth. The Difference option allows you to specify the angular difference between the rotor and the stator (in electrical degrees) when creating the geometry. The Teeth-Teeth option specifies that none of the rotor teeth or permanent magnets will be cut in half; only entire teeth or permanent magnets will be modeled. You can modify some of these options to determine their effect on the geometry.
6. For this analysis, use a geometry that includes a Periodic multiplier of 1 with the Teeth-Teeth box selected and the Difference box deselected.
7. Choose OK to accept the options and exit.

Create the Maxwell 2D Project

Once the geometry has been analyzed, create the Maxwell 2D project.

➤ Create the Maxwell project:
1. Choose Analysis/View Geometry again, and then choose File/Exit to exit the Maxwell 2D Modeler. Because Create Maxwell 2D Project may be disabled after you change the options, you need to view the geometry again before trying to create the project.
2. Choose Analysis/Create Maxwell 2D Project. A window appears.
3. Specify a Project Name and Path for this switched reluctance motor. The name of the pre-solved project is srm_fea.
4. Choose Create. A Maxwell 2D project is created using the specified geometry options.
5. Choose OK to close the message window.
6. Return to the Project Manager to continue with the rest of this example. Leave RMxpert open to refer to later in the example.

This completes the RMxpert design of the switched reluctance motor. You can continue the analysis of this design using the time transient FEA software program, EMpulse.
Finite Element Analysis

Define the finite element parameters for the switched reluctance motor.

The transient solver of Maxwell 2D uses the time domain finite element method; it solves the magnetic fields, together with the electrical equations of the drive circuit and the motion problem, to predict the dynamic and transient behavior of the switched reluctance motor.

Taking into account the symmetry, the following geometry needs to be solved (a 4-phase SRM with 8 rotor poles and 6 stator poles):

Open the srm_fea.pjt project you previously exported from RMxprt. If it does not appear in the projects list, you may need to refresh the list by clicking on the project directory again.

Set Up the Geometry

- Open the project, and set up the geometry:
  1. From the Project Manager in the Maxwell Control Panel, open the Maxwell 2D project you created in the previous section. If you are using the pre-solved project, its name is srm_fea.pjt. Upon opening the project, notice that the Transient Solver, the XY Drawing Plane, and Define Model are already set.
  2. Choose Define Model/Draw Model to open the Maxwell 2D Modeler. The model appears in the modeler window.
  3. Choose Window/Change View/Zoom In, and zoom in on the air gap. There is an additional object in the air gap, called Band, which is used during the solution process to determine which objects are stationary and which objects rotate. This Band object is used later in the example and should not be deleted.
  4. Choose Exit, and save the changes.
**Assign Material Properties**

Assign material properties to each object. Because this example requires materials not included in the material database, you need to create them in the Material Manager.

**Add a New Material**

Add a new nonlinear material called `Steel_gba` to the local material database, with a zero electric conductivity and the B-H curve exported from the RMxpert model. The core is assumed to be laminated; therefore, the electric conductivity is considered to be zero. If you prefer to use a better approximation for the lamination, please consult the online technical support FAQ for EMPulse, on the Ansoft web site at www.ansoft.com.

➤ Add a new material:

1. Choose *Setup Materials* to access the Material Manager.
2. Choose *Material/Add*.
3. Change the name to *Steel_gba* in the *Material Properties* area.
4. Select *Nonlinear Material*.
5. Choose *B H Curve*. The *B-H Curve Entry* window appears.
7. Select the *statr_eq.bh* file, which was created inside the RMxpert project *srm.pjt*. Make certain that the *bh Format* button is selected.
8. Choose *OK* to import the file and return to the *B-H Curve Entry* window.
9. Choose *Exit* to exit the window and return to the Material Manager.
10. Choose *Enter*. The new material is now available in the database for this project.

**Assign the Materials**

➤ Assign materials to the objects:

1. Assign the following materials:
   - Assign vacuum to the *AirGap*, *AirRotor*, and *Band*.
   - Assign copper to all the windings.
   - Assign Steel_gba to the *Rotor* and *Stator*.
   - Assign steel_stainless to the *Shaft*.
   - Exclude the background from the model. The problem will have boundary conditions assigned to every outside edge; therefore, the background is excluded from the solution.
2. Choose *Exit*, and save the changes made in the Material Manager.
Setting the Boundaries and Sources

The first step in defining the boundary conditions is to define the Master/Slave boundary. You then need to define the value boundary and set up the sources. Finally, you need to define the external circuit.

Choose **Setup Boundaries/Sources** to define the electric circuit and the boundaries.

### Define the Master Boundary

➤ Define the master boundary:

1. Choose **Window/New** and then **Window/Tile** to open an additional window and arrange the windows in tile format.
2. Choose **Window/Change View/Zoom In**, and zoom in on the air gap so that the area where the Band and the inside diameter of the stator cross the x-axis (positive direction) can be easily seen.
3. Choose **Edit/Select/Trace**. Starting in the window with the full model shown, click on the center axis of the motor (u=0, v=0), and then click on the following intersection:
   • Rotor Inside Diameter (u=15, v=0)
4. Switch to the window where the air gap is enlarged, and click on each of the following intersections:
   • Rotor Outside Diameter (u=37, v=0)
   • Band (u=37.25, v=0)
   • Stator Inside Diameter (u=37.5, v=0)
5. Switch back to the window with the full model, and double-click on the following intersection to end the definition:
   • Stator Outside Diameter (u=60, v=0).
6. Choose **Assign/Boundary/Master**.
7. Choose Assign.

### Define the Slave Boundary

Again, use the **Edit/Select/Trace** command to define the slave boundary.

➤ Define the slave boundary:

1. In the second window, zoom in on the air gap so that the area where the Band and the inside diameter of the stator cross the x-axis (negative direction) can be easily seen.
2. Choose **Edit/Select/Trace**. Starting in the window with the full model shown, click on the center axis of the motor (u=0, v=0), and then click on the Rotor Inside Diameter (u=-15, v=0).
3. Switch to the window where the air gap is enlarged, and click on each of the following intersections:
   • Rotor Outside Diameter (u=-37, v=0)
   • Band (u=-37.25, v=0)
   • Stator Inside Diameter (u=-37.5, v=0)
4. Switch back to the window with the full model, and double-click on the Stator Outside Diameter (u=-60, v=0) to end the definition.
5. Choose **Assign/Boundary/Slave**, and select **Slave = — Master**. When solving for one or an odd number of poles of an electrical machine, use the **Slave = — Master** symmetry. When solving for an even number of poles, use the **Slave = +Master** symmetry.
6. Choose Assign.
Define the Value Boundary

Define the remaining boundaries.

- Define the value boundary:
  1. To assign the outside diameter of the stator a zero value boundary, choose Edit/Select/Edge, and click on the outside diameter of the stator. Click the right mouse button when done selecting.
  2. Choose Assign/Boundary/Value, and change the name from value1 to Zero_Flux. Keep the Value set to 0. A zero value boundary means that all of the flux will be contained in the motor; there will be no leakage flux.
  3. Choose Assign.

Source Setup

The stator phases in the switched reluctance motor are triggered according to the rotor position. Starting with the current version of the software, a graphical definition of the electric drive circuit is fully supported in a Spice type schematic capture. The coupling between the magnetic field and the electric circuit is “tight”; the matrix system which is solved at each time step contains magnetic unknowns (magnetic vector potential in each node) and electric unknowns (loop currents).

- Define the sources:
  1. Choose Edit/Select/Object/By Clicking, and then select the two objects making up the phase “A” (the positive path and the negative path of the coil). Click the right mouse button to end your selection.
  2. Next click on Assign/Source/Solid, and select External Connection. This means that you want to draw the electric connection of this phase in the Schematic Capture Editor. Change the name from Source1 to A.
  3. Click on Winding, and specify the polarity of each object (positive for the positive path of the coil, and negative for the negative path). Choose Assign to assign each polarity.
  4. Enter 284 in the Total turns as seen from terminal field, and enter 1 in the Number of Parallel Branches field. Enter 0 in the Initial Current field. Click OK to exit the Winding Setup window.
  5. Choose Assign.
  6. Using the same procedure as in steps 1 through 5, above, define the remaining 3 phases of the motor. For the “D” phase, two return paths belonging to different coils are displayed on the screen, so assign a negative polarity to both objects.

Note:

In general, PhA and PhReA, and so on, represent a single winding (go and return). In this example, the entire coil is displayed for the phases “A”, “B”, and “C”. However, since you are only modeling a portion of the motor, for “D”, the positive path is not currently displayed; instead, two return paths belonging to different coils are displayed.

7. Choose Edit/External Circuit. The Edit External Circuit window appears, displaying a list of the externally connected windings set up in your model. Your external circuit will contain an inductor corresponding to each of these windings.
8. Select Create new circuit, and then choose Launch Schematic Capture. Schematic Capture appears.
9. Choose Option/Sizing, select B (16 x 10) as the Paper Size, and choose OK.
10. Draw the circuit shown in the following figure:

Each phase of the motor is represented as an inductor (LA, LB, LC, and LD) connected in series with its resistance and its end turn inductance. The phase inductance has a predefined value of 1H, but the actual value is derived from the finite element model. The resistance and the end turn inductance values must be entered, since they are not derived from the finite element calculation.

Transistors are represented by unidirectional switches (diodes in series with position controlled switches). Anti-parallel diodes (or freewheeling diodes) ensure that the current has a return path when the switches are open and the phases are disconnected from the source. The small subcircuit defined at the top left of the main circuit controls the switches.

The following tables contain detailed descriptions of circuit components:

**VSA – Pulsed voltage source:**
- V1 (initial value) = 0 V
- V2 (pulsed value) = 1 V
- TD (delay time) = 15 sec
- TR (rise time) = 1e-9 sec
- TF (fall time) = 1e-9 sec
- PF (pulse width) = 14 sec
- PER (period) = 60 sec

**VSB – Pulsed voltage source:**
- V1 (initial value) = 0 V
- V2 (pulsed value) = 1 V
- TD (delay time) = 0 sec
- TR (rise time) = 1e-9 sec
- TF (fall time) = 1e-9 sec
- PF (pulse width) = 14 sec
- PER (period) = 60 sec
11. Using the values in the table above, add a resistor and inductor to the circuit for each coil, representing the winding resistance and end turn inductance for each coil.

12. Draw the subcircuit. The small subcircuit defined at the top left of the main circuit controls the switches. Each phase is turned on and off according to the rotor’s position. The voltage sources VSA, VSB, VSC, and VSD are time dependent sources.

13. Add capacitor C1 and the voltage source Vsrc to the main circuit.

14. Add the switches to the main circuit:
   • For each switch, select the Positive Voltage Controlled Terminal and the Negative Voltage Controlled Terminal, according to the table below:

<table>
<thead>
<tr>
<th>Switches</th>
<th>Positive Voltage Controlled Terminal</th>
<th>Negative Voltage Controlled Terminal</th>
</tr>
</thead>
<tbody>
<tr>
<td>S1 and S4</td>
<td>VSA:p</td>
<td>VSA:m</td>
</tr>
<tr>
<td>S3 and S6</td>
<td>VSB:p</td>
<td>VSB:m</td>
</tr>
<tr>
<td>S2 and S5</td>
<td>VSC:p</td>
<td>VSC:m</td>
</tr>
<tr>
<td>S7 and S8</td>
<td>VSD:p</td>
<td>VSD:m</td>
</tr>
</tbody>
</table>

VSC – Pulsed voltage source: 
- V1 (initial value) = 0 V
- V2 (pulsed value) = 1 V
- TD (delay time) = 45 sec
- TR (rise time) = 1e-9 sec
- TF (fall time) = 1e-9 sec
- PF (pulse width) = 14 sec
- PER (period) = 60 sec

VSD – Pulsed voltage source: 
- V1 (initial value) = 0 V
- V2 (pulsed value) = 1 V
- TD (delay time) = 30 sec
- TR (rise time) = 1e-9 sec
- TF (fall time) = 1e-9 sec
- PF (pulse width) = 14 sec
- PER (period) = 60 sec

RSA = RSB = RSC = RSD = 1 ohm
RA = RB = RC = RD = 4.20481 ohm
LA = LB = LC = LD = 1 H (predefined value)
LAend = LBend = LCend = LDend = 599.669 uH
C1 = 100 uF
Vsrc = 266 V
• Define a model for the switches. In the Voltage-Controlled Switch window, choose Edit. Enter a name for the model, and enter the following parameters:
  • VT (threshold voltage) = 0.9 V
  • VH (hysteresis voltage) = 0 V
  • RON = 0.001 ohm
  • ROFF = 1e5 ohm
• Choose Update, and then choose Done to return to the previous window.
• Select the model definition from the list, and choose OK to accept the switch definition. All of the switches use the same model.

15. Add the diodes to the main circuit:
• Select a model for the diodes. For diodes DS1-DS8, select D1. For diodes D1-D8, select Dfreewheel.

Models D1 and Dfreewheel use the same parameters, so you can select either model for any of the diodes in this circuit. The differentiation is made here simply to stress that the two different types of diodes behave differently and serve different purposes. Diodes DS1-DS8 work in series with position controlled switches to represent transis-

tors. Anti-parallel diodes D1-D8 ensure that the current has a return path when the switches are open and the phases are disconnected from the source.

Note:

• Optionally, if you want to define a model, choose Edit. Use the default parameters in the Diode Model Definition window. Enter a name for the model, and choose Update. Choose Done to return to the Diode window. Select the model from the list, and choose OK. The default parameters for the model should be:
  • IS (saturation current) = 1e-14
  • R5 (ohmic resistance) = 0
  • N (emission coefficient) = 1
  • TT (transit time) = 1e-10
  • CJ0 (zero-bias junction capacitance) = 2e-12
  • VJ (junction potential) = 0.6
  • M (grading coefficient) = 0.5
  • Eg (activation energy) = 1.11
  • XTI (saturation current exponent) = 3
  • KF (flicker noise coefficient) = 0
  • AF (flicker noise exponent) = 1
  • FC (forward cap depletion coefficient) = 0.5
  • BV (reverse breakdown voltage) = 1e30
  • IBV (current at breakdown voltage) = 0.001
  • TNOM (parameter measurement temperature) = 27

16. When the electric circuit is entirely drawn, choose File/Save, and then File/Exit. The Define Source Type window appears, asking you to define the source type. By default, all of the sources are time dependent, so you must specify which one is speed dependent (the time in the source definition is replaced by the speed of the rotor) or position dependent (the time in the source definition is replaced by the rotor’s position). In the current model, the transient sources (VSA, VSB, VSC, and VSD) are all position dependent.

17. Move all of the sources to the Position Dependent list. Choose OK to return to the Edit External Circuit window.

18. Make certain that all of your windings have inductors in the circuit. Choose OK to return to the 2D Boundary/Source Manager.

19. Choose File/Save, and then File/Exit to exit the 2D Boundary/Source Manager and return to the Projects window. The boundaries and sources are now defined.
Setup Solution

Since adaptive refinement is unavailable for the transient solver, the quality of the manual mesh is critical to the accuracy and the convergence of the field solution. The mesh must be fine in regions where a large magnetic field gradient occurs (air-gaps) and larger elsewhere; for practical use, generating a mesh which is too fine can result in excessive computational time.

Manual Mesh

➤ Manually create the mesh:

1. Choose Setup Solution/Options from the Executive Commands menu. The Solve Setup window appears.
3. Choose Mesh/Seed/QuadTree. The QuadTree Seed window appears. Accept 6 as the Number of levels, and choose OK.
4. Choose Mesh/Make. The basic mesh is generated for the model. This mesh is too coarse to provide the most accurate solution and must be refined. To refine the mesh, you need to take into account the areas which are critical for the solution accuracy. In this example, the critical areas are the band, the air-gap, and the rotor bars. During the manual refinement, you can specify the desired number of triangles in each object.

Refine the Mesh

➤ Refine the mesh:

1. Choose Refine/Object. The Object Refinement window appears, allowing you to refine the mesh further. The goal is to have a uniform mesh with a sufficient number of elements, as shown in the following table:

<table>
<thead>
<tr>
<th>Object</th>
<th>Number of elements</th>
</tr>
</thead>
<tbody>
<tr>
<td>AirGap</td>
<td>1000</td>
</tr>
<tr>
<td>Band</td>
<td>1300</td>
</tr>
<tr>
<td>AirRotor</td>
<td>500</td>
</tr>
<tr>
<td>Any object in the Phases</td>
<td>150</td>
</tr>
<tr>
<td>Rotor</td>
<td>1000</td>
</tr>
<tr>
<td>Shaft</td>
<td>250</td>
</tr>
<tr>
<td>Stator</td>
<td>2000</td>
</tr>
</tbody>
</table>

2. If the number of elements for an object does not fall within a few percent of the values listed above, then select its name from the Object Name list, and enter the appropriate value in the Refine Number field. Choose Accept to accept each new value. Note that the values for the air gap, band, and stator are the ones that require the greatest number of elements to obtain the most accurate solution.
3. Choose OK.
You can modify the mesh still further by adding individual points, using the Refine/Point command. Pay particular attention to the region surrounding the air gap and the top of the stator poles because this is the area in which the error will be highest, and the mesh will need to be refined the most.
4. Choose **Refine/Point**. The **Point Refinement** window appears.
5. Leave **Circumcircle** selected, and choose **OK**.
6. Click to refine the mesh along the band object and the stator poles. Click the right mouse button to exit refinement mode.
7. Choose **Mesh/Line Match**, and select the edges of both the master and slave boundaries, to ensure that the meshing points will match at your matching boundaries. Make certain to choose the origin as the first point for both the master and the slave boundaries. (Remember to check the status bar at the bottom of the window for a description of what action is expected next after each click.) If the points do not match, you will receive an error message about a missing transcript file during the nominal solution.
8. Choose **File/Exit**, and save the changes to the mesh as you exit from the window. When you return to the **Solve Setup** window, notice that the **Starting Mesh** option is changed to use the **Current** mesh.
Set Up Options for the Transient Analysis

For this example, use the following settings to define the solution options for the transient analysis.

- Define the solution options:
  1. Leave Starting Mesh set to Current.
  2. Select Direct as the Solver Choice. Use this option whenever you generate a solution using the transient solver.
  3. Select Start from time zero as the Solution starting point.
  4. Enter 0.006 seconds in the Stop time field.
  5. Enter 1e-5 seconds in the Time step field.
  6. Enter 0.002 seconds in the Save fields time step field. This instructs the solver to write the field solution out every 2 milliseconds.
  7. Enter 65 mm in the Model depth (mm) field. The stack factor of the motor (0.95) is taken into account, with the help of the equivalent BH curves imported from RMxpert. If you do not have the equivalent BH curves for the materials, you can use the actual BH curves and an equivalent depth, given by the actual depth multiplied by the stack factor.
  8. Enter 2 in the Symmetry multiplier field. Because you are modeling only one-half of the model, use this multiplier to generate a solution for the entire geometry.
  9. Choose OK to accept the values and return to the Executive Commands window.

Motion Setup

With the solution parameters defined, now define the motion parameters for the transient model.

- Define the motion setup:
  1. Choose Setup Solution/Motion Setup from the Executive Commands window. The Motion Setup window appears.
  2. Select the Band object, and then choose Set Band. The band is defined as a stationary object that contains all moving objects.
  3. Select Rotation as the Type of Motion.
  4. Choose Set Position, and select (0,0) as the center of rotation.
  5. Choose Mechanical Setup. The Mechanical Setup window appears.
  6. Deselect Consider Mechanical Transient, and enter 1951 in the Constant Angular Velocity field. Make sure the units list beside the field is set to rpm.
  7. Choose OK to close the Mechanical Setup window.
  8. Choose Exit, and save the changes as you exit the Motion Setup window.

Solve the Nominal Problem

Choose Solve/Nominal Problem from the Executive Commands menu. The progress bar reports the solution status.

To display the transient data, such as voltages, currents, torque, and power loss, choose Solutions/Transient Data. Choose Refresh during the solution process, and the plots will be redrawn after the software completes the current time step.
Post Processing

Access the transient data:
1. Choose Post Process/Transient Data. A file browser appears, listing the directories containing the plots.
2. Select one of the time step solutions (.dat files).
3. Choose OK. The plot appears in the PlotData window. After you’ve opened one plot, choose Plot/Open to open a different plot.

The following figures show three of the transient plots for the sample problem:
Average Value of a Transient Curve

Once you are in the Transient Data Post Processor, you can analyze the transient curve.

➤ Analyze the curve:

1. From within PlotData, choose Tools/Calculator. The Signal Calculator appears.
2. Load the file torque.dat into the calculator stack.
3. Choose Sample. The Data Sampling window appears.
4. Leave Sample in set to Time.
5. Select Spacing from the Specify by options.
6. Enter 0.00145 seconds in the Start field
7. Enter 0.00529 seconds in the Stop field.
8. Enter 1e-6 seconds in the Spacing field.
9. Choose OK to return to the calculator.
10. Choose Preview to make certain you selected the right start time and stop time. Make certain the spacing is fine enough to correctly represent the curve.
11. Choose Sum.
13. Choose n.
15. Choose max.
16. Choose Pop.
17. Choose Exch.
18. Choose the divide button. A result of approximately 2.98513 Nm appears, representing the average value of the selected range of the curve, compared with 2.69233 Nm given by RMxprt.
19. Choose Done to exit the Signal Calculator.
20. Choose File/Exit to exit PlotData.
Access the Field Solution

Access the field solution:

1. Choose **Post Process/Fields** from the Executive Commands menu. The **Post-Process Saved Fields** window appears, listing the saved field solutions.
2. Select any one of the saved time step solutions.
3. Choose **Post Process**. Choose **Post/Plot** to plot field quantities such as flux density and flux lines.

The following figure shows the field solution at 0.004 seconds: