16 March 2018

Motor-CAD Software Tutorial:

Modelling the Nissan Leaf Motor using Motor-CAD

Contents

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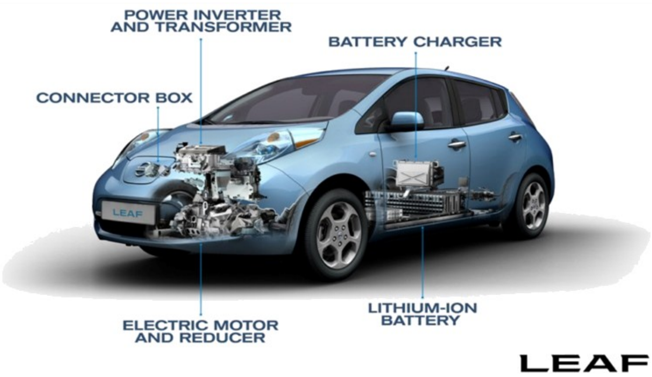
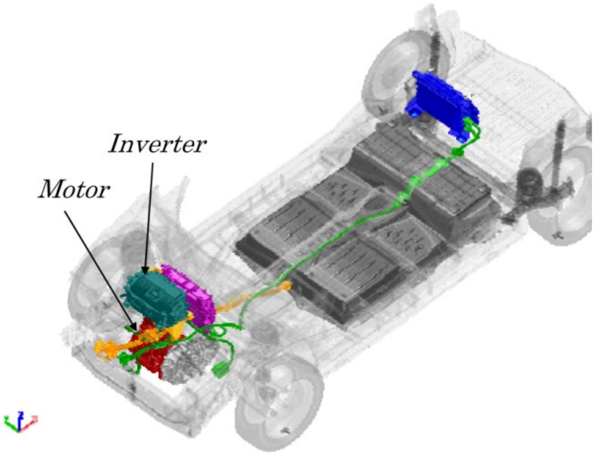
1. Description

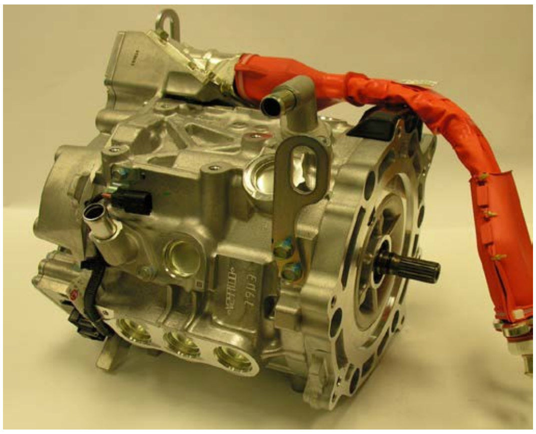
The brushless permanent magnet (BPM) machine of the 2012 Nissan LEAF is modelled in Motor-CAD. We obtain detailed electromagnetic and thermal performance results for a single operating point, efficiency maps showing the performance across the full operating range and combined electromagnetic and thermal performance for a complex drive cycle.

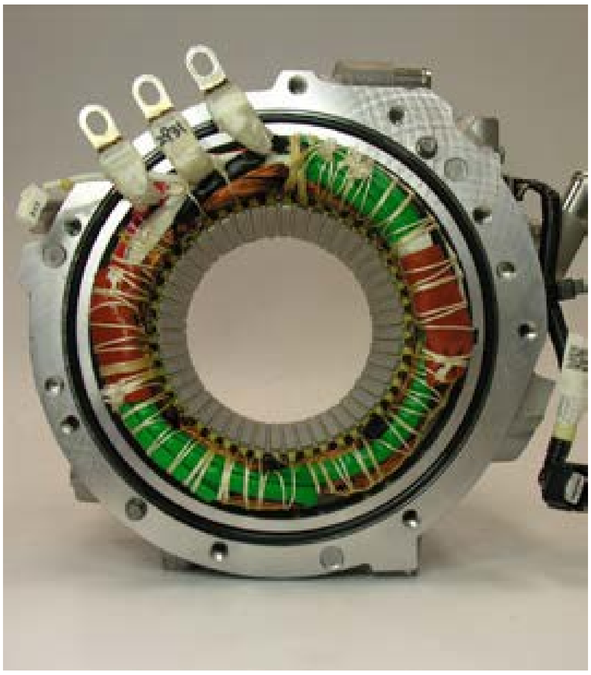
The model information, hardware images and performance test data have been drawn from the following reports:

- Tim Burress, "Benchmarking of Competitive Technologies", Oak Ridge National Laboratory, May 2012. http://energy.gov/sites/prod/files/2014/03/f10/ape006_burress_2012_p.pdf
- Tim Burress, "Benchmarking State-of-the-Art Technologies", Oak Ridge National Laboratory, May 2013. http://energy.gov/sites/prod/files/2014/03/f13/ape006_burress_2013_o.pdf
- "Annual Progress Report Advanced Power Electronics and Electric Motors Program" Vehicle Technologies Program, U.S Department of Energy. January 2013.
- Susan A. Rogers, "Annual Progress Report for the Advanced Power Electronics and Electric Motors Program" Vehicle Technologies Program, U.S Department of Energy. December 2013. http://energy.gov/sites/prod/files/2014/04/f15/2013_apeem_report.pdf
- John M.Miller, "Electric Motor R&D", Oak Ridge National Laboratory, May 2013. http://energy.gov/sites/prod/files/2014/03/f13/ape051_miller_2013_o.pdf
- Yoshinori Sato, Shigeaki Ishikawa, Takahito Okubo, Makoto Abe, and Katsunori Tamai, ―Development of High Response Motor and Inverter System for the Nissan LEAF Electric Vehicle,‖ International World Congress and Exhibition, Detroit, Michigan, April 12–14, 2011, paper 2011-01-0350.




Inverter
Motor



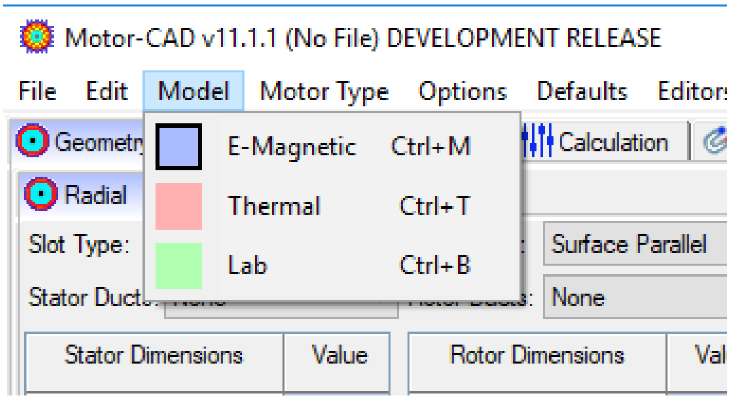


2. Starting Motor-CAD

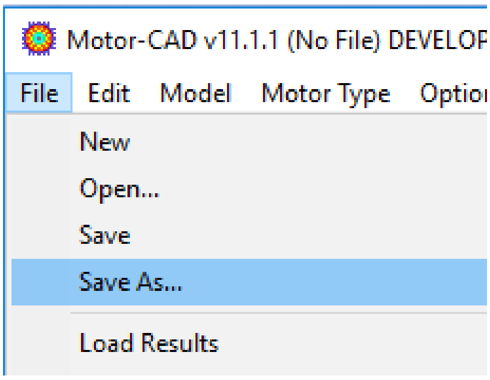
Install Motor-CAD on the computer by launching the *Motor-CAD_Setup.exe* (file name will depend on the version selected) and following the instructions. The recommended version of Motor-CAD for this tutorial is v11.1.

When the installation is finished, run Motor-CAD and it will start with a default brushless permanent magnet synchronous machine.

We will start by configuring the electromagnetic model. Select **Model -> E-Magnetic** from the main menu to show the electromagnetic context *(tip: a blue background on the active tab indicates electromagnetic context*).

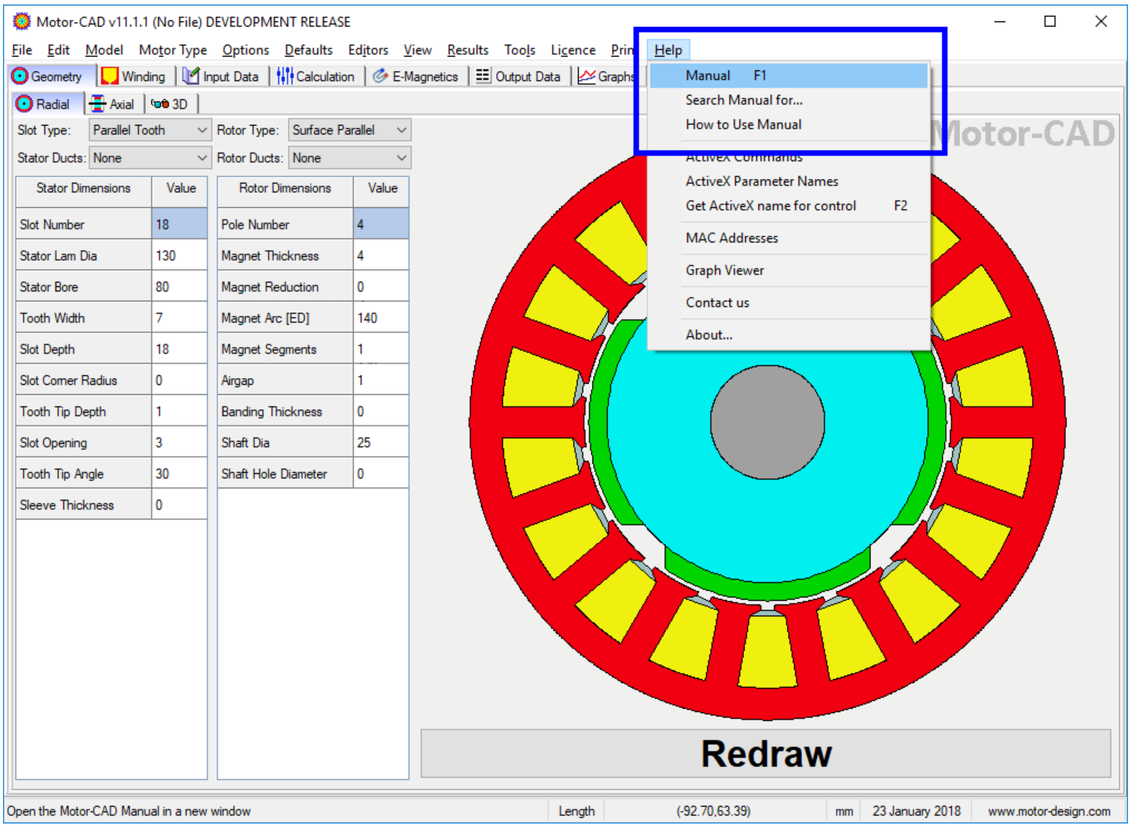


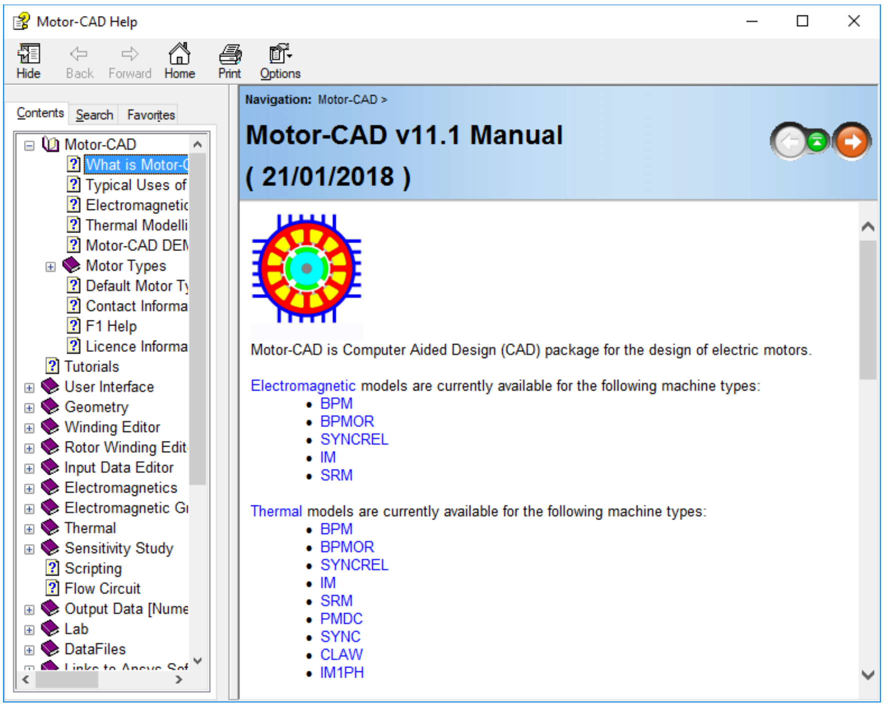
Select **File -> Save As…** to save the file as **Nissan_LEAF_1_Geometry.mot** in the desired location.



i. Motor-CAD Manual

There is a comprehensive manual included with Motor-CAD which can be accessed at any time by selecting **Help -> Manual** from the main menu, or pressing **F1**.

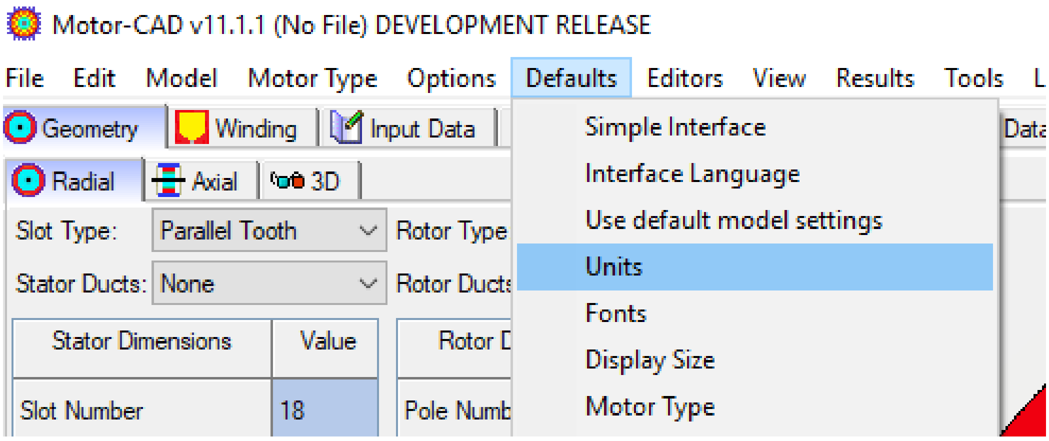


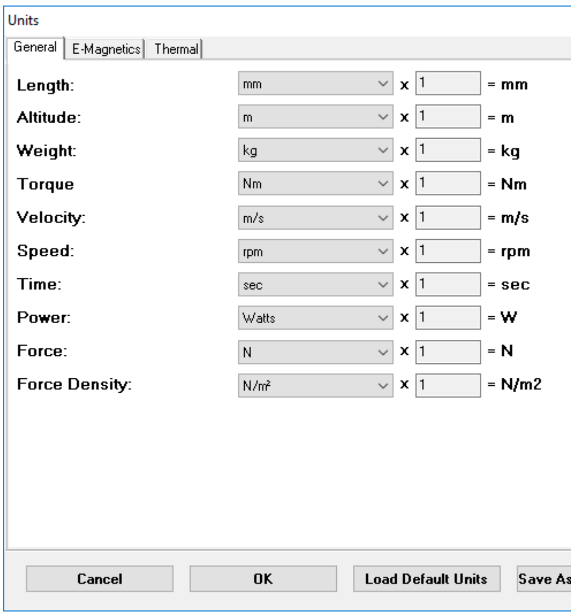


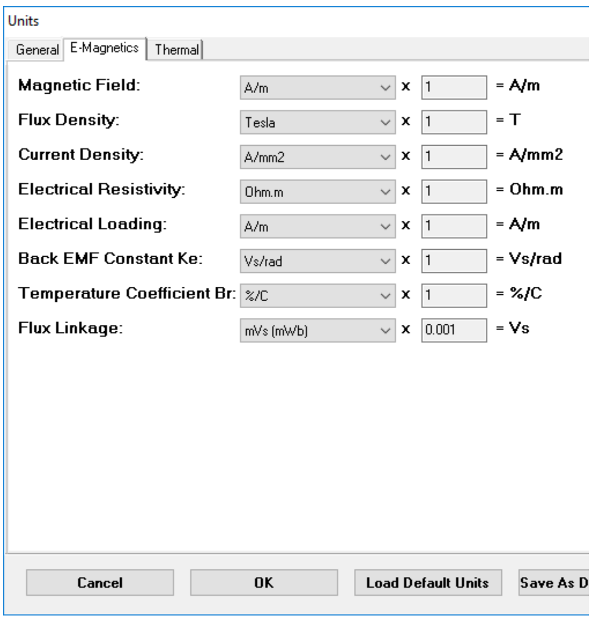
ii. Default Units

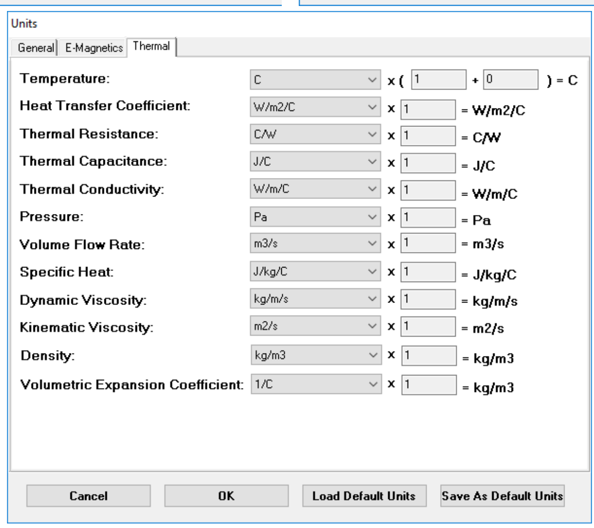
Motor-CAD allows users to select different units to use for the input/output parameters. For this tutorial we will be working mostly in SI units.

Open the **Units** dialog from **Defaults -> Units**, and set the units as shown below:





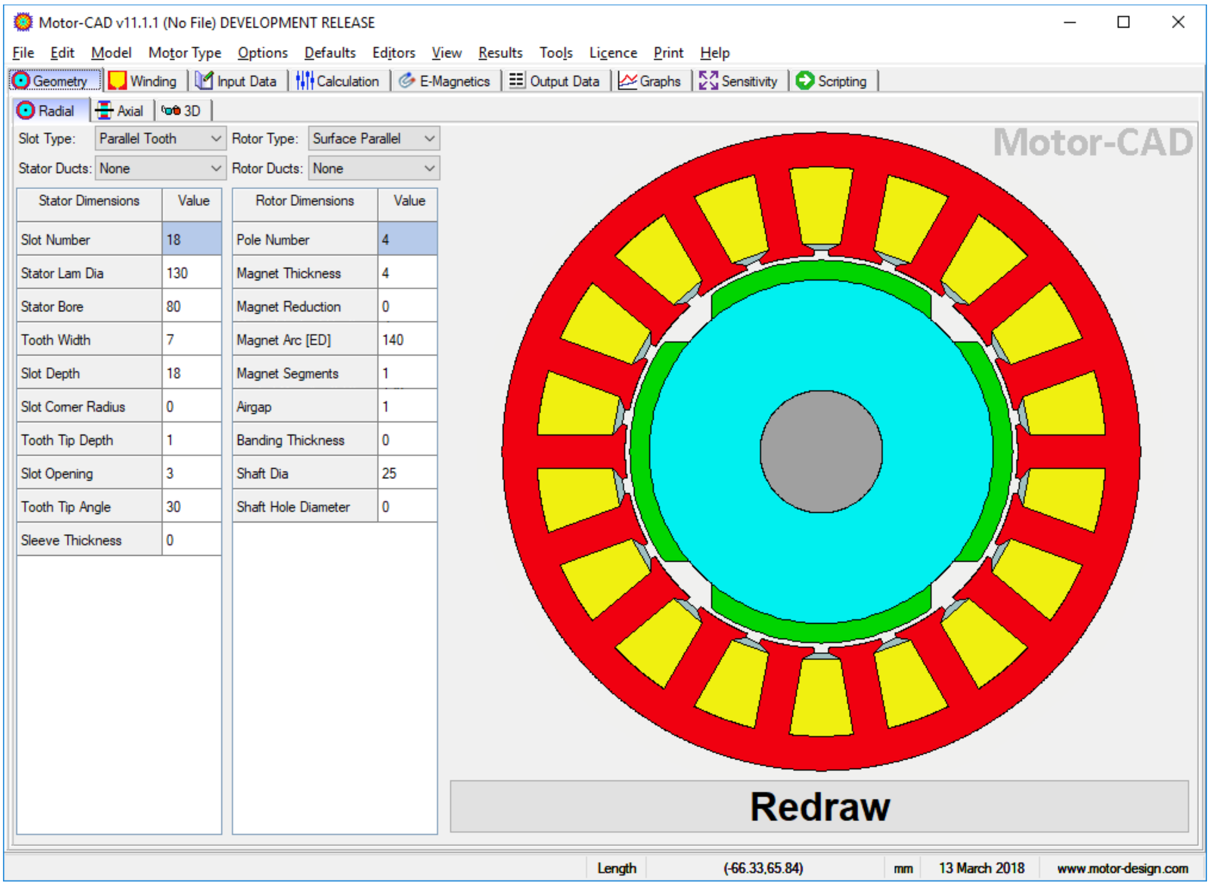




3. Electromagnetic Model

The following main tabs are available in the E-Magnetic context for sine-wave driven BPM machines. Generally in Motor-CAD we work through the tabs from left to right in order to set up the model, run the calculations and analyse the results.

Tab	Description
Geometry	Define & view the machine geometry (radial, axial, 3d)
Winding	Define & view the stator winding (winding pattern, conductors)
Input Data	Specify materials used in the model, adjust advanced settings (calculation methods, FEA settings, build factors, etc)
Calculation	Specify the operating point & run the calculations
E-Magnetics	E-Magnetic 2D FEA – view results, customise FEA geometry, measure quantities, design optimisation
Output Data	View numerical results (from FEA and analytic calculations)
Graphs	View results waveforms from transient simulations
Sensitivity	Sensitivity analysis - vary input parameters and analyse effect on machine performance
Scripting	Create & run Visual Basic scripts in Motor-CAD



i. Geometry Inputs

The **Geometry** tab in Motor-CAD is used to define the machine geometry using the **Axial** and **Radial** views. In the electromagnetic context, only parameters that are considered in the electromagnetic model are displayed and so some machine components (e.g. housing, mounting etc) are hidden.

In the **Geometry -> Radial** tab, we set the radial geometry of the stator as follows:

Stator Parameter	Value	Units
Slot Type	Parallel Tooth	
Stator Ducts	None	
Slot Number	48	
Stator Lam Dia	198	mm
Stator Bore	132	mm
Tooth Width	4.15	mm
Slot Depth	21.1	mm
Slot Corner Radius	2	mm
Tooth Tip Depth	1.2	mm
Slot Opening	2.814	mm
Tooth Tip Angle	27	degrees
Sleeve Thickness	0	mm

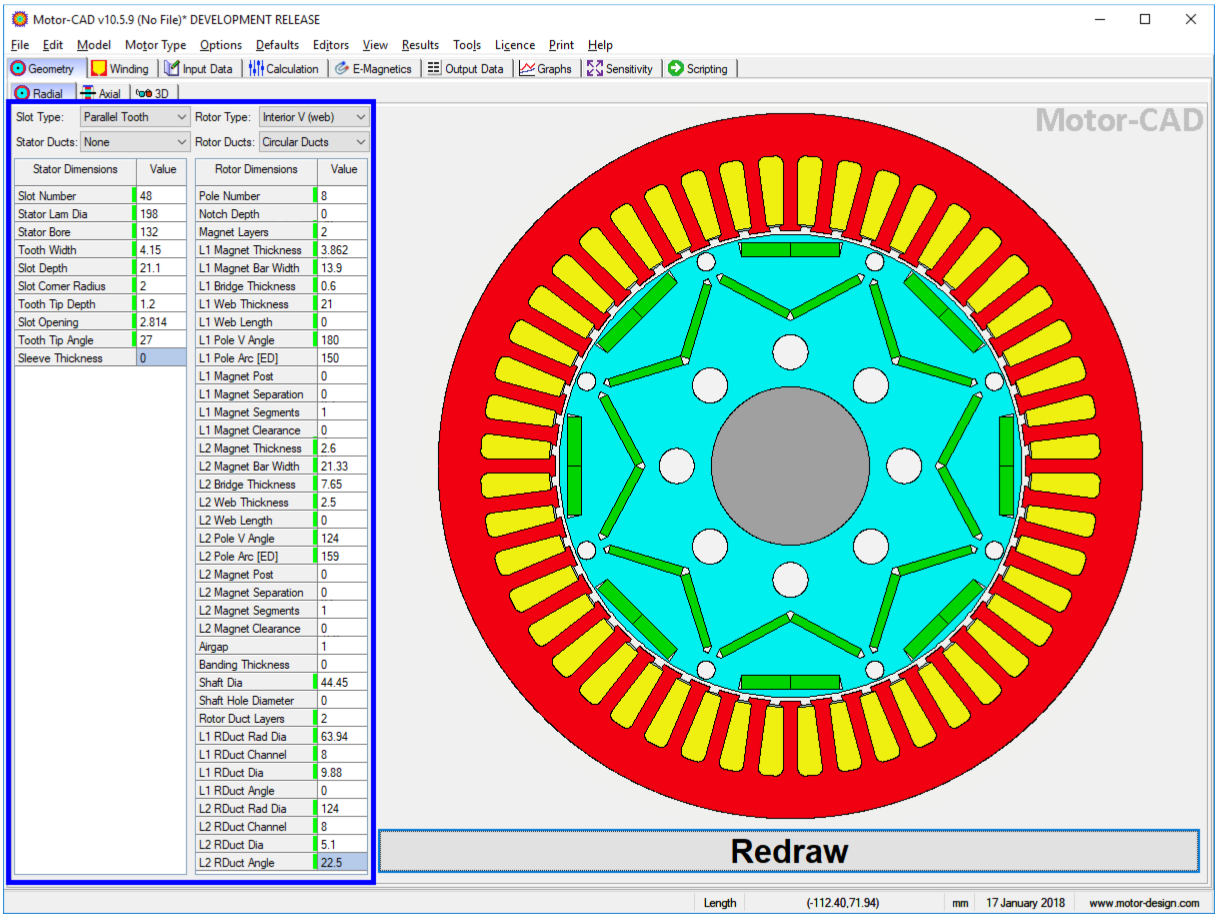
After editing parameters, press **Enter** or click the **Redraw** button to update the drawing. As the tables are edited, green highlighting shows which values have been changed.

We set up the rotor magnet geometry by changing the following parameters:

Rotor Parameter	Value	Units
Rotor Type	Interior V (web)	
Pole Number	8	
Notch Depth		
Magnet Layers	2	
L1 Magnet Thickness	3.862	mm
L1 Magnet Bar Width	13.9	mm
L1 Bridge Thickness	0.6	mm
L1 Web Thickness	21	mm
L1 Web Length	0	mm
L1 Pole V Angle	180	degrees
L1 Pole Arc	150	degrees
L2 Magnet Thickness	2.6	mm
L2 Magnet Bar Width	21.33	
L2 Bridge Thickness	7.65	mm
L2 Web Thickness	2.5	mm
L2 Web Length	0	mm
L2 Pole V Angle	124	degrees
L2 Pole Arc	159	degrees
Airgap	1	mm
Shaft Dia	44.45	mm

Here we also define the cooling ducts in the rotor. These are considered in the electromagnetic model since the presence of ducts in the rotor iron will change the electromagnetic behaviour of the motor.

Rotor Parameter	Value	Units
Rotor Ducts	Circular Ducts	
Rotor Duct Layers	2	
L1 RDuct Rad Dia	63.94	mm
L1 RDuct Channel	8	
L1 RDuct Dia	9.88	mm
L1 RDuct Angle	0	degrees
L2 RDuct Rad Dia	124	mm
L2 RDuct Channel	8	
L2 RDuct Dia	5.1	mm
L2 RDuct Angle	22.5	mm

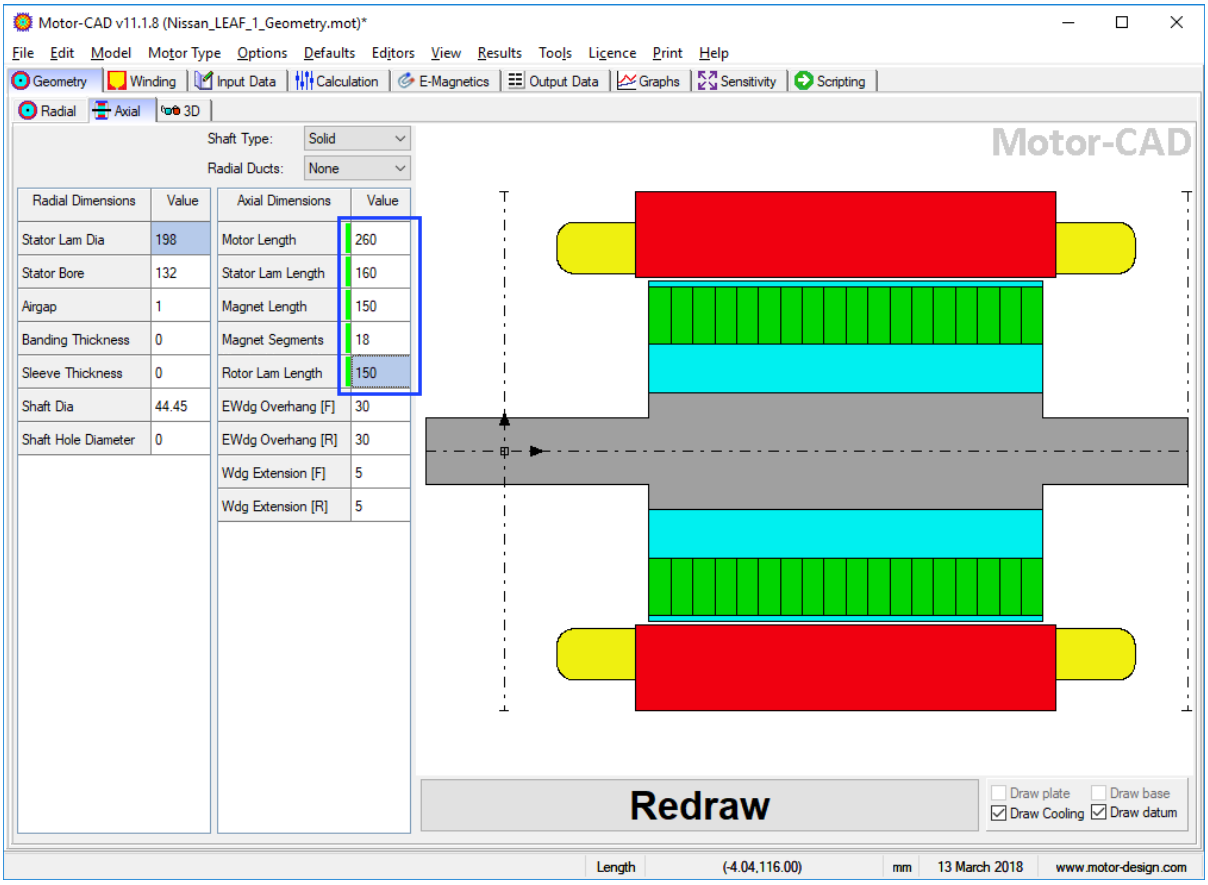


Now save the file using **File -> Save** or **Ctrl+S**.

In the **Geometry -> Axial** tab we set the axial dimensions of the motor:

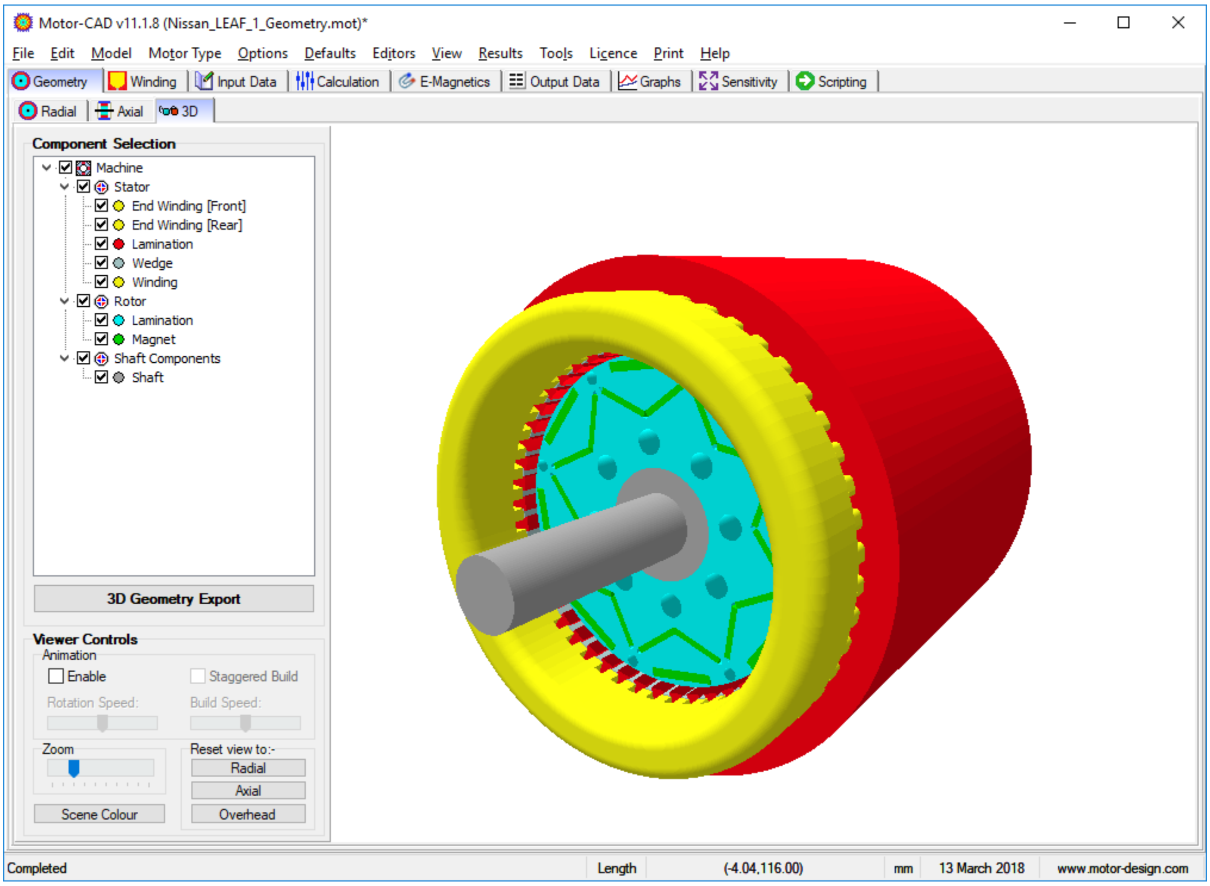
Axial Parameter	Value	Units
Motor Length	260	mm
Stator Lam Length	160	mm
Magnet Length	150	mm
Magnet Segments	18	
Rotor Lam Length	150	mm

Again, press **Enter** or click **Redraw** to update the drawing.



The geometry definition for the electromagnetic analysis is now complete and the changes can be saved using **File -> Save** or **Ctrl+S**.

The **Geometry -> 3D** tab shows a 3D view of the motor to allow visualisation of the machine. Transparency levels of components can be set by right-clicking them in the component list. Components or groups of components can also be hidden by deselecting checkboxes in the list.



ii. Winding Definition

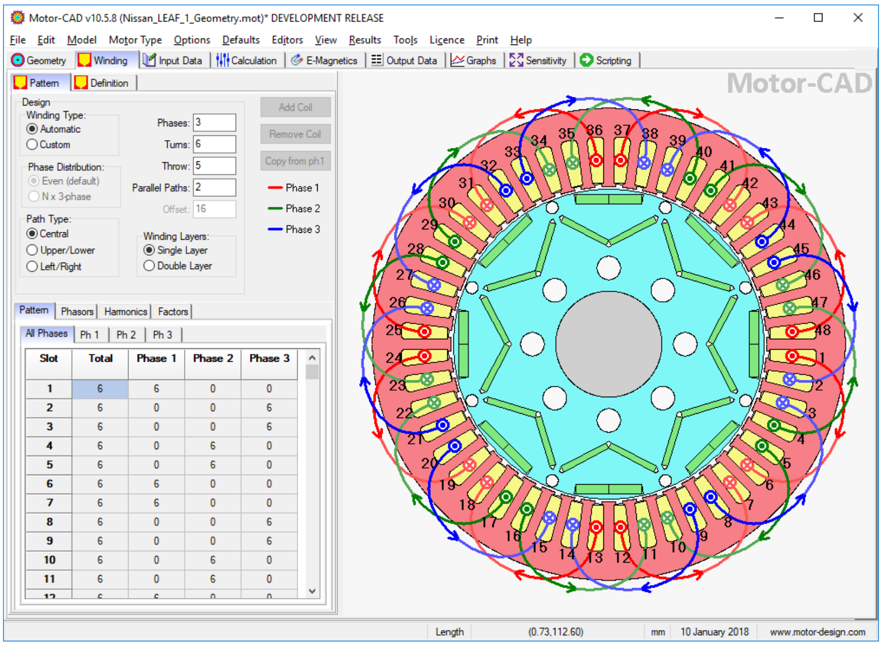
Now that the geometry is defined, we use the **Winding** tab to define the conductors and insulation inside the stator slots. The **Definition** tab is used to define and visualise the position of the conductors with the insulation, impregnation, liner and wedge, making it easy to test and check different winding configurations. The **Pattern** tab provides quick configuration and visualisation of the winding layout with the connection of the coils, as well as analysis of the phasors, winding factors and harmonic content.

Winding Pattern

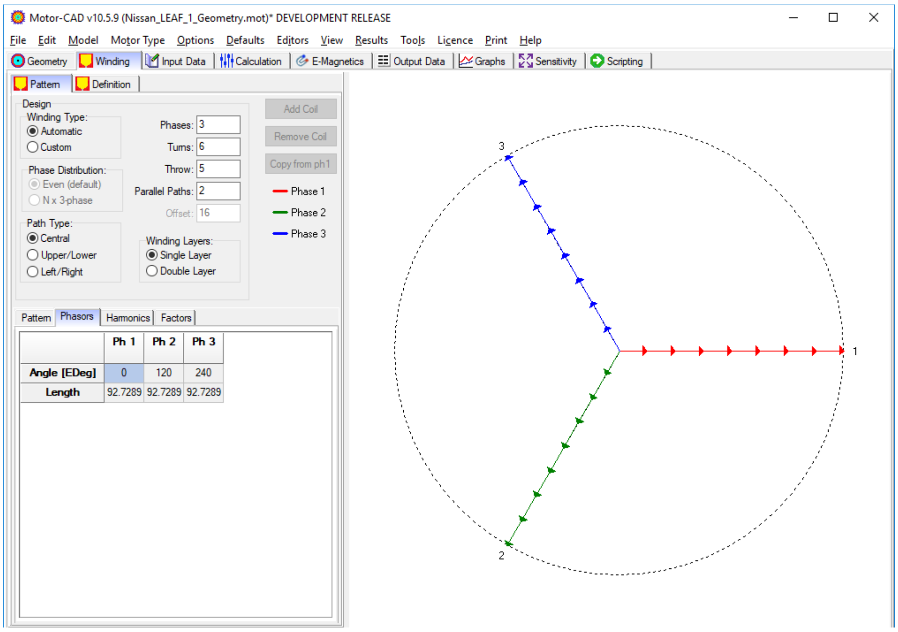
The electromagnetic winding definition starts with the configuration of the coils, their connection and the type of winding used in the design. Under **Winding -> Pattern**, set the following:

Parameter	Value
Winding Type	Automatic
Path Type	Central
Winding Layers	Single Layer
Phases	3
Turns	6
Throw	5
Parallel Paths	2

Motor-CAD will automatically generate an optimal winding pattern based on the specified throw as shown below:

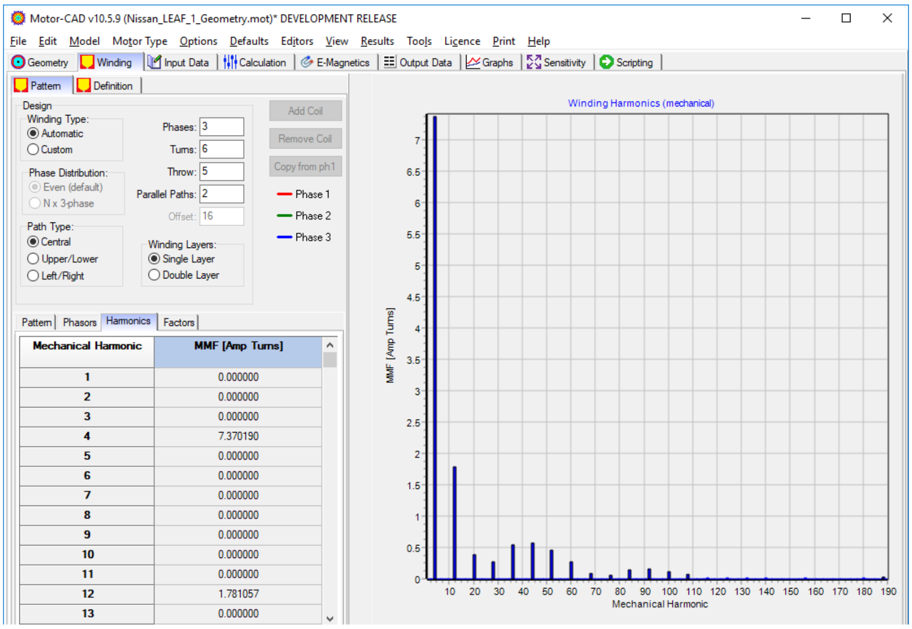


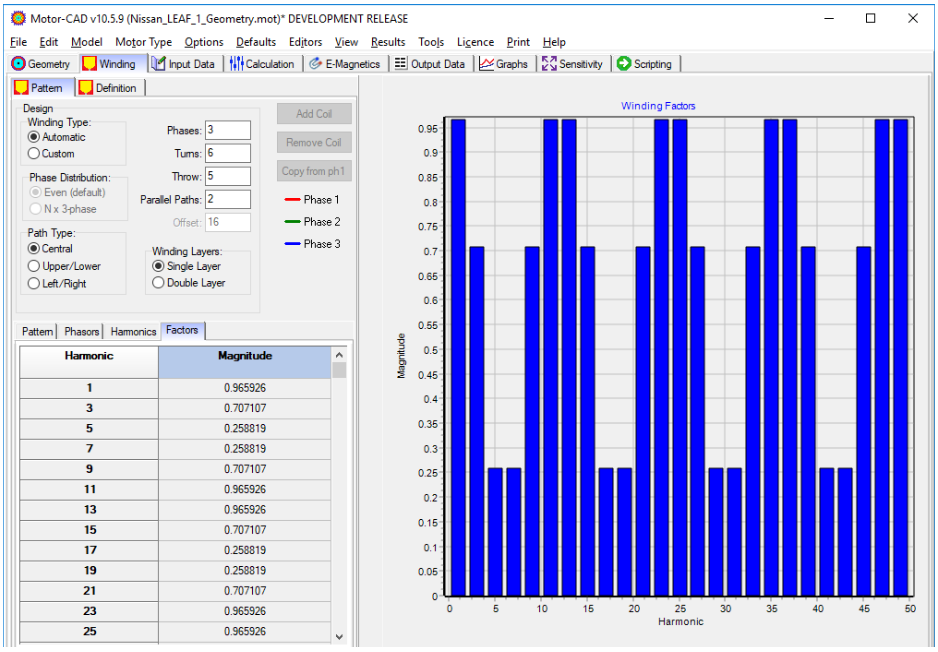
By selecting the **Phasors** tab, we can check that the phasors are 120° apart with equal lengths.



Harmonic Analysis

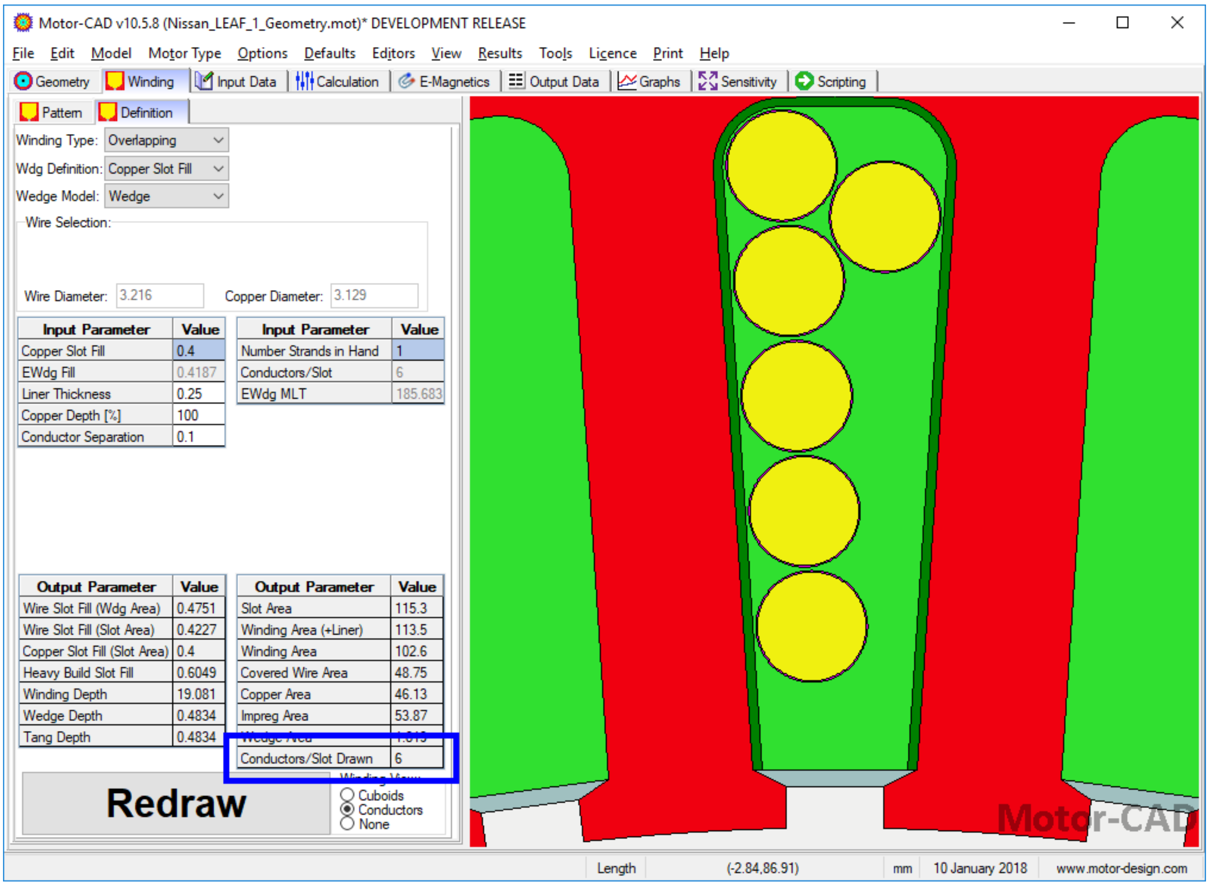
Before any simulations are performed, mechanical MMF harmonics and winding factors are analysed analytically based on the winding pattern. Under **Winding -> Pattern**, we can check these values under the **Harmonics** and **Factors** tabs.





Conductor Definition

Now navigate to the **Winding -> Definition** tab. Here, the number of conductors in the slot is defined by the coil configuration and the number of strands in hand. We have 6 turns per coil, with a single coil in each and 1 strand in hand slot so we have 6 x 1 x 1 = 6 conductors/slot.



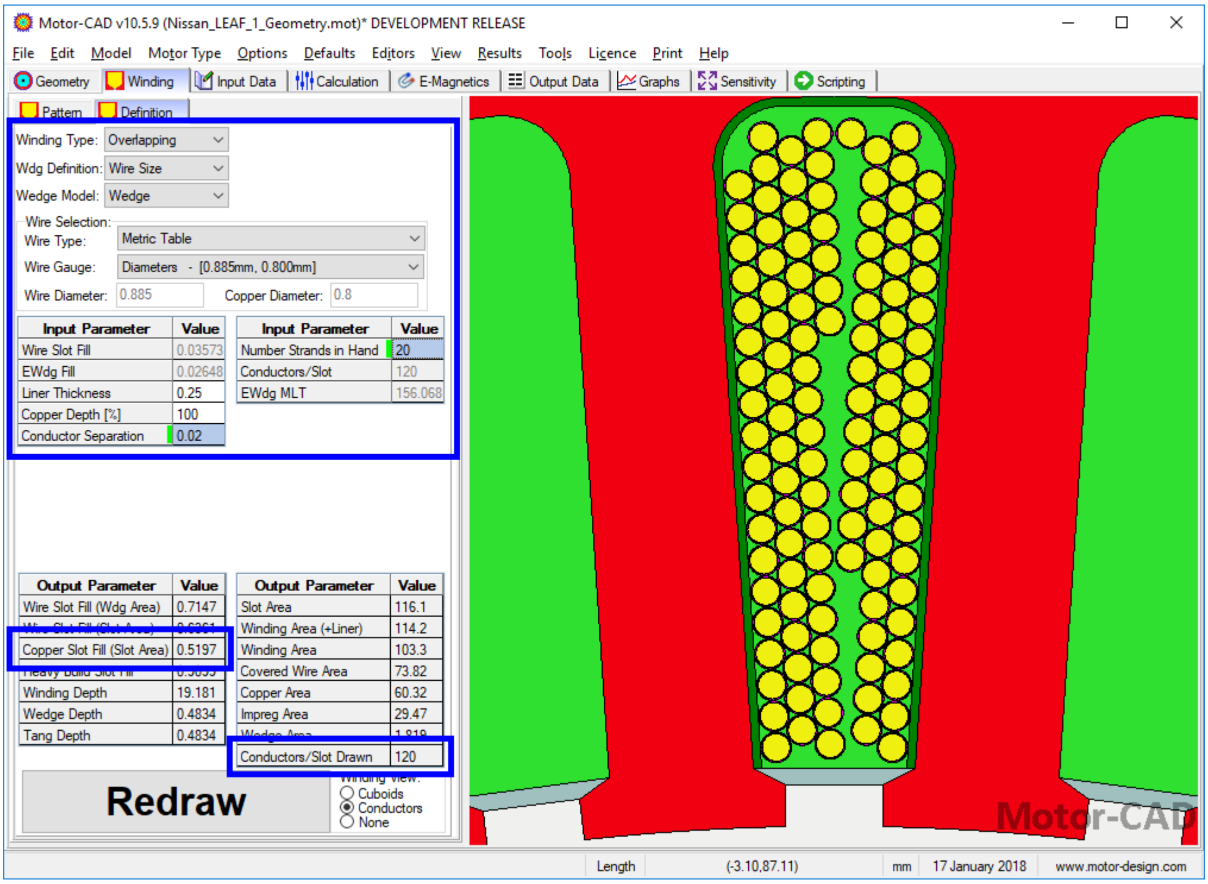
Now define the conductors with the following settings. Note that we have an overlapping winding since this design uses a distributed winding pattern.

Parameter	Value	Units
Winding Type	Overlapping	
Winding Definition	Wire Size	
Wedge Model	Wedge	
Wire Type	Metric Table	
Wire Gauge	[0.885mm, 0.800mm]	
Liner Thickness	0.25	mm
Copper Depth	100	%
Conductor Separation	0.02	mm
Number Strands in Hand	20	

We can verify that the winding is specified correctly by checking that we have **120 Conductors/Slot** and the **Copper Slot Fill** is approximately **52%**.

*(Tip: The **Conductors/Slot Drawn** parameter will be highlighted in red if the required number of conductors cannot fit into the defined slot.)*

Again, save the file with the changes.



iii. Materials Input

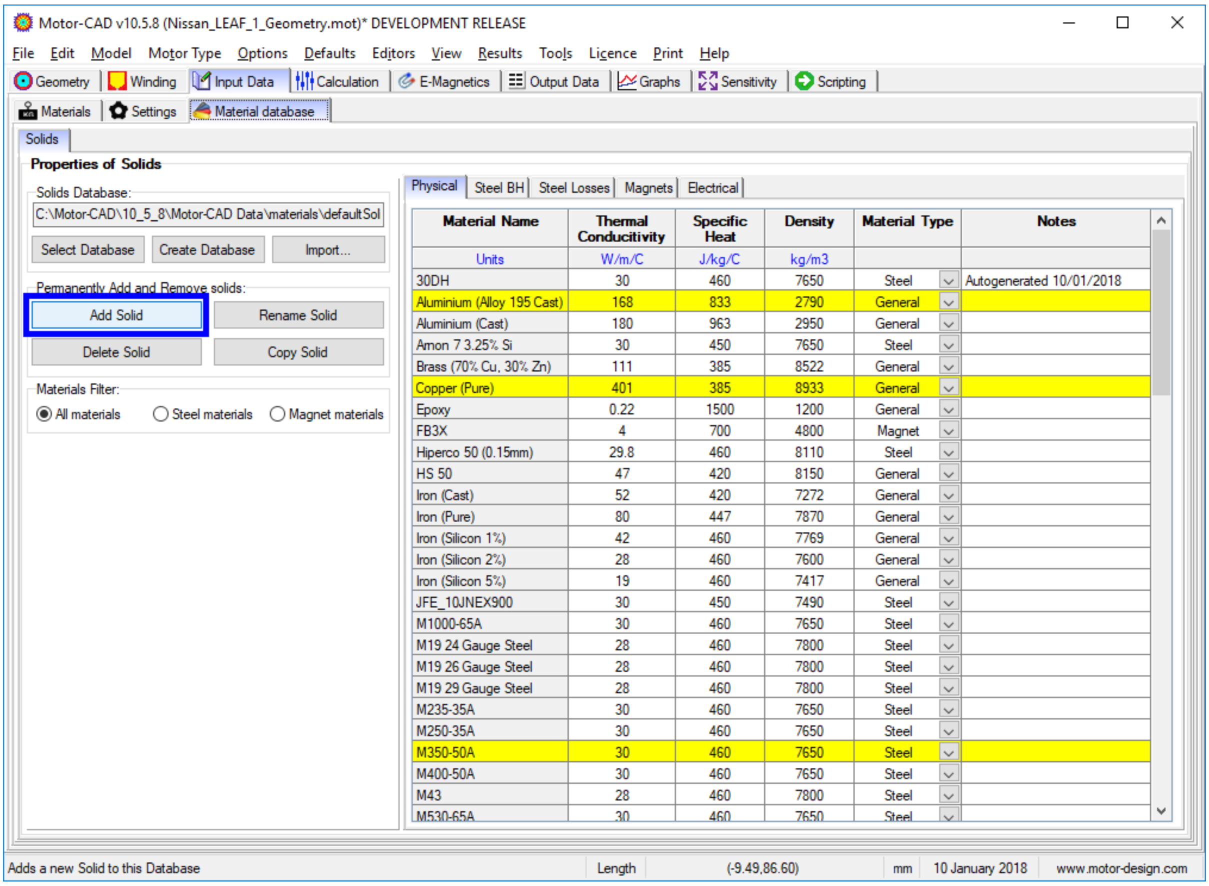
The next step is to configure the materials used in the motor, in particular the magnetic steel and magnets.

Materials Database

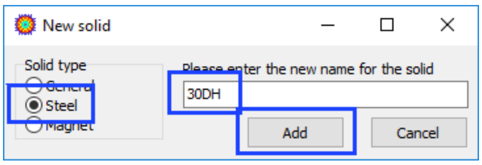
Motor-CAD provides a database of materials, which can be viewed under **Input Data -> Material database**. The default database contains full details of many commonly used materials. The user can then add details for any materials not included by default. The materials currently used in the model are highlighted in yellow in the interface.

The LEAF motor uses the 30DH steel, which is not included in the default database of materials supplied with Motor-CAD. We will therefore have to add the material data to the database from the manufacturer's specifications.

To add a new material, click the **Add Solid** button.

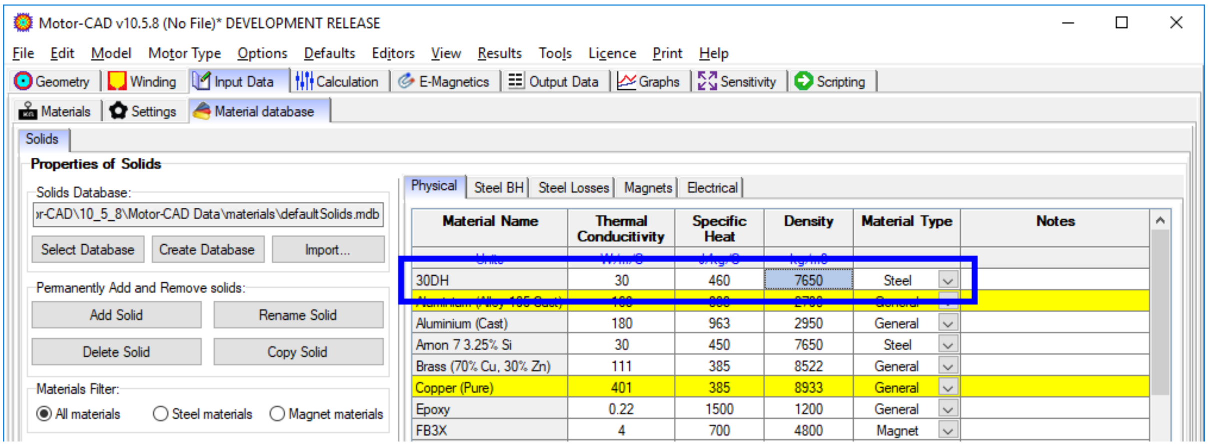


In the dialog that appears we type the name, set the **Solid type** to **Steel** and click **Add**.



The new material is added to the database and can be viewed in the alphabetical list. We now enter the material properties. Under the **Physical** tab we set:

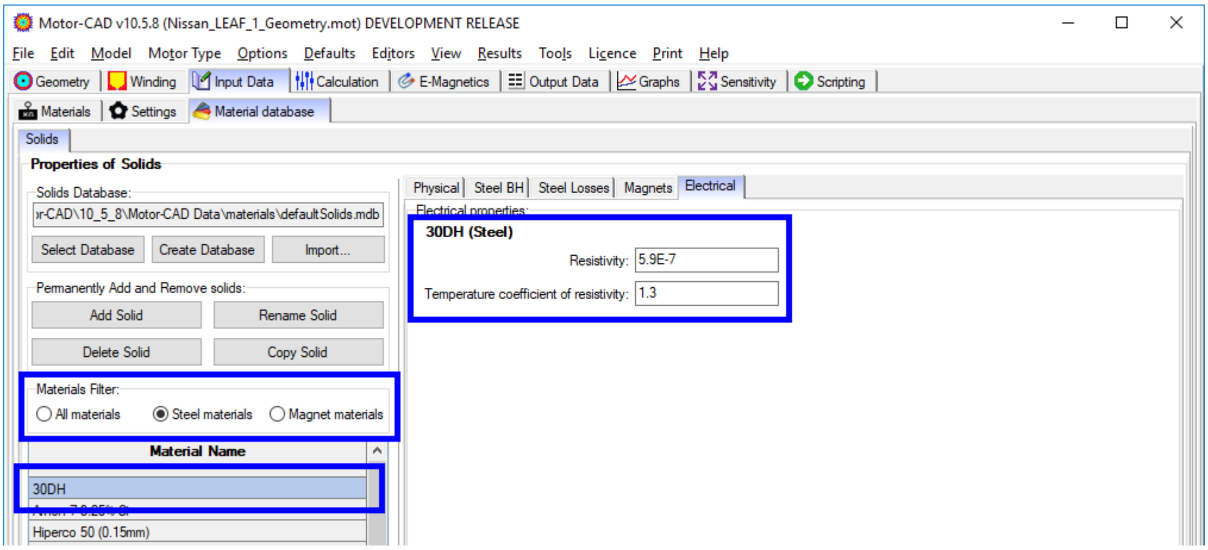
Property	Value	Units
Thermal Conductivity	30	W/m/C
Specific Heat	460	J/kg/C
Density	7650	kg/m3



Notes can also be added to the material.

The electrical properties are configured under the **Electrical** tab. Before editing the values we check that the new material 30DH is selected in the list on the left. We can use the **Materials Filter** to display only **Steel materials**, making it easier to locate and select the correct material.

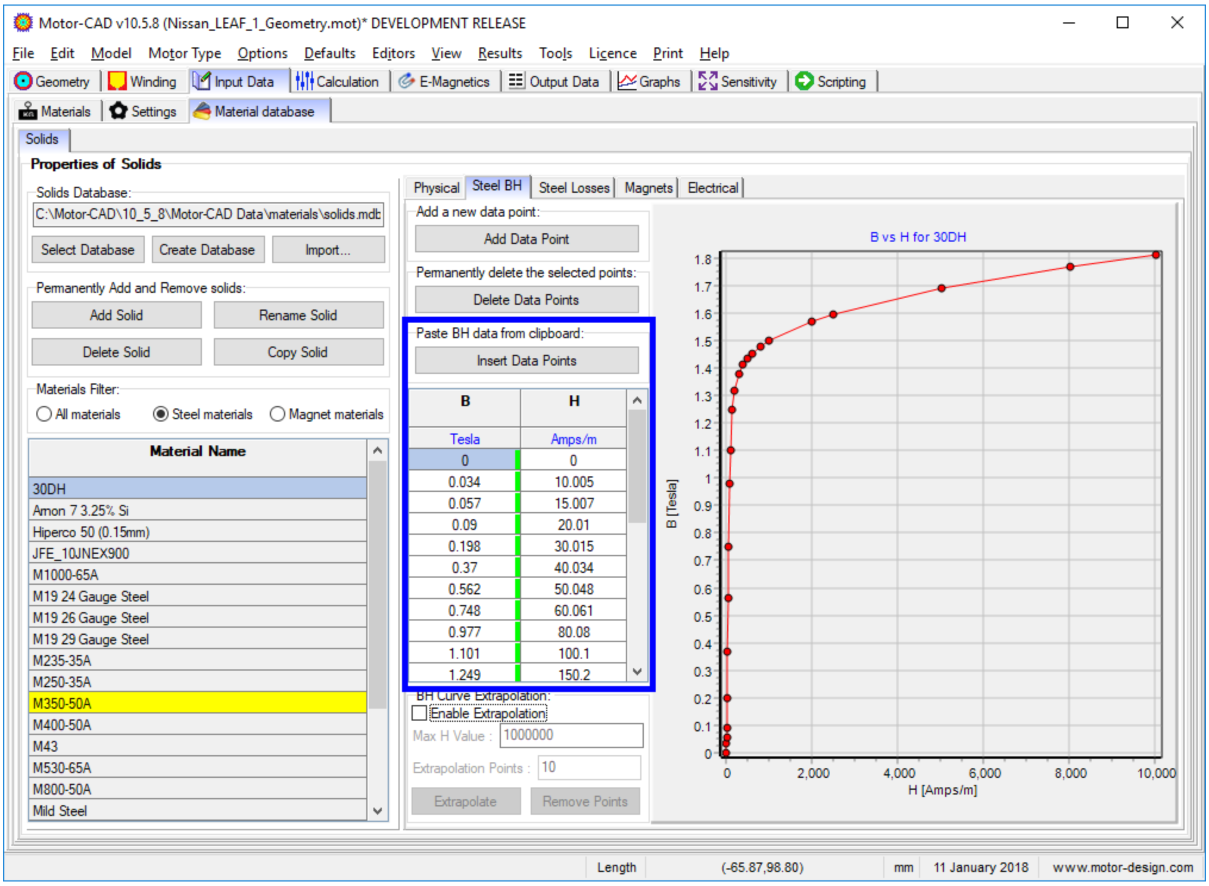
Property	Value	Units
Resistivity	5.9E-7	Ohm
Temperature coefficient of resistivity	1.3	/C



The magnetic properties of the steel are configured in the **Steel BH** tab. Here we enter the BH curve data into the table.

Note that the units must be correct for the data we enter. If the manufacturer provides data in alternative units, the data can either be converted before entering into Motor-CAD, or the default units in Motor-CAD can be modified by selecting **Defaults -> Units** from the main menu to allow entering of data using alternative units

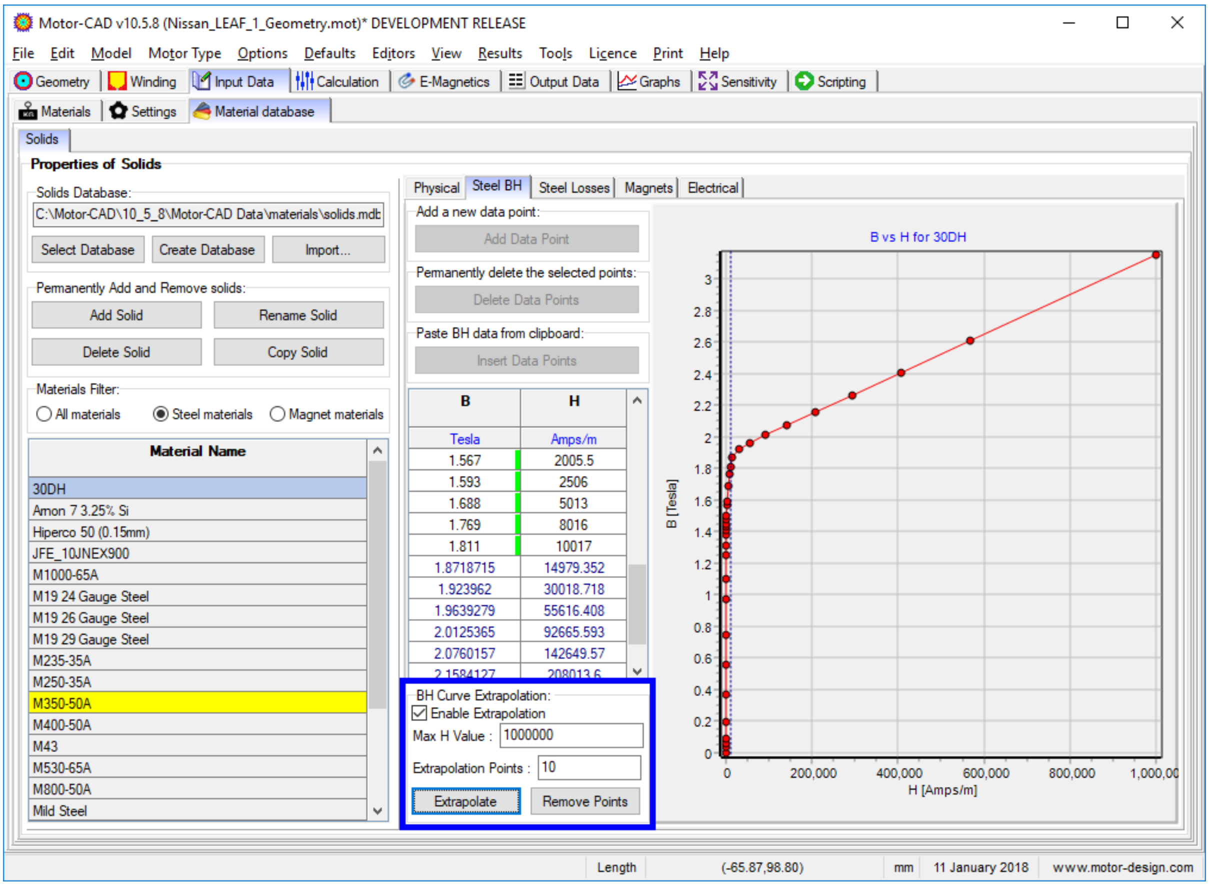
For this example, we already have the data in the correct SI units. Copy the B and H values (without header row) from the file **30DH Steel.xslx** and then paste the data to the table using the **Insert Data Points** button or selecting the first data cell and using **Ctrl+V**. The graph on the right hand side will then update to reflect the data we have added.



In addition to the manufacturer's data, Motor-CAD can estimate further BH points beyond the maximum values of the experimental data typically available. Select the **Enable Extrapolation** option to enable this functionality. Enter a maximum H value which will give a good safety margin for the expected flux density values in the simulation, and select the number of points to provide a good set of data. In this case, the following values are appropriate:

Parameter	Value	Units
Max H Value	1000000	Amps/m
Extrapolation Points	10	

Now click **Extrapolate** and the points are added to the graph and table. Note that the extrapolated values are shown in blue in the table to distinguish from the experimental data, and a vertical blue dotted line on the graph indicates the limit of the experimental data. Also note that the experimental BH values cannot be edited while extrapolation is enabled.

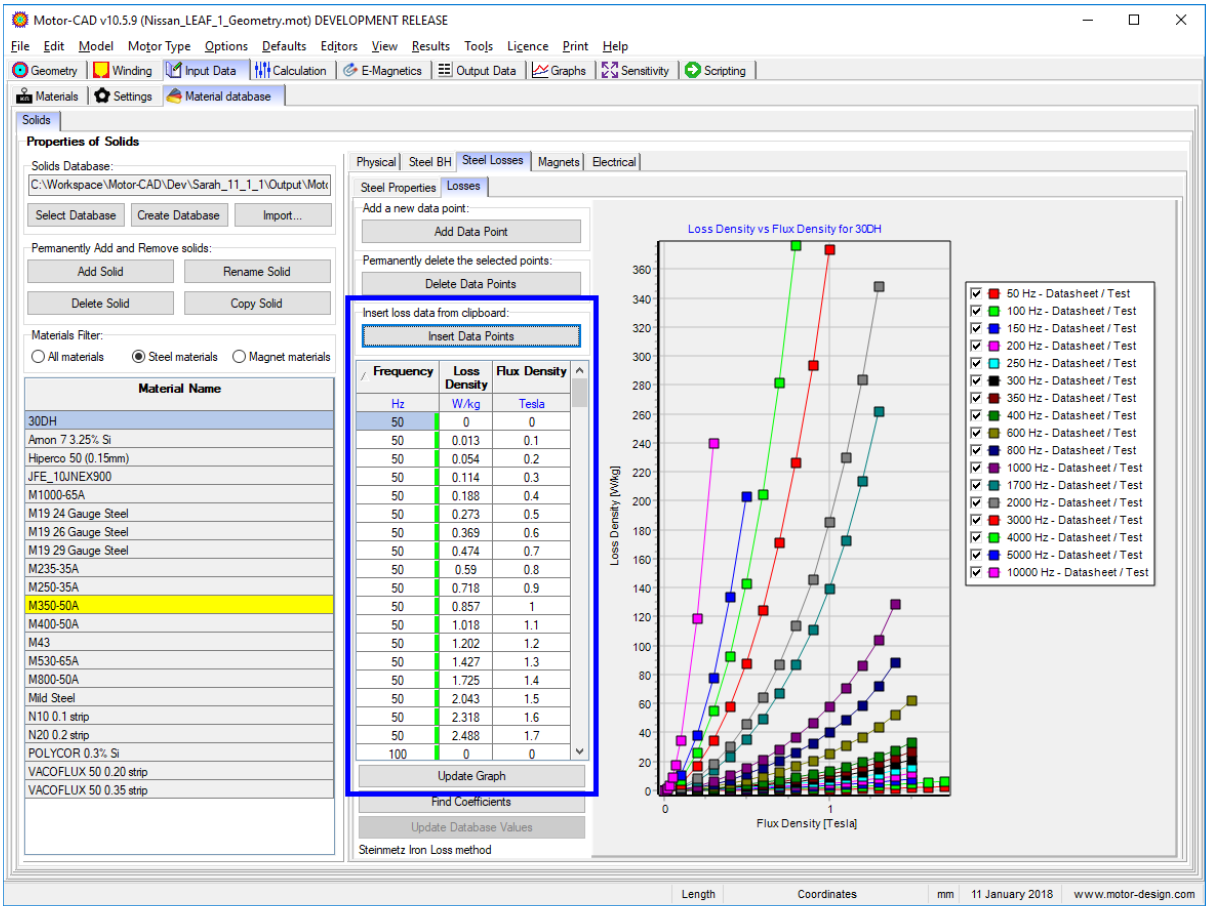


Now we define the iron loss properties of the steel under the **Steel Losses** data.

In Motor-CAD, iron losses are calculated based on loss coefficients, using either the Bertotti or Modified Steinmetz method. The Steinmetz method is used by default; advanced users can select the Bertotti method if required under the **Input Data -> Settings -> Losses** tab. Further information on iron loss calculation methods is provided in the Motor-CAD manual.

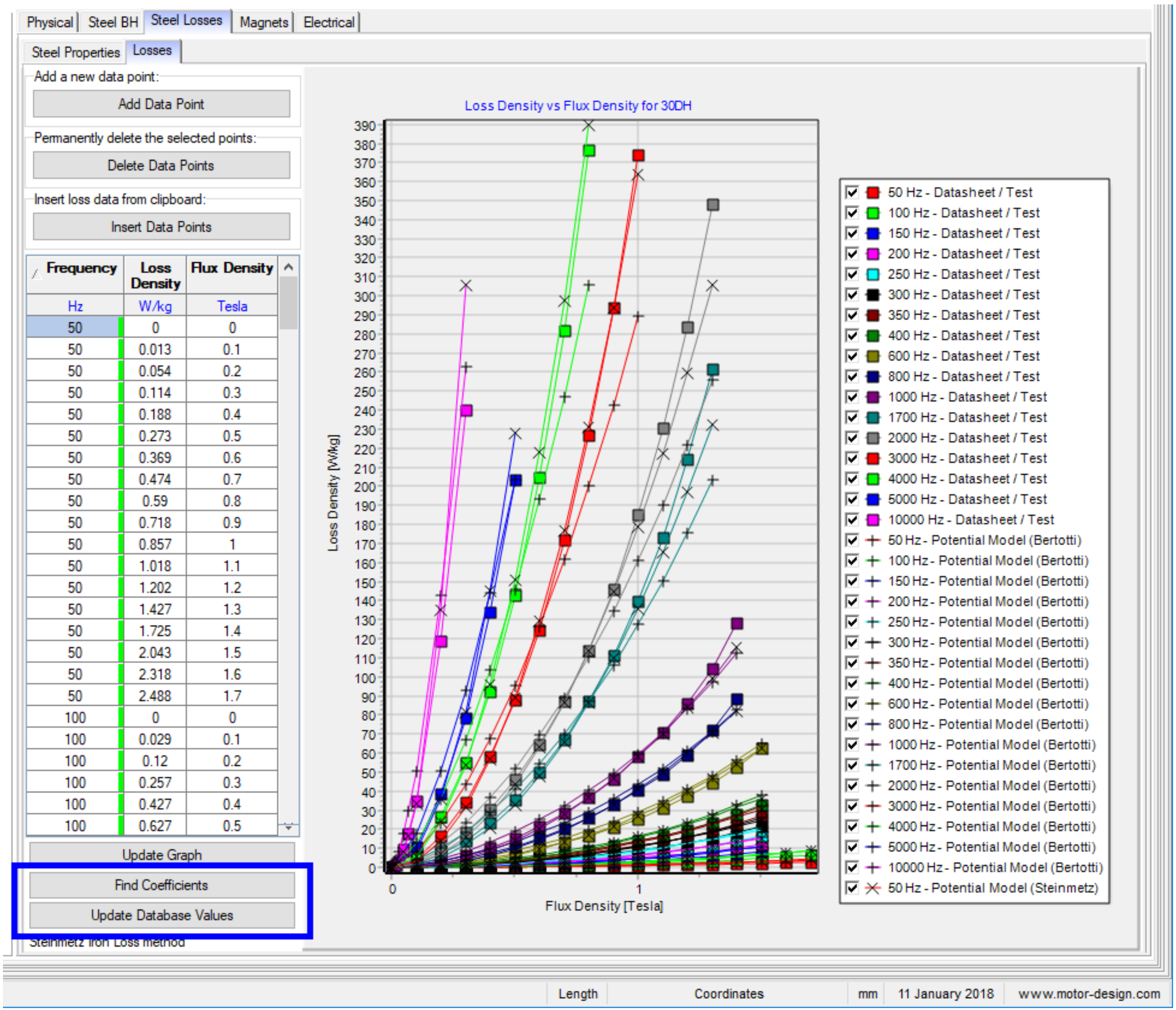
The loss coefficients can be entered manually in the **Steel Properties** tab, or these coefficients can be estimated by Motor-CAD based on experimental values of power loss density at different frequencies and flux densities. Since we have loss data available for the 30DH steel, we will enter the experimental values under the **Losses** tab.

Once again, copy the loss data from the file **30DH Steel.xlsx** (frequency, loss density and B values). Under the **Losses** tab, paste the data to the table using **Insert Data Points** or selecting the first row in the table and using **Ctrl+V**. Click **Update Graph** to update the graph with the new data.



We will now calculate the loss coefficients from the experimental data using Motor-CAD. Click on the **Find Coefficients** button. This uses an iterative curve fitting method to find the iron loss coefficients that best fit the data. This may take several minutes; the progress of the curve fitting is shown in the status bar at the bottom of the Motor-CAD window.

After the curve fitting is complete, additional curves will be displayed on the chart to show the loss models using the calculated coefficients. If we are happy that the potential models match the data well, we select **Update Database Values** to store the calculated coefficients to the database.

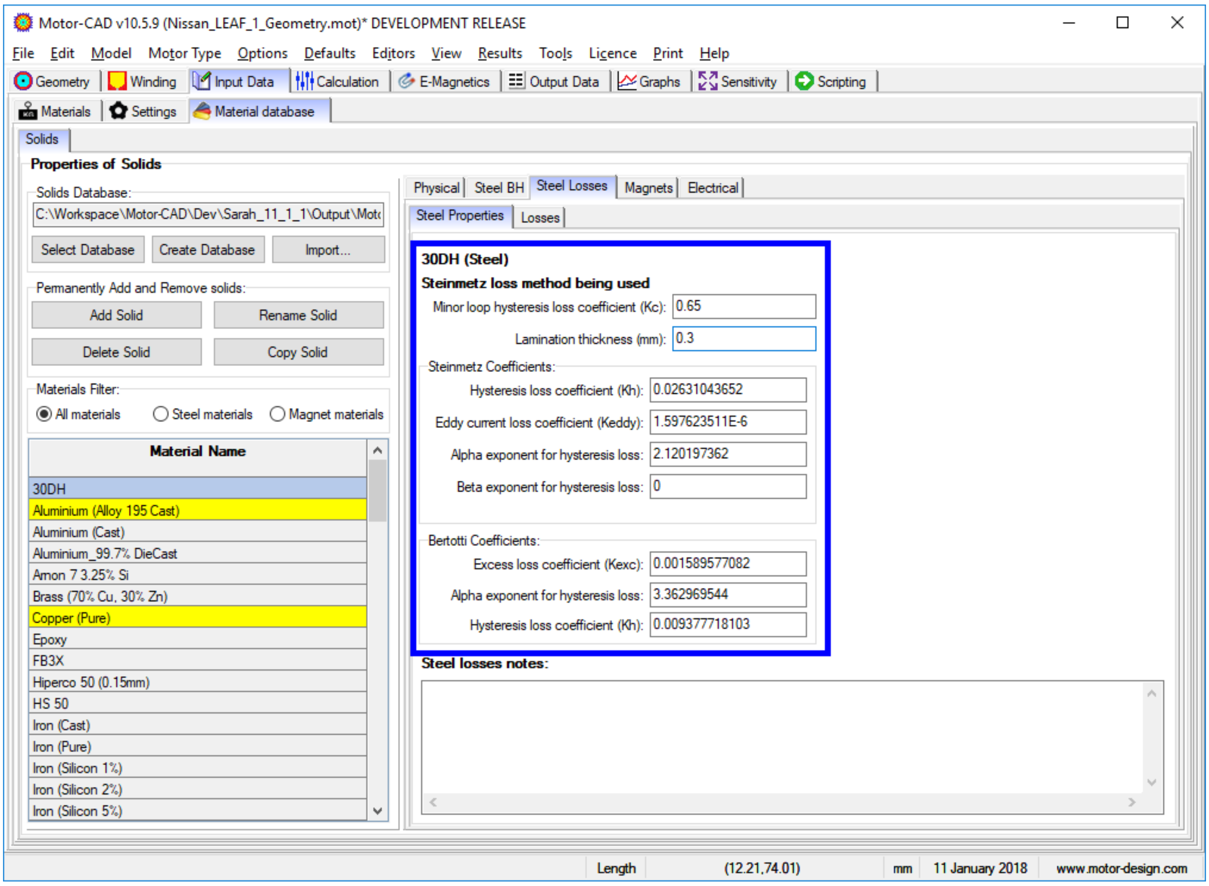


The coefficients calculated can be seen in the **Steel Properties** tab.

Note that the minor loop hysteresis loss coefficient is set to 0.65. This is an empirical value which cannot be calculated and is neglected when extracting other loss coefficients. The default value of 0.65 is chosen based on previous studies and can be edited by the user. Also note that there may be minor differences in the calculated coefficients due to the iterative nature of the calculation.

We also need to specify the lamination thickness of the steel. For the 30DH steel we set:

Parameter	Value	Units
Lamination thickness	0.3	mm



This completes the process of adding the new steel to the materials database. When saving the .mot file, all data relating to the materials used in the model will be contained in the file. In addition, the materials database file can be shared to allow organisations to work from a standard set of materials.

Assigning Component Materials

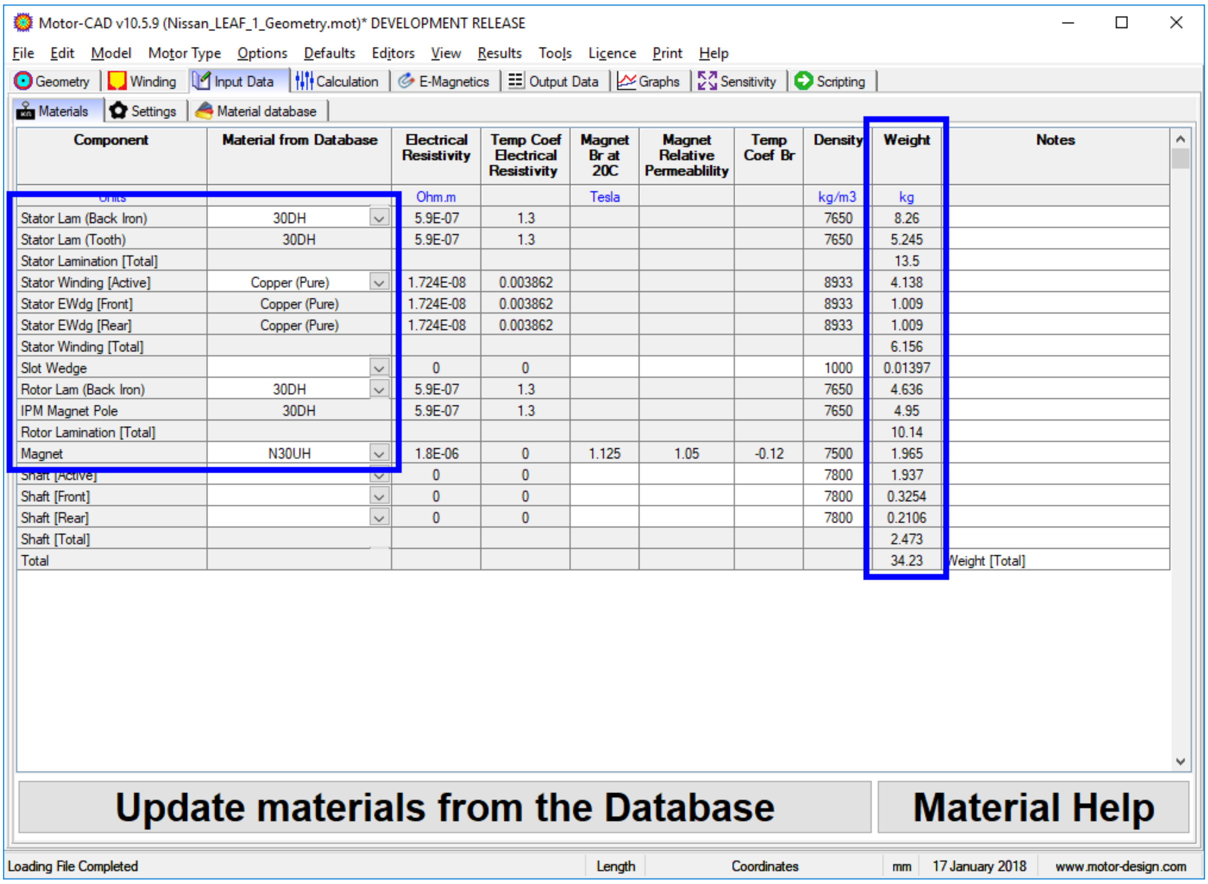
We now select the materials used for each component in the Motor-CAD model under the **Input Data -> Materials** tab. We select the following materials using the material dropdowns:

Component	Material
Stator Lam	30DH
Stator Winding	Copper (Pure)
Rotor Lam	30DH
Magnet	N30UH

The Copper and N30UH materials are already defined in the default Motor-CAD materials database.

Note that, in the electromagnetic model, some components must use the same material, for example the Stator Lam (Back Iron) and Stator Lam (Tooth). This is because the electromagnetic model simulates these components together in a single region. Later, in the thermal context, we will see that it is possible to specify different materials for these components for the thermal model only.

This table also shows the calculated weights of all the components in the electromagnetic design. We can check the total weight to ensure that the geometry and materials have been set up correctly.



Component	Material from Database	Electrical Resistivity	Temp Coef Electrical Resistivity	Magnet Br at 20C	Magnet Relative Permeablility	Temp Coef Br	Density	Weight	Notes
Units		Ohm.m		Tesla			kg/m3	kg	
Stator Lam (Back Iron)	30DH	5.9E-07	1.3				7650	8.26	
Stator Lam (Tooth)	30DH	5.9E-07	1.3				7650	5.245	
Stator Lamination [Total]								13.5	
Stator Winding [Active]	Copper (Pure)	1.724E-08	0.003862				8933	4.138	
Stator EWdg [Front]	Copper (Pure)	1.724E-08	0.003862				8933	1.009	
Stator EWdg [Rear]	Copper (Pure)	1.724E-08	0.003862				8933	1.009	
Stator Winding [Total]								6.156	
Slot Wedge		0	0				1000	0.01397	
Rotor Lam (Back Iron)	30DH	5.9E-07	1.3				7650	4.636	
IPM Magnet Pole	30DH	5.9E-07	1.3				7650	4.95	
Rotor Lamination [Total]								10.14	
Magnet	N30UH	1.8E-06	0	1.125	1.05	-0.12	7500	1.965	
Shaft [Active]		0	0				7800	1.937	
Shaft [Front]		0	0				7800	0.3254	
Shaft [Rear]		0	0				7800	0.2106	
Shaft [Total]								2.473	
Total								34.23	Weight [Total]

Now save the file again with **File -> Save** or **Ctrl+S**.

4. Electromagnetic Analysis

The E-Magnetic module in Motor-CAD allows 2D FEA electromagnetic analysis and loss calculation to obtain the working conditions and performance of the machine. It also has an automatic link to the thermal model in Motor-CAD for subsequent thermal analysis.

Save the file as **Nissan_LEAF_2_Electromagnetic.mot**.

i. FEA Simulations in Motor-CAD

The **Calculation** tab is where the operating conditions and simulations to run are selected. There are many different electromagnetic FEA calculations which can be performed in Motor-CAD. For a detailed description of the performance tests available, please refer to the Motor-CAD manual.

On the left part of the tab we specify the operating conditions for the tests: shaft speed, current, phase advance (for on load tests) and DC bus voltage. The voltage specified here is used to find the voltage available to the motor from the DC bus. During operation this is compared to the voltage required by the motor and a warning is given if there is insufficient voltage available.

Note that the Motor-CAD E-Magnetic module will not limit the operating point to within the voltage limit. It will give a warning and then it is up to the user to modify the operating point or increase the DC bus voltage.

The winding temperature is used to calculate the electrical resistance of the winding from the dimensions and the winding configuration. The magnet temperature defines the remanence of the magnets from the thermal coefficient in the materials database. For more details on these calculations, please refer to the Motor-CAD manual.

The E-Magnetics – Thermal coupling options allow the user to transfer data between Motor-CAD's E-Magnetic and Thermal modules. The losses calculated in the e-magnetic solution can be passed to the thermal module and machine temperatures from the solved thermal model can be passed to the e-magnetic module for more accurate performance and loss calculations. These values can be transferred in either direction as a single step or Motor-CAD can iteratively solve the e-magnetic and thermal models together until the power losses and temperatures converge.

We can also specify the drive mode, winding connection, magnetisation direction of the magnets, and stator or rotor skew.

We set the following operating conditions:

Parameter	Value	Units
Shaft Speed	3000	RPM
Line Current Definition	Peak	
Peak Current	480	A
DC Bus Voltage	375	V
Phase Advance	45	Elec deg

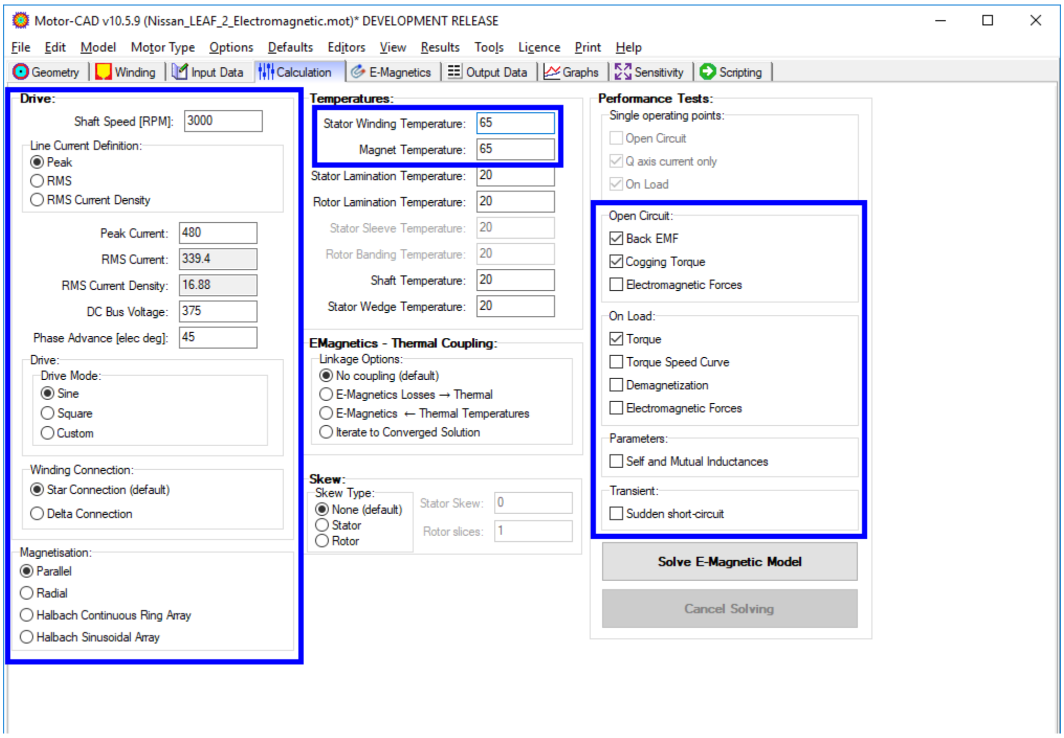
We also set the drive, connection and magnetisation options:

Parameter	Value	Units
Drive Mode	Sine	
Winding Connection	Star Connection	
Magnetisation	Parallel	

At this point we will use a rough estimate of the magnet and stator winding temperatures. These temperatures can significantly affect the performance of the machine, so it is best to give an estimate here. The other component temperatures are not so crucial so we will leave these at their default values. We can get a good first estimate of the machine behaviour using these values and then refine the model later based on the thermal calculations. Set the following:

Parameter	Value	Units
Stator Winding Temperature	65	°C
Magnet Temperature	65	°C

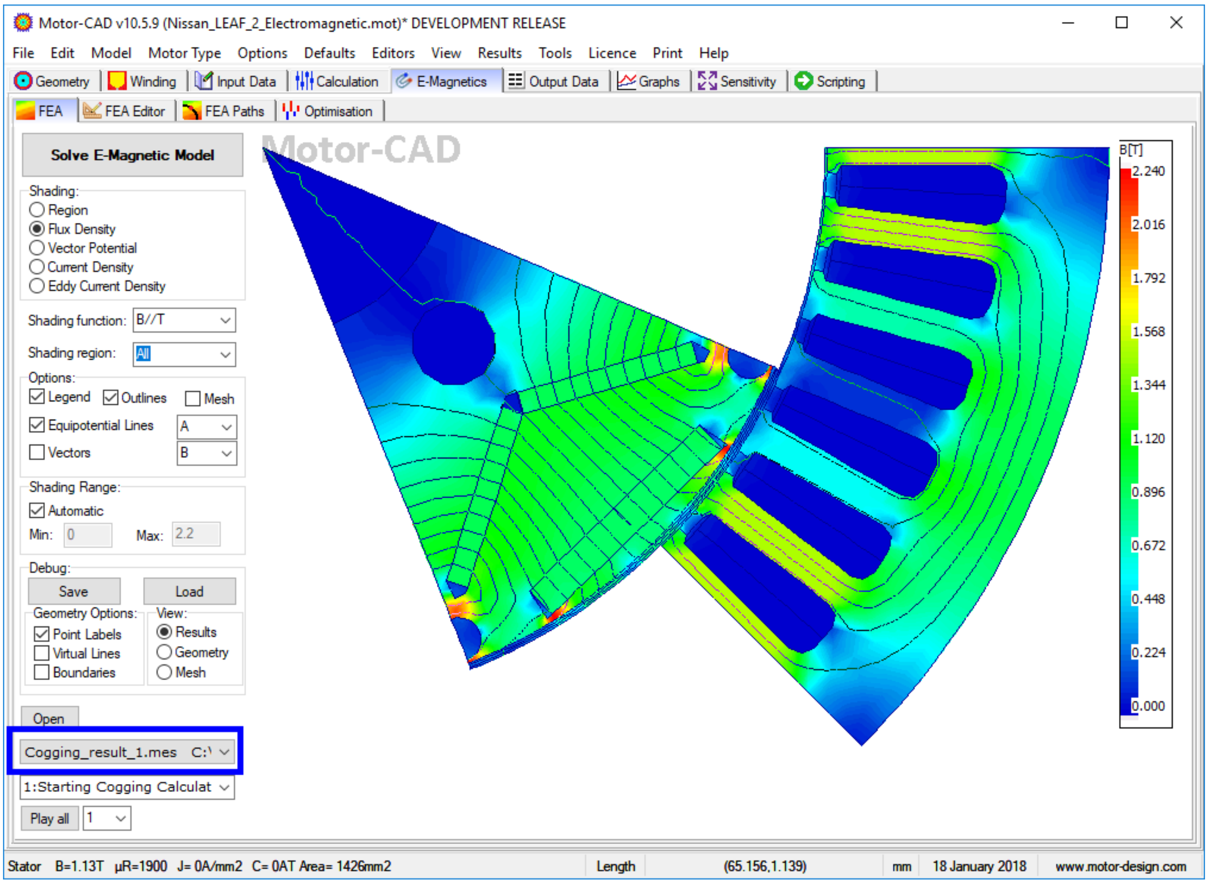
All the performance tests except for the **Back EMF, Cogging Torque** and **Torque** calculations should be disabled. The simulation is then run by clicking the **Solve E-Magnetic Model** button. The simulation should complete within 1 minute.



ii. Results

FEA Plots

The **E-Magnetics -> FEA** tab shows the FEA geometry, mesh and results while simulations are being solved, and after the solution is completed.



A separate results file is generated for each calculation, including the single operating points that are always simulated regardless of the performance tests selected by the users. The results for each calculation can be viewed by selecting the results file from the dropdown list in the left hand pane as highlighted above.

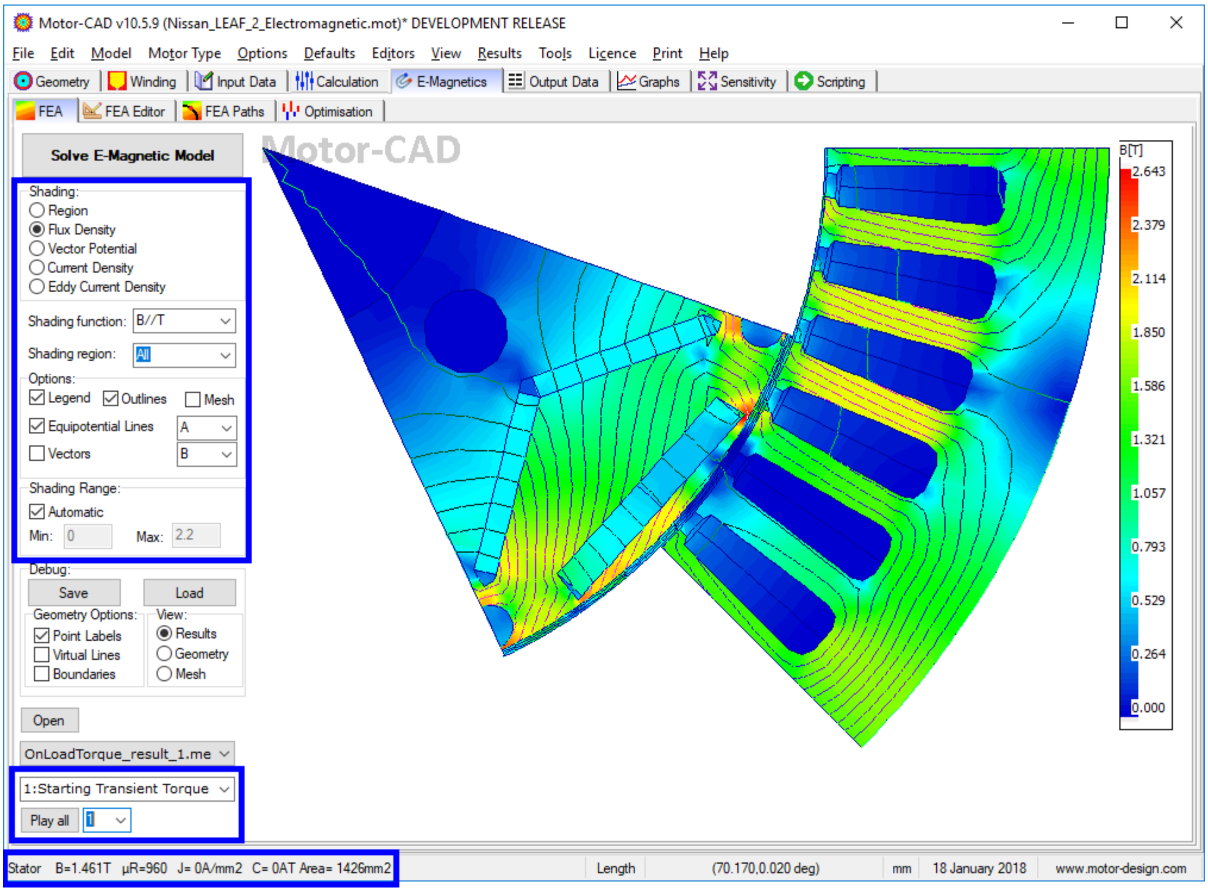
The results available will depend on which performance tests have been run, and also on more advanced simulation settings e.g. magnetic solver type. For this example, we have the following result files to choose from:

File	Description
Cogging	**Cogging Torque** calculation
On Load Torque	On load transient torque (**Torque** calculation)
On Load Loss	Loss calculation from on load transient torque (**Torque** calculation)
Static OC	Single point no load (**Q Axis current** calculation – always performed)
Open Circuit Transient	Open circuit transient (**Back EMF** calculation)
Open Circuit Loss	Loss calculation from open circuit transient (**Back EMF** calculation)
Static Load	Single point on load (**On Load** calculation – always performed)

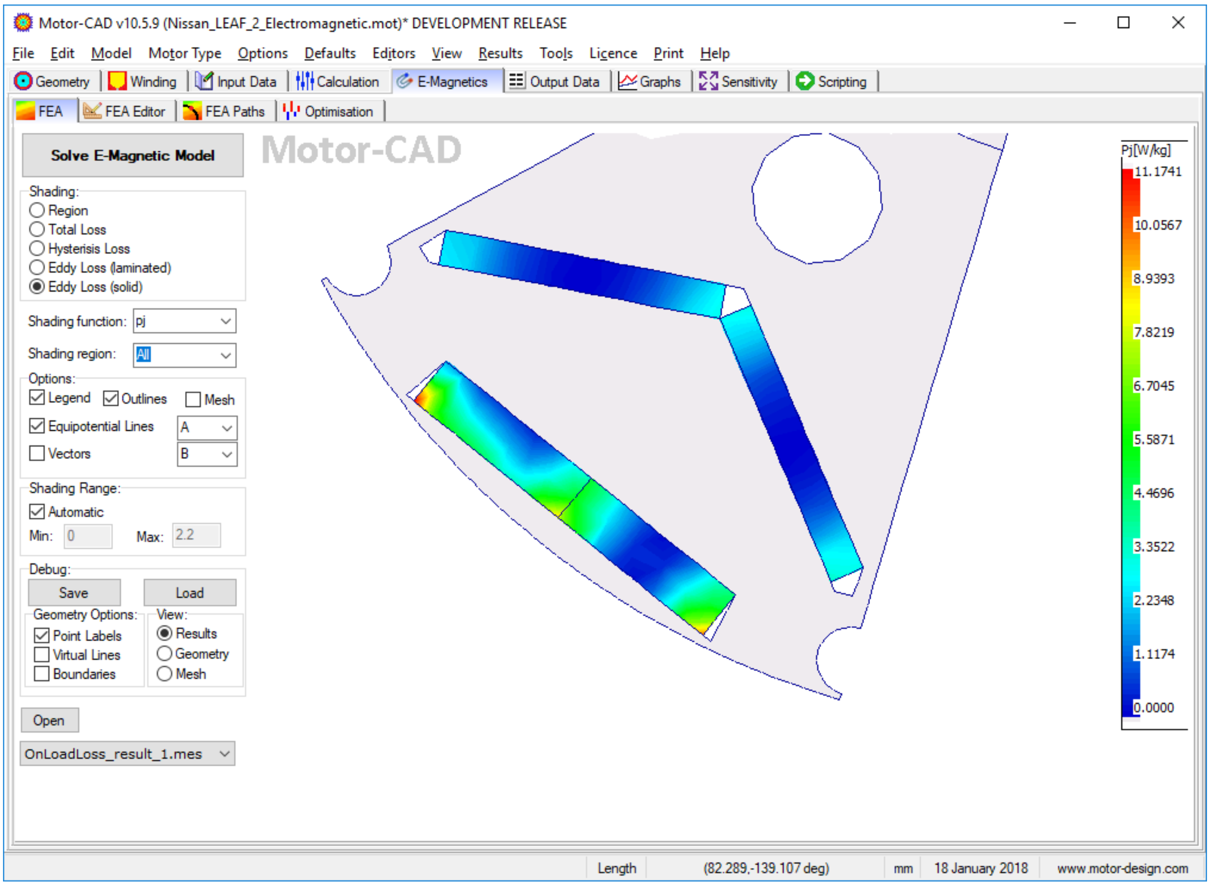
Select **OnLoadTorque_result_1.mes** from the dropdown to view the results from the transient torque simulation. The **Shading** options now allow us to choose the quantity that is displayed on the FEA plot, alternatively different quantities can be selected from the **Shading function** dropdown. Select **Flux Density** to view the flux in the machine.

For each time step during the transient simulation we have a different flux plot. We can view the results at particular time steps by selecting the time or step number from the dropdown menu or use the **Play all** button to view an animation of the flux over time. The plot can also be customised with the **Options** settings.

When the mouse is hovered over the plot, detailed information about the point under the mouse cursor is shown in the status bar. This includes the region name, flux density, permeability, and region area.



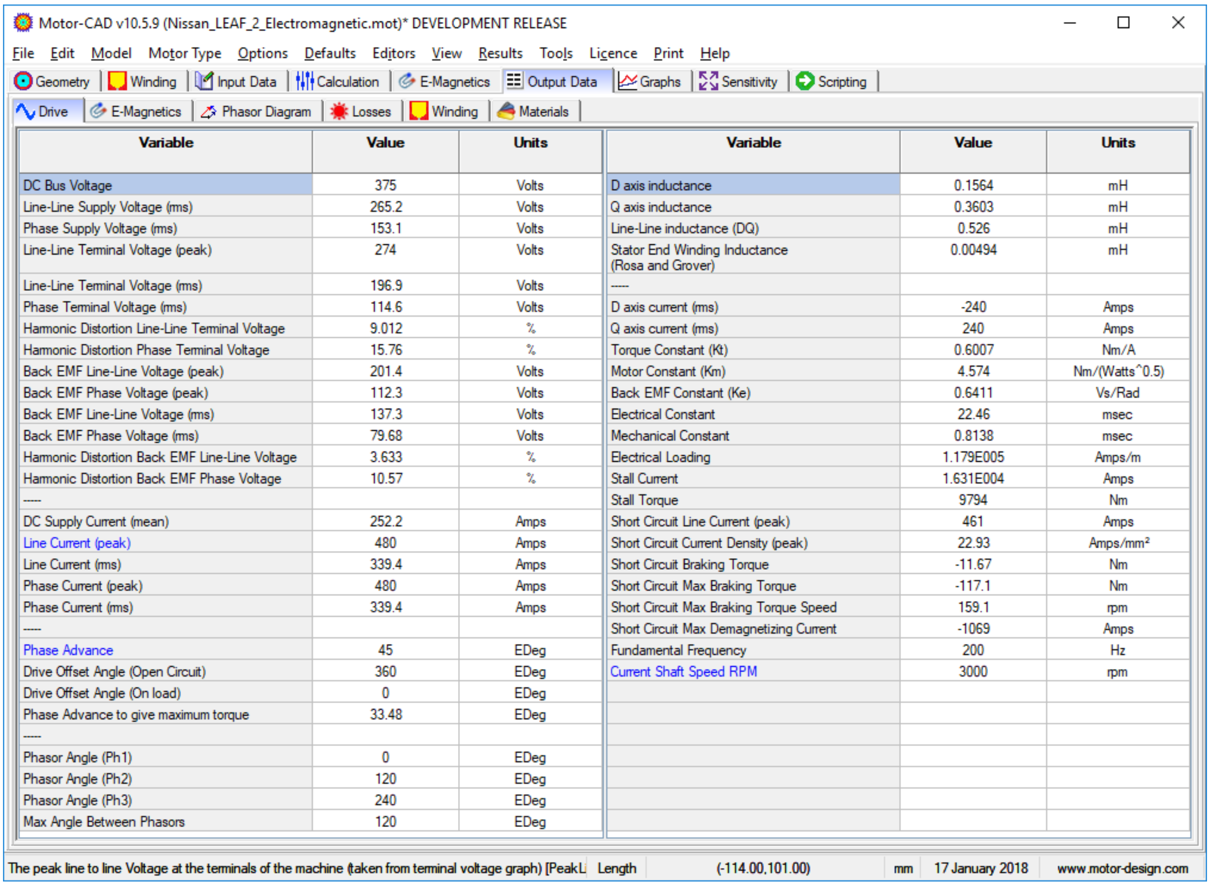
It can also be useful to visualise the losses in the machine. From the file dropdown, select **OnLoadLoss_result_1.mes** to open the loss results from the transient torque calculation. Note that there are no time step controls available since the losses are calculated over the full electrical cycle. Here we can use the **Shading** option to view different types of loss. For example, by selecting **Eddy Loss (solid)** we can see the distribution of eddy current losses in the magnets, noticing that the losses are concentrated in the magnet corners and so these areas could be prone to thermal hotspots.



Note that previously calculated flux plots can also be loaded into the FEA viewer using the **Open** button.

Output Data Sheets

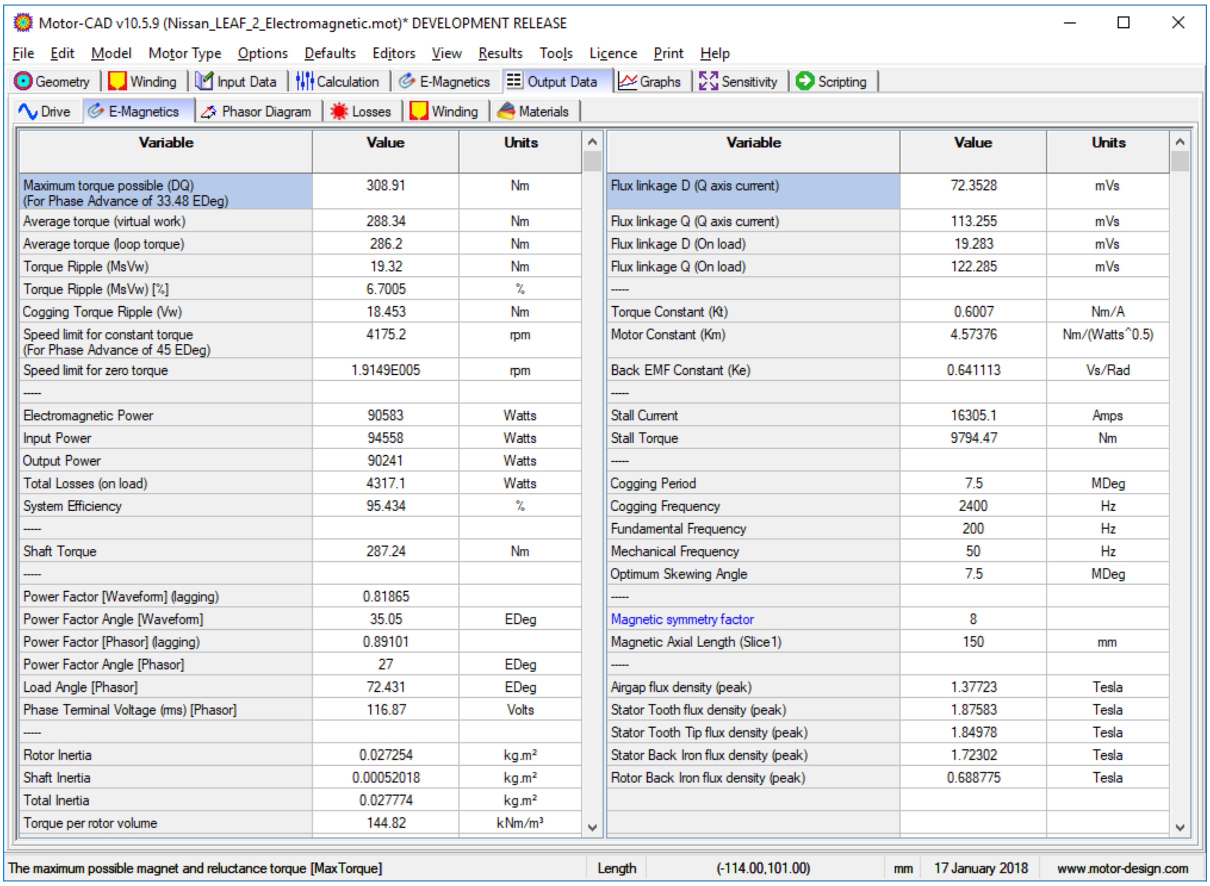
The **Output Data** sheets provide detailed numerical information on the machine showing many different parameters calculated by Motor-CAD. For further information on any of the output parameters, please refer to the Motor-CAD manual.



Variable	Value	Units	Variable	Value	Units
DC Bus Voltage	375	Volts	D axis inductance	0.1564	mH
Line-Line Supply Voltage (rms)	265.2	Volts	Q axis inductance	0.3603	mH
Phase Supply Voltage (rms)	153.1	Volts	Line-Line inductance (DQ)	0.526	mH
Line-Line Terminal Voltage (peak)	274	Volts	Stator End Winding Inductance (Rosa and Grover)	0.00494	mH
Line-Line Terminal Voltage (rms)	196.9	Volts	-----		
Phase Terminal Voltage (rms)	114.6	Volts	D axis current (rms)	-240	Amps
Harmonic Distortion Line-Line Terminal Voltage	9.012	%	Q axis current (rms)	240	Amps
Harmonic Distortion Phase Terminal Voltage	15.76	%	Torque Constant (Kt)	0.6007	Nm/A
Back EMF Line-Line Voltage (peak)	201.4	Volts	Motor Constant (Km)	4.574	Nm/(Watts^0.5)
Back EMF Phase Voltage (peak)	112.3	Volts	Back EMF Constant (Ke)	0.6411	Vs/Rad
Back EMF Line-Line Voltage (rms)	137.3	Volts	Electrical Constant	22.46	msec
Back EMF Phase Voltage (rms)	79.68	Volts	Mechanical Constant	0.8138	msec
Harmonic Distortion Back EMF Line-Line Voltage	3.633	%	Electrical Loading	1.179E005	Amps/m
Harmonic Distortion Back EMF Phase Voltage	10.57	%	Stall Current	1.631E004	Amps
-----			Stall Torque	9794	Nm
DC Supply Current (mean)	252.2	Amps	Short Circuit Line Current (peak)	461	Amps
Line Current (peak)	480	Amps	Short Circuit Current Density (peak)	22.93	Amps/mm²
Line Current (rms)	339.4	Amps	Short Circuit Braking Torque	-11.67	Nm
Phase Current (peak)	480	Amps	Short Circuit Max Braking Torque	-117.1	Nm
Phase Current (rms)	339.4	Amps	Short Circuit Max Braking Torque Speed	159.1	rpm
-----			Short Circuit Max Demagnetizing Current	-1069	Amps
Phase Advance	45	EDeg	Fundamental Frequency	200	Hz
Drive Offset Angle (Open Circuit)	360	EDeg	Current Shaft Speed RPM	3000	rpm
Drive Offset Angle (On load)	0	EDeg			
Phase Advance to give maximum torque	33.48	EDeg			

Phasor Angle (Ph1)	0	EDeg			
Phasor Angle (Ph2)	120	EDeg			
Phasor Angle (Ph3)	240	EDeg			
Max Angle Between Phasors	120	EDeg			

Motor Design Limited



Motor-CAD v10.5.9 (Nissan_LEAF_2_Electromagnetic.mot)* DEVELOPMENT RELEASE

File Edit Model Motor Type Options Defaults Editors View Results Tools Licence Print Help

Geometry | Winding | Input Data | Calculation | E-Magnetics | Output Data | Graphs | Sensitivity | Scripting

Drive | E-Magnetics | Phasor Diagram | Losses | Winding | Materials

Variable	Value	Units
Maximum torque possible (DQ) (For Phase Advance of 33.48 EDeg)	308.91	Nm
Average torque (virtual work)	288.34	Nm
Average torque (loop torque)	286.2	Nm
Torque Ripple (MsVw)	19.32	Nm
Torque Ripple (MsVw) [%]	6.7005	%
Cogging Torque Ripple (Vw)	18.453	Nm
Speed limit for constant torque (For Phase Advance of 45 EDeg)	4175.2	rpm
Speed limit for zero torque	1.9149E005	rpm

Electromagnetic Power	90583	Watts
Input Power	94558	Watts
Output Power	90241	Watts
Total Losses (on load)	4317.1	Watts
System Efficiency	95.434	%

Shaft Torque	287.24	Nm

Power Factor [Waveform] (lagging)	0.81865	
Power Factor Angle [Waveform]	35.05	EDeg
Power Factor [Phasor] (lagging)	0.89101	
Power Factor Angle [Phasor]	27	EDeg
Load Angle [Phasor]	72.431	EDeg
Phase Terminal Voltage (rms) [Phasor]	116.87	Volts

Rotor Inertia	0.027254	kg.m²
Shaft Inertia	0.00052018	kg.m²
Total Inertia	0.027774	kg.m²
Torque per rotor volume	144.82	kNm/m³

Variable	Value	Units
Flux linkage D (Q axis current)	72.3528	mVs
Flux linkage Q (Q axis current)	113.255	mVs
Flux linkage D (On load)	19.283	mVs
Flux linkage Q (On load)	122.285	mVs

Torque Constant (Kt)	0.6007	Nm/A
Motor Constant (Km)	4.57376	Nm/(Watts^0.5)
Back EMF Constant (Ke)	0.641113	Vs/Rad

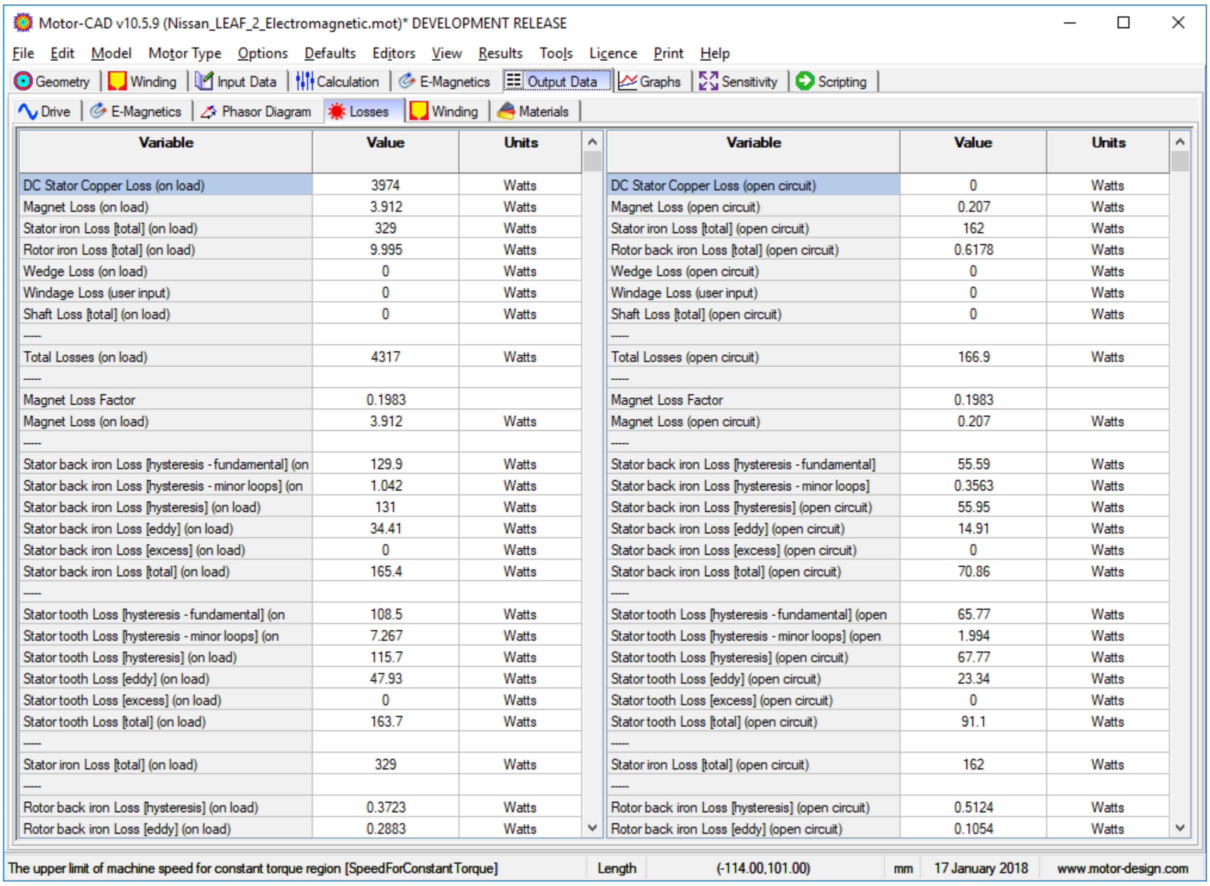
Stall Current	16305.1	Amps
Stall Torque	9794.47	Nm

Cogging Period	7.5	MDeg
Cogging Frequency	2400	Hz
Fundamental Frequency	200	Hz
Mechanical Frequency	50	Hz
Optimum Skewing Angle	7.5	MDeg

Magnetic symmetry factor	8	
Magnetic Axial Length (Slice1)	150	mm

Airgap flux density (peak)	1.37723	Tesla
Stator Tooth flux density (peak)	1.87583	Tesla
Stator Tooth Tip flux density (peak)	1.84978	Tesla
Stator Back Iron flux density (peak)	1.72302	Tesla
Rotor Back Iron flux density (peak)	0.688775	Tesla

The maximum possible magnet and reluctance torque [MaxTorque] | Length | (-114.00,101.00) | mm | 17 January 2018 | www.motor-design.com



Motor-CAD v10.5.9 (Nissan_LEAF_2_Electromagnetic.mot)* DEVELOPMENT RELEASE

File Edit Model Motor Type Options Defaults Editors View Results Tools Licence Print Help

Geometry | Winding | Input Data | Calculation | E-Magnetics | Output Data | Graphs | Sensitivity | Scripting

Drive | E-Magnetics | Phasor Diagram | Losses | Winding | Materials

Variable	Value	Units
DC Stator Copper Loss (on load)	3974	Watts
Magnet Loss (on load)	3.912	Watts
Stator iron Loss [total] (on load)	329	Watts
Rotor iron Loss [total] (on load)	9.995	Watts
Wedge Loss (on load)	0	Watts
Windage Loss (user input)	0	Watts
Shaft Loss [total] (on load)	0	Watts

Total Losses (on load)	4317	Watts

Magnet Loss Factor	0.1983	
Magnet Loss (on load)	3.912	Watts

Stator back iron Loss [hysteresis - fundamental] (on	129.9	Watts
Stator back iron Loss [hysteresis - minor loops] (on	1.042	Watts
Stator back iron Loss [hysteresis] (on load)	131	Watts
Stator back iron Loss [eddy] (on load)	34.41	Watts
Stator back iron Loss [excess] (on load)	0	Watts
Stator back iron Loss [total] (on load)	165.4	Watts

Stator tooth Loss [hysteresis - fundamental] (on	108.5	Watts
Stator tooth Loss [hysteresis - minor loops] (on	7.267	Watts
Stator tooth Loss [hysteresis] (on load)	115.7	Watts
Stator tooth Loss [eddy] (on load)	47.93	Watts
Stator tooth Loss [excess] (on load)	0	Watts
Stator tooth Loss [total] (on load)	163.7	Watts

Stator iron Loss [total] (on load)	329	Watts

Rotor back iron Loss [hysteresis] (on load)	0.3723	Watts
Rotor back iron Loss [eddy] (on load)	0.2883	Watts

Variable	Value	Units
DC Stator Copper Loss (open circuit)	0	Watts
Magnet Loss (open circuit)	0.207	Watts
Stator iron Loss [total] (open circuit)	162	Watts
Rotor back iron Loss [total] (open circuit)	0.6178	Watts
Wedge Loss (open circuit)	0	Watts
Windage Loss (user input)	0	Watts
Shaft Loss [total] (open circuit)	0	Watts

Total Losses (open circuit)	166.9	Watts

Magnet Loss Factor	0.1983	
Magnet Loss (open circuit)	0.207	Watts

Stator back iron Loss [hysteresis - fundamental]	55.59	Watts
Stator back iron Loss [hysteresis - minor loops]	0.3563	Watts
Stator back iron Loss [hysteresis] (open circuit)	55.95	Watts
Stator back iron Loss [eddy] (open circuit)	14.91	Watts
Stator back iron Loss [excess] (open circuit)	0	Watts
Stator back iron Loss [total] (open circuit)	70.86	Watts

Stator tooth Loss [hysteresis - fundamental] (open	65.77	Watts
Stator tooth Loss [hysteresis - minor loops] (open	1.994	Watts
Stator tooth Loss [hysteresis] (open circuit)	67.77	Watts
Stator tooth Loss [eddy] (open circuit)	23.34	Watts
Stator tooth Loss [excess] (open circuit)	0	Watts
Stator tooth Loss [total] (open circuit)	91.1	Watts

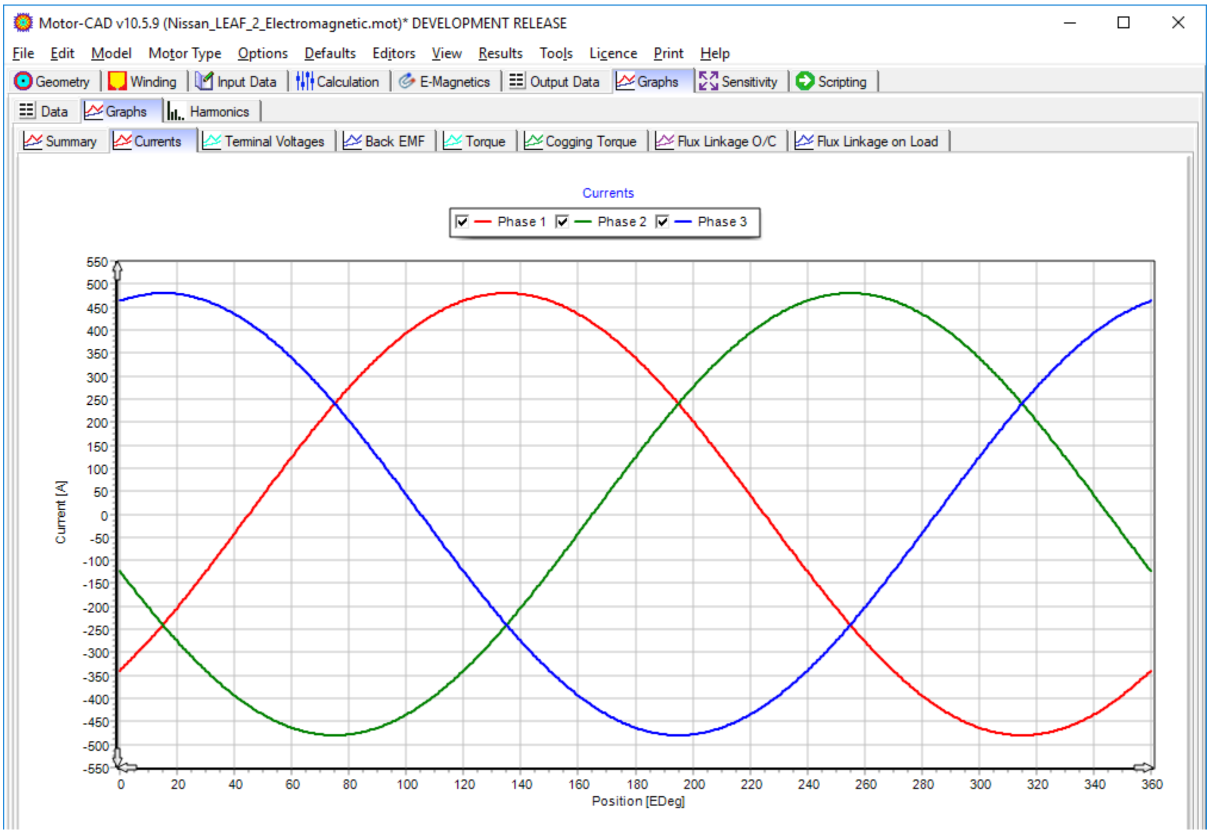
Stator iron Loss [total] (open circuit)	162	Watts

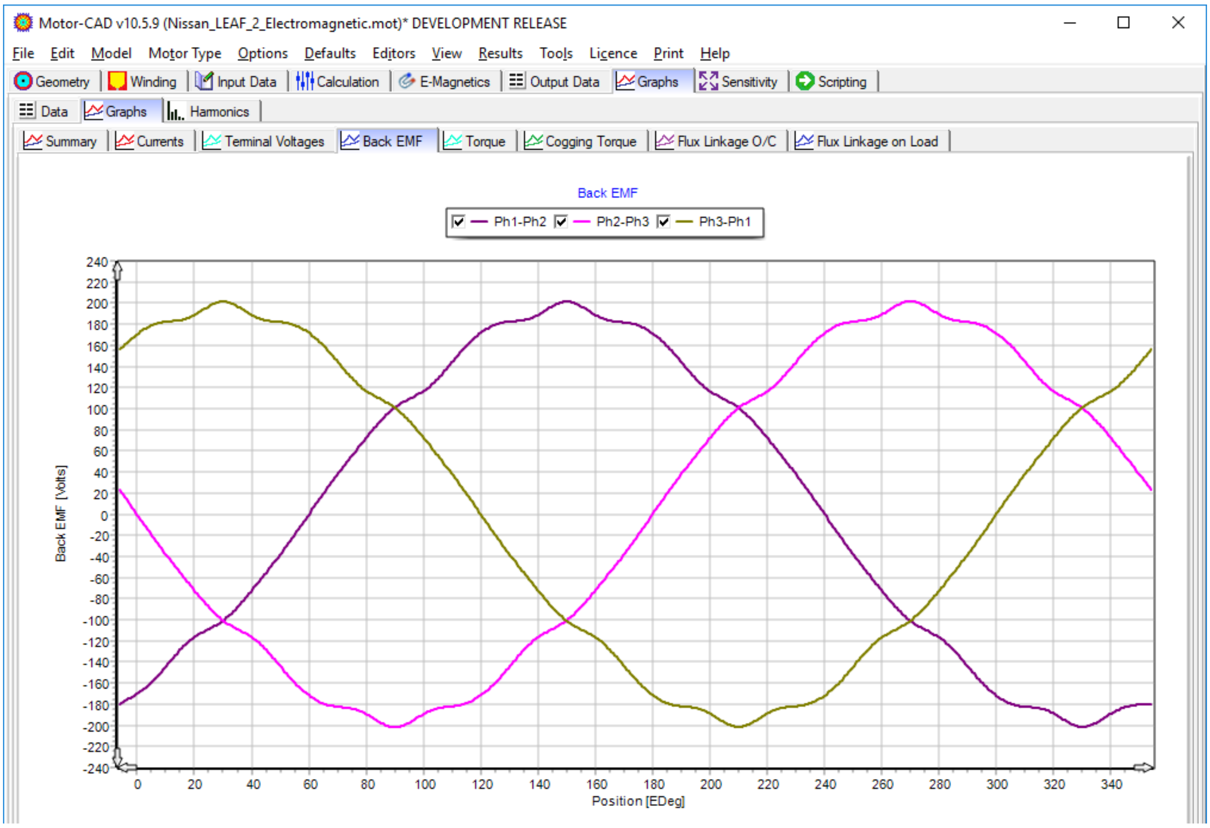
Rotor back iron Loss [hysteresis] (open circuit)	0.5124	Watts
Rotor back iron Loss [eddy] (open circuit)	0.1054	Watts

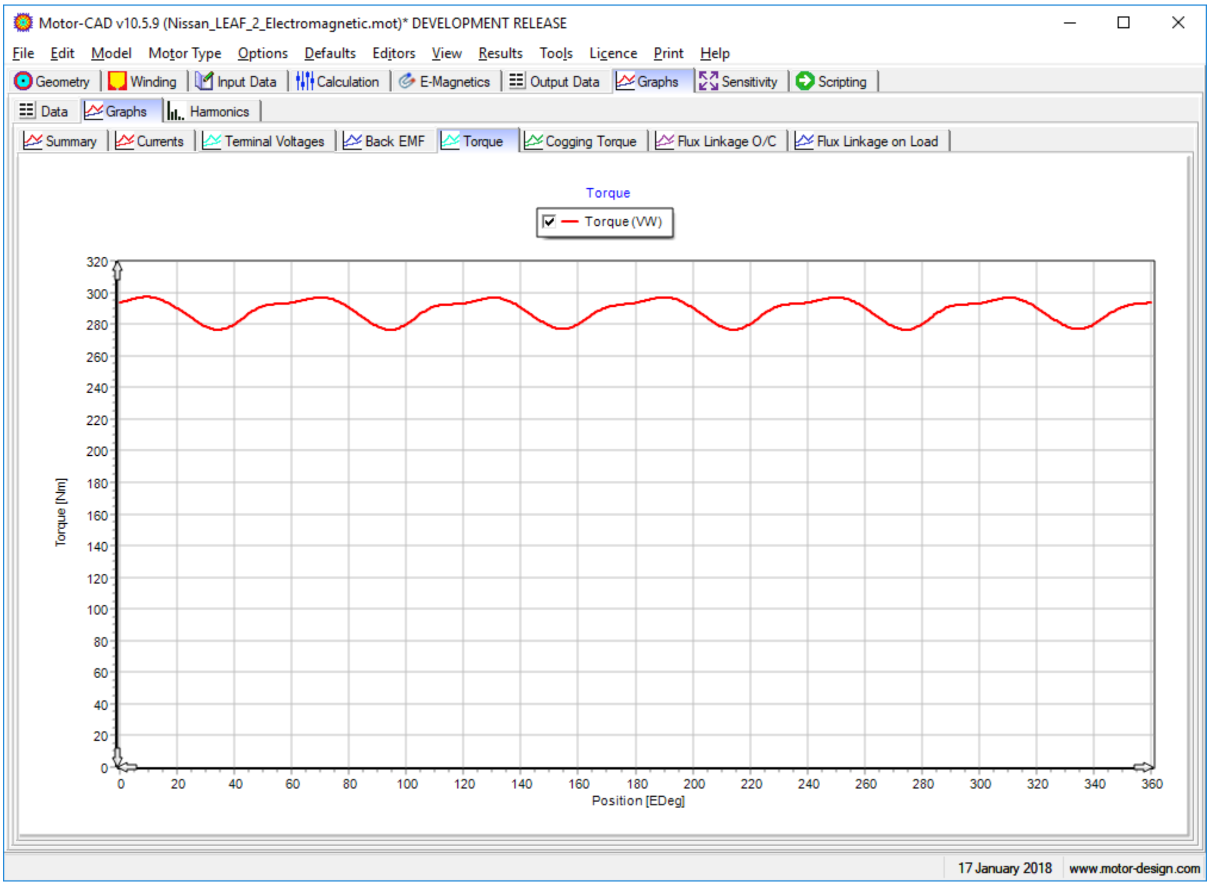
The upper limit of machine speed for constant torque region [SpeedForConstantTorque] | Length | (-114.00,101.00) | mm | 17 January 2018 | www.motor-design.com

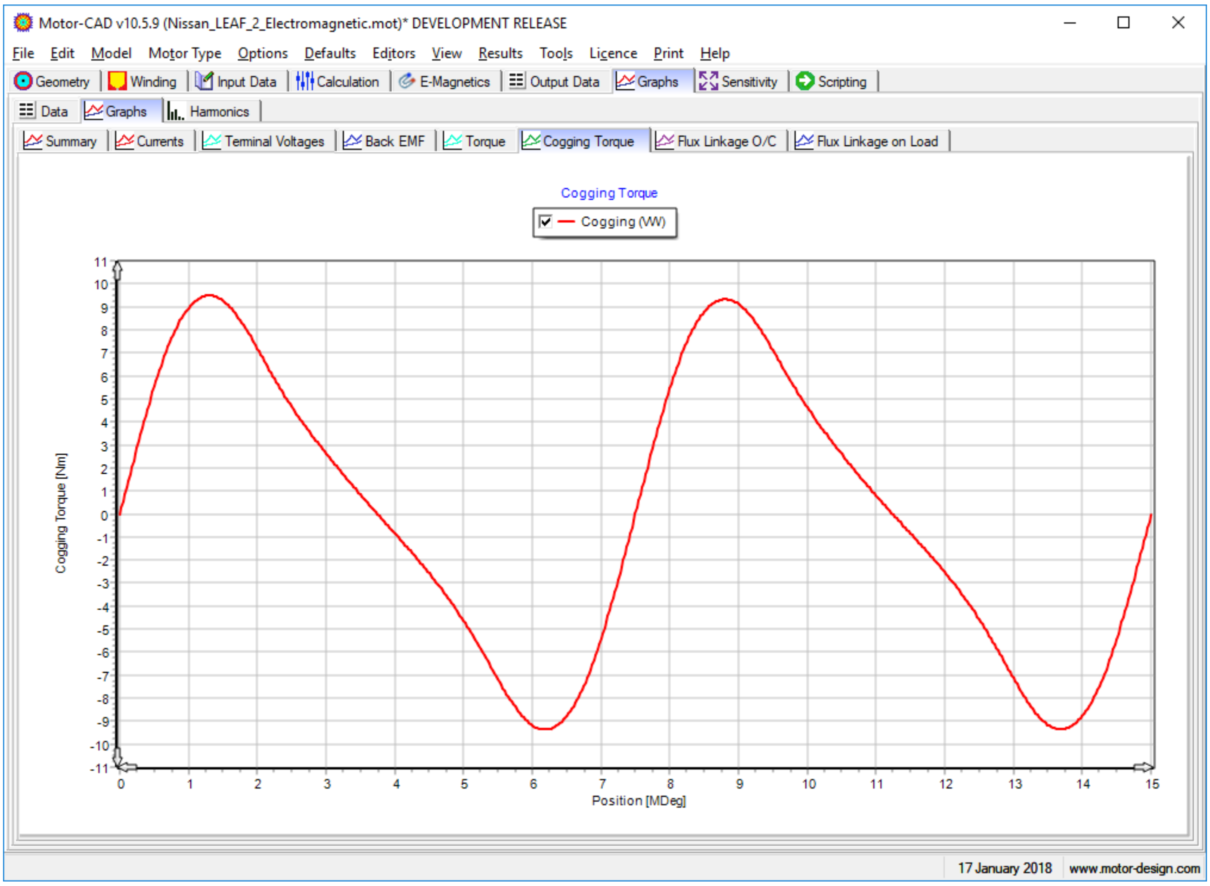
Graphs

The resulting waveforms from the simulation can be viewed in the **Graphs** tab.






Motor-CAD v10.5.9 (Nissan_LEAF_2_Electromagnetic.mot)* DEVELOPMENT RELEASE
File Edit Model Motor Type Options Defaults Editors View Results Tools Licence Print Help
Geometry Winding Input Data Calculation E-Magnetics Output Data Graphs Sensitivity Scripting
Data Graphs Harmonics
Summary Currents Terminal Voltages Back EMF Torque Cogging Torque Flux Linkage O/C Flux Linkage on Load
Torque
Torque (VW)
Torque [Nm]
Position [EDeg]
17 January 2018
www.motor-design.com


Motor-CAD v10.5.9 (Nissan_LEAF_2_Electromagnetic.mot)* DEVELOPMENT RELEASE
File Edit Model Motor Type Options Defaults Editors View Results Tools Licence Print Help
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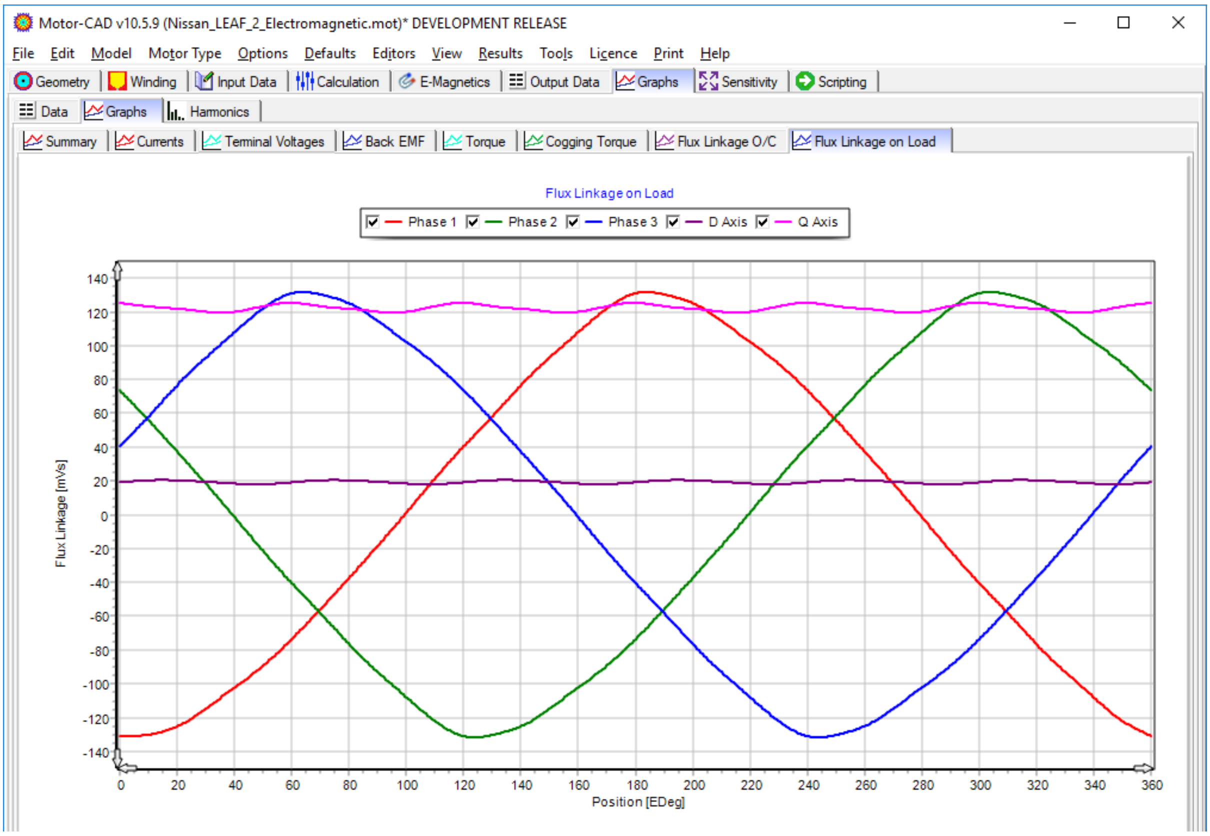
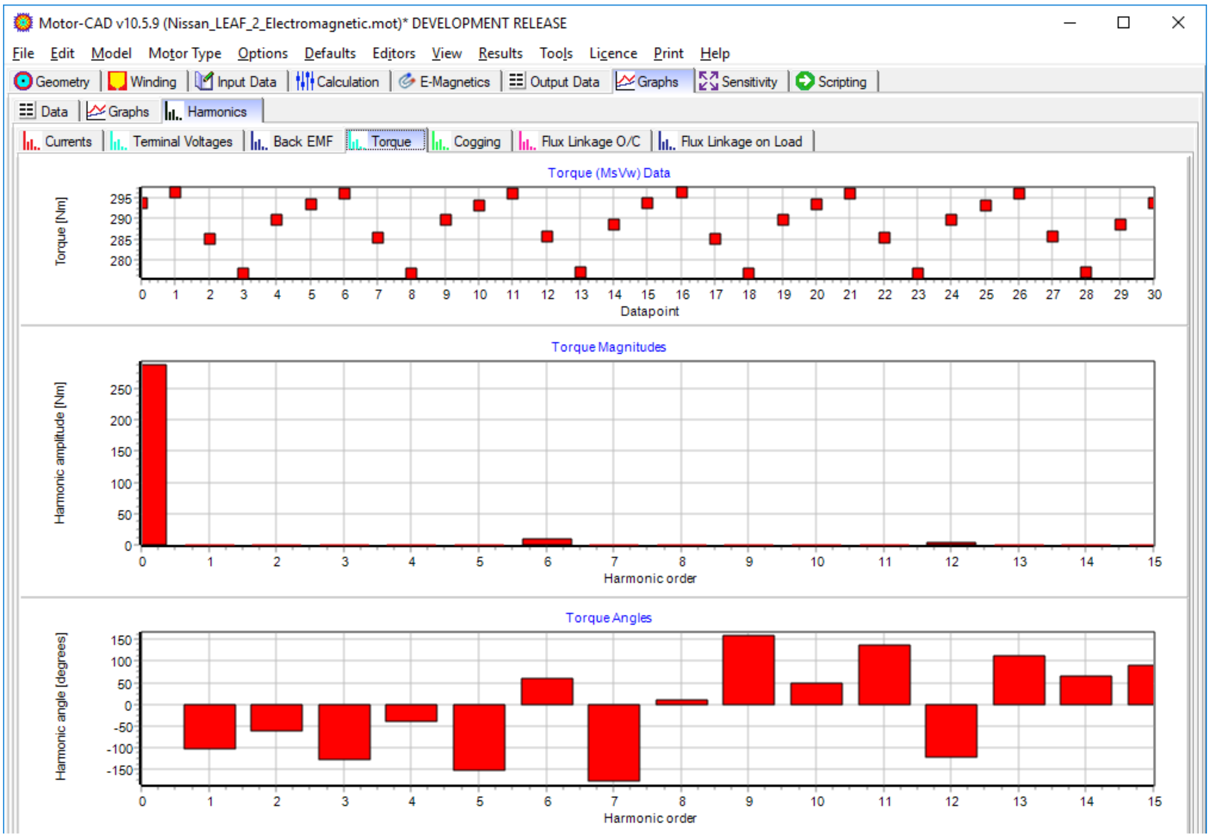
Data Graphs Harmonics
Summary Currents Terminal Voltages Back EMF Torque Cogging Torque Flux Linkage O/C Flux Linkage on Load
Cogging Torque
Cogging (VW)
Cogging Torque [Nm]
Position [MDeg]
17 January 2018
www.motor-design.com

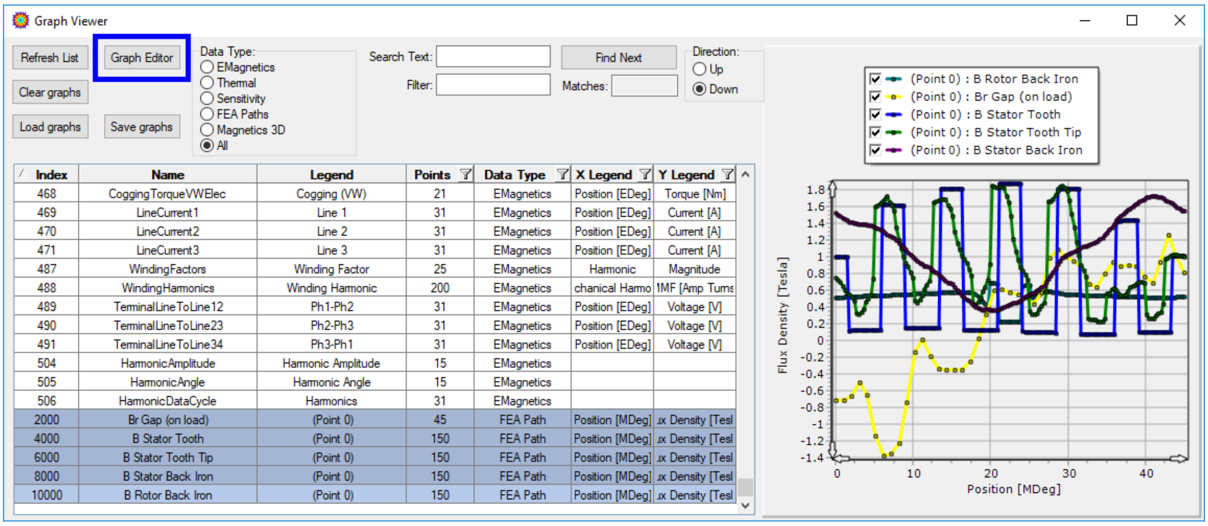


We can also check the harmonic analysis of the waveforms under **Graphs -> Harmonics**. Note the characteristic 6th and 12th harmonics in the torque waveform.



Custom Graphs

In addition to the graph shown in the **Graphs** tab, many other quantities are calculated and saved by Motor-CAD during the simulation. Under **Help -> Graph Viewer** there is a graph viewer available where the user can view any of these graphs. Multiple series can be plotted on a single graph. Using the in-built **Graph Editor** the user can customise the graphs as well as copying the data for use in an external application. For more information please refer to the Motor-CAD manual.

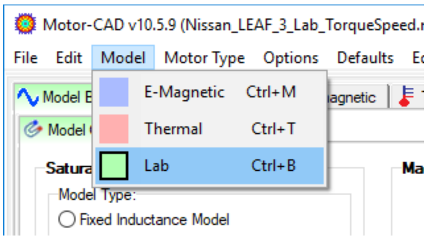


5. Efficiency Maps and Drive Cycle Analysis with Motor-CAD Lab

Motor-CAD's Lab module allows us to quickly and accurately calculate the machine performance over the full operational envelope. We can create efficiency maps, study the thermally constrained operational envelope, and analyse performance over complex driving cycles.

The Lab module uses a hybrid model that combines the accuracy of FEA calculations with the speed of analytic results. We first build the Lab model, performing a series of FEA simulations to fully characterise the saturation and loss behaviour of the machine. Once this model build is complete we use it to accurately calculate the machine performance with analytic methods.

Switch to the Lab context using **Model -> Lab** from the main menu (*tip: a green background on the active tab indicates Lab context*).



As this is the first time we have viewed the Lab context a single static FEA calculation will be performed to characterise the fixed inductance performance of the machine at a single rotor position. The results can be seen in the **Fixed Inductance Model** section of the interface.

The following tabs are available in the Lab context:

Tab	Description
Model Build	Configure & build the Lab model
Calculation	Specify operating conditions, build factors, mechanical losses, model scaling
Electromagnetic	Calculation of peak torque/speed curves and 2d maps of electromagnetic performance
Thermal	Calculation of machine performance within thermal limits
Duty Cycle	Calculation of machine performance over a driving cycle
Operating Point	Calculation at a single operating point
Calibration	Calculation of performance during open circuit/short circuit tests
Settings	Advanced settings & options

Save the Motor-CAD file as **Nissan_LEAF_3_Lab_TorqueSpeed.mot**.

i. Peak Torque/Speed Estimation

We will use the Lab module to calculate a peak torque/speed curve.

The Lab model must be built before any calculations can be performed. On the **Model Build -> Model Options** page, we set the following:

Parameter	Value	Units
Model Type	Saturation Model (Single Step)	
Model Resolution	Coarse	
Loss Model	Neglect	
Maximum Speed	10000	rpm
Max Stator Current (Peak)	480	A

The **Saturation Model** options are explained below:

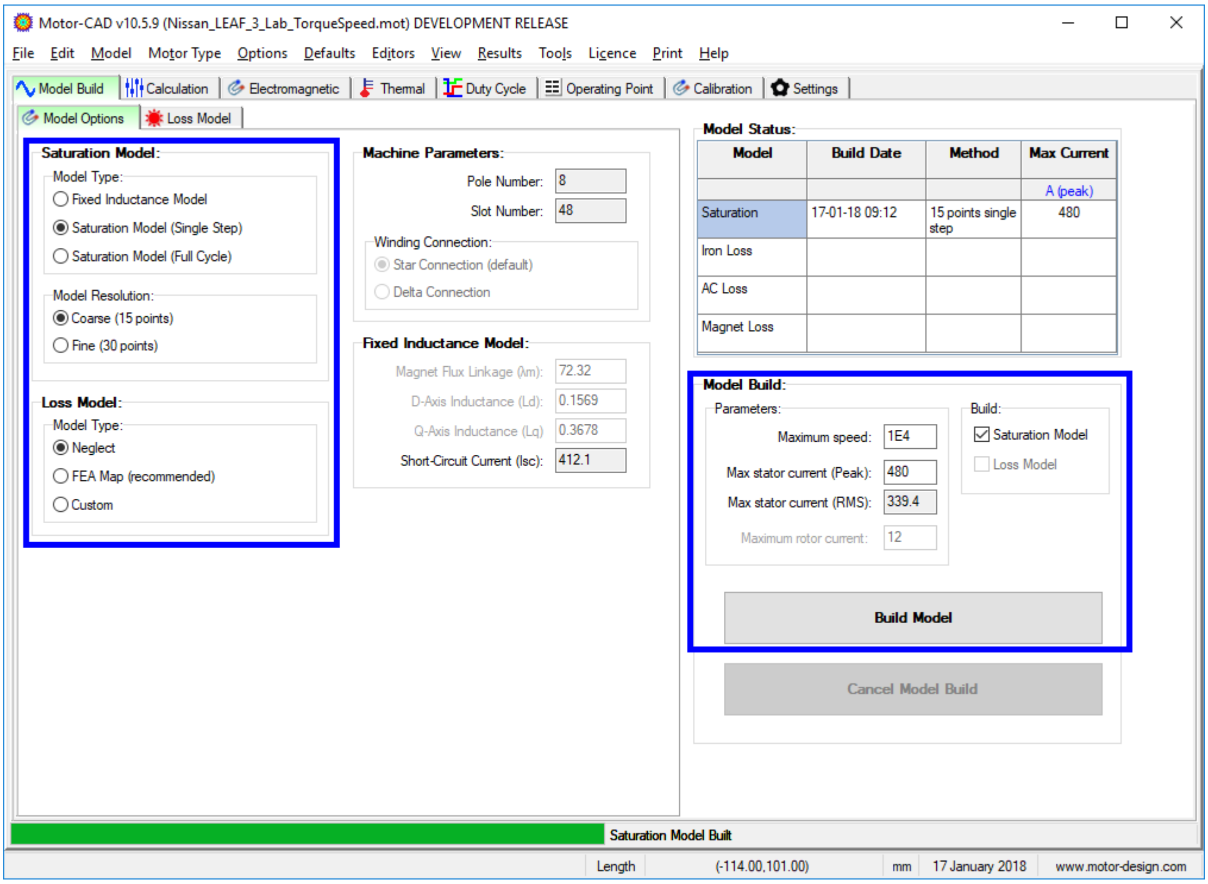
- Fixed Inductance – assumes a constant value of inductance across the full operating range. No saturation model build required.
- Saturation Model (Single Step) – characterises the machine saturation with static FEA simulations at different current & phase advance values, each using only a single rotor position. Assumes that flux linkages are invariant with rotor position.
- Saturation Model (Full Cycle) – characterises the machine saturation with FEA simulations at different current & phase advance values. For each point, the machine is simulated using the full electrical cycle and the flux linkage values are averaged.

More details can be found in the Motor-CAD manual.

For now we choose to build the coarse, single step saturation model and neglect the losses. While not an accurate way of calculating the machine performance across the full operating range or analysing the efficiency of the machine, this will very quickly give a good estimation of the peak performance.

We choose the maximum model build speed and current to cover the full operating range that we will be using.

Ensure that the **Saturation Model** checkbox is enabled and click **Build Model** to start building the model. The simulations should complete within 10-20 seconds. Note that, once the model is built, the **Model Status** table will be updated to show the details of the saved model.



Note that if any changes are made to the settings in the **Model Build** tab (e.g. loss model type is changed), the model must be rebuilt. If any changes are made to the machine geometry, winding or materials in the E-Magnetic or Thermal context, the Lab model also must be re-built to reflect the changes. This will not be done automatically.

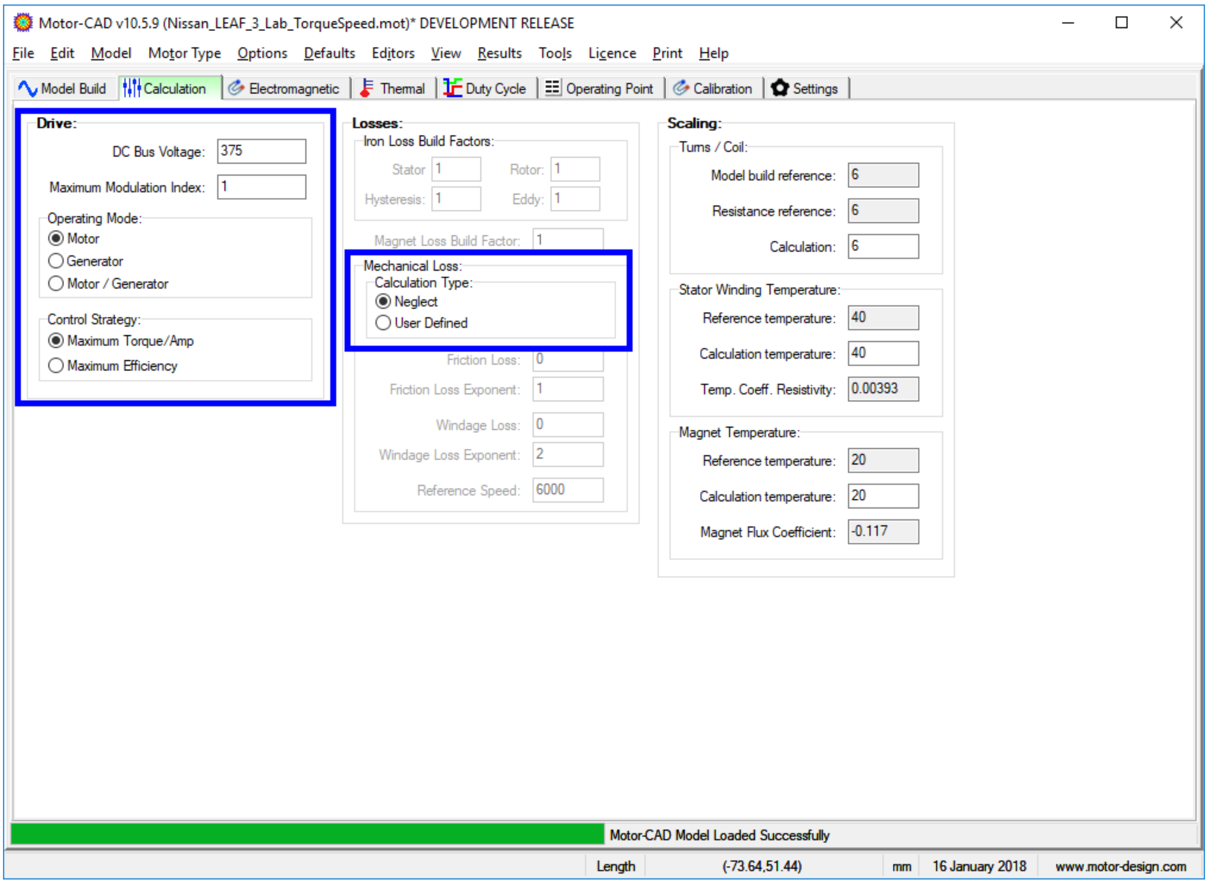
Now that the model is built, we use the **Calculation** tab to set the operating conditions for the calculations. Note that any values on this page can be changed after the model build is complete. We use the following settings:

Parameter	Value	Units
DC Bus Voltage	375	V
Maximum Modulation Index	1	
Operating Mode	Motor	
Control Strategy	Maximum Torque/Amp	
Mechanical Loss	Neglect	

For each point calculated in Lab, the current and phase advance are optimised to give the best operating conditions. Here, the user can select whether this optimisation should use the Maximum Torque/Amp (MTPA) or Maximum Efficiency (ME) control strategy.

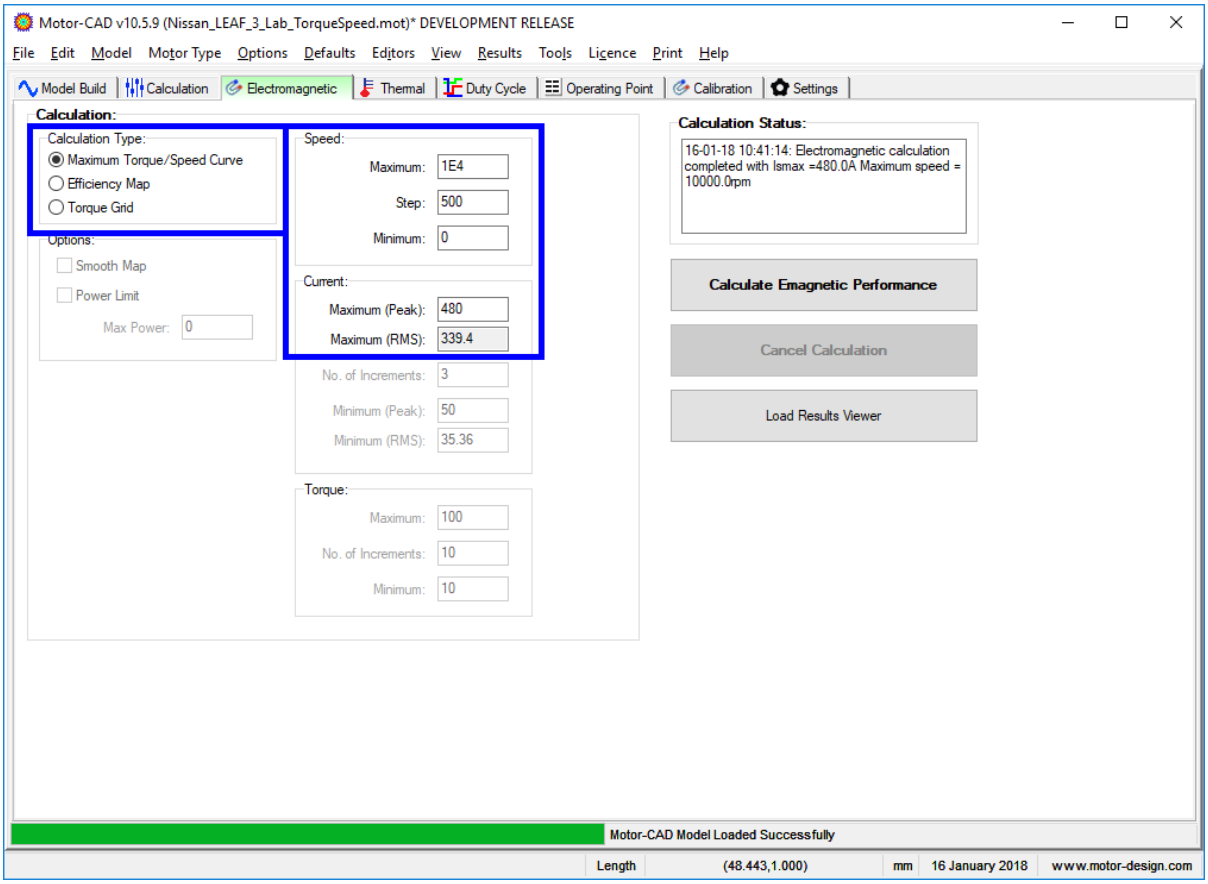
Note that the loss build factors are disabled since we are neglecting the losses.

The **Scaling** options on the right-hand side of the page can be used to quickly adjust the model temperature or the number of turns/coil without rebuilding the model. We will leave these as their default values i.e. no scaling.

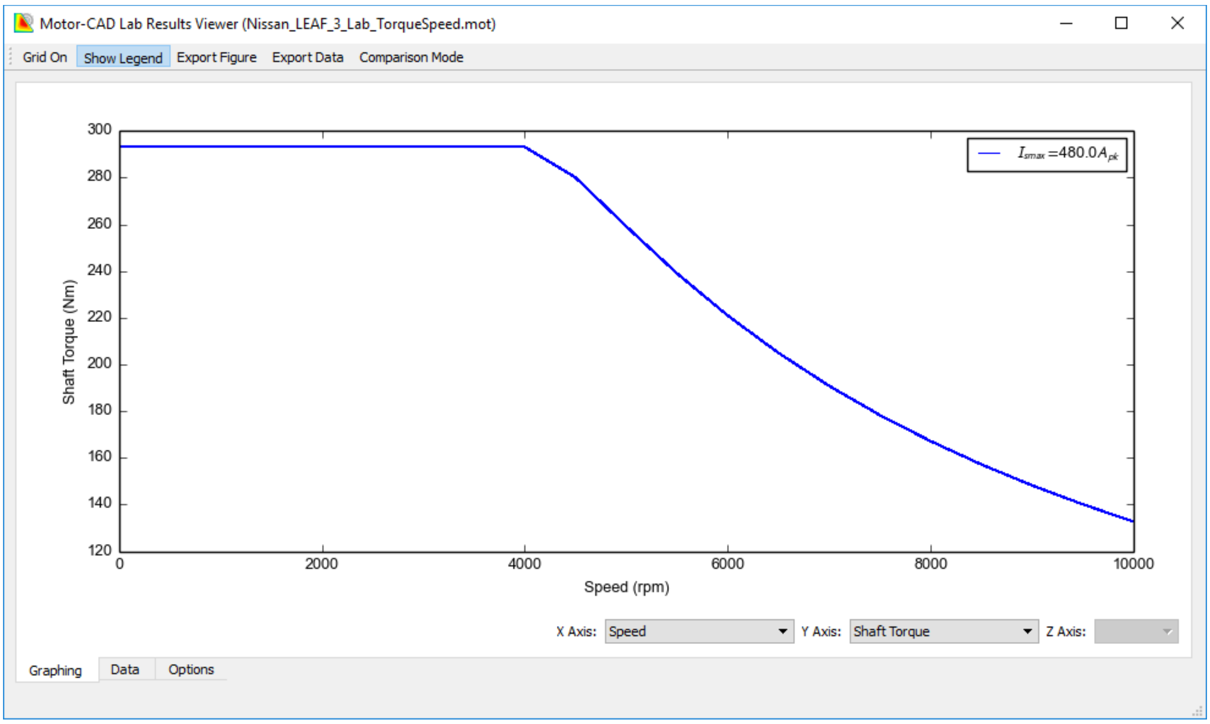


We can now use the **Electromagnetic** tab to calculate the peak torque/speed curve. We set up the options as follows:

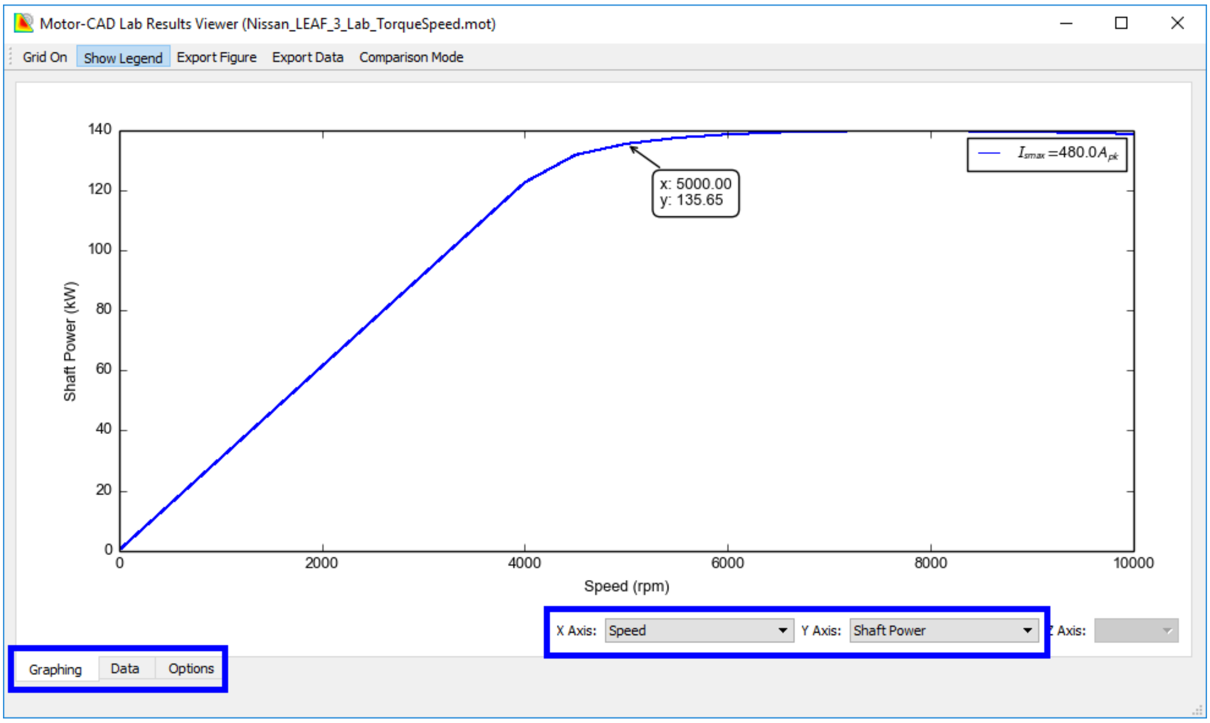
Parameter	Value	Units
Calculation Type	Maximum torque/Speed Curve	
Speed: Maximum	10000	rpm
Speed: Step	500	rpm
Speed: Minimum	0	rpm
Current: Maximum (Peak)	480	A



Click **Calculate Emagnetic Performance**, and the calculation should complete in a few seconds. The results are automatically shown in a new window. Previously calculated results can also be loaded at a later point with the **Load Results Viewer** button.



By default the viewer shows the torque vs speed graph, other values can be plotted by changing the **X Axis** or **Y Axis** dropdown, e.g. shaft power vs speed. The raw data can be viewed and exported under the **Data** tab, and the plot can be customised further under the **Options** tab. Exact values at any point can be found by clicking on the graph at the point of interest.



ii. Efficiency Maps

Save the file as **Nissan_LEAF_4_Lab_EfficiencyMap.mot**. The interface shows the E-Magnetic context, use **Model -> Lab** to return to the Lab context.

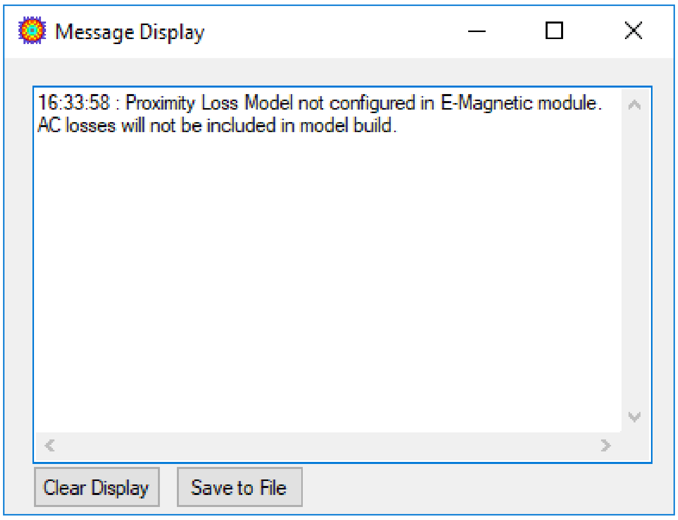
Before calculating the efficiency map, recall that we built the Lab model using the single step saturation model, neglecting the losses. While this is a very good way to get a fast estimation of the peak torque/speed performance, it will not give such accurate results for the efficiency map. We will therefore rebuild the model with more detail to get the best accuracy.

On the **Model Build -> Model Options** tab, change the following settings:

Parameter	Value
Model Type	Saturation Model (Full Cycle)
Model Resolution	Fine
Loss Model	FEA Map

When using the FEA map loss model it is always recommended to use the settings above for the saturation model. This allows the saturation model to be built using the same FEA simulations as the loss model, reducing the calculation time and ensuring maximum model accuracy.

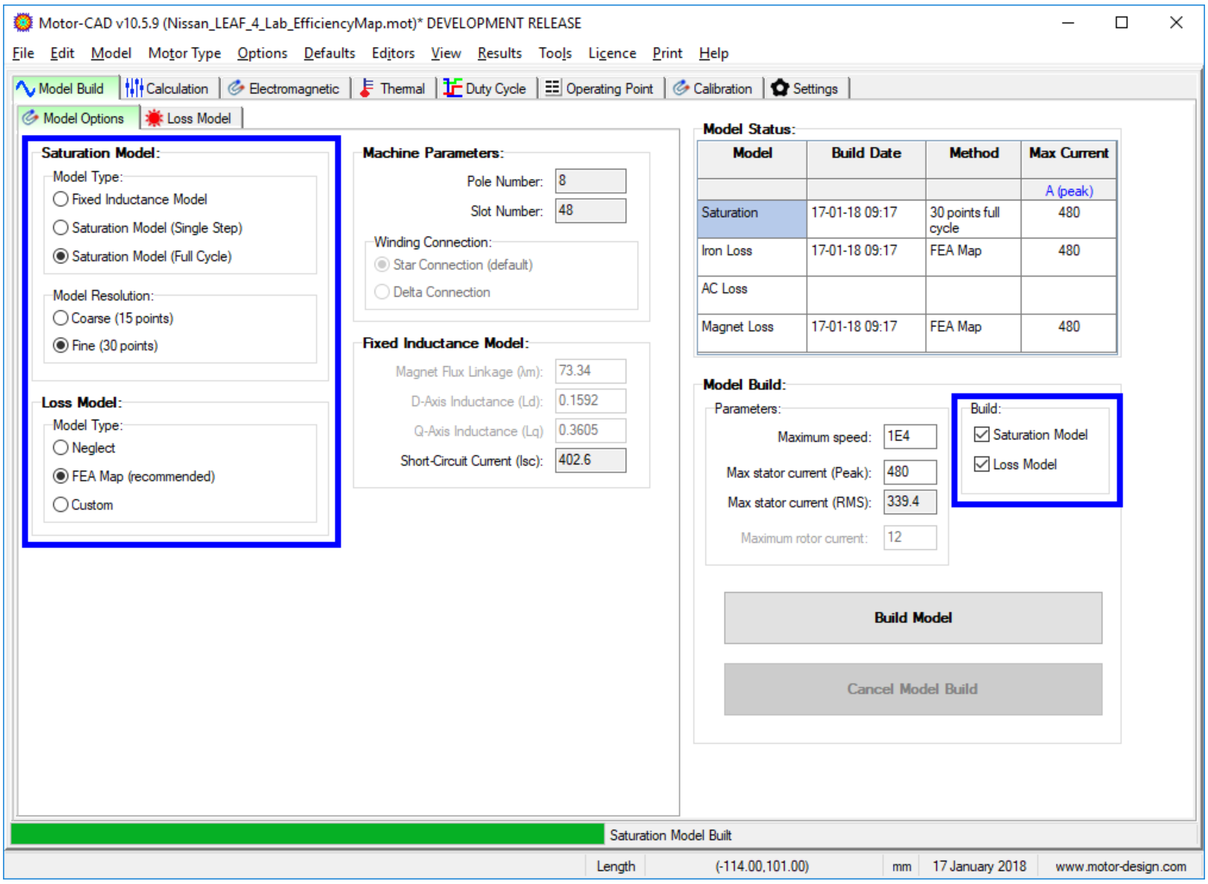
A message will appear in the **Message Display** window:



This is just informing us that the proximity losses (AC losses) will not be included in the Lab model since they have not been configured in the E-Magnetic model. This is fine for now – later on, in the **Advanced E-Magnetic Modelling** section, we will add proximity losses to our E-Magnetic model and then return to Lab to include them in the Lab model.

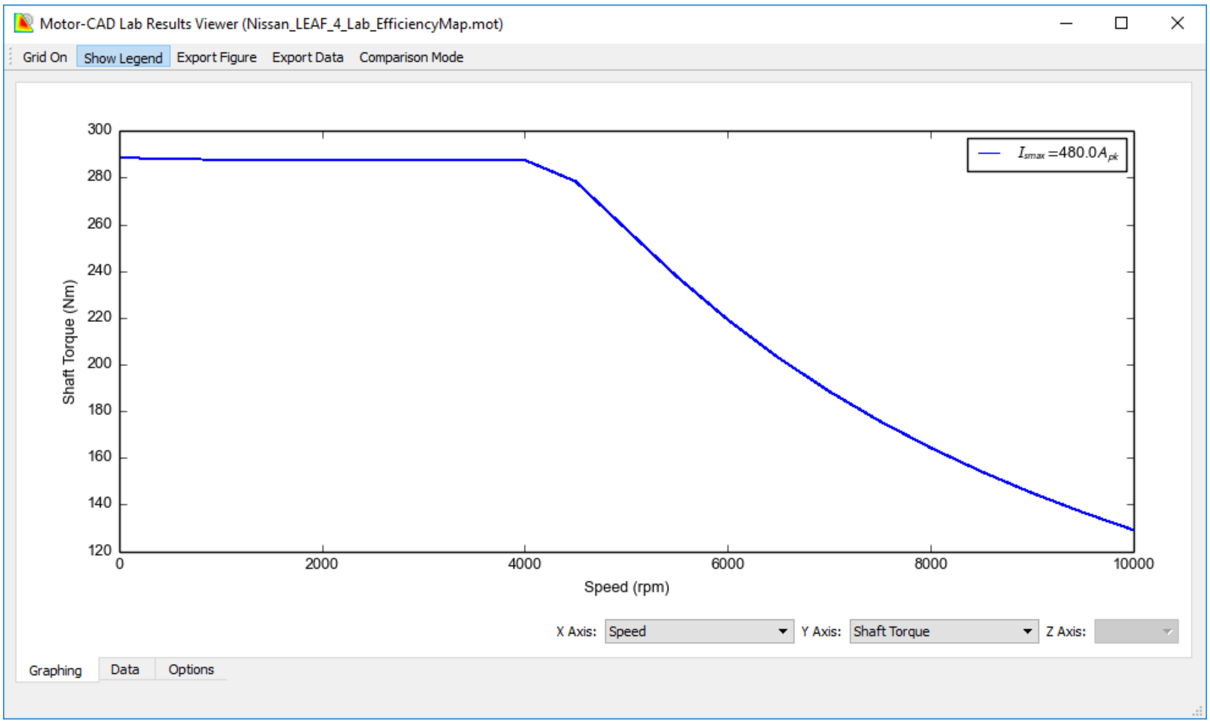
Notice that some of the cells in the **Model Status** table are now highlighted in red. This indicates that the saved model build does not match the selected options, and the model must be rebuilt before any calculations can be performed.

We keep the maximum model build speed and current the same as before. Ensure that both the **Saturation Model** and **Loss Model** checkboxes are enabled under **Build**, and click **Build Model**. This time the model build will take a little longer, this should complete within around 5 minutes.



Now we navigate to the **Electromagnetic** tab in order to calculate the efficiency map. First, we will check the accuracy of our previous single-step model by re-calculating the peak torque/speed curve. With the same settings used previously, we click **Calculate Emagnetic Performance** to generate the peak curve.

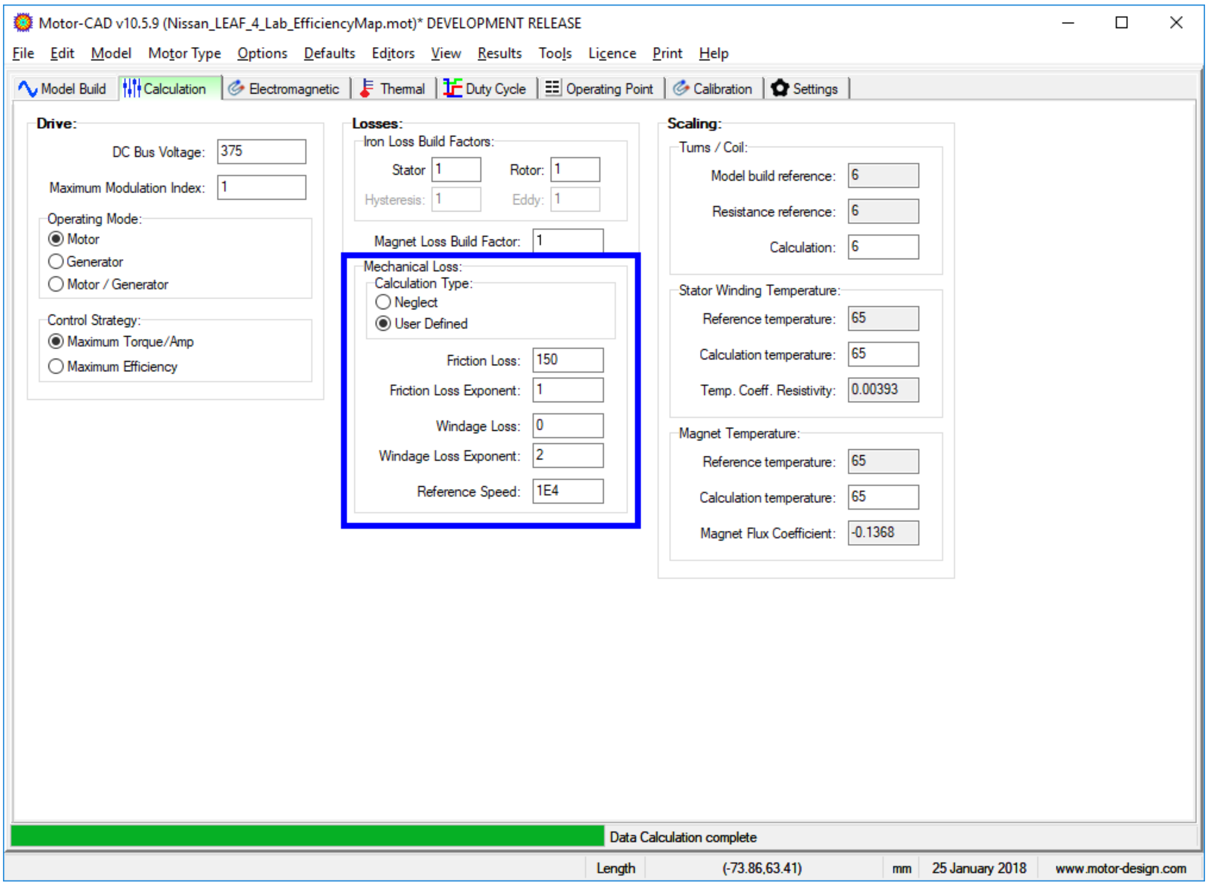
We can see that the curve is very similar to the previous result, with a slightly lower torque throughout due to the inclusion of the loss model.



We will now calculate the full efficiency map. Close the viewer and return to the Motor-CAD window. As well as including the copper, iron and magnet losses through FEA-based models, we can also defined the mechanical losses. These are typically comprised of a friction (e.g. bearing losses) and windage loss component.

Mechanical losses are defined under the **Calculation** tab. For the LEAF motor, we have the following loss model:

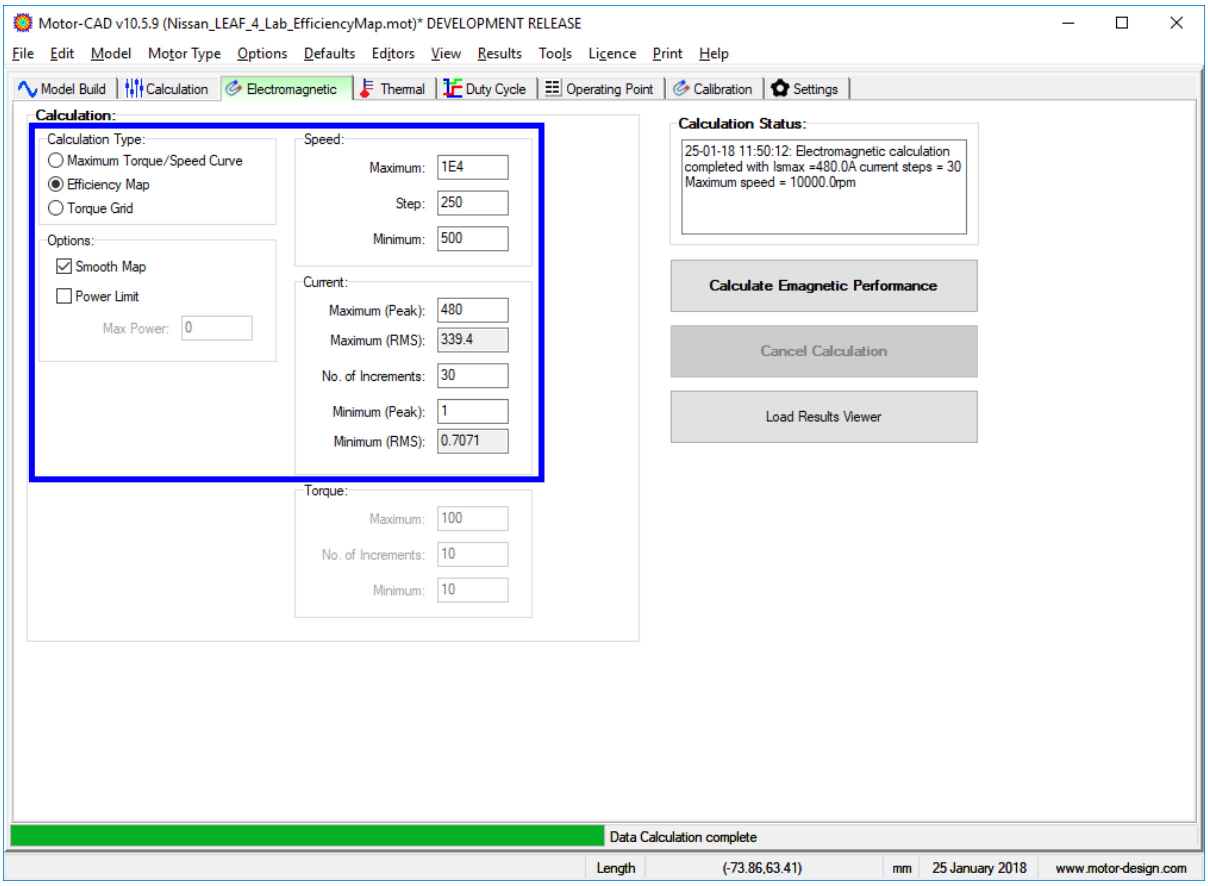
Parameter	Value	Units
Calculation Type	User Defined	
Friction Loss	150	W
Friction Loss Exponent	1	
Windage Loss	0	W
Windage Loss Exponent	2	
Reference Speed	10000	rpm



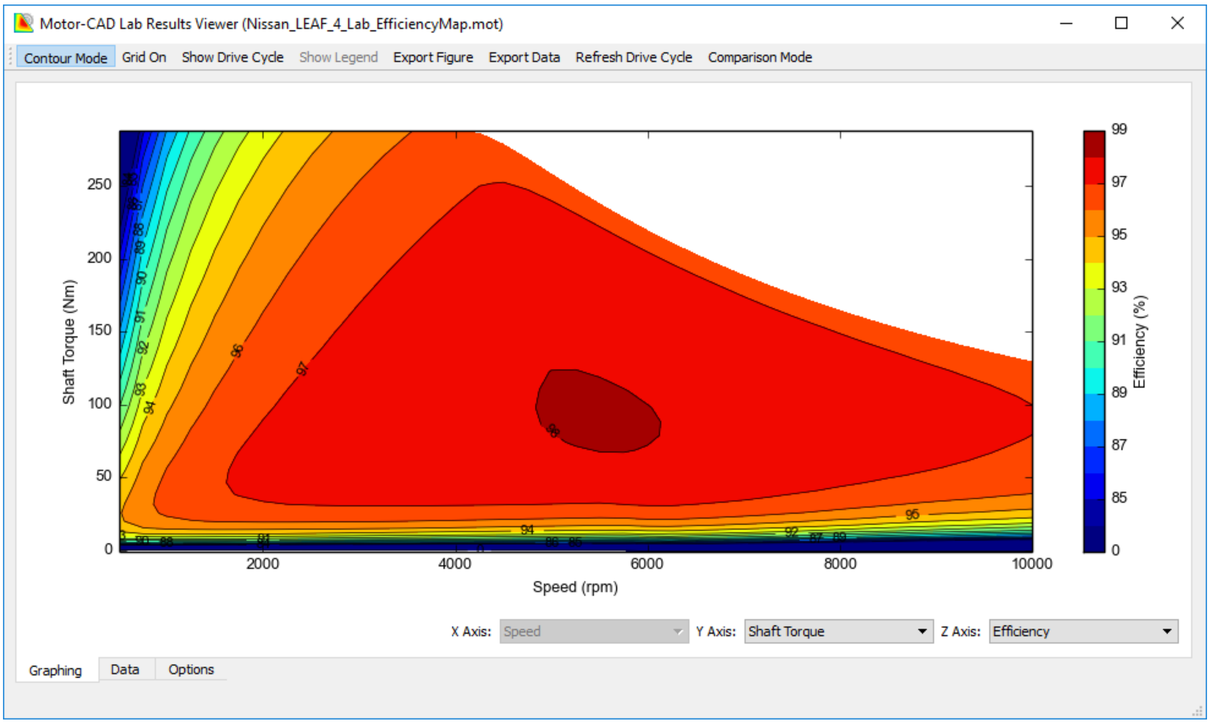
Under the **Electromagnetic** tab, set the following options:

Parameter	Value	Units
Calculation Type	Efficiency Map	
Speed: Maximum	10000	rpm
Speed: Step	250	rpm
Speed: Minimum	500	rpm
Current: Maximum (Peak)	480	A
Current: No. of Increments	30	
Current: Minimum (Peak)	1	
Smooth Map	Enabled	

The minimum speed/current, number of increments, and smooth map option are chosen to improve the visualisation of the efficiency map.



Click **Calculate Emagnetic Performance** to run the calculation. Again, the efficiency map is shown automatically. Other values can be plotted by selecting from the **Y Axis** and **Z Axis** dropdown, and the appearance of the plot (e.g. min/max values, number of contour lines) can be customised in the **Options** tab.



iii. Thermal Envelope

The **Thermal** tab can be used to calculate the continuous thermal performance of the machine for steady-state or transient conditions. The resulting thermal envelope will show the maximum capability of the machine within the specified maximum temperatures.

Since we have not yet configured the thermal model for the LEAF, we will return to the thermal envelope calculations later in the tutorial.

iv. Drive Cycle

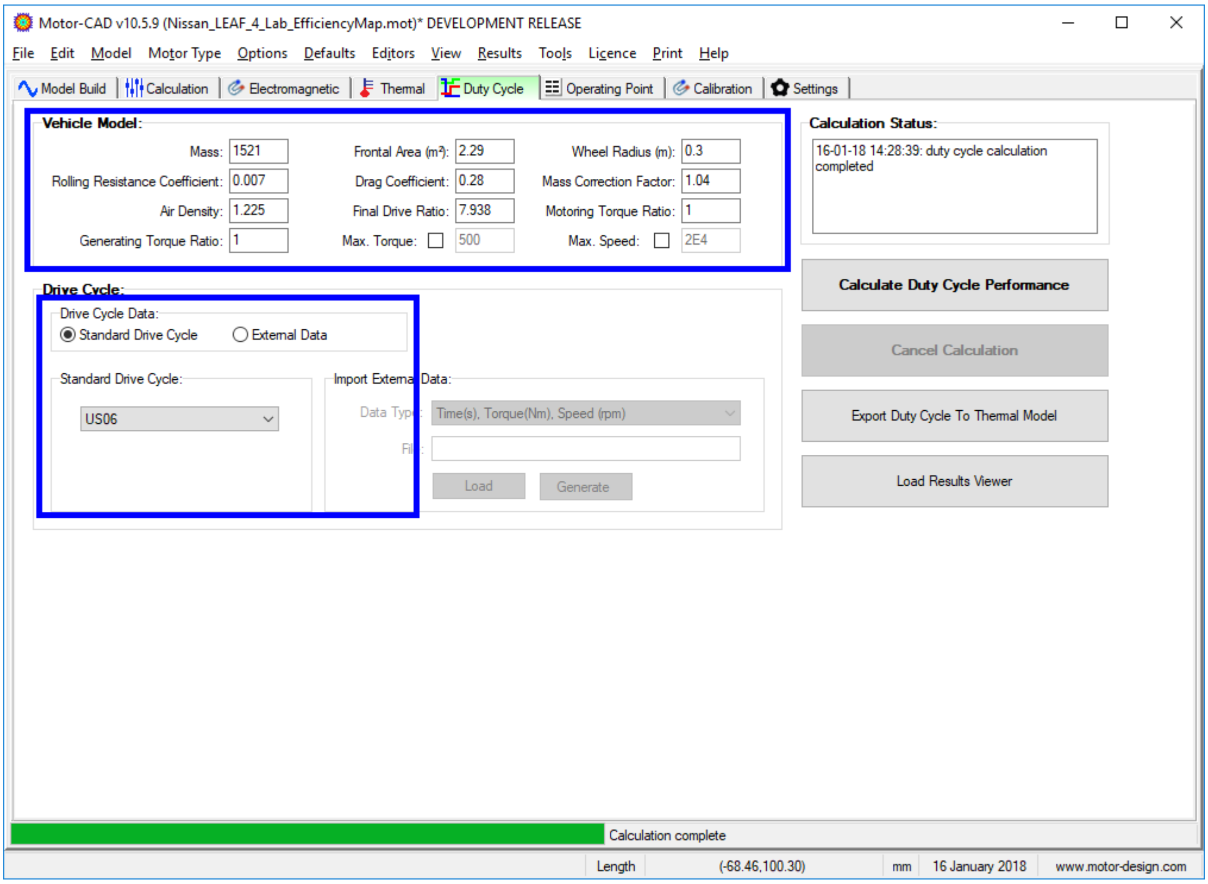
The Lab module includes a vehicle model, based on a simple analysis of the forces acting on the vehicle, which can be used to calculate torque/speed points for a standard speed vs time driving cycle. Many standard test cycles are included, or users can specify a custom drive cycle with an external data file.

For the Nissan LEAF, we have the following vehicle model parameters:

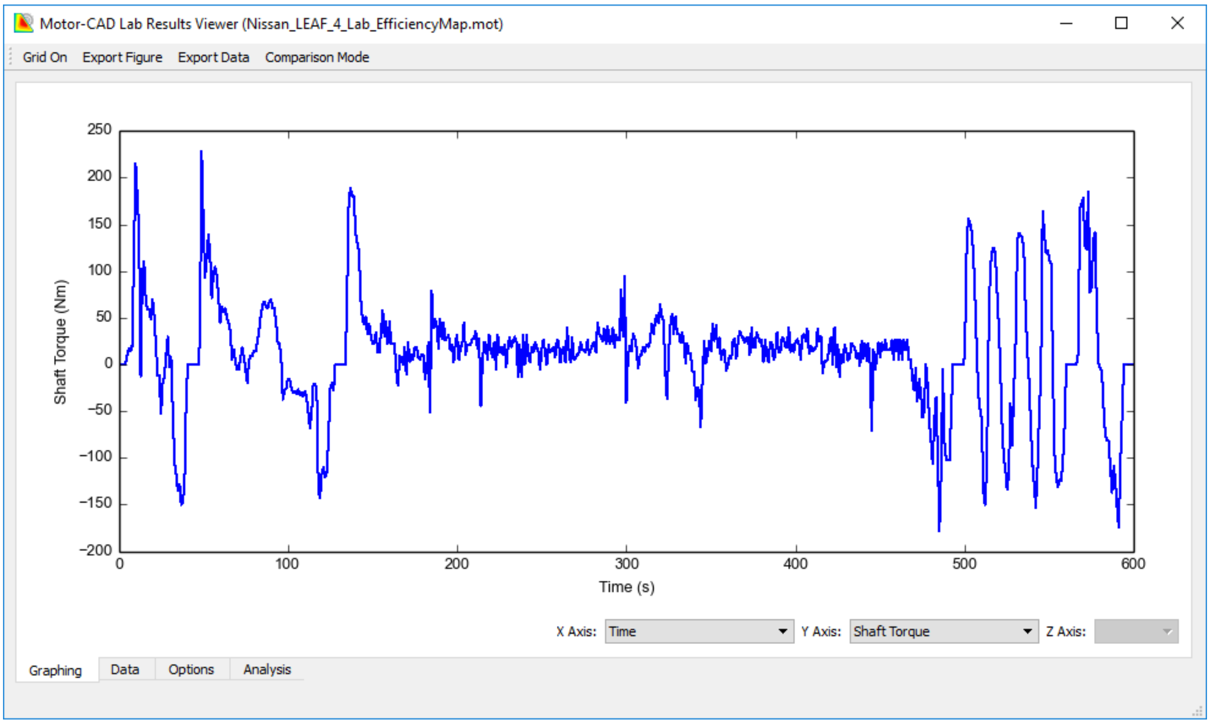
Parameter	Value	Units
Mass	1521	kg
Rolling Resistance Coefficient	0.007	
Air Density	1.225	kg/m^3
Generating Torque Ratio	1	
Frontal Area	2.29	m^2
Drag Coefficient	0.28	
Final Drive Ratio	7.938	
Max. Torque	Disabled	
Wheel Radius	0.3	m
Mass Correction Factor	1.04	
Motoring Torque Ratio	1	
Max. Speed	Disabled	

We will simulate the US06 standard drive cycle. This is a standard testing cycle designed to test the real-world performance of vehicles, defined by a speed vs time profile.

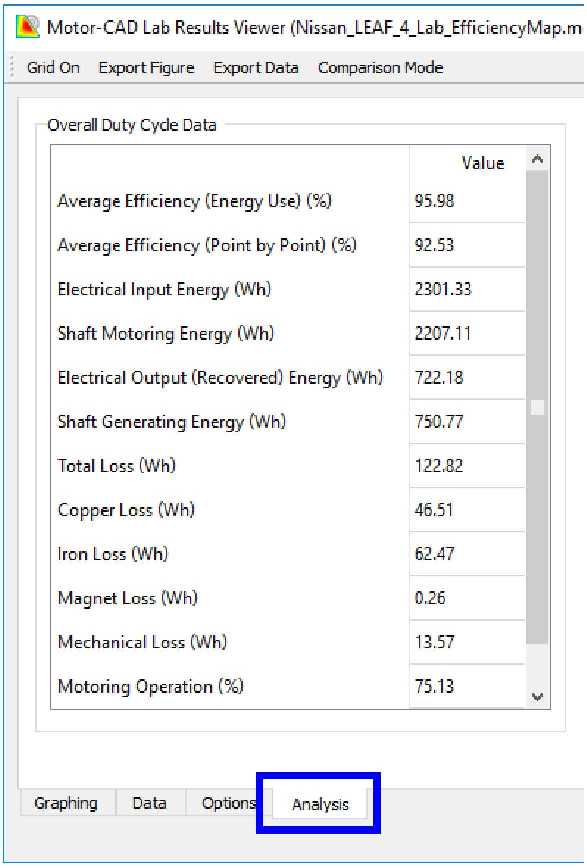
Parameter	Value
Drive Cycle Data	Standard Drive Cycle
Standard Drive Cycle	US06



Click **Calculate Duty Cycle Performance** to run the calculation. This should complete within about 2 minutes and by default the viewer shows the torque profile over the cycle.

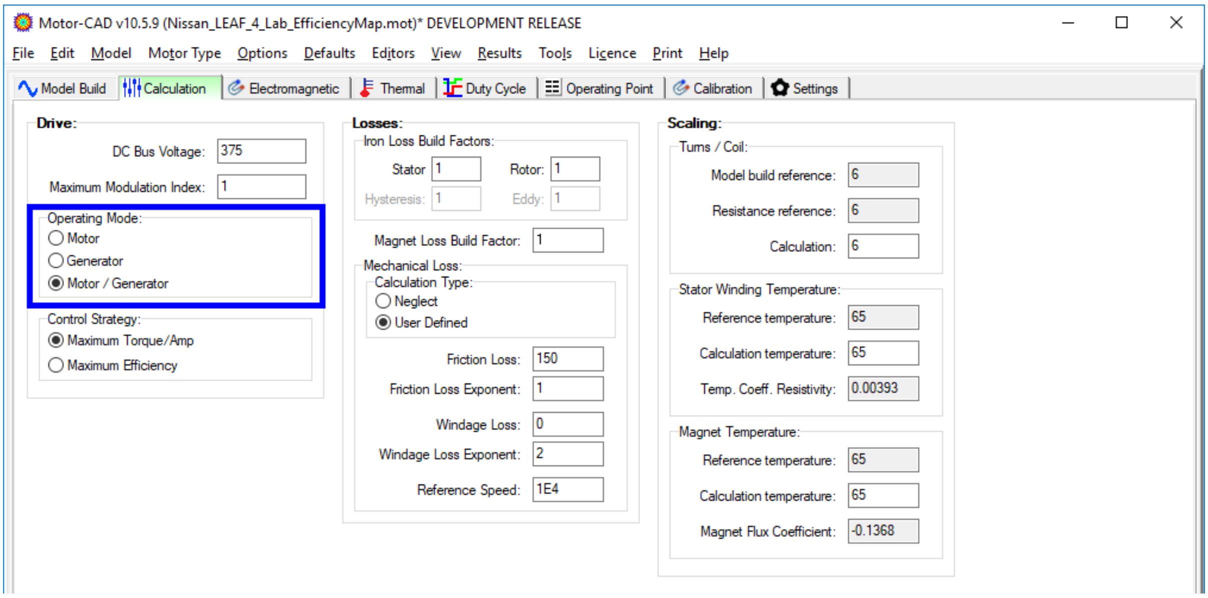


The **Analysis** tab shows various useful parameters calculated over the cycle e.g. average efficiency, total input energy, total losses, etc.

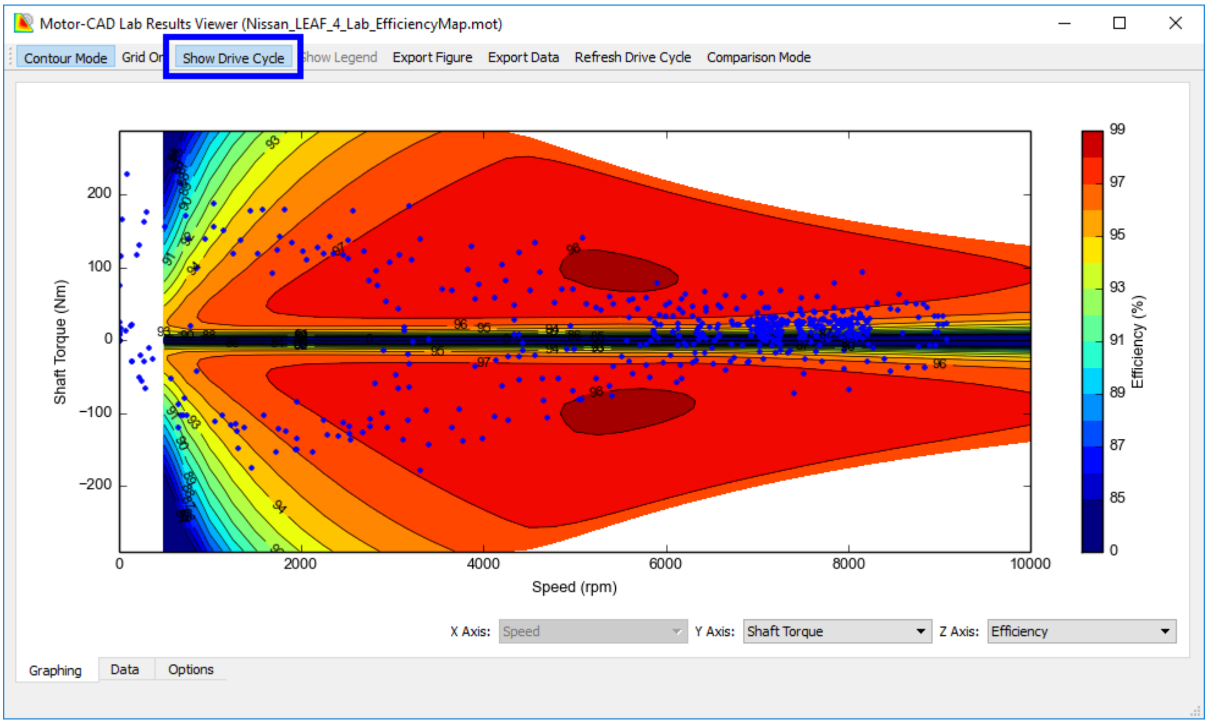


	Value
Average Efficiency (Energy Use) (%)	95.98
Average Efficiency (Point by Point) (%)	92.53
Electrical Input Energy (Wh)	2301.33
Shaft Motoring Energy (Wh)	2207.11
Electrical Output (Recovered) Energy (Wh)	722.18
Shaft Generating Energy (Wh)	750.77
Total Loss (Wh)	122.82
Copper Loss (Wh)	46.51
Iron Loss (Wh)	62.47
Magnet Loss (Wh)	0.26
Mechanical Loss (Wh)	13.57
Motoring Operation (%)	75.13

Lab can also include the duty cycle operating points on the efficiency map. Since the duty cycle contains both motoring and generating points, we will first need to set the **Operating Mode** to **Motor / Generator** under the **Calculation** tab.



We then return to the **Electromagnetic** tab and **Calculate Emagnetic Performance** again. When the results are shown, select the **Show Drive Cycle** option to display the operating points on the graph.



The duty cycle loss values can be exported to the Thermal module in order to calculate the thermal performance over the cycle. We will come back to this step later, after we have configured the thermal model.

v. Single Operating Point

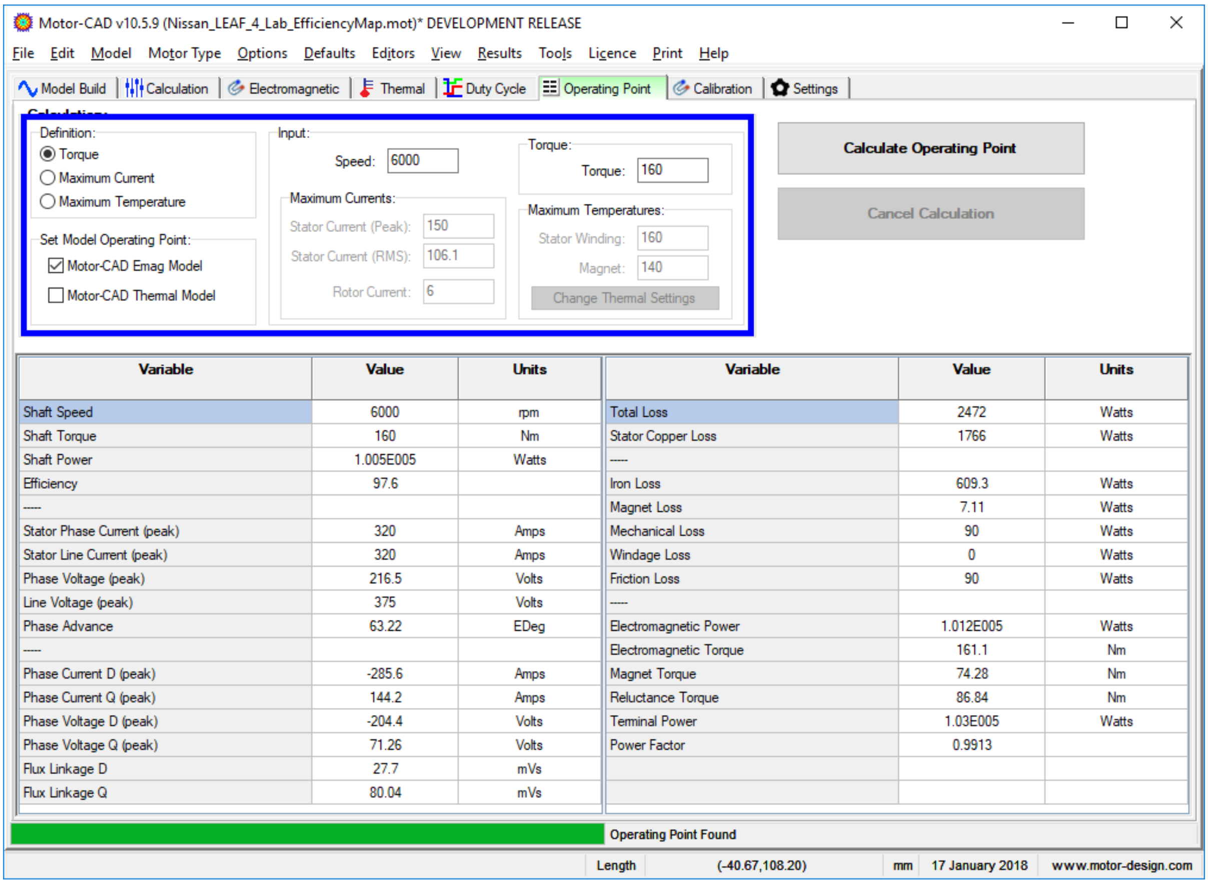
The **Operating Point** tab allows the user to calculate the machine performance at a single point. At a given shaft speed, this finds the optimum operating conditions for the specified maximum current, torque or maximum temperatures, according to the chosen control strategy.

This can be useful to quickly find the optimum current and phase advance values for a single operating point, and then investigate the machine performance more closely at this point using the E-Magnetic or Thermal modules.

Set the following conditions:

Parameter	Value	Units
Definition	Torque	
Speed	6000	rpm
Torque	160	Nm
Set Motor-CAD Emag Model	Enabled	
Set Motor-CAD Thermal Model	Disabled	

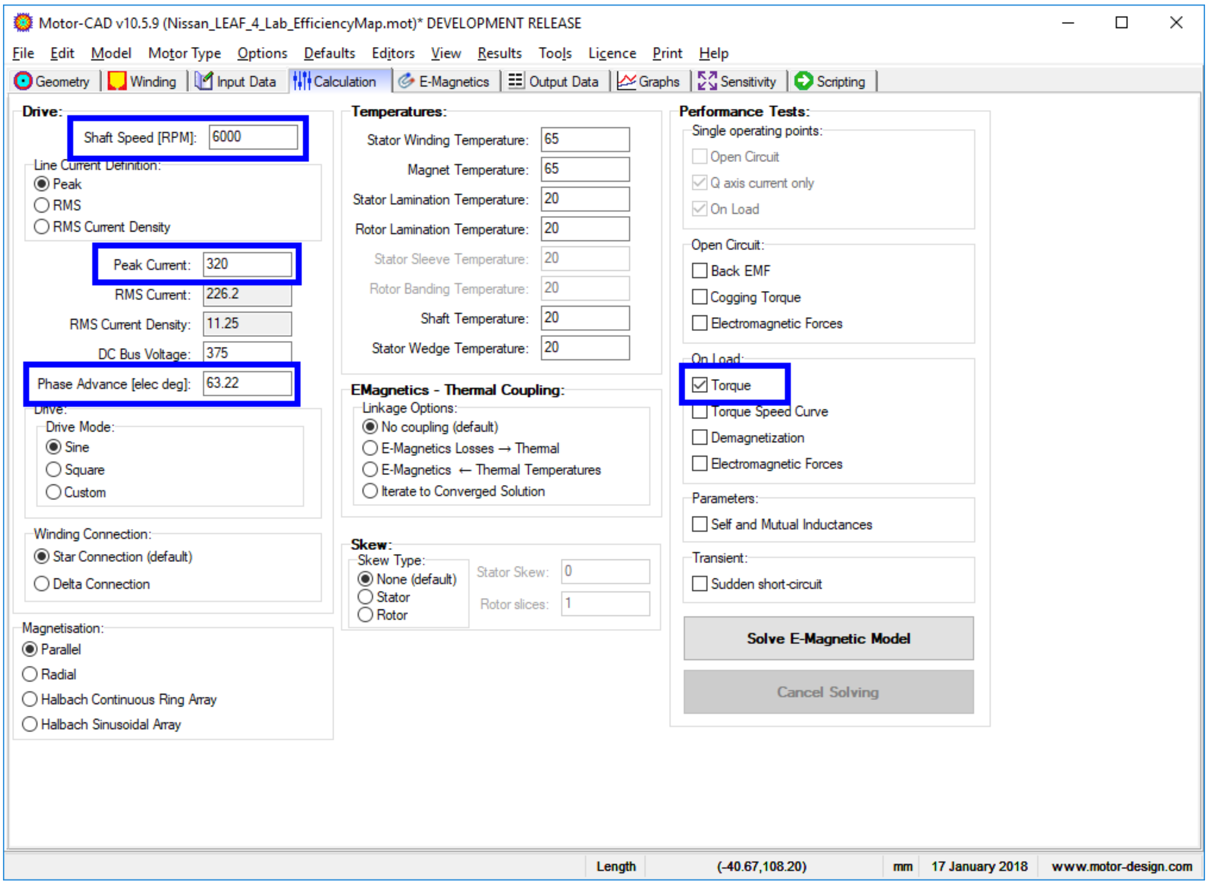
Click **Calculate Operating Point** to run the calculation, this should only take a moment, and the table will be updated with the results.



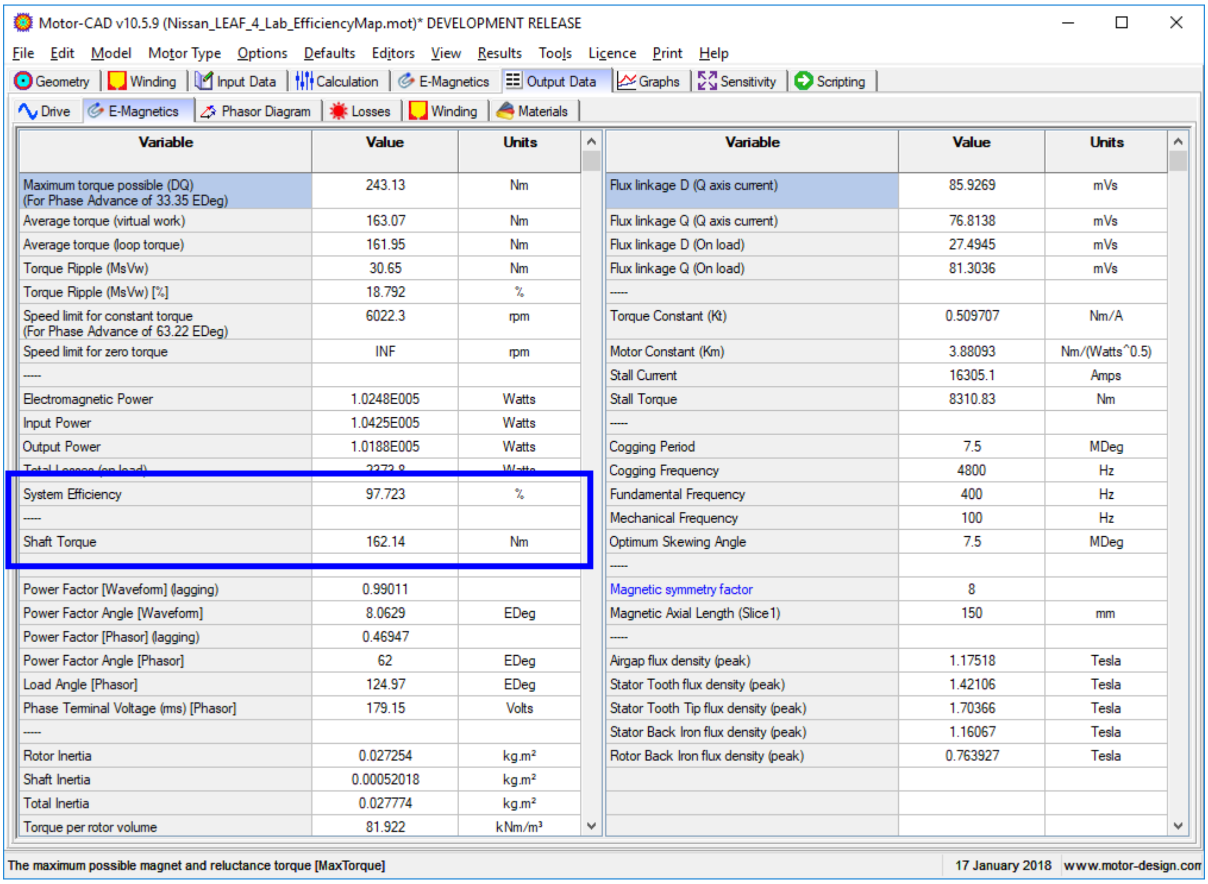
We can see that, with the MTPA (Maximum Torque per Amp) control strategy, the optimum point is found at 320 A supply current with a phase advance of 63.2 electrical degrees, giving a motor efficiency of 97.6%. Since we have selected the **Set Motor-CAD Emag Model** option, these operating conditions will be set automatically in the E-Magnetic module. We can now run the full transient FEA solution for this operating point to verify the results from the Lab model.

Return to the E-Magnetic context using **Model -> E-Magnetic** from the main menu (or **Ctrl+M**). In the **Calculation** tab, we can see that the current, shaft speed and phase advance from the Lab operating point have been set here.

Deselect all performance tests except for the **Torque** calculation and solve the model.



Under **Output Data -> E-Magnetics**, we see that the shaft torque and efficiency found from the transient FEA solution are within 1.5% of the values calculated from the Lab model. We can view other detailed results for this operating point, for example flux plots, torque waveforms, harmonic analysis, loss distribution, etc.



Variable	Value	Units
Maximum torque possible (DQ) (For Phase Advance of 33.35 EDeg)	243.13	Nm
Average torque (virtual work)	163.07	Nm
Average torque (loop torque)	161.95	Nm
Torque Ripple (MsVw)	30.65	Nm
Torque Ripple (MsVw) [%]	18.792	%
Speed limit for constant torque (For Phase Advance of 63.22 EDeg)	6022.3	rpm
Speed limit for zero torque	INF	rpm

Electromagnetic Power	1.0248E005	Watts
Input Power	1.0425E005	Watts
Output Power	1.0188E005	Watts
Total Losses (on load)	2372.8	Watts
System Efficiency	97.723	%

Shaft Torque	162.14	Nm
Power Factor [Waveform] (lagging)	0.99011	
Power Factor Angle [Waveform]	8.0629	EDeg
Power Factor [Phasor] (lagging)	0.46947	
Power Factor Angle [Phasor]	62	EDeg
Load Angle [Phasor]	124.97	EDeg
Phase Terminal Voltage (rms) [Phasor]	179.15	Volts

Rotor Inertia	0.027254	kg.m²
Shaft Inertia	0.00052018	kg.m²
Total Inertia	0.027774	kg.m²
Torque per rotor volume	81.922	kNm/m³

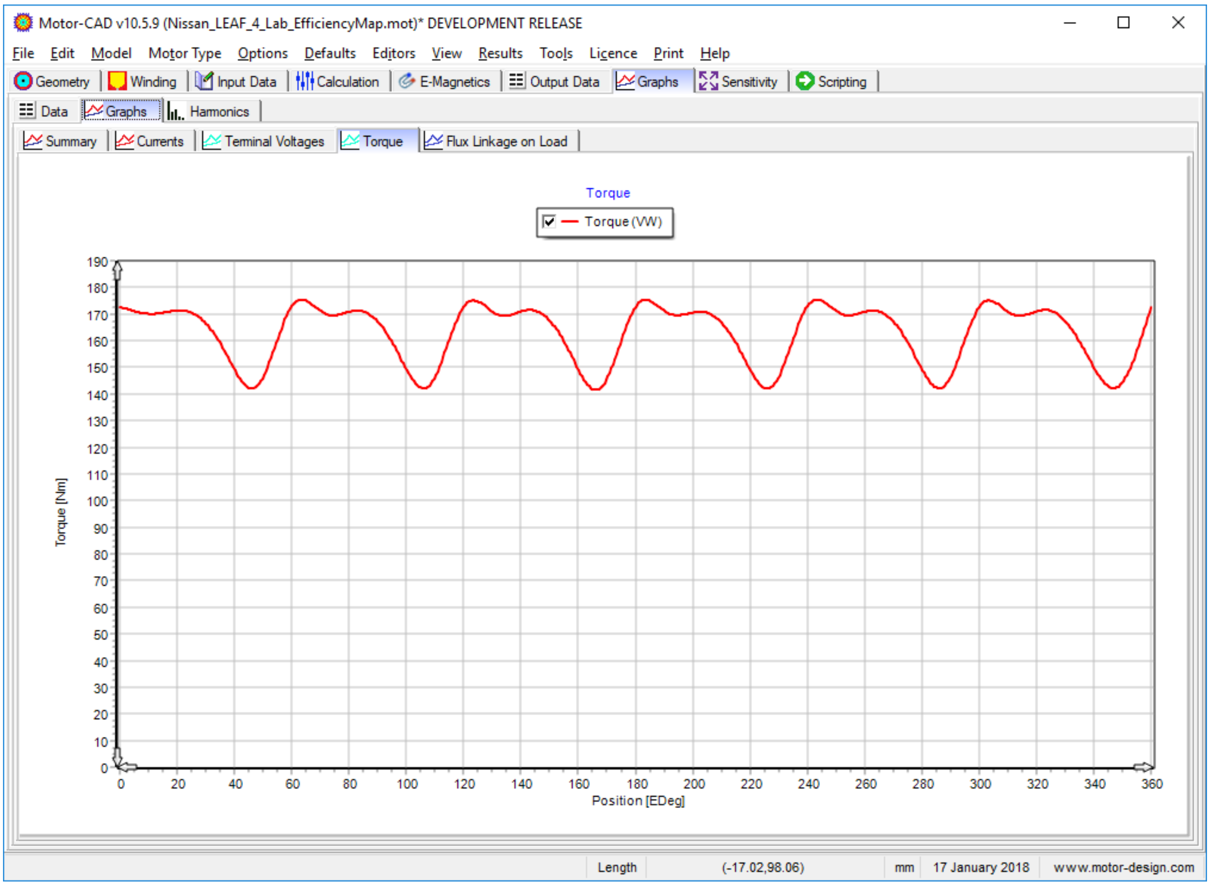
Variable	Value	Units
Flux linkage D (Q axis current)	85.9269	mVs
Flux linkage Q (Q axis current)	76.8138	mVs
Flux linkage D (On load)	27.4945	mVs
Flux linkage Q (On load)	81.3036	mVs

Torque Constant (Kt)	0.509707	Nm/A
Motor Constant (Km)	3.88093	Nm/(Watts^0.5)
Stall Current	16305.1	Amps
Stall Torque	8310.83	Nm

Cogging Period	7.5	MDeg
Cogging Frequency	4800	Hz
Fundamental Frequency	400	Hz
Mechanical Frequency	100	Hz
Optimum Skewing Angle	7.5	MDeg

Magnetic symmetry factor	8	
Magnetic Axial Length (Slice1)	150	mm

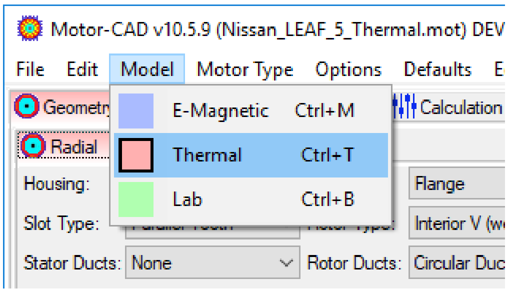
Airgap flux density (peak)	1.17518	Tesla
Stator Tooth flux density (peak)	1.42106	Tesla
Stator Tooth Tip flux density (peak)	1.70366	Tesla
Stator Back Iron flux density (peak)	1.16067	Tesla
Rotor Back Iron flux density (peak)	0.763927	Tesla



6. Thermal Model

The thermal model in Motor-CAD solves lumped parameter thermal networks in order to obtain the working temperatures of the machine. FEA thermal simulations can also be used in order to validate the lumped parameter model.

Switch to the thermal context with **Model -> Thermal** or **Ctrl+T** (*tip: a red background on the active tab indicates thermal context*). Save the file as **Nissan_LEAF_5_Thermal.mot**.



The following main tabs are available in the thermal context:

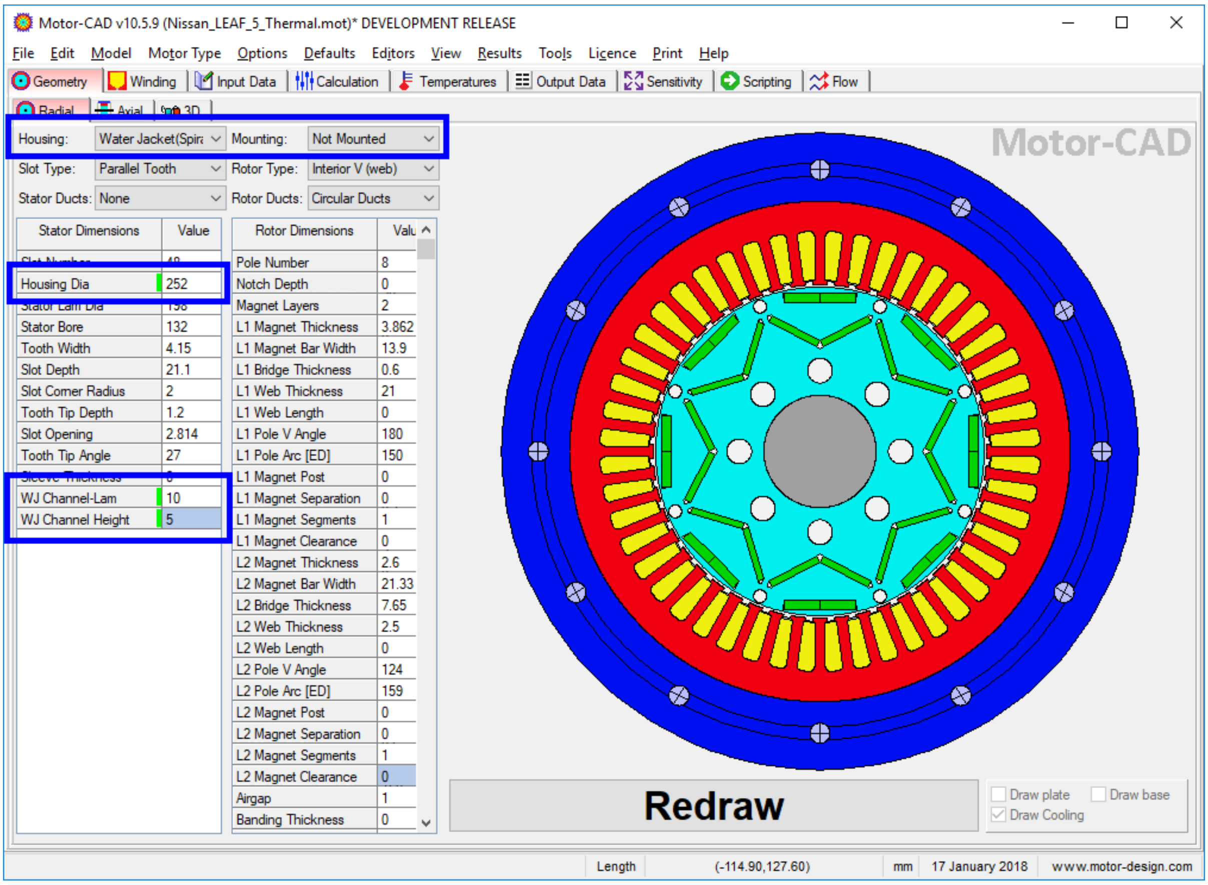
Tab	Description
Geometry	Define & view the machine geometry (radial, axial, 3d)
Winding	Define & view the stator winding
Input Data	Specify materials used in the model, define losses, define cooling systems, adjust advanced settings
Calculation	Specify the calculation options & run the calculations
Temperatures	View temperatures, lumped parameter thermal circuit, 2D thermal FEA, thermal model validation, design optimisation
Output Data	View numerical results
Transient Graph	View temperature & power results from transient simulations (only available when running transient calculation)
Sensitivity	Sensitivity analysis - vary input parameters and analyse effect on machine performance
Scripting	Create & run Visual Basic scripts in Motor-CAD

i. Geometry

In the Thermal context, some additional geometry is now shown e.g. housing, mounting. This was hidden in the E-Magnetic context since it was not relevant to the electromagnetic model. We must now configure the thermal geometry parameters.

Under **Geometry -> Radial**, set the following:

Stator Parameter	Value	Units
Housing	Water Jacket (Spiral)	
Mounting	Not Mounted	
Housing Dia	252	mm
WJ Channel-Lam	10	mm
WJ Channel Height	5	mm

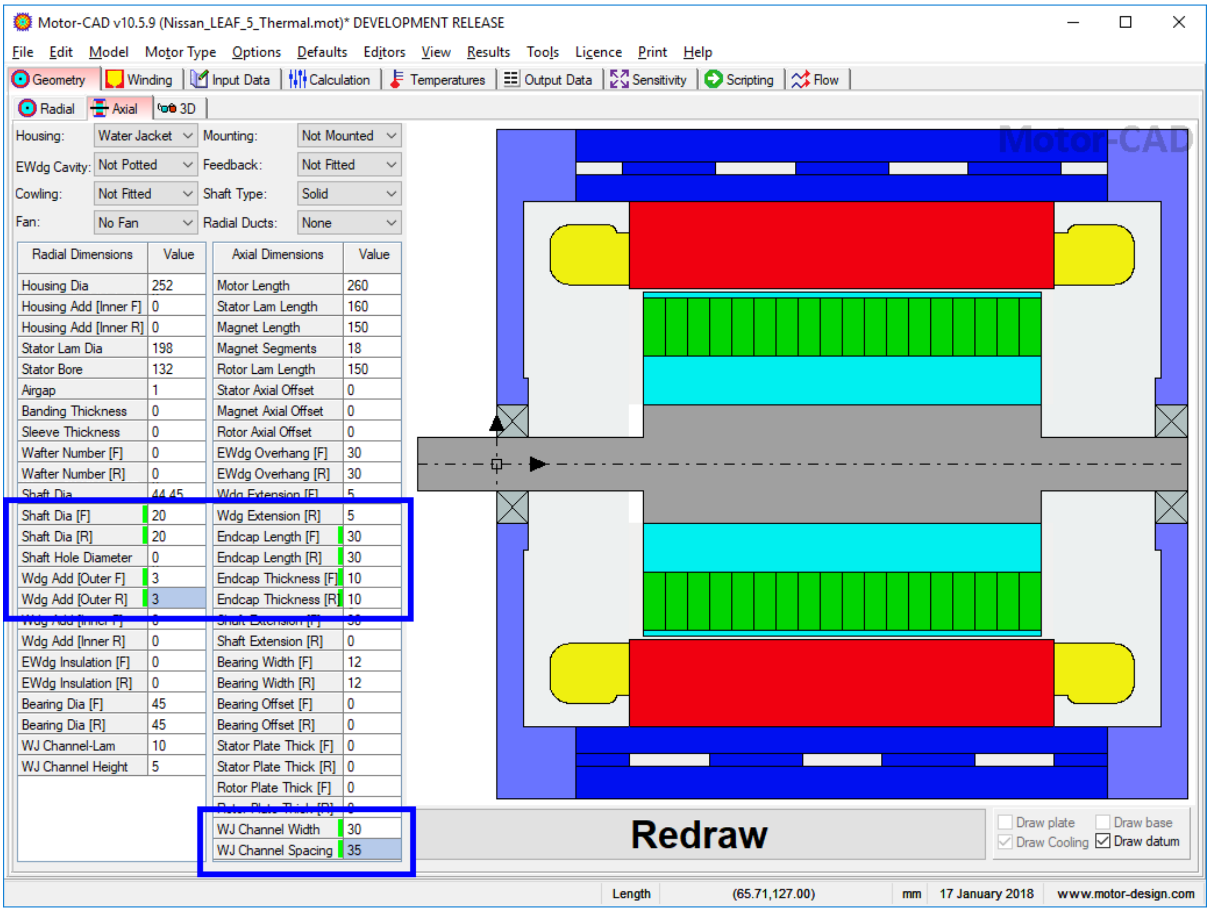


Recall: press **Enter** or click **Redraw** to update the drawing.

Under **Geometry -> Axial**, set the following:

Radial Parameter	Value	Units
Shaft Dia [F]	20	mm
Shaft Dia [R]	20	mm
Wdg Add [Outer F]	3	mm
Wdg Add [Outer R]	3	mm

Axial Parameter	Value	Units
Endcap Length [F]	30	mm
Endcap Length [R]	30	mm
Endcap Thickness [F]	10	mm
Endcap Thickness [R]	10	mm
WJ Channel Width	30	mm
WJ Channel Spacing	35	mm



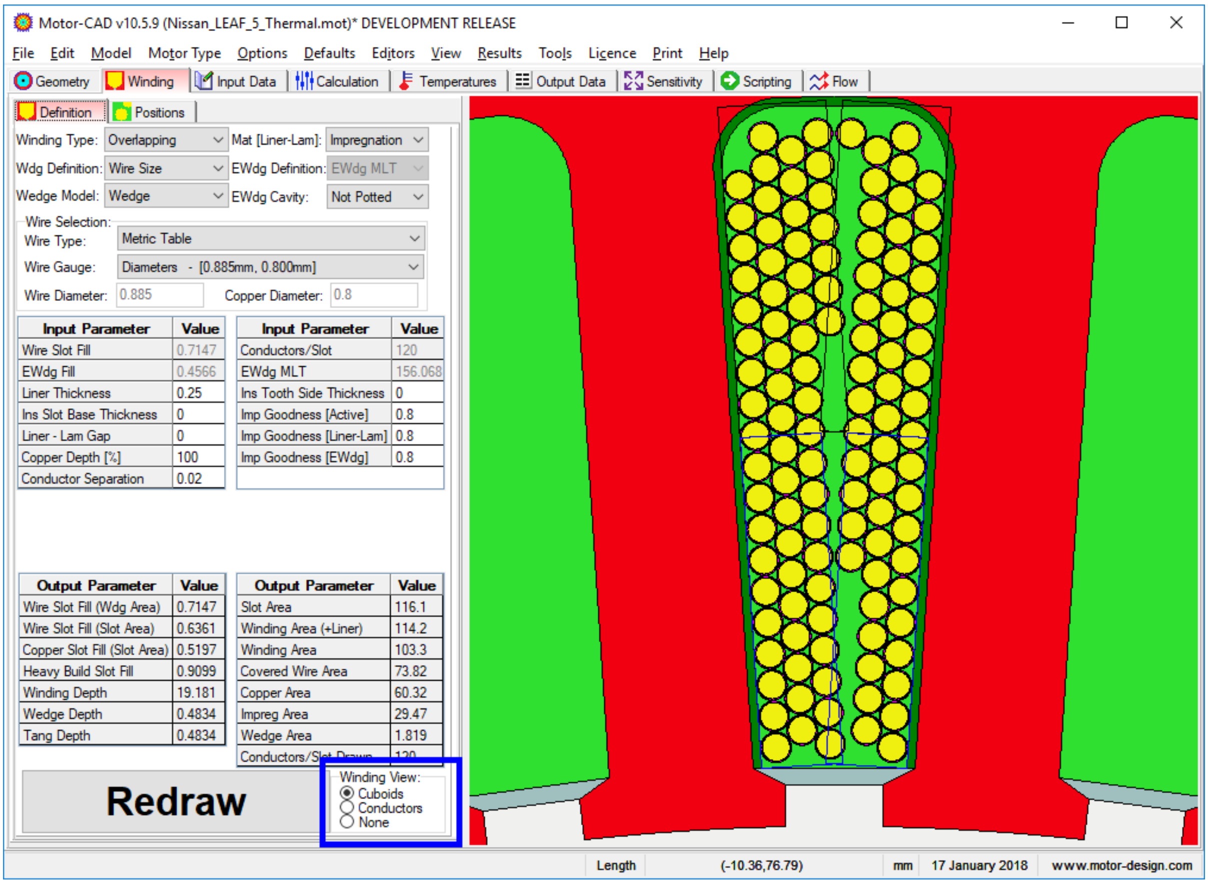
ii. Winding Model

The **Winding -> Definition** tab allows the configuration of the winding.

The winding pattern is not shown since it is used in the electromagnetic model only and instead the individual position of the conductors can be customised under **Winding -> Positions**. Usually this is not necessary since Motor-CAD automatically places the conductors in the slot based on common manufacturing methods, but it can be useful for advanced users. The conductor positions are also used for thermal FEA simulations.

The Motor-CAD model uses cuboids to represent the thermal behaviour of the winding within the lumped parameter network. The effective thermal conductivity and capacitance of each cuboid is calculate from the areas of copper, wire enamel and impregnation together with the material thermal properties. This allows an accurate, computationally efficient approximation of the thermal behaviour of the coils. A higher number of cuboids will increase the resolution of the model and is useful for machines with a non-uniform distribution of conductors or losses in the slot, but will also increase computation time in the thermal model.

The cuboids used in the model are drawn on the cross-section when the **Winding View** is set to **Cuboids**. The number of cuboids and their dimensions can be customised by dragging the cuboid outlines using the mouse or under **Input Data -> Settings -> Winding**, for now we will use the default cuboid definition.



iii. Cooling System Definition

The cooling setup is defined under **Input Data -> Cooling**, with options for individual cooling systems configured in separate tabs.

The water jacket is the main cooling path for this machine. We have already defined the geometry of the water jacket, and now we need to configure the options and fluid flow through the jacket.

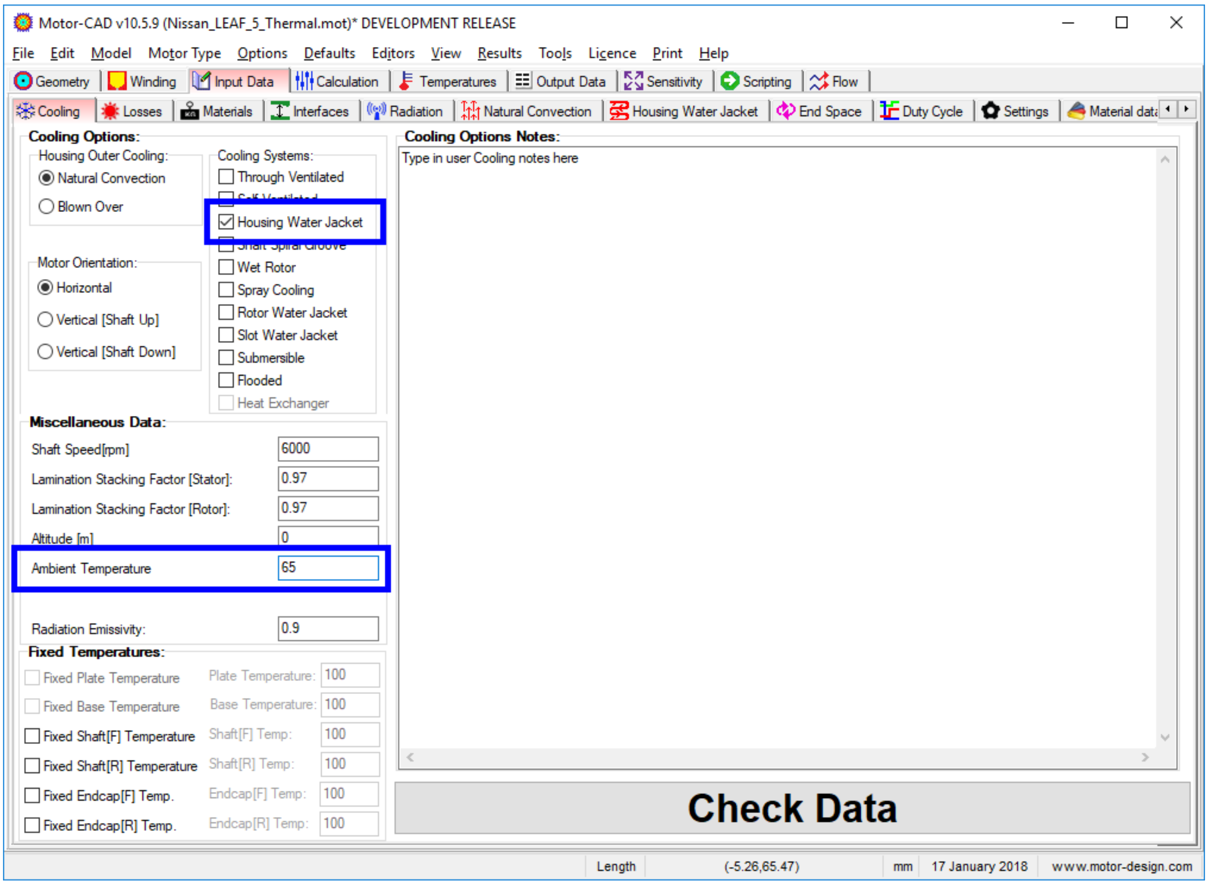
Under **Input Data -> Cooling**, the **Housing Water Jacket** option is automatically enabled. This is required to provide the cooling through the water jacket. Here other cooling types can be enabled and general options for the motor environment are configured.

There are several tutorials providing details of other cooling systems in Motor-CAD, these are available at https://www.motor-design.com/publications/tutorials/.

We change the following:

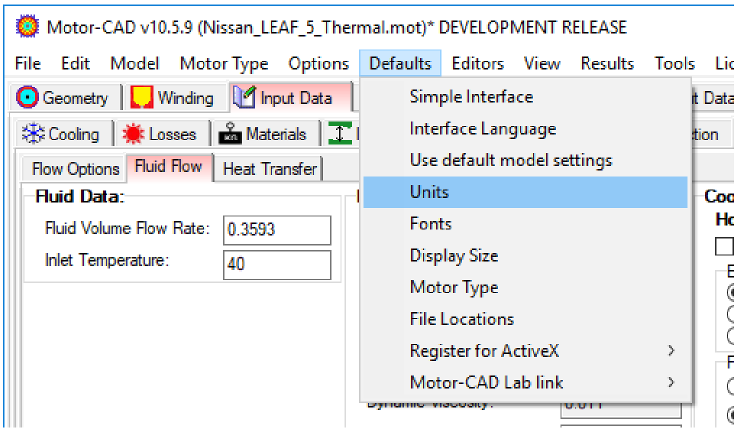
Parameter	Value	Units
Ambient Temperature	65	°C

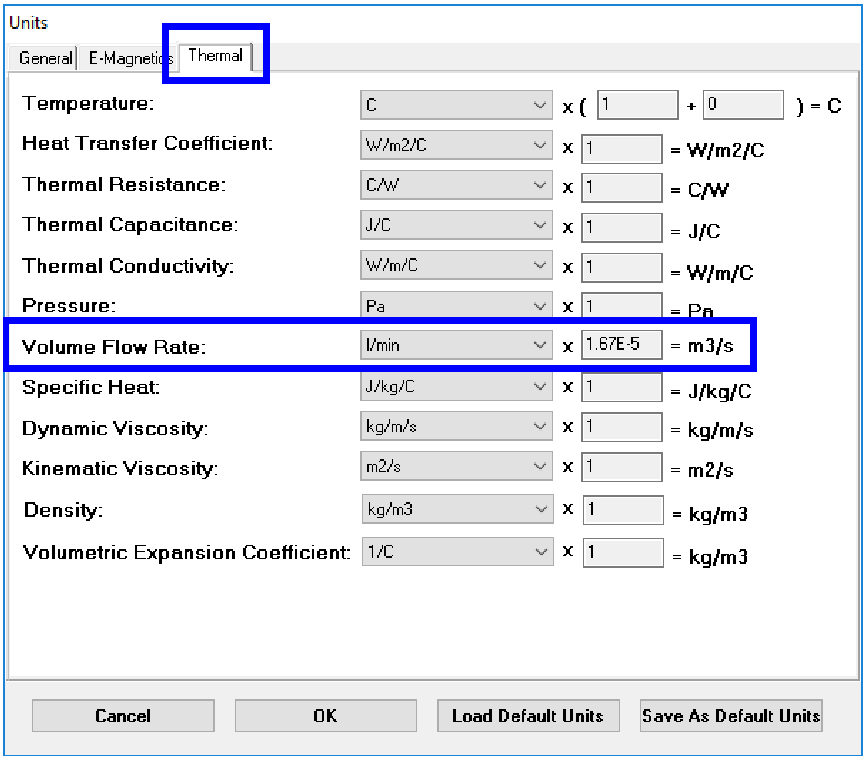
All other parameters are left at their default values. Note that the shaft speed of 6000rpm has been inherited from the E-Magnetic model, based on the last simulation that we performed.



Housing Water Jacket

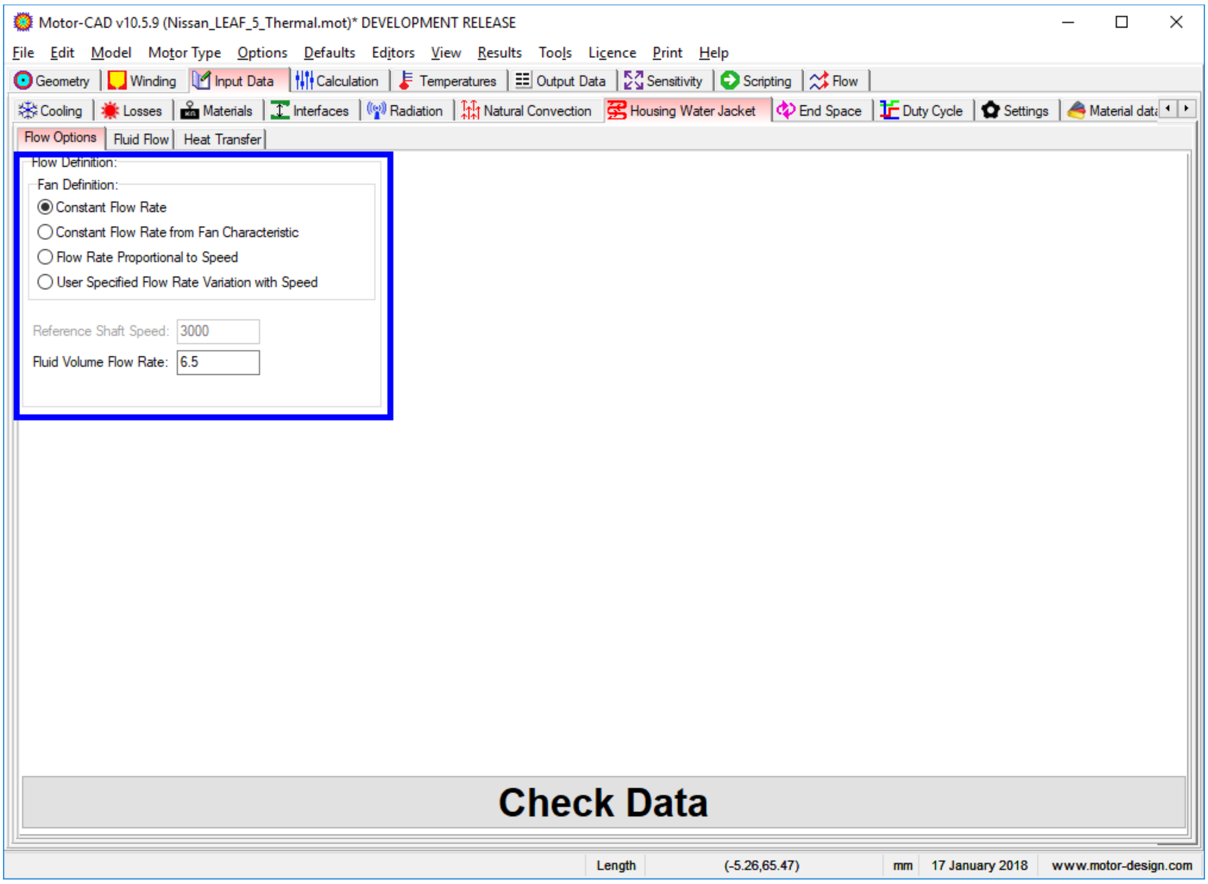
We will now configure the settings for the water jacket. The flow rate will be defined in litres per minute instead of the using the SI unit of m^3/s, so first we need to change the default unit using **Defaults -> Units** from the main menu. In the **Units** dialog, navigate to the **Thermal** tab and set the **Volume Flow Rate** unit to **l/min**. Click **OK** to save the new units.





Under **Input Data -> Housing Water Jacket -> Flow Options**, we set the basic flow options for the water jacket:

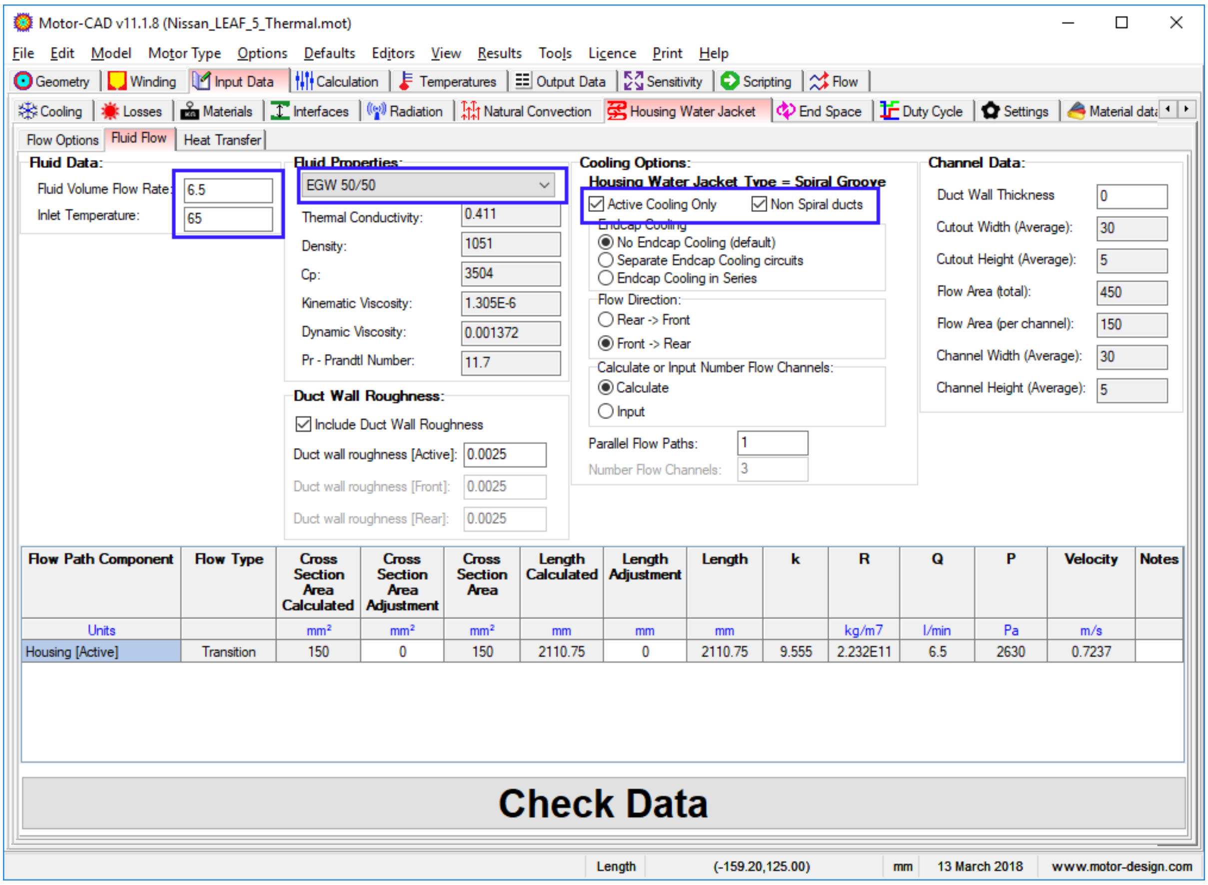
Parameter	Value	Units
Flow Definition	Constant Flow Rate	
Fluid Volume Flow Rate	6.5	l/min



Under **Input Data -> Housing Water Jacket -> Fluid Flow**, we define the fluid properties and other details of the flow through the water jacket:

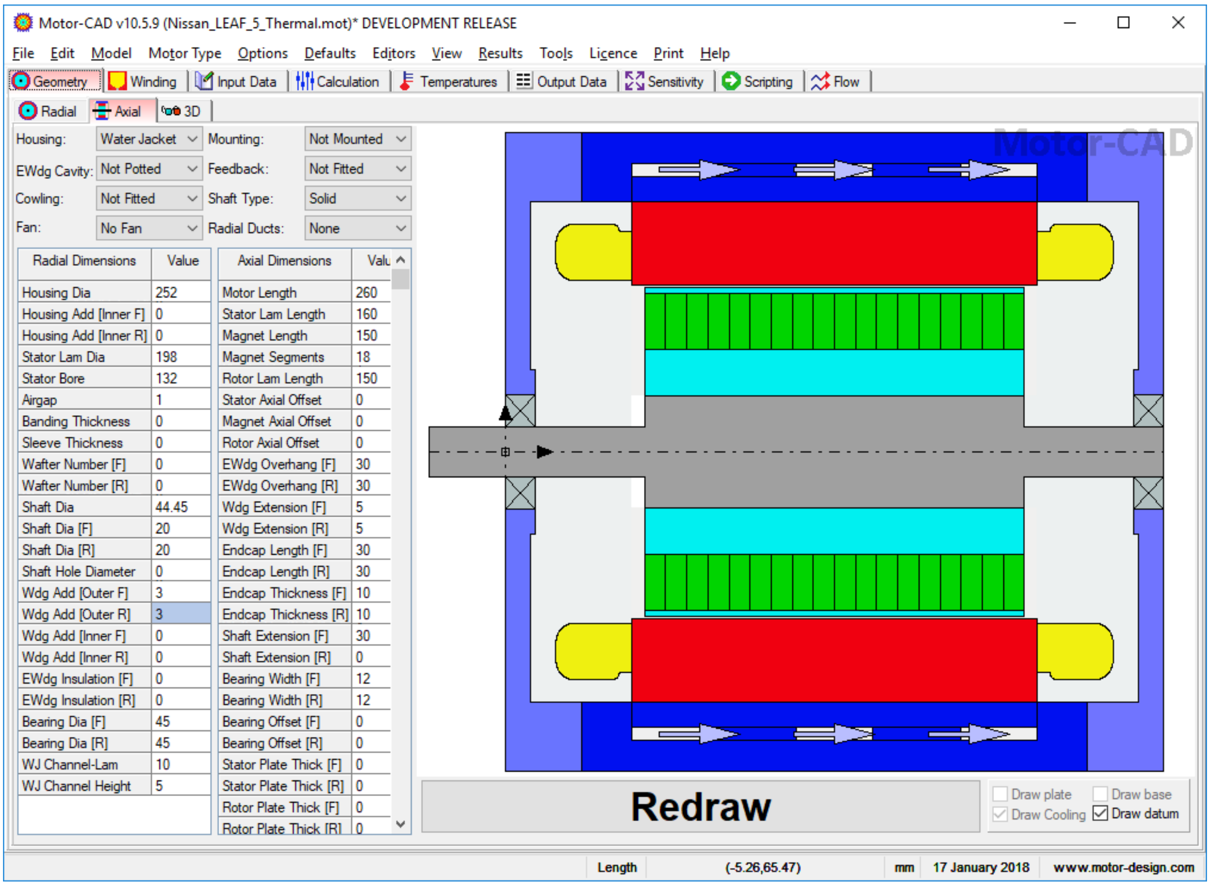
Parameter	Value	Units
Inlet Temperature	65	°C
Fluid Properties	EGW 50/50	
Include Duct Wall Roughness	Enabled	
Duct wall roughness	0.0025	
Active Cooling Only	Enabled	
Non Spiral Ducts	Enabled	
Endcap Cooling	No Endcap Cooling	
Flow Direction	Front -> Rear	
Calculate or Input Number Flow Channels	Calculate	
Parallel Flow Paths	1	
Duct Wall Thickness	0	mm

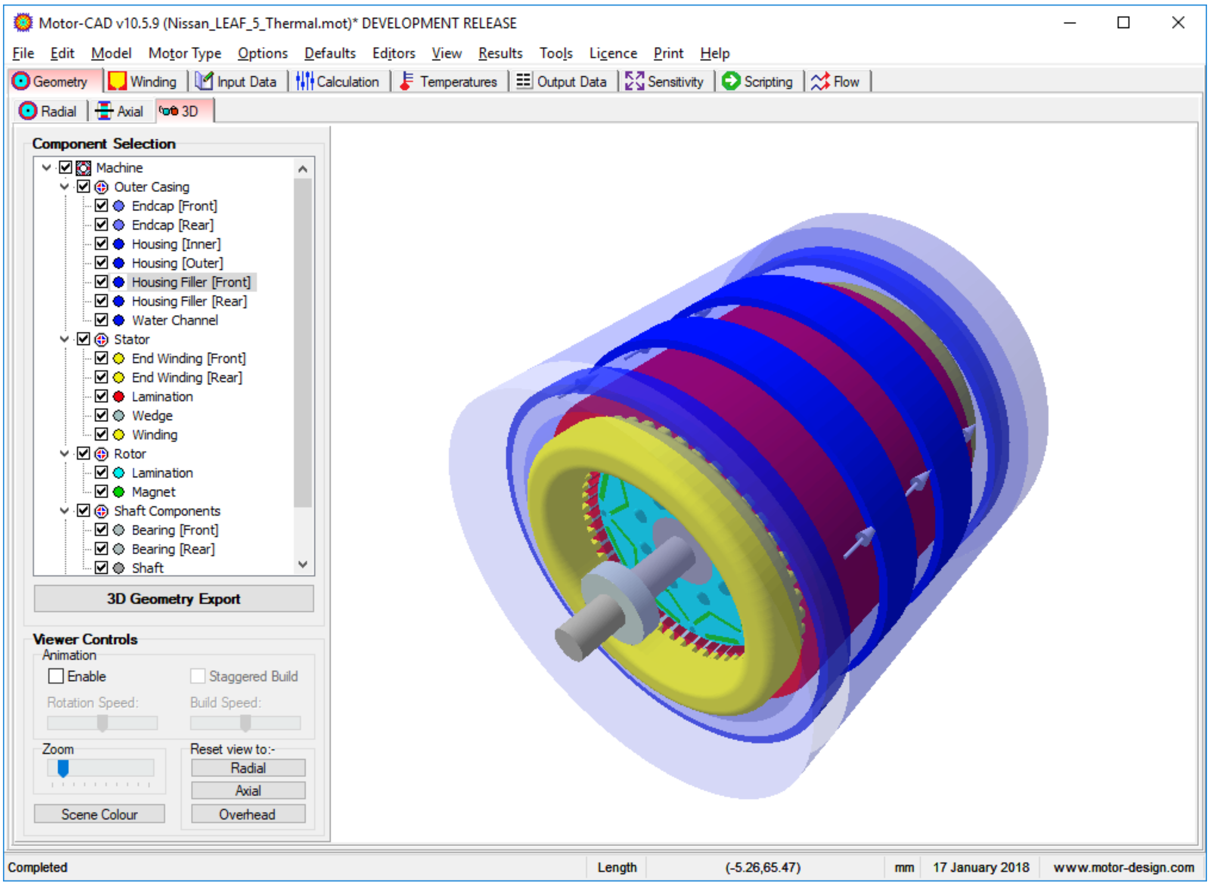
Here we have chosen define the fluid properties based on values from the database. The cooling fluid used is EGW50/50, a mix of ethylene glycol and water commonly used as a vehicle coolant. Motor-CAD has a default database of fluids which can be used. Custom fluids can be added or the database properties viewed and modified from the **Material Database -> Fluids** tab. For more information please refer to the Motor-CAD manual.



The fluid flow table shows the calculated area, flow rate and pressure values for the housing water jacket as well as other thermal parameters. Under the **Heat Transfer** tab, a similar table gives the calculated heat transfer parameters.

The final configuration of the water jacket can be visualised using cross-sectional or 3d views under the **Geometry** tab.


Motor-CAD v10.5.9 (Nissan_LEAF_5_Thermal.mot)* DEVELOPMENT RELEASE
File Edit Model Motor Type Options Defaults Editors View Results Tools Licence Print Help
Geometry Winding Input Data Calculation Temperatures Output Data Sensitivity Scripting Flow
Radial Axial 3D
Housing: Water Jacket
Mounting: Not Mounted
EWdg Cavity: Not Potted
Feedback: Not Fitted
Cowling: Not Fitted
Shaft Type: Solid
Fan: No Fan
Radial Ducts: None
Radial Dimensions Value
Housing Dia 252
Housing Add [Inner F] 0
Housing Add [Inner R] 0
Stator Lam Dia 198
Stator Bore 132
Airgap 1
Banding Thickness 0
Sleeve Thickness 0
Wafter Number [F] 0
Wafter Number [R] 0
Shaft Dia 44.45
Shaft Dia [F] 20
Shaft Dia [R] 20
Shaft Hole Diameter 0
Wdg Add [Outer F] 3
Wdg Add [Outer R] 3
Wdg Add [Inner F] 0
Wdg Add [Inner R] 0
EWdg Insulation [F] 0
EWdg Insulation [R] 0
Bearing Dia [F] 45
Bearing Dia [R] 45
WJ Channel-Lam 10
WJ Channel Height 5
Axial Dimensions Valu
Motor Length 260
Stator Lam Length 160
Magnet Length 150
Magnet Segments 18
Rotor Lam Length 150
Stator Axial Offset 0
Magnet Axial Offset 0
Rotor Axial Offset 0
EWdg Overhang [F] 30
EWdg Overhang [R] 30
Wdg Extension [F] 5
Wdg Extension [R] 5
Endcap Length [F] 30
Endcap Length [R] 30
Endcap Thickness [F] 10
Endcap Thickness [R] 10
Shaft Extension [F] 30
Shaft Extension [R] 0
Bearing Width [F] 12
Bearing Width [R] 12
Bearing Offset [F] 0
Bearing Offset [R] 0
Stator Plate Thick [F] 0
Stator Plate Thick [R] 0
Rotor Plate Thick [F] 0
Rotor Plate Thick [R] 0
Motor-CAD
Redraw
Draw plate
Draw base
Draw Cooling
Draw datum
Length
(-5.26,65.47)
mm
17 January 2018
www.motor-design.com

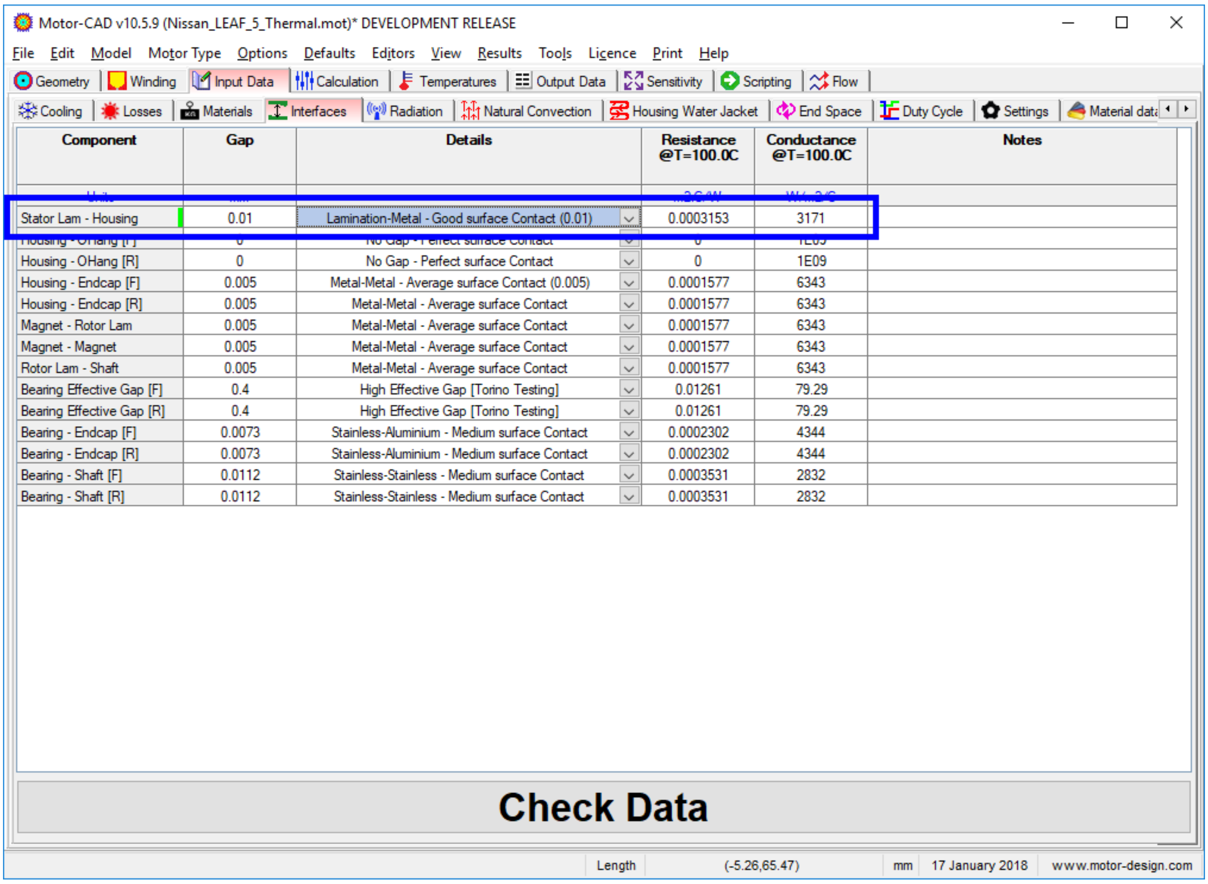

Motor-CAD v10.5.9 (Nissan_LEAF_5_Thermal.mot)* DEVELOPMENT RELEASE
File Edit Model Motor Type Options Defaults Editors View Results Tools Licence Print Help
Geometry Winding Input Data Calculation Temperatures Output Data Sensitivity Scripting Flow
Radial Axial 3D
Component Selection
Machine
Outer Casing
Endcap [Front]
Endcap [Rear]
Housing [Inner]
Housing [Outer]
Housing Filler [Front]
Housing Filler [Rear]
Water Channel
Stator
End Winding [Front]
End Winding [Rear]
Lamination
Wedge
Winding
Rotor
Lamination
Magnet
Shaft Components
Bearing [Front]
Bearing [Rear]
Shaft
3D Geometry Export
Viewer Controls
Animation
Enable
Staggered Build
Rotation Speed:
Build Speed:
Zoom
Reset view to:-
Radial
Axial
Scene Colour
Overhead
Completed
Length
(-5.26,65.47)
mm
17 January 2018
www.motor-design.com

Interface Gaps

Depending on manufacturing tolerances and the materials used the interface gaps between components can vary significantly. A larger interface gap will increase the thermal resistance between components and reduce the effectiveness of the cooling, which can result in large temperature rises in the machine. It is therefore important to configure the interface gaps in the thermal model in order to match the real-world conditions as closely as possible.

Typical values of the air gaps between components are provided in Motor-CAD based on significant experience and real-world testing. This helps the user to set up the model accurately without an in-depth knowledge of manufacturing processes.

For the Nissan LEAF most of the interface gaps automatically estimated by Motor-CAD are accurate. The gap between the stator lamination and the housing is better than average due to the manufacturing processes and so for the **Stator Lam – Housing** component we select **Lamination-Metal – Good surface contact (0.01)**.

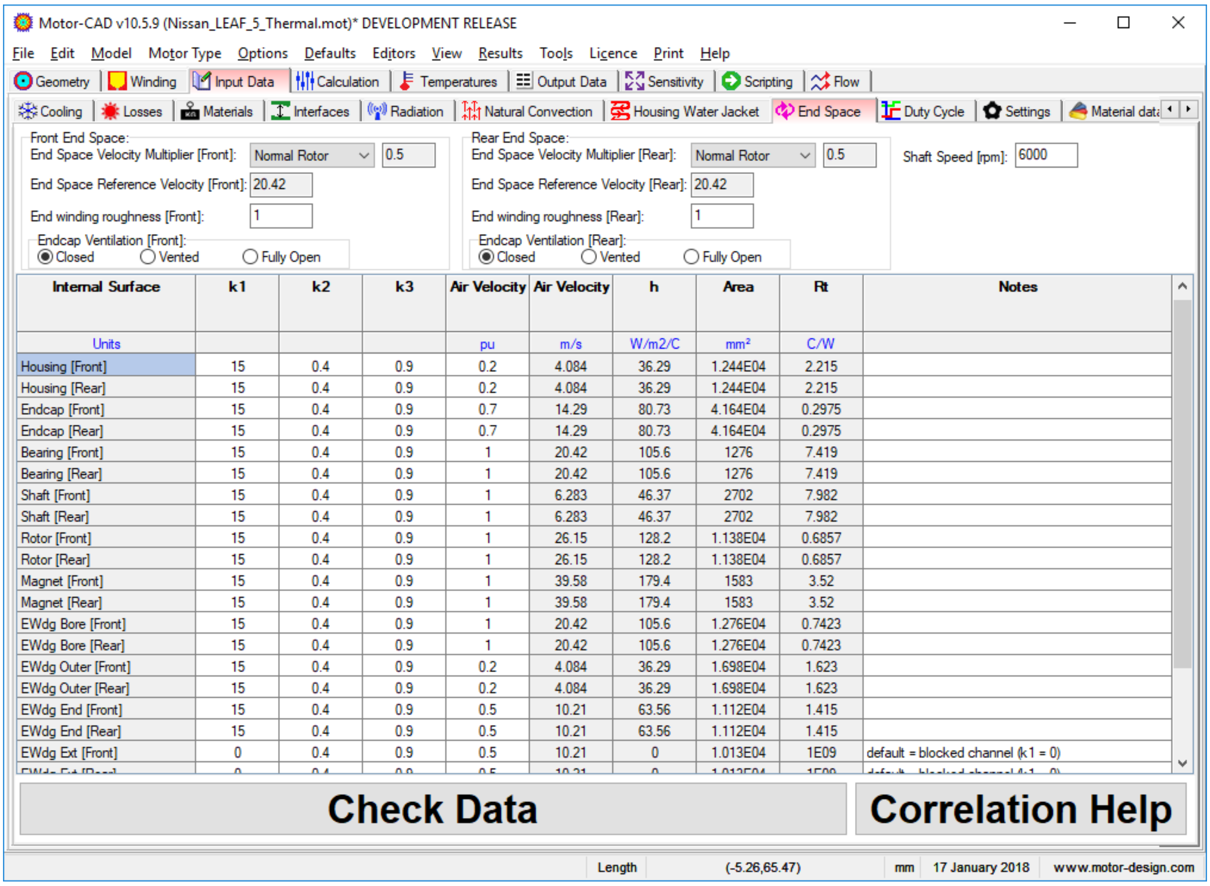


Component	Gap	Details	Resistance @T=100.0C	Conductance @T=100.0C	Notes
Stator Lam - Housing	0.01	Lamination-Metal - Good surface Contact (0.01)	0.0003153	3171	
Housing - OHang [F]	0	No Gap - Perfect surface Contact	0	1E09	
Housing - OHang [R]	0	No Gap - Perfect surface Contact	0	1E09	
Housing - Endcap [F]	0.005	Metal-Metal - Average surface Contact (0.005)	0.0001577	6343	
Housing - Endcap [R]	0.005	Metal-Metal - Average surface Contact	0.0001577	6343	
Magnet - Rotor Lam	0.005	Metal-Metal - Average surface Contact	0.0001577	6343	
Magnet - Magnet	0.005	Metal-Metal - Average surface Contact	0.0001577	6343	
Rotor Lam - Shaft	0.005	Metal-Metal - Average surface Contact	0.0001577	6343	
Bearing Effective Gap [F]	0.4	High Effective Gap [Torino Testing]	0.01261	79.29	
Bearing Effective Gap [R]	0.4	High Effective Gap [Torino Testing]	0.01261	79.29	
Bearing - Endcap [F]	0.0073	Stainless-Aluminium - Medium surface Contact	0.0002302	4344	
Bearing - Endcap [R]	0.0073	Stainless-Aluminium - Medium surface Contact	0.0002302	4344	
Bearing - Shaft [F]	0.0112	Stainless-Stainless - Medium surface Contact	0.0003531	2832	
Bearing - Shaft [R]	0.0112	Stainless-Stainless - Medium surface Contact	0.0003531	2832	

End Space Cooling

The end space cooling can be configured under **Input Data -> End Space**. Several different endcap cooling options are available including ventilation and wafters. For this model we have no extra cooling in the end space so we leave the values at their defaults.

The internal convection cooling from inside the endcaps (from end winding, rotor, endcaps, housing etc) is calculated automatically using empirical correlations based on experience and real-world testing. The calculated parameters for heat dissipation are shown in the table here and can be modified, though this is not usually necessary to achieve a good result.



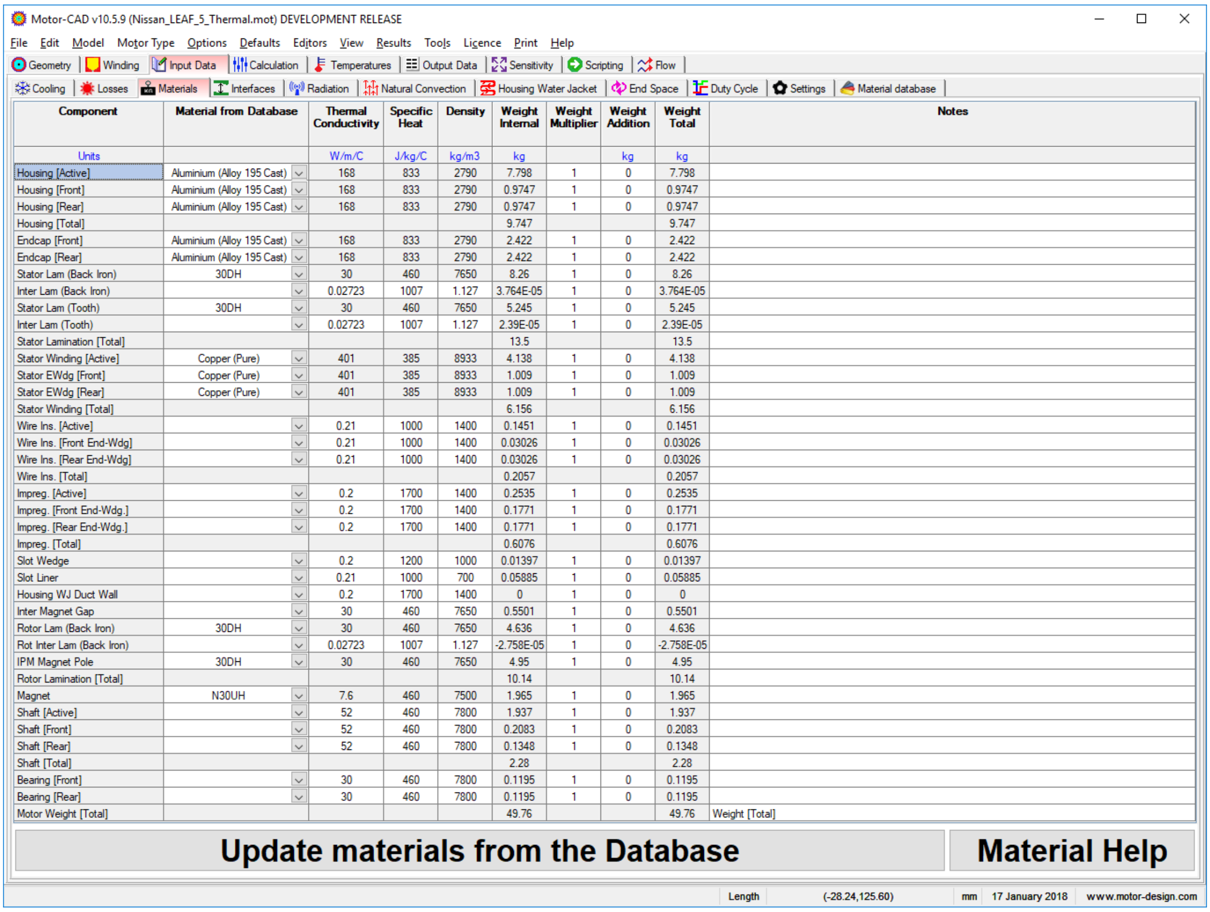
Internal Surface	k1	k2	k3	Air Velocity	Air Velocity	h	Area	Rt	Notes
Units				pu	m/s	W/m2/C	mm²	C/W	
Housing [Front]	15	0.4	0.9	0.2	4.084	36.29	1.244E04	2.215	
Housing [Rear]	15	0.4	0.9	0.2	4.084	36.29	1.244E04	2.215	
Endcap [Front]	15	0.4	0.9	0.7	14.29	80.73	4.164E04	0.2975	
Endcap [Rear]	15	0.4	0.9	0.7	14.29	80.73	4.164E04	0.2975	
Bearing [Front]	15	0.4	0.9	1	20.42	105.6	1276	7.419	
Bearing [Rear]	15	0.4	0.9	1	20.42	105.6	1276	7.419	
Shaft [Front]	15	0.4	0.9	1	6.283	46.37	2702	7.982	
Shaft [Rear]	15	0.4	0.9	1	6.283	46.37	2702	7.982	
Rotor [Front]	15	0.4	0.9	1	26.15	128.2	1.138E04	0.6857	
Rotor [Rear]	15	0.4	0.9	1	26.15	128.2	1.138E04	0.6857	
Magnet [Front]	15	0.4	0.9	1	39.58	179.4	1583	3.52	
Magnet [Rear]	15	0.4	0.9	1	39.58	179.4	1583	3.52	
EWdg Bore [Front]	15	0.4	0.9	1	20.42	105.6	1.276E04	0.7423	
EWdg Bore [Rear]	15	0.4	0.9	1	20.42	105.6	1.276E04	0.7423	
EWdg Outer [Front]	15	0.4	0.9	0.2	4.084	36.29	1.698E04	1.623	
EWdg Outer [Rear]	15	0.4	0.9	0.2	4.084	36.29	1.698E04	1.623	
EWdg End [Front]	15	0.4	0.9	0.5	10.21	63.56	1.112E04	1.415	
EWdg End [Rear]	15	0.4	0.9	0.5	10.21	63.56	1.112E04	1.415	
EWdg Ext [Front]	0	0.4	0.9	0.5	10.21	0	1.013E04	1E09	default = blocked channel (k1 = 0)

Advanced Cooling Options

The **Radiation** and **Natural Convection** tabs under **Input Data** provide further options for customising the model. As with the end space cooling, coefficients and settings here are calculated based on extensive experience and testing, and typically do not need to be modified to achieve a good result.

iv. Materials Input

The thermal properties of the materials can be configured in the **Input Data -> Materials** tab. The interface is similar to the electromagnetic model but here there are more components to configure. The total motor weight now includes the thermal components (e.g. housing, mounting, etc).



Component	Material from Database	Thermal Conductivity	Specific Heat	Density	Weight Internal	Weight Multiplier	Weight Addition	Weight Total	Notes
Units		W/m/C	J/kg/C	kg/m3	kg		kg	kg	
Housing [Active]	Aluminium (Alloy 195 Cast)	168	833	2790	7.798	1	0	7.798	
Housing [Front]	Aluminium (Alloy 195 Cast)	168	833	2790	0.9747	1	0	0.9747	
Housing [Rear]	Aluminium (Alloy 195 Cast)	168	833	2790	0.9747	1	0	0.9747	
Housing [Total]					9.747			9.747	
Endcap [Front]	Aluminium (Alloy 195 Cast)	168	833	2790	2.422	1	0	2.422	
Endcap [Rear]	Aluminium (Alloy 195 Cast)	168	833	2790	2.422	1	0	2.422	
Stator Lam (Back Iron)	30DH	30	460	7650	8.26	1	0	8.26	
Inter Lam (Back Iron)		0.02723	1007	1.127	3.764E-05	1	0	3.764E-05	
Stator Lam (Tooth)	30DH	30	460	7650	5.245	1	0	5.245	
Inter Lam (Tooth)		0.02723	1007	1.127	2.39E-05	1	0	2.39E-05	
Stator Lamination [Total]					13.5			13.5	
Stator Winding [Active]	Copper (Pure)	401	385	8933	4.138	1	0	4.138	
Stator EWdg [Front]	Copper (Pure)	401	385	8933	1.009	1	0	1.009	
Stator EWdg [Rear]	Copper (Pure)	401	385	8933	1.009	1	0	1.009	
Stator Winding [Total]					6.156			6.156	
Wire Ins. [Active]		0.21	1000	1400	0.1451	1	0	0.1451	
Wire Ins. [Front End-Wdg]		0.21	1000	1400	0.03026	1	0	0.03026	
Wire Ins. [Rear End-Wdg]		0.21	1000	1400	0.03026	1	0	0.03026	
Wire Ins. [Total]					0.2057			0.2057	
Impreg. [Active]		0.2	1700	1400	0.2535	1	0	0.2535	
Impreg. [Front End-Wdg.]		0.2	1700	1400	0.1771	1	0	0.1771	
Impreg. [Rear End-Wdg.]		0.2	1700	1400	0.1771	1	0	0.1771	
Impreg. [Total]					0.6076			0.6076	
Slot Wedge		0.2	1200	1000	0.01397	1	0	0.01397	
Slot Liner		0.21	1000	700	0.05885	1	0	0.05885	
Housing WJ Duct Wall		0.2	1700	1400	0	1	0	0	
Inter Magnet Gap		30	460	7650	0.5501	1	0	0.5501	
Rotor Lam (Back Iron)	30DH	30	460	7650	4.636	1	0	4.636	
Rot Inter Lam (Back Iron)		0.02723	1007	1.127	-2.758E-05	1	0	-2.758E-05	
IPM Magnet Pole	30DH	30	460	7650	4.95	1	0	4.95	
Rotor Lamination [Total]					10.14			10.14	
Magnet	N30UH	7.6	460	7500	1.965	1	0	1.965	
Shaft [Active]		52	460	7800	1.937	1	0	1.937	
Shaft [Front]		52	460	7800	0.2083	1	0	0.2083	
Shaft [Rear]		52	460	7800	0.1348	1	0	0.1348	
Shaft [Total]					2.28			2.28	
Bearing [Front]		30	460	7800	0.1195	1	0	0.1195	
Bearing [Rear]		30	460	7800	0.1195	1	0	0.1195	
Motor Weight [Total]					49.76			49.76	Weight [Total]

v. Losses

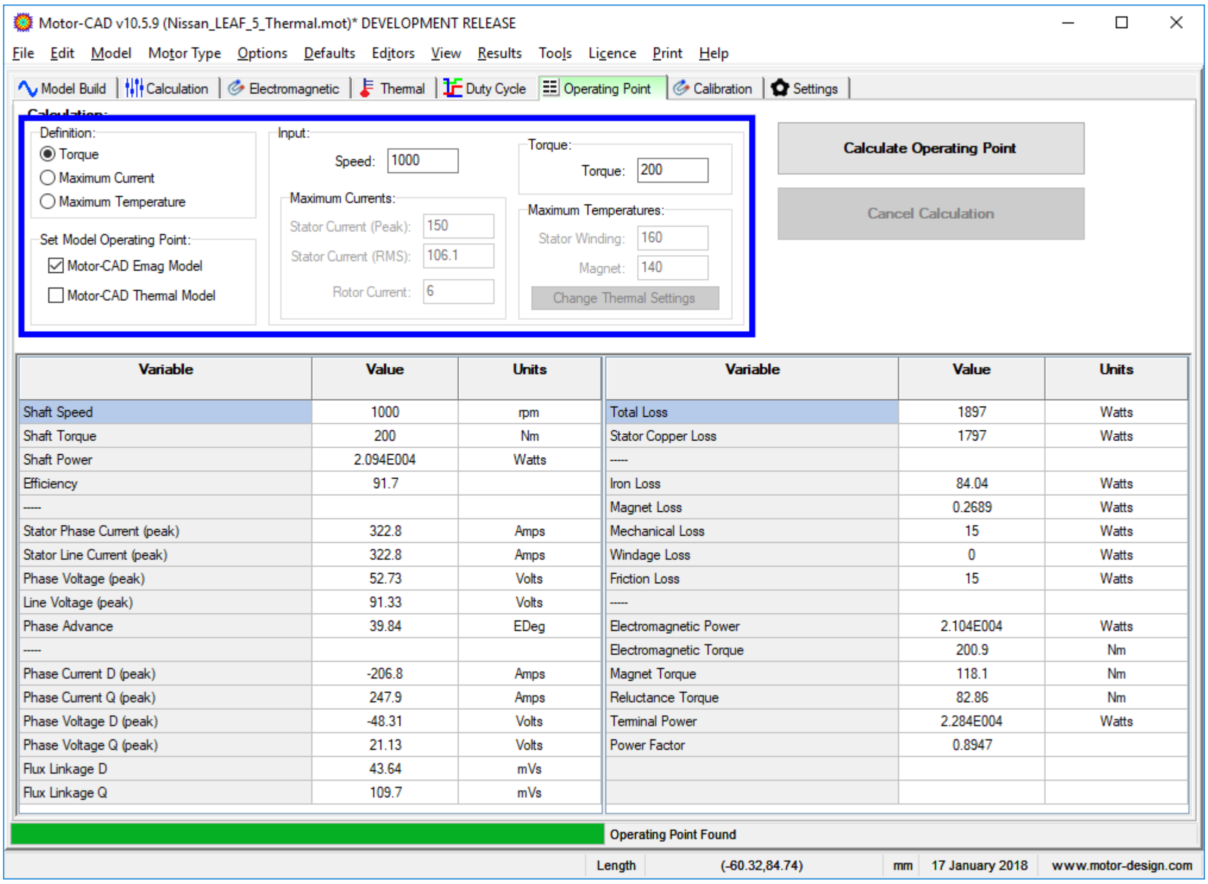
The machine losses are specified under the **Input Data -> Losses -> Loss Models** tab. The losses can be input directly for different components or the losses can be set automatically from the E-Magnetic or Lab modules based on the calculated values. There are several different loss models allowing for the losses to vary with speed and temperature. In this example we will use the results from the electromagnetic calculation to set the component losses.

We will start by simulating a low-speed operating point, using the Lab module to find the operating conditions. Switch to the Lab context using **Menu->Model -> Lab**.

Navigate to the **Operating Point** tab and set the following parameters:

Parameter	Value	Units
Definition	Torque	
Speed	1000	rpm
Torque	200	Nm
Set Motor-CAD Emag Model	Enabled	
Set Motor-CAD Thermal Model	Disabled	

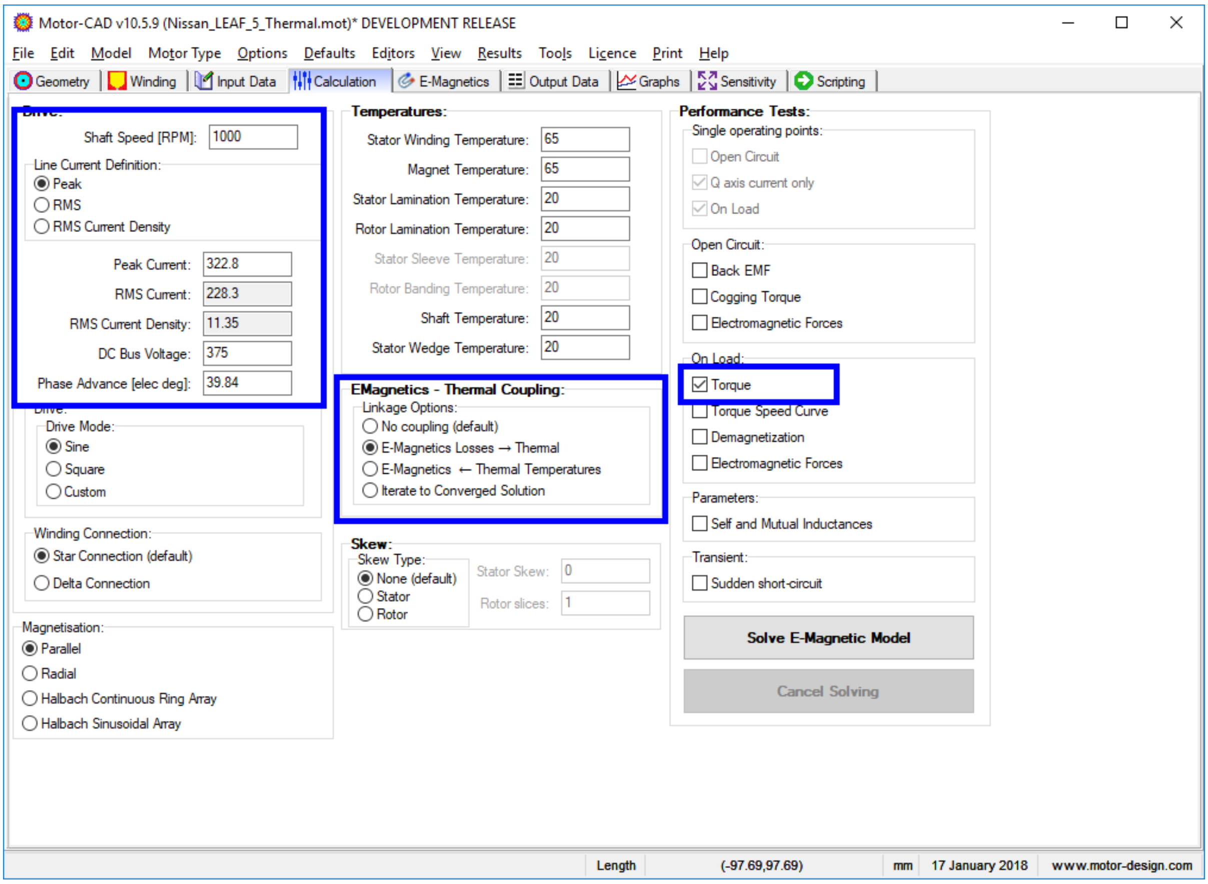
Click **Calculate Operating Point**. Once the calculation is complete, the results will be shown and the calculated current & phase advance values will be set in the E-Magnetic model. Note that we could directly set the losses into the Thermal model here by enabling the **Set Motor-CAD Thermal Model** checkbox, however here will demonstrate how the losses can be transferred from the E-Magnetic model.



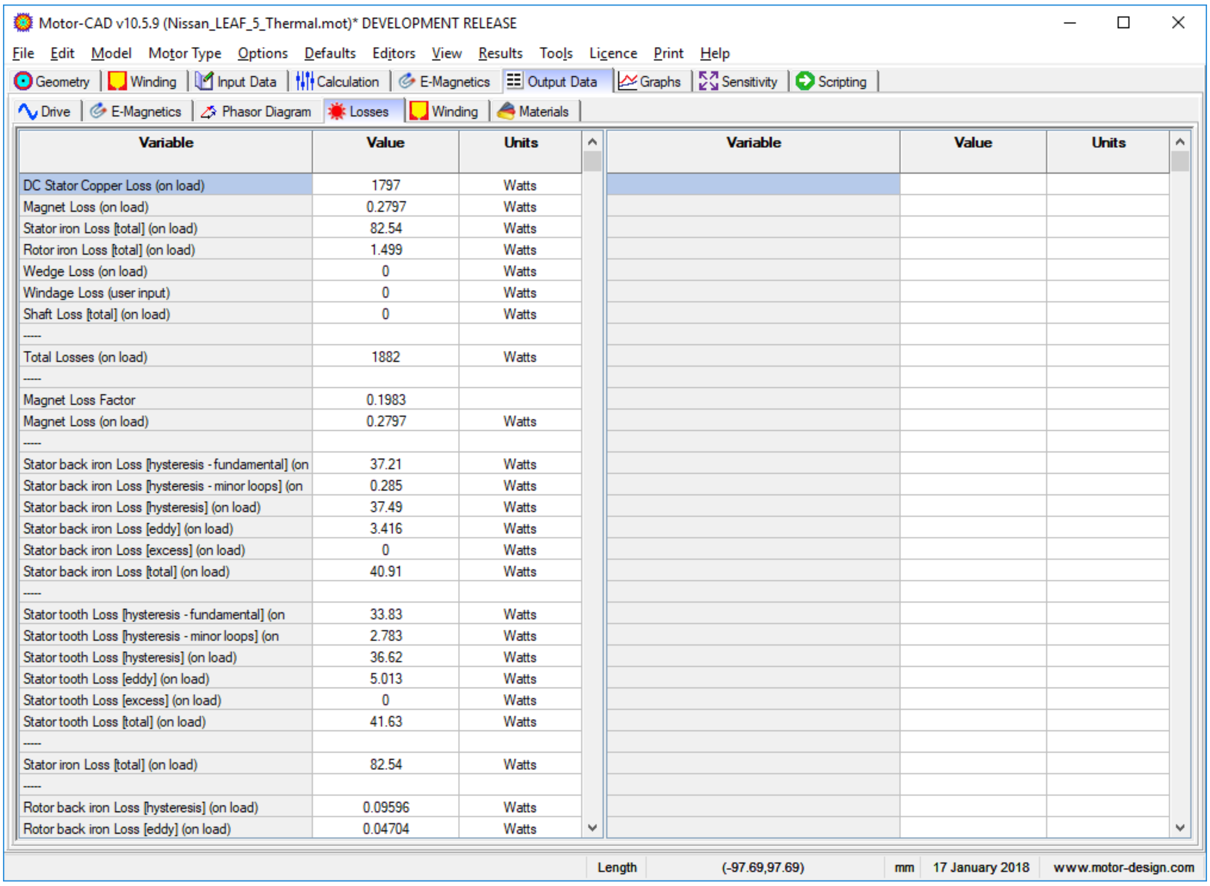
Switch to the electromagnetic module using **Menu->Model -> E-Magnetic**.

In the **Calculation** tab check that the operating conditions have been set correctly and ensure that the **Torque** calculation is selected to ensure an accurate loss calculation. Also set the **E-Magnetics - Thermal Coupling** option to **E-Magnetics Losses -> Thermal** so that the calculated loss values will be transferred automatically to the thermal model.

Here we can also import the temperatures from the solved thermal model or run a coupled solution where the electromagnetic and thermal models are solved iteratively to converge the loss and temperature values.



Now **Solve** the model. Once solving is completed, check the loss values under **Output Data -> Losses**.



Variable	Value	Units
DC Stator Copper Loss (on load)	1797	Watts
Magnet Loss (on load)	0.2797	Watts
Stator iron Loss [total] (on load)	82.54	Watts
Rotor iron Loss [total] (on load)	1.499	Watts
Wedge Loss (on load)	0	Watts
Windage Loss (user input)	0	Watts
Shaft Loss [total] (on load)	0	Watts

Total Losses (on load)	1882	Watts

Magnet Loss Factor	0.1983	
Magnet Loss (on load)	0.2797	Watts

Stator back iron Loss [hysteresis - fundamental] (on	37.21	Watts
Stator back iron Loss [hysteresis - minor loops] (on	0.285	Watts
Stator back iron Loss [hysteresis] (on load)	37.49	Watts
Stator back iron Loss [eddy] (on load)	3.416	Watts
Stator back iron Loss [excess] (on load)	0	Watts
Stator back iron Loss [total] (on load)	40.91	Watts

Stator tooth Loss [hysteresis - fundamental] (on	33.83	Watts
Stator tooth Loss [hysteresis - minor loops] (on	2.783	Watts
Stator tooth Loss [hysteresis] (on load)	36.62	Watts
Stator tooth Loss [eddy] (on load)	5.013	Watts
Stator tooth Loss [excess] (on load)	0	Watts
Stator tooth Loss [total] (on load)	41.63	Watts

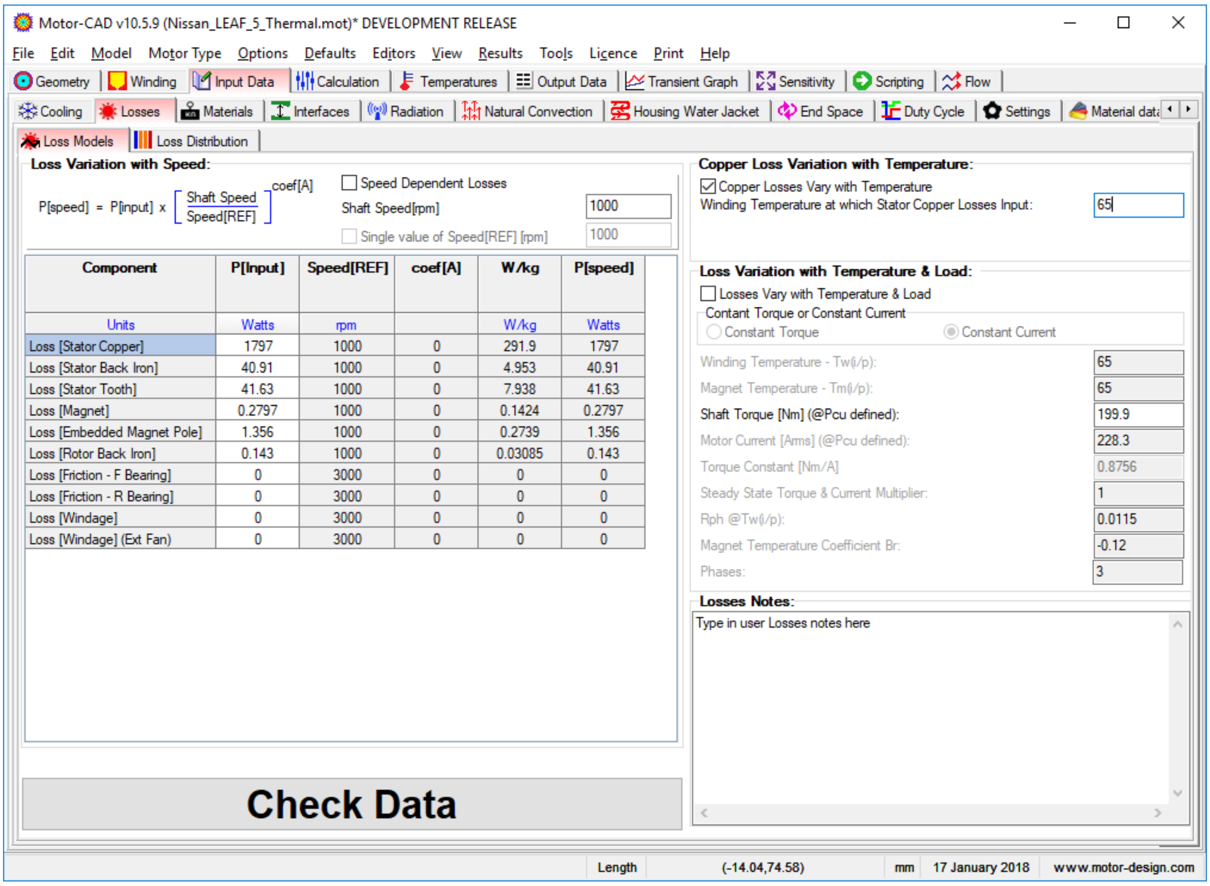
Stator iron Loss [total] (on load)	82.54	Watts

Rotor back iron Loss [hysteresis] (on load)	0.09596	Watts
Rotor back iron Loss [eddy] (on load)	0.04704	Watts

Return to the thermal model using **Menu->Model -> Thermal** and check the imported loss values under **Losses -> Loss Models**.

Here we also set the following loss model options:

Parameter	Value	Units
Speed Dependent Losses	Disabled	
Single value of Speed [REF]	Disabled	
Copper Loss Variation with Temperature	Enabled	
Winding Temperature at which Stator Copper Losses Input	65	°C
Losses Vary with Temperature & Load	Disabled	



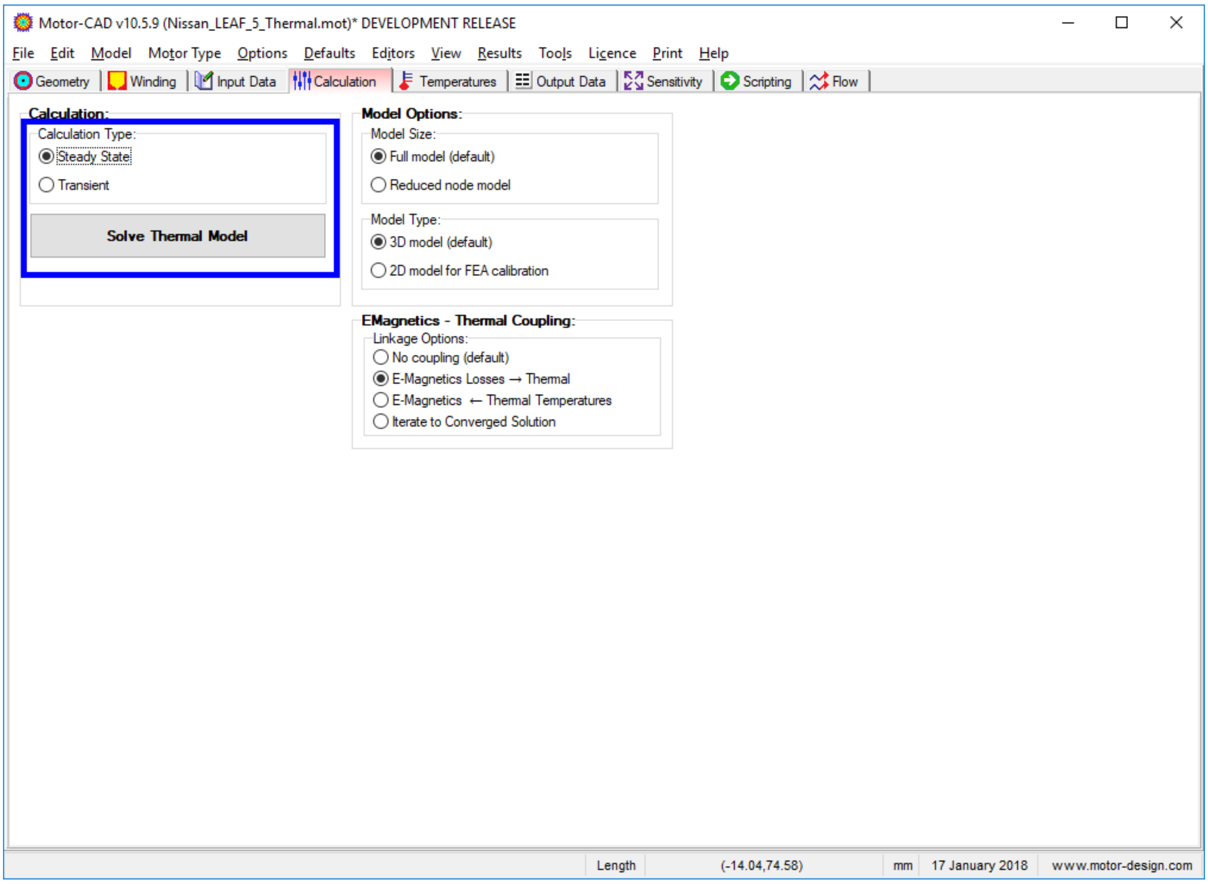
Note that there are no mechanical losses transferred as these are not currently calculated in the electromagnetic model. Friction losses can be input by the user, and windage losses can either be input directly or calculated automatically by Motor-CAD based on the fluid properties. For more details please refer to the Motor-CAD manual.

7. Thermal Analysis

Based on the input geometry, losses and model settings Motor-CAD creates a 3D lumped parameter circuit model to characterise the thermal behaviour of the machine. Each component is represented with a thermal resistance and capacitance. Losses are represented as power sources, and power is dissipated to the ambient node by the cooling systems. By solving this equivalent thermal circuit Motor-CAD can accurately estimate the temperatures in each part of the machine.

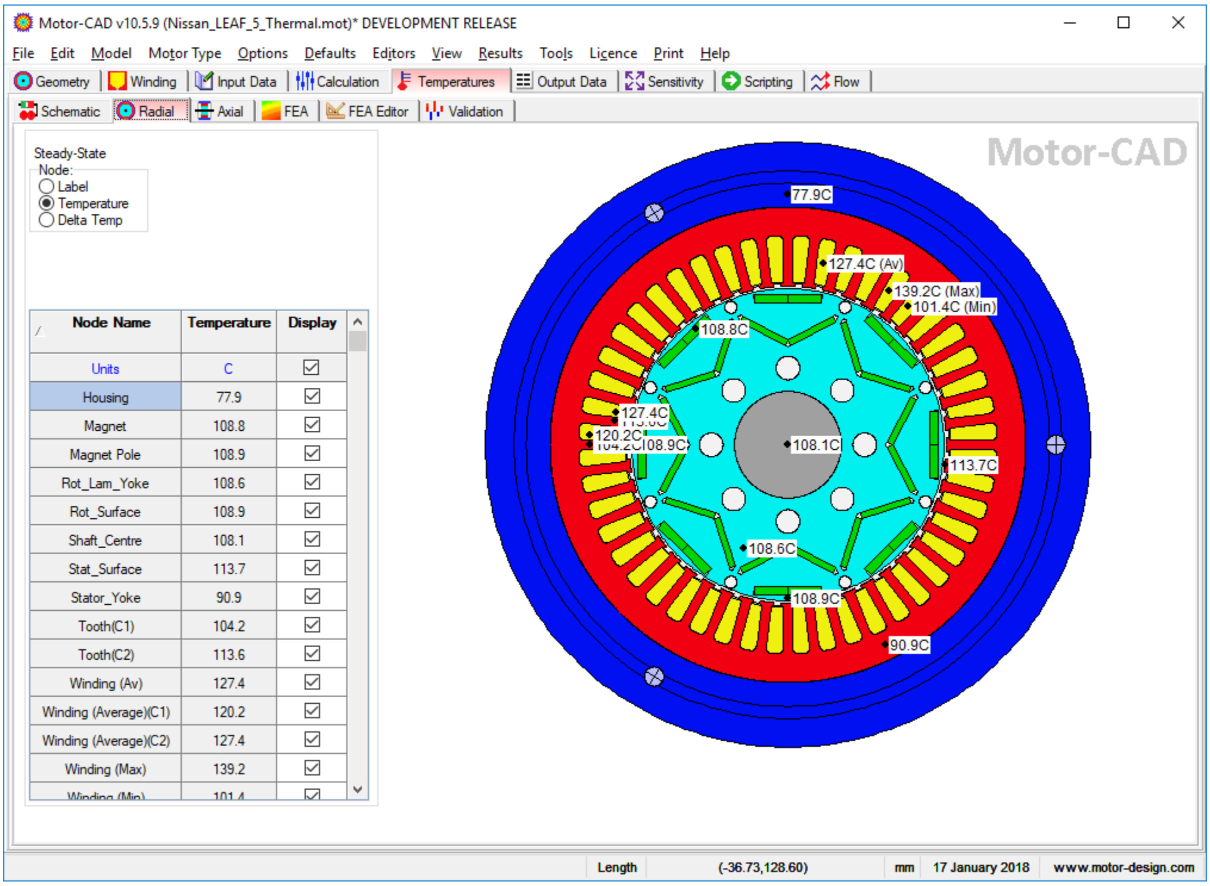
i. Steady-State Calculation

Under the **Calculation** tab, we make sure the **Calculation Type** is set to **Steady State** and click **Solve Thermal Model** or press **Ctrl+R** to run the calculation.



When solving is complete Motor-CAD will automatically show the results. Under the **Temperatures -> Radial** and **Temperatures -> Axial** tabs we can view the final machine temperatures on the radial/axial cross-section drawings.

Throughout the thermal module the colours used to represent components in the model match those used in the cross-section drawings.



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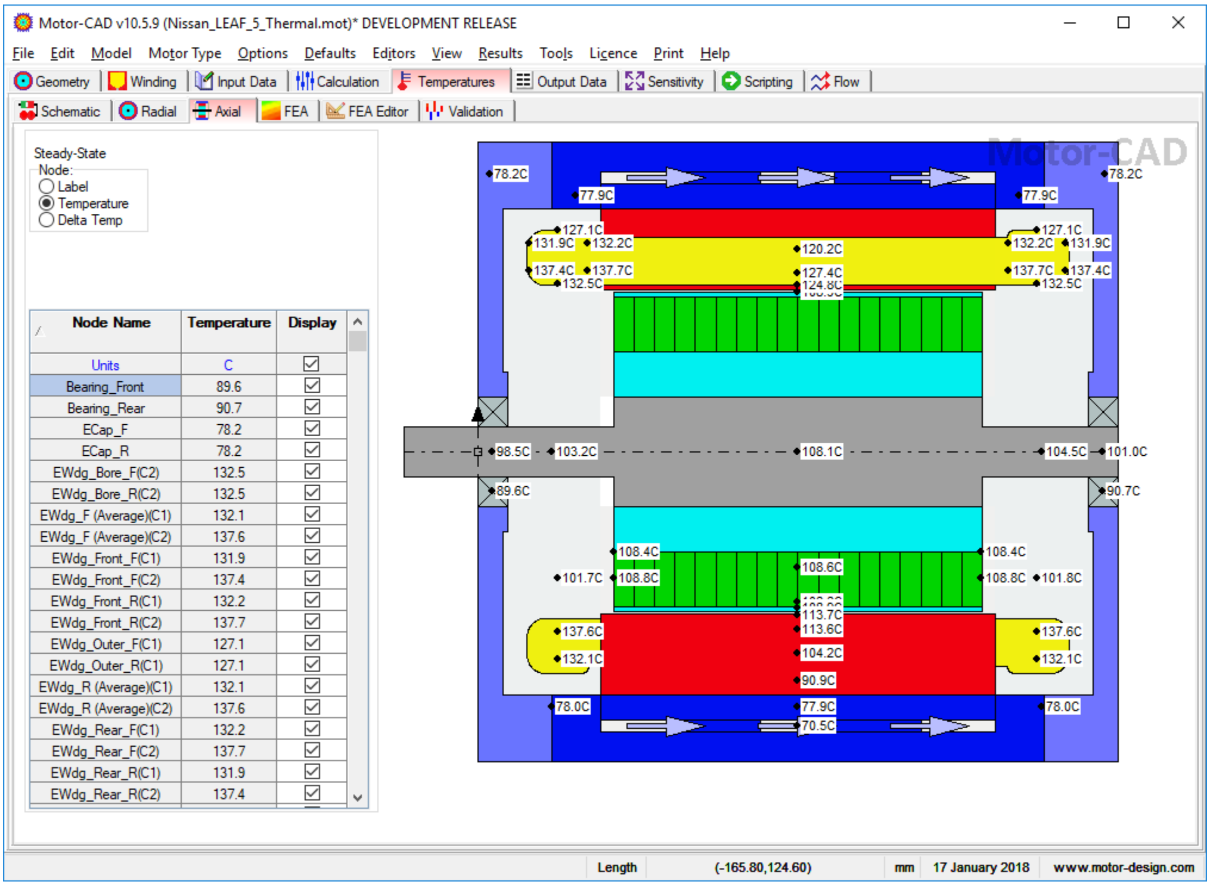
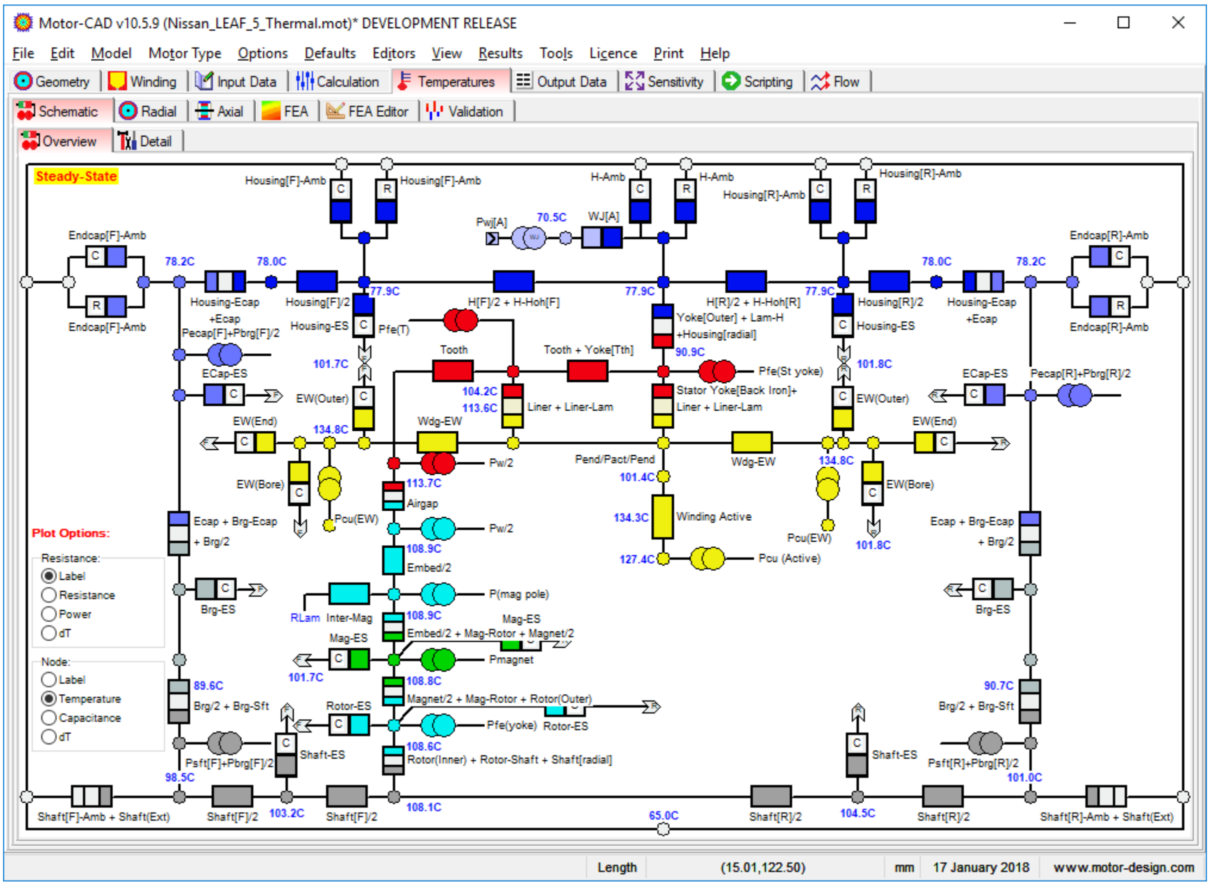


ii. Lumped Parameter Thermal Model

As described above Motor-CAD's thermal model is based on creating and solving a lumped parameter thermal network. The **Temperatures -> Schematic -> Overview** tab shows a schematic overview of the solved network.

From top to bottom, the schematic is laid out as follows: the shaft at the bottom of the schematic with the bearings and the endcaps on both sides, left and right. Following in the centre of the schematic and connected to the shaft is the rotor lamination, the interior magnets, the rotor again, the airgap, the winding (with the active part and the end-windings), the stator lamination, the housing with the water jacket as a heat extractor and the ambient surrounding the model with natural convection and radiation.

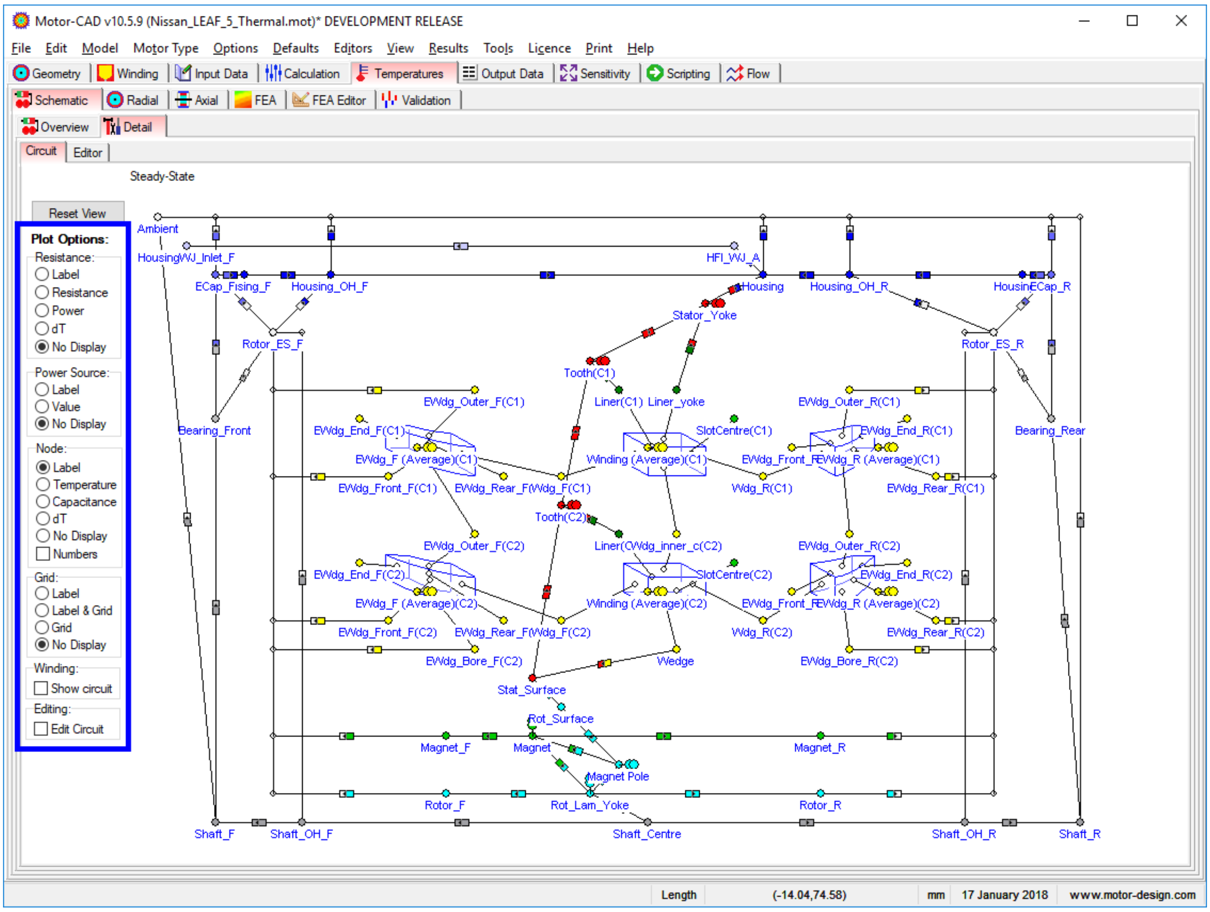
The colours used in the schematic match those used in the cross-sectional and 3d drawings.



The complete thermal network can be viewed under **Temperatures -> Schematic -> Detail -> Circuit**. This is similar to the schematic view shown above but provides more detail on the complete thermal circuit, including all connections between the components.

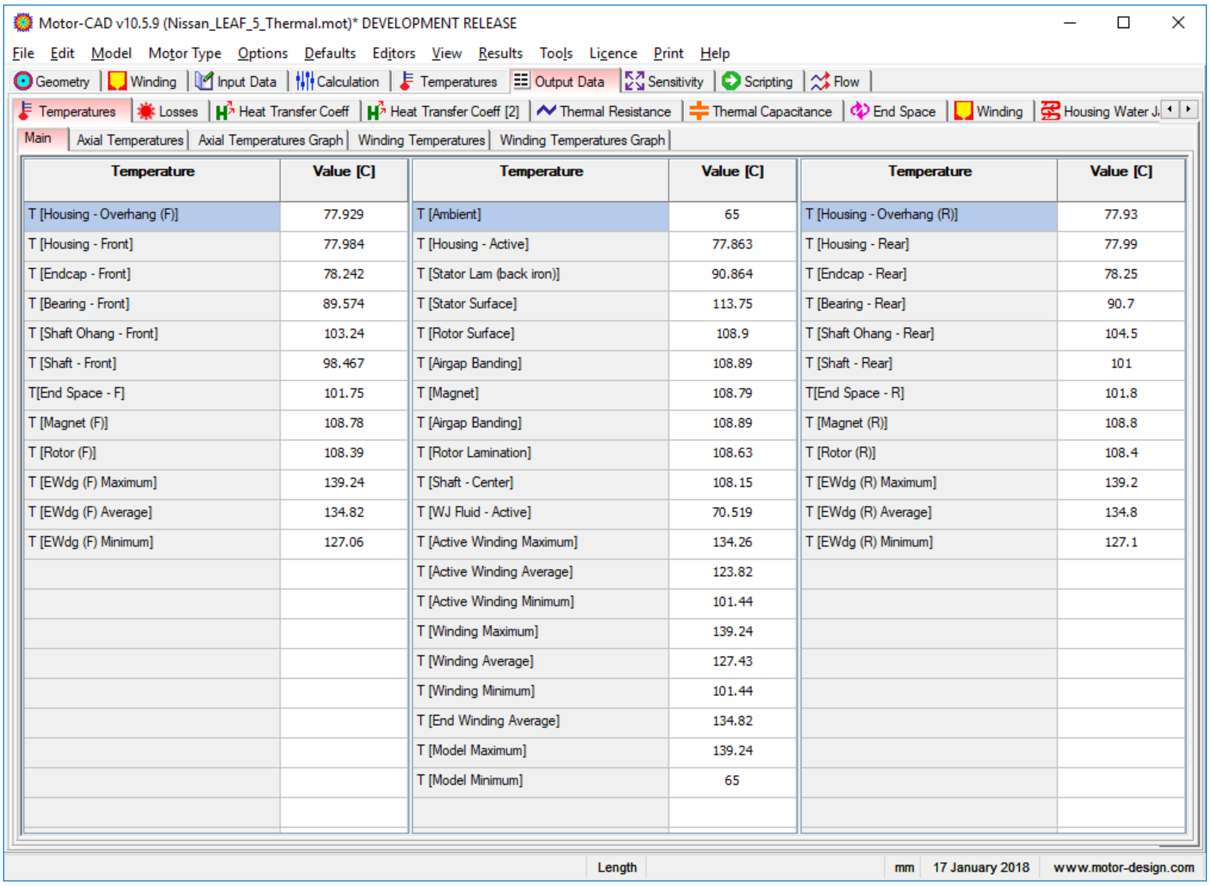
The visualisation of the names and values of thermal resistances, temperatures, power sources and nodes can be customised using the **Plot Options** on the left hand side. Here we select the following options to simplify the view:

Parameter	Value
Resistance	No Display
Power Source	No Display
Node	Label
Grid	No Display

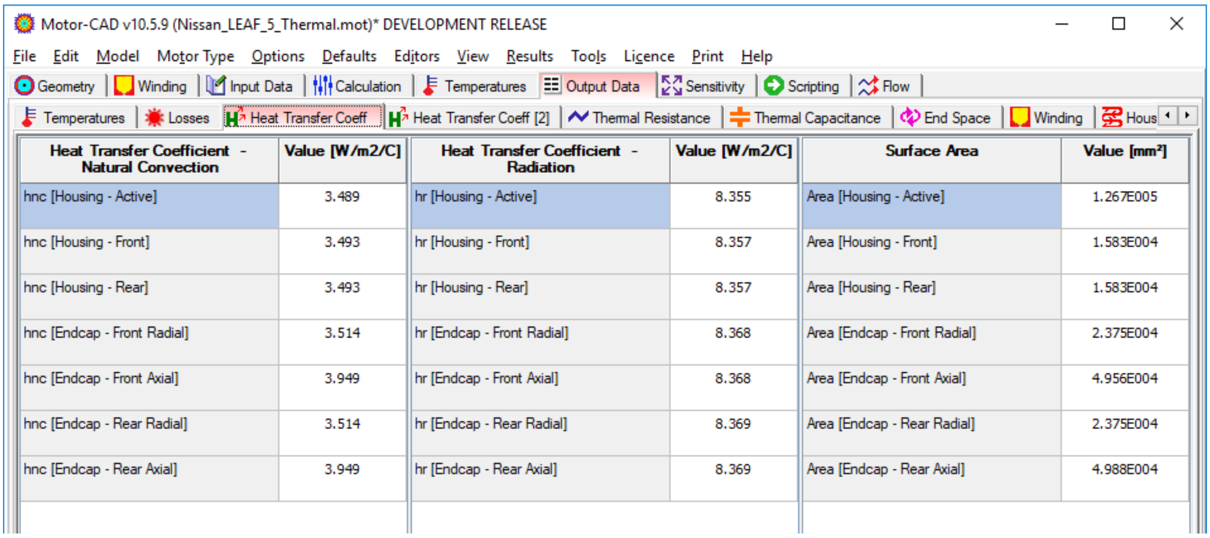


Here we can also understand the cuboidal model used for the stator windings, shown in yellow in the centre of the circuit. We have two rows of winding nodes, C1 (cuboid 1) and C2 (cuboid 2), with the front end winding nodes on the left and rear end winding nodes on the right.

The **Output Data** sheets provide detailed results from the thermal simulation, including temperatures, heat transfer coefficients, thermal resistances, etc. For more information on any output parameters, please refer to the Motor-CAD manual.



Temperature	Value [C]	Temperature	Value [C]	Temperature	Value [C]
T [Housing - Overhang (F)]	77.929	T [Ambient]	65	T [Housing - Overhang (R)]	77.93
T [Housing - Front]	77.984	T [Housing - Active]	77.863	T [Housing - Rear]	77.99
T [Endcap - Front]	78.242	T [Stator Lam (back iron)]	90.864	T [Endcap - Rear]	78.25
T [Bearing - Front]	89.574	T [Stator Surface]	113.75	T [Bearing - Rear]	90.7
T [Shaft Ohang - Front]	103.24	T [Rotor Surface]	108.9	T [Shaft Ohang - Rear]	104.5
T [Shaft - Front]	98.467	T [Airgap Banding]	108.89	T [Shaft - Rear]	101
T[End Space - F]	101.75	T [Magnet]	108.79	T[End Space - R]	101.8
T [Magnet (F)]	108.78	T [Airgap Banding]	108.89	T [Magnet (R)]	108.8
T [Rotor (F)]	108.39	T [Rotor Lamination]	108.63	T [Rotor (R)]	108.4
T [EWdg (F) Maximum]	139.24	T [Shaft - Center]	108.15	T [EWdg (R) Maximum]	139.2
T [EWdg (F) Average]	134.82	T [WJ Fluid - Active]	70.519	T [EWdg (R) Average]	134.8
T [EWdg (F) Minimum]	127.06	T [Active Winding Maximum]	134.26	T [EWdg (R) Minimum]	127.1
		T [Active Winding Average]	123.82		
		T [Active Winding Minimum]	101.44		
		T [Winding Maximum]	139.24		
		T [Winding Average]	127.43		
		T [Winding Minimum]	101.44		
		T [End Winding Average]	134.82		
		T [Model Maximum]	139.24		
		T [Model Minimum]	65		



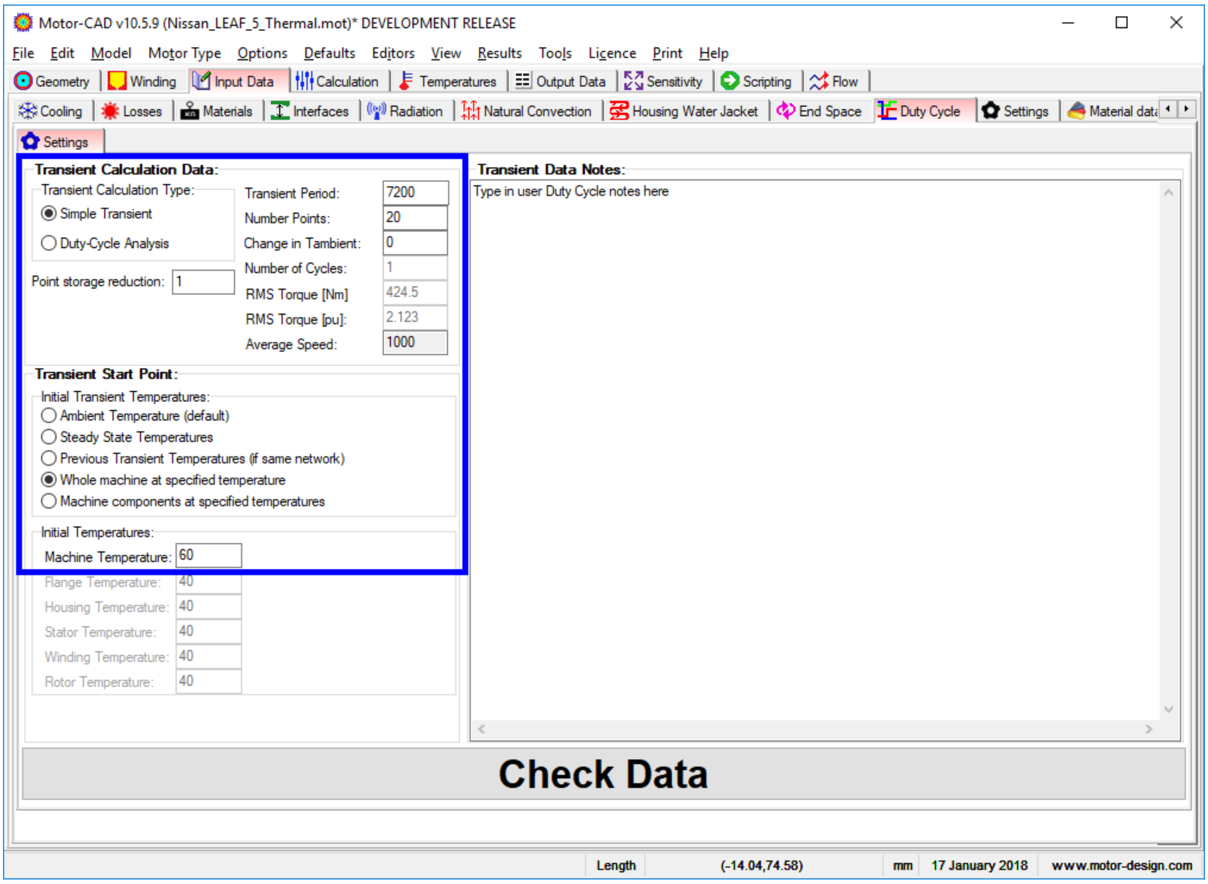
Heat Transfer Coefficient - Natural Convection	Value [W/m2/C]	Heat Transfer Coefficient - Radiation	Value [W/m2/C]	Surface Area	Value [mm²]
hnc [Housing - Active]	3.489	hr [Housing - Active]	8.355	Area [Housing - Active]	1.267E005
hnc [Housing - Front]	3.493	hr [Housing - Front]	8.357	Area [Housing - Front]	1.583E004
hnc [Housing - Rear]	3.493	hr [Housing - Rear]	8.357	Area [Housing - Rear]	1.583E004
hnc [Endcap - Front Radial]	3.514	hr [Endcap - Front Radial]	8.368	Area [Endcap - Front Radial]	2.375E004
hnc [Endcap - Front Axial]	3.949	hr [Endcap - Front Axial]	8.368	Area [Endcap - Front Axial]	4.956E004
hnc [Endcap - Rear Radial]	3.514	hr [Endcap - Rear Radial]	8.369	Area [Endcap - Rear Radial]	2.375E004
hnc [Endcap - Rear Axial]	3.949	hr [Endcap - Rear Axial]	8.369	Area [Endcap - Rear Axial]	4.988E004

iii. Simple Transient

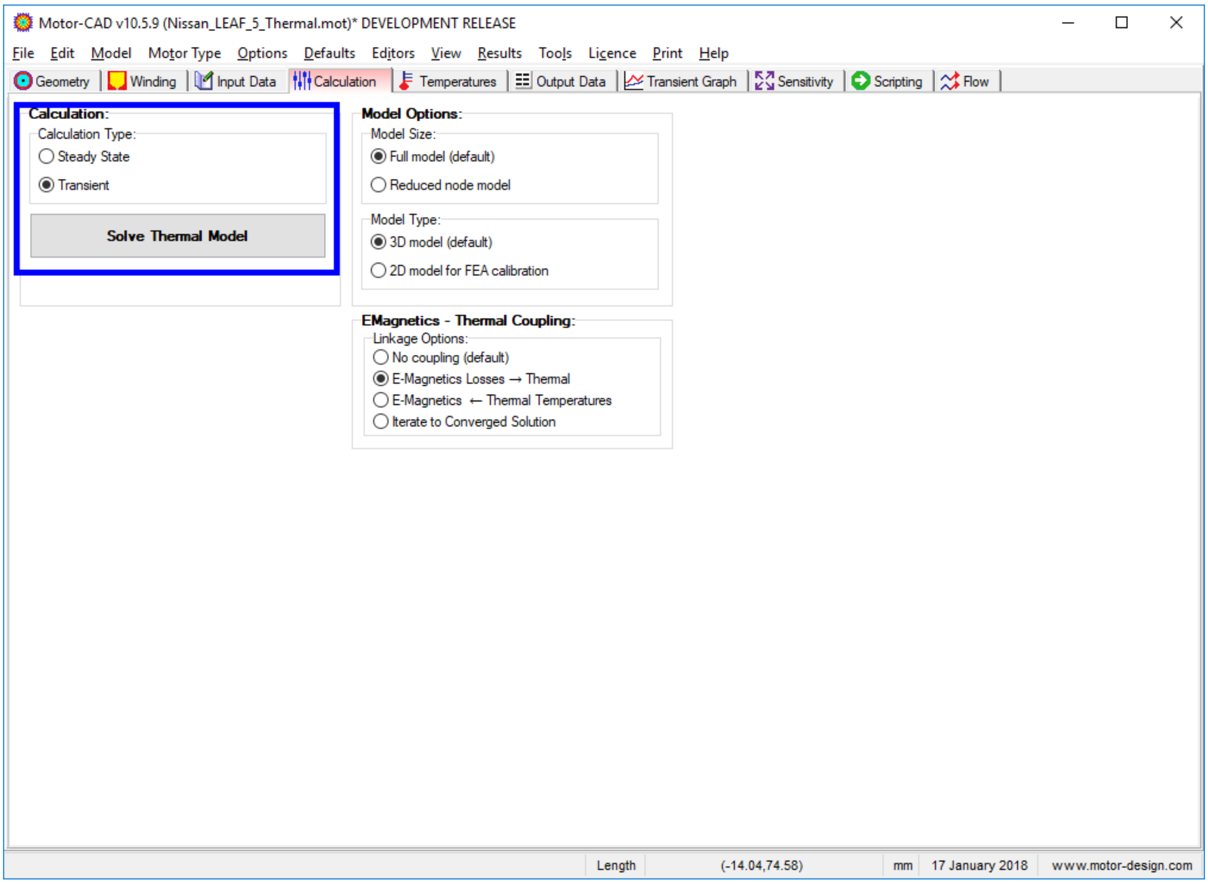
We can also use the Motor-CAD model to simulate the machine temperatures during a thermal transient. There are two ways to simulate a transient in Motor-CAD – either with a simple transient, where the operating point is constant throughout the transient period or with a duty-cycle analysis where the operating conditions (e.g. torque, speed, losses) vary throughout the cycle. First we will simulate a simple transient case.

We define the transient under **Input Data -> Duty Cycle -> Settings** as follows:

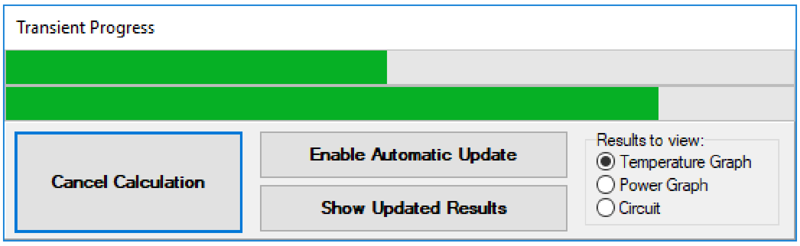
Parameter	Value	Units
Transient Calculation Type	Simple Transient	
Point Storage Reduction	1	
Transient Period	7200	seconds
Number Points	20	
Change in Tambient	0	°C
Initial Transient Temperatures	Whole machine at specified temperature	
Machine Temperature	60	°C



We then go to the **Calculation** tab, set the **Calculation Type** to **Transient** and then **Solve** the model.

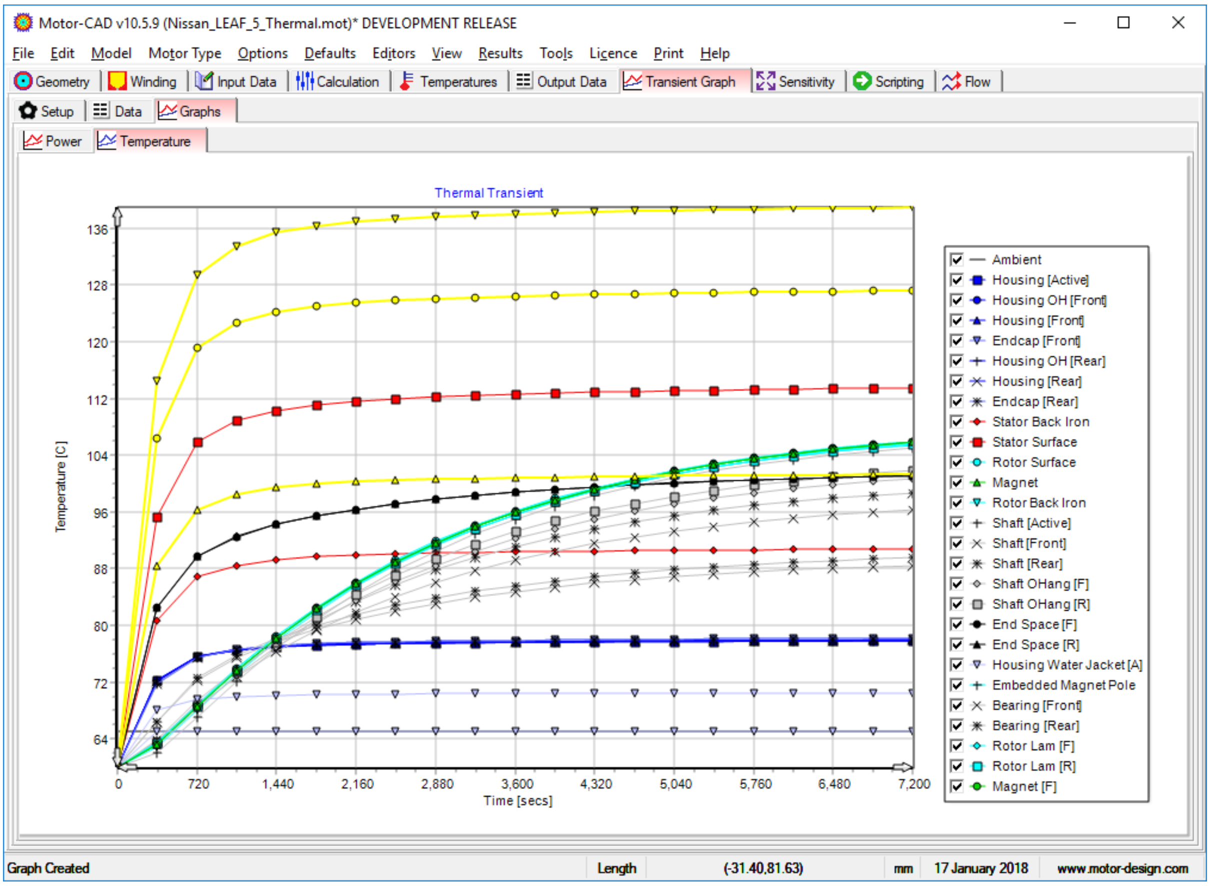


During solving, the transient progress bar shows the progress of the simulation. By default the results are not shown during the solution for speed, but can be displayed using the options here.

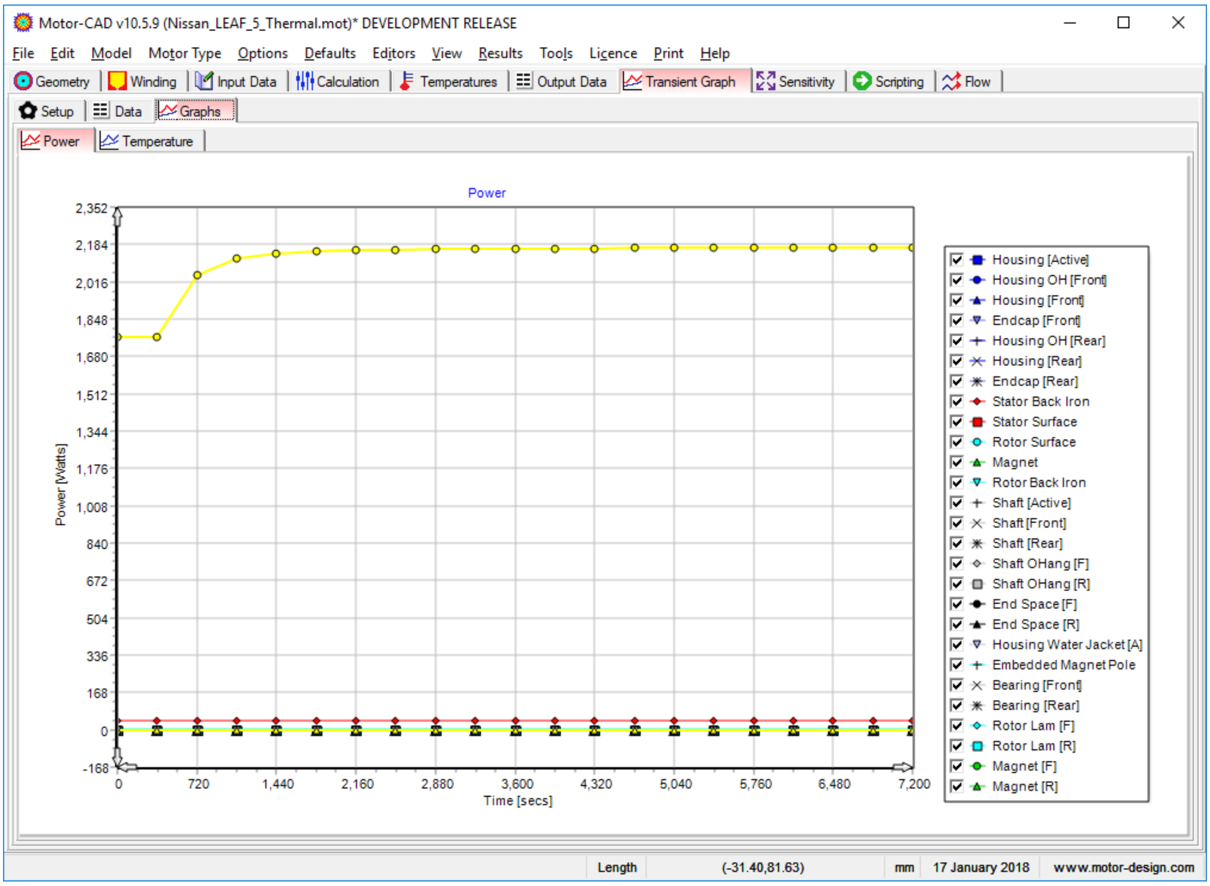


When solving is completed, the results are plotted against time in the **Transient Graph** tab. By default the temperature and power values are plotted for common nodes of interest. Using the **Setup** tab, the graphs can be customised to display the results for any nodes. The chart titles, axis limits and series options can also be changed. The **Data** tab provides the raw data for viewing or exporting, and the **Graphs** tab displays the plots.

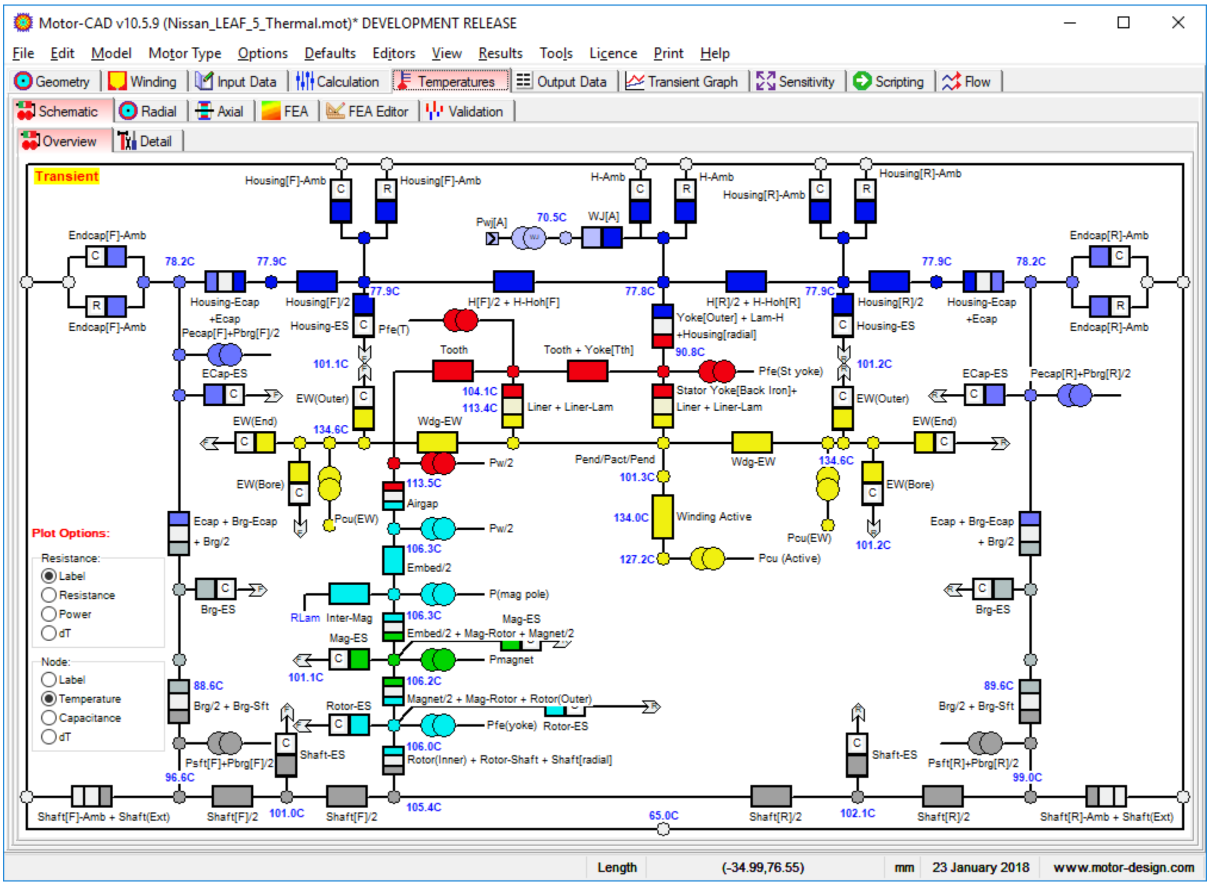
In the **Temperatures** graph, we see the temperatures rapidly increase at the start of the transient and then converge towards their steady-state values. Note that the colours in the graph match those used in the cross-section drawings and the thermal network schematics.

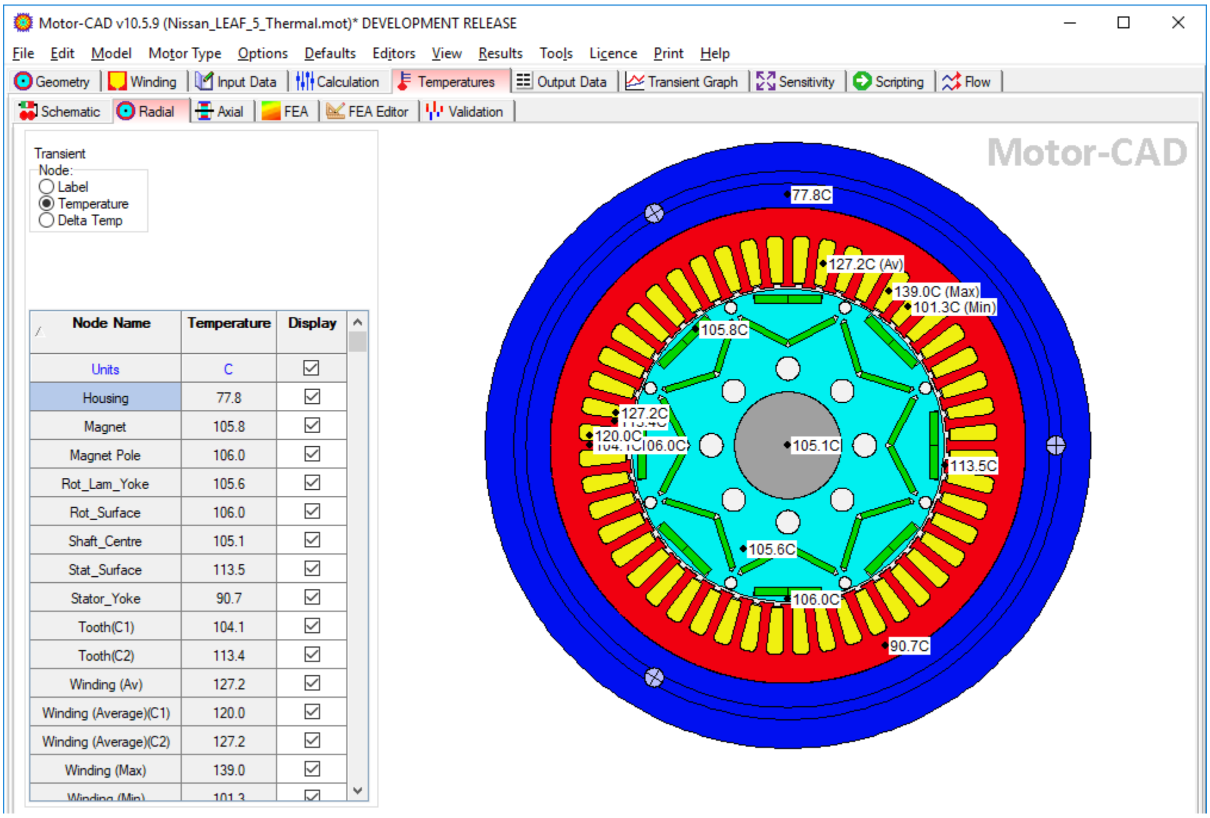


The **Power** graph shows the power dissipated in the motor over the transient period. We see that the losses in the stator copper increase over time due to the use of the **Copper Losses Vary with Temperature** model we enabled in the **Input Data -> Losses** tab (section 6.v.). The power dissipated in all other nodes is constant with temperature and so do not change over time.



The **Temperatures -> Schematic/Radial/Axial** and **Output Data** tabs show the final values at the end of the transient calculation.

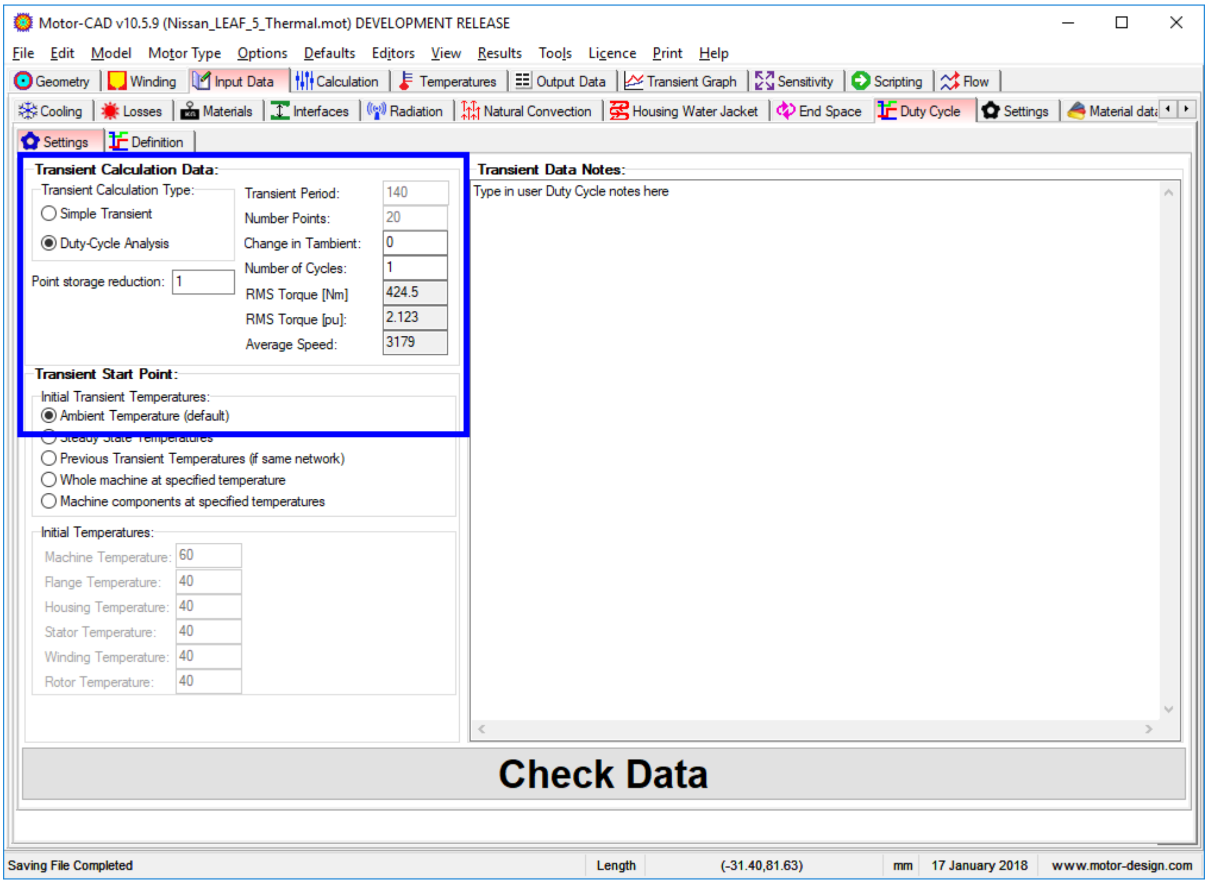




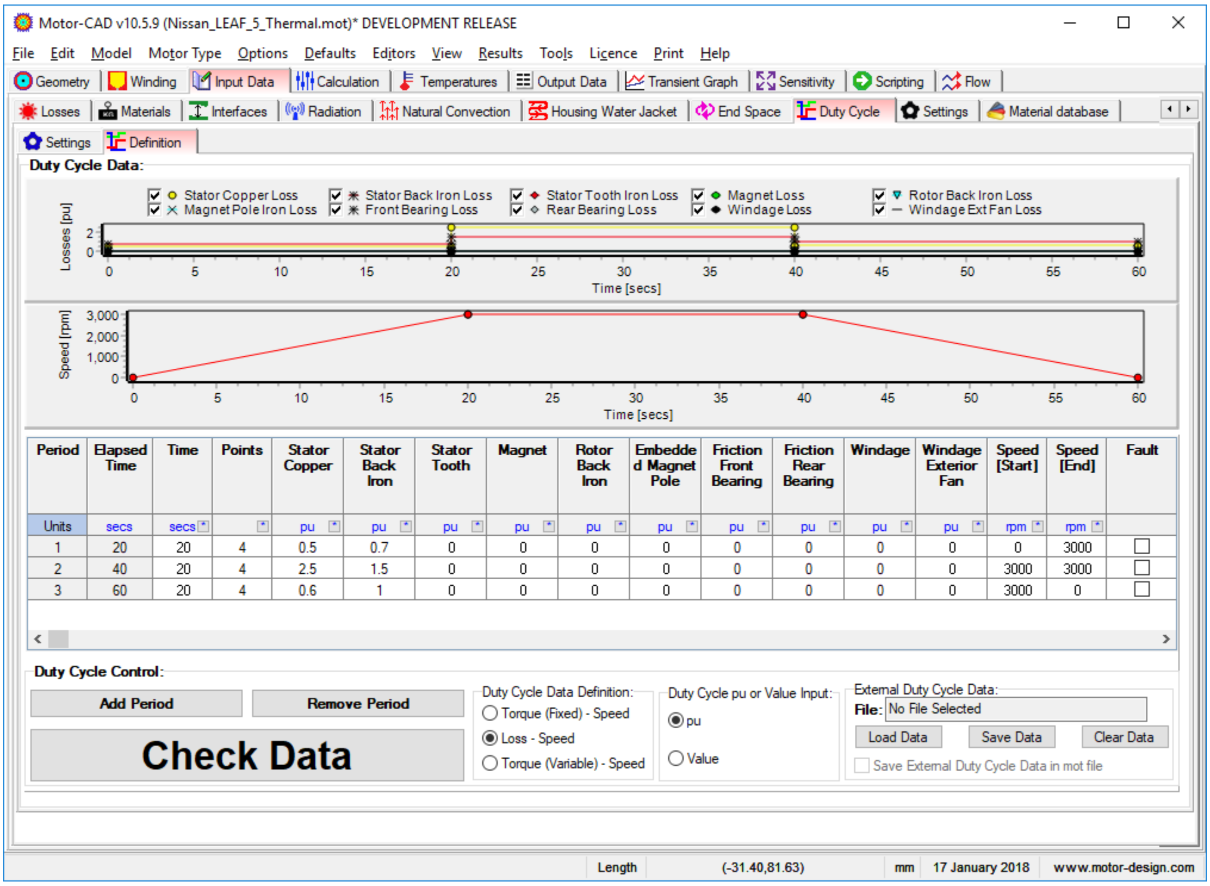
iv. Duty Cycle with Lab

We will now simulate a more complex duty cycle. Under **Input Data -> Duty Cycle -> Settings**, we set the following:

Parameter	Value	Units
Transient Calculation Type	Duty-Cycle Analysis	
Point Storage Reduction	1	
Change in Tambient	0	°C
Number of Cycles	1	
Initial Transient Temperatures	Ambient Temperature	



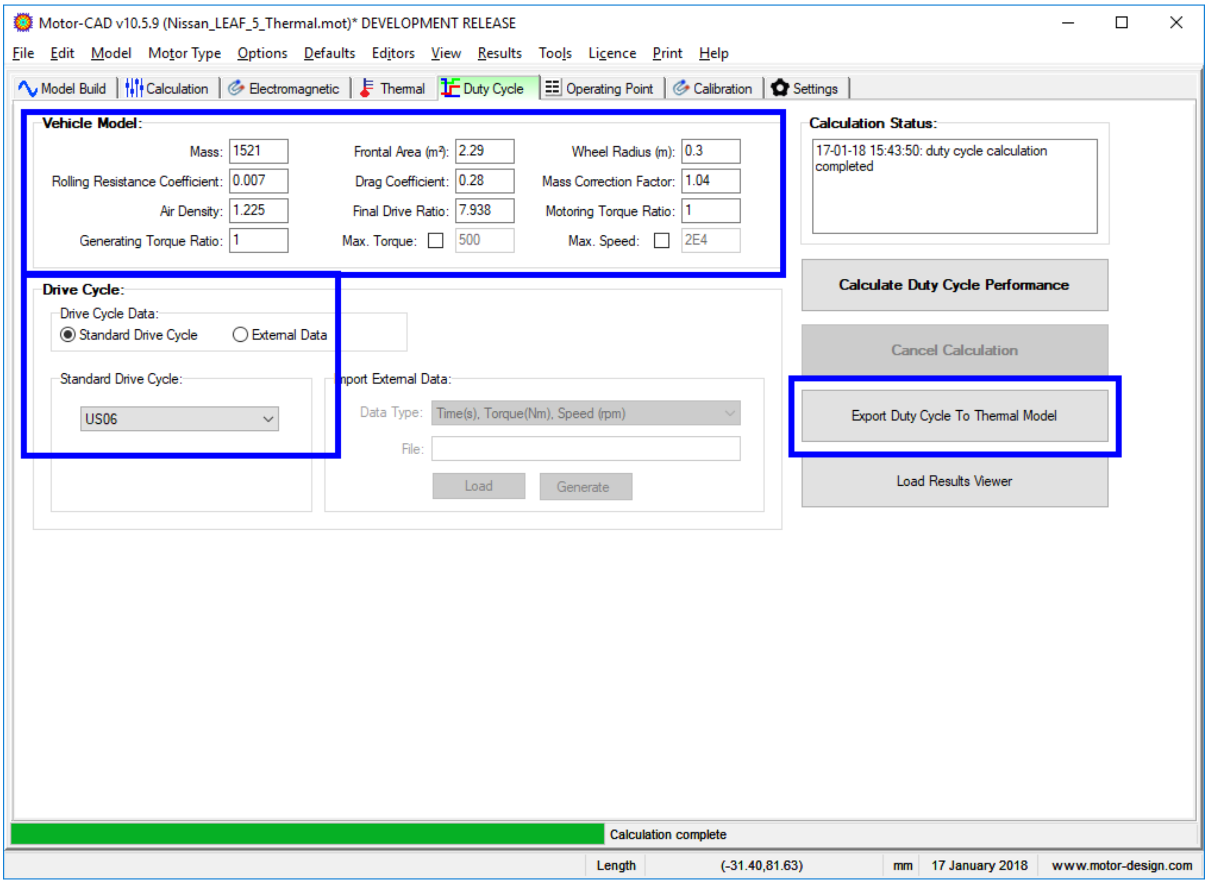
The duty cycle values (e.g. losses, shaft speed at each point) are defined under **Input Data -> Duty Cycle -> Definition**. In the thermal model, the duty cycle is typically defined by loss & shaft speed values vs time.

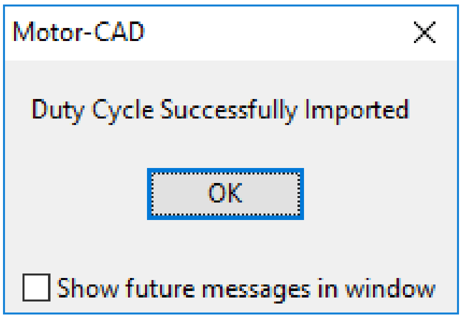


However, when designing a machine it is more usual to define the duty cycle with a torque/speed profile over time. From this an electromagnetic model is used to find the power losses over time, and then this defines the thermal duty cycle. Here the Lab module is a valuable tool since we can very quickly calculate losses over a duty cycle and export the values to the thermal model.

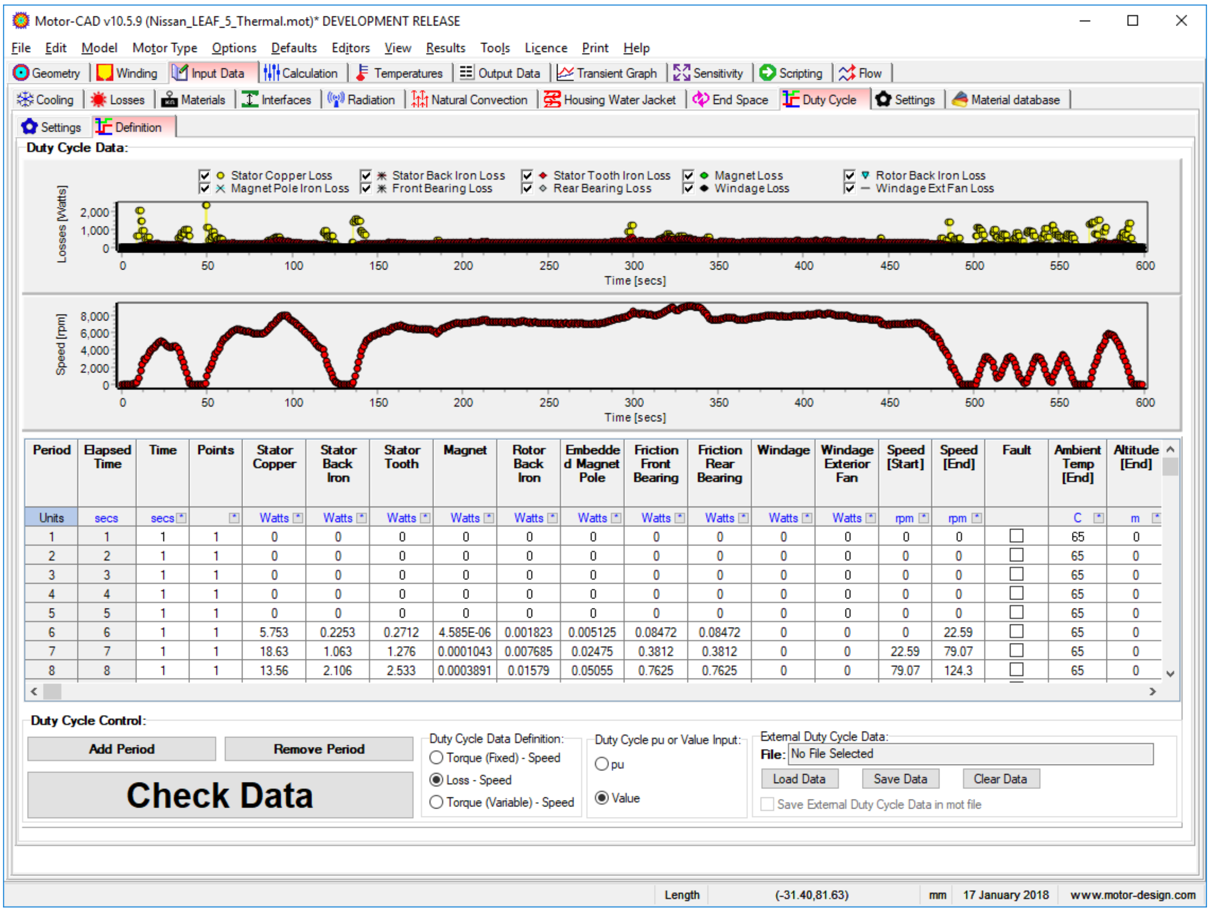
Switch to the Lab module using **Menu->Model -> Lab** and navigate to the **Duty Cycle** tab. Recall that we previously set up the vehicle model for the LEAF with the **US06** duty cycle. Check the settings are correct and click **Calculate Duty Cycle Performance** to run the calculation.

Once the calculation is complete, click **Export Duty Cycle To Thermal Model**. This will export the calculated loss data from the duty cycle to the thermal model. This will be confirmed by a message.

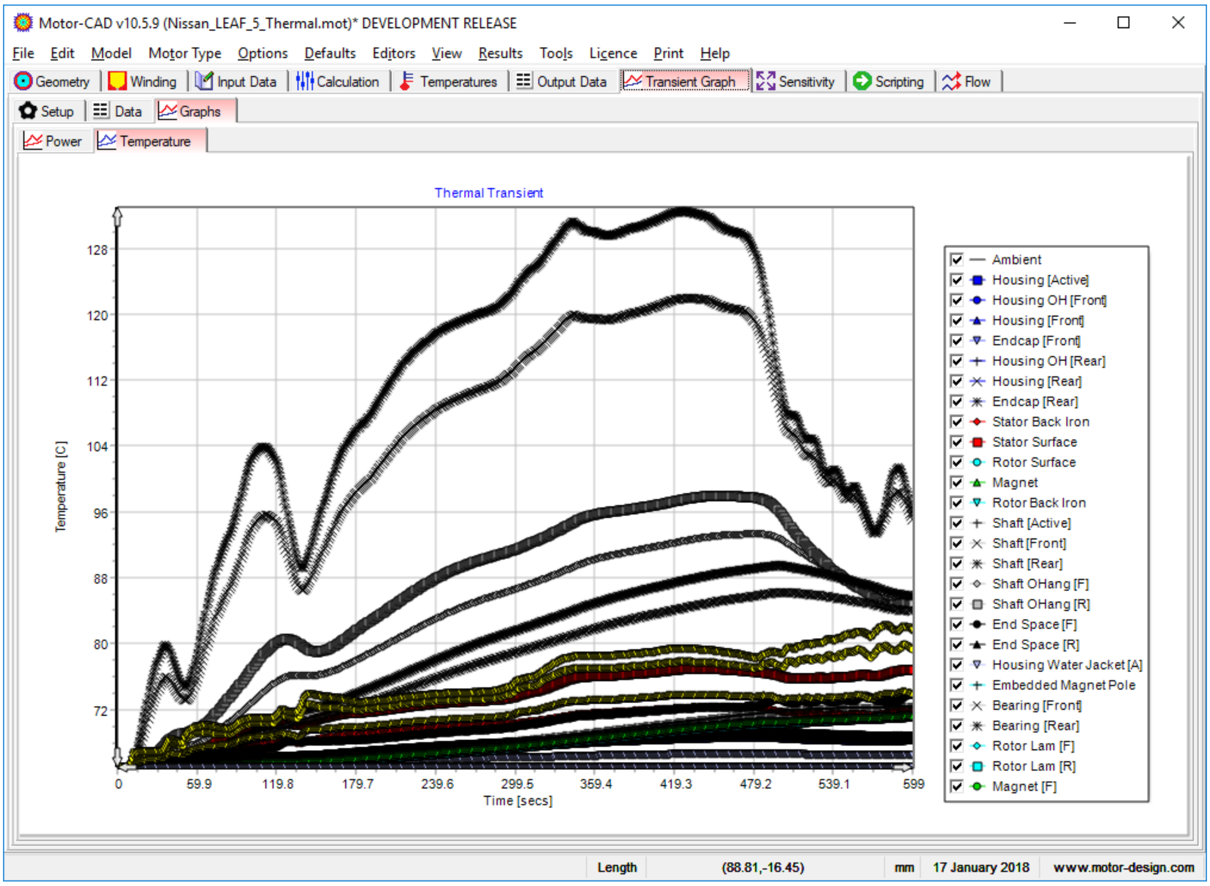




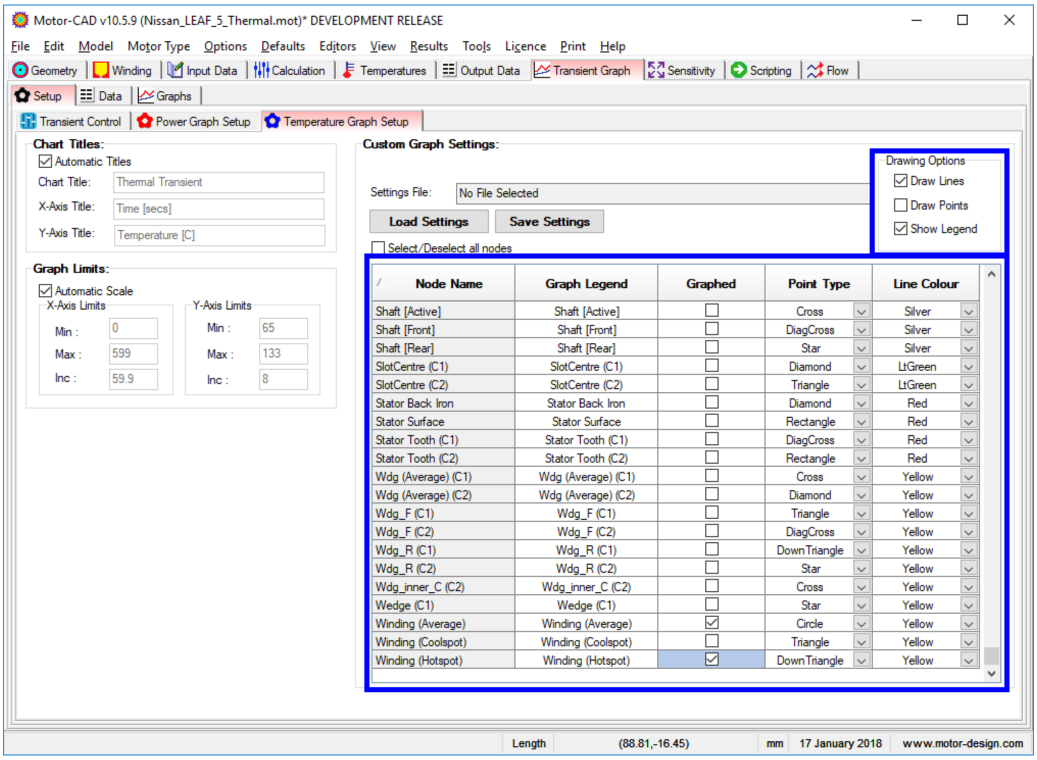
Now return to the thermal model and check the duty cycle data under **Input Data -> Duty Cycle -> Definition**.

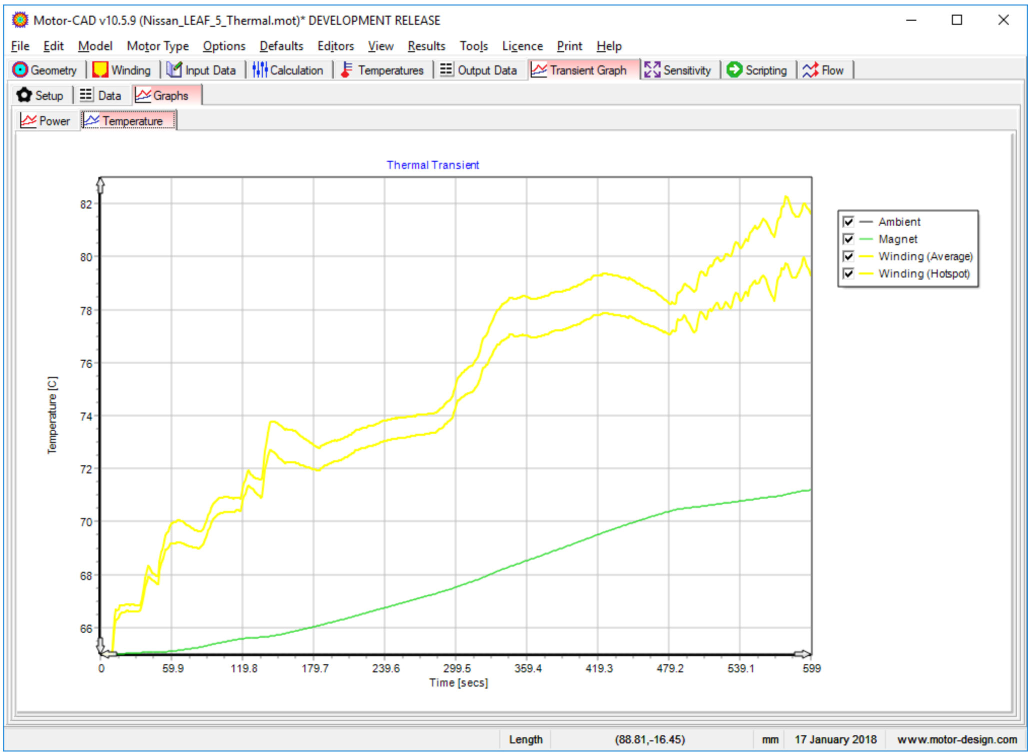


Go to the **Calculation** tab, check that the **Calculation Type** is set to **Transient** and **Solve** the thermal model.

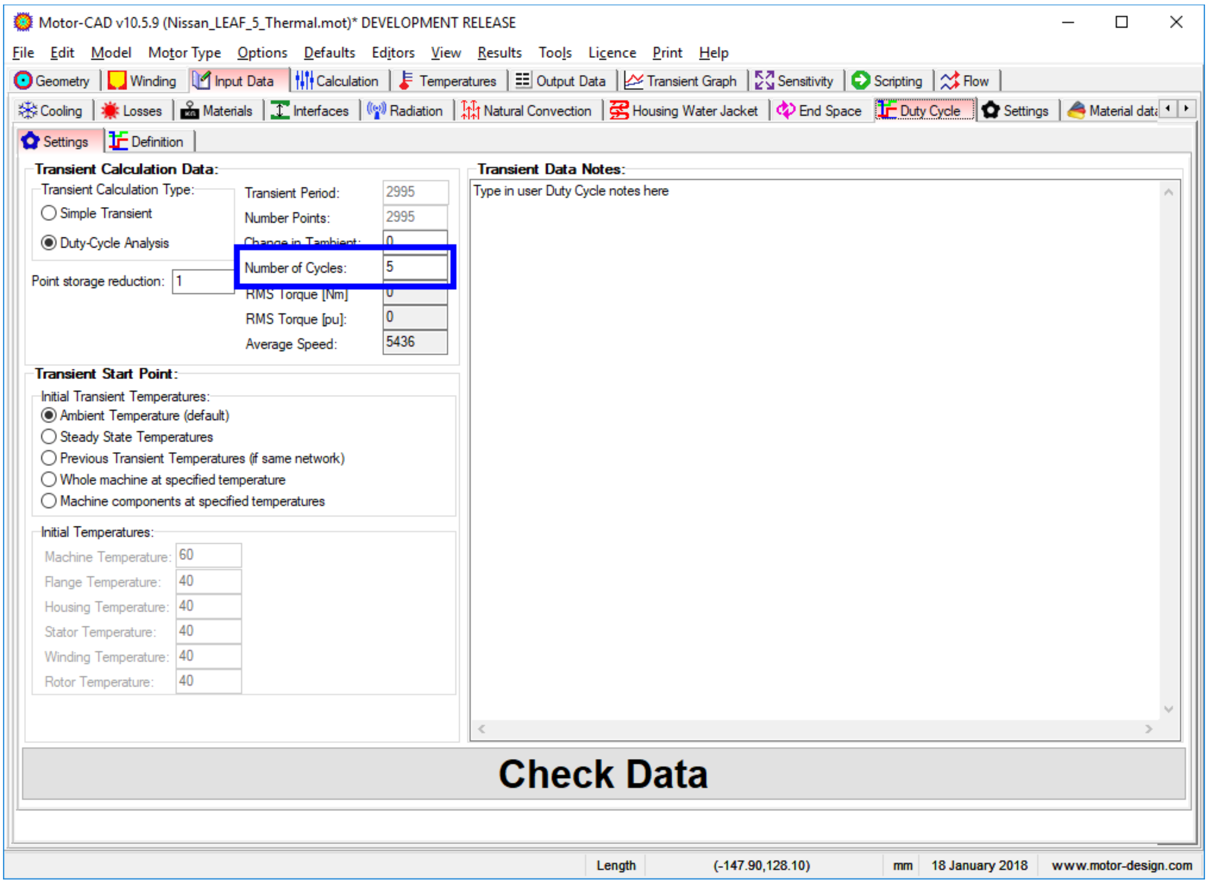


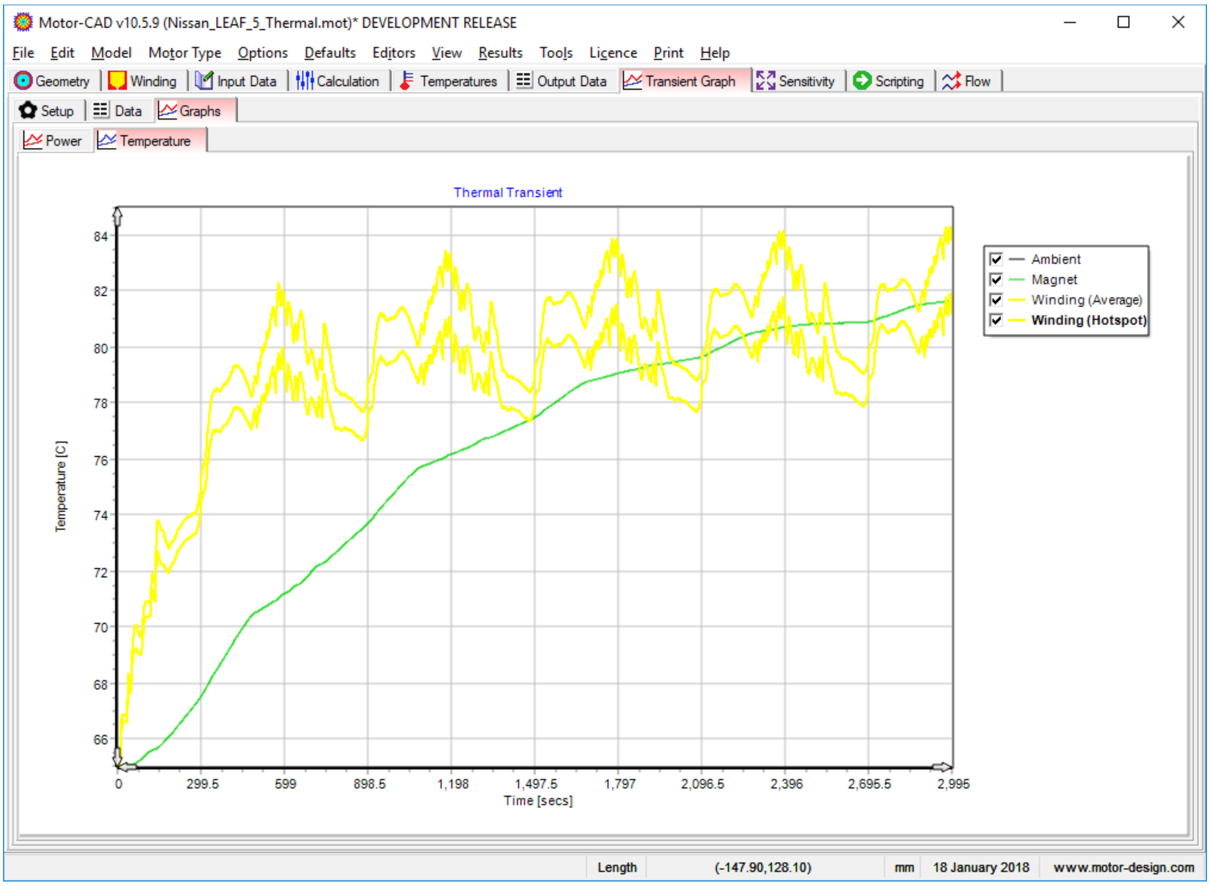
We are particularly interested in the stator winding and magnet temperatures. Under **Transient Graph -> Setup -> Temperature Graph Setup**, customise the transient graph to show only the **Ambient, Magnet, Winding (Average)** and **Winding (Hotspot)** nodes (the **Select/Deselect all nodes** checkbox can be useful here). Deselect the **Draw Points** option.



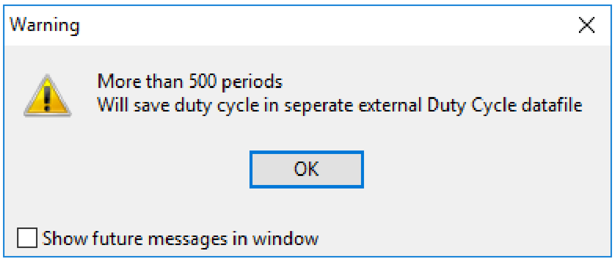


Furthermore, more than one cycle of the duty cycle can be simulated. Change the **Number of Cycles** to **5** under **Input Data -> Duty Cycle -> Settings**, and then run the calculation again from the **Calculation** tab.





Note that, when saving the file, the following message appears:



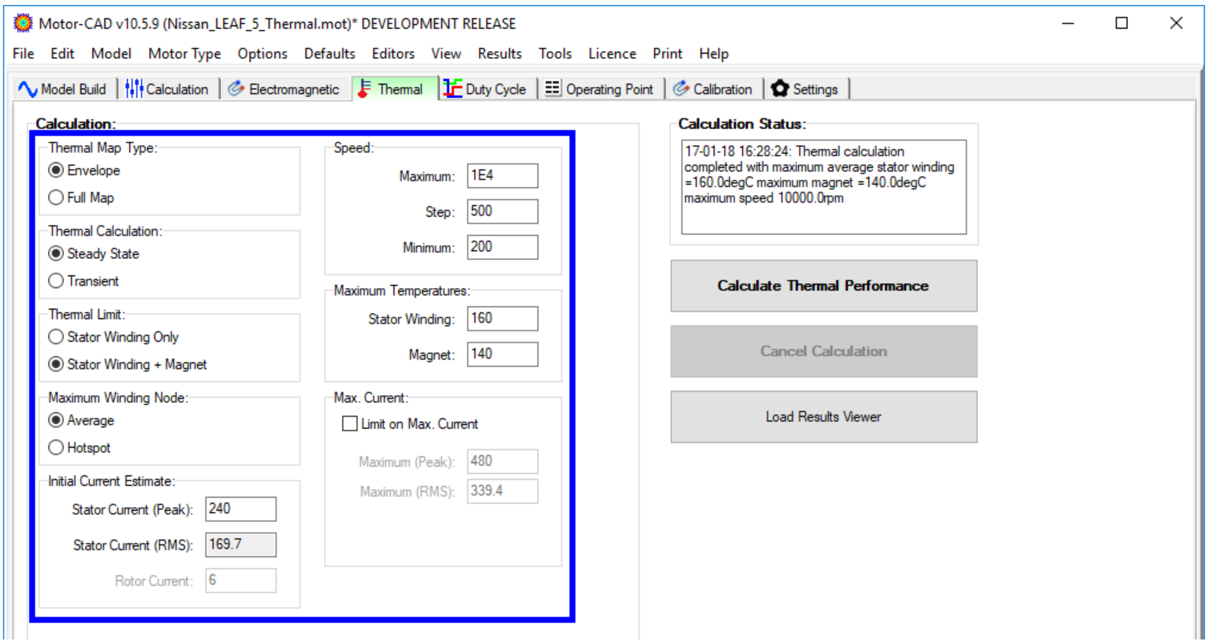
For duty cycles with fewer than 500 periods, Motor-CAD will save the duty cycle data in the .mot file. Otherwise, the data is automatically saved to a separate external file to prevent the size of the .mot file from growing too large. Here a location must be selected for saving the external file.

v. Continuous Thermal Performance with Lab

The thermal envelope gives the torque and power that the machine can produce continuously at different rotating speeds for a given value of maximum working temperature. The Lab module calculates the power losses in the machine using the FEA map model that we have built, and then uses the thermal model to iteratively find the maximum electromagnetic performance at the specified temperatures.

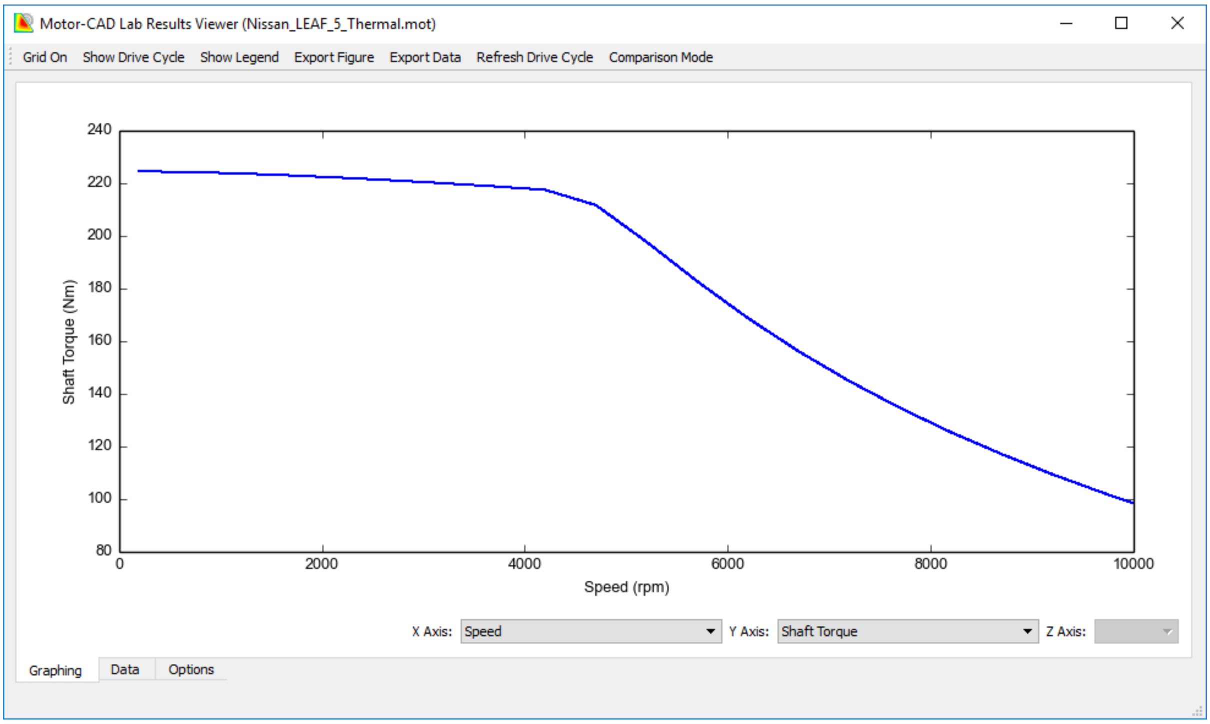
Here we will calculate the continuous thermal envelope for steady-state conditions. Switch to the Lab model and go to the **Thermal** tab. Set the following:

Parameter	Value	Units
Thermal Map Type	Envelope	
Thermal Calculation	Steady State	
Thermal Limit	Stator Winding + Magnet	
Maximum Winding Node	Average	
Initial Current Estimate (Peak)	240	A
Speed: Maximum	10000	rpm
Speed: Step	500	rpm
Speed: Minimum	200	rpm
Maximum Temperature: Stator Winding	160	°C
Maximum Temperature: Magnet	140	°C
Limit on Max. Current	Disabled	

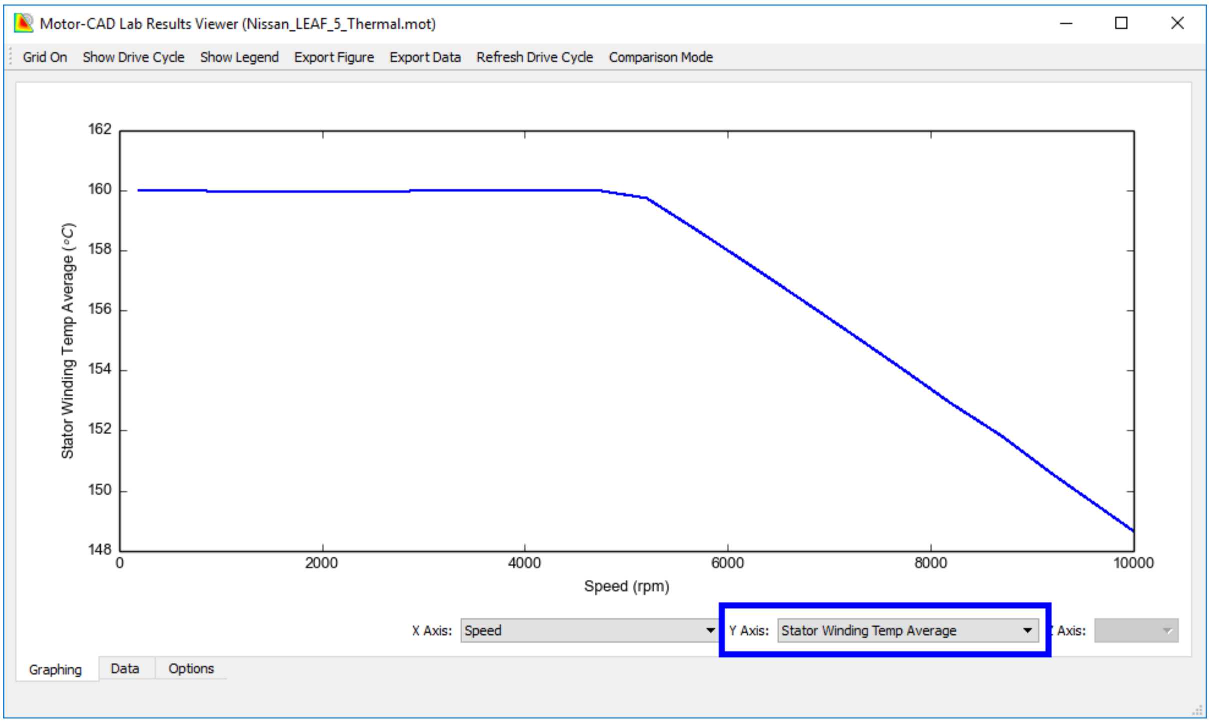


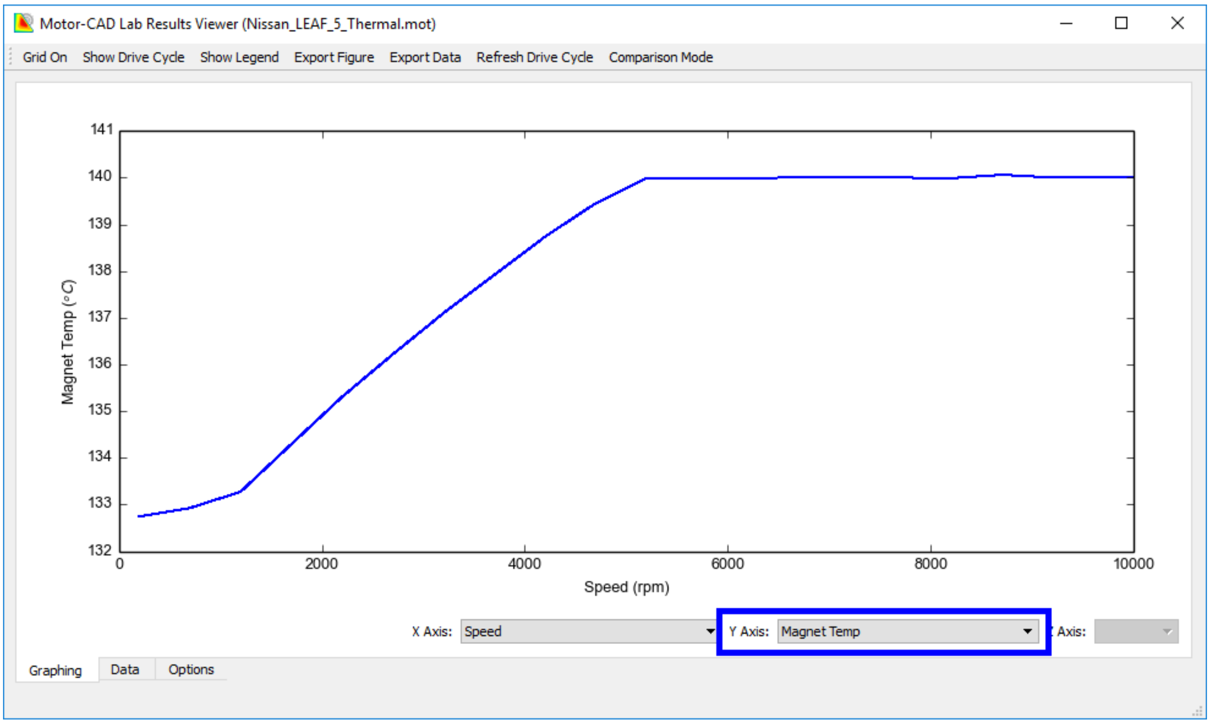
Click **Calculate Thermal Performance** to run the calculation. Note that, since the electromagnetic and thermal calculations must be iterated to find the optimum working point at maximum temperature, this calculation can take some time. The calculation can also be sensitive to the **Initial Current Estimate** so it is advised to ensure that a sensible value is used; typically ½ of the model build current is appropriate.

By comparing to the peak torque/speed curve calculated previously (see section 5), we can see that the machine cannot operate continuously at peak performance within the thermal limits.



By plotting **Stator Winding Temp Average** and **Magnet Temp** on the **Y Axis**, we can see that the machine performance is constrained by the winding temperature at low speeds, and by the magnet temperature at high speeds.





The thermal capability of the machine can also be calculated for a transient period, using either a simple transient or complex duty cycle. This is done by configuring the transient in the Thermal model and then setting the **Thermal Calculation** to **Transient**. It should be noted that this calculation can take a long time and may be infeasible if the transient thermal calculation takes too long. It is recommended to use the simplest transient calculation possible and optimise the number of points to maintain a reasonable calculation time.

8. Advanced E-Magnetic Modelling

We will now demonstrate some of the more advanced features of Motor-CAD's electromagnetic model. Save the file as **Nissan_LEAF_6_Advanced.mot** and switch to the **E-Magnetic** model.

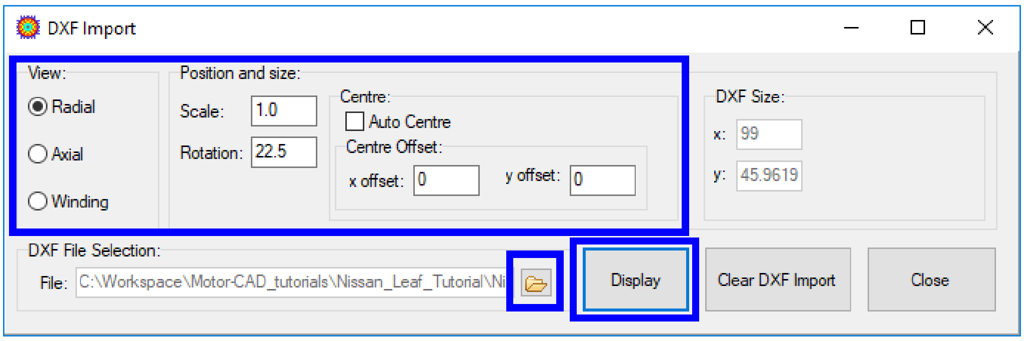
i. Custom DXF Geometry

The 2D FEA using Motor-CAD's parameterised geometric model gives a very fast estimation of the electromagnetic performance and generally gives accurate prediction of average torque and power loss. However, sometimes the precise machine geometry cannot be reproduced using the parameter model, and simulating the exact geometry including e.g. flux barriers can provide more accurate prediction of torque ripple.

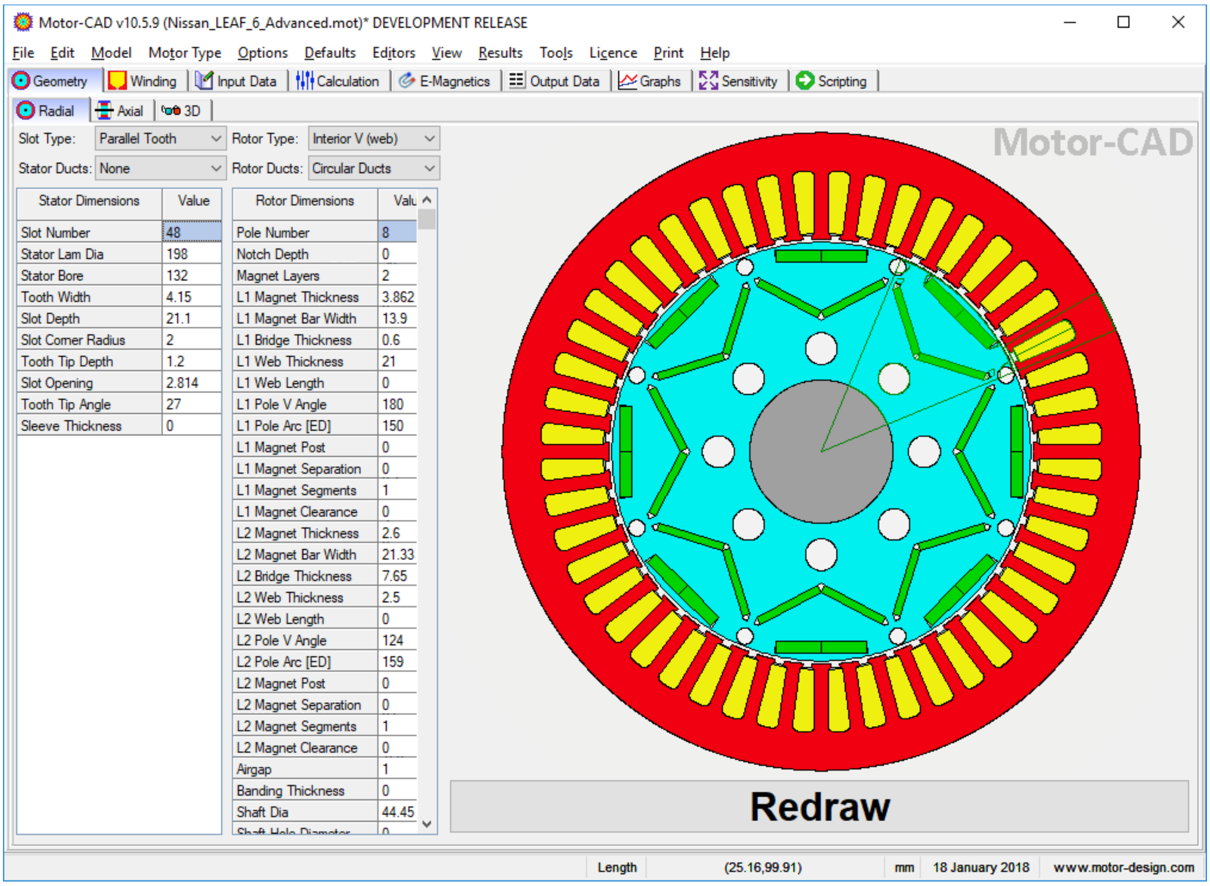
For geometries which cannot be reproduced exactly with the parameter model, dxf files can be imported into Motor-CAD for simulation. There is a detailed tutorial which describes the requirements for an imported DXF and the procedure for importing the geometry, available at https://www.motor-design.com/publications/tutorials/.

The Nissan LEAF motor has some minor differences to the model we have created in Motor-CAD, and we will now import the DXF geometry. We open the **DXF Import** dialog by selecting **File -> Geometry Import** from the main menu. Using the file open button, we select the attached file **leaf_dxf.dxf** and select the following settings:

Parameter	Value	Units
View	Radial	
Scale	1.0	
Rotation	22.5	°
Auto Centre	Disabled	
x offset	0.0	mm
y offset	0.0	mm



Click **Display** to show the DXF outline on the **Geometry -> Radial** cross-section, and then close the dialog.



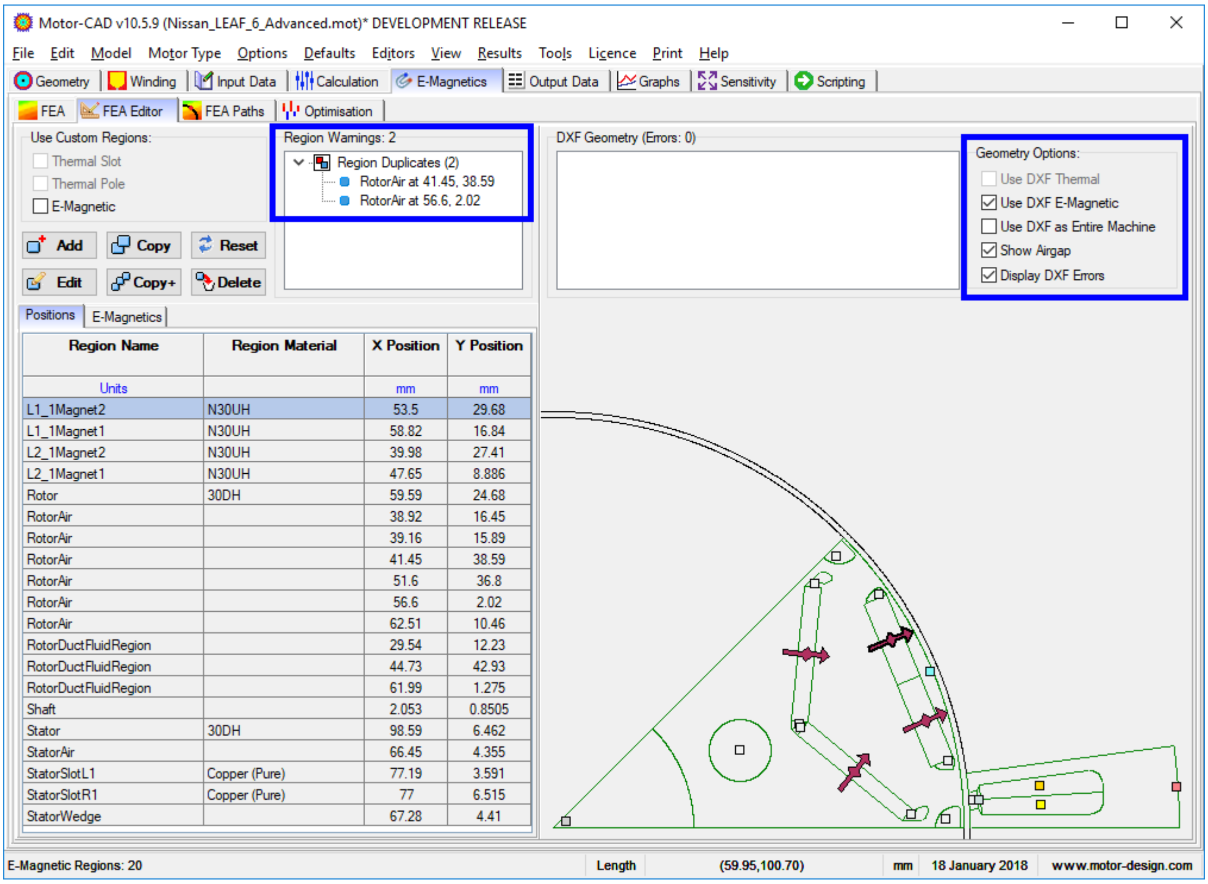
When using imported DXF geometry, it is important that the parameterised Motor-CAD model matches the DXF geometry as closely as possible. This view can be used to modify the model parameters and check how well the geometry matches. The most important parameters are:

- Stator slot number, shape and dimensions
- Pole number, rotor type and dimensions
- Outer and bore diameter of the stator lamination
- Airgap thickness
- Shaft and shaft hole diameters (if any)
- Number, size and position of ducts in both stator and rotor
- Sleeve/banding definition

In particular, the airgap thickness and location simulated in the FEA model will be defined based on the Motor-CAD parameters rather than the DXF, so this must match as closely as possible for a good result.

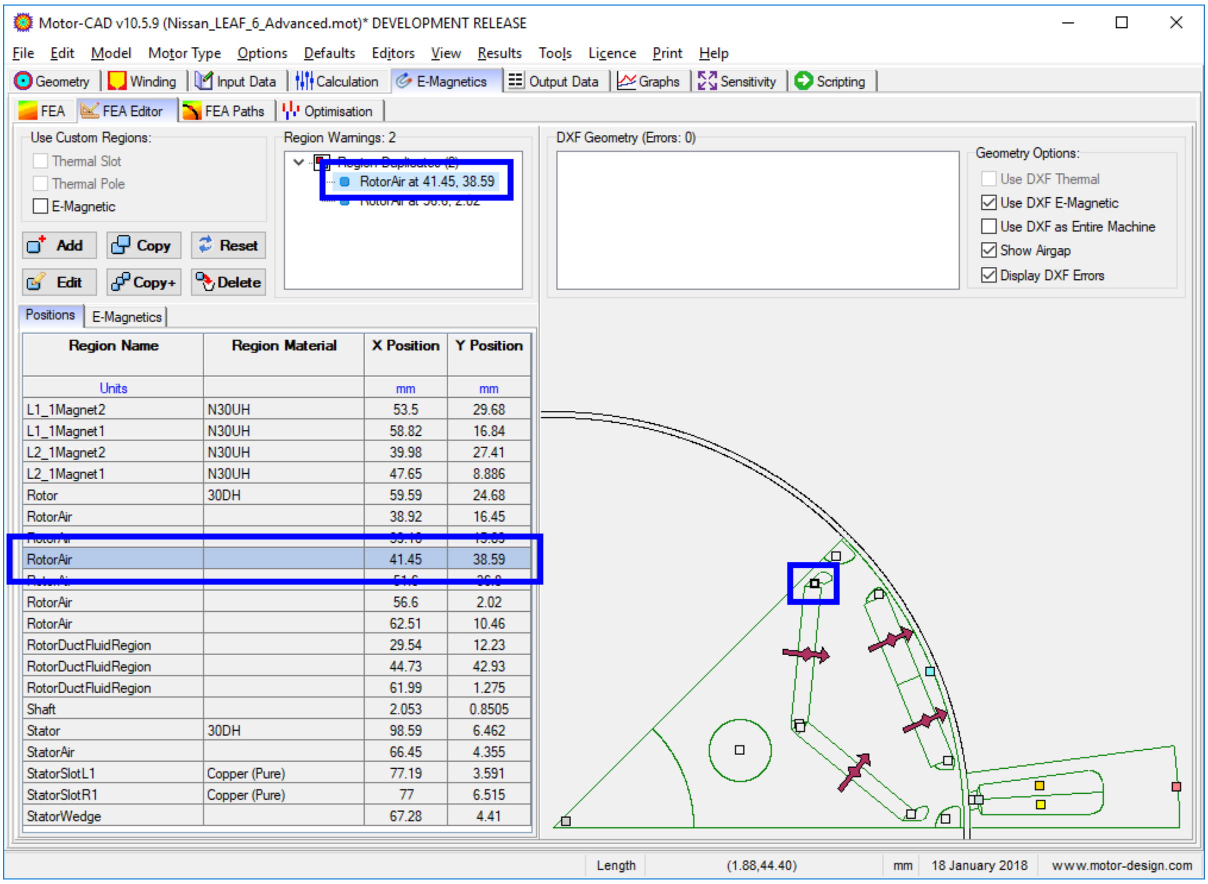
For the FEA simulation, the DXF geometry needs to be activated in the FEA Editor. Under the **E-Magnetics -> FEA Editor** tab, set the following geometry options:

Parameter	Value
Use DXF E-Magnetic	Enabled
Use DXF as Entire Machine	Disabled
Show Airgap	Enabled
Display DXF Errors	Enabled



Note that the geometry shown is now based on the imported DXF rather than the Motor-CAD template geometry. We now need to match up the FEA regions to the imported DXF geometry. All regions which have a complete boundary should be defined by placing a region identifier within the boundary. The regions are indicated by coloured rectangles or, in the case of permanent magnets, by an arrow indicating the magnetisation direction. Clicking on a region selects it and highlights its entry in the region table, and vice versa.

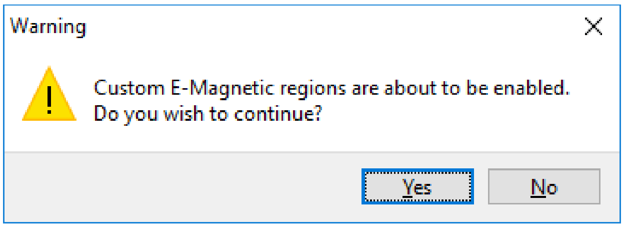
We notice immediately that there are some **Region Warnings** indicating that we have duplicate regions defined. For the first warning click on the warning text to highlight the problematic region in the table and the drawing.



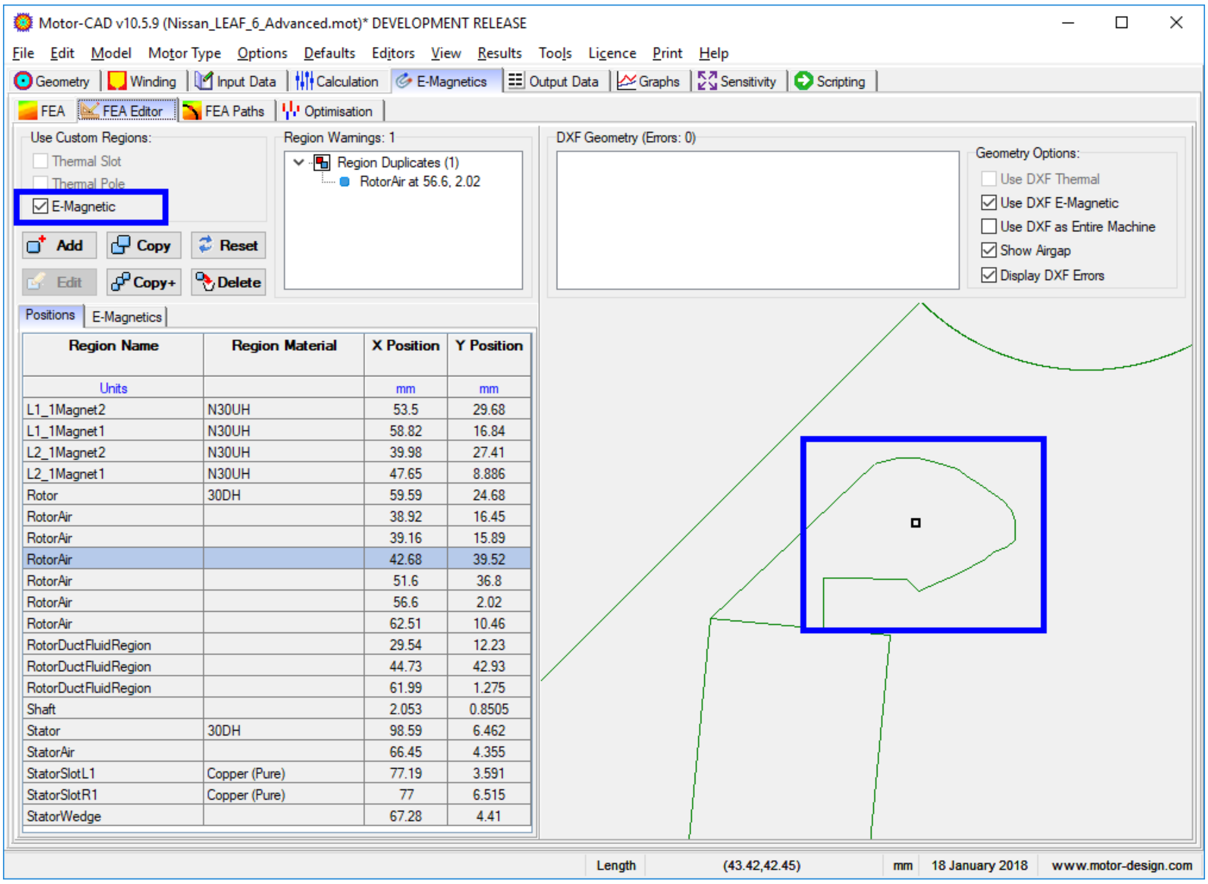
Now that we know where the problem is we can zoom in to inspect the region more closely. Zoom in by drawing a rectangle with the left mouse button over the area of interest or zoom out by clicking with the left mouse button on the drawing. We can pan the drawing by holding down the right mouse button and dragging the view.

By zooming in on the region, we see that the point defining the rotor air region at the end of the magnet is incorrectly placed in the rotor lamination. This is because the region markers have been placed based on the Motor-CAD parameterised geometry, and the custom shape of this region in the DXF does not quite match. We need to move this region marker inside the enclosed air region. We do this by selecting the region with the left mouse button and using drag and drop to place it in the correct location. It is generally recommended to place region markers in the centre of the region, as region markers placed too close to boundary lines may generate warnings or errors.

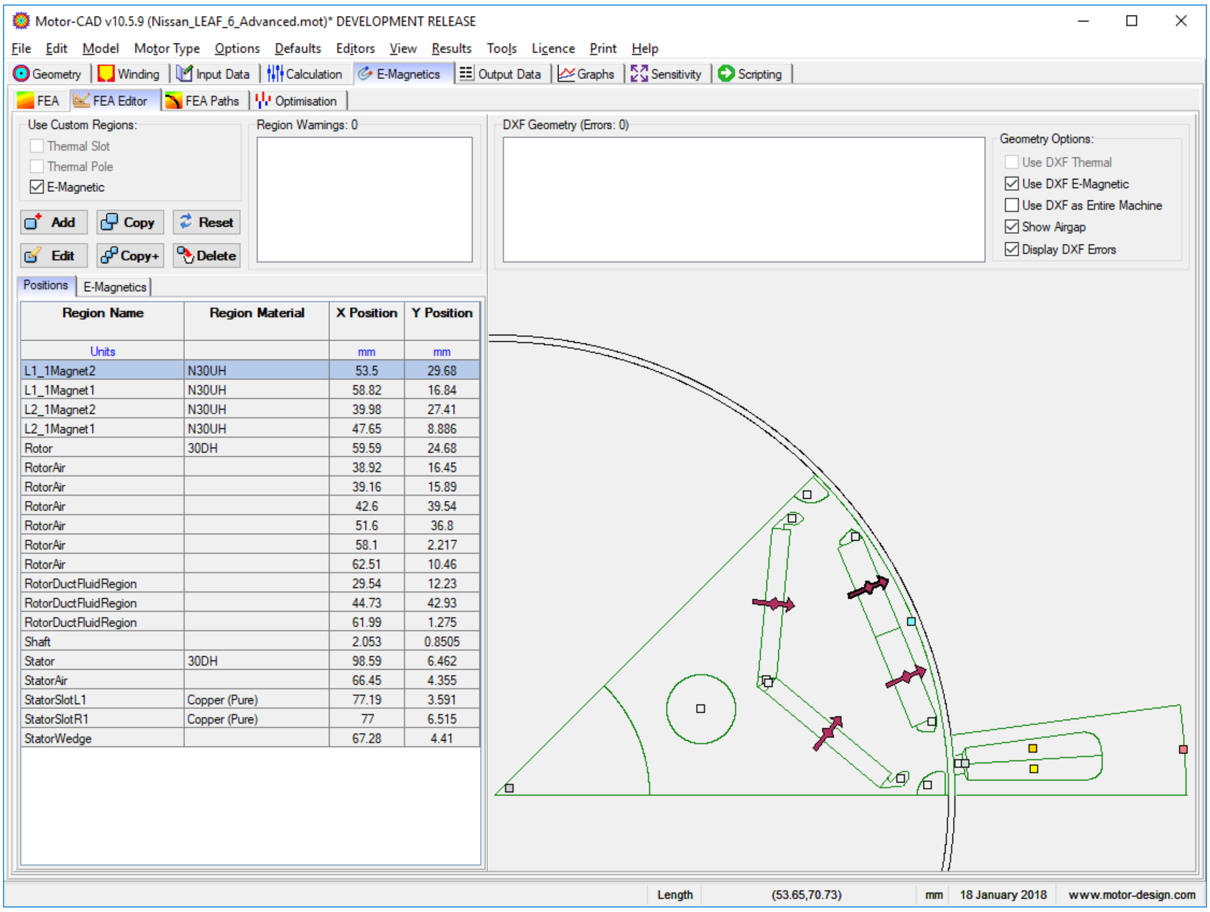
When we move the region, the following message appears:



This is warning that we are about to start using custom regions for the FEA simulation instead of the default regions generated by Motor-CAD. We click **Yes** to continue with the region editing and notice that the **Use Custom E-Magnetic Regions** checkbox has been automatically enabled.



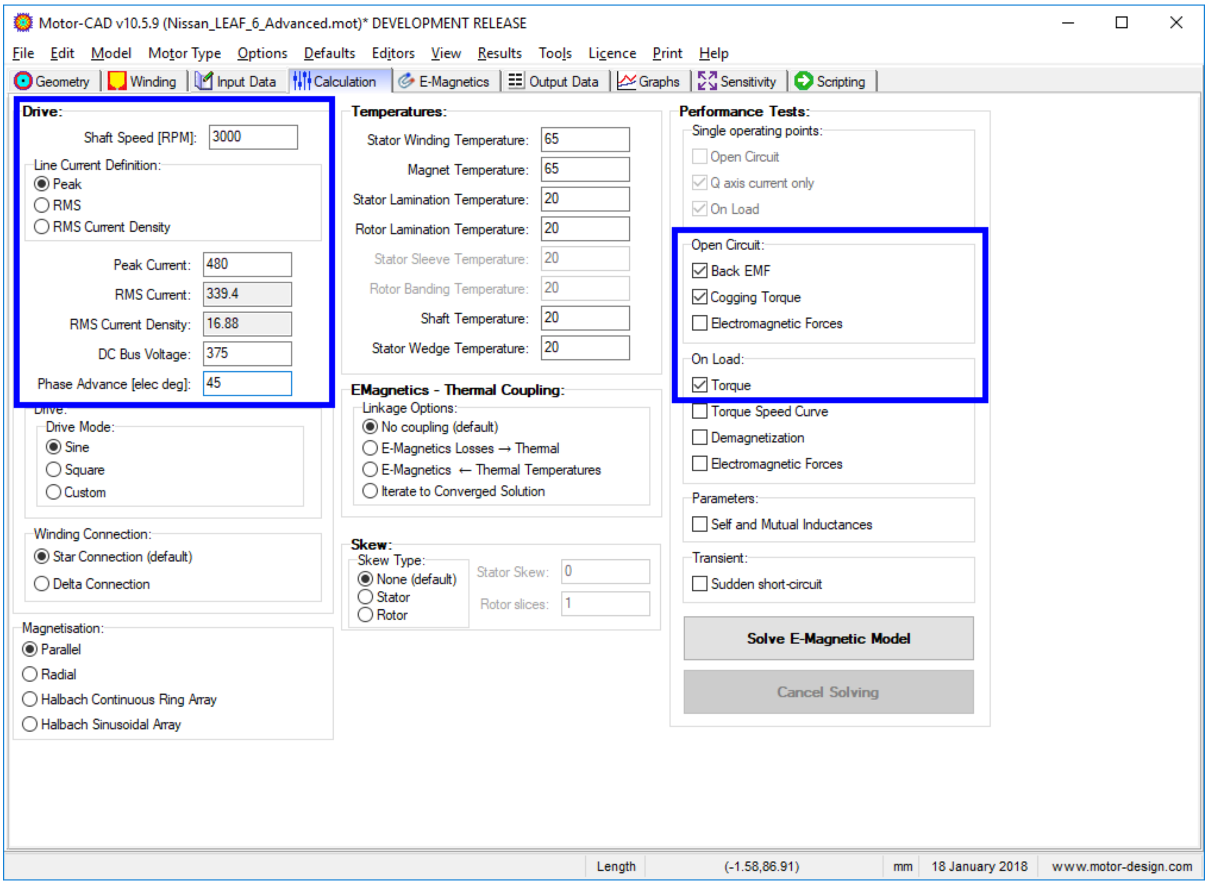
Now that the region has been moved to the correct position, the first warning has disappeared. We repeat the process for the second warning, which refers to the air region at the end of another magnet, so that there are no remaining warnings. We now visually check all regions to make sure they are correct.



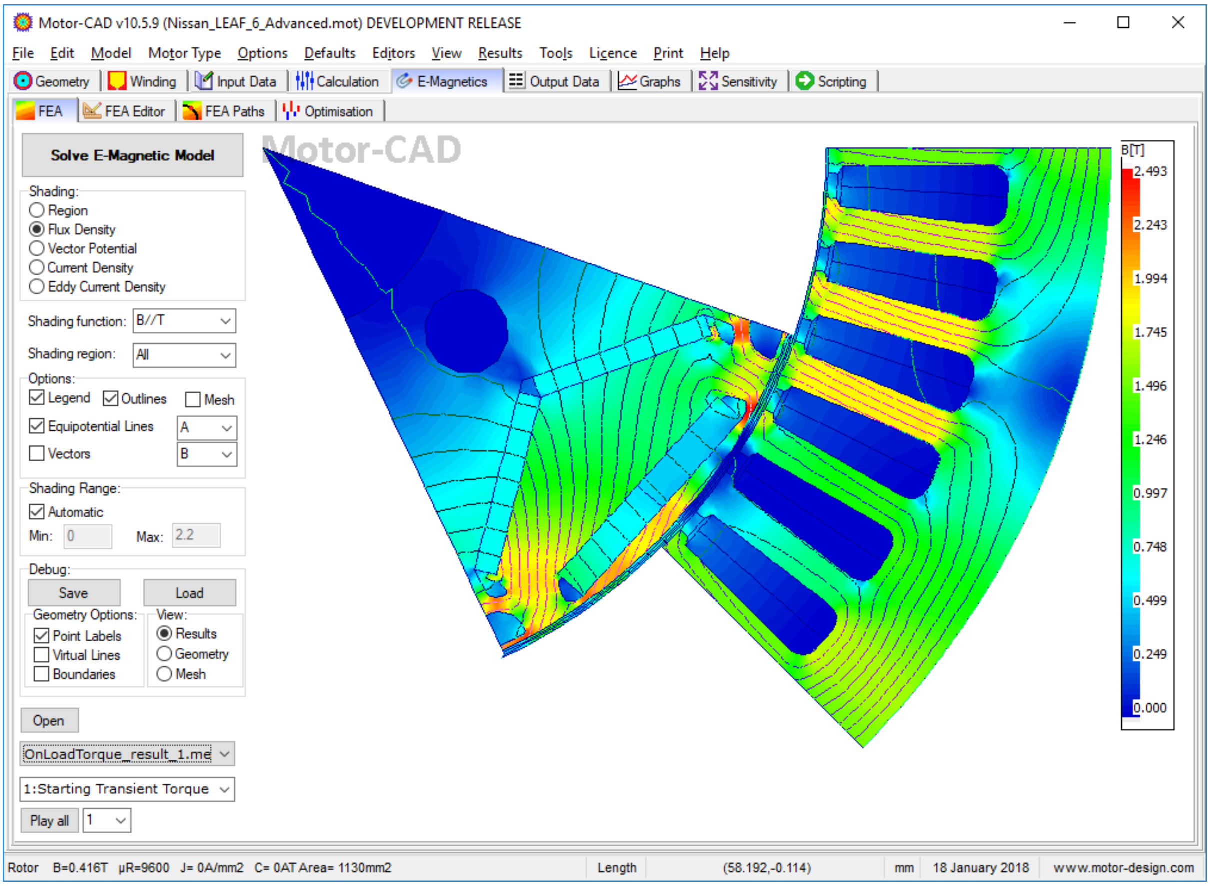
We now go to the **Calculation** page. In order to compare with the FEA calculations performed in section 4 without the DXF geometry, we set the following:

Parameter	Value	Units
Shaft Speed	3000	RPM
Peak Current	480	A
Phase Advance	45	Elec deg

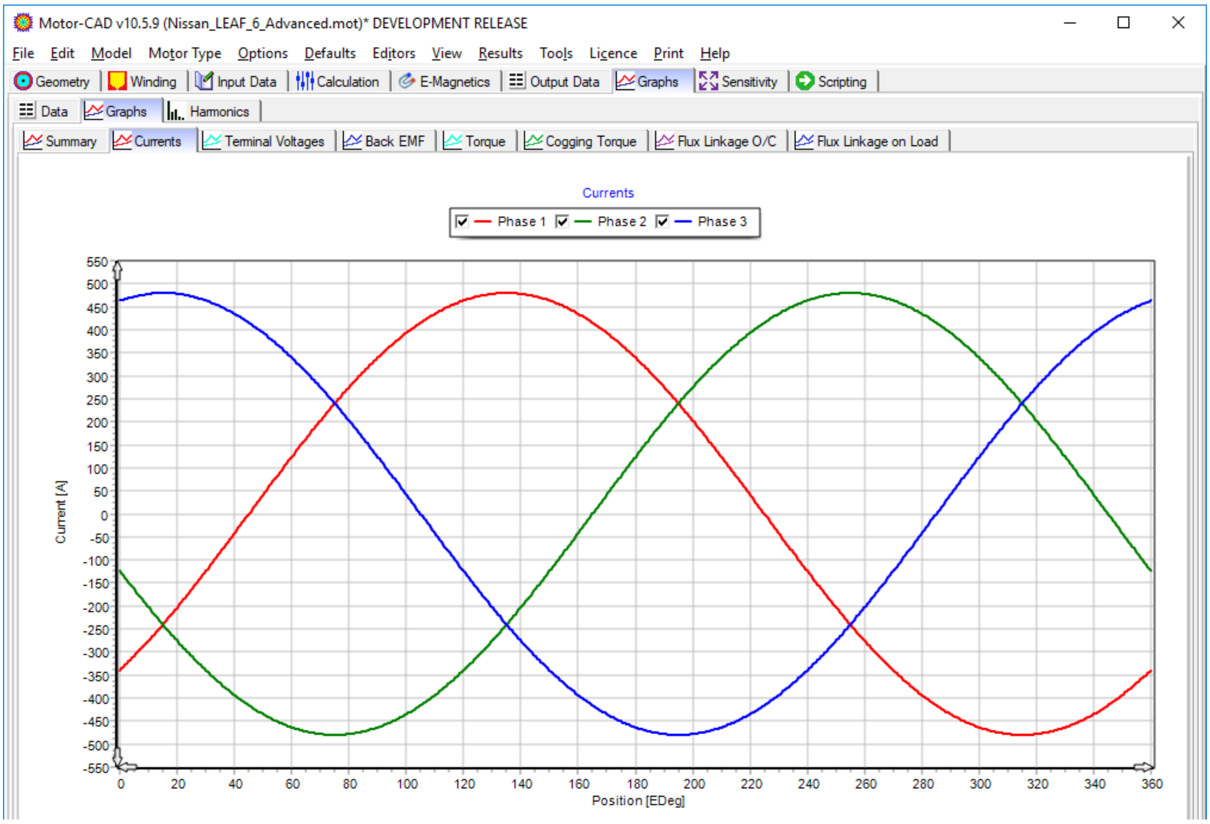
We enable only the **Torque**, **Back EMF** and **Cogging Torque** calculations and **Solve** the model.

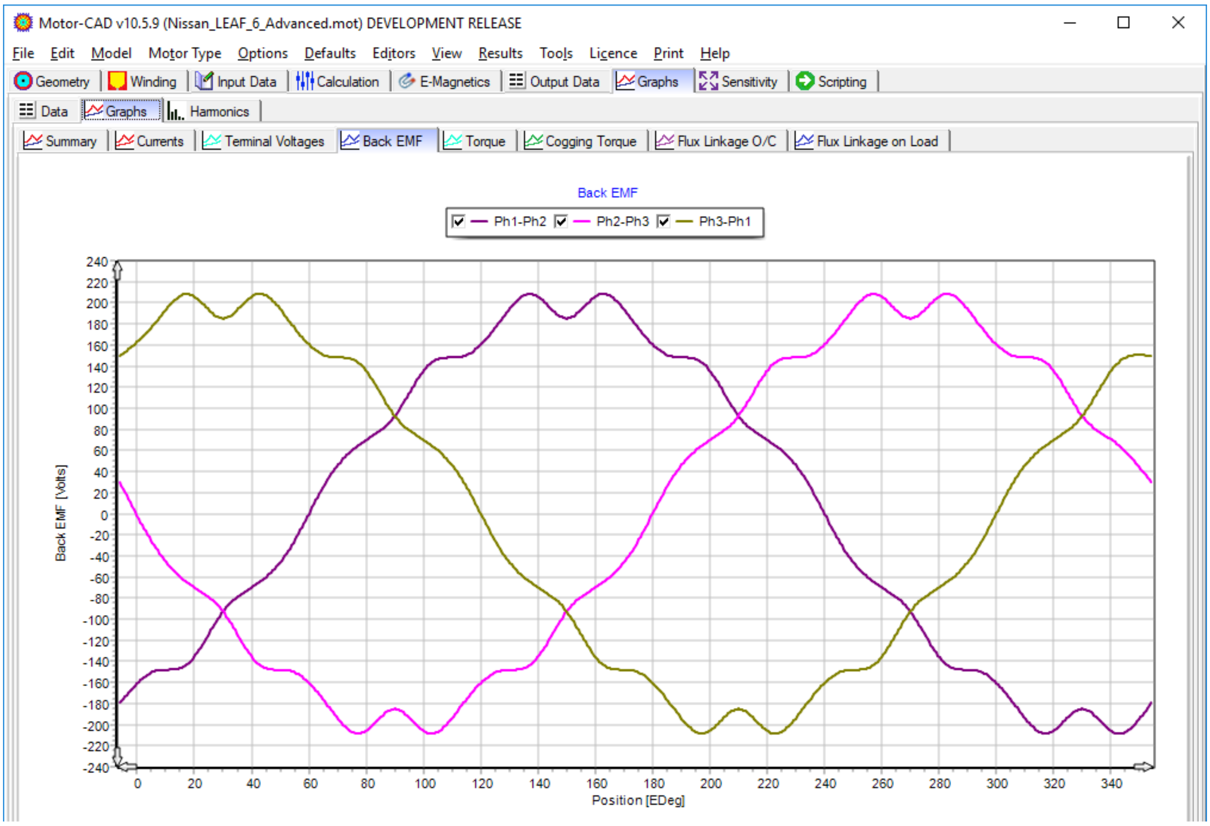


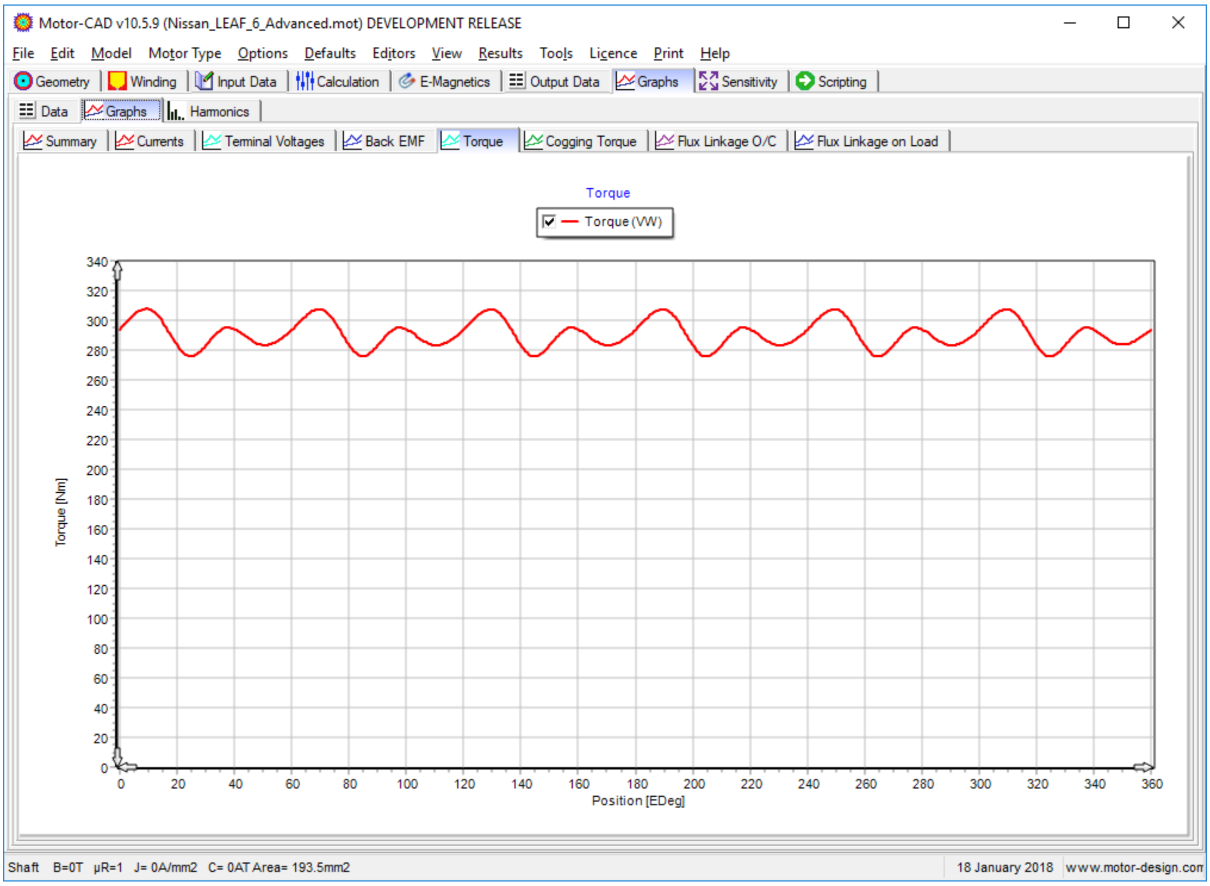
When solving is completed we can view the results. Under **E-Magnetics -> FEA**, we see that now the DXF geometry has been used for the simulation.

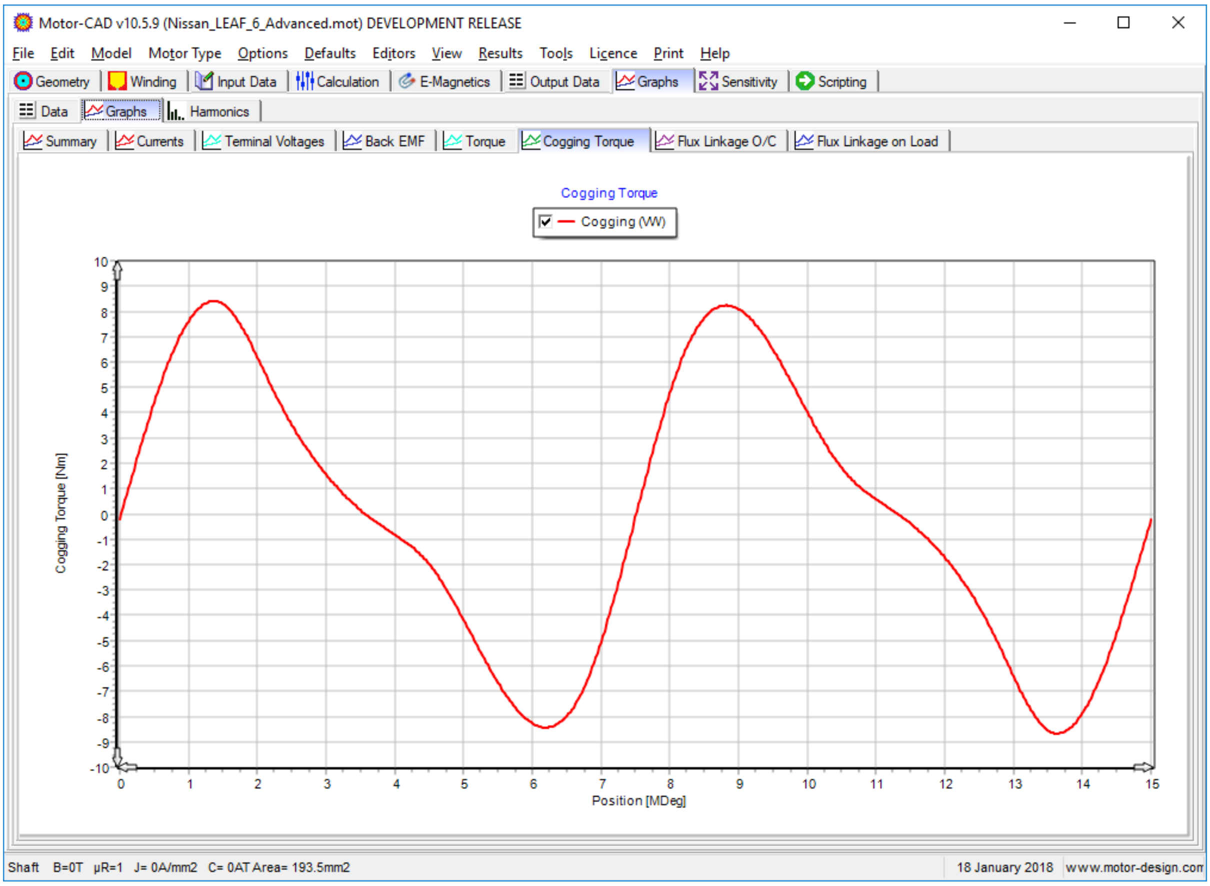


We can check the impact of the geometry customisation on the machine performance in the **Graphs**.






Motor-CAD v10.5.9 (Nissan_LEAF_6_Advanced.mot) DEVELOPMENT RELEASE
File Edit Model Motor Type Options Defaults Editors View Results Tools Licence Print Help
Geometry Winding Input Data Calculation E-Magnetics Output Data Graphs Sensitivity Scripting
Data Graphs Harmonics
Summary Currents Terminal Voltages Back EMF Torque Cogging Torque Flux Linkage O/C Flux Linkage on Load
Torque
Torque (VW)
Torque [Nm]
Position [EDeg]
Shaft B=0T μR=1 J= 0A/mm2 C= 0AT Area= 193.5mm2
18 January 2018 www.motor-design.com


Motor-CAD v10.5.9 (Nissan_LEAF_6_Advanced.mot) DEVELOPMENT RELEASE
File Edit Model Motor Type Options Defaults Editors View Results Tools Licence Print Help
Geometry Winding Input Data Calculation E-Magnetics Output Data Graphs Sensitivity Scripting
Data Graphs Harmonics
Summary Currents Terminal Voltages Back EMF Torque Cogging Torque Flux Linkage O/C Flux Linkage on Load
Cogging Torque
Cogging (VW)
Cogging Torque [Nm]
Position [MDeg]
Shaft B=0T μR=1 J= 0A/mm2 C= 0AT Area= 193.5mm2
18 January 2018 www.motor-design.com

ii. Calculation Settings

Motor-CAD provides advanced settings for the electromagnetic calculations including simulation options and manufacturing factors in **Input Data -> Settings**. Here we will use some of these settings to improve the accuracy of the LEAF model. Further information on all settings can be found in the Motor-CAD manual.

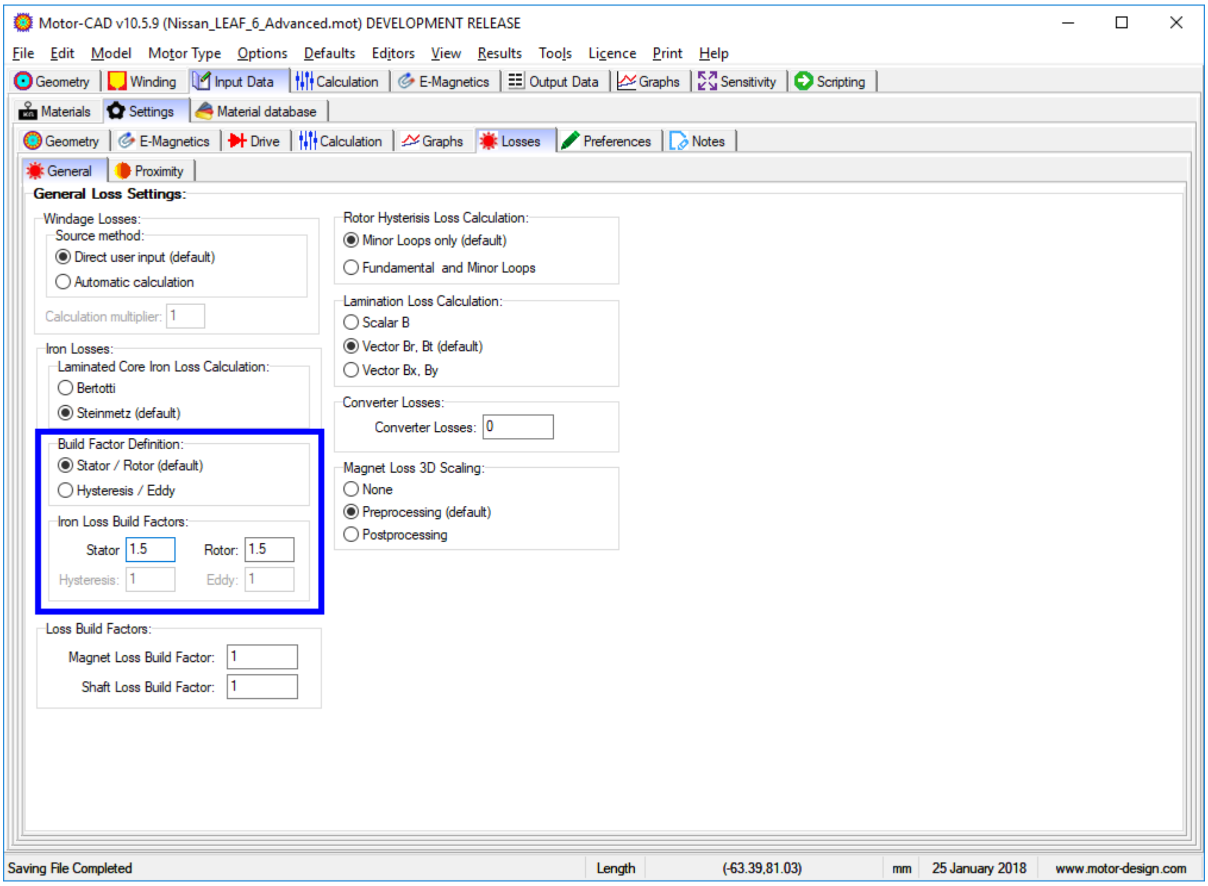
Loss Build Factors

The measured power loss in steel materials is often greater than the characterised loss density given in the datasheets due to the manufacturing processes used. These effects are considered in the model by the use of build factors. The required build factor will depend on many factors but typically will be between 1 to 3. Build factors are defined under the **Input Data -> Settings -> Losses -> General** tab.

For the 30DH steel used in the LEAF motor we will use:

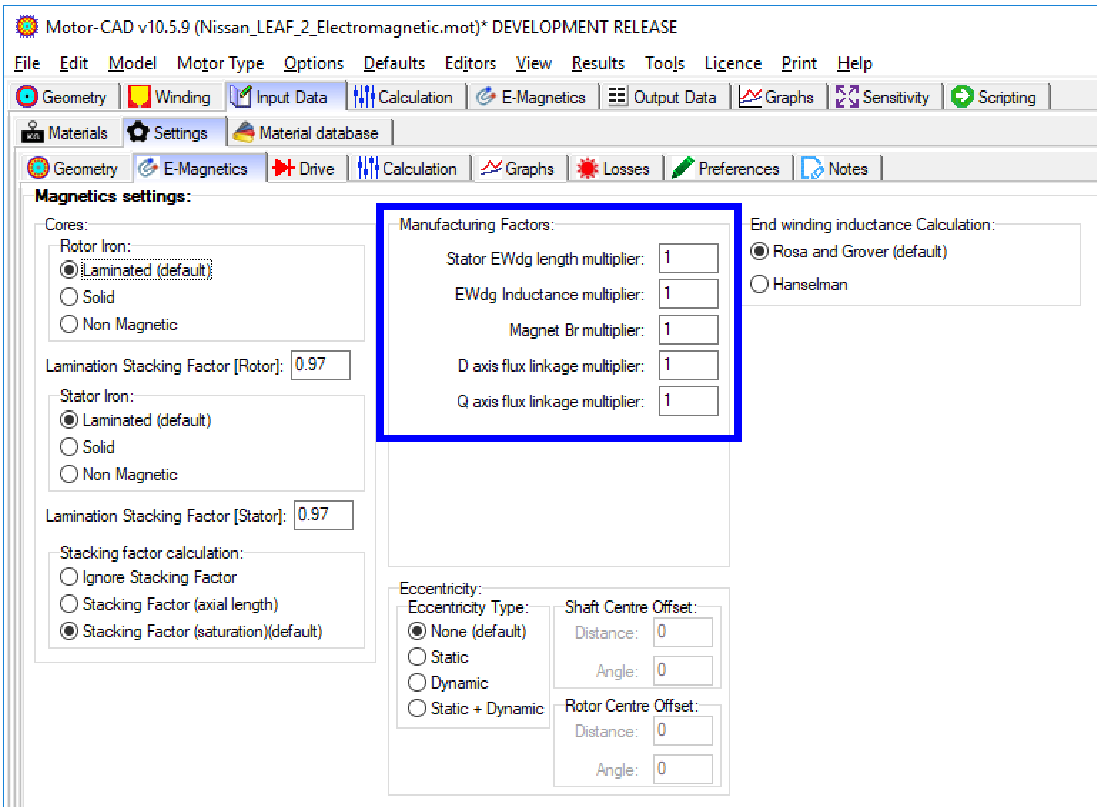
Parameter	Value
Stator Build Factor	1.5
Rotor Build Factor	1.5

Build factors are also available for magnet and shaft losses but are not required for this model.



Manufacturing Factors

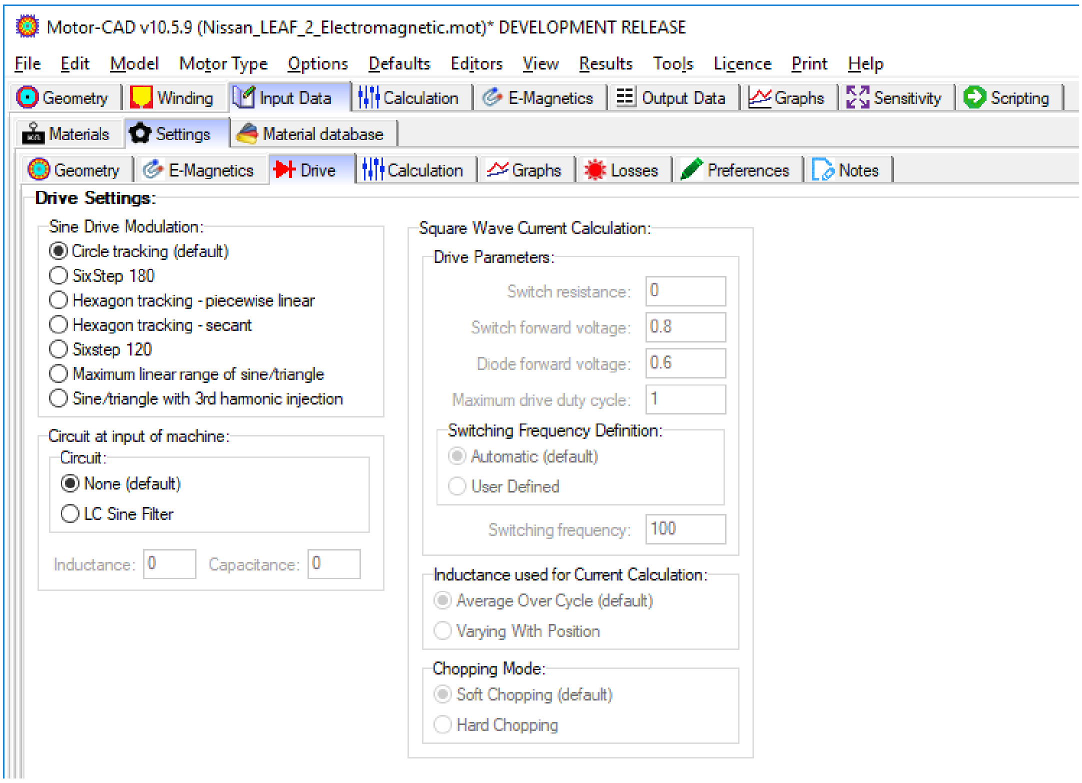
In the case of complex geometries or external factors the resistance, inductance or flux densities may need to be adjusted. These factors are typically calibrated with experimental test data and can be found under **Input Data -> Settings -> E-Magnetics**.



Drive Settings

Details of the drive control can be configured under **Input Data -> Settings -> Drive**. For sine wave driven machines, such as the LEAF, it is important to specify the correct **Sine Drive Modulation** strategy to enable Motor-CAD to calculate the voltage available from the inverter. For this model **Circle tracking** is used.

Here it is also possible to define an LC filter circuit at the input of the machine. For square wave driven machines or other machine types (e.g. SRM), this page also provides more sophisticated drive options.



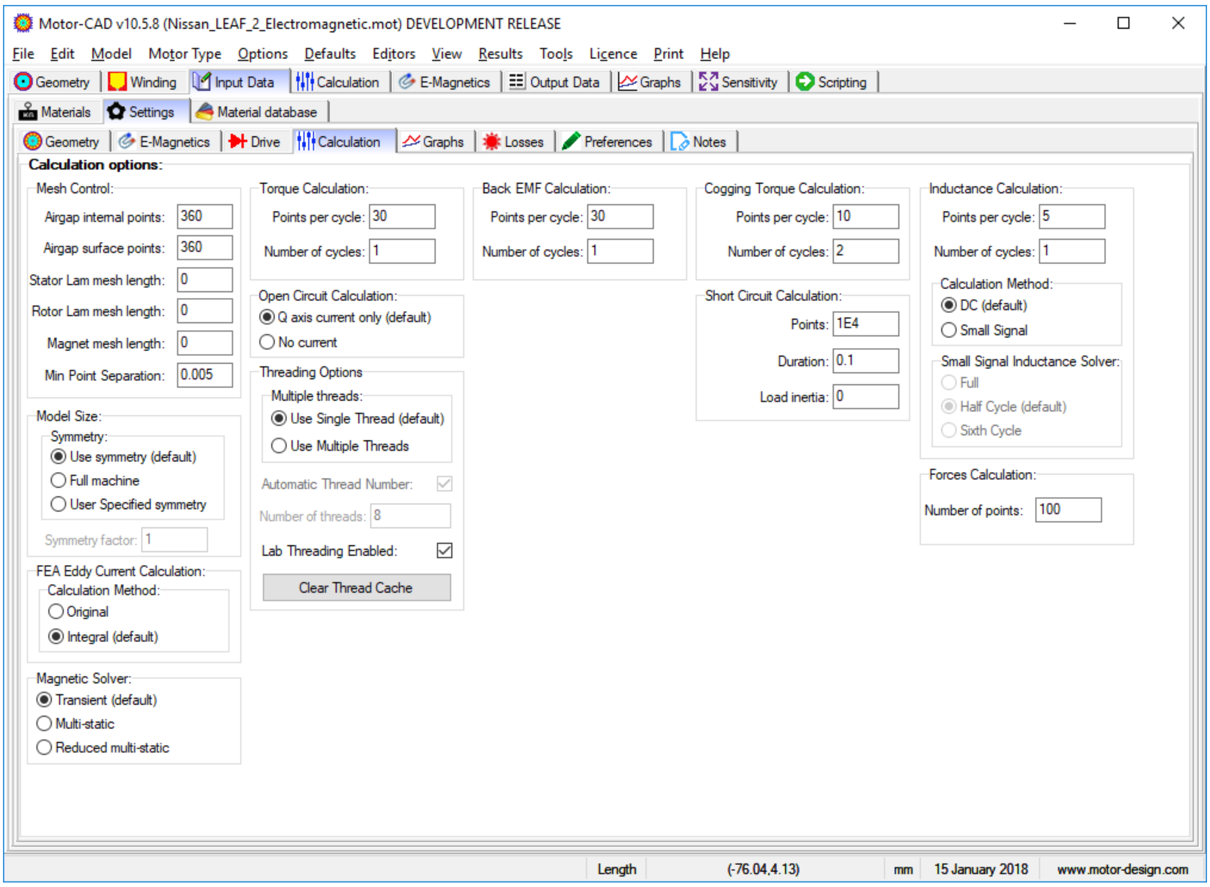
Calculation Settings

The **Input Data -> Settings -> Calculation** tab is used to configure the settings used in the FEA simulations.

The **Mesh Control** options allow the user to change the number of points used for the mesh in the airgap, as well as the maximum mesh element length in the stator, rotor or magnet. Normally the default values work well and these should only be changed if there are problems meshing the model.

Motor-CAD automatically uses symmetry to reduce the size of the model solved in the FEA, enabling a significant reduction in calculation time without loss of accuracy. The **Model Size** settings can be modified if the user wishes to simulate the full machine or to force Motor-CAD to use a particular symmetry factor. The time taken to simulate the model reduces with the square of the symmetry factor, so that simulating a ½ machine will take ¼ of the time to solve compared to a full machine.

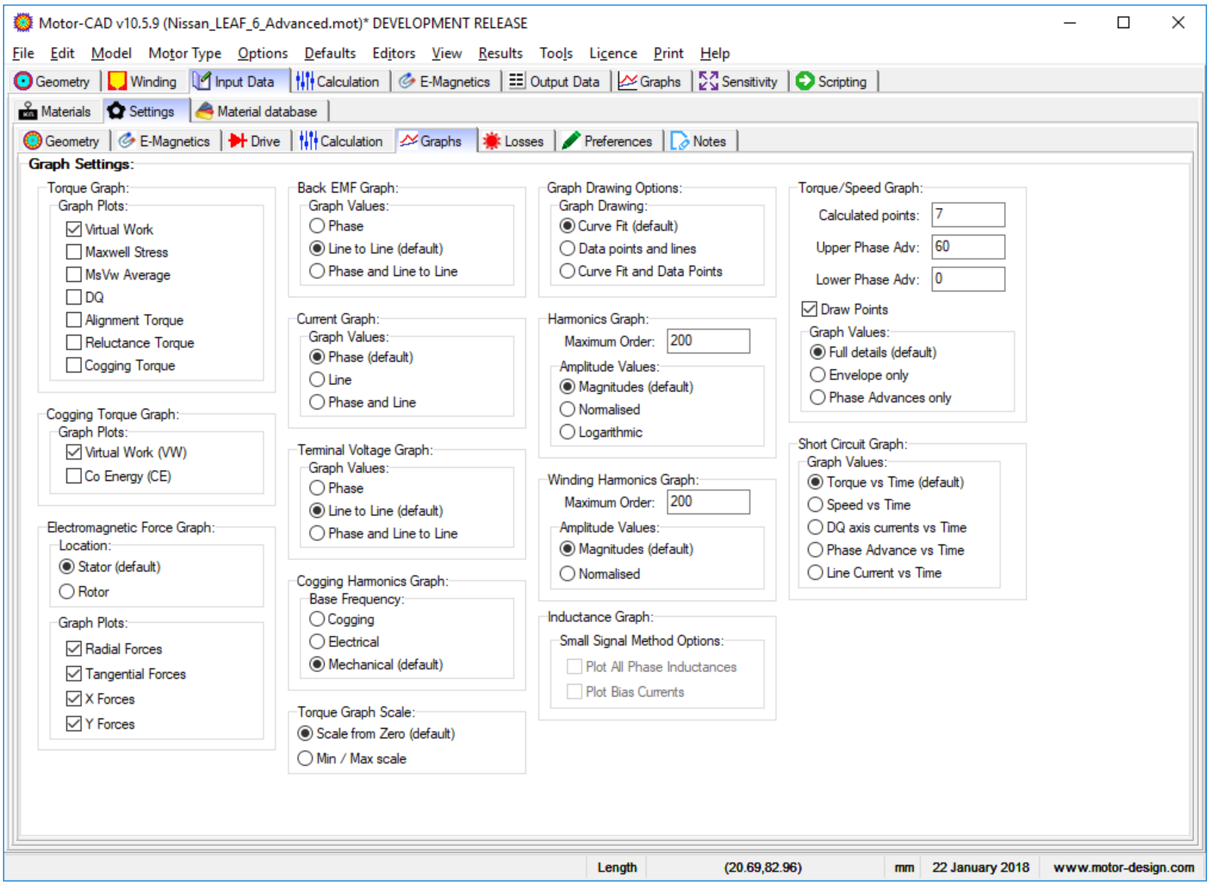
The **Magnetic Solver** option allows the user to perform multi-static FEA simulations instead of using the full transient solver to reduce the calculation time. This can be useful for optimisation routines however it should be noted that the full transient solver is required for an accurate estimation of losses.



Graph Display Settings

The **Input Data -> Settings -> Graphs** tab is used to configure the display of graphs in Motor-CAD.

In Motor-CAD, for a sine wave driven BPM machine, we have 3 standard torque calculation methods: Maxwell Stress (MS), Virtual Work (VW) and DQ axis analytic torque (DQ). Details of the methods can be found in the Motor-CAD manual. As default Motor-CAD displays the torque values from the Virtual Work method, however it can be useful to compare the torque values calculated using the different methods.



iii. Proximity Losses

The losses in the stator winding due to proximity and skin effects (commonly known as AC losses) can be estimated in Motor-CAD using two different methods: Hybrid FEA or Full FEA.

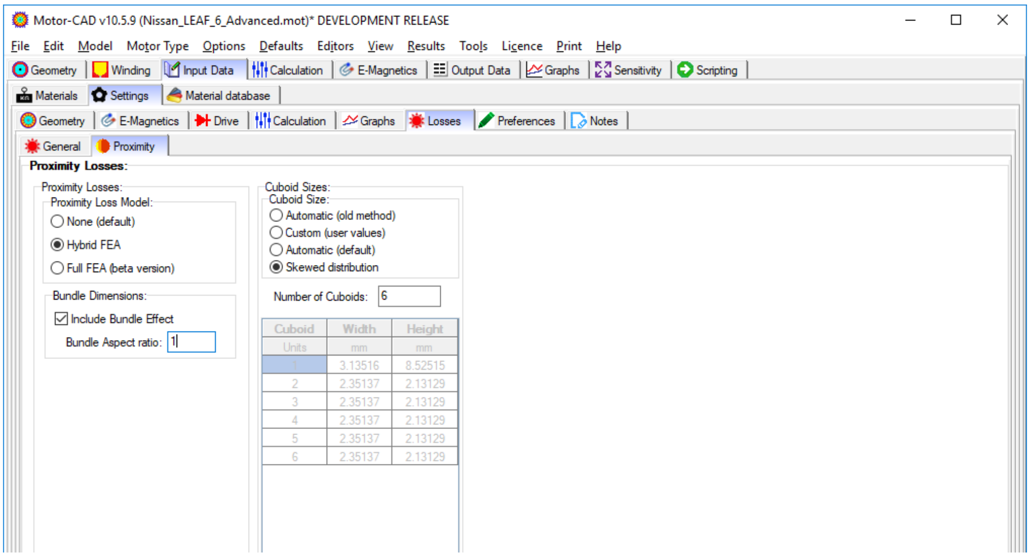
The Hybrid FEA method uses the flux density levels in the slot to estimate the proximity losses. The flux densities are taken from the FEA simulation based on the cuboid positions, and proximity losses are calculated using analytic equations for each cuboid. It is not possible to account for skin depth effects using this method so particular care must be taken with machines operating at high speeds or with large conductors where these effects can be significant.

In the Full FEA method individual conductors are simulated in a single slot and the induced eddy currents are calculated. The Full FEA method is more accurate, but the calculations take longer, so the choice of method depends on whether the model accuracy or calculation speed is the higher priority.

There is a more detailed tutorial on AC loss calculations in Motor-CAD, available at https://www.motor-design.com/publications/tutorials/.

Under **Input Data -> Settings -> Losses -> Proximity**, set the following:

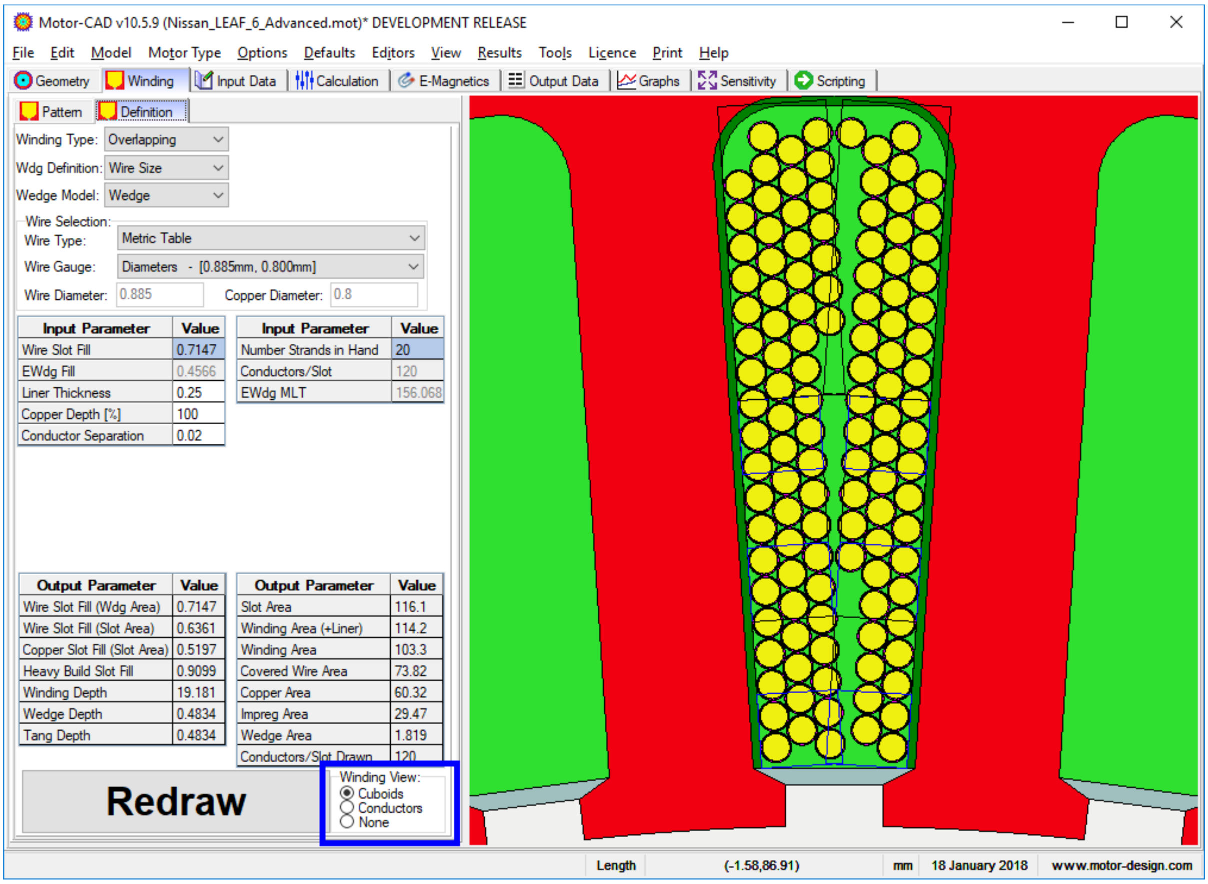
Parameter	Value
Proximity Loss Model	Hybrid FEA
Include Bundle Effect	Enabled
Bundle Aspect Ratio	1
Cuboid Size	Skewed distribution
Number of Cuboids	6



The proximity losses are typically larger towards the slot opening due to the magnetic field generated by the rotor. Selecting the **Skewed distribution** option allows Motor-CAD to increase the number of cuboids around the slot opening, increasing the resolution in this region and hence improving the accuracy of the proximity loss calculation.

Note that the bundle aspect ratio describes the height:width ratio of the conductor bundle. It is important to ensure that this value is accurate.

In the **Winding -> Definition** tab, set the **Winding View** to **Cuboids** in order to visualise the cuboids defined by Motor-CAD for calculation of the proximity losses. We can see that the cuboids placed at the slot opening are smaller than those at the bottom of the slot. Note that the cuboids are numbered from the bottom of the slot down towards the opening.

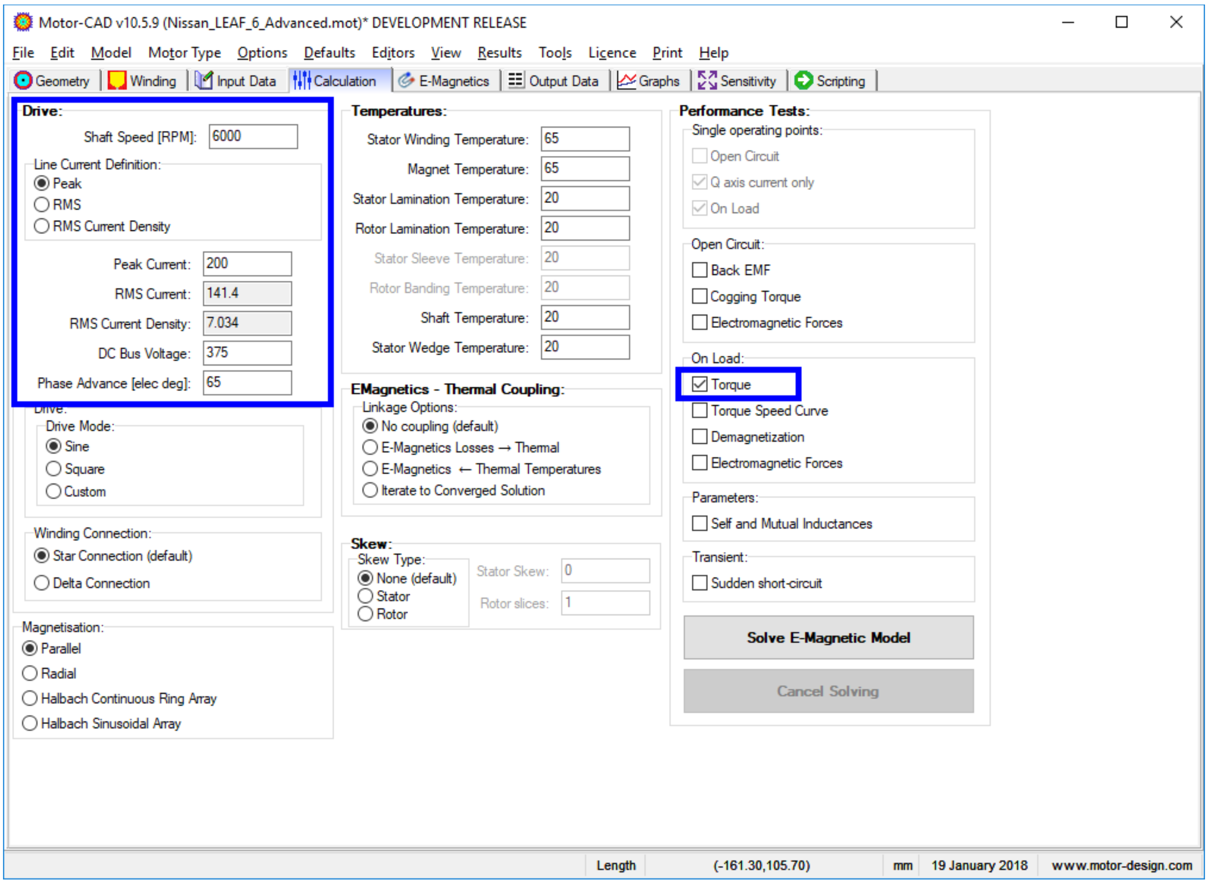


When using the electromagnetic model only, increasing the number of cuboids does not affect the calculation time and therefore it would be recommended to use 20 cuboids (same as the number of strands in hand) for increased accuracy. However, in the thermal model, increasing the number of cuboids will increase the complexity of the thermal circuit and therefore the amount of time taken to solve the model. We have therefore chosen 6 cuboids as a compromise between the accuracy and thermal calculation time.

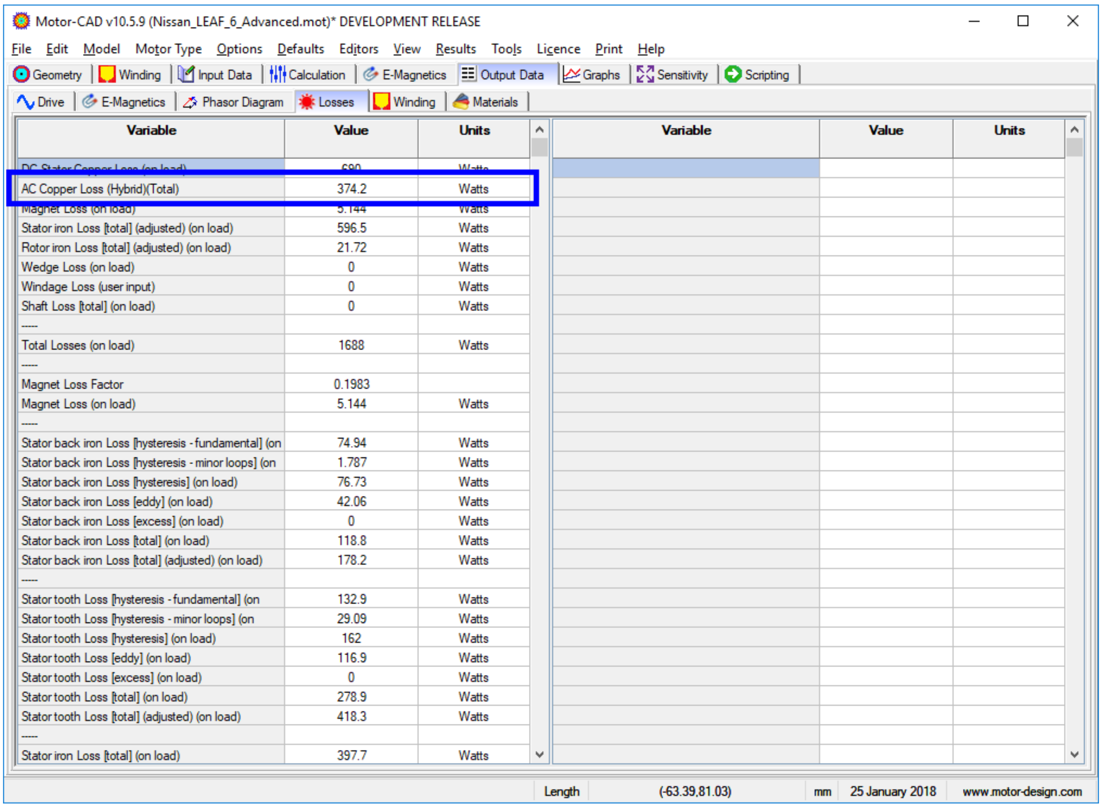
We will now solve the electromagnetic model to see the resulting losses. AC effects are more significant at higher speeds, so we therefore choose a high-speed operating point. We choose the following:

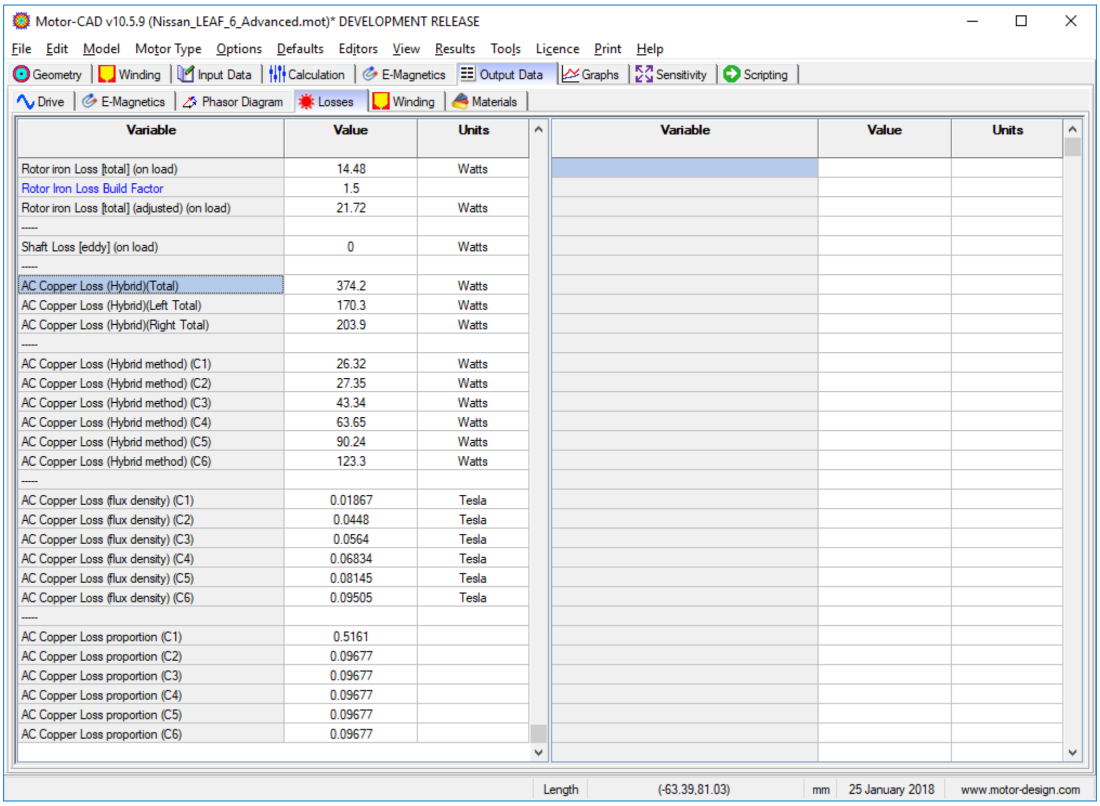
Parameter	Value	Units
Shaft Speed	6000	rpm
Peak Current	200	A
Phase Advance	65	Elec deg

Ensure that the **Torque** calculation is enabled and **Solve** the model.

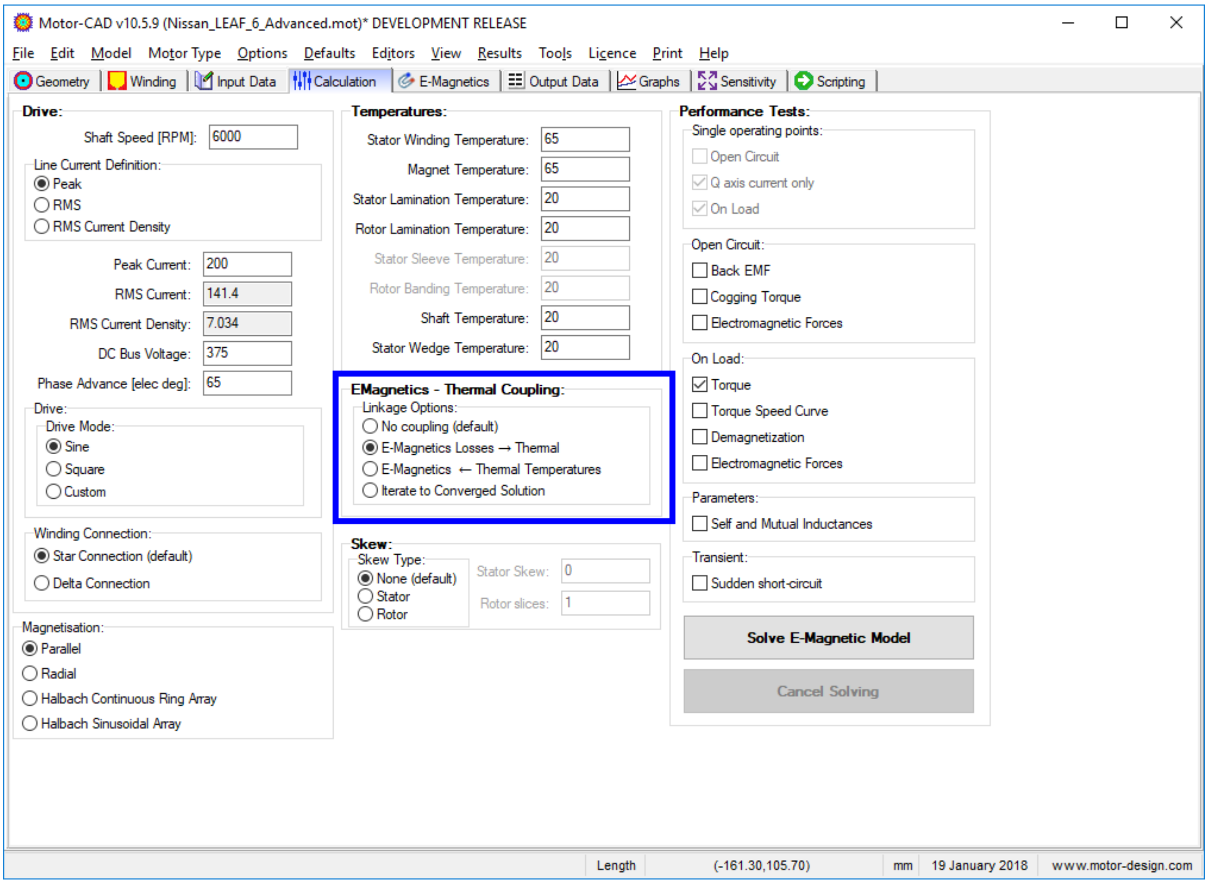


Once the solving is completed, we can see the calculated losses under the **Output Data -> Losses** tab. In the left-hand table, the total **AC Copper Loss** is reported at the top of the table. We can scroll down to see full details of the calculated AC losses, including a breakdown of the losses in individual cuboids.

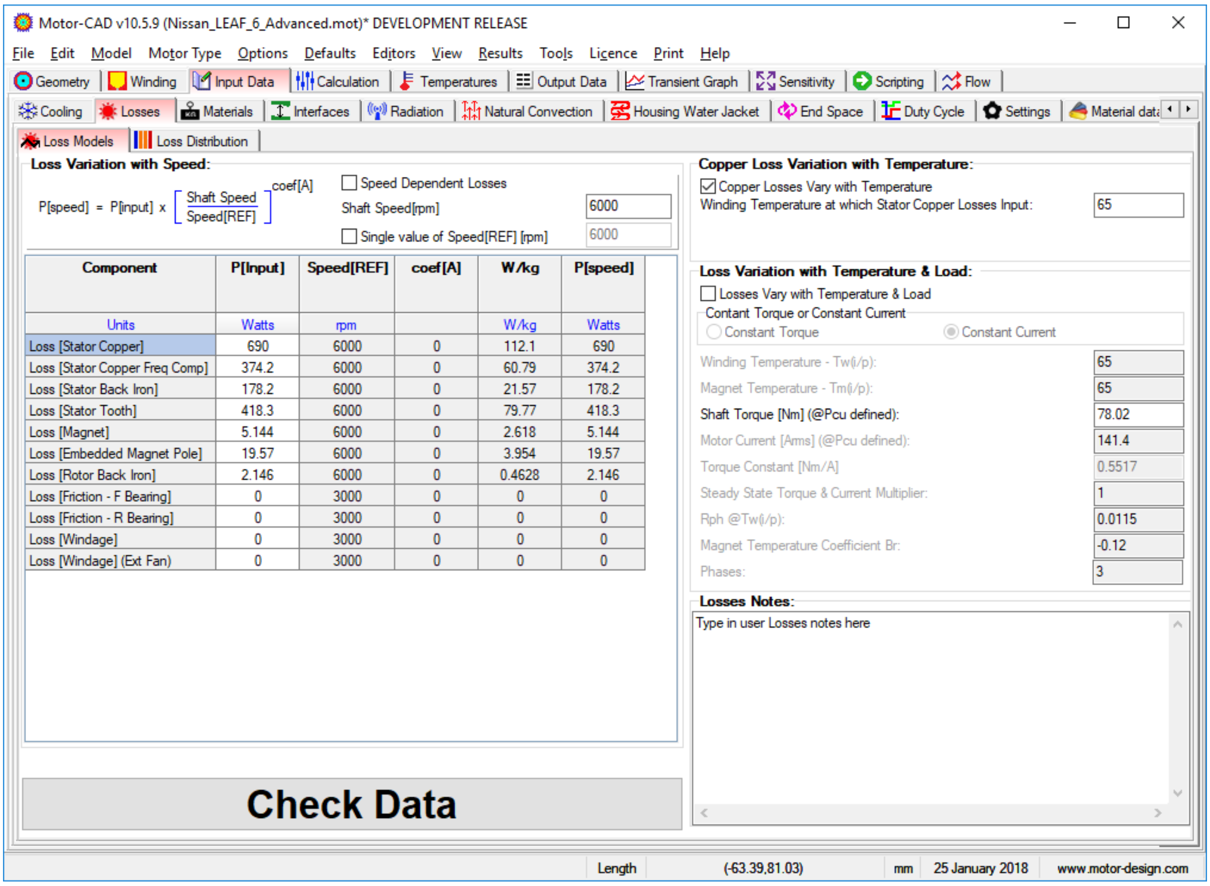




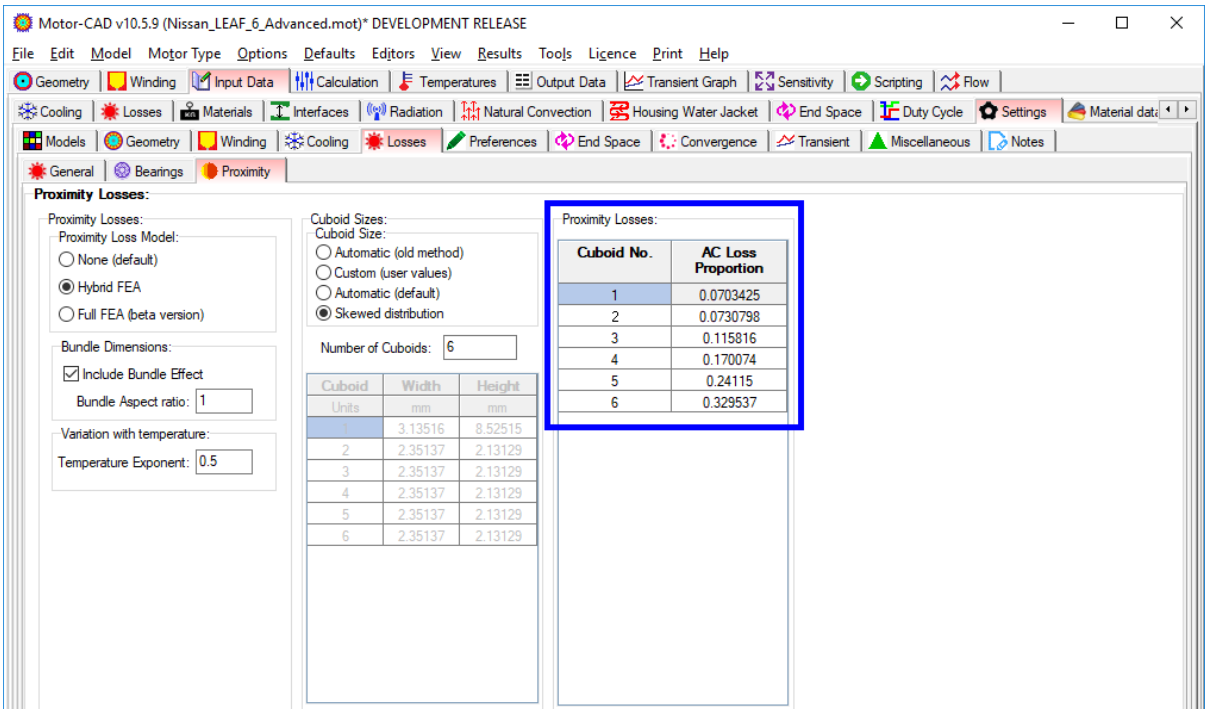
We can see the impact of the AC losses, including the distribution across the cuboids, on the machine temperatures by solving the thermal model for this operating point. In the **Calculation** tab, we set **EMagnetics - Thermal Coupling** to **E-Magnetics Losses -> Thermal**. This transfers the calculated losses into the thermal model – note that we do not need to solve the e-magnetic model again.



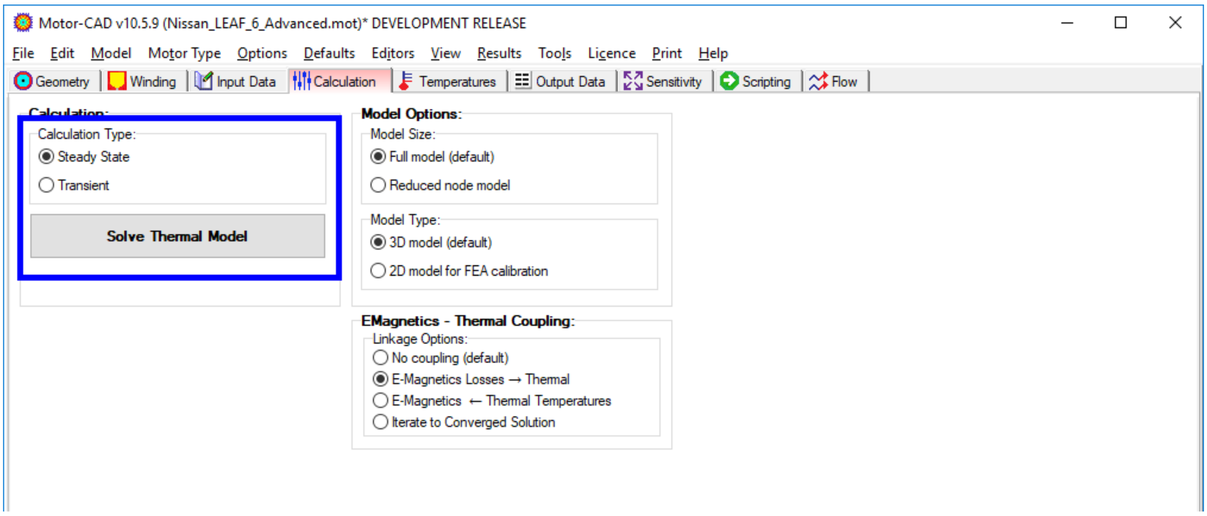
Now switch to the thermal model and view the losses under **Input Data -> Losses -> Loss Models**. The AC losses are labelled as **Loss [Stator Copper Freq Comp]**.



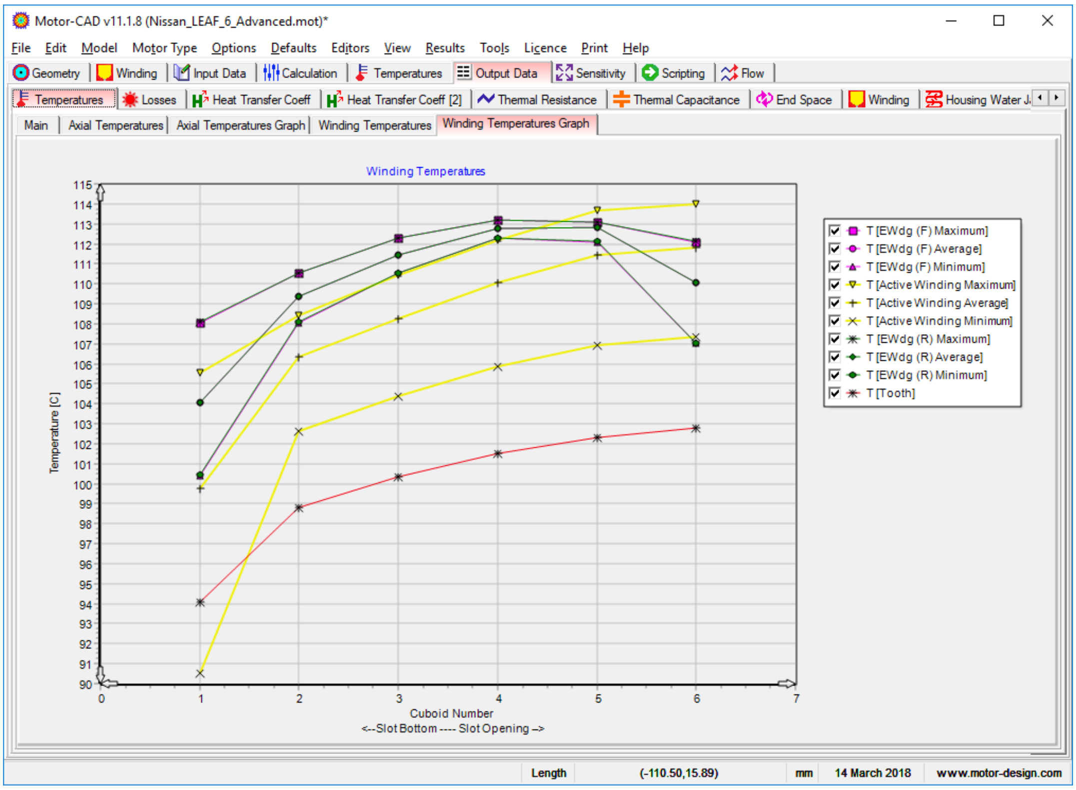
We can see the AC loss distribution over the cuboids under **Input Data -> Settings -> Losses -> Proximity**. This distribution is taken from the e-magnetic results.



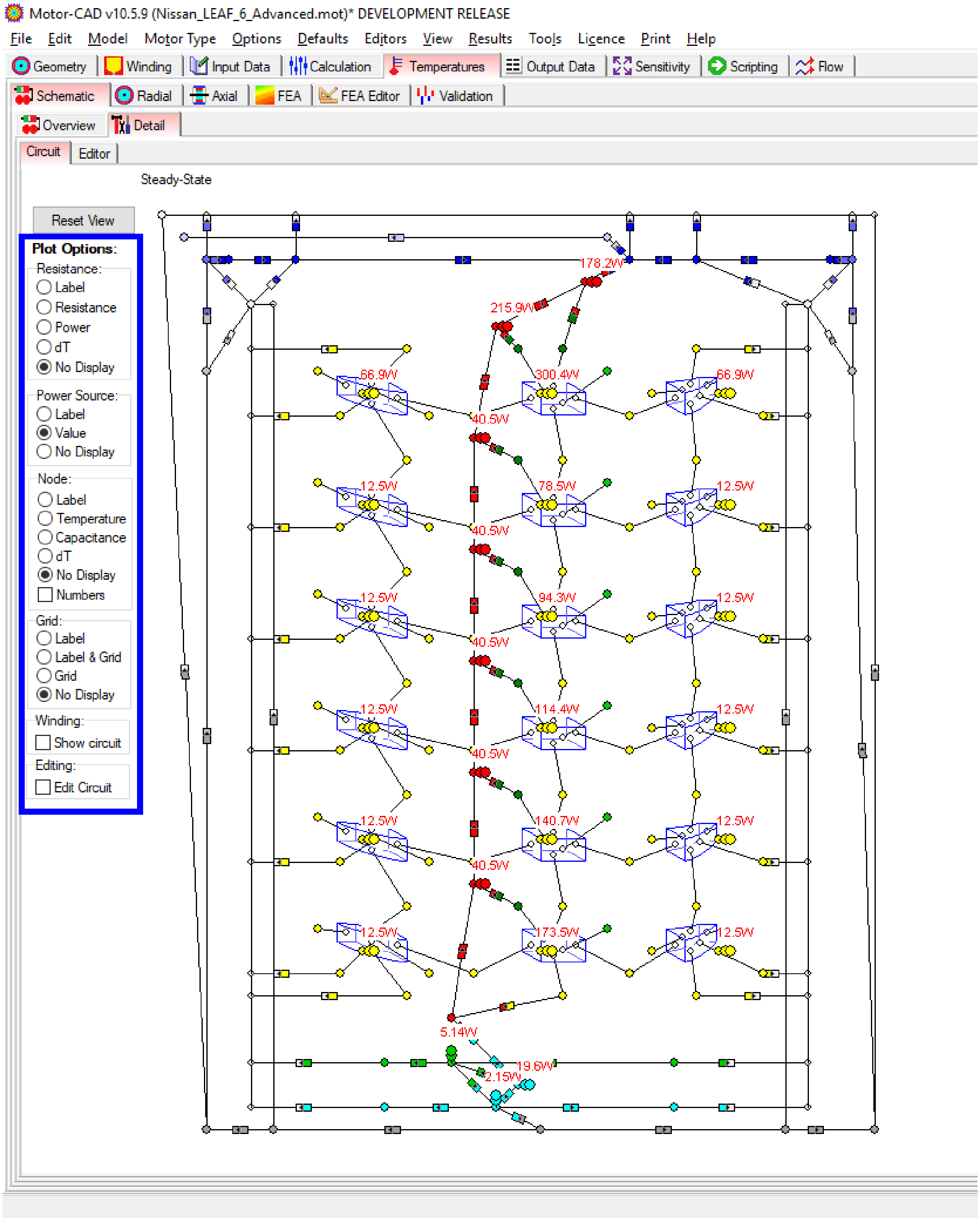
We now go to the **Calculation** tab, set the **Calculation Type** to **Steady State** and solve the thermal model.



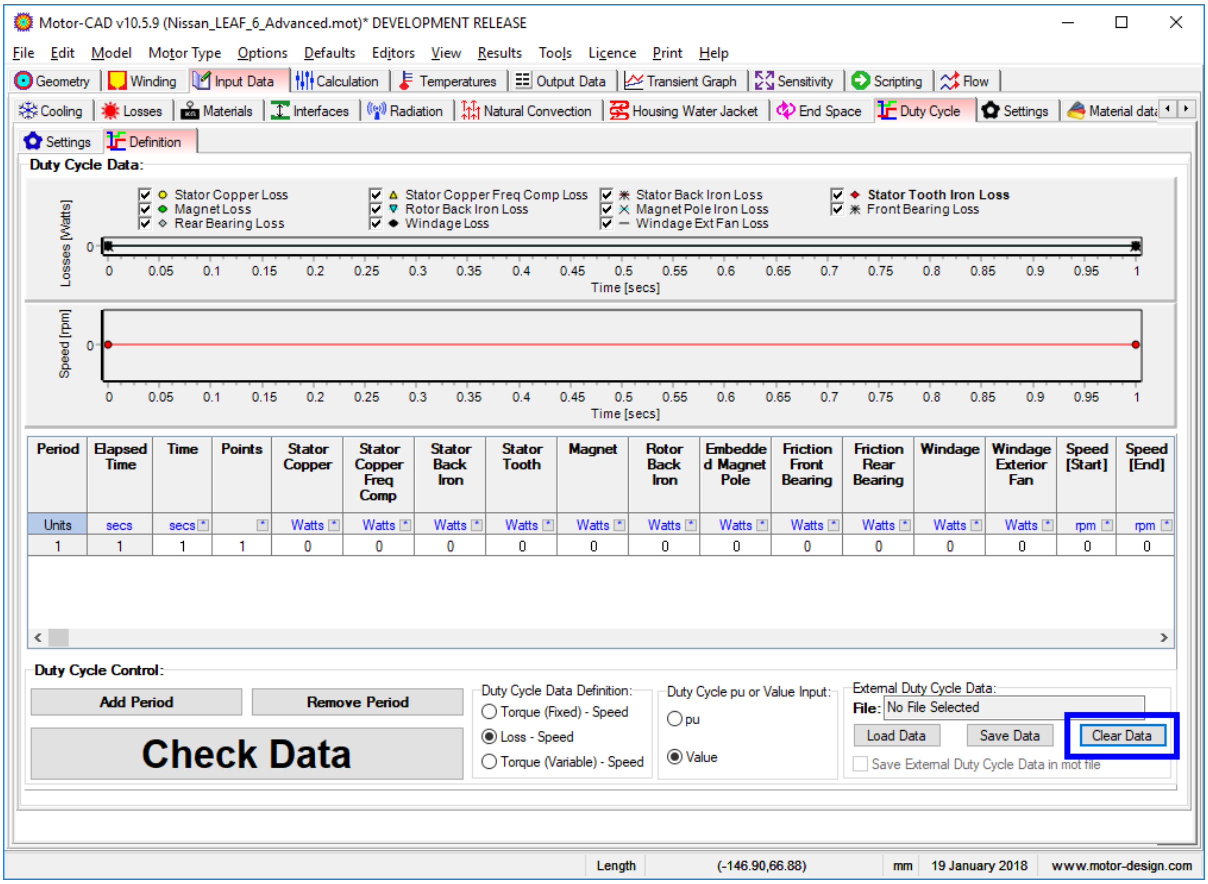
In the OutputData->**Temperatures -> Winding Temperature Graph** tab we can see the temperature distribution from the slot opening to slot bottom. For each cuboid we have the temperature in the winding and in the stator tooth. We can see the temperature increasing towards the slot opening.



In the **Temperatures -> Schematic -> Detail -> Circuit** tab, we can see the distribution of the losses in the thermal network. Note that we have used the **Plot Options** to display only the **Power Source Value** on the drawing.



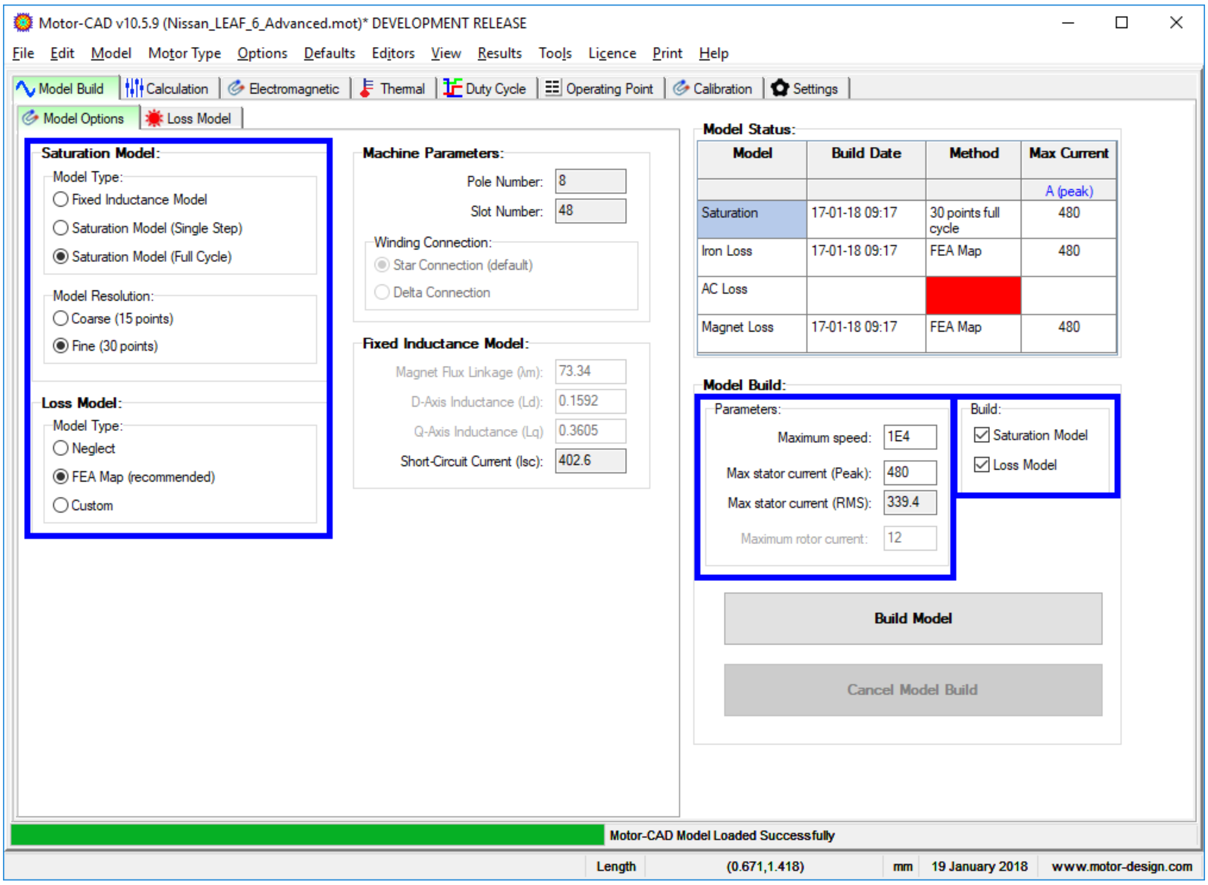
Note: now that we have included the proximity losses in the model, the thermal duty cycle data previously saved to an external file is no longer valid since it will not contain the proximity loss data. We therefore need to remove the external duty cycle data file that we saved in section 7.iv. Under **Input Data -> Duty Cycle -> Definition**, use the **Clear Data** button to clear the external duty cycle data.



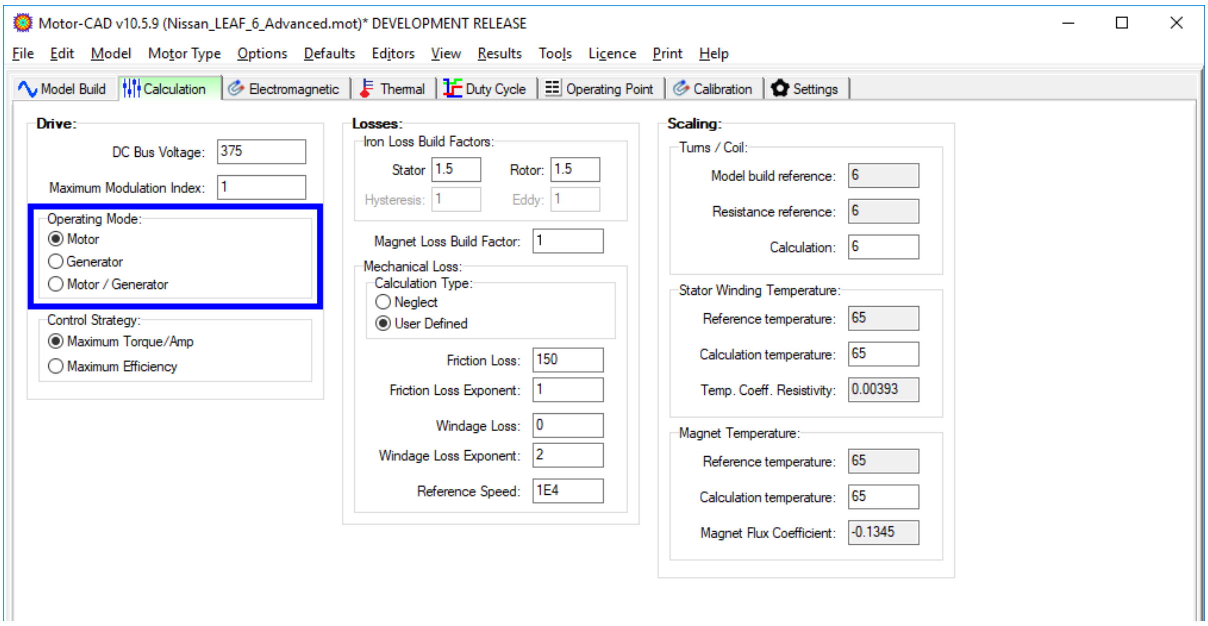
iv. Lab Model with Advanced E-Magnetic Model

Now we need to re-build the Lab model taking into account the new geometry. Switch to the Lab context and go to the **Model Build -> Model Options** tab. Note that, by using the **FEA Map** option for the **Loss Model**, the AC losses are automatically included if they are enabled in the electromagnetic model.

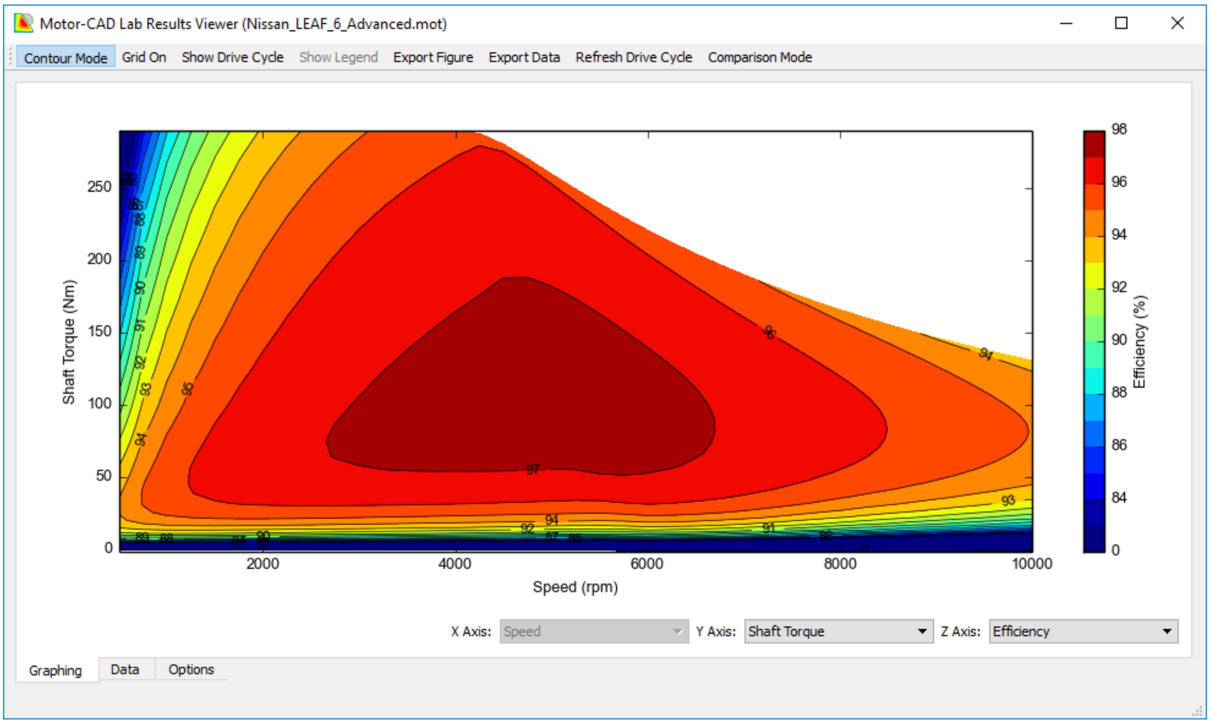
Check the settings, ensure that both the **Saturation Model** and **Loss Model** build options are enabled, and click **Build Model**.



Under the **Calculation** tab, set the **Operating Mode** to **Motor** and check the other settings. Notice that the **Iron Loss Build Factors** specified in the E-Magnetic model are also used here



Under the **Electromagnetic** tab, we check the settings and click **Calculate Emagnetic Performance** to generate the efficiency map.



9. Advanced Thermal Modelling

We will now demonstrate some of the more advanced features of Motor-CAD's thermal model. Save the file with **Menu->File -> Save** and switch to the thermal model **Menu -> Model -> Thermal**.

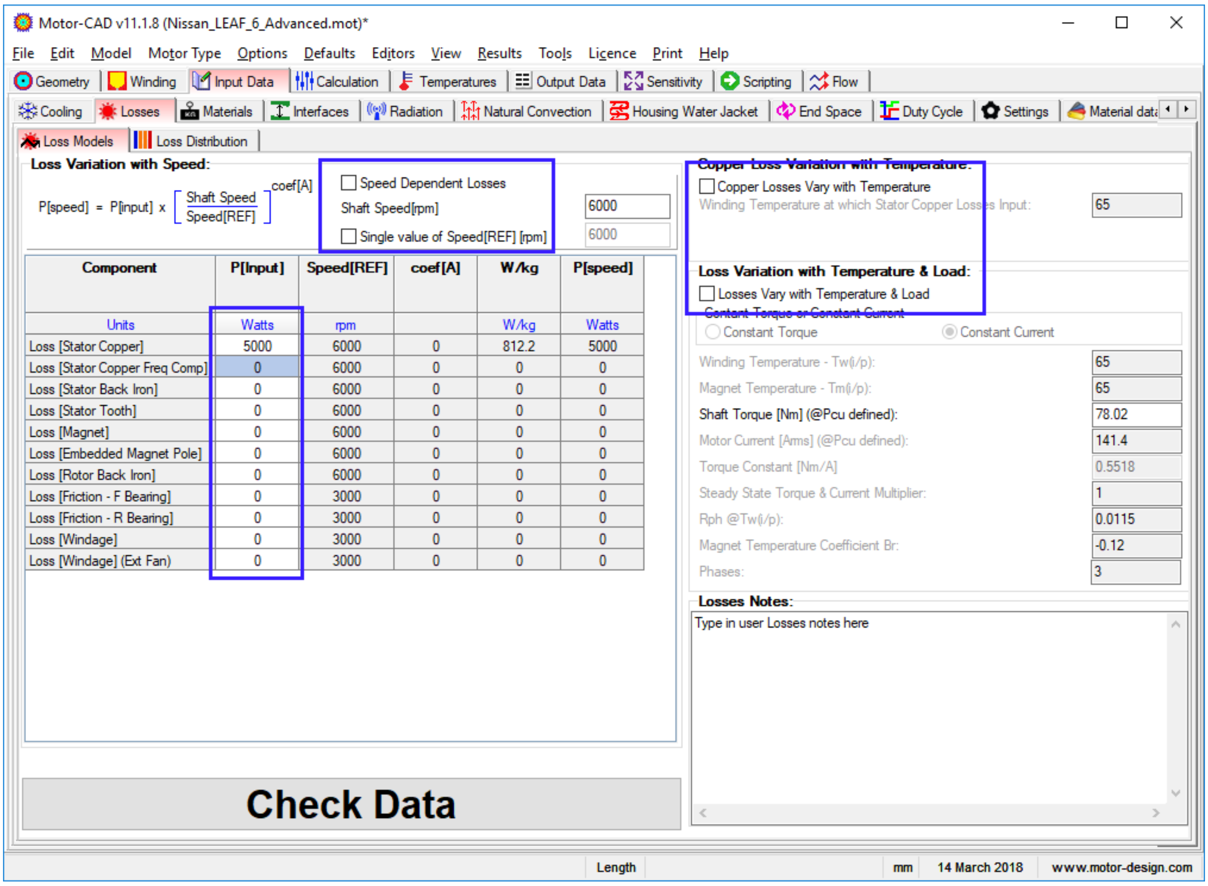
i. Slot Conduction and Winding Model Validation

The cuboidal model used in Motor-CAD for the heat transfer calculation within the slot can be calibrated with FEA simulations. The calibration of the cuboidal model consists in isolating the active winding from the end-effects, configuring power loss only in the active winding and comparing the thermal results of the model to the FEA results.

Under **Input Data -> Losses -> Loss Models**, we set losses only in the stator copper:

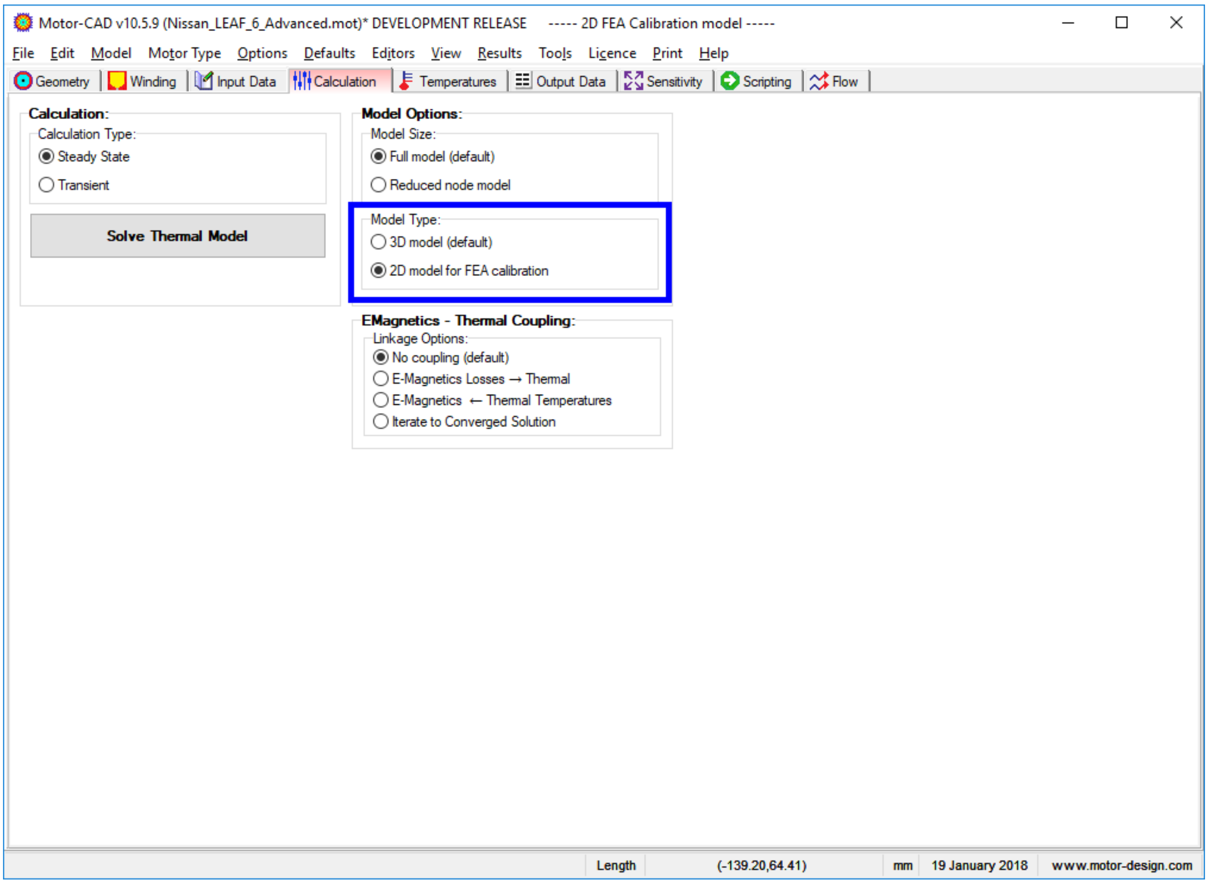
Component	Loss	Units
Loss [Stator Copper]	5000	W
All other components	0	W

We also disable all loss variation with speed, temperature and load. This enables accurate calibration of the model at a single operating point.



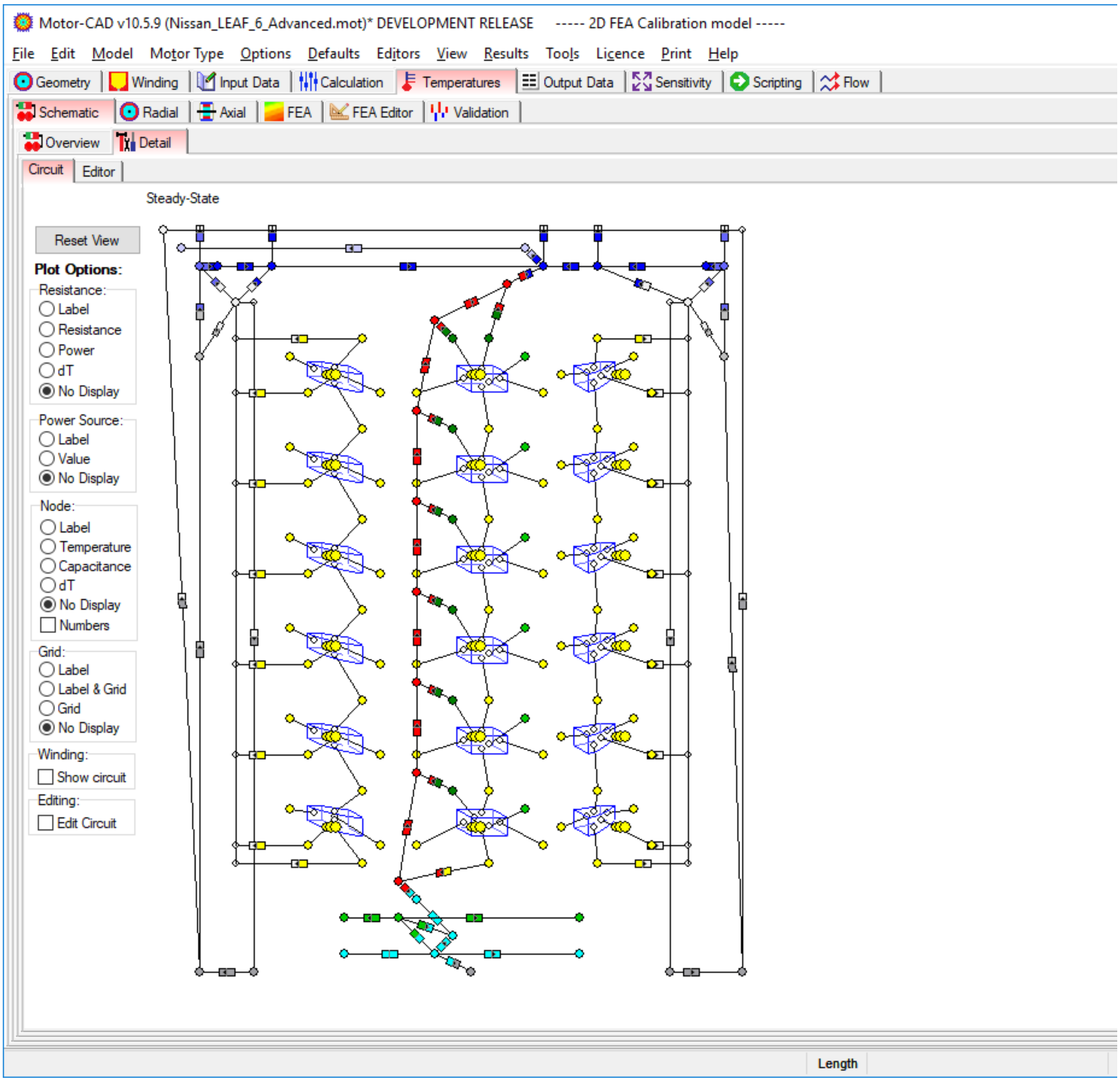
In the **Calculation** tab, we set the following:

Parameter	Value
Calculation Type	Steady State
Model Size	Full Model
Model Type	2d model for FEA calibration
E-Magnetics - Thermal Coupling	No coupling



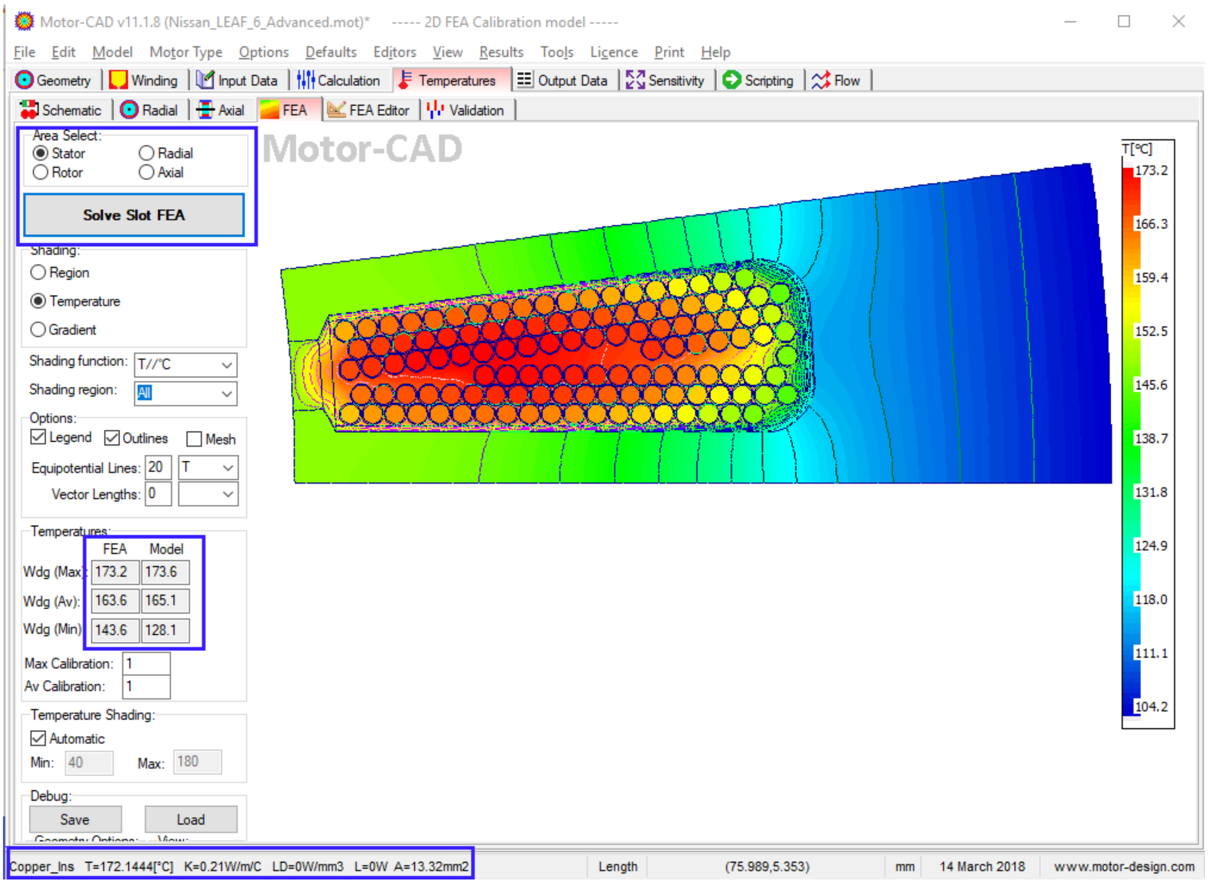
Now solve the model. We notice that the Motor-CAD window caption has been changed to indicate the model is in 2D FEA calibration mode.

By using the 2D model Motor-CAD neglects thermal connections along the axial length of the machine between the windings, stator and rotor. We can see in the **Temperatures -> Schematic -> Detail -> Circuit** tab that the cuboidal elements that represent the active winding are only connected to the rotor and the stator, therefore neglecting the end space effects.



Now we have solved the full thermal circuit using the 2D Fea calibration model we can perform a thermal simulation using thermal FEA. This is solved in the **Temperatures -> FEA** tab. Set the **Area Select** to **Stator** and click **Solve Slot FEA**.

The plot can be customised using the options in the left hand panel, and a comparison is reported between the FEA and analytic model for the minimum, average and maximum winding temperatures. When the mouse is hovered over the plot, the status bar displays detailed information about the point under the mouse cursor, including region name, temperature and losses.



The results usually are well matched between the FEA results and the analytic model. In this example, the difference in the average temperatures is less than 2°C.

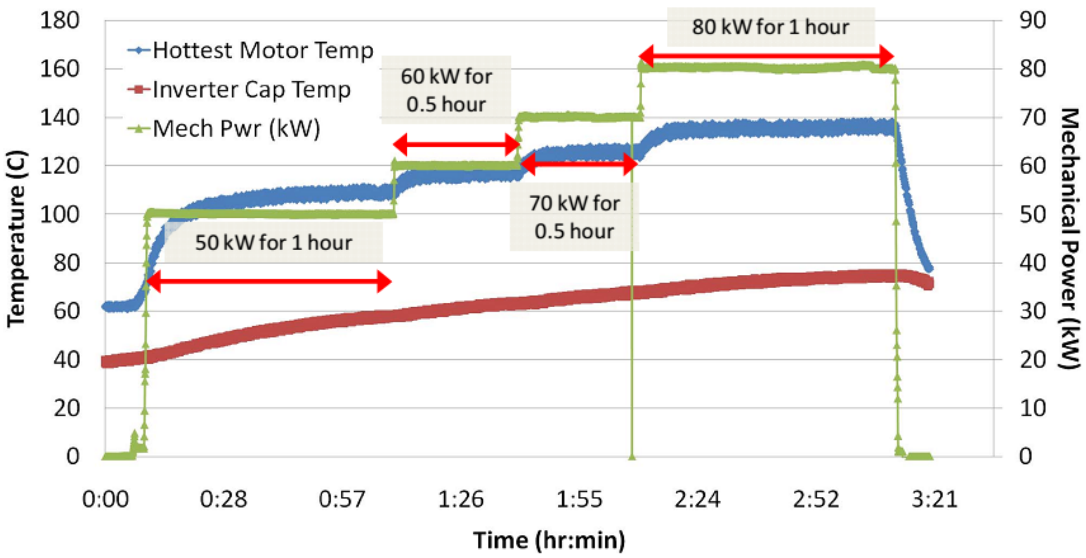
Sometimes the predicted temperature can be different due to the random position of the conductors inside the slot. In this case the size of the cuboids could be updated in order to modify the ratio of copper and impregnation. This would change the thermal conductivity of the winding. However this FEA solution is only valid for the position of the conductors shown and often the conductor positions are not exactly known.

After the 2D calibration has been performed and we are happy with the results, we restore the full 3D model by setting the **Model Type** to **3D model** under the **Calculation** tab.

ii. Custom Thermal Tests

As well as simulating standard testing cycles, Lab can calculate the machine performance over custom duty cycles based on external data files provided by the user. Once the electromagnetic performance has been calculated in Lab, we can then export the calculated loss values to the thermal model to simulate the thermal behaviour over the cycle. We can use this functionality to simulate a thermal test carried out on the LEAF motor.

The graph below shows the results from a thermal test performed under laboratory conditions on the Nissan LEAF machine. The test lasted for 3 hours and the machine was operated with different loads while rotating at 7000rpm.



To simulate this test in Motor-CAD, we generate a text file containing the time, torque and speed values for the test. The values must be in SI units (seconds, Nm, rpm) and the file must contain only the numerical values.

- Start at 0 Nm (0 kW)
- 1 hour at 68.2 Nm (50 kW)
- 30 mins at 81.85 Nm (60 kW)
- 30 mins at 95.49 Nm (70 kW)
- 1 hour at 109.1 Nm (80 kW)
- Finish at 0 Nm (0 kW)

Nissan LEAF Custom Transient.dat

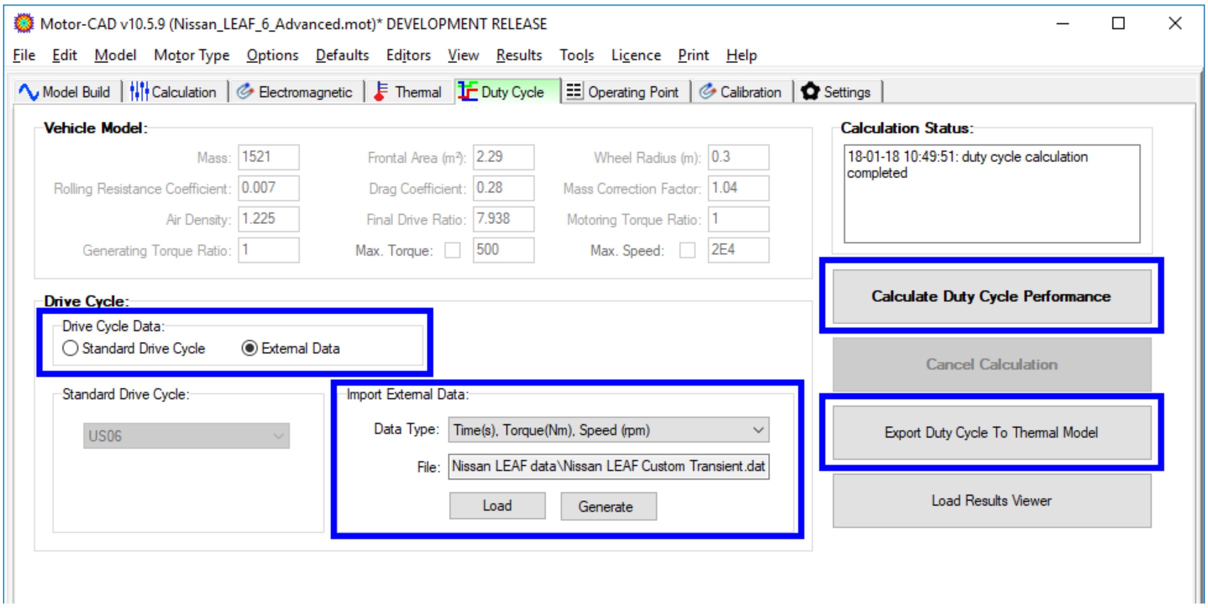
File Edit Format View Help

0	0	7000
1	68.20	7000
3600	68.20	7000
3601	81.85	7000
5400	81.85	7000
5401	95.49	7000
7200	95.49	7000
7201	109.1	7000
10800	109.1	7000
10801	0	7000

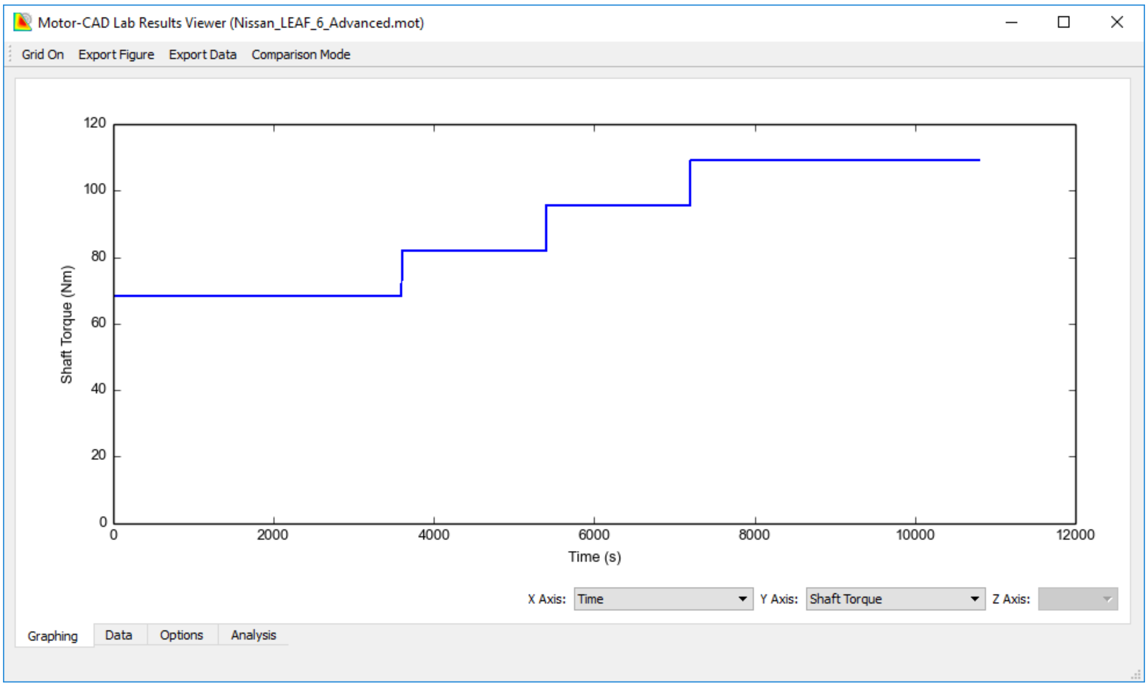
Go to the **Duty Cycle** tab in the Lab context and set the following:

Parameter	Value
Drive Cycle Data	External Data
Data Type	Time(s), Torque(Nm), Speed (rpm)

Notice that the vehicle model input is now disabled since the vehicle model is not used in this calculation. Use the **Load** button to select the custom duty cycle file, and then click **Calculate Duty Cycle Performance**.

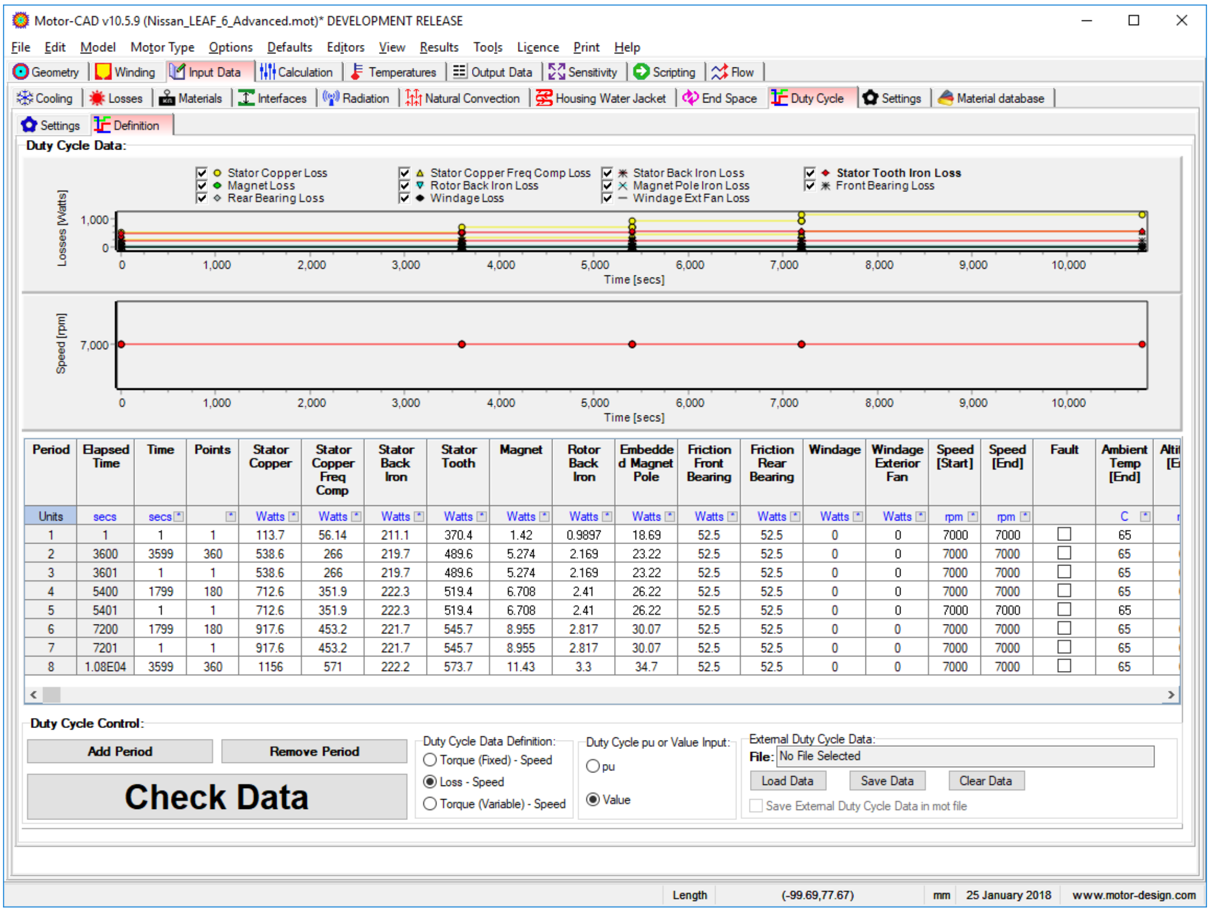


The resulting torque profile matches the values we have requested.

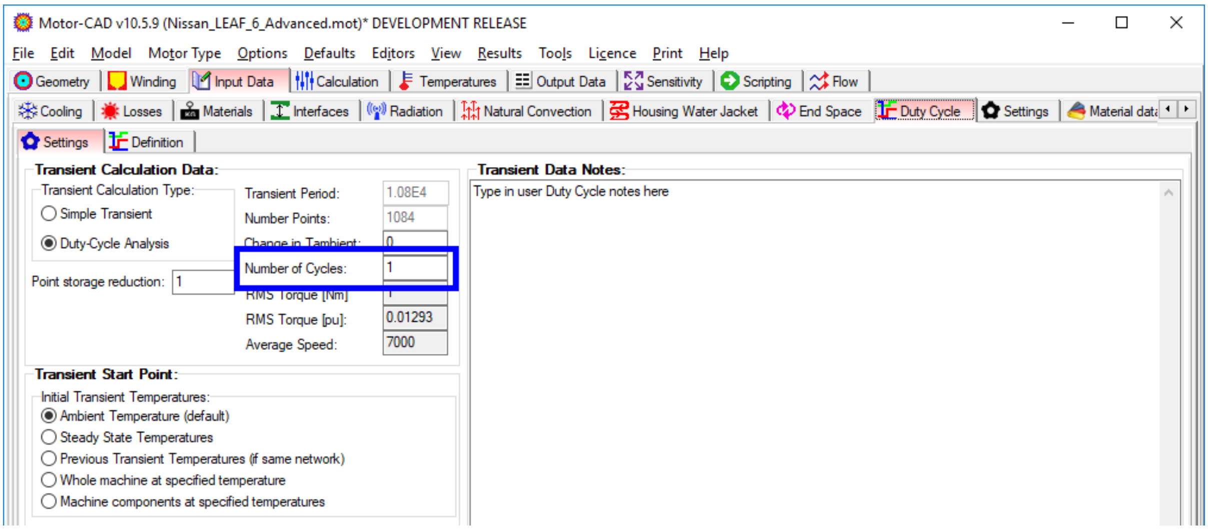


We now close the viewer and click **Export Duty to Thermal Model** to export the power loss, speed and time values to the thermal model.

We now return to the thermal model **Menu -> Model - > Thermal** and check the imported duty cycle under **Input Data -> Duty Cycle -> Definition**.

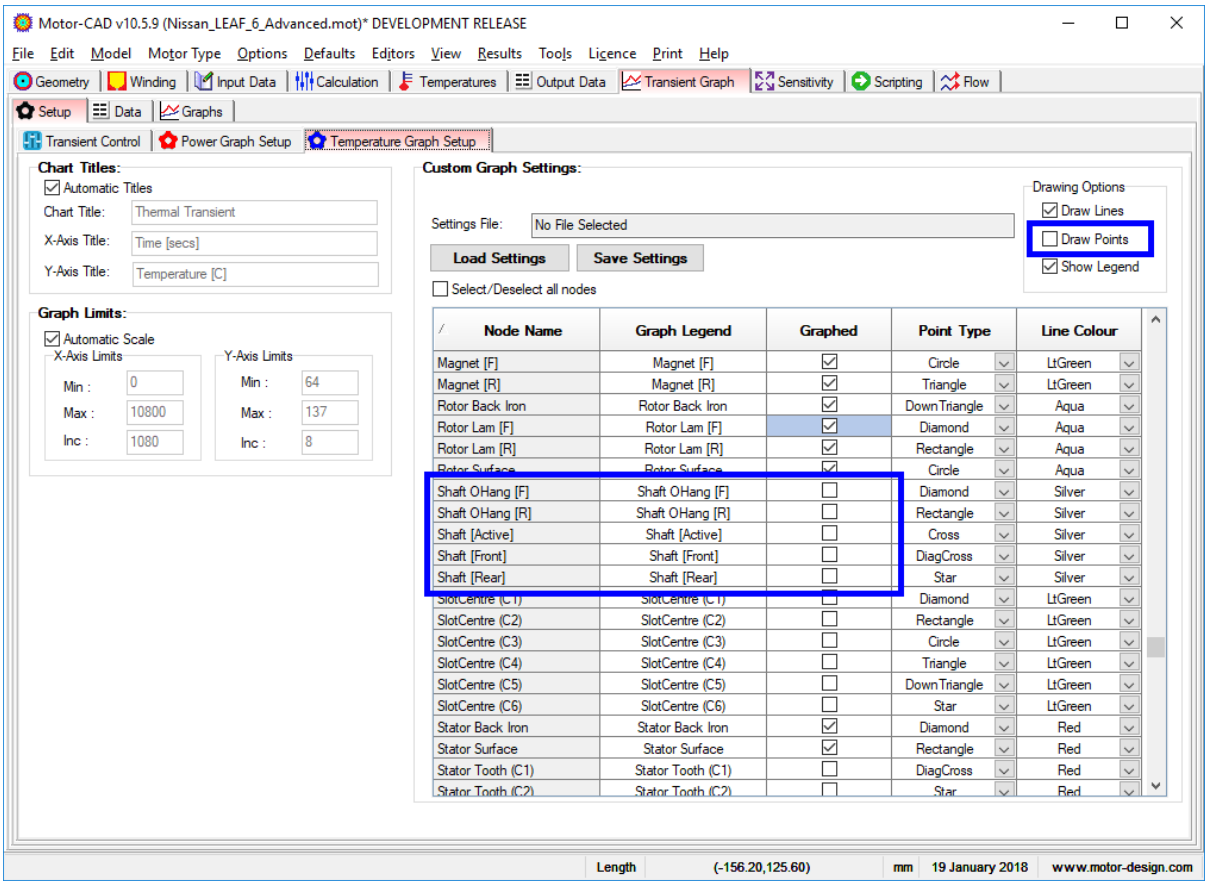


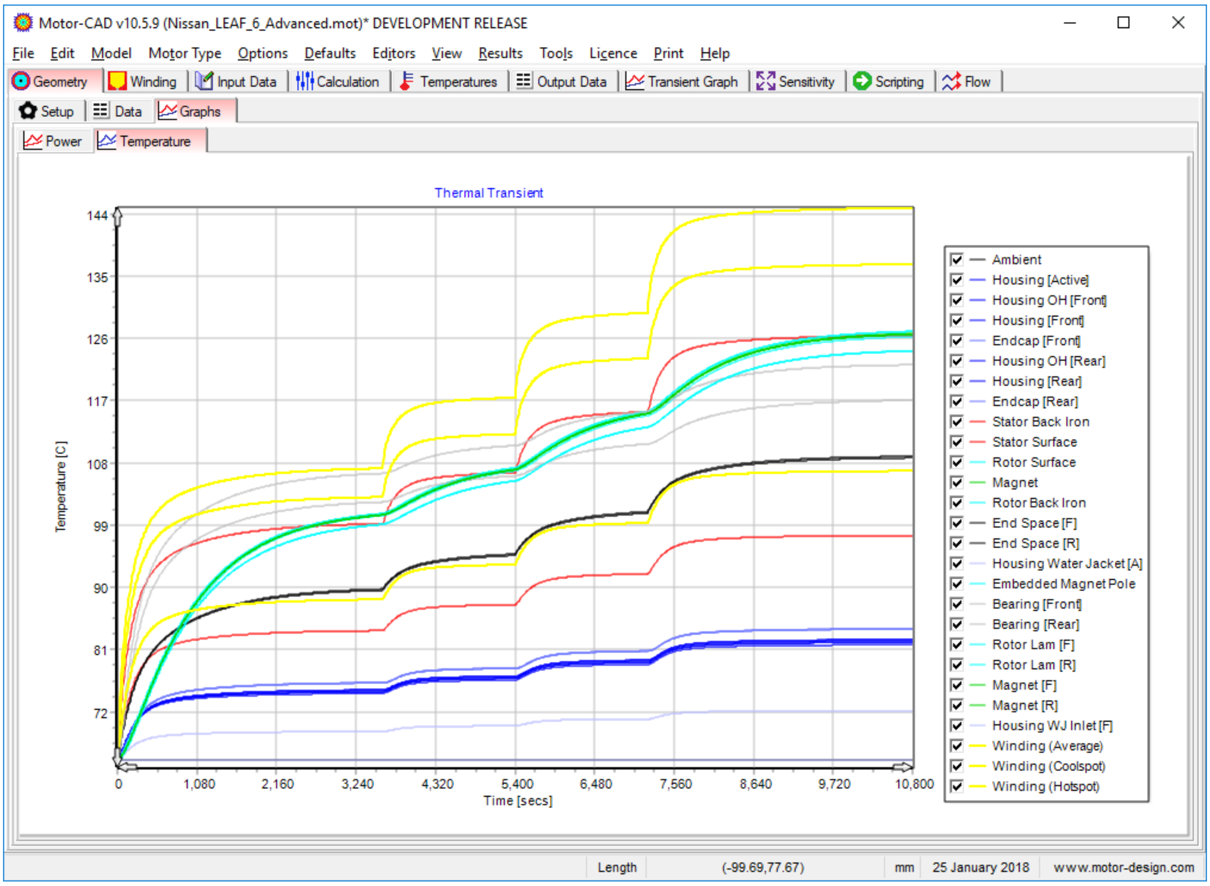
Under **Input Data -> Duty Cycle -> Settings**, we reset the **Number of Cycles** back to 1, since the cycle is only run once for the test.



Under the **Calculation** tab, we set the **Calculation Type** to **Transient** and **Solve** the thermal model.

When solving is completed, we customise the graph under **Transient Graph -> Setup -> Temperature Graph Setup** to hide the shaft nodes and disable the **Draw Points** option, and then view the resulting temperature graph.




Motor-CAD v10.5.9 (Nissan_LEAF_6_Advanced.mot)* DEVELOPMENT RELEASE
File Edit Model Motor Type Options Defaults Editors View Results Tools Licence Print Help
Geometry Winding Input Data Calculation Temperatures Output Data Transient Graph Sensitivity Scripting Flow
Setup Data Graphs
Power Temperature
Thermal Transient
Temperature [C]
Time [secs]
Ambient
Housing [Active]
Housing OH [Front]
Housing [Front]
Endcap [Front]
Housing OH [Rear]
Housing [Rear]
Endcap [Rear]
Stator Back Iron
Stator Surface
Rotor Surface
Magnet
Rotor Back Iron
End Space [F]
End Space [R]
Housing Water Jacket [A]
Embedded Magnet Pole
Bearing [Front]
Bearing [Rear]
Rotor Lam [F]
Rotor Lam [R]
Magnet [F]
Magnet [R]
Housing WJ Inlet [F]
Winding (Average)
Winding (Coolspot)
Winding (Hotspot)
Length
(-99.69,77.67)
mm
25 January 2018
www.motor-design.com

10. Conclusions

We have modelled the brushless permanent magnet (BPM) machine of the 2012 Nissan LEAF using Motor-CAD's E-Magnetic, Thermal and Lab modules. We have obtained detailed electromagnetic and thermal performance results for a single operating point, efficiency maps showing the performance across the full operating range and combined electromagnetic and thermal performance for a complex drive cycle.

For further information on using Motor-CAD, please refer to the Motor-CAD manual under **Help -> Manual** in Motor-CAD, or see other software tutorials at https://www.motor-design.com/publications/tutorials/.