

# Motor-CAD Software Tutorial:

# Modelling the Nissan Leaf Motor using Motor-CAD

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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, II International World Congress and Exhibition, Detroit, Michigan, April 12–14, 2011, paper 2011-01-0350.



















# 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*).

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Select **File -> Save As...** to save the file as **Nissan\_LEAF\_1\_Geometry.mot** in the desired location.

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### 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.

Тар	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.

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

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

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  $6 \times 1 \times 1 = 6$  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.

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	HS 50	47	420	8150	General	$\sim$		
	Iron (Cast)	52	420	7272	General	$\sim$		
	Iron (Pure)	80	447	7870	General	$\sim$		
	Iron (Silicon 1%)	42	460	7769	General	$\sim$		
	Iron (Silicon 2%)	28	460	7600	General	$\sim$		
	Iron (Silicon 5%)	19	460	7417	General	$\sim$		
	JFE_10JNEX900	30	450	7490	Steel	$\sim$		
	M1000-65A	30	460	7650	Steel	$\sim$		
	M19 24 Gauge Steel	28	460	7800	Steel	$\sim$		
	M19 26 Gauge Steel	28	460	7800	Steel	$\sim$		
	M19 29 Gauge Steel	28	460	7800	Steel	$\sim$		
	M235-35A	30	460	7650	Steel	$\sim$		
	M250-35A	30	460	7650	Steel	$\sim$		
	M350-50A	30	460	7650	Steel	$\sim$		
	M400-50A	30	460	7650	Steel	$\sim$		
	M43	28	460	7800	Steel	$\sim$		
	M530-65A	30	460	7650	Steel	$\sim$		¥
	1							
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In the dialog that appears we type the name, set the **Solid type** to **Steel** and click **Add**.

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Solid type	Diesse er 30DH	ter the new name	for the sol	id
Omagnet		Add	Can	cel



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

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	Brass (70% Cu, 30% Zn)	111	385	8522	General	$\sim$			
Materials Filter:	Copper (Pure)	401	385	8933	General	$\sim$			
All materials     O Steel materials     Magnet materials	Ероху	0.22	1500	1200	General	$\sim$			
	FB3X	4	700	4800	Magnet	$\sim$			

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



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Select Database Create Database Import	30DH (Steel) Resistivity: 5.9E-7		
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Add Solid Rename Solid			
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Materials Filter:			
○ All materials			
Material Namo			
30DH			
Hiperco 50 (0.15mm)			

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.xsIx** 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.

Motor



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

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Select Database Create Database Import		
Permanently Add and Remove solids:	Steinmetz loss method being used	
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Delete Celta	Lamination thickness (mm): 0.3	
Delete Solid Copy Solid	Steinmetz Coefficients:	
Materials Filter:	Hysteresis loss coefficient (Kh): 0.02631043652	
All materials     O Steel materials     Magnet materials	Edd	
	Eddy current loss coefficient (Reddy): 1.3376233112-6	
Material Name ^	Alpha exponent for hysteresis loss: 2.120197362	
30DH	Beta exponent for hysteresis loss: 0	
Auminium (Alloy 195 Cast)		
Aluminium (Cast)		
Auminium_99.7% DieCast	Bertotti Coefficients:	
Amon 7 3.25% Si	Excess loss coefficient (Kexc): 0.001589577082	
Brass (70% Cu, 30% Zn)	Alpha exponent for hysteresis loss: 3.362969544	
Copper (Pure)	Hysteresis loss coefficient (Kh): 0.009377718103	
Ероху		
FB3X	Steel losses notes:	
Hiperco 50 (0.15mm)		~
HS 50		
Iron (Cast)		
Iron (Silicon 1%)		
Iron (Silicon 2%)		$\sim$
Iron (Silicon 5%)	<	>
, , ,	4 <u>]   </u>	

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 Databa	ase	Electrical Resistivity	Temp Coef Electrical Resistivity	Magnet Brat 20C	Magnet Relative Permeablility	Temp Coef Br	Density	Weight	Notes	
Onits			Ohm.m		Tesla			kg/m3	kg		
tator Lam (Back Iron)	30DH	$\sim$	5.9E-07	1.3				7650	8.26		
tator Lam (Tooth)	30DH		5.9E-07	1.3				7650	5.245		
tator Lamination [Total]									13.5		
tator Winding [Active]	Copper (Pure)	$\sim$	1.724E-08	0.003862				8933	4.138		
tator EWdg [Front]	Copper (Pure)		1.724E-08	0.003862				8933	1.009		
tator EWdg [Rear]	Copper (Pure)		1.724E-08	0.003862				8933	1.009		
tator Winding [Total]									6.156		
lot Wedge		$\sim$	0	0				1000	0.01397		
lotor Lam (Back Iron)	30DH	$\sim$	5.9E-07	1.3				7650	4.636		
PM Magnet Pole	30DH		5.9E-07	1.3				7650	4.95		
otor Lamination [Total]									10.14		
lagnet	N30UH	$\sim$	1.8E-06	0	1.125	1.05	-0.12	7500	1.965		
nan (Active)		$\sim$	0	0				7800	1.937		
haft [Front]		$\sim$	0	0				7800	0.3254		
haft [Rear]		$\sim$	0	0				7800	0.2106		
haft [Total]									2.473		
otal									34.23	Veight [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	А
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.

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<u>File Edit Model Motor Type Options Defau</u>	llts Editors <u>V</u> iew <u>R</u> esults Too <u>l</u> s Li <u>c</u> e	nce <u>P</u> rint <u>H</u> elp		
🖸 Geometry 🛛 🌄 Winding 🗎 🗹 Input Data 👫 Calc	ulation 🛛 🔗 E-Magnetics 🛛 🎫 Output Data 🗎	Graphs 2 Sensitivity Scripting		
Geometry     Winding     Minding     Minding	videtion	Graphs          § Sensitivity          Scripting          Performance Tests:          Single operating points.          Open Circuit          Q axis current only         On Load           Open Circuit:          Back EMF          Cogging Torque          Bectromagnetic Forces          On Load:          Torque Speed Curve          Demagnetization          Bectromagnetic Forces          Parameters:          Self and Mutual Inductances          Transient:          Sudden short-circuit          Solve E-Magnetic Model          Cancel Solving		
	I			



### 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 ( <b>Torque</b> calculation)
On Load Loss	Loss calculation from on load transient torque ( <b>Torque</b> calculation)
Static OC	Single point no load ( <b>Q Axis current</b> calculation – always performed)
Open Circuit Transient	Open circuit transient ( <b>Back EMF</b> calculation)
Open Circuit Loss	Loss calculation from open circuit transient ( <b>Back EMF</b> calculation)
Static Load	Single point on load ( <b>On Load</b> 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.

Geometry	Calculation	metice == Output Date	Graphe 57 Sensitivity		
Drive	Calculation Ge-Mag	ding A Materials			
Variable	Value	Units	Variable	Value	Units
DC Bus Voltage	375	Volts	D axis inductance	0.1564	mH
ine-Line Supply Voltage (ms)	265.2	Volts	Q axis inductance	0.3603	mH
hase Supply Voltage (ms)	153.1	Volts	Line-Line inductance (DQ)	0.526	mH
ine-Line Terminal Voltage (peak)	274	Volts	Stator End Winding Inductance (Rosa and Grover)	0.00494	mH
ine-Line Terminal Voltage (rms)	196.9	Volts			
hase Terminal Voltage (ms)	114.6	Volts	D axis current (ms)	-240	Amps
armonic Distortion Line-Line Terminal Voltage	9.012	%	Q axis current (ms)	240	Amps
armonic Distortion Phase Terminal Voltage	15.76	%	Torque Constant (Kt)	0.6007	Nm/A
ack EMF Line-Line Voltage (peak)	201.4	Volts	Motor Constant (Km)	4.574	Nm/(Watts^0.5
ack EMF Phase Voltage (peak)	112.3	Volts	Back EMF Constant (Ke)	0.6411	Vs/Rad
ack EMF Line-Line Voltage (ms)	137.3	Volts	Electrical Constant	22.46	msec
ack EMF Phase Voltage (ms)	79.68	Volts	Mechanical Constant	0.8138	msec
armonic Distortion Back EMF Line-Line Voltage	3.633	%	Electrical Loading	1.179E005	Amps/m
armonic Distortion Back EMF Phase Voltage	10.57	%	Stall Current	1.631E004	Amps
			Stall Torque	9794	Nm
C Supply Current (mean)	252.2	Amps	Short Circuit Line Current (peak)	461	Amps
ne Current (peak)	480	Amps	Short Circuit Current Density (peak)	22.93	Amps/mm <sup>2</sup>
ne Current (ms)	339.4	Amps	Short Circuit Braking Torque	-11.67	Nm
hase Current (peak)	480	Amps	Short Circuit Max Braking Torque	-117.1	Nm
hase Current (ms)	339.4	Amps	Short Circuit Max Braking Torque Speed	159.1	rpm
			Short Circuit Max Demagnetizing Current	-1069	Amps
hase Advance	45	EDeg	Fundamental Frequency	200	Hz
rive Offset Angle (Open Circuit)	360	EDeg	Current Shaft Speed RPM	3000	rpm
rive Offset Angle (On load)	0	EDeg			
hase Advance to give maximum torque	33.48	EDeg			
hasor Angle (Ph1)	0	EDeg			
hasor Angle (Ph2)	120	EDea			
hasor Angle (Ph3)	240	EDeg			
lax Angle Between Phasors	120	EDeg			



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<u>F</u>ile <u>E</u>dit <u>M</u>odel Mo<u>t</u>or Type <u>O</u>ptions <u>D</u>efaults Ed<u>i</u>tors <u>V</u>iew <u>R</u>esults Too<u>l</u>s Li<u>c</u>ence <u>P</u>rint <u>H</u>elp

O Geometry | 🛄 Winding | 🕅 Input Data | 👫 Calculation | ⊘ E-Magnetics 📰 Output Data | 🖉 Graphs | 💆 Sensitivity | 🔾 Scripting |

✓ Drive	ram 🛛 🌞 Losses 🛛 🌄 Wind	ding 🛛 🐣 Materials						
Variable	Value	Units	^	Variable		Value	Units	^
Maximum torque possible (DQ) (For Phase Advance of 33 48 EDeg)	308.91	Nm	F	lux linkage D (Q axis current)		72.3528	mVs	
Average torque (virtual work)	288.34	Nm	F	lux linkage Q (Q axis current)		113.255	mVs	
Average torque (loop torque)	286.2	Nm	F	lux linkage D (On load)		19.283	mVs	
Torque Ripple (MsVw)	19.32	Nm	F	lux linkage Q (On load)		122.285	mVs	
Torque Ripple (MsVw) [%]	6.7005	%	-					
Cogging Torque Ripple (Vw)	18.453	Nm	Т	orque Constant (Kt)		0.6007	Nm/A	
Speed limit for constant torque (For Phase Advance of 45 EDeg)	4175.2	rpm	N	fotor Constant (Km)		4.57376	Nm/(Watts <sup>^</sup> 0.5)	
Speed limit for zero torque	1.9149E005	rpm	E	lack EMF Constant (Ke)		0.641113	Vs/Rad	
			-					
Electromagnetic Power	90583	Watts	S	itall Current		16305.1	Amps	
Input Power	94558	Watts	S	itall Torque		9794.47	Nm	
Output Power	90241	Watts	-					
Total Losses (on load)	4317.1	Watts	C	ogging Period		7.5	MDeg	
System Efficiency	95.434	%	C	ogging Frequency		2400	Hz	
			F	undamental Frequency		200	Hz	
Shaft Torque	287.24	Nm	N	Mechanical Frequency		50	Hz	
			C	ptimum Skewing Angle		7.5	MDeg	
Power Factor [Waveform] (lagging)	0.81865		-					
Power Factor Angle [Waveform]	35.05	EDeg	N	lagnetic symmetry factor		8		
Power Factor [Phasor] (lagging)	0.89101		N	lagnetic Axial Length (Slice1)		150	mm	
Power Factor Angle [Phasor]	27	EDeg	-					
Load Angle [Phasor]	72.431	EDeg	A	irgap flux density (peak)		1.37723	Tesla	
Phase Terminal Voltage (ms) [Phasor]	116.87	Volts	S	itator Tooth flux density (peak)		1.87583	Tesla	
			S	itator Tooth Tip flux density (peak)		1.84978	Tesla	
Rotor Inertia	0.027254	kg.m²	S	itator Back Iron flux density (peak)		1.72302	Tesla	
Shaft Inertia	0.00052018	kg.m²	F	Rotor Back Iron flux density (peak)		0.688775	Tesla	
Total Inertia	0.027774	kg.m²						
Torque per rotor volume	144.82	kNm/m³	~					¥
ne maximum possible magnet and reluctance torq	ue [MaxTorque]		Len	gth (-114.00,101.00)	mm	17 January 2018	www.motor-design.c	orr

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ile <u>E</u> dit <u>M</u> odel Mo <u>t</u> or Type <u>O</u> ptions <u>D</u>	efaults Ed <u>i</u> tors <u>V</u> iew	v <u>R</u> esults Too <u>l</u> s	Lig	ence <u>P</u> rint <u>H</u> elp			
🖸 Geometry 🛛 🌄 Winding 🗎 🔟 Input Data 🗎 👫	Calculation Second	netics 📃 Output D	ata	Graphs 2 Sensitivity Scripting			
∧ Drive   🧼 E-Magnetics   🎝 Phasor Diagram	🜞 Losses 📘 Wind	ding 👌 🐣 Materials					
Variable	Value	Units	^	Variable	Value	Units	1
DC Stator Copper Loss (on load)	3974	Watts		DC Stator Copper Loss (open circuit)	0	Watts	_
Magnet Loss (on load)	3.912	Watts		Magnet Loss (open circuit)	0.207	Watts	
Stator iron Loss [total] (on load)	329	Watts		Stator iron Loss [total] (open circuit)	162	Watts	
Rotor iron Loss [total] (on load)	9.995	Watts		Rotor back iron Loss [total] (open circuit)	0.6178	Watts	
Wedge Loss (on load)	0	Watts		Wedge Loss (open circuit)	0	Watts	
Windage Loss (user input)	0	Watts		Windage Loss (user input)	0	Watts	
Shaft Loss [total] (on load)	0	Watts		Shaft Loss [total] (open circuit)	0	Watts	
Total Losses (on load)	4317	Watts		Total Losses (open circuit)	166.9	Watts	
Magnet Loss Factor	0.1983			Magnet Loss Factor	0.1983		
Magnet Loss (on load)	3.912	Watts		Magnet Loss (open circuit)	0.207	Watts	
Stator back iron Loss [hysteresis - fundamental] (on	129.9	Watts		Stator back iron Loss [hysteresis - fundamental]	55.59	Watts	
Stator back iron Loss [hysteresis - minor loops] (on	1.042	Watts		Stator back iron Loss [hysteresis - minor loops]	0.3563	Watts	
Stator back iron Loss [hysteresis] (on load)	131	Watts		Stator back iron Loss [hysteresis] (open circuit)	55.95	Watts	
Stator back iron Loss [eddy] (on load)	34.41	Watts		Stator back iron Loss [eddy] (open circuit)	14.91	Watts	
Stator back iron Loss [excess] (on load)	0	Watts		Stator back iron Loss [excess] (open circuit)	0	Watts	
Stator back iron Loss [total] (on load)	165.4	Watts		Stator back iron Loss [total] (open circuit)	70.86	Watts	
Stator tooth Loss [hysteresis - fundamental] (on	108.5	Watts		Stator tooth Loss [hysteresis - fundamental] (open	65.77	Watts	
Stator tooth Loss [hysteresis - minor loops] (on	7.267	Watts		Stator tooth Loss [hysteresis - minor loops] (open	1.994	Watts	
Stator tooth Loss [hysteresis] (on load)	115.7	Watts		Stator tooth Loss [hysteresis] (open circuit)	67.77	Watts	
Stator tooth Loss [eddy] (on load)	47.93	Watts		Stator tooth Loss [eddy] (open circuit)	23.34	Watts	
Stator tooth Loss [excess] (on load)	0	Watts		Stator tooth Loss [excess] (open circuit)	0	Watts	
Stator tooth Loss [total] (on load)	163.7	Watts		Stator tooth Loss [total] (open circuit)	91.1	Watts	
Stator iron Loss [total] (on load)	329	Watts		Stator iron Loss [total] (open circuit)	162	Watts	
Rotor back iron Loss [hysteresis] (on load)	0.3723	Watts		Rotor back iron Loss [hysteresis] (open circuit)	0.5124	Watts	
Rotor back iron Loss (eddv) (on load)	0.2883	Watts	¥	Rotor back iron Loss [eddy] (open circuit)	0.1054	Watts	


#### Graphs

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







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



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## **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.

🧔 Graph Vi	ewer					– 🗆 X
Refresh List Clear graphs Load graphs	Graph Editor Data Type: EMagne O Themal Sensitiv FEA Pat Magneti Nagneti	tics Search ity ths cs 3D	Text:		Find Next         Direction           Ø Up         Ø Up           Matches:         Image: O Down	<ul> <li>✓ ● (Point 0) : B Rotor Back Iron</li> <li>✓ ● (Point 0) : B Gap (on load)</li> <li>✓ ● (Point 0) : B Stator Tooth</li> <li>✓ ● (Point 0) : B Stator Tooth Tip</li> <li>✓ ● (Point 0) : B Stator Back Iron</li> </ul>
🛆 Index	Name	Legend	Points 7	Data Type 🛛	🛛 X Legend 🍸 Y Legend 🍸	^
468	CoggingTorqueVWElec	Cogging (VW)	21	EMagnetics	Position [EDeg] Torque [Nm]	
469	LineCurrent1	Line 1	31	EMagnetics	Position [EDeg] Current [A]	
470	LineCurrent2	Line 2	31	EMagnetics	Position [EDeg] Current [A]	
471	LineCurrent3	Line 3	31	EMagnetics	Position [EDeg] Current [A]	
487	WindingFactors	Winding Factor	25	EMagnetics	Harmonic Magnitude	
488	WindingHarmonics	Winding Harmonic	200	EMagnetics	chanical Harmo IMF [Amp Turns	Ë 0.6
489	TerminalLineToLine12	Ph1-Ph2	31	EMagnetics	Position [EDeg] Voltage [V]	≥ 0.4
490	TerminalLineToLine23	Ph2-Ph3	31	EMagnetics	Position [EDeg] Voltage [V]	
491	TerminalLineToLine34	Ph3-Ph1	31	EMagnetics	Position [EDeg] Voltage [V]	
504	HarmonicAmplitude	Harmonic Amplitude	15	EMagnetics		0.2
505	HarmonicAngle	Hamonic Angle	15	EMagnetics		
506	HarmonicDataCycle	Harmonics	31	EMagnetics		-0.8
2000	Br Gap (on load)	(Point 0)	45	FEA Path	Position [MDeg] Jx Density [Tesl	-1
4000	B Stator Tooth	(Point 0)	150	FEA Path	Position [MDeg] .x Density [Tesl	-1.2
6000	B Stator Tooth Tip	(Point 0)	150	FEA Path	Position [MDeg] .x Density [Tesl	-1.4 -1.4
8000	B Stator Back Iron	(Point 0)	150	FEA Path	Position [MDeg] .x Density [Tesl	0 10 20 30 40
10000	B Rotor Back Iron	(Point 0)	150	FEA Path	Position [MDeg] Jx Density [Tesl	Position [MDeg]



# 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:

Таb	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	А

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.

el Options 🏾 🜞 Loss Model	· · · · ·	Model Stature				
ration Model:	Machine Parameters:	Model Status.	Build Date	Method	Max Current	
del Type:	Pole Number: 8					
Fixed Inductance Model	Slot Number: 48	Saturation	17-01-18 09:12	15 points single	A (peak) 480	
Saturation Model (Single Step)	Whether Connections	outration	17 01 10 03.12	step	400	
Saturation Model (Full Cycle)	Vinding Connection:     Star Connection (default)	Iron Loss				
del Resolution:	O Delta Connection	AC Loss				
Coarse (15 points)		Magnet Loss				
Fine (30 points)	Fixed Inductance Model:					
	Magnet Flux Linkage (\m): 72.32	Medal Duild:				
Model:	D-Axis Inductance (Ld): 0.1569	Parameters		Build		
del Type:	Q-Axis Inductance (La) 0.3678	Marchens.			ration Model	
Neglect	Short-Circuit Current (Isc): 412.1	IVId:	ximum speed:		Madal	
FEA Map (recommended)		Max stator c	urrent (Peak): 480	LOSS	Model	
Custom		Max stator c	urrent (RMS): 339.4	ł		
		Maximum	rotor current: 12			
			Build I	Model		
			Cancel Mo	odel Build		

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 rebuilt 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.

Motor-CAD v10.5.9 (Nissan_LEAF_3_Lab_Torqu File Edit Model Motor Type Options Defa	eSpeed.mot)* DEVELOPMENT RELEASE ults Editors View Results Tools Licence	Print Help		- 🗆 X
Model Build	ic │ 🖡 Thermal │ 🚰 Duty Cycle │ ☷│ Operating Point	Calibration		
Drive:     DC Bus Voltage:     375       Maximum Modulation Index:     1       Operating Mode:     Image: Control Strategy:       Image: Motor     Image: Control Strategy:       Image: Maximum Torque/Amp       Image: Maximum Efficiency	Image: Loss Build Factors:         Stator 1         Rotor: 1         Hysteresis: 1       Eddy: 1         Magnet Loss Build Factor: 1         Mechanical Loss:         © Neglect         O User Defined         Friction Loss Exponent: 1         Windage Loss Exponent: 2         Reference Speed: 6000	Scaling: Tums / Coli: Model build reference: 6 Resistance reference: 6 Calculation: 6 Stator Winding Temperature: Reference temperature: 40 Calculation temperature: 40 Calculation temperature: 20 Magnet Temperature: 20 Calculation temperature: 20 Magnet Flux Coefficient: -0.117	93	
	Motor-c			unun meter design com
	Length	(-/3.64,51.44)	mm 16 January 2018	www.motor-design.com

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	А



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✓ Model Build   H Calculation   G Electro	omagnetic 📕 Thermal	Duty Cycle	Derating Point	Calibration Settings				
Calculation:	Second		1	Calculation Status:				
Maximum Torque/Speed Curve	Maximum:	1F4		16-01-18 10:41:14: Electromagneti completed with Ismax =480.0A Max	c calculation			
C Efficiency Map	Maximan.			10000.0rpm				
○ Torque Grid	Step:	500						
Uptions:	Minimum:	0						
Smooth Map	Current:			Calculate Emagnetic Perf	ormance			
Power Limit	Maximum (Peak):	480			Uniditio			
Max Power: 0	Maximum (RMS):	339.4						
	No. of Increments:	3	•	Cancel Calculatio	n			
	Minimum (Deally)	50						
	Minimum (Peak):	25.20		Load Results Viewer	·			
	Minimum (RMS):	33.30						
	Torque:							
	Maximum:	100						
	No. of Increments:	10						
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	en difficiti.							
			Motor-C	AD Model Loaded Successfully				
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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.

wiessage Display	_		Х
16:33:58 : Proximity Loss Model not configure AC losses will not be included in model build.	ed in E-Magnet	ic module.	^
			~

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.



Difference of the second of t	ficiencyMap.mot)* DEVELOPMENT RELEASE Defaults Editors View Results Tools gnetic ) F Thermal ) 17 Duty Cycle ) 🎫 Op	Li <u>c</u> ence <u>P</u> rint erating Point ] @	: <u>H</u> elp Calibration <b>\</b>	Settings		-	
Ger Model Options 🔆 Loss Model			Model Statue				
Saturation Model:	Machine Parameters:		Model	Build Date	Method	Max Current	
Fixed Inductance Model     Saturation Model (Single Step)	Slot Number: 48		Saturation	17-01-18 09:17	30 points full cycle	A (peak) 480	
Saturation Model (Full Cycle)	Winding Connection:  Star Connection (default)		Iron Loss	17-01-18 09:17	FEA Map	480	
Model Resolution: O Coarse (15 points)	O Delta Connection		AL Loss Magnet Loss	17-01-18 09:17	FEA Map	480	
(     Fine (30 points)  Loss Model:  Model Type:  Neglect  E A Map (recommended)	Hixed Inductance Model: Magnet Flux Linkage (vm): 73.3 D-Avis Inductance (Ld): 0.15 Q-Avis Inductance (Lq) 0.36 Short-Circuit Current (Isc): 402.	4 92 05 6	Model Build: Parameters: Ma Max stator c	ximum speed: 1E4	Build:	uration Model is Model	
Custom			Max stator o	rotor current: 12			1
				Build M	Aodel		
				Cancel Mo	del Build		
		Saturation M	odel Built				
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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

	Motor
<b>EC</b>	Design
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Motor-CAD v10.5.9 (Nissan_LEAF_4_Lab_Efficiency File Edit Model Motor Type Options Default	yMap.mot)* DEVELOPMENT RELEASE ts Editors View Results Tools Licence	Print Help			- 0	×
✓ Model Build III Calculation	↓ F Thermal ↓ H Duty Cycle ↓ I Operating Point	Calibration				
Drive:       DC Bus Voltage:       375         Maximum Modulation Index:       1         Operating Mode: <ul> <li>Motor</li> <li>Generator</li> <li>Motor / Generator</li> <li>Control Strategy:</li> <li>Maximum Torque/Amp</li> <li>Maximum Efficiency</li> </ul>	Losses: Iron Loss Build Factors: Stator 1 Rotor: 1 Hysteresis: 1 Eddy: 1 Magnet Loss Build Factor: 1 Mechanical Loss: Calculation Type: Neglect © User Defined Friction Loss: 150 Friction Loss Exponent: 1 Windage Loss: 0 Windage Loss Exponent: 2 Reference Speed: 1E4	Scaling: Tums / Coll: Model build reference: [ Resistance reference: [ Calculation: [ Stator Winding Temperature: Reference temperature: Calculation temperature: Temp. Coeff. Resistivity: [ Magnet Temperature: Reference temperature: Calculation temperature: [ Calculation temperature: Magnet Flux Coefficient: [	6 6 65 65 0.00393 65 65 -0.1368			
	Data C	lculation complete				
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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	А
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.



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File Edit Model Motor type Options			100 <u>i</u> s Li <u>c</u> ence <u>P</u>					
			== Operating Point	Calendation Status				
Calculation Type:     Maximum Torque/Speed Curve     Efficiency Map     Torque Grid	Speed: Maximum: Step:	1E4 250		25-01-18 11:50:12: Electromagnetic completed with Ismax =480.0A curre Maximum speed = 10000.0pm	c calculation ent steps = 30			
Options:	Minimum:	500						
Smooth Map	Current: Maximum (Reak):	480		Calculate Emagnetic Perfo	ormance			
Max Power: 0	Maximum (RMS):	339.4		Cancel Calculation	n			
	No. of Increments:	30						
	Minimum (Peak):	0 7071		Load Results Viewer				
	Minimum (rvivis).	0.7071						
	Torque:		•					
	Maximum:	100						
	No. of Increments:	10						
	Minimum:	10						
			Data Cal	ulation complete				
				(-73.86,63.41)	mm 25 January 2018	www.m	otor-desig	n.com

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.

Parameter	Value	Units
Mass	1521	kg
Rolling Resistance Coefficient	0.007	
Air Density	1.225	kg/m³
Generating Torque Ratio	1	
Frontal Area	2.29	m²
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	

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



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

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<u>File Edit Model Motor Type Options Defaults Editors View Results Tools Licence Print Help</u>	
🔨 Model Build   👫 Calculation   🔗 Electromagnetic   🗦 Thermal 👫 Duty Cycle 📃 Operating Point   🔗 Calibration   🏠	Settings
Vehicle Model:	Calculation Status:
Mass:     1521     Frontal Area (m²):     2.29     Wheel Radius (m):     0.3       Rolling Resistance Coefficient:     0.007     Drag Coefficient:     0.28     Mass Correction Factor:     1.04       Air Density:     1.225     Final Drive Ratio:     7.938     Motoring Torque Ratio:     1       Generating Torque Ratio:     1     Max. Torque:     500     Max. Speed:     2E4	16-01-18 14:28:39: duty cycle calculation completed
Drive Cycle:	Calculate Duty Cycle Performance
Unve Cycle Uata: Standard Drive Cycle External Data	Cancel Calculation
Standard Drive Cycle:     Import External Data:       US06     Data Typ::   Time(s), Torque(Nm), Speed (pm)	Export Duty Cycle To Thermal Model
Load Generate	Load Results Viewer
Calculation complete	
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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.

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<u>File Edit Model Motor Type Options D</u> efa	ults Ed <u>i</u> tors <u>V</u> iew <u>R</u> esults Too <u>l</u> s Li <u>c</u> ence	<u>P</u> rint <u>H</u> elp			
Nodel Build	c 🛛 🖡 Thermal 🛛 🏪 Duty Cycle 🗍 🧮 Operating Po	int 🛛 🤣 Calibration 🛛 🏠 Settings			
DC Bus Voltage:       375         Maximum Modulation Index:       1         Operating Mode:       Motor         Maximum Torque/Amp       Maximum Torque/Amp         Maximum Efficiency       Maximum Efficiency	Losses: Iron Loss Build Factors: Stator 1 Rotor: 1 Hysteresis: 1 Eddy: 1 Magnet Loss Build Factor: 1 Mechanical Loss: Calculation Type: O Neglect © User Defined Friction Loss: 150 Friction Loss Exponent: 1 Windage Loss: 0 Windage Loss Exponent: 2 Reference Speed: 1E4	Scaling: Tums / Coll: Model build reference: Resistance reference: Calculation: Stator Winding Temperature: Reference temperature: Temp. Coeff. Resistivity: Magnet Temperature: Reference temperature: Reference temperature: Reference temperature: Magnet Flux Coefficient:	6         6         65         65         0.00393         65         65         65         65         60		

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.

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Nodel Build Calculation	netic 🛛 🖡 Thermal 🛛 🎦	Duty Cycle 📃 Operat	ting Point 🔗 Calibration 🚺 Settings		
Definition:         Definition:         Maximum Current         Maximum Temperature         Set Model Operating Point:         ✓ Motor-CAD Emag Model         Motor-CAD Themal Model	Speed: 6000 dimum Currents: tor Current (Peak): 150 tor Current (RMS): 106.1 Rotor Current: 6	Torque: Tor Maximum Te Stator Win May Change	rque: 160  mperatures:  Calce  ing: 160  gnet: 140  Thermal Settings	Jate Operating Point	
Variable	Value	Units	Variable	Value	Units
Shaft Speed	6000	rpm	Total Loss	2472	Watts
Shaft Torque	160	Nm	Stator Copper Loss	1766	Watts
Shaft Power	1.005E005	Watts			
Efficiency	97.6		Iron Loss	609.3	Watts
			Magnet Loss	7.11	Watts
Stator Phase Current (peak)	320	Amps	Mechanical Loss	90	Watts
Stator Line Current (peak)	320	Amps	Windage Loss	0	Watts
Phase Voltage (peak)	216.5	Volts	Friction Loss	90	Watts
Line Voltage (peak)	375	Volts			
Phase Advance	63.22	EDeg	Electromagnetic Power	1.012E005	Watts
			Electromagnetic Torque	161.1	Nm
Phase Current D (peak)	-285.6	Amps	Magnet Torque	74.28	Nm
Phase Current Q (peak)	144.2	Amps	Reluctance Torque	86.84	Nm
Phase Voltage D (peak)	-204.4	Volts	Terminal Power	1.03E005	Watts
Phase Voltage Q (peak)	71.26	Volts	Power Factor	0.9913	
Flux Linkage D	27.7	mVs			
Flux Linkage Q	80.04	mVs			
J			Operating Point Found		
			Length (-40.67,108.20)	mm 17 January 2018	www.motor-design.com



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.

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🖸 Geometry 🛛 🌄 Winding 🗎 🗹 Input Data 👫 Calcula	tion 🛛 🔗 E-Magnetics 🛛 🎫 Outpu	ıt Data 🛛 🚧 Graphs	Scripting				
Drive:	Temperatures:	P	erformance Tests:				
Shaft Speed [RPM]: 6000	Stator Winding Temperature: 65		Single operating points:				
Line Current Definition:	Magnet Temperature: 65		Open Circuit				
Peak	Stator Lamination Temperature: 20		Q axis current only				
O RMS	Pater Lamination Temperature: 20		✓ On Load				
	Rotor Lamination Temperature: 20		Open Circuit:				
Peak Current: 320	Stator Sleeve Temperature: 20		Back EMF				
RMS Current: 226.2	Rotor Banding Temperature: 20		Cogging Torque				
RMS Current Density: 11.25	Shaft Temperature: 20		Electromagnetic Forces				
DC Bus Voltage: 375	Stator Wedge Temperature: 20		On Load				
Phase Advance [elec deg]: 63.22	EMagnetics - Thermal Coupling:		✓ Torque				
Unve:	Linkage Options:		Torque Speed Curve				
Drive Mode:	No coupling (default)     E Magnetics Lasses		Demagnetization				
O Square	○ E-Magnetics Losses → Thermal ○ E-Magnetics ← Thermal Tempe	ratures	Electromagnetic Forces				
OCustom	Iterate to Converged Solution		Parameters				
			Self and Mutual Inductances				
Winding Connection:	Skew:						
Star Connection (default)	Skew Type: Stator Skew:	0	Iransient:				
O Delta Connection	Stator Botor elices	1	Sudden short-circuit				
Magnetisation:	O Rotor						
Parallel			Solve E-Magnetic M	odel			
◯ Radial		i					
O Halbach Continuous Ring Array			Cancel Solving				
🔿 Halbach Sinusoidal Array							
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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.



Motor-CAD v10.5.9 (Nissan_LEAF_4_Lab_E	fficiencyMap.mot)* DEVE	LOPMENT RELEASE		<b>5</b>		- 0	×
le Edit Model Motor lype Options	Defaults Editors View	<u>Kesults lool</u> s	Lig	ence Print Help			
🖸 Geometry 🛛 🛃 Winding 🛛 🖉 Input Data 🛉	Calculation   🔗 E-Mag	netics 📰 Output Da	ata	Graphs 22 Sensitivity Scripting			
🔨 Drive 🔗 E-Magnetics 🛛 🎝 Phasor Diagra	ım 🛛 🌞 Losses 🛛 🌄 Wind	ding 🛛 🐣 Materials 🗎					
Variable	Value	Units	^	Variable	Value	Units	^
Maximum torque possible (DQ) (For Phase Advance of 33.35 EDeg)	243.13	Nm		Flux linkage D (Q axis current)	85.9269	mVs	
Average torque (virtual work)	163.07	Nm		Flux linkage Q (Q axis current)	76.8138	mVs	
Average torque (loop torque)	161.95	Nm		Flux linkage D (On load)	27.4945	mVs	
Torque Ripple (MsVw)	30.65	Nm		Flux linkage Q (On load)	81.3036	mVs	
Torque Ripple (MsVw) [%]	18.792	%					
Speed limit for constant torque (For Phase Advance of 63.22 EDeg)	6022.3	rpm		Torque Constant (Kt)	0.509707	Nm/A	
Speed limit for zero torque	INF	rpm		Motor Constant (Km)	3.88093	Nm/(Watts <sup>0.5</sup> )	
				Stall Current	16305.1	Amps	
Electromagnetic Power	1.0248E005	Watts		Stall Torque	8310.83	Nm	
Input Power	1.0425E005	Watts					
Output Power	1.0188E005	Watts		Cogging Period	7.5	MDeg	
Total Lassas (on load)	2222.0	Wotto		Cogging Frequency	4800	Hz	
System Efficiency	97.723	%	Ш	Fundamental Frequency	400	Hz	
			Ш	Mechanical Frequency	100	Hz	
Shaft Torque	162.14	Nm	Ш	Optimum Skewing Angle	7.5	MDeg	
	_		-				
Power Factor [Waveform] (lagging)	0.99011			Magnetic symmetry factor	8		
Power Factor Angle [Waveform]	8.0629	EDeg		Magnetic Axial Length (Slice1)	150	mm	
Power Factor [Phasor] (lagging)	0.46947						
Power Factor Angle [Phasor]	62	EDeg		Airgap flux density (peak)	1.17518	Tesla	
Load Angle [Phasor]	124.97	EDeg		Stator Tooth flux density (peak)	1.42106	Tesla	
Phase Terminal Voltage (rms) [Phasor]	179.15	Volts		Stator Tooth Tip flux density (peak)	1.70366	Tesla	
				Stator Back Iron flux density (peak)	1.16067	Tesla	
Rotor Inertia	0.027254	kg.m²		Rotor Back Iron flux density (peak)	0.763927	Tesla	
Shaft Inertia	0.00052018	kg.m²					
Total Inertia	0.027774	kg.m²					
Torque per rotor volume	81,922	k Nm/m <sup>3</sup>	¥				~





# 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**.

🔯 Motor-CAD v10.5.9 (Nissan_LEAF_5_Thermal.mot) DEV							
File	Edit	Mode	Motor Typ	oe Op	tions	Defaults	Е
🖸 Ge	ometr		E-Magnetic	Ctrl+I	м	Calculation	n
OR	adial		Thermal	Ctrl+	т		
Housi	ng:		Lab	Ctrl+	в	Flange	
Slot T	ype:		0 10001	11010	احررت	Interior V (v	N
Stator	Duct	s: None	•	~ Roto	or Ducts	: Circular Du	iC

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 <u>https://www.motor-design.com/publications/tutorials/</u>.

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.

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<u>File Edit Model Motor T</u>	ype <u>O</u> ptions <u>D</u> efaults	d <u>i</u> tors <u>V</u> iew <u>R</u> esults Too <u>l</u> s Li <u>c</u> ence <u>P</u> rint <u>H</u> elp	
💽 Geometry 📘 Winding 👢	Input Data Calculatio	Fremperatures 🗄 Output Data 🚰 Sensitivity 🕞 Scripting 🔀 Flow	
🔆 Cooling 🏾 🌞 Losses 🛛 🔒	Materials	🖁 Radiation   👫 Natural Convection   🚰 Housing Water Jacket   💠 End Space   🎦 Duty Cycle   😭 Settings	Aterial data 🔹
Cooling Options:		Cooling Options Notes:	
Housing Outer Cooling:	Cooling Systems:	Type in user Cooling notes here	^
Natural Convection	Ihrough Ventilated		
O Blown Over	Housing Water Jacket		
Motor Orientation:	Wet Rotor		
Horizontal	Spray Cooling		
◯ Vertical [Shaft Up]	Rotor Water Jacket Slot Water Jacket		
O Vertical [Shaft Down]	Submersible		
	Flooded		
	Heat Exchanger		
Miscellaneous Data:			
Shaft Speed[rpm]	6000		
Lamination Stacking Factor [S	tator]: 0.97		
Lamination Stacking Factor [R	lotor]: 0.97		
Altitude [m]	0		
Ambient Temperature	65		
Radiation Emissivity:	0.9		
Fixed Temperatures:	Dista Tana astura 100		
Fixed Plate Temperature	Flate Temperature: 100		
Fixed Base Temperature	Base Temperature: 100		
Fixed Shaft[F] Temperature	Shaft[F] Temp: 100		~
Fixed Shaft[R] Temperature	Shaft[R] Temp: 100	۲ <u>ــــــــــــــــــــــــــــــــــــ</u>	>
Fixed Endcap[F] Temp.	Endcap[F] Temp: 100	Check Data	
Fixed Endcap[R] Temp.	Endcap[R] Temp: 100	CHECK Data	
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#### **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<sup>3</sup>/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 **I/min**. Click **OK** to save the new units.

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File Edit Model Motor Type (	Options C	Defaults Edito	ors View	Results	Tools Lic
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🕸 Cooling 🛛 🌞 Losses 🛛 📥 Materia	als 🗋 🚺 I	Interface L	anguage		tion
Flow Options Fluid Flow Heat Trans	sfer	Use defaul	t model s	ettings	
Fluid Data:		Units			Coc
Huid Volume How Rate: 0.3593		Display Siz	e		
40		Motor Typ	e		E
		File Locati	ons		ξ
		Register fo	or ActiveX		
		Motor-CA	D Lab link	c	> (
		ynumic viacoary		0.011	
Unite					
General F-Magnetics Thermal					
Temperature:	C	~	<b>x</b> (1	+ [	) = C
Heat Transfer Coefficient:	- W/m2/C	~	× 1		
	W/III2/C	¥	^	= ₩/	m2/C
Inermai Resistance:	C/W	~	<b>x</b> 1	= C/	~
Thermal Capacitance:	J/C	~	<b>x</b> 1	= J/0	>
Thermal Conductivity:	W/m/C	~	<b>x</b> 1	= W/	m/C
Pressure:	Pa	~	<b>x</b> 1	= Pa	
Volume Flow Rate:	1/min	~	<b>x</b> 1.67E	-5 = <b>m</b> 3	i/s
Specific Heat:	J/kg/C	~	<b>x</b> 1	= J/k	cg/C
Dynamic Viscosity:	kg/m/s	~	<b>x</b> 1	= kg	/m/s
Kinematic Viscosity:	m2/s	~	<b>x</b> 1	= m2	/s
Density:	kg/m3	~	<b>x</b> 1	= kg	/m3
Volumetric Expansion Coefficient:	1/C	~	<b>x</b> 1	= kg	/m3
Cancel OK		Load Defaul	t Units	Save As	Default 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



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💿 Geometry 📘 Winding 📝 Input Data 🔢 Calculation 🗼 Temperatures 🔠 Output Data 💱 Sensitivity 🕞 Scripting 😹 Row			
🕸 Cooling   🌞 Losses   🏔 Materials   🝸 Interfaces   🕼 Radiation   🔛 Natural Convection 🛛 🔀 Housing Water Jacket   💠 End Space   🎦 Duty Cycle   🏠 Setting:	s 🛛 📥 M	Naterial data	4 +
Row Options Ruid Row Heat Transfer			
How Definition:			
Fan Definition:			
Constant Flow Rate			
Constant Row Rate from Fan Characteristic			
O How Rate Proportional to Speed			
User Specified How Rate Vanation with Speed			
Reference Shaft Sneed: 3000			
Huid Volume How Hate: 6.5			
Check Data			
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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.

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Geometry Winding	Input Data	ns <u>D</u> eraults		ew <u>R</u> esult	s ioo <u>i</u> s Li ≣≣lOutout Dat	a Sensitiv	ity C Scri	inting 🗠	Flow						
	Materials	1 Interfaces	() Radiation	It Natur	al Convection	Housing V	Vater Jacket	End	Space 1	Duty Cycle	Setting	s 🛛 🙈 Materia	ldata III		
Row Options Ruid Row Heat Transfer															
Fluid Data:		Fluid Prop	erties:		Co	oling Options	:			Chann	el Data:				
Fluid Volume Flow Rate:	6.5	EGW 50/	50		~ H	ousing Water	Jacket Tv	oe = Spira	al Groove	Durat	Nall Thiskney				
Inlet Temperature:	65	Thermal Co	onductivity:	0.411		Active Cooling	Only 🗹	Non Spira	al ducts	Duci		55 U			
· · ·	00	Demeitur		1051		No Endcap (	Cooling (defau	ult)		Cutou	t Width (Aver	age): 30			
		Density.		2504		O Separate En	dcap Cooling	circuits		Cutou	t Height (Ave	rage): 5			
		Up:		3504		C Endcap Coo	ling in Series			Flow /	Area (total):	450			
		Kinematic	Viscosity:	1.305E-6		How Direction:				Dow	 Naa (aar abay	nnol): 150			
		Dynamic V	iscosity:	0.001372	2	Front -> Rear					vea (per cria	nnei). 150			
		Pr - Prandt	Number:	11.7	11.7 Calculate or Input Number Flow Channels:						Channel Width (Average): 30				
		Duct Wall	Roughness:			Calculate					Channel Height (Average): 5				
			Duct Wall Pour	abaeee		◯ Input									
						Parallel Flow Paths: 1									
		Duct wall ro	Duct wall roughness [Active]: 0.0025				nnels: 3								
		Duct wall ro	ughness [Front]	: 0.0025											
		Duct wall ro	ughness [Rear]	0.0025											
Flow Path Component	<b>По</b> w Туре	Cross Section Area Calculated	Cross Section Area Adjustment	Cross Section Area	Length Calculated	Length Adjustment	Length	k	R	Q	Р	Velocity	Notes		
Units		mm <sup>2</sup>	mm <sup>2</sup>	mm <sup>2</sup>	mm	mm	mm		kg/m7	1/min	Pa	m/s			
Housing [Active]	Transition	150	0	150	2110.75	0	2110.75	9.555	2.232E11	6.5	2630	0.7237			
				C	chec	k Dat	a								
<u></u>															
						Length	(-159.20	,125.00)	m	m 13 Ma	rch 2018	www.motor-o	lesign.com		

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.





#### **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)**.

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Geometry Vinding	MI Input Data	Calculation 🛛 🖡 Temperatures 🛛 🎫 Output Data 📔	Sensitivity 🔂 Sa	ripting 🔀 Flow					
🔆 Cooling 🛛 🌞 Losses	Materials 1	nterfaces Radiation	Housing Water Jacket	End Space	Duty Cycle	Settings	🛛 🦂 Mat	erial data	• •
Component	Gap	Details	Resistance	Conductance		Notes			
			@T=100.0C	@T=100.0C					
11.7			20.41	W/ 2/C	_				- 11
Stator Lam - Housing	0.01	Lamination-Metal - Good surface Contact (0.01)	0.0003153	3171					- 11
Thousing - Orlang [r]	Ū	No dap - r ened surrace contact	2 0	ILUJ					
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					
		Check	Data						
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## 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.

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🖸 Geometry 🛛 🌄 Winding	🛃 Input Data	Calcula	tion 🛛 🖡 Ter	nperatures 🛛 🗮	Output Data	Sensitiv	rity 🛛 😳 Scriptir	ng 🛛 🗱 Flow			
🔆 Cooling 🛛 🌞 Losses 🖌	Materials	1 Interfaces	Radiation	n 1 11 Natural (	Convection	Housing V	Vater Jacket	End Space	🗾 🚹 Duty Cycle 🛛 🤷 Setting:	s 🛛 📥 Material data 🔹	F
Front End Space:				Rear End	Space:						
End Space Velocity Multiplie	r [Front]: Norr	mal Rotor	~ 0.5	End Space	e Velocity Multip	lier [Rear]:	Normal Rotor	~ 0.5	Shaft Speed [rpm]: 6000		
End Space Reference Veloc	ty [Front]: 20.4	2		End Space	e Reference Ve	locity [Rear]:	20.42				
End winding roughness [From	nt]:			End windir	ng roughness [H	(ear]:	1				
Endcap Ventilation [Front]:     O Closed	ed O Ful	lv Open		Endcap \	/entilation [Rea d OVe	r]: nted (	) Fully Open				
laternal Surface	L 1	L2	L2	Air Valasitu	Air Velecitu	L.	Ama	Di	Natas		
Internal Surrace	KI	ĸz	кэ	Air velocity	AIF VEIOCITY	n	Area	rst.	Notes		
Units				pu	m/s	W/m2/C	mm <sup>2</sup>	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	1/9.4	1583	3.52			
Magnet [Rear]	15	0.4	0.9	1	39.58	1/9.4	1583	3.52			
EWdg Bore [Front]	15	0.4	0.9	1	20.42	105.6	1.2/6E04	0.7423			
EWdg Bore [Rear]	15	0.4	0.9	1	20.42	105.6	1.2/6E04	0.7423			
EWdg Outer [Front]	15	0.4	0.9	0.2	4.084	36.29	1.698E04	1.623			
Evvdg Outer [Rear]	15	0.4	0.9	0.2	4.084	36.29	1.698E04	1.623			
Evvag End [Front]	15	0.4	0.9	0.5	10.21	63.56	1.112E04	1.415			
Evvog End [Rear]	15	0.4	0.9	0.5	10.21	63.56	1.112E04	1.415	defends - blacked about -1.4.4	0	
Evvag Ext [Front]	0	0.4	0.9	0.5	10.21	0	1.013E04	100	default = blocked channel (k I =	0)	¥
			_	_					_		
		C	heck	Data	1				Correlatio	on Help	
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#### **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).

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File Edit Model Motor Type Options Defaults Editors View Besults Tools Licence Print Help												
🖸 Geometry 📘 Winding 🖉	Input Data	ion	🗜 Temperature	es 🛛 🖽 Ou	tput Data	Sensitiv	ity 🛛 😳 Scr	ipting 🛛 😂	Flow			
🔆 Cooling 🛛 🌞 Losses 🛛 📸 🛚	Materials 11 Interfaces	((-))	Radiation	Natural Com	vection	Housing V	Vater Jacket	C End S	pace	Duty Cycle 🛛 🧙 Settings 🛛 🙈 Material database		
Component	Material from Databa	se	Thermal Conductivity	Specific Heat	Density	Weight Internal	Weight Multiplier	Weight Addition	Weight Total	Notes		
Linite		_	W/m/C	14 a/C	ka/m2	ka		ka	ka			
Housing [Active]	Aluminium (Alloy 195 Caet		168	833	2790	7 798	1	0	7 798			
Housing [Front]	Aluminium (Alloy 195 Cast	Ť	168	833	2790	0.9747	1	0	0.9747			
Housing [Rear]	Aluminium (Alloy 195 Cast	V	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 [Bear]	Aluminium (Alloy 195 Cast	V	168	833	2790	2 422	1	0	2 422			
Stator Lam (Back Iron)	30DH	V	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	5		
Stator Lam (Tooth)	30DH	~	30	460	7650	5.245	1	0	5.245			
Inter Lam (Tooth)	00011	V	0.02723	1007	1.127	2.39E-05	1	0	2.39E-05			
Stator Lamination [Total]			01011110			13.5			13.5			
Stator Winding [Active]	Copper (Pure)	$\sim$	401	385	8933	4,138	1	0	4,138			
Stator EWdg [Front]	Copper (Pure)	$\sim$	401	385	8933	1.009	1	0	1.009			
Stator EWdg [Rear]	Copper (Pure)	$\sim$	401	385	8933	1.009	1	0	1.009			
Stator Winding [Total]						6.156			6.156			
Wire Ins. [Active]		$\sim$	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-Wdo]			0.21	1000	1400	0.03026	1	0	0.03026			
Wire Ins. [Total]						0.2057		-	0.2057			
Impreg. [Active]		$\sim$	0.2	1700	1400	0.2535	1	0	0.2535			
Impreg. [Front End-Wdg.]		$\sim$	0.2	1700	1400	0.1771	1	0	0.1771			
Impreg. [Rear End-Wdg.]		$\sim$	0.2	1700	1400	0.1771	1	0	0.1771			
Impreg. [Total]						0.6076			0.6076			
Slot Wedge		$\sim$	0.2	1200	1000	0.01397	1	0	0.01397			
Slot Liner		$\sim$	0.21	1000	700	0.05885	1	0	0.05885			
Housing WJ Duct Wall		$\sim$	0.2	1700	1400	0	1	0	0			
Inter Magnet Gap		$\sim$	30	460	7650	0.5501	1	0	0.5501			
Rotor Lam (Back Iron)	30DH	$\sim$	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	5		
IPM Magnet Pole	30DH	<	30	460	7650	4.95	1	0	4.95			
Rotor Lamination [Total]						10.14			10.14			
Magnet	N30UH	$\sim$	7.6	460	7500	1.965	1	0	1.965			
Shaft [Active]		$\sim$	52	460	7800	1.937	1	0	1.937			
Shaft [Front]		$\sim$	52	460	7800	0.2083	1	0	0.2083			
Shaft [Rear]		$\sim$	52	460	7800	0.1348	1	0	0.1348			
Shaft [Total]						2.28			2.28			
Bearing [Front]		$\sim$	30	460	7800	0.1195	1	0	0.1195			
Bearing [Rear]		$\sim$	30	460	7800	0.1195	1	0	0.1195			
Motor Weight [Total]						49.76			49.76	Weight [Total]		
	Update materials from the Database Material Help											
										Length (-28.24,125.60) mm 17 January 2018 www.mote	or-design	n.com

#### 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.

Motor-CAD v10.5.9 (Nissan_LEAF_5_Therma	I.mot)* DEVELOPMENT	RELEASE	icanca Drint Halp		-		×
	actic I E Thermal I H		ting Reint Collinguing				
	neuc   🎸 mennai   🦺	Duty Cycle Opera	ting Foint Graibration Graibration				_
Definition:							
Torque	Speed: 1000	Torque:	Calcul	ate Operating Point			
Maximum Current	Speed. 1000	To	rque: 200				
Maximum Temperature Max	imum Currents:	New T					
Stat	or Current (Peak): 150	Maximum re	Ca	ncel Calculation			
Set Model Operating Point:	or Current (RMS): 106.1	Stator Win	ding: 160				
Motor-CAD Emag Model	or current (rivio).	Ma	gnet: 140				
Motor-CAD Thermal Model	Rotor Current: 6	Change	Thermal Settings				
Variable	Value	Units	Variable	Value	l	Jnits	
Shaft Speed	1000	rpm	Total Loss	1897	1	Natts	
Shaft Torque	200	Nm	Stator Copper Loss	1797	1	Natts	
Shaft Power	2.094E004	Watts					
Efficiency	91.7		Iron Loss	84.04	1	Natts	
			Magnet Loss	0.2689	1	Natts	
Stator Phase Current (peak)	322.8	Amps	Mechanical Loss	15	1	Natts	
Stator Line Current (peak)	322.8	Amps	Windage Loss	0	1	Natts	
Phase Voltage (peak)	52.73	Volts	Friction Loss	15	1	Natts	
Line Voltage (peak)	91.33	Volts					
Phase Advance	39.84	EDeg	Electromagnetic Power	2.104E004	1	Natts	
			Electromagnetic Torque	200.9		Nm	
Phase Current D (peak)	-206.8	Amps	Magnet Torque	118.1		Nm	
Phase Current Q (peak)	247.9	Amps	Reluctance Torque	82.86		Nm	
Phase Voltage D (peak)	-48.31	Volts	Terminal Power	2.284E004	1	Natts	
Phase Voltage Q (peak)	21.13	Volts	Power Factor	0.8947			
Flux Linkage D	43.64	mVs					
Flux Linkage Q	109.7	mVs					
p			Operating Point Found				
			Length (-60.32,84.74)	mm 17 January 2018	www.mc	otor-desig	jn.com



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.

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<u>File Edit Model Motor Type Options De</u>	faults Ed <u>i</u> tors <u>V</u> iew <u>R</u> esults	Too <u>l</u> s Li <u>c</u> ence	<u>P</u> rint <u>H</u> elp			
💽 Geometry 🛛 🌄 Winding 🕅 🕅 Input Data 👬 C	alculation 🔗 E-Magnetics 🖽 🤇	Dutput Data 🛛 🛃	Graphs 🛛 🖉 Sensitivity 📄 🕞 Scripting			
Dire.	Temperatures:		Performance Tests:			
Shaft Speed [RPM]: 1000	Stator Winding Temperature:	65	Single operating points.			
Line Current Definition:	Magnet Temperature:	65				
ORMS	Stator Lamination Temperature:	20	✓ On Load			
RMS Current Density	Rotor Lamination Temperature:	20	0			
Peak Current: 322.8	Stator Sleeve Temperature:	20	Back EMF			
RMS Current: 228.3	Rotor Banding Temperature:	20	Cogging Torque			
RMS Current Density: 11.35	Shaft Temperature:	20	Electromagnetic Forces			
DC Bus Voltage: 375	Stator Wedge Temperature:	20	On Load:			
Phase Advance [elec deg]: 39.84	EMagnetics - Thermal Coup	ling:	✓ Torque			
Drive Mode:	Linkage Options:		Torque Speed Curve			
Sine	<ul> <li>F-Magnetics Losses → The</li> </ul>	mal	Demagnetization			
	○ E-Magnetics ← Thermal Te	emperatures	Electromagnetic Forces			
Ocustom	Iterate to Converged Solution	on				
			Parameters:			
Winding Connection:	CI.		Self and Mutual Inductances			
<ul> <li>Star Connection (default)</li> </ul>	Skew: Skew Type:		Transient:			
Delta Connection	None (default)     Stator Ske	w: 0	Sudden short-circuit			
	O Stator Rotor slice	es: 1				
Magnetisation:	ORotor					
Parallel			Solve E-Magnetic Model			
◯ Radial						
O Halbach Continuous Ring Array			Cancel Solving			
O Halbach Sinusoidal Array						
<u> </u>		Length	(-97.69,97.69) mm 17 Janua	ary 2018 www	v.motor-des	ign.com


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

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<u>File Edit Model Motor Type Options D</u>	efaults Ed <u>i</u> tors <u>V</u> iew	/ <u>R</u> esults Too <u>l</u> s	Lig	<u>c</u> ence <u>P</u> rint <u>H</u> elp				
🖸 Geometry 🛛 🌄 Winding 🛛 🔟 Input Data 🗎 🚺	Calculation 🛛 🔗 E-Magr	netics 📃 Output Da	ata	Graphs Sensitivity	Scripting			
∧ Drive Ø E-Magnetics A Phasor Diagram	🔆 Losses 🚺 Wind	ling 🛛 🐣 Materials 🗎						
Variable	Value	Units	^	Variable		Value	Units	^
DC Stator Copper Loss (on load)	1797	Watte						
Magnet Loss (on load)	0 2797	Watts						- 11
Stator iron Loss (total) (on load)	82.54	Watts						- 11
Rotor iron Loss Itotal] (on load)	1.499	Watts						- 11
Wedge Loss (on load)	0	Watts						- 11
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	Υ.					Y
5			L	_ength (-97.69,97.0	69) mm	17 January 2018	www.motor-desig	n.com



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	

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Geometry Winding	Input Data	Calculation	F Temperatu	ures Ì ☷ Out	put Data 🛛 🚧 Tra	ansient Graph 53 Sensitivity 🕞 Scripting 😭 Flow	
Athentic March 8		1111					A
	atenais   🚣	Interfaces   WW F	adiation   1	Natural Conv	ection   Section	ing water Jacket   🌳 End Space   🖵 Duty Cycle   🖤 Settings   (	Material data
🔆 Loss Models 🚺 Loss Distri	bution						
Loss Variation with Speed:						Copper Loss Variation with Temperature:	
Shaft	_coet	f[A] Speed	Dependent Lo	osses		Copper Losses Vary with Temperature	ort
P[speed] = P[input] x Spee	d[REF]	Shaft Spe	ed[rpm]		1000	Winding Temperature at which Stator Copper Losses Input:	65
		Single	value of Spee	d[REF] [rpm]	1000		
Component	P[Input]	Speed[REF]	coef[A]	W/kg	P[speed]	Loss Variation with Temperature & Load:	
-			• •				
						Contant Torque or Constant Current	
Units	Watts	rpm		W/kg	Watts	Constant Torque  Constant Current	
Loss [Stator Copper]	1797	1000	0	291.9	1797	Winding Temperature - Twili/n):	65
Loss [Stator Back Iron]	40.91	1000	0	4.953	40.91	Manual Tana ant an Tart (a)	05 CF
Loss [Stator Tooth]	41.63	1000	0	7.938	41.63	Magnet Temperature - Tm(i/p):	60
Loss [Magnet]	1.250	1000	0	0.1424	1.256	Shaft Torque [Nm] (@Pcu defined):	199.9
Loss [Embedded Magnet Fole]	0.142	1000	0	0.2735	0.142	Motor Current [Arms] (@Pcu defined):	228.3
Loss [Friction - E Bearing]	0.145	3000	0	0.05005	0.145	Torque Constant [Nm/A]	0.8756
Loss [Friction - B Bearing]	0	3000	0	0	0	Steady State Torque & Current Multiplier:	1
Loss [Windage]	0	3000	0	0	0	Roh @Tw(i/p):	0.0115
Loss [Windage] (Ext Fan)	0	3000	0	0	0	Magnet Temperature Coefficient Br:	.0.12
						Magner Temperature Coenticient br.	-0.12
						Phases:	3
						Losses Notes:	
						Type in user Losses notes here	~
			-4-				~
	Ch	eck D	ata			<	>
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					Length	(-14.04,74.56) mm 17 January 2018 WV	/w.motor-design.com

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.

Eie Edit Model MotorType Options Defaults Editors View Besults Toojs Ligence Enint Help © Generity ↓ Windrig ↓ Prod. Data ↓ Cacduden ↓ Temperatures Ⅲ Output Data ↓ Songtring ☆ Row ↓ Model State: © Editadiation: © Generity ↓ Model Options: © Generity ↓ Model Options: © Generity ↓ Output Data ↓ Data ↓ Output Data ↓	Motor-CAD v10.5.9 (Nissan_LEAF_5_Thermal.mot)* DEVELOPMENT	ELEASE		_		х
● Winding ● Winding ● Rout Data ● Calculation       ● Temperatures       ● Duty Data ● Calculation:	<u>File Edit Model Motor Type Options Defaults Editors View</u>	<u>R</u> esults Too <u>l</u> s Li <u>c</u> ence <u>P</u> rint <u>H</u> elp				
Calculation:       Model Options:         Image: State	🖸 Geometry 🛛 💭 Winding 🗎 🔐 Input Data 🛛 👫 Calculation 🛛 🖡 Tempe	rures   🖽 Output Data   🌄 Sensitivity   🕞 Scripting   💢 Flow				
Length (-14.04,74.58) mm 17 January 2018 www.motor-design.com	Calculation       Import Data       Model Options         Oraculation Type:       Import Data       Model Size:       Import Data         Import Data       Import Data       Model Options       Model Size:       Import Data         Import Data       Import Data       Import Data       Model Options       Model Size:       Import Data       Import Data       Model Size:       Import Data       Import Data       Import Data       Model Size:       Import Data       Import Data       Import Data       Model Size:       Import Data       Im	uites → Oupur Data v Sensitivity Schung v How ault) emodel ault) EA calibration emal Coupling: iefault) osses → Themal ← Themal Temperatures rerged Solution				
	7	Length (-14.04,74.58) mm 17	7 January 2018	www.mc	tor-desig	n.com



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.









# 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.

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🖸 Geometry 📘 Winding 📔 Input Data 🛛 🚻 Calculation 🛛 🗦 Temperatures 🔠 Output Data 🛛 🚰 Sensitivity 💽 Scripting 🛛 😂 Flow								
🗜 Temperatures 🛚 🌞 Losses 🛛 💾 Heat Transfer Coeff 🛛 🙀 Heat Transfer Coeff [2] 🛹 Themal Resistance 👌 📫 Thermal Capacitance 🛛 🏟 End Space 🗋 🌄 Winding 🛛 🔀 Housing Water J 🚺								
Main Axial Temperatures Axial Temperatures Graph Winding Temperatures Winding Temperatures Graph								
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					
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🖡 Temperatures 🛛 🌞 Losses 🔢 Hea	🗜 Temperatures   🌞 Losses 📕 Heat Transfer Coeff 🛛 👫 Heat Transfer Coeff [2]   🖍 Thermal Resistance   ≑ Thermal Capacitance   💠 End Space   🌄 Winding   🛃 Hous 💶							
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

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Geometry Winding	nut Data		atures EEL Output Data 52 Sensit		1				
Cooling Losses	erials	Badiation	H Natural Convection	Water Jacket	Duty Cycle	Settings	🙈 м	aterial dat	
Settings									
Transient Calculation Data:			Transient Data Notes:						
Transient Calculation Type:	Transient Period:	7200	Type in user Duty Cycle notes here						~
Simple Transient	Number Points:	20							
O Duty-Cycle Analysis	Change in Tambient:	0							
	Number of Cycles:	1							
Point storage reduction: 1	RMS Torque [Nm]	424.5							
	RMS Torque [pu]:	2.123							
	Average Speed:	1000							
Transient Start Point:									
Initial Transient Temperatures:									
Ambient Temperature (default     Steady State Temperatures	)								
Ambient Temperature (default     Steady State Temperatures     Previous Transient Temperatu	) ures (if same network)								
Ambient Temperature (default     Steady State Temperatures     Previous Transient Temperatu     Whole machine at specified te	) ures (if same network) emperature								
Ambient Temperature (default     Steady State Temperatures     Previous Transient Temperatu     Whole machine at specified te     Machine components at spece	) ures (if same network) emperature ified temperatures								
Ambient Temperature (default     Steady State Temperatures     Previous Transient Temperatures     Whole machine at specified t     Machine components at spec     Initial Temperatures:	) ures (if same network) emperature ified temperatures								
Ambient Temperature (default     Steady State Temperatures     Previous Transient Temperatures     Whole machine at specified t     Machine components at spec     Initial Temperatures:     Machine Temperature;     60	) ures (if same network) emperature ifiled temperatures								
Ambient Temperature (default     Steady State Temperatures     Previous Transient Temperatures     Whole machine at specofied t     Machine components at spec     Initial Temperatures:     Machine Temperature:     60     Range Temperature:     40	) ures (ff same network) emperature uffied temperatures								
Ambient Temperature (default     Steady State Temperatures     Previous Transient Temperatures     Whole machine a specified t     Machine components at spec     Initial Temperatures:     Machine Temperature:     60     Range Temperature:     40     Housing Temperature:	) ures (if same network) emperature uffied temperatures								
Ambient Temperature (default     Steady State Temperatures     Previous Transient Temperatures     Whole machine at specified t     Machine components at spec     Initial Temperatures:     Machine Temperature:     60     Range Temperature:     40     Housing Temperature:     40     Stator Temperature:	) ures (if same network) emperature uffied temperatures								
Ambient Temperature (default     Steady State Temperatures     Previous Transient Temperatures     Whole machine at specified t     Machine components at spec     Initial Temperatures:     Machine Temperature:     60     Range Temperature:     40     Housing Temperature:     40     Stator Temperature:     40     Winding Temperature:     40	) ures (if same network) emperature uffied temperatures								
Ambient Temperature (default     Steady State Temperatures     Previous Transient Temperatures     Whole machine at specified t     Machine components at spec     Initial Temperatures:     Machine Temperature:     Machine Temperature:     Machine Temperature:     40     Housing Temperature:     40     Stator Temperature:     40     Winding Temperature:     40	) ures (if same network) emperature ified temperatures								
Ambient Temperature (default     Steady State Temperatures     Previous Transient Temperatures     Whole machine a specified t     Machine components at spec     Initial Temperatures:     Machine Temperature:     Machine Temperature:     Machine Temperature:     Machine Temperature:     40     Housing Temperature:     40     Stator Temperature:     40     Winding Temperature:     40	) ures (if same network) emperature ified temperatures								~
Ambient Temperature (default     Steady State Temperatures     Previous Transient Temperatures     Whole machine at specified t     Machine components at spec     Initial Temperatures:     Machine Temperature:     Machine Temperature:     Machine Temperature:     40     Housing Temperature:     40     Stator Temperature:     40     Winding Temperature:     40     Kotor Temperature:     40	) ures (if same network) emperature ified temperatures		<					>	~
Ambient Temperature (default Steady State Temperatures Previous Transient Temperatures Whole machine at specified t Machine components at specified t Machine Temperatures: Machine Temperature: Housing Temperature: 40 Stator Temperature: 40 Winding Temperature: 40 Rotor Temperature: 40	) ures (ff same network) emperature ified temperatures		<ul> <li>Check Date</li> </ul>	ta				>	÷
Ambient Temperature (default     Steady State Temperatures     Previous Transient Temperatures     Whole machine at specified t     Machine components at spec     Initial Temperatures:     Machine Temperature:     40     Housing Temperature:     40     Stator Temperature:     40     Winding Temperature:     40     Rotor Temperature:     40	) ures (f same network) emperature ified temperatures		Check Date	ta				>	×
Ambient Temperature (default     Steady State Temperatures     Previous Transient Temperatures     Previous Transient Temperature     Whole machine at specified t     Machine components at spec     Initial Temperatures:     Machine Temperature:     40     Housing Temperature:     40     Housing Temperature:     40     Winding Temperature:     40     Rotor Temperature:     40	) ures (f same network) emperature ified temperatures		<ul> <li>Check Date</li> </ul>	ta				>	~



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

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Geometry Winding M Input Data	ation France Temperatures I III Outout Data   27 Transient Graph   57 Sensitivity   Scripting   12 Row			
Calculation: Calculation Type: O Steady State Transient Solve Thermal Model	Model Options: Model Size: (a) Full model (default) (b) Reduced node model Model Type: (a) 3D model (default) (c) 2D model for FEA calibration			
	EMagnetics - Thermal Coupling: Unkage Options: ○ No coupling (default) ④ E-Magnetics Losses → Thermal ○ E-Magnetics ← Thermal Temperatures ○ Iterate to Converged Solution			
<u> </u>	Length (-14.04,74.58) mm 17 January 2018	www.mo	otor-desig	n.com

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 LabWe 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	

虊 Motor-CAD v10.5.9 (Nissan_LEAF_5_Thermal.mot) DEVELOPMENT R	ELEASE	- 🗆 X
<u>File Edit Model Motor Type Options Defaults Editors View</u>	<u>R</u> esults Too <u>l</u> s Li <u>c</u> ence <u>P</u> rint <u>H</u> elp	
💽 Geometry 🛛 🌄 Winding 🛛 🕅 Input Data 🛛 👫 Calculation 🛛 🖡 Tempera	atures 🗄 Output Data 🛛 🚈 Transient Graph 🛛 🖓 Sensitivity 🛛 😜 Scripting 🛛 💥 Flow	
🛠 Cooling   🌞 Losses 🔒 Materials 🗊 Interfaces 🕅 Radiation 🗍	🗄 Natural Convection 🛛 🚰 Housing Water Jacket 🛛 🚸 End Space 🛛 🚹 Duty Cycle 🛛 🟠 Settings	Aterial data 🔹 🕨
Settings		
Transient Calculation Data:	Transient Data Notes:	
Transient Calculation Type: Transient Period: 140	Type in user Duty Cycle notes here	~
O Simple Transient Number Points: 20		
Duty-Cycle Analysis     Change in Tambient:		
Number of Cycles: 1		
RMS Torque [Nm] 424.5		
RMS Torque [pu]: 2.123		
Average Speed: 3179		
-Transient Start Point:		
Initial Transient Temperatures:		
O Previous Transient Temperatures (if same network)		
O Whole machine at specified temperature		
Machine components at specified temperatures		
Initial Temperatures:		
Machine Temperature: 60		
Flange Temperature: 40		
Housing Temperature: 40		
Stator remperature: 40		
Refer Temperature: 40		
notor remperature. 40		
	<	>
	Check Data	
Saving File Completed	Length (-31.40,81.63) mm 17 January 2018	www.motor-design.com



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.

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🖸 Geometry	/ 📘 Win	ding 🚺	Input Data	a Calc	ulation 🛛 🖡	Temperatur	res 📃 🖽 Out	put Data	🚈 Transient	Graph	Sensitivity	Scriptir	ng 🛛 🗱 Flov	v			
🛎 Losses	Materi	ials 1.1	Interfaces	Radiat	tion 1 It Na	tural Conve	ction	Iousing Wat	er Jacket	End Space	e 📴 Dut	Cycle	Settings	A Materia	al database		• •
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		Z o State	Conner	Lora 🗖	- Stator Ba	ak kan Lar	···· •• ••	ator Tooth	Iron Loro 🗸	í 🌢 Magnai	loss		Rotor Back Ir	on Loss			
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ses [	2										-					*	
Los	0	5		10	15	20	25	3 Time	0 [secs]	35	40	45	50		55	60	
Speed [rpm]	E 3,000 2,000 0 0																
	Ó		5	10	15	20	25	Tim	30 le [secs]	35	40	45	50		55	60	
Period	Elapsed Time	Time	Points	Stator Copper	Stator Back Iron	Stator Tooth	Magnet	Rotor Back Iron	Embedde d Magnet Pole	Friction Front Bearing	Friction Rear Bearing	Windage	Windage Exterior Fan	Speed [Start]	Speed [End]	Fau	It
Units	secs	secs *	•	pu 🗈	pu 🖿	pu 🗈	pu 🗈	pu 🗈	pu 🗈	pu 🗈	pu 🗈	pu 🗈	pu 🗈	rpm 🗈	rpm 🔳		
1	20	20	4	0.5	0.7	0	0	0	0	0	0	0	0	0	3000		
2	40	20	4	2.5	1.5	0	0	0	0	0	0	0	0	3000	3000		
3	60	20	4	0.6	1	0	0	0	0	0	0	0	0	3000	0		
۲																	>
Duty Cy	cle Contro	d:							_			Estampl D	the Corelia D-1	-			
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	(	Che	ck	Data	3		● Loss - Spe ○ Torque (Va	ed ariable) - Sp	eed O Va	lue		Save E	ixternal Duty	Save Data Cycle Data	in mot file	ear Data	
								Leng	ıth	(-31.40,8	(1.63)	mm	17 Janua	ry 2018	www.mo	otor-desi	ign.com

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.

Motor-CAD v10.5.9 (Nissan_LEAF_5_Thermal.mot)* D File Edit Model Motor Type Ontions Defaults	EVELOPMENT RELEASE	– 🗆 X
		Settings
Vabicle Model:		
Mass: 1521 Fro Rolling Resistance Coefficient: 0.007 Dra Air Density: 1.225 Fina Generating Torque Ratio: 1 Max.	Ital Area (m <sup>2</sup> ):         2.29         Wheel Radius (m):         0.3           ag Coefficient:         0.28         Mass Correction Factor:         1.04           al Drive Ratio:         7.938         Motoring Torque Ratio:         1           Torque:         500         Max. Speed:         2E4	17-01-18 15:43:50: duty cycle calculation completed
Drive Cycle:		Calculate Duty Cycle Performance
Drive Cycle Data:    Standard Drive Cycle	Edward Data:	Cancel Calculation
US06 Div	ata Type: Time(s), Torque(Nm), Speed (rpm)	Export Duty Cycle To Thermal Model
	Load Generate	Load Results Viewer
	Calculation complete	
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	Motor-CAD	×
	Duty Cycle Successfully Importe	ed

OK

Show future messages in window



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.

Transient Co	ntrol 🛛 🏠 Po	wer Graph Setu	p 🏠 Temperatur	e Graph Setup						
hart Titles			_	Custom Graph Settin	gs:					
Automatic	Titles							- 1	Drawing Optic	ons
Chart Title: Themal Transient								-	✓ Draw Lin	ies
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iraph Limite				Node Name	Graph Legend	Graphed	Point Type		Line Color	ur i
✓] Automatic X-Axis Limit	Scale	Y-Axis Limit	S	0.070.0.1				_		_
	0	Mar .	CE	Shaft [Active]	Shaft [Active]		Cross	~	Silver	$\sim$
Min :	U	MILL .	60	Shaft [Front]	Shaft [Front]		DiagCross	~	Silver	~
Max :	599	Max :	133	Shaft [Rear]	Shart [Rear]		Star		Silver	
Inc :	59.9	Inc -	8	SlotCentre (CT)	SlotCentre (CT)		Diamond	~	LtGreen	$\sim$
				SlotCentre (C2)	SlotCentre (C2)		Inangle	~	LtGreen	~
				Stator Back Iron	Stator Back Iron		Diamond	~	Red	~
				Stator Surrace	Stator Sulface		Rectangle	~	Red	~
				Stator Tooth (C1)	Stator Tooth (C1)		DiagCross	~	Red	
				Stator Tooth (C2)	Stator Tooth (C2)		Rectangle	~	Hed	~
				VVdg (Average) (C1)	Wdg (Average) (C1)		Cross	~	Tellow	
				Wdg (Average) (C2)	Wdg (Average) (C2)		Triamond	×	Tellow	
				Wdg_F(C1)	Wdg_F(CI)		DipeCreate	~	Yellow	~
					Wdg_F (C2)		Daum Triangle	~	Velleur	
				Wdg_R (C1)	Wdg_R (C1)		Star	~	Vollow	~
				Wdg_in(c2)	Wdg_h (C2)		Crose	~	Yellow	
				Wedge (C1)	Wedge (C1)		Star		Yellow	
				Winding (Average)	Winding (Average)		Circle	~	Yellow	
				Winding (Average)	Winding (Cooleast)		Triangle	Ť.	Yellow	Ť
				Winding (Coolspot)	Winding (Hotepot)		DownTriangle	~	Yellow	
				winding (Hotspot)	winuing (Hotspot)		DownInangle	$\sim$	rellow	$\sim$





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.

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Eile Edit Model MotorType Options Defaults Editors View Results Tools Licence Print Help			
💿 Geometry 📘 Winding 🔣 Input Data 👫 calculation 👃 Temperatures 🖽 Output Data 🔛 ransient Graph 🔯 Sensitivity 💽 Scripting 💢 Row			
🛠 Cooling   🌞 Losses   🏯 Materials   🛨 Interfaces   🖗 Radiation   🔛 Natural Convection   😤 Housing Water Jacket   🚸 End Space 🚺 Duty Cycle   🏠 Settings	🛛 🦂 Ma	terial data	• •
Settings			
Transient Calculation Data: Transient Data Notes:			
Transient Calculation Type: Transient Period: 2995 Type in user Duty Cycle notes here			^
Simple Transient Number Points: 2995			
Duty-Cycle Analysis     Change in Tambient			
Number of Cycles: 5			
roint storage reduction:			
RMS Torque [pu]: 0			
Average Speed: 5436			
Transient Start Point:			
Initial Transient Temperatures:			
Ambient Temperature (default)			
O Bready State Temperatures			
Previous transient temperatures     insertion temperatures			
Machine components at specified temperatures			
Initial Temperatures:			
Machine Temperature: 60			
Hange Temperature: 40			
Housing Temperature: 40			
Stato Temperature: 40			
Winding Temperature: 40			
Rotor Temperature: 40			
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Check Data			
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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	А
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	

Nodel Build   👫 Calculation   🏈 Elec	tromagnetic 📕 Thermal [ 🛨 Duty Cycle 🛛 📰 Operating	g Point   🔗 Calibration   🎧 Settings	
alculation; Thermal Map Type: Envelope Full Map Thermal Calculation: Steady State Transient	Speed: Maximum: 1E4 Step: 500 Minimum: 200 Maximum Temperatures:	Calculation Status: 17-01-18 16:28:24: Thermai calculation completed with maximum average stator winding =160.0degC maximum magnet =140.0degC maximum speed 10000.0pm Calculate Thermal Performance	
Themal Limit: Stator Winding Only Stator Winding + Magnet	Stator Winding: 160 Magnet: 140	Cancel Calculation	
Maximum Winding Node: Average  Hotspot	Max. Current:	Load Results Viewer	
Initial Current Estimate: Stator Current (Peak): 240 Stator Current (RMS): 169.7	Maximum (RMS): 339.4		



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 <a href="https://www.motor-design.com/publications/tutorials/">https://www.motor-design.com/publications/tutorials/</a>.

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	0
Auto Centre	Disabled	
x offset	0.0	mm
y offset	0.0	mm

Ӧ DXF Import			_		×
View: Radial Axial Winding	Position and size:       Centre:         Scale:       1.0         Auto Centre         Rotation:       22.5         x offset:       y offset:         0       y offset:	DXF Size: x: 99 y: 45.9619			
DXF File Selection File: C:\Workspa	: ace\Motor-CAD_tutorials\Nissan_Leaf_Tutorial\Ni	Clear DXF Import		Close	

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



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🖸 Geometry 📘 Wind	ding 🛛 🛃 lr	nput Data 🛛 🚺 Calculatio	n 🛛 🌛 E-Magnei	ics 🛛 🖽 Outp	out Data 🛛 🗠	Graphs	Sensitivity 🛛 🕤	Scripting					
🖸 Radial 🗧 Axial	🝽 3D												
Slot Type: Parallel To	ooth ~	Rotor Type: Interior V (	web) 🗸							R/L	stor	01	
						_				IAIR	JUUI	-07	
Stator Ducts: None	~	Rotor Ducts: Circular Du	icts 🗸				- 👝 🛑 📒		_				
Stator Dimensions	Value	Rotor Dimensions	Valu 🔨			1			70		_		
Slot Number	48	Pole Number	8			$\sim$							
Stator Lam Dia	198	Notch Depth	0						5/				
Stator Bore	132	Magnet Layers	2				C C	0	$\sim$				
Tooth Width	4.15	L1 Magnet Thickness	3.862								$\sim$		
Slot Depth	21.1	L1 Magnet Bar Width	13.9										
Slot Comer Radius	2	L1 Bridge Thickness	0.6			K/		$\gamma$ /	1		/		
Tooth Tip Depth	1.2	L1 Web Thickness	21					$\mathcal{I}_{\mathcal{L}}$					
Slot Opening	2.814	L1 Web Length	0					$\rightarrow$					
Tooth Tip Angle	27	L1 Pole V Angle	180						/				
Sleeve Thickness	0	L1 Pole Arc [ED]	150				_ /	1 1					
		L1 Magnet Post	0				$\bigcirc$		$\bigcirc$				
		L1 Magnet Separation	0				$\smile$	/	$\bigcirc$				
		L1 Magnet Segments	1								_		
		L1 Magnet Clearance	0					10	>				
		L2 Magnet Thickness	2.6										
		L2 Magnet Bar Width	21.33				<b>1</b> (		1		$\sim$		
		L2 Bridge Thickness	7.65					~	//		$\sim$		
		L2 Web Thickness	2.5									/	
		L2 Web Length	0								~ /		
		L2 Pole V Angle	124										
		L2 Pole Arc [ED]	159					- A					
		L2 Magnet Post	0							$\smile$ ,			
		L2 Magnet Separation	0			<u> </u>			57				
		L2 Magnet Segments	1										
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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.

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FEA 🔛 FEA Editor	🍾 FEA Paths 🛛 🕌 Optimisa	tion		
Use Custom Regions:	Region Wan	nings: 0		DXF Geometry (Errors: 0)
Thermal Slot		_		Geometry Options:
Thermal Pole				Use DXF Thermal
F-Magnetic				Use DXF E-Magnetic
				Use DXF as Entire Machine
📑 Add 🗗 Copy				
🗹 Edit 🔂 Copy+	Delete			
Positions E-Magnetics				
Region Name	Region Material	X Position	Y Position	
Units		mm	mm	
L1 1Magnet2	N30UH	53.5	29.68	
L1 1Magnet1	N30UH	58.82	16.84	1 🔪
L2 1Magnet2	N30UH	39.98	27.41	1
L2 1Magnet1	N30UH	47.65	8.886	
Rotor	30DH	59.59	24.68	
RotorAir		38.92	16.45	
RotorAir		39.16	15.89	
RotorAir		42.6	39.54	
RotorAir		51.6	36.8	
BotorAir		58.1	2 217	
RotorAir		62.51	10.46	
RotorDuctFluidRegion		29.54	12.23	
RotorDuctFluidBegion		44.73	42.93	
RotorDuctFluidRegion		61.99	1 275	
Shaft		2 053	0.8505	
Stator	30DH	98.59	6 462	
StatorAir		66.45	4.355	
StatorSlotL1	Copper (Pure)	77.19	3.591	
StatorSlotB1	Copper (Pure)	77	6.515	
StatorWedge		67.28	4 41	
		07.20		
<u></u>				
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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	А
Phase Advance	45	Elec deg

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

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Geometry Winding I nput Data	culation 🕜 E-Magnetics 💷 C	Output Data 🏼   🚧 Graph	s   🖓 🔂 Sensitivity   🕑 Scripting			
Drive:	Temperatures:		Performance Tests:			
Shaft Speed [RPM]: 3000	Stator Winding Temperature:	65	Single operating points:			
Line Current Definition:	Magnet Temperature:	65	Open Circuit			
Peak     Duc	Stator Lamination Temperature	20	Q axis current only			
O RMS	Reter Leninetien Temperature:	20	🗹 On Load			
	Notor Lamination Temperature.	20	Open Circuit:			
Peak Current: 480	Stator Sleeve Temperature:	20	Back EMF			
RMS Current: 339.4	Rotor Banding Temperature:	20	Cogging Torque			
RMS Current Density: 16.88	Shaft Temperature:	20	Electromagnetic Forces			
DC Bus Voltage: 375	Stator Wedge Temperature:	20	On Load:			
Phase Advance [elec deg]: 45	- EMagnetics - Thermal Coup	lina:	✓ Torque			
Drive.	Linkage Options:		Torque Speed Curve			
Drive Mode:	No coupling (default)					
Sine	○ E-Magnetics Losses → The	mal				
OSquare	○ E-Magnetics ← Thermal Te	emperatures	Electromagnetic Forces			
Custom	<ul> <li>Iterate to Converged Solution</li> </ul>	n	Parameters:			
Winding Connection:			Self and Mutual Inductances			
Star Connection (default)	Skew: Skew.Type:		Transient:			
	None (default)     Stator Ske	w: 0				
	O Stator Rotor slice	es: 1				
Magnetisation:	Hotor		Salva E Magnetia Madal			
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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**.







## 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.

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🔆 General 🔶 Proximity							
General Loss Settings:							
Windage Losses:	Rotor Hysterisis Loss Calculation:						
Direct user input (default)	Minor Loops only (default)						
Automatic calculation	O Fundamental and Minor Loops						
Calculation multiplier: 1	Lamination Loss Calculation:						
	Vector Br. Bt (default)						
Laminated Core Iron Loss Calculation:	O Vector Bx, By						
OBertotti	Converter Lesson						
Steinmetz (default)	Converter Losses:						
Build Factor Definition:	Conventer Losses.						
Stator / Rotor (default)	Magnet Loss 3D Scaling:						
O Hysteresis / Eddy	O None						
Iron Loss Build Factors:	Preprocessing (default)						
Stator 1.5 Rotor: 1.5							
Hustenseis: 1 Eddy: 1							
Ludy.							
Loss Build Factors:							
Magnet Loss Build Factor: 1							
Shaft Loss Build Factor: 1							
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# **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**.

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Magnetics settings:		•		
Cores: Rotor Iron: Solid Non Magnetic Lamination Stacking Factor [Rotor]: 0.97 Stator Iron: Laminated (default) Solid	Manufacturing Factors: Stator EWdg length multiplier: 1 EWdg Inductance multiplier: 1 Magnet Br multiplier: 1 D axis flux linkage multiplier: 1 Q axis flux linkage multiplier: 1	-End winding inductance Calculation:		
Non Magnetic     Lamination Stacking Factor [Stator]: 0.97     Stacking factor calculation:	Eccentricity: © None (default) O Static O Dynamic O Static + Dynamic Angle: 0 Rotor Centre Offset: Distance: 0 Rotor Centre Offset: Distance: 0 Angle: 0 Angle: 0 Angle: 0			


#### **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.

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🚵 Materials 😧 Settings 🦂 Material database	
Geometry	Calculation 🛛 🛩 Graphs 🛛 🌞 Losses 🛛 🧪 Preferences 🛛 🌄 Notes 🗎
Drive Settings: Sine Drive Modulation: © Circle tracking (default) SixStep 180 Hexagon tracking - piecewise linear Hexagon tracking - secant Sixstep 120 Maximum linear range of sine/triangle Sine/triangle with 3rd harmonic injection	Square Wave Current Calculation:         Drive Parameters:         Switch resistance:         0         Switch forward voltage:         0.6         Maximum drive duty cycle:
Circuit at input of machine: Circuit: None (default)	Switching Frequency Definition: Automatic (default) User Defined
	Switching frequency: 100
	Inductance used for Current Calculation: Average Over Cycle (default) Varying With Position
	Chopping Mode: Soft Chopping (default) Hard Chopping



#### **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 <sup>1</sup>/<sub>2</sub> machine will take <sup>1</sup>/<sub>4</sub> 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.

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💿 Geometry 🛛 🏈 E-Magnetics 🛛 🖊	Drive Calculation Araphs	🛛 🌞 Losses 🖌 🧪 Preferences 📘 🗋	Notes		
Calculation options:					
Mesh Control:	Torque Calculation:	Back EMF Calculation:	Cogging Torque Calculation:	Inductance Calculation:	
Airgap internal points: 360	Points per cycle: 30	Points per cycle: 30	Points per cycle: 10	Points per cycle: 5	
Airgap surface points: 360	Number of cycles: 1	Number of cycles: 1	Number of cycles: 2	Number of cycles: 1	
Stator Lam mesh length: 0	Open Circuit Calculation:		Short Circuit Calculation:	Calculation Method:	
Rotor Lam mesh length: 0	Q axis current only (default)		Points: 1E4	Small Signal	
Min Point Separation: 0.005	Threading Options		Duration: 0.1	Small Signal Inductance Solver:	
	Multiple threads:		Load inertia: 0	⊖ Full	
Model Size:	Use Single Thread (default)			Half Cycle (default)	
Symmetry: Use symmetry (default)	O Use Multiple Threads			<ul> <li>Sixth Cycle</li> </ul>	
O Full machine	Automatic Thread Number:			Forces Calculation:	
User Specified symmetry	Number of threads: 8			Number of points: 100	
Symmetry factor: 1	Lab Threading Enabled:				
FEA Eddy Current Calculation:	_				
Calculation Method:	Clear Thread Cache				
Onginal					
Integral (default)					
Magnetic Solver:					
Transient (default)					
O Multi-static					
O Reduced multi-static					
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#### **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 <u>https://www.motor-design.com/publications/tutorials/</u>.

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

Motor-CAD v10.5.9 (Nissan\_LEAF\_6\_Advanced.mot)\* DEVELOPMENT RELEASE × <u>File Edit Model Motor Type Options Defaults Editors View Results Tools Licence Print H</u>elp 🖸 Geometry 📘 Winding 🔰 Input Data 👫 Calculation 🛛 🛷 E-Magnetics 🛛 🏥 Output Data 🛛 💆 Graphs 🛛 💆 Sensitivity 🛛 😜 Scripting 🗎 📸 Materials 😧 Settings 🖂 Material database 🔕 Geometry | 🖉 E-Magnetics | 🌺 Drive | 👫 Calculation | 🖉 Graphs 🛛 🗰 Losses 📝 Preferences | 🗋 Notes | 🔆 General 🔶 Proximity Proximity Losses: Proximity Losses: Proximity Loss Model: Cuboid Sizes: Cuboid Size: Automatic (old method)
 Custom (user values) O None (default) Hybrid FEA Automatic (default) Skewed distribution O Full FEA (beta version) Bundle Dimensions Number of Cuboids: 6 Include Bundle Effect Bundle Aspect ratio: 1

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



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	А
Phase Advance	65	Elec deg

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

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Drive:	Temperatures:		Performance Tests:			
Shaft Speed [RPM]: 6000	Stator Winding Temperature:	65	Single operating points:			
Line Current Definition:	Magnet Temperature:	65	Open Circuit			
Peak     RMS	Stator Lamination Temperature:	20	✓ Q axis current only			
O RMS Current Density	Rotor Lamination Temperature:	20	Of Eddu			
Peak Current: 200	Stator Sleeve Temperature:	20	Open Circuit:			
BMS Current: 141.4	Rotor Banding Temperature:	20				
RMS Current Density: 7.034	Shaft Temperature:	20				
DC Bus Voltage: 375	Stator Wedge Temperature:	20	On Load:			
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○ Square	○ E-Magnetics ← Thermal Te	emperatures	Electromagnetic Forces			
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Star Connection (default)	Skew Type: Stator Ske	w: 0	Transient:			
O Delta Connection	Stator Botor slice	es: 1	Sudden short-circuit			
Magnetisation: Parallel	ORotor		Solve E-Magnetic Model			
			Cancel Solving			
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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.

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🔨 Drive 🛛 🏈 E-Magnetics 🗎 🎝 Phasor Diagram	🌞 Losses 📘 Wir	nding 🛛 📥 Materia	ls				
Variable	Value	Units	^	Variable	Value	Units	^
DC States Copper Less (on lead)	con	Watto.					-
AC Copper Loss (Hybrid)(Total)	374.2	Watts					
Magnet Loss (on load)	5,144	vvatts	-				
Stator iron Loss [total] (adjusted) (on load)	596.5	Watts					
Rotor iron Loss [total] (adjusted) (on load)	21.72	Watts					
Wedge Loss (on load)	0	Watts					
Windage Loss (user input)	0	Watts					
Shaft Loss [total] (on load)	0	Watts					
Total Losses (on load)	1688	Watts					_
Magnet Loss Factor	0.1983						
Magnet Loss (on load)	5.144	Watts					
Stator back iron Loss [hysteresis - fundamental] (on	74.94	Watts					
Stator back iron Loss [hysteresis - minor loops] (on	1.787	Watts					
Stator back iron Loss [hysteresis] (on load)	76.73	Watts					
Stator back iron Loss [eddy] (on load)	42.06	Watts					
Stator back iron Loss [excess] (on load)	0	Watts					
Stator back iron Loss [total] (on load)	118.8	Watts					
Stator back iron Loss [total] (adjusted) (on load)	178.2	Watts					
Stator tooth Loss [hysteresis - fundamental] (on	132.9	Watts					
Stator tooth Loss [hysteresis - minor loops] (on	29.09	Watts					
Stator tooth Loss [hysteresis] (on load)	162	Watts					
Stator tooth Loss [eddy] (on load)	116.9	Watts					
Stator tooth Loss [excess] (on load)	0	Watts					
Stator tooth Loss [total] (on load)	278.9	Watts					
Stator tooth Loss [total] (adjusted) (on load)	418.3	Watts					
States inc. Loss Batall (on load)	207.7	Mana					

Geometry Winding Mont Data	Calculation Calculation	netice EE Output D	ata	Graphe 57 Sensitivity Scripting			
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Variable	Value	Units	^	Variable	Value	Units	^
Rotor iron Loss [total] (on load)	14.48	Watts					
Rotor Iron Loss Build Factor	1.5						
Rotor iron Loss [total] (adjusted) (on load)	21.72	Watts					
Shaft Loss [eddy] (on load)	0	Watts					
AC Copper Loss (Hybrid)(Total)	374.2	Watts					
AC Copper Loss (Hybrid)(Left Total)	170.3	Watts					
AC Copper Loss (Hybrid)(Right Total)	203.9	Watts					
AC Copper Loss (Hybrid method) (C1)	26.32	Watts					
AC Copper Loss (Hybrid method) (C2)	27.35	Watts					
AC Copper Loss (Hybrid method) (C3)	43.34	Watts					
AC Copper Loss (Hybrid method) (C4)	63.65	Watts					
AC Copper Loss (Hybrid method) (C5)	90.24	Watts					
AC Copper Loss (Hybrid method) (C6)	123.3	Watts					
AC Copper Loss (flux density) (C1)	0.01867	Tesla					
AC Copper Loss (flux density) (C2)	0.0448	Tesla					
AC Copper Loss (flux density) (C3)	0.0564	Tesla					
AC Copper Loss (flux density) (C4)	0.06834	Tesla					
AC Copper Loss (flux density) (C5)	0.08145	Tesla					
AC Copper Loss (flux density) (C6)	0.09505	Tesla					
AC Copper Loss proportion (C1)	0.5161						
AC Copper Loss proportion (C2)	0.09677						
AC Copper Loss proportion (C3)	0.09677						
AC Copper Loss proportion (C4)	0.09677						
AC Copper Loss proportion (C5)	0.09677						
AC Copper Loss proportion (C6)	0.09677						



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.

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O RMS Current Density	Rotor Lamination Temperature:	20						
Peak Current: 200	Stator Sleeve Temperature:	20	Open Circuit:					
RMS Current: 141.4	Rotor Banding Temperature:	20		que				
RMS Current Density: 7.034	Shaft Temperature:	20	Electromagn	etic Forces				
DC Bus Voltage: 375	Stator Wedge Temperature:	20	On Load:					
Phase Advance [elec deg]: 65	EMagnetics - Thermal Coup	ling:	✓ Torque					
Drive:	Linkage Options:		Torque Spee	ed Curve				
Drive Mode:	O No coupling (default)		Demagnetiza	ation				
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Caston			Parameters:					
Winding Connection:	Glamm		Self and Mut	tual Inductances				
Star Connection (default)	Skew Type:	0	Transient:					
O Delta Connection	None (default)     Stator Ske	ew: U	Sudden shore	t-circuit				
	O Stator O Rotor	es: 1						
Magnetisation: Parallel			Solve	e E-Magnetic Model				
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O Halbach Continuous Ring Array			(	Cancel Solving				
🔿 Halbach Sinusoidal Array								
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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]**.

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Loss Models	ibution							
Loss Variation with Speed:						Copper Loss Variation with Temperature:		
	_coe	f[A] Speed	Dependent Lo	osses		Copper Losses Vary with Temperature		
P[speed] = P[input] x Shaf	t Speed	Shaft Spe	ed[mm]		6000	Winding Temperature at which Stator Copper Losses Input:	65	
L oper	aluci 1	Single	value of Spee	d[REE] [mm]	6000			
				aft in 1 fibrid				
Component	P[Input]	Speed[REF]	coef[A]	W/kg	P[speed]	Loss Variation with Temperature & Load:		
						Losses Vary with Temperature & Load		
Units	Watts	rpm		W/kg	Watts	Contant Torque or Constant Current		
Loss [Stator Copper]	690	6000	0	112.1	690	Constant Torque		
Loss [Stator Copper Freq Comp]	374.2	6000	0	60.79	374.2	Winding Temperature - Tw(i/p):	65	
Loss [Stator Back Iron]	178.2	6000	0	21.57	178.2	Magnet Temperature - Tm(i/p):	65	
Loss [Stator Tooth]	418.3	6000	0	79.77	418.3	Shaft Torque [Nm] (@Pcu defined):	78.02	
Loss [Magnet]	5.144	6000	0	2.618	5.144	Motor Current [Arms] (@Pcu defined);	141.4	
Loss [Embedded Magnet Pole]	19.57	6000	0	3.954	19.57	Torque Constant [Nm/A]	0 5517	
Loss [Rotor Back Iron]	2.146	6000	0	0.4628	2.146	Charle Constant (Minoria)	1	
Loss [Friction - F Bearing]	0	3000	0	0	0	Steady State Torque & Current Multiplier.	1	
Loss [Friction - R Bearing]	0	3000	0	0	0	Rph @Tw(i/p):	0.0115	
Loss [Windage]	0	3000	0	0	0	Magnet Temperature Coefficient Br:	-0.12	
Loss (windage) (Ext Fan)	0	3000	U	U	U	Phases:	3	
						Losses Notes:		
						Type in user Losses notes here		~
	Ch	eck D	ata			<		>
								_
[*					Length	( C2 30 01 02) 25 J 2010	and an also of the state	

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.

<ul> <li>Motor-CAD v10.5.9 (Nissan_LEAF_6_Adva File Edit Model Motor Type Options</li> <li>Geometry Winding Input Data</li> <li>Cooling Losses Advantata</li> <li>Models Geometry Winding Search</li> <li>Winding Proximity Losses:</li> </ul>	Inced.mot)* D Defaults E Calculation Interfaces	DEVELOPMEN idjtors Viev V Tempe Radiation	NT RELEASE v <u>R</u> esults ratures 1	Tools Li <u>c</u> ence Pri Dutput Data   ⊉ Trar nvection   ∰ Housin   � End Space   €	nt <u>H</u> elp Isient Graph   🚰 g Water Jacket   C ; Convergence   a	Sensitivity   🖸	Scripting   😂 Fli   🚰 Duty Cycle 🛦 Miscellaneous	ow Settings	M	laterial da	×
Proximity Losses:	Cuboid Size	s:		Proximity Losses:							
Proximity Loss Model: O None (default)		e: tic (old method (upor upluop)	i)	Cuboid No.	AC Loss Proportion	1					
Hybrid FEA	Automat	tic (default)		1	0.0703425						
O Full FEA (beta version)	Skewed	distribution		2	0.0730798	1					
Bundle Dimensions:	Number of	Cuboids: 6		3	0.115816						
Include Bundle Effect				4	0.170074	-					
Bundle Aspect ratio: 1	Cuboid	Width	Height	6	0.329537						
Variation with temperature	1	3.13516	8.52515			1					
	2	2.35137	2.13129								
Temperature Exponent: 0.5	3	2.35137	2.13129								
	4	2.35137	2.13129								
	5	2.35137	2.13129								
	6	2.35137	2.13129								



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

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<u>File Edit Model Motor Type Options Def</u>	aults Ed <u>i</u> tors <u>V</u> iew <u>R</u> esults Too <u>l</u> s Li <u>c</u> ence <u>P</u> rint <u>H</u> elp		
💽 Geometry 🛛 🌄 Winding 🛛 🕼 Input Data 🛛 👫 Ca	Iculation 🗜 Temperatures 🗄 Output Data 🔯 Sensitivity 🕞 Scripting 🖾 Flow		
- Calculation:	Model Options:		
Calculation Type:	Model Size:		
Steady State	Full model (default)		
⊖ Transient	O Reduced node model		
Solve Thermal Model	Model Type: ③ 3D model (default) 〇 2D model for FEA calibration		
	EMagnetics - Thermal Coupling: Linkage Options: ○ No coupling (default) ④ E-Magnetics Losses → Thermal ○ E-Magnetics ← Thermal Temperatures ○ Iterate to Converged Solution		

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.

Motor-CAD v10.5.9 (Nissan_LEAF_6_Advanced.mot)* DEVELOPMENT RELEASE
Eile Edit Model Motor Type Options Defaults Editors View Results Tools Ligence Print Help
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1



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.

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l	Jnits	secs	secs	•	Watts 🖿	Watts 🖿	Watts 🗈	Watts 🔺	Watts 🗈	Watts 🗈	Watts 🗶	Watts 🔳	Watts 🗶	Watts 🔳	Watts 🖿	rpm 🗈	rpm 🖿
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									Lengt	1	(-146.90,6	56.88)	mm	19 Janua	ry 2018	www.moto	r-design.com



### 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**.

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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

Motor-CAD v10.5.9 (Nissan_LEAF_6_Advanced	mot)* DEVELOPMENT RELEASE	D:	- 🗆 X
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Drive:       DC Bus Voltage: 375         Maximum Modulation Index:       1         Operating Mode:       Image: 1         Image: 1       Image: 1         Operating Mode:       Image: 1         Image: 1       Image: 1         Image: 2       Image: 1         Image: 2       Image: 2         Imag	Losses: Iron Loss Build Factors: Stator [1.5 Rotor: [1.5 Hysteresis: 1 Eddy: 1 Magnet Loss Build Factor: 1 Mechanical Loss: Calculation Type: Neglect (a) User Defined Friction Loss: 150 Friction Loss Exponent: 1 Windage Loss Exponent: 2 Reference Speed: 1E4	Scaling:         Tums / Coll:         Model build reference:         Resistance reference:         Calculation:         Calculation:         Stator Winding Temperature:         Reference temperature:         Reference temperature:         65         Calculation temperature:         Reference temperature:         65         Calculation temperature:         65         Calculation temperature:         65         Magnet Temperature:         65         Magnet Rux Coefficient:         -0.1345	

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.

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Loss Models	ibution					
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	coef[	A] Speed	Dependent Lo	osses		Copper Losses Vary with Temperature
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		Single	value of Spee	d[REF] [rpm]	6000	
Component	P[Input]	Speed[REF]	coef[A]	W/kg	P[speed]	Loss Variation with Temperature & Load
						Losses Vary with Temperature & Load
11-3-	Matta			101.4	10/-11-	Contant Torque or Constant Current
Units	5000	rpm 6000	0	912.2	5000	Constant Torque Constant Current
Loss [Stator Copper]	0	6000	0	0	0	Winding Temperature - Tw(i/p): 65
Loss [Stator Back Iron]	0	6000	0	0	0	Magnet Temperature - Tm(i/p): 65
Loss [Stator Tooth]	0	6000	0	0	0	Shaft Torque [Nm] (@Pcu defined); 78.02
Loss [Magnet]	0	6000	0	0	0	Motor Current [Ams] (@Pcu defined): 141.4
Loss [Embedded Magnet Pole]	0	6000	0	0	0	Torque Constant [Nm/A]
Loss [Rotor Back Iron]	0	6000	0	0	0	Chandre Constante [Vinit/A]
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Loss [Windage]	0	3000	0	0	0	Magnet Temperature Coefficient Br: -0.12
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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)

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3600	)	68.20	700	0	
3601	L	81.85	700	0	
5400	)	81.85	700	0	
5401	L	95.49	700	0	
7200	)	95.49	700	0	
7201	L	109.1	700	0	
1080	00	109.1	700	0	
1080	)1	0	700	0	



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

Parameter Drive Cycle Data Data Type	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**.

Eile       Edit       Model       Model       Model       Ligence       Print       Help         Model Build       Mass:       Calculation       Electromagnetic       Thermal       Duty Cycle       Deparating Point       Calibration       Settings         Vehicle       Model       Mass:       1521       Frontal Area (m?):       2.29       Wheel Radius (m):       0.3       Image: Calculation       Settings         Rolling Resistance Coefficient:       0.007       Drag Coefficient:       0.28       Mass Correction Factor:       1.04       Image: Calculation       Calculation       Calculation       Completed       Completed       Completed       Completed       Completed       Calculate       Calculate </th
✓ Model Buld       M Calculation       Image: Bectromagnetic       Image: Themal       Image: Duty Cycle       Image: Operating Point       Image: Calculation       Image: Calculation         Vehicle Model:       Mass:       1521       Frontal Area (m?):       2.29       Wheel Radius (m):       0.3         Rolling Resistance Coefficient:       0.007       Drag Coefficient:       0.28       Mass Correction Factor:       1.04         Air Density:       1.225       Final Drive Ratio:       7.938       Motoring Torque Ratio:       1         Generating Torque Ratio:       1       Max.       Torque:       500       Max.       2E4
Vehicle Model:       Mass:       1521       Frontal Area (m <sup>2</sup> ):       2.29       Wheel Radius (m):       0.3         Rolling Resistance Coefficient:       0.007       Drag Coefficient:       0.28       Mass Correction Factor:       1.04         Air Density:       1.225       Final Drive Ratio:       7.938       Motoring Torque Ratio:       1         Generating Torque Ratio:       1       Max. Torque:       500       Max. Speed:       2E4
Mass:       1521       Frontal Area (m <sup>2</sup> ):       2.29       Wheel Radius (m):       0.3         Rolling Resistance Coefficient:       0.007       Drag Coefficient::       0.28       Mass Correction Factor:       1.04         Air Density:       1.225       Final Drive Ratio:       7.938       Motoring Torque Ratio:       1         Generating Torque Ratio:       1       Max. Torque:       500       Max. Speed:       2E4
Rolling Resistance Coefficient:       0.007       Drag Coefficient:       0.28       Mass Correction Factor:       1.04         Air Density:       1.225       Final Drive Ratio:       7.938       Motoring Torque Ratio:       1         Generating Torque Ratio:       1       Max. Torque:       500       Max. Speed:       2E4
Air Density:       1.225       Final Drive Ratio:       7.938       Motoring Torque Ratio:       1         Generating Torque Ratio:       1       Max. Torque:       500       Max. Speed:       2E4
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Standard Drive Cycle:     Import External Data:       US06     Data Type:       Time(s), Torque(Nm), Speed (rpm)       File:         Nissan LEAF data Viissan LEAF Custom Transient.dat
Load Generate Load Results Viewer

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**.

Dotor-(	CAD v10.5.9 <u>M</u> odel N	) (Nissan Ao <u>t</u> or Tyj	_LEAF_6_A	Advanced.m ons <u>D</u> efaul	iot)* DEVELO	DPMENT RI View F	ELEASE Sesults To	o <u>l</u> s Li <u>c</u> ence	<u>P</u> rint	Help							-	· 🗆	×
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3	3601	1700	100	538.6	266	219.7	489.6	5.274 c 700	2.169	23.22	52.5	52.5	0	0	7000	7000		65	+
5	5401	1/33	100	712.6	351.5	222.3	519.4	6.708	2.41	26.22	52.5	52.5	0	0	7000	7000		65	+
6	7200	1799	180	917.6	453.2	221.7	545.7	8.955	2.817	30.07	52.5	52.5	0	0	7000	7000		65	
7	7201	1	1	917.6	453.2	221.7	545.7	8.955	2.817	30.07	52.5	52.5	0	0	7000	7000		65	
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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.

Motor-CAD v10.5.9 (Nissan LEAE	6 Advanced mot)* [		T REI EASE	_		×
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Ambient Temperature (default)						
Steady State Temperatures						
O Previous Transient Temperatures	(if same network)					
Whole machine at specified temp	perature					
Machine components at specified	d temperatures					



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 v <u>E</u> dit <u>M</u> ode	10.5.9 (Nissa el Mo <u>t</u> or Tj	n_LEAF_6_Adv ype <u>O</u> ptions	anced.mot)* DEVI <u>D</u> efaults Ed <u>i</u> to	ELOPMENT RELEASE ors <u>V</u> iew <u>R</u> esults Too <u>l</u> s	Li <u>c</u> ence <u>P</u> rint <u>H</u> elp			-		;
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				Rotor Surface	Rotor Surface		Circle 🗸	Aqua	$\sim$	
				Shaft OHang [F]	Shaft OHang [F]		Diamond 🗸	Silver	$\sim$	
				Shaft OHang [R]	Shaft OHang [R]		Rectangle 🗸	Silver	$\sim$	
				Shaft [Active]	Shaft [Active]		Cross 🗸	Silver	$\sim$	
				Shaft [Front]	Shaft [Front]		DiagCross 🗸	Silver	$\sim$	
				Shaft [Rear]	Shaft [Rear]		Star 🗸	Silver	$\sim$	
				SlotCentre (CT)	SlotCentre (CT)		Diamond 🗸	LtGreen	$\sim$	
				SlotCentre (C2)	SlotCentre (C2)		Rectangle 🗸	LtGreen	$\sim$	
				SlotCentre (C3)	SlotCentre (C3)		Circle 🗸	LtGreen	$\sim$	
				SlotCentre (C4)	SlotCentre (C4)		Triangle 🗸	LtGreen	$\sim$	
				SlotCentre (C5)	SlotCentre (C5)		DownTriangle 🗸	LtGreen	$\sim$	
				SlotCentre (C6)	SlotCentre (C6)		Star 🗸	LtGreen	$\sim$	
				Stator Back Iron	Stator Back Iron		Diamond 🗸	Red	$\sim$	
				Stator Surface	Stator Surface		Rectangle 🗸	Red	$\sim$	
				Stator Tooth (C1)	Stator Tooth (C1)		DiagCross 🗸	Red	$\sim$	
				Stator Tooth (C2)	Stator Tooth (C2)		Star 🗸	Red	$\sim$	¥
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## 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 <u>https://www.motor-design.com/publications/tutorials/</u>.