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Motor Design Software by Motor Design Engineers

Motor Design Ltd
4 Scotland Street | Ellesmere | Shropshire | SY12 0EG | UK
Tel. +44 (0)1691 623305

Open Source Electric Motor Models for Commercial EV & Hybrid Traction Motors

Dr David Staton
Dr James Goss

CWIEME 2017 (Berlin)

Topics:

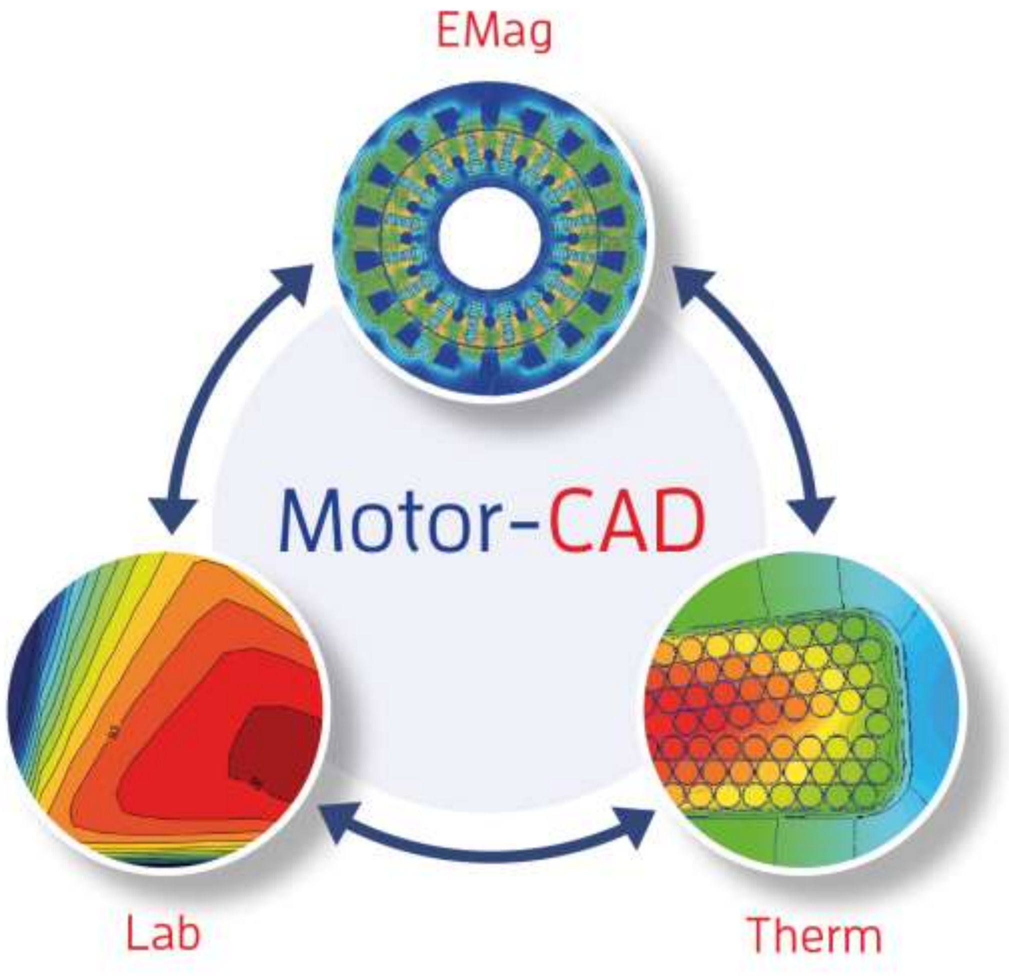
- Introduction
  - Motor Design Ltd (MDL)
  - Teardown Analysis and Benchmarking
  - Open Source Electric Motor Models
- Open Source Motor Examples
  - Nissan LEAF
  - Honda ACCORD
  - TESLA Model S
  - Toyota PRIUS
  - Chevrolet Volt
  - BMW i3
  - ………….
- Electromagnetic & Thermal Model Validation Procedure for PMSMs

Motor Design Ltd (MDL)

- MDL was founded in 1998
- Develop Motor-CAD software for electric motor design
- High level of customer support and engineering know-how
- Motor design software developed by motor engineers
- Also provide motor design consultancy & training
- Involved in large government funded research projects:
  - **Evoque_e** / **Concept_e** – Electric vehicle development with Jaguar-Land-Rover (JLR)
  - **HVEMS** – High Volume E-Machines Manufacturing Supply research. Make-Like-Production prototyping facility in the UK with Jaguar-Land-Rover (JLR)
  - **ELETAD** – Helicopter electric tail rotor
  - **HERRB** – Helicopter main rotor brake/generator
  - …………
- Consultancy and funded projects aid in Motor-CAD software development
- ANSYS Strategic Partners with Motor-CAD links to ANSYS software

Motor-CAD Software

- Motor-CAD makes it easy and fast to do motor design and analysis by having three integrated modules:
  - **EMag**: A fast 2D finite element module for accurate electromagnetic and electrical performance prediction
  - **Therm**: Combined lumped circuit and finite element thermal analysis for motor cooling system optimisation
  - **Lab**: Virtual testing module that includes the fast calculation of efficiency and loss maps and transient thermal simulation of complex duty cycles



Teardown and Benchmarking Studies

- Teardown or Reverse Engineering analysis gives information on how an existing motor is manufactured

- Reverse Engineering benefits from electromagnetic and thermal simulation to gain a full understanding of a teardown motors performance
  - Also helps identify difficult to measure design parameters like magnets material, winding connection, etc.

- Benchmarking allows comparative design improvement studies based on existing state of the art motor solutions

- Such analysis is also useful for motor design software providers to validate and demo the design workflow

Teardown and Benchmarking Studies

- There is much open source teardown information for commercial electric and hybrid traction motors
  - Most prolific in this area is the Oak Ridge National Labs (ORNL) in USA

- Most OEM's and Tier 1 companies involved in EV traction also do their own teardown analysis

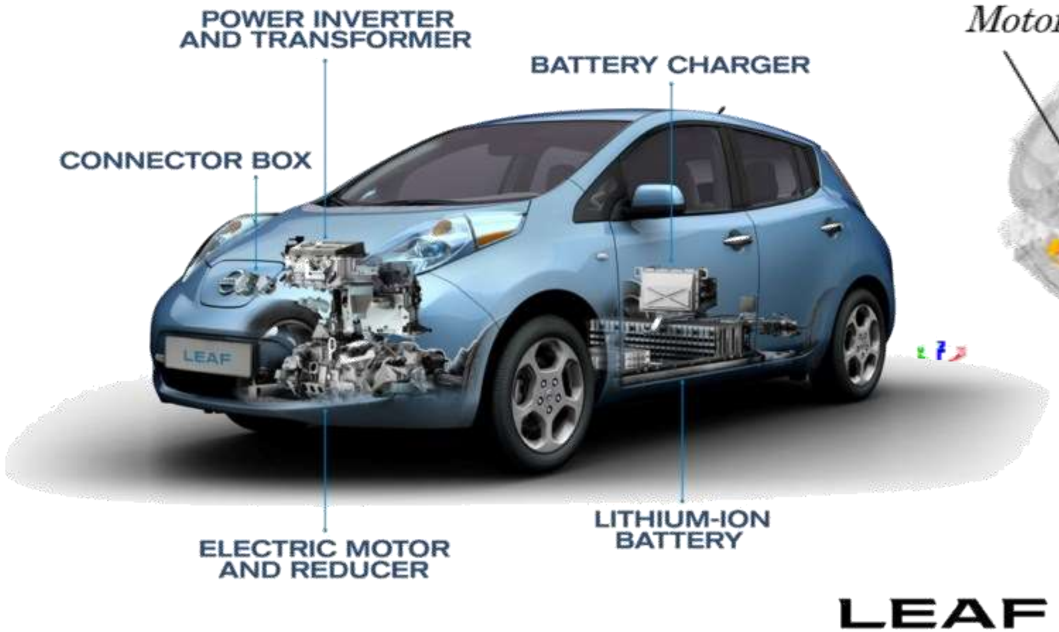
- Commercial benchmarking and teardown analysis reports also available
  - BMW i3
    - https://estore.ricardo.com/wp-content/uploads/2015/11/2014MY-BMW-i3-Benchmarking-Overview_-v1.2-PREVIEW.pdf
  - TESLA Model S
    - https://estore.ricardo.com/wp-content/uploads/2015/09/Tesla-Model-S-60_Benchmarking-Overview_v2-Preview.pdf

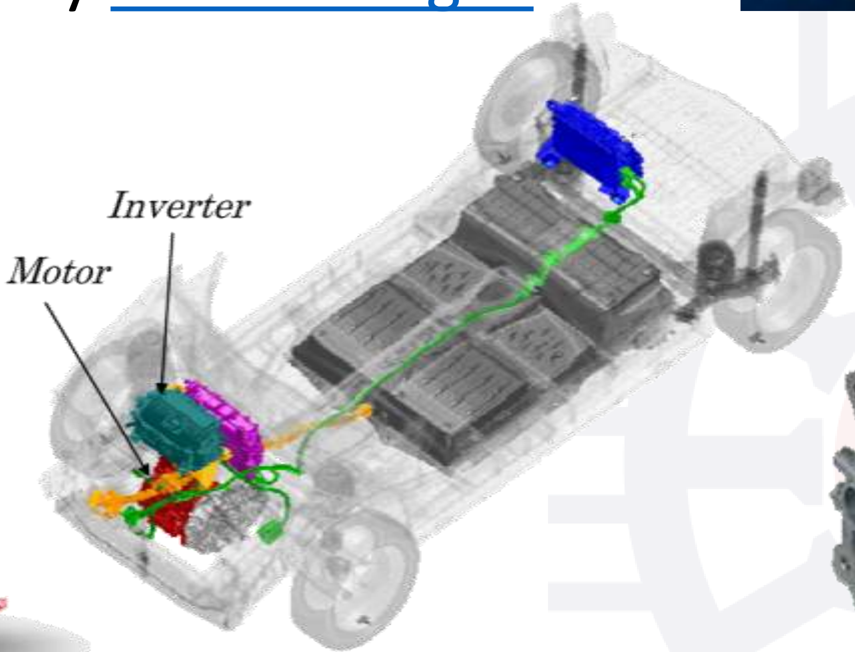
Open Source Electric Motor Models

- In this presentation we will give examples of electric motor models that have been developed by MDL using open source data
- The motors we will show are:
  - Nissan LEAF 2012 Model
  - TESLA Model S
  - Honda ACCORD 2005 Model
  - Toyota Prius 2004 Model
  - Chevrolet Volt
  - BMW i3

Modelling the Nissan LEAF Motor

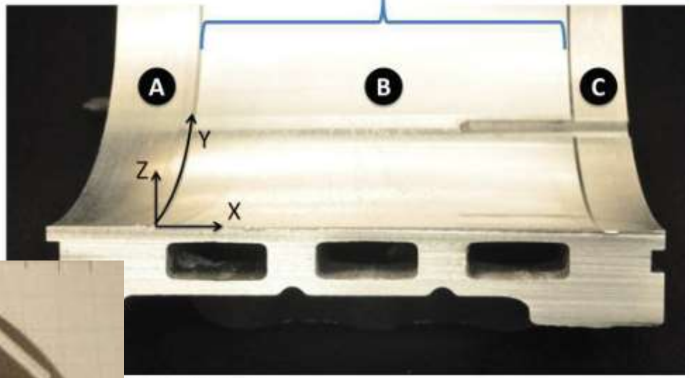
- Much data available on web relating to the Nissan LEAF EV Traction Motor (2012 LEAF)
  - Oak Ridge National Laboratory www.ornl.gov
  - SAE International
  - ……..



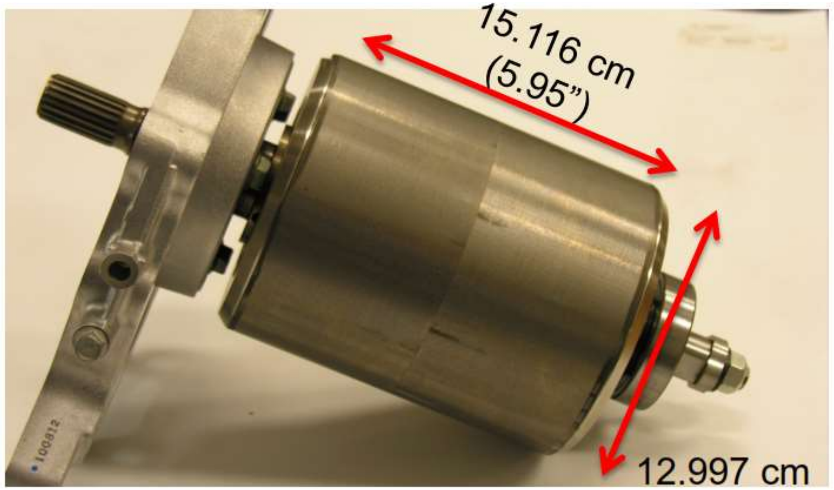


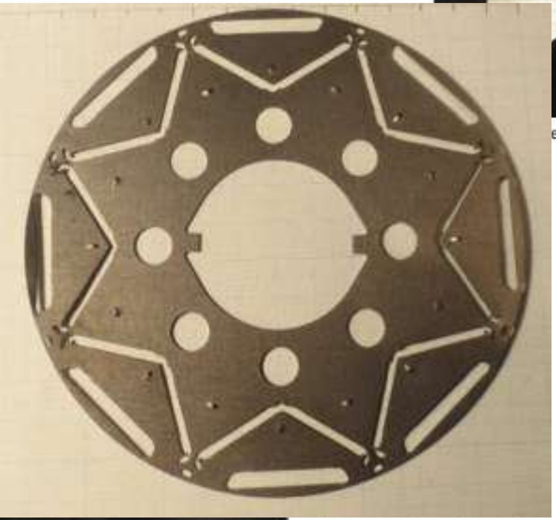
ORNL LEAF Motor Data

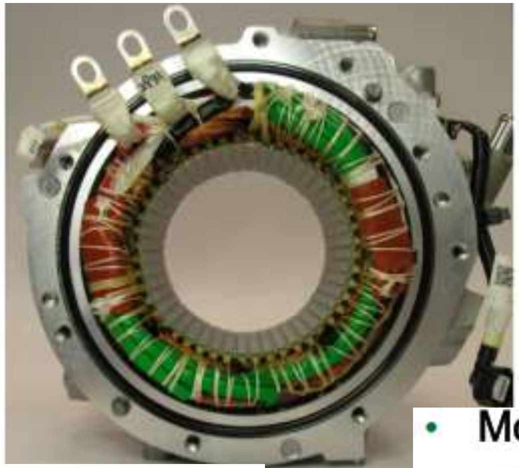
- Here we see the stator, winding, rotor and housing

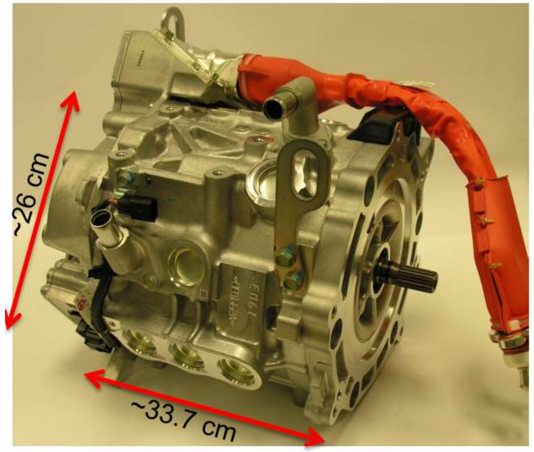


evin Bennion, NREL





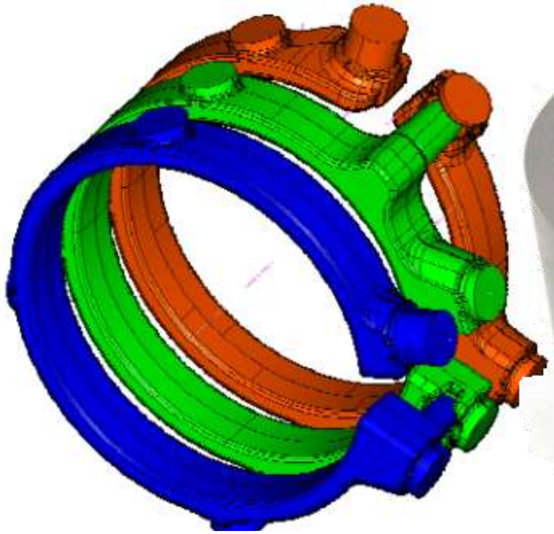




- Motor dimensions
  - Stator OD: 198.12 mm
  - Stator bore: 130.96 mm
  - Stator stack: 151.38 mm
  - Rotor OD: 129.97 mm
  - Rotor stack: 151.16 mm
  - Rotor mass: 16.45 kg (with magnets)
  - Magnet only mass: 1.895 kg
- Winding design
  - 48 slots, 8 pole, 3 phase, SPP=2
  - NIH = 20 of #20 AWG

SAE International LEAF Motor Data

- Here we see the water jacket, stator and rotor



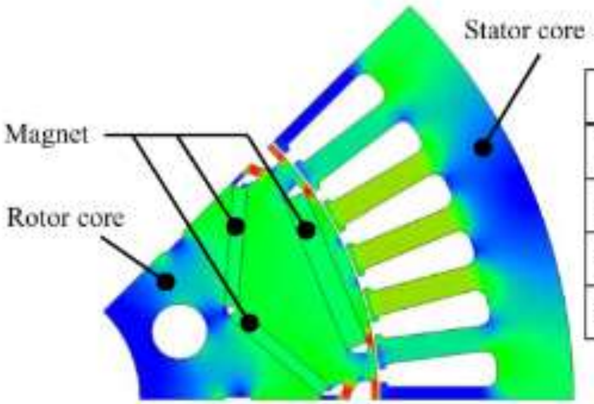


SAE International

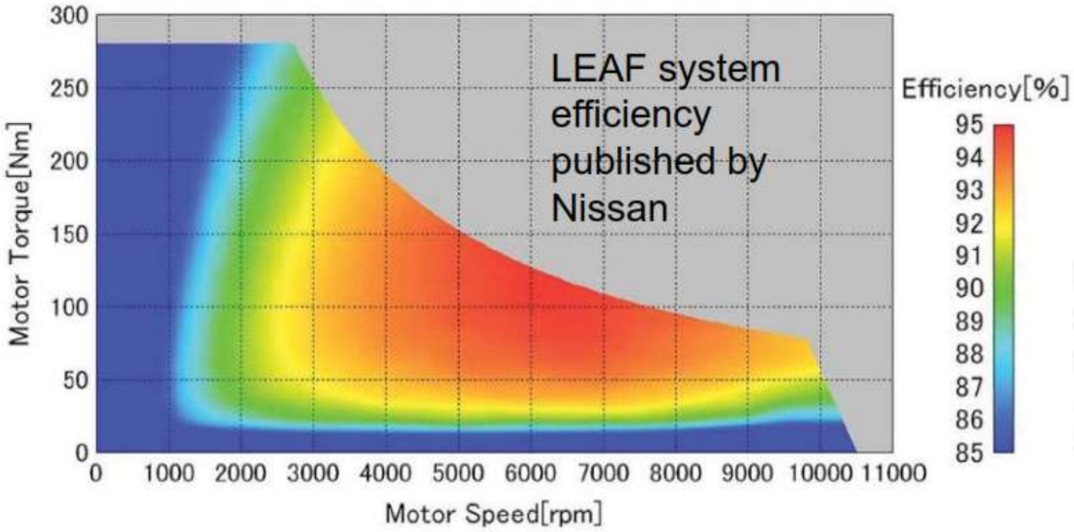
Development of High Response Motor and Inverter System for the Nissan LEAF Electric Vehicle

2011-01-0350
Published
04/12/2011

Yoshinori Sato, Shigeaki Ishikawa, Takahito Okubo, Makoto Abe and Katsunori Tamai
Nissan Motor Co., Ltd.



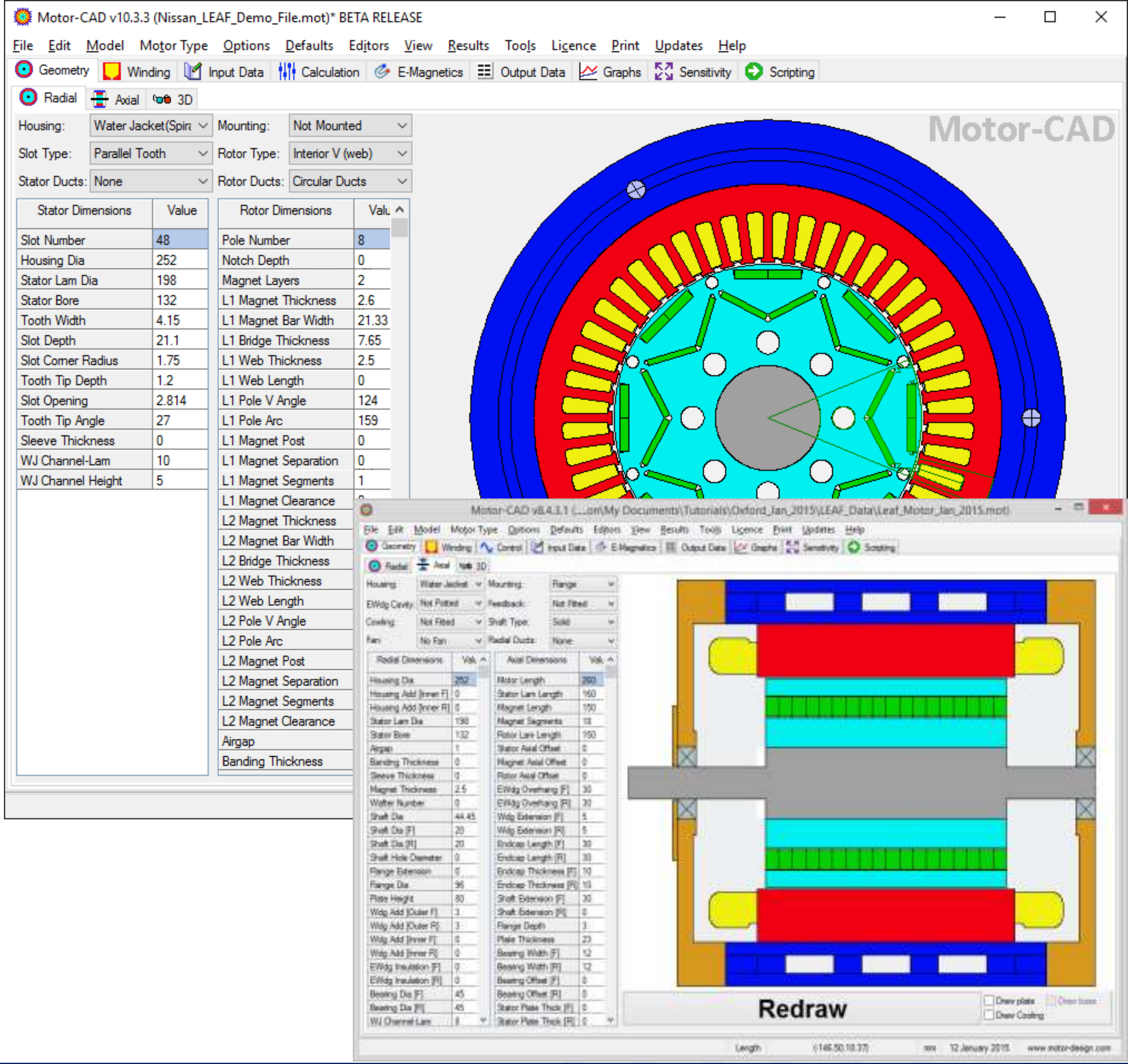
Performance	Nissan LEAF
Max. torque	280 Nm
Max. power	80 kW
Top motor speed	10,390 rpm
Motor weight	Approx. 58 kg



"Power from Within", Nissan LEAF Special Edition of SAE Vehicle Electrification, p. 17, Feb. 23, 2011.

LEAF Geometry

- ➢ Motor dimensions from teardown analysis put into motor models
- ➢ 48-slot, 8-pole Interior Permanent Magnet (IPM) Brushless Permanent Magnet (BPM) Design



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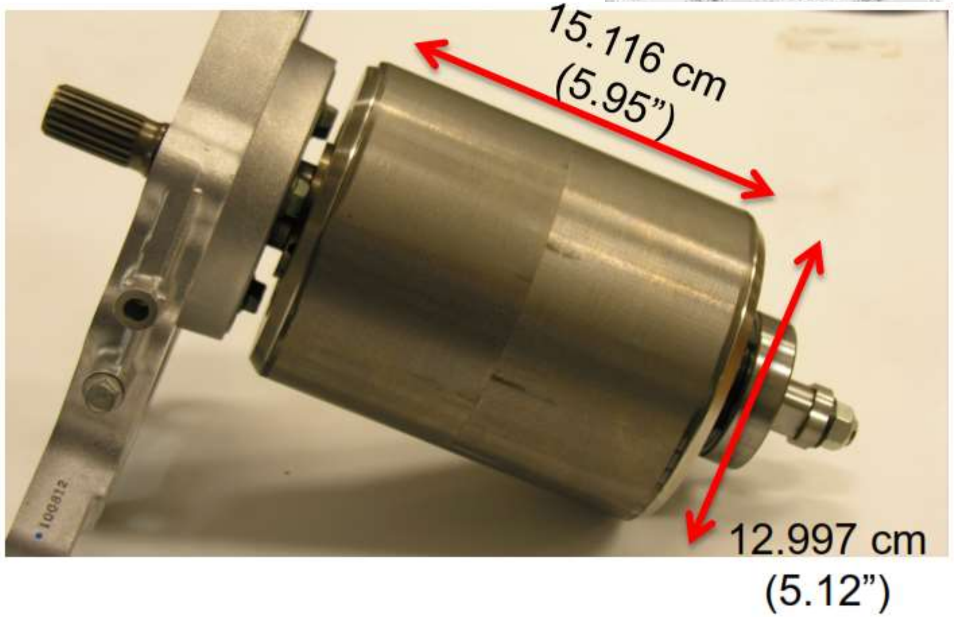
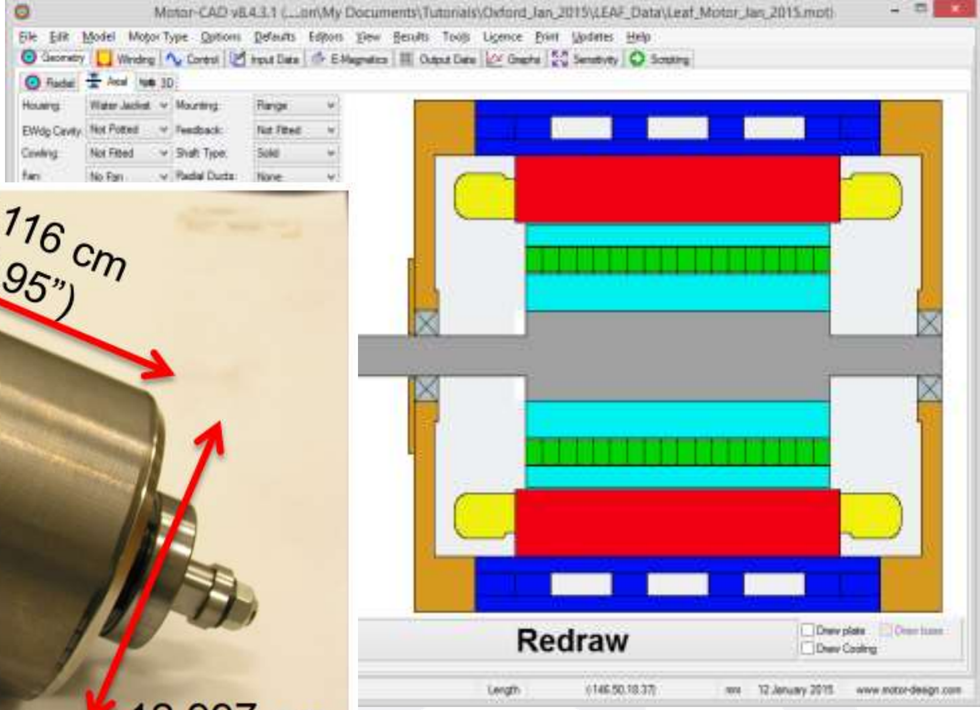
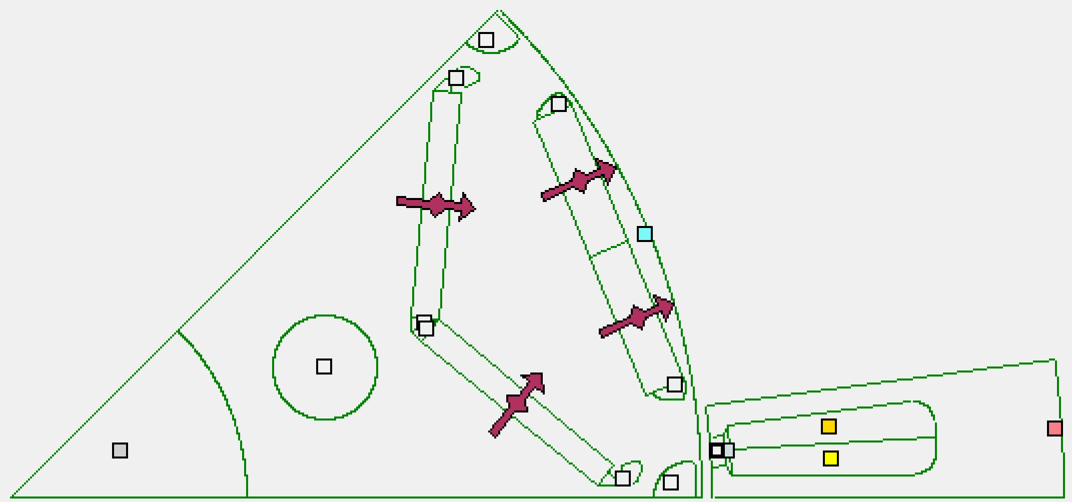
- Winding design
  - 48 slots, 8 pole, 3 phase, SPP=2
  - NIH = 20 of #20 AWG

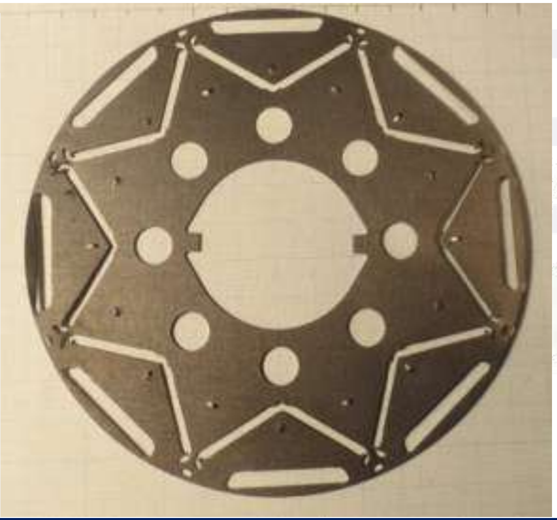
LEAF Geometry (Stator & Rotor)

- Two magnet layers:
  - One flat magnet and one v-magnet
  - Axial segmentation to reduce magnet eddy current losses



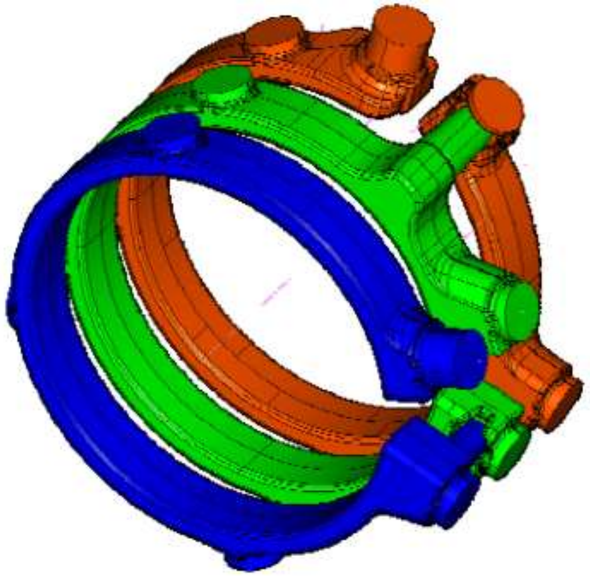


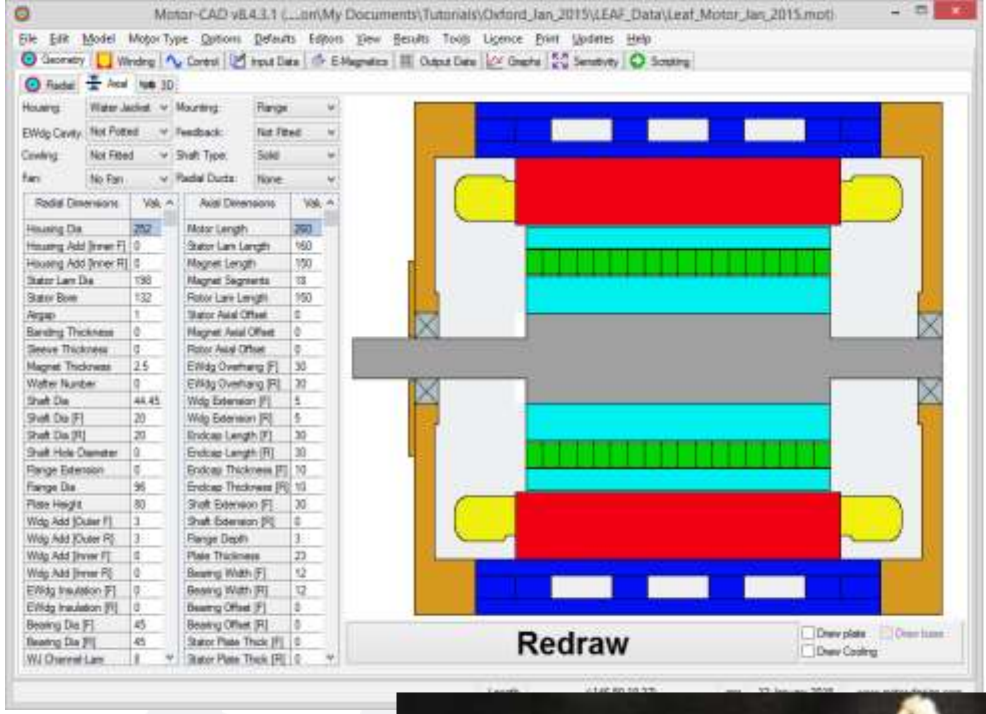


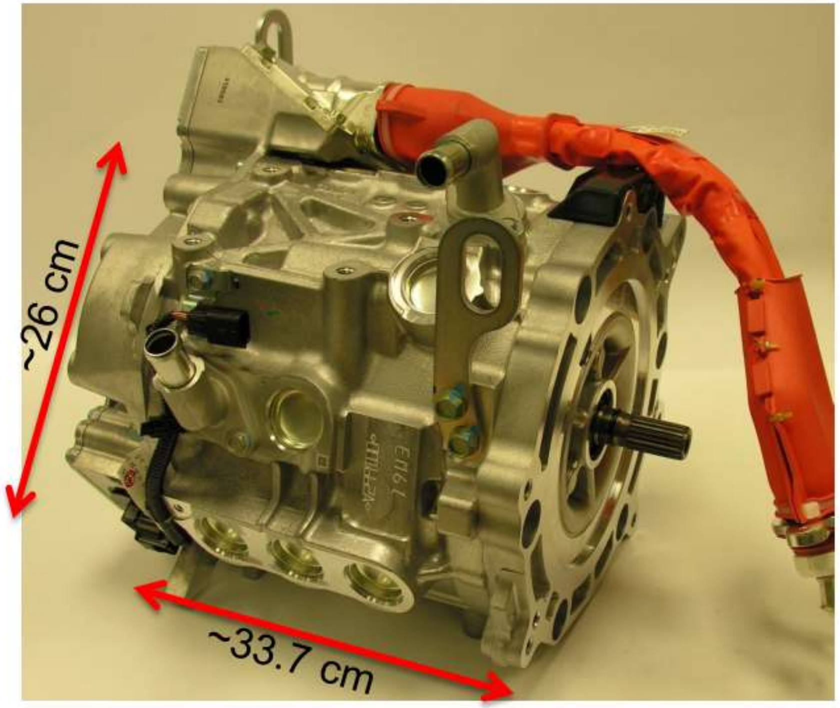


LEAF Geometry (Housing)

- 3 circumferential channels in housing act as a water jacket and forms the main cooling for the LEAF motor







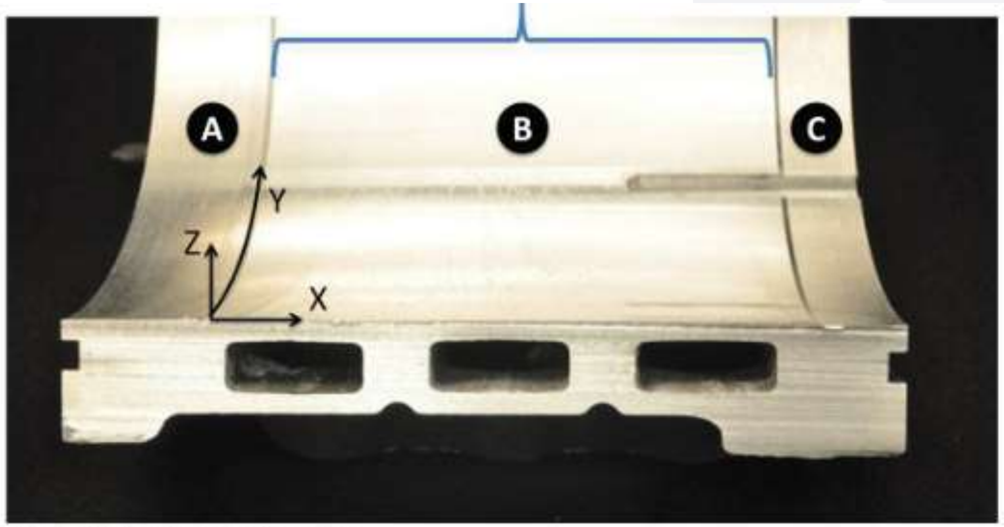


Photo Credit: Kevin Bennion, NREL

LEAF Winding Design

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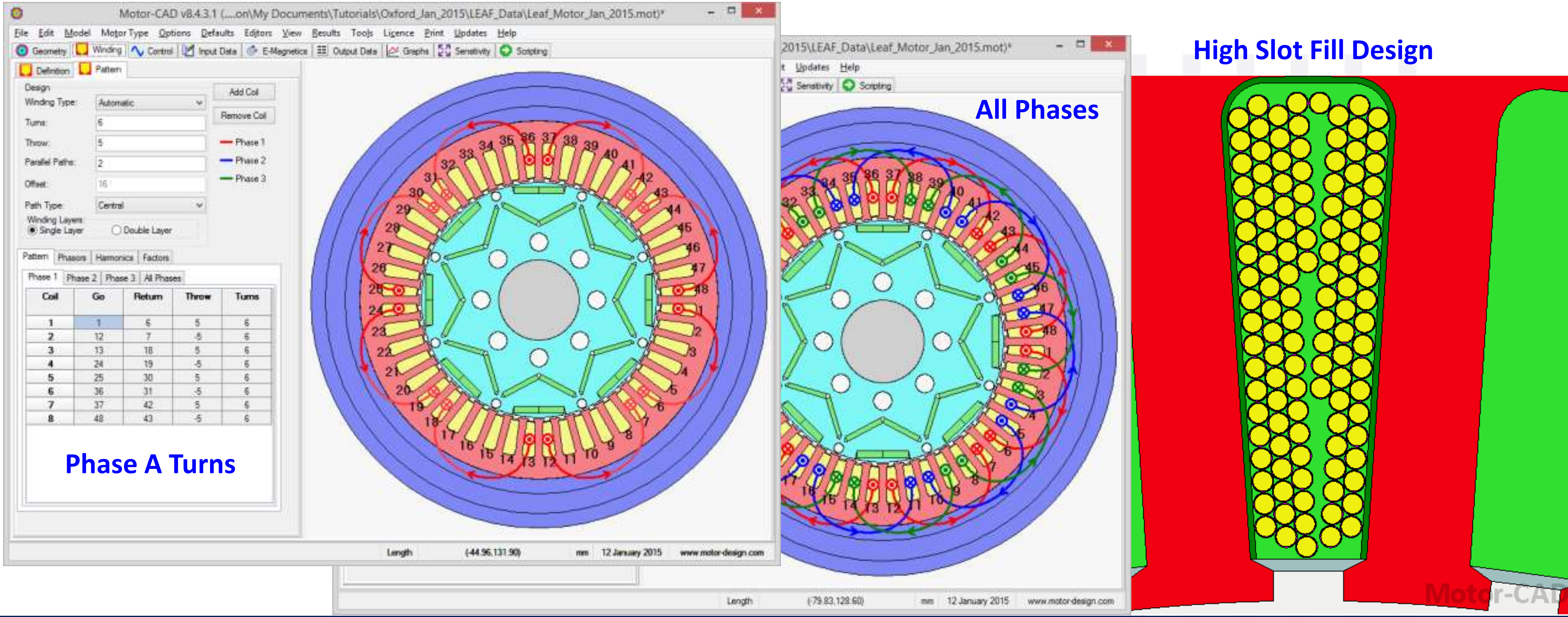
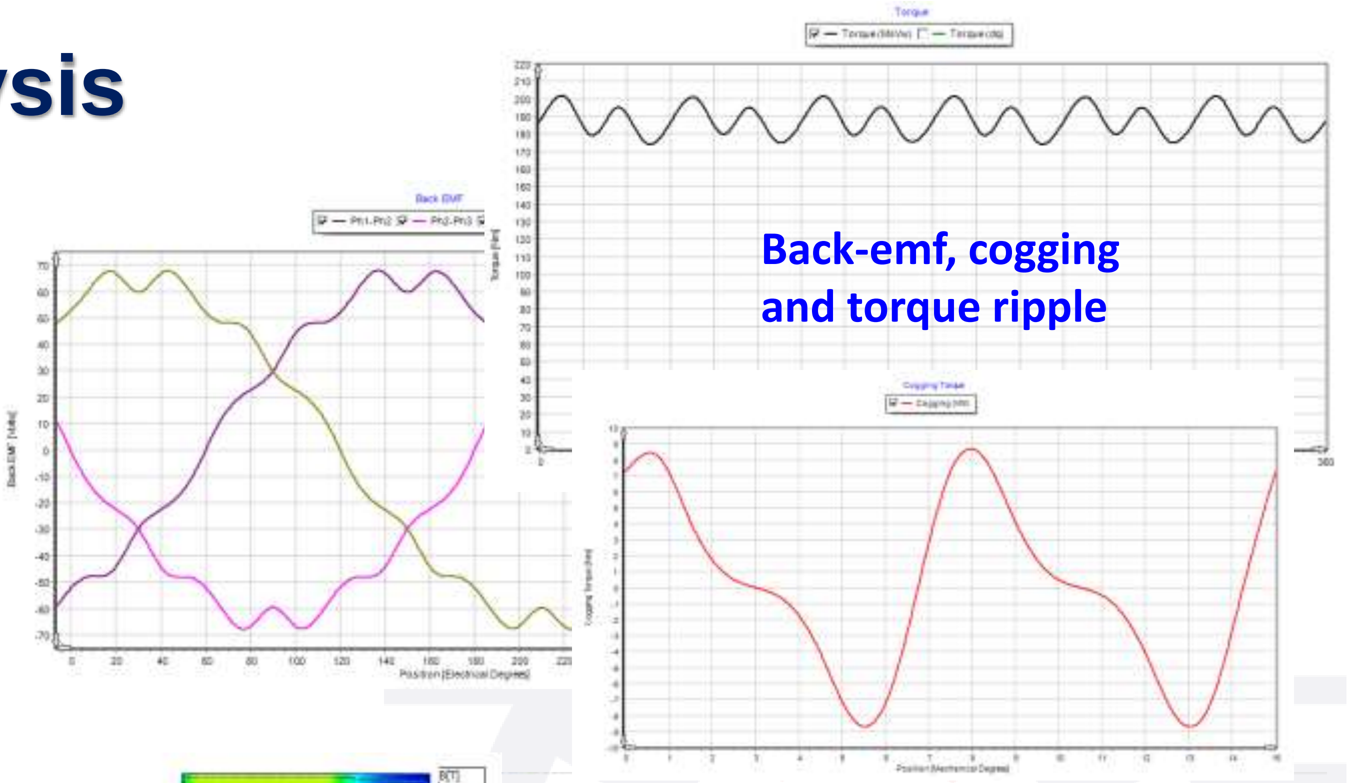
- 48 slots with distributed winding
- High slot fill as shown below

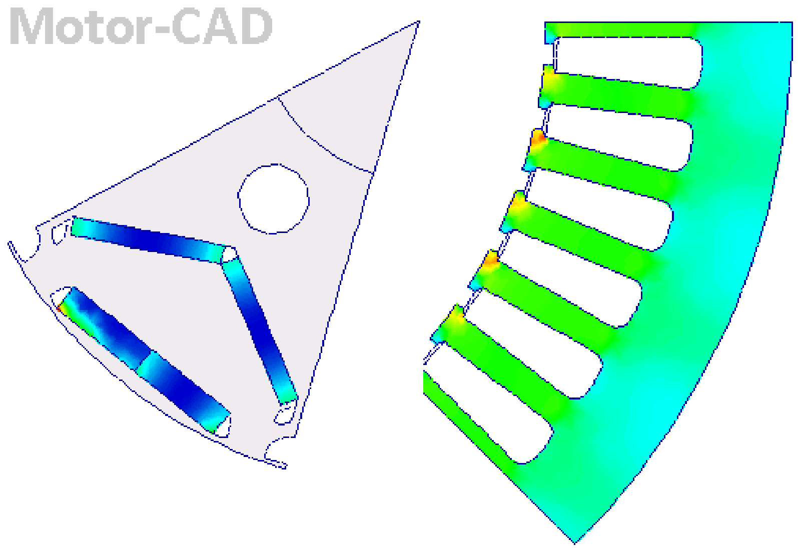


LEAF Electromagnetic Analysis

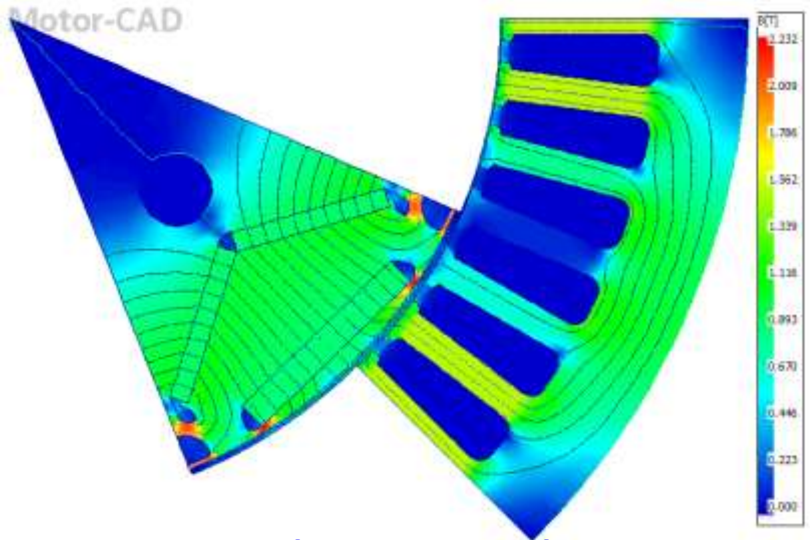
- We can calculate the open circuit and on-load electromagnetic performance and compare with test data
- This helps identify difficult to measure design quantities like magnet grade



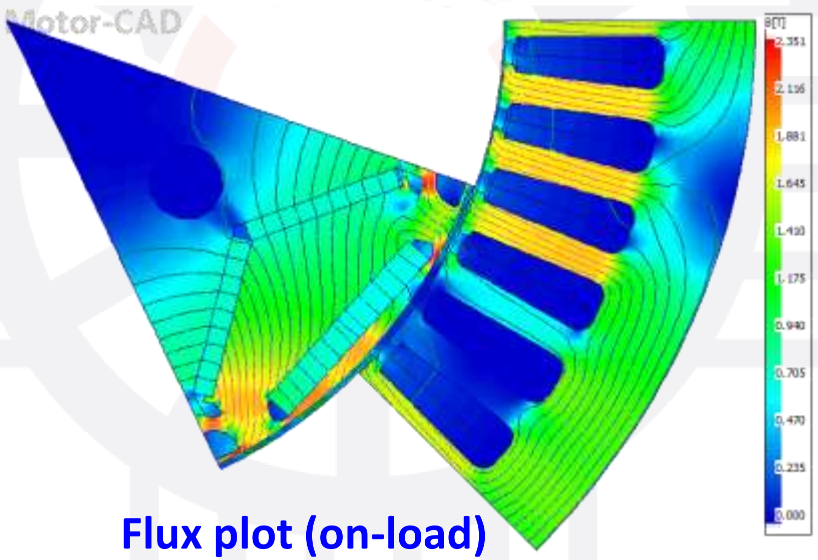
Back-emf, cogging and torque ripple



Loss density plots



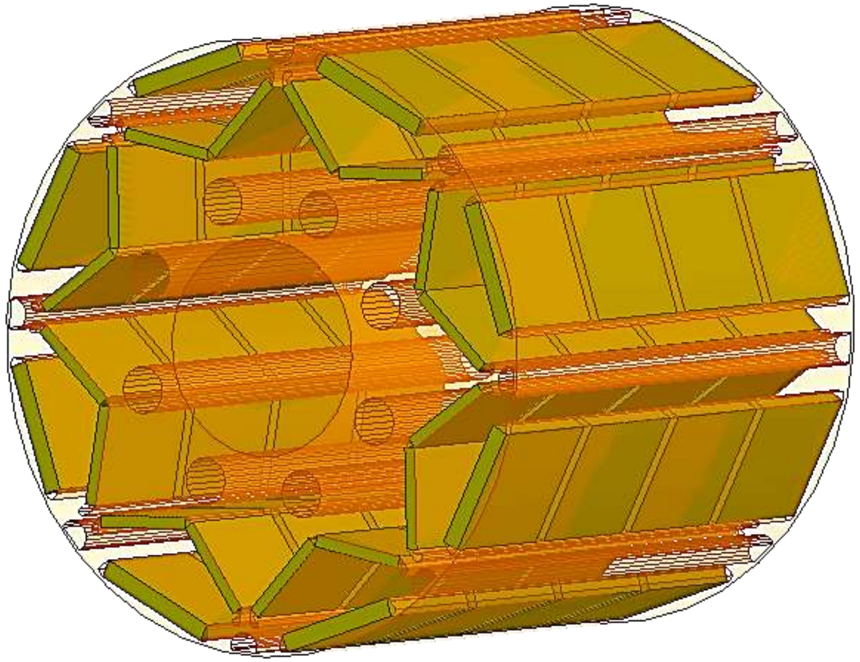
Flux plot (open-circuit)



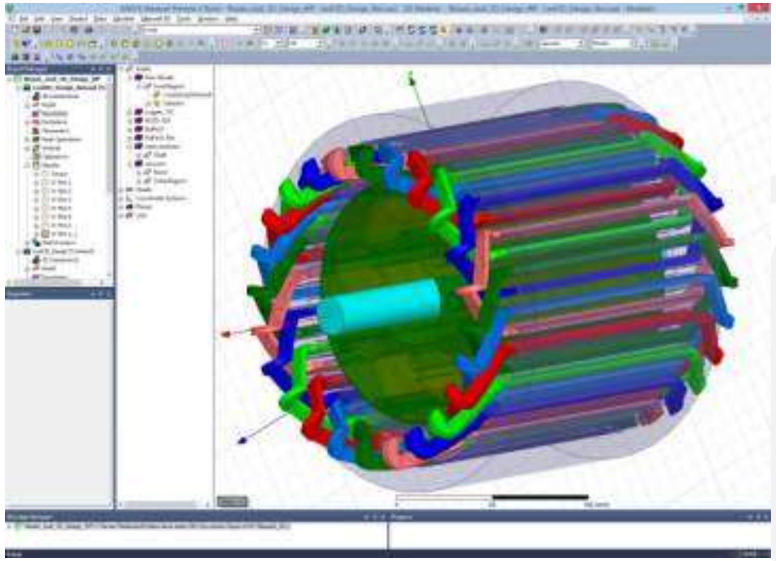
Flux plot (on-load)

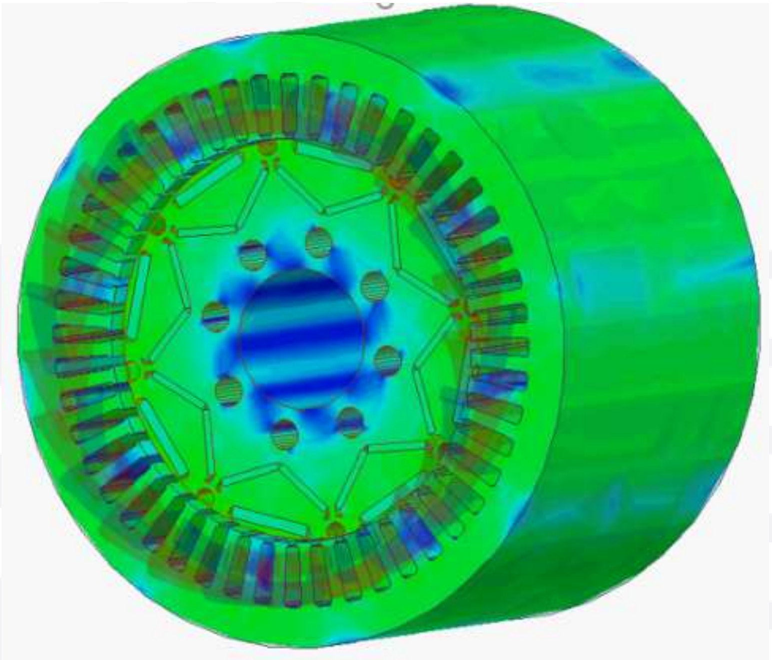
LEAF Electromagnetic Analysis (3D)

- We can calculate 3D electromagnetic effects such as end leakage and magnet loss reduction due to axial segmentation



Axial split PM topology to reduce eddy effects

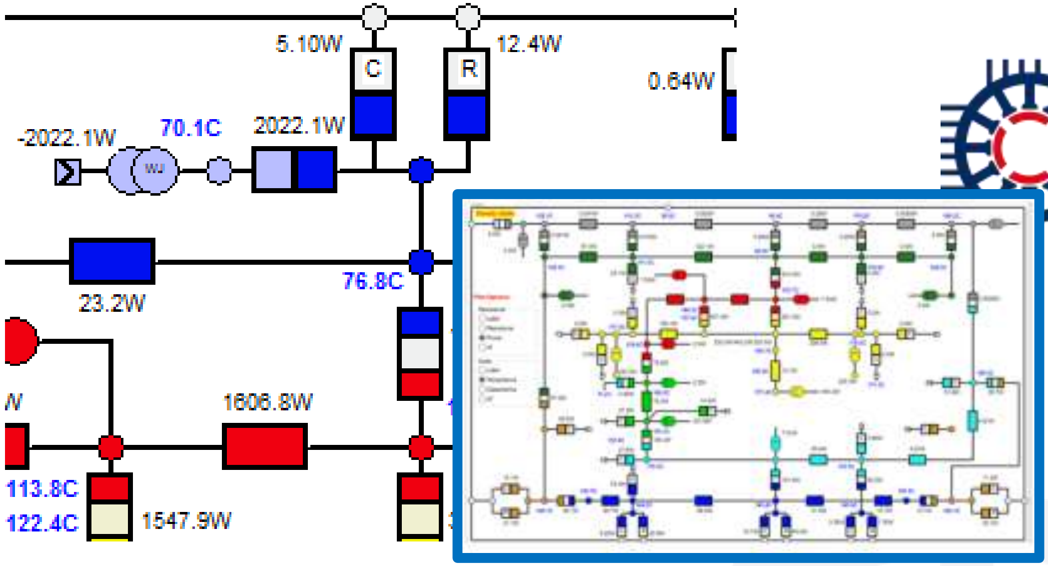




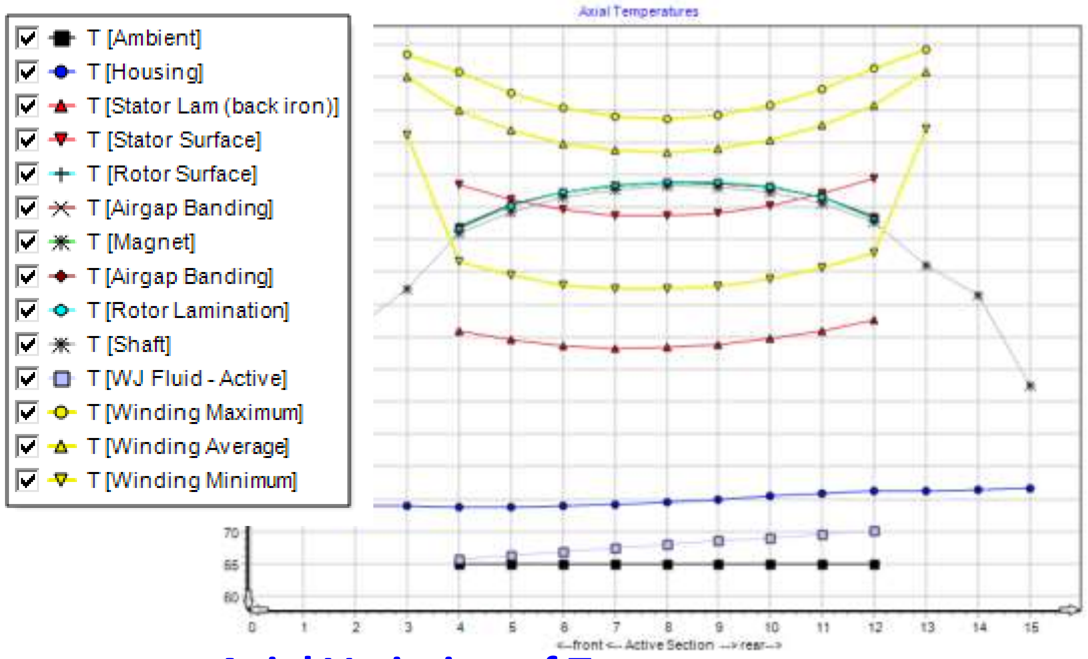
Field distribution at rated load condition

LEAF Thermal Analysis

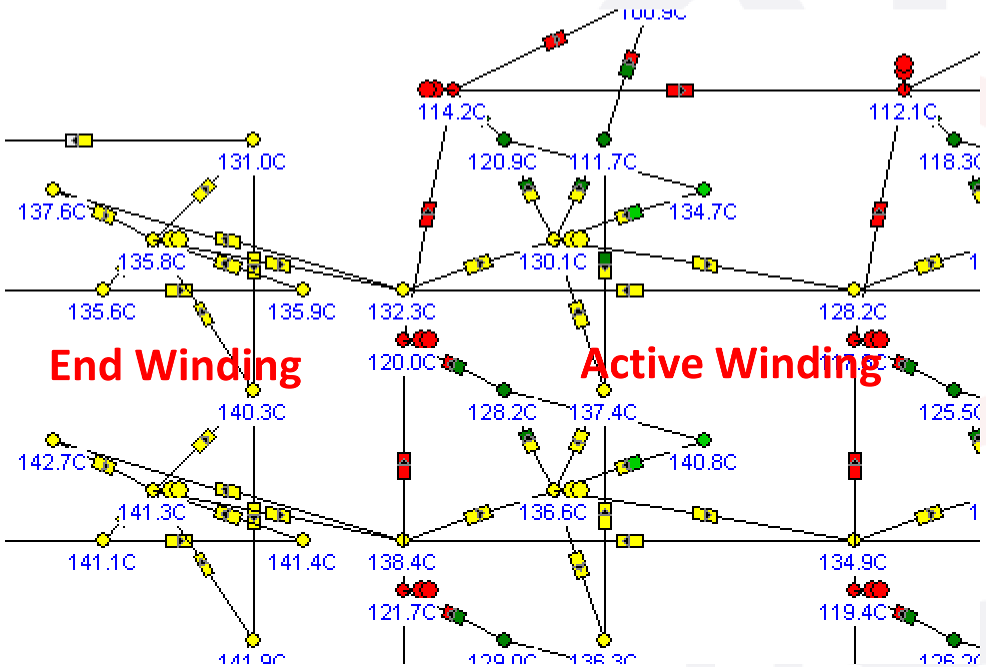
- We can predict the steady-state thermal performance using a lumped circuit thermal model
  - Predicts heat transfer and fluid flow
  - Near instantaneous steady-state calculation as not FEA or CFD



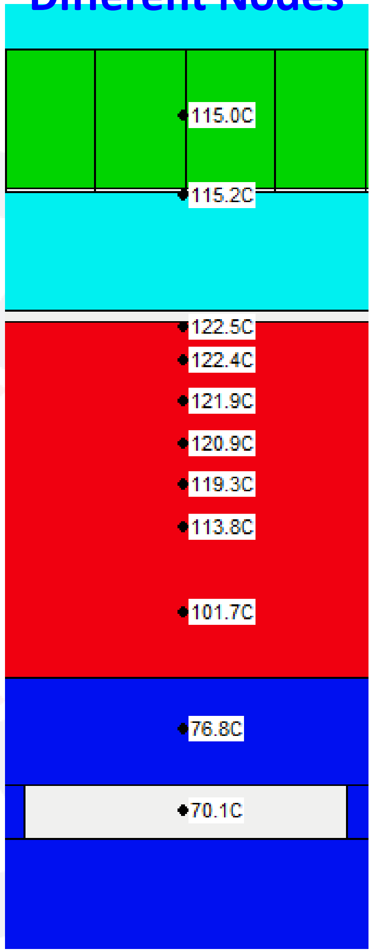
Simplified and actual thermal resistance network



Axial Variation of Temperature



Temperatures at Different Nodes



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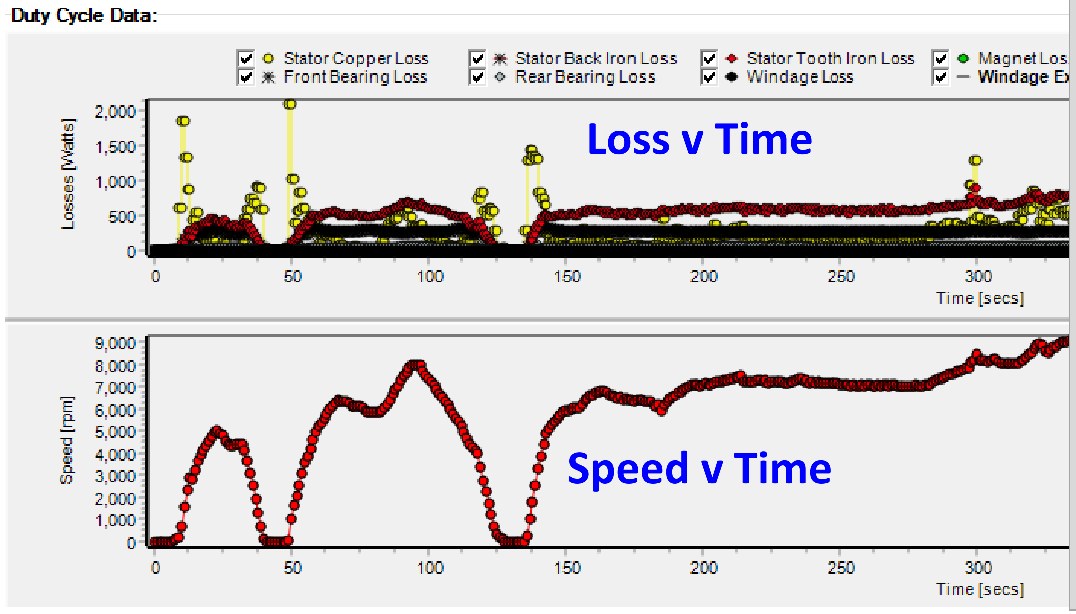
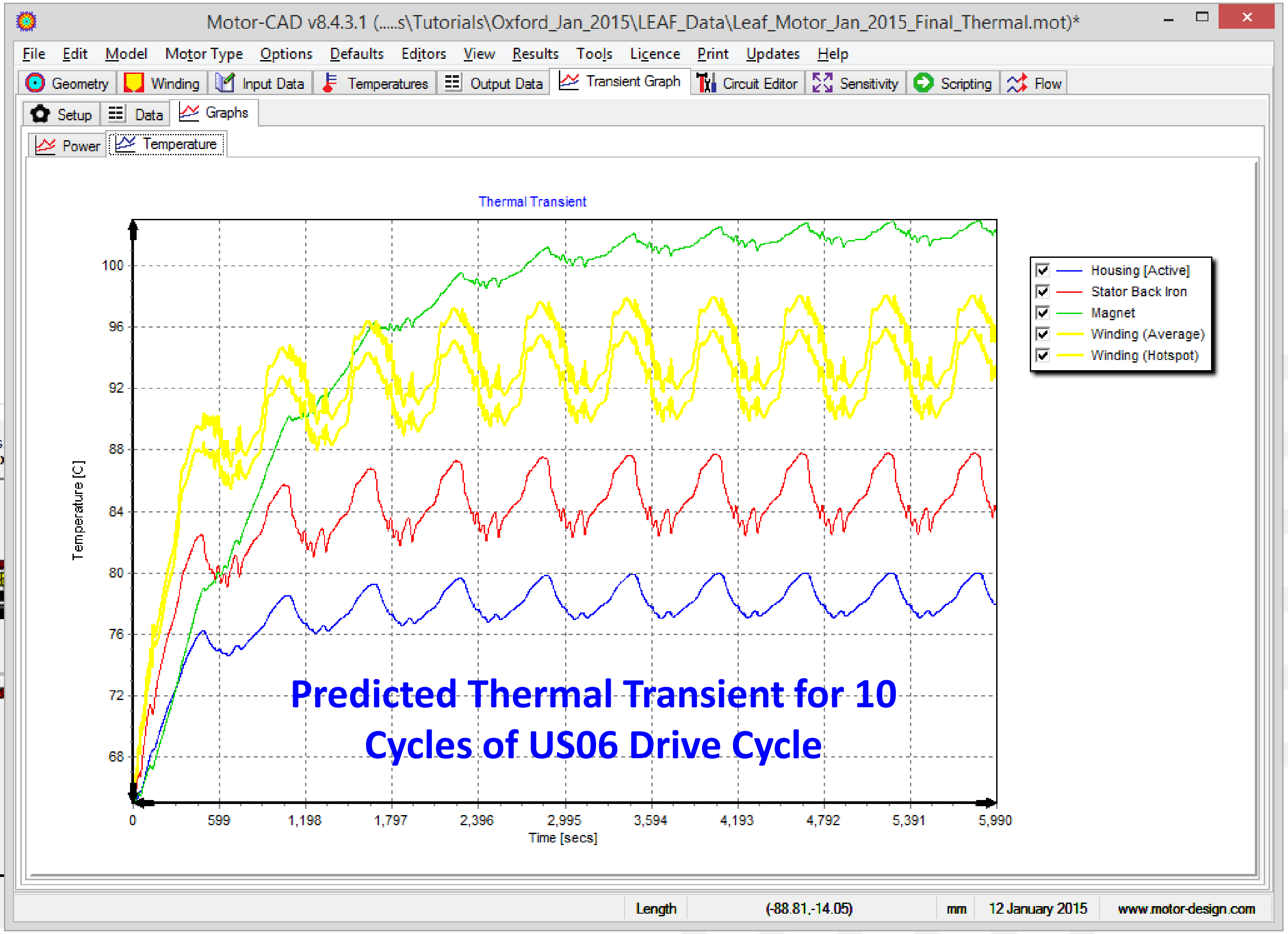
LEAF Thermal Analysis (Lumped Circuit)

- We can quickly predict the transient thermal performance using a very fast lumped circuit thermal model
  - Seconds to calculate the thermal transient even if a very complex duty cycle



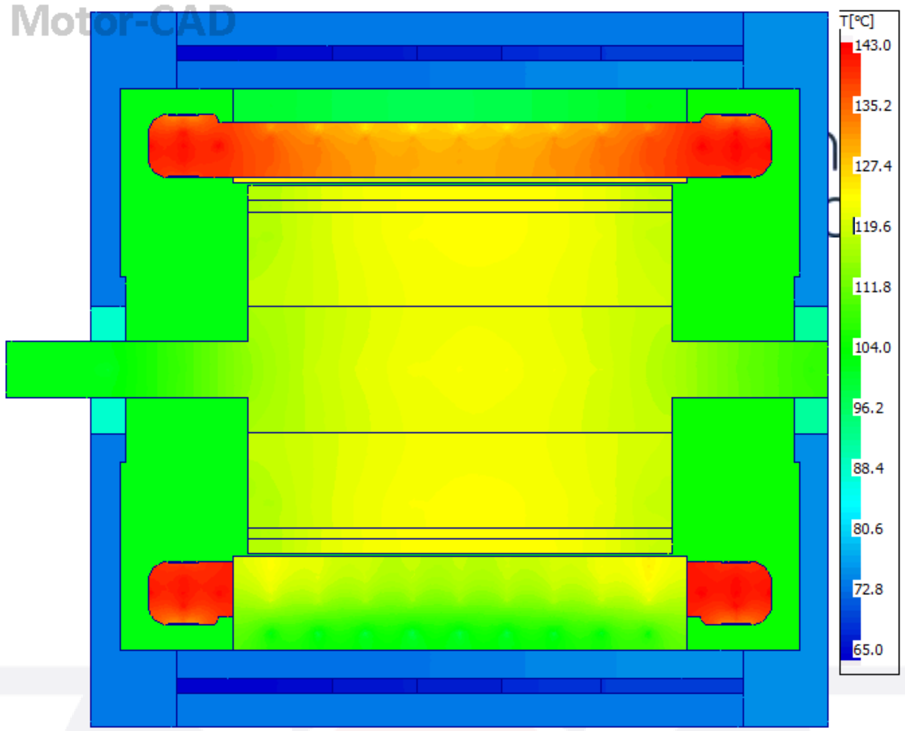


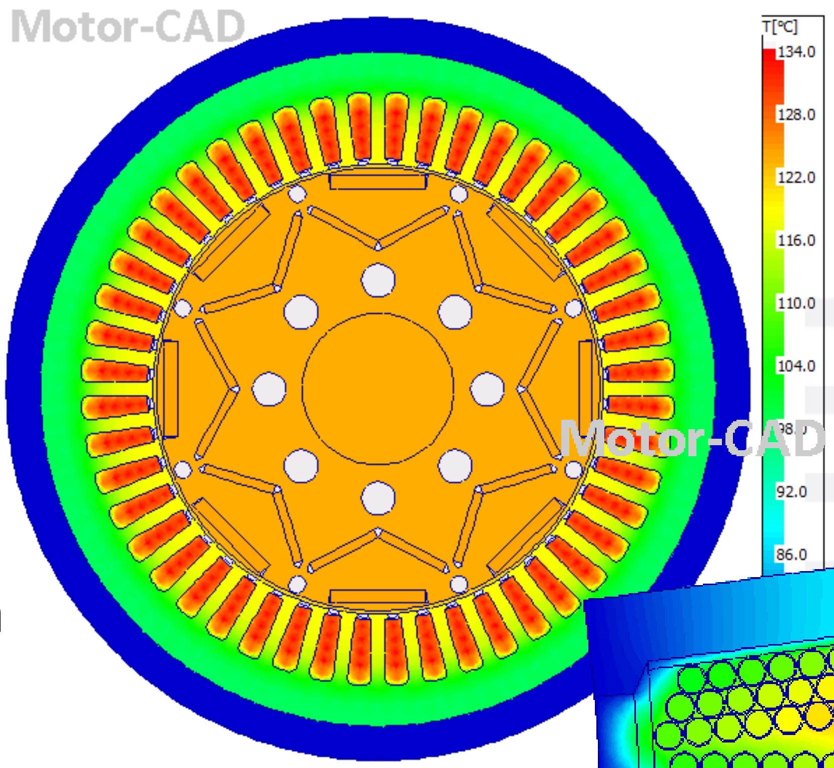
LEAF Thermal Analysis (FEA)

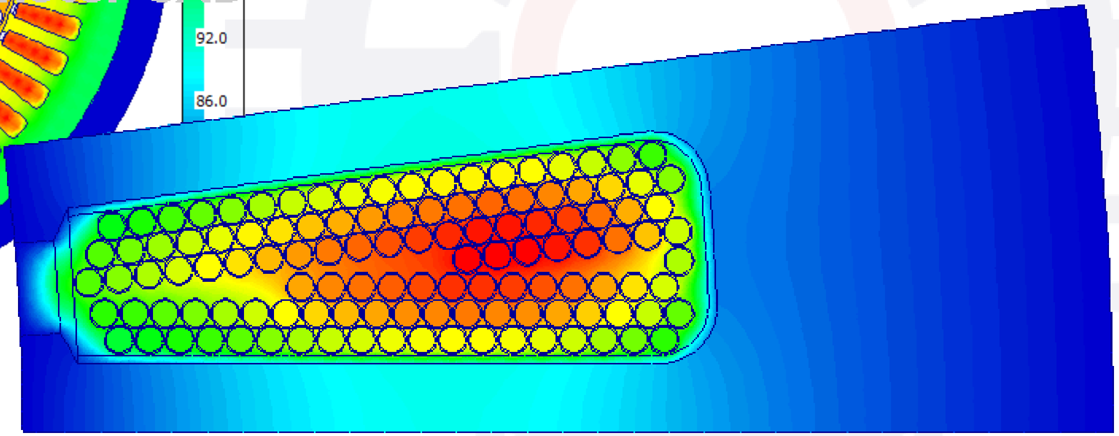
- We can use thermal finite element analysis (FEA) to predict heat transfer in components like the slot and winding

- We can plot the steady state temperature over the radial and axial cross-section using the lumped circuit thermal calculation results which is much faster than using a 3D FEA or CFD solution

Lumped Circuit Results Used to Plot Temperature Distribution





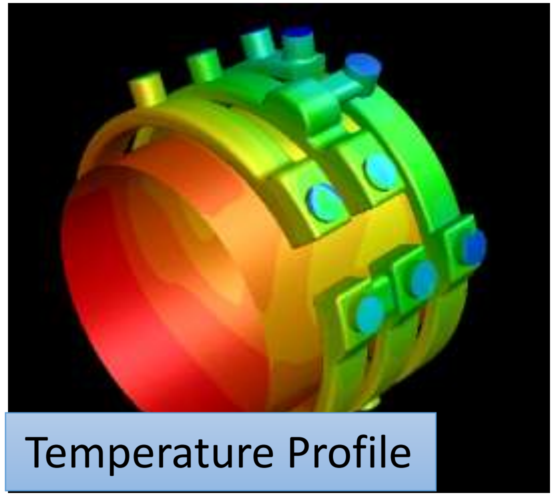


Thermal FEA Analysis for the Slot

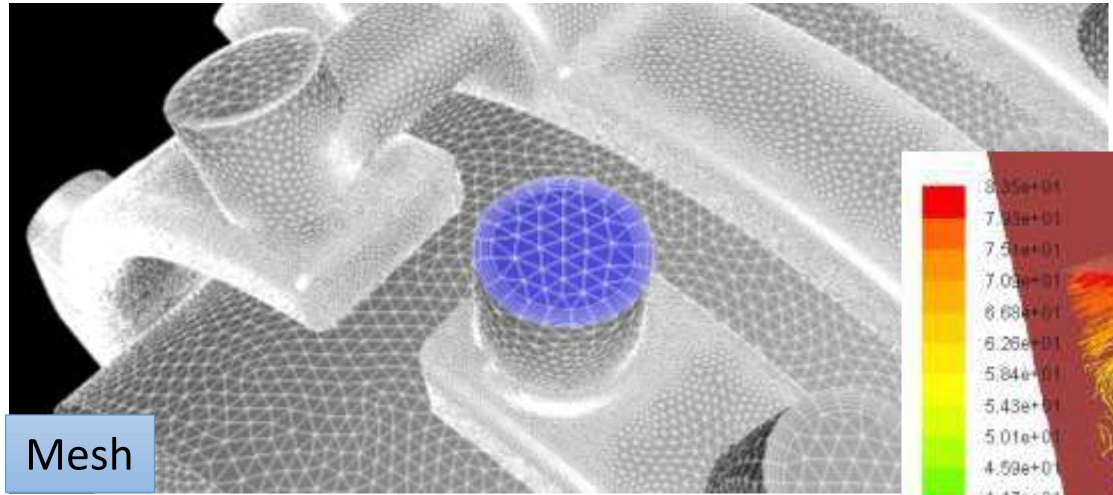
LEAF Thermal Analysis (CFD)

- We can use computation fluid dynamics (CFD) to predict fluid flow

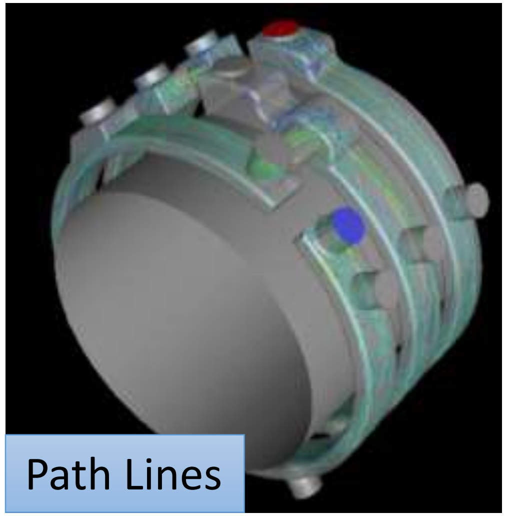
Water Jacket Fluid Flow



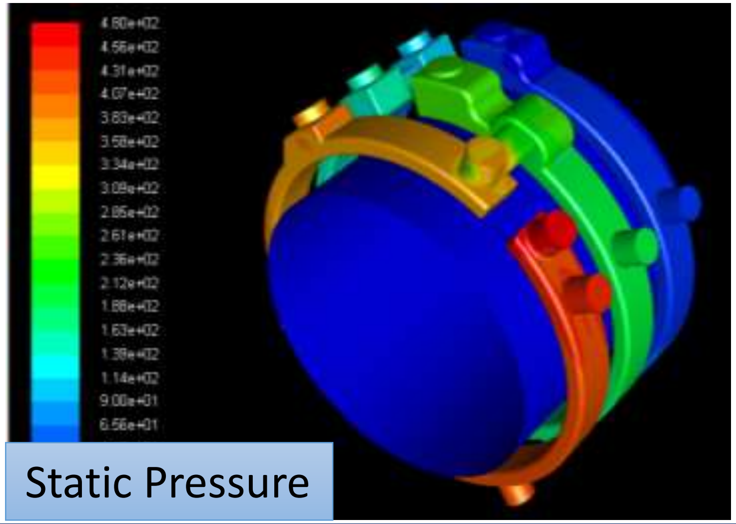
Temperature Profile



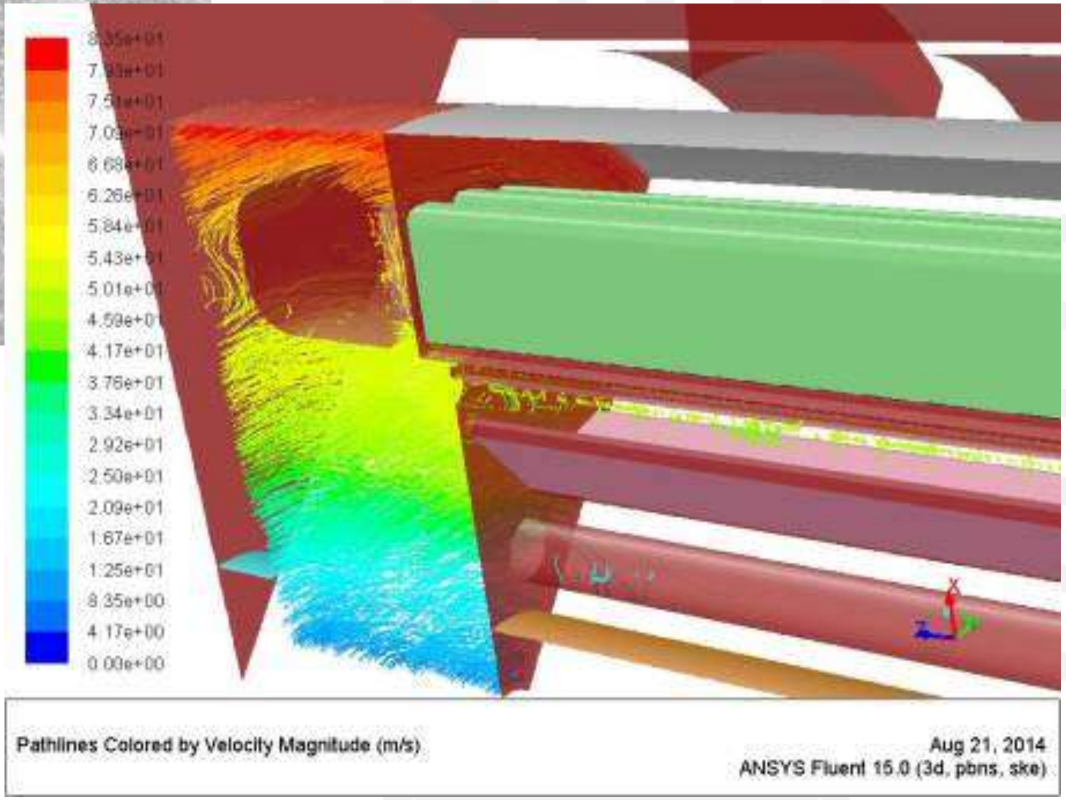
Mesh



Path Lines



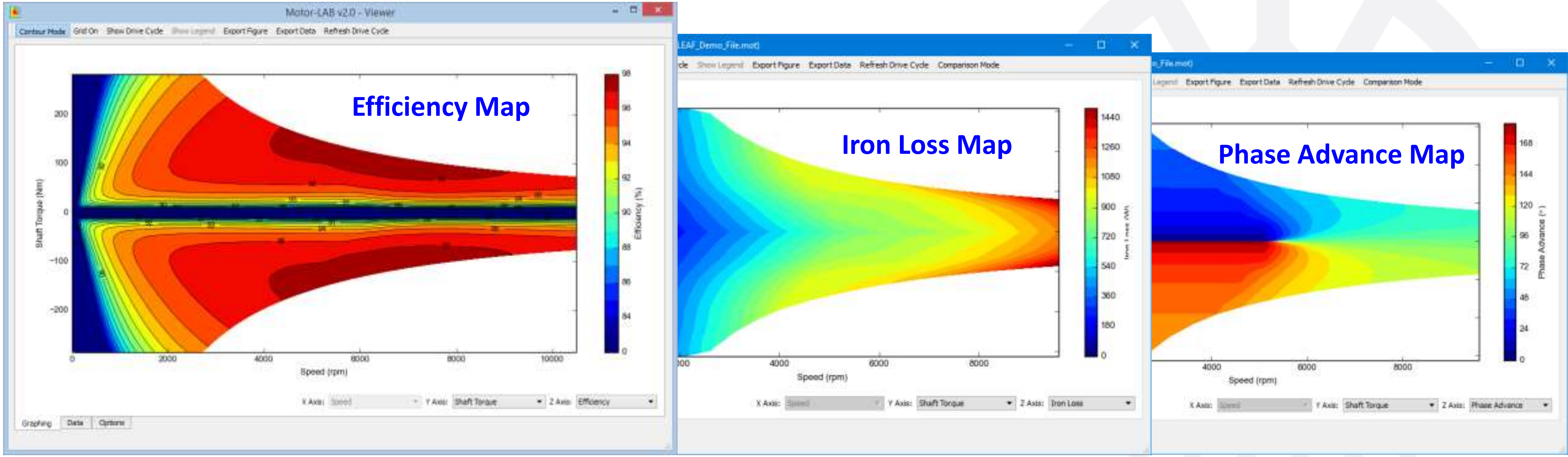
Static Pressure



Internal Air Flow

LEAF Efficiency Loss Prediction

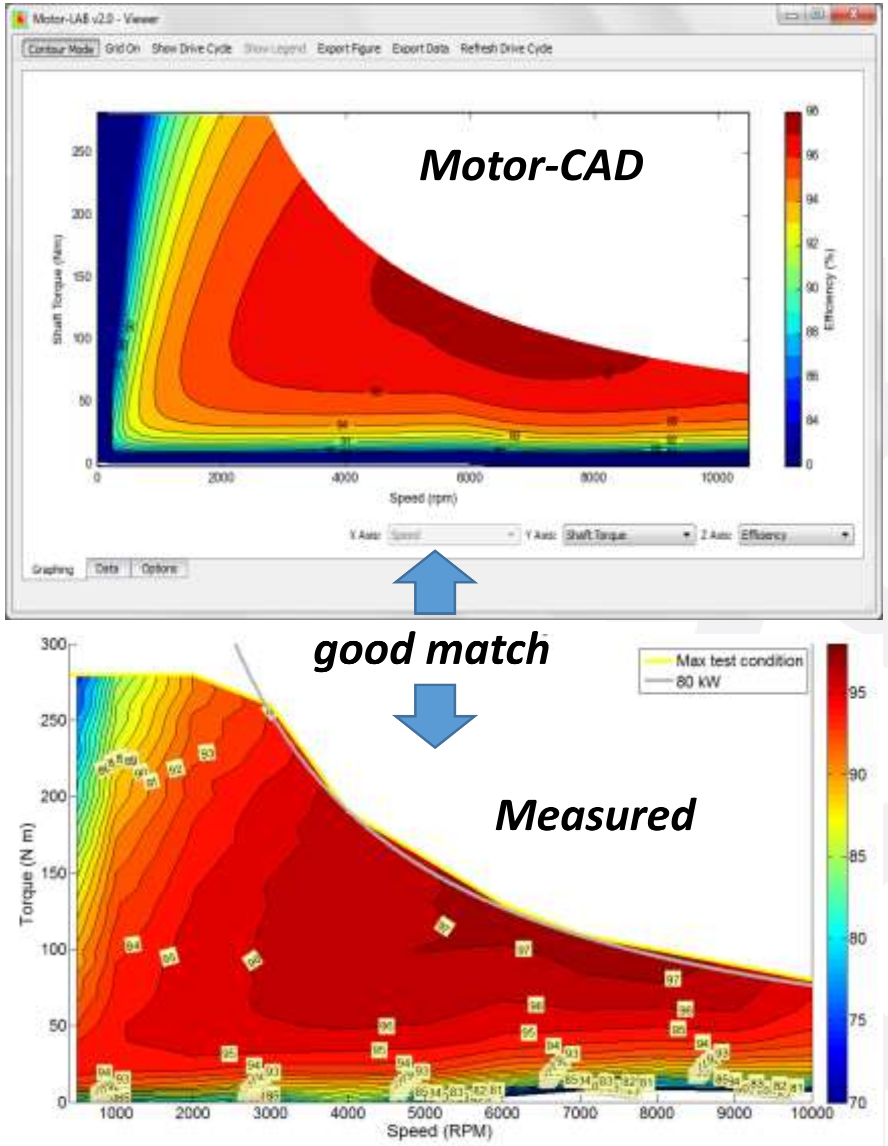
- We can calculate the electromagnetic performance at a range of torque and and speed values and then plot the efficiency map
- We can also plot other maps such as loss maps
- We can pre-calculate the optimum phase advance angle for maximum torque/amp or maximum efficiency control to minimize the number of FEA calculations required
  - The LEAF motor has a 80kW maximum power limit imposed by the drive



Validation of Electromagnetic Model (LEAF)

- We can validate the electromagnetic calculation by comparing the calculated and measured efficiency maps

- Excellent match in this case



Predicted Efficiency Map

Measured Efficiency Map

Validation of Thermal Model (LEAF)

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- We can validate the thermal model by comparing calculated and measured thermal transients
- In this case we show the winding thermal transient for the motor operating at 50kW, 60kW, 70kW and 80kW (all at 7000rpm)
  - Excellent match between the calculated and measured winding hotspot

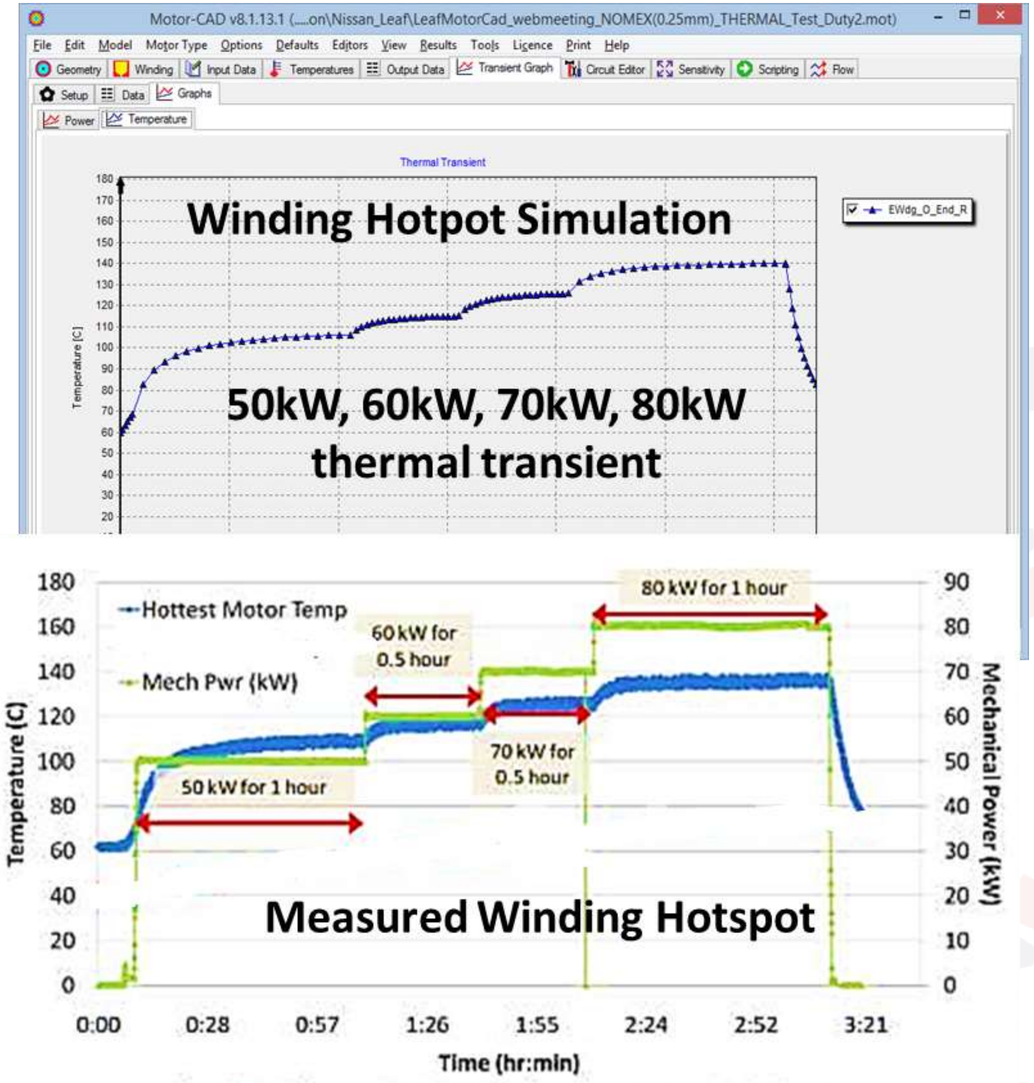
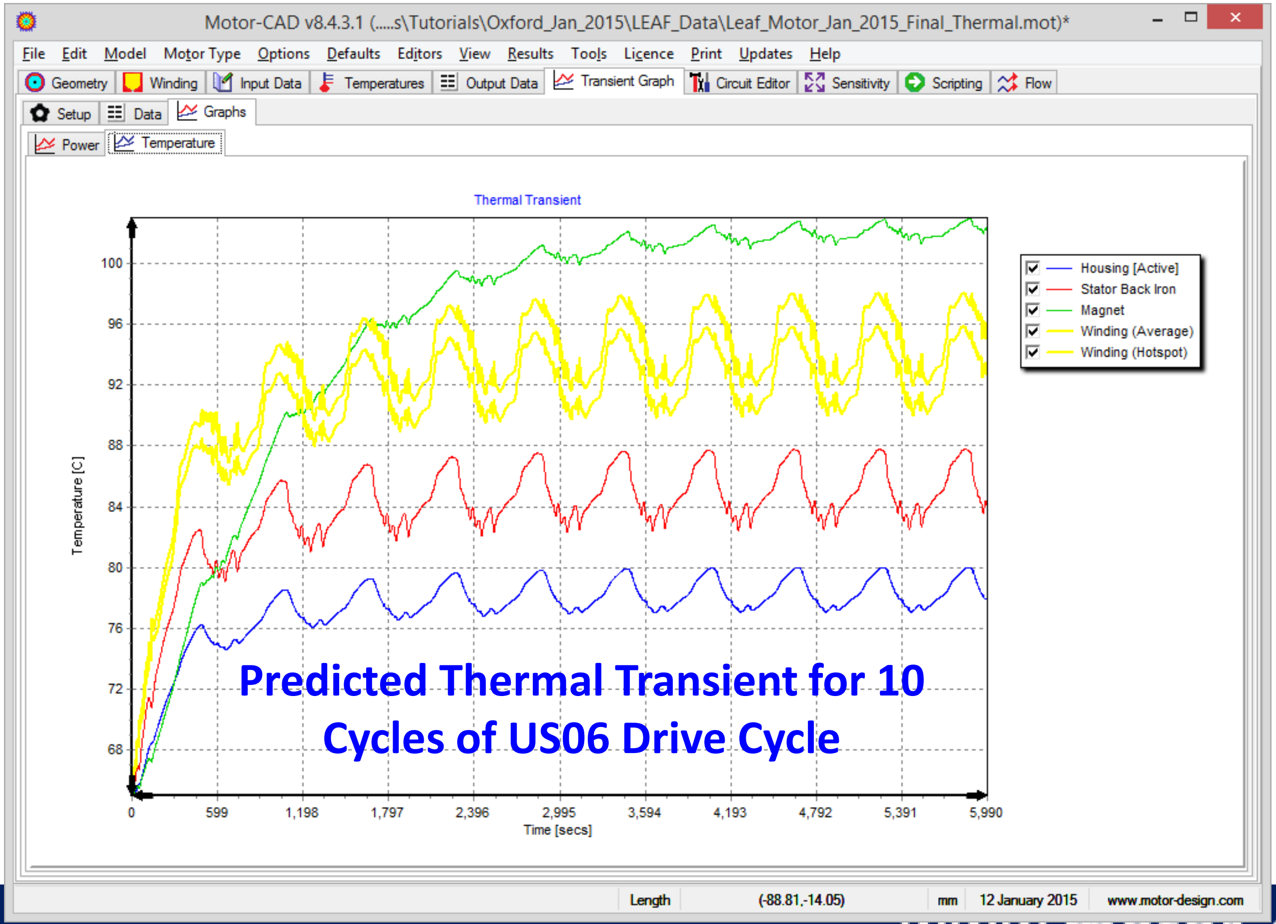
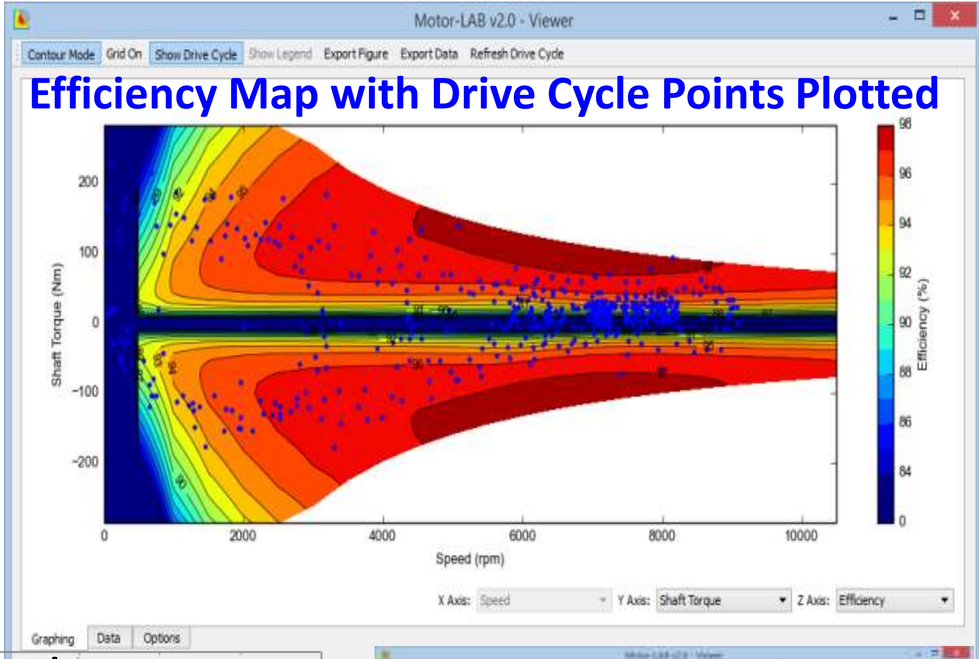


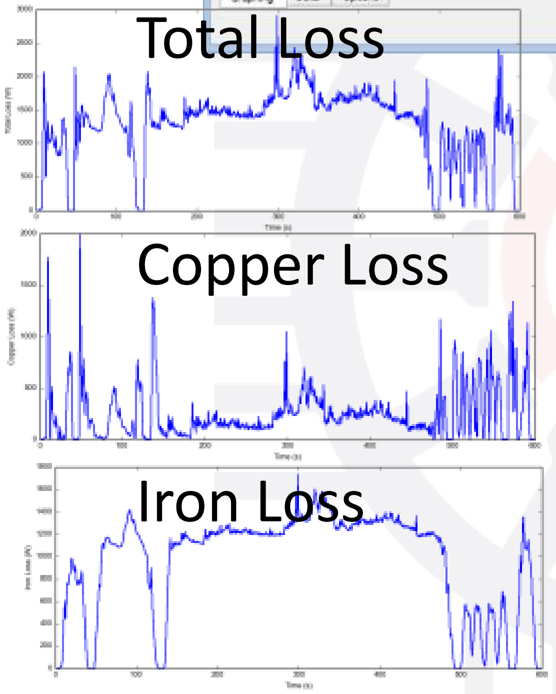
Fig. 15. Nissan LEAF continuous test at 7,000 rpm.

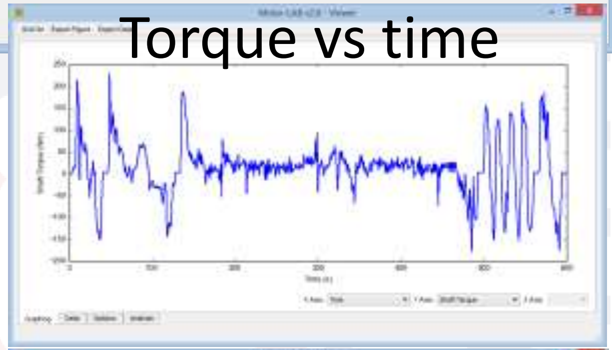
Drive Cycle Prediction (LEAF)

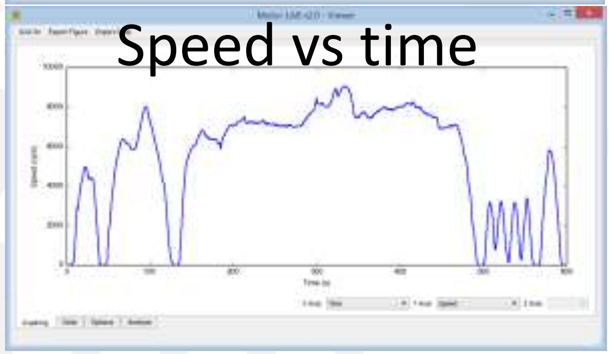
- Here we see a prediction of the efficiency map and a thermal transient calculation of 10 repetitive cycles of the US06 Drive Cycle – calculated in a few minutes as based on a network solution











Modelling the Tesla Model S Motor

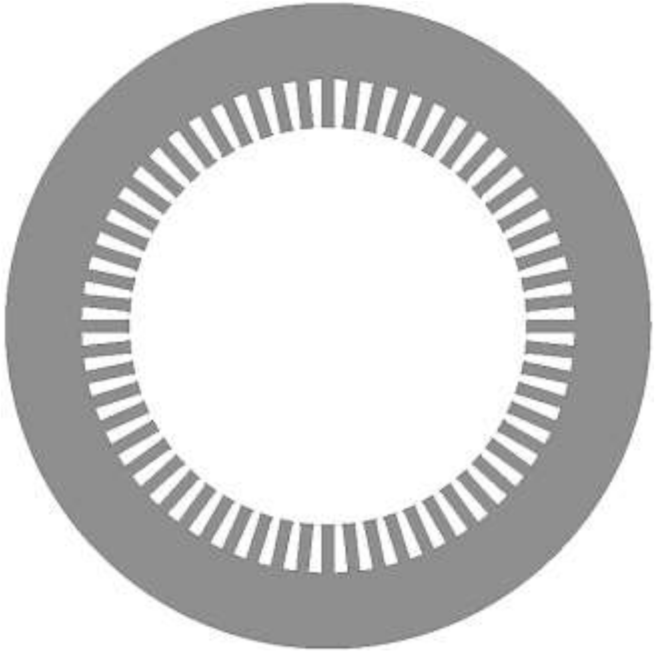
- A limited amount of published data is available for the Tesla Model S EV Traction Motor
  - Prof Ki-Chan Kim (Hanbat Uni.) Presentation at ANSYS Convergence Conference, Korea, Oct 2014
  - Tesla Patents
- There is much more commercial data available
  - https://estore.ricardo.com/wp-content/uploads/2015/09/Tesla-Model-S-60_Benchmarking-Overview_v2-Preview.pdf

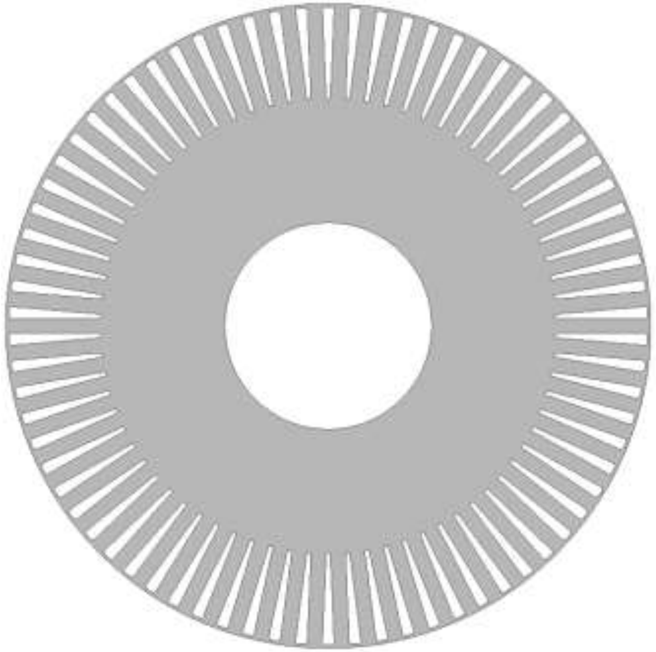
Published Data for the Tesla Model S Motor

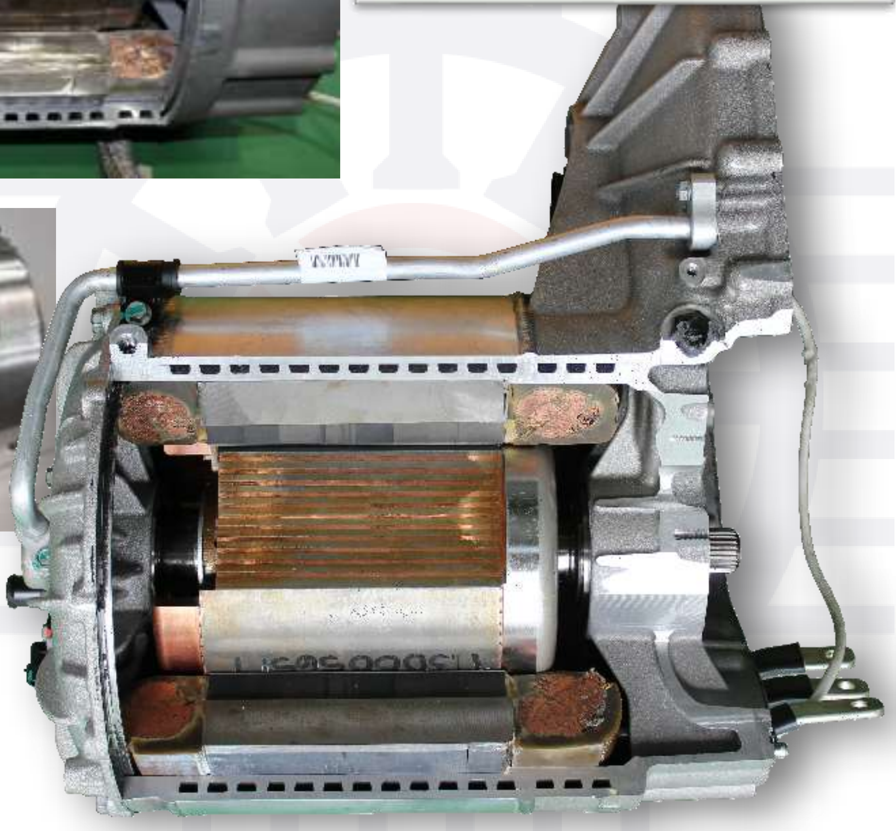
- stator, rotor, winding and water-jacket details show

Parameter	Value
Winding layers	2
Parallel branches	2
Conductors per slot	2
Number of strands	26
Wire diameter	1.1Φ
Number of Turns	1

Parameter	Motor	
	Stator	Rotor
Outer diameter	254Φ	155.8Φ
Inner diameter	157Φ	50Φ
Number of slots	60slots	74slots
Stack length	152.6mm	153.8mm
Skew	-	1.5mm (0.23pitch)

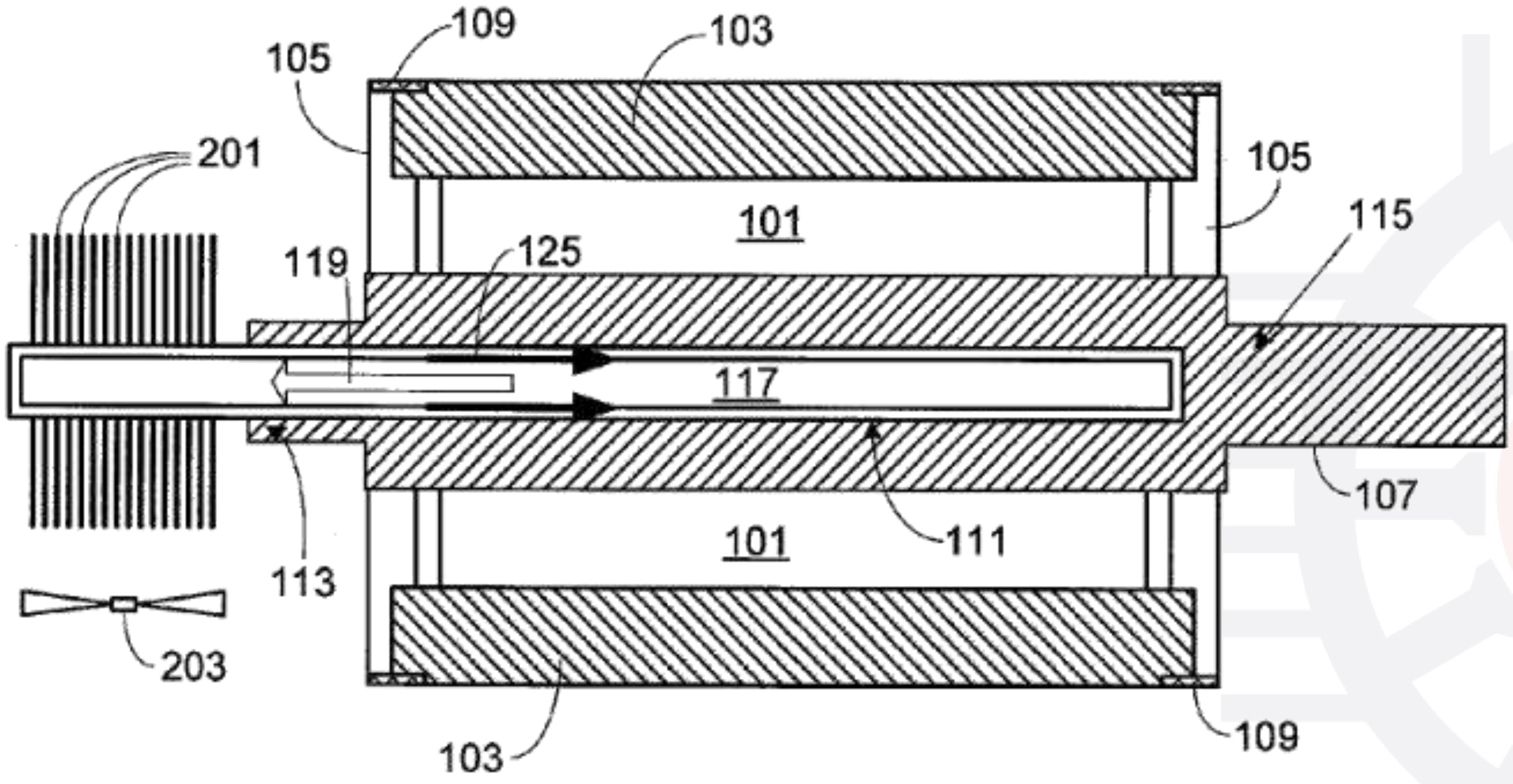






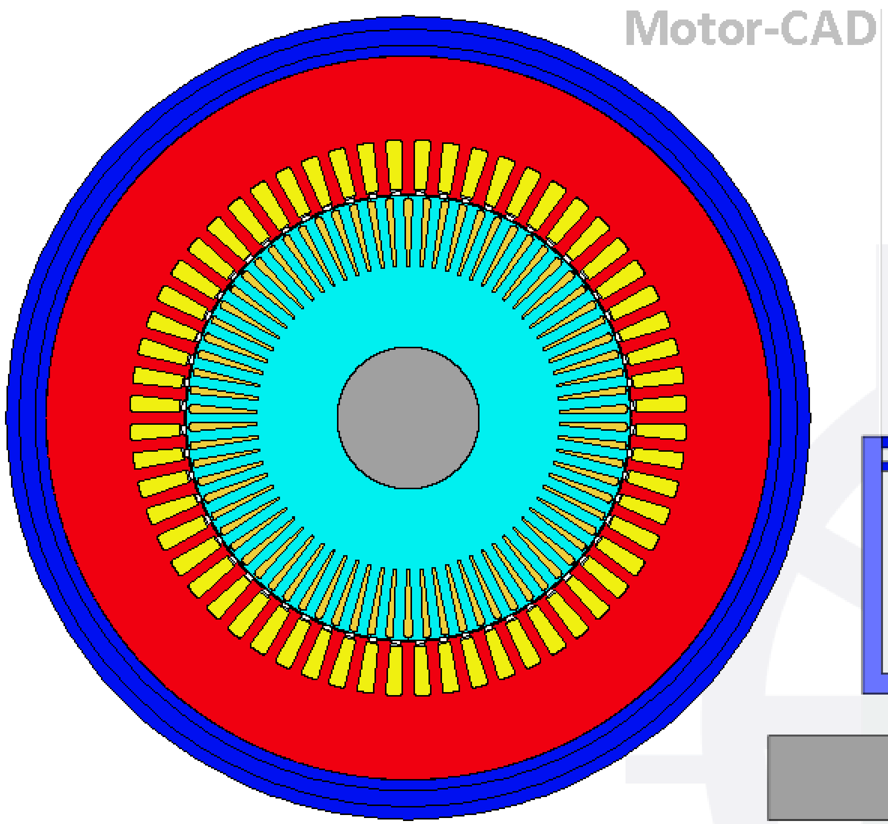
Published Data for the Tesla Model S Motor

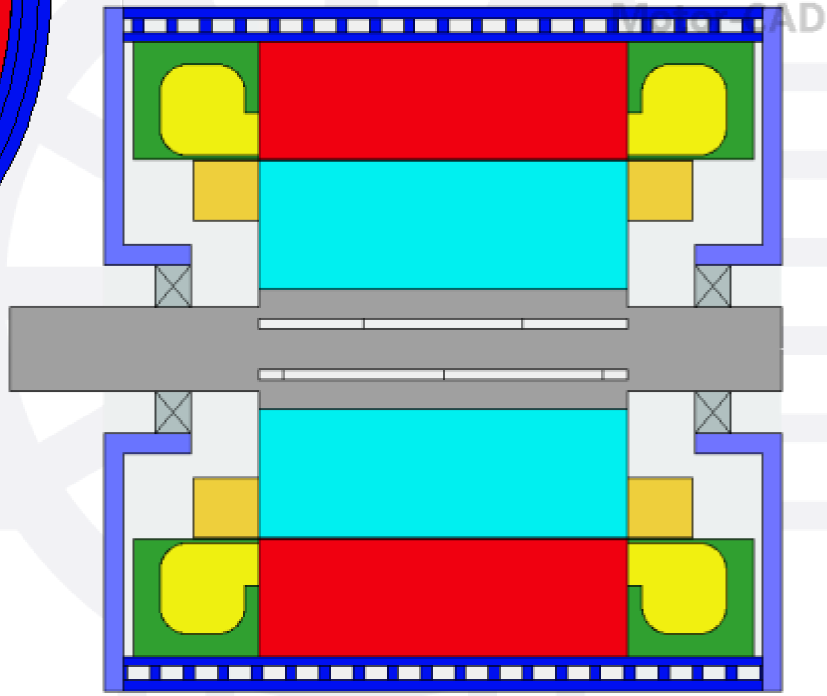
- The rotor cooling system details are taken from a Tesla patent
- We can see the rotor cooling channels below



Tesla Model S Geometry

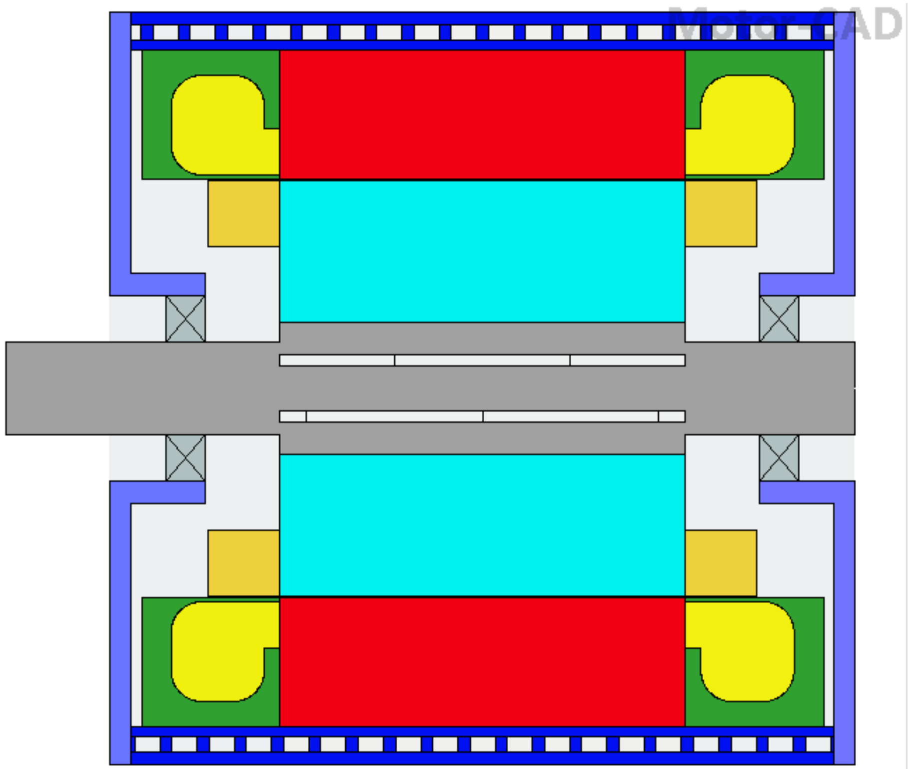
- Put motor dimensions from teardown analysis into the motor model
- 60-slot, 4-pole, 74 rotor bars fabricated copper rotor induction motor design
- We can also see the rotor cooling channels

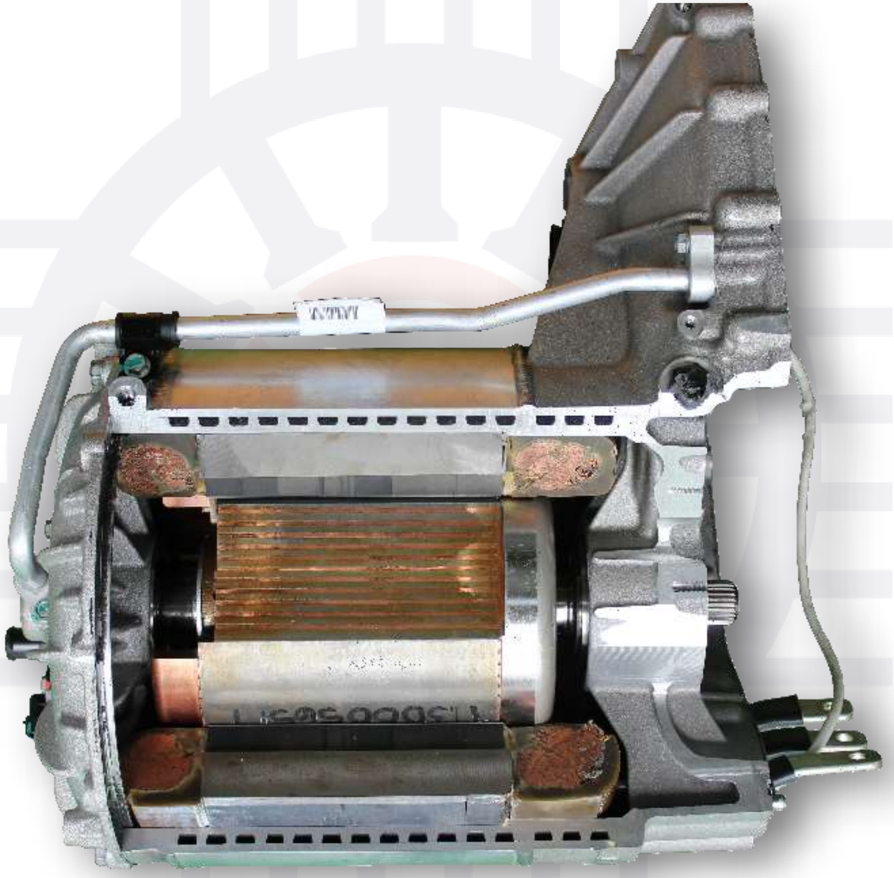




Tesla Model S (Cooling System)

- Circumferential channels in housing act as a water jacket
- Additional rotor liquid cooling is shown
- We can also see the potted end windings



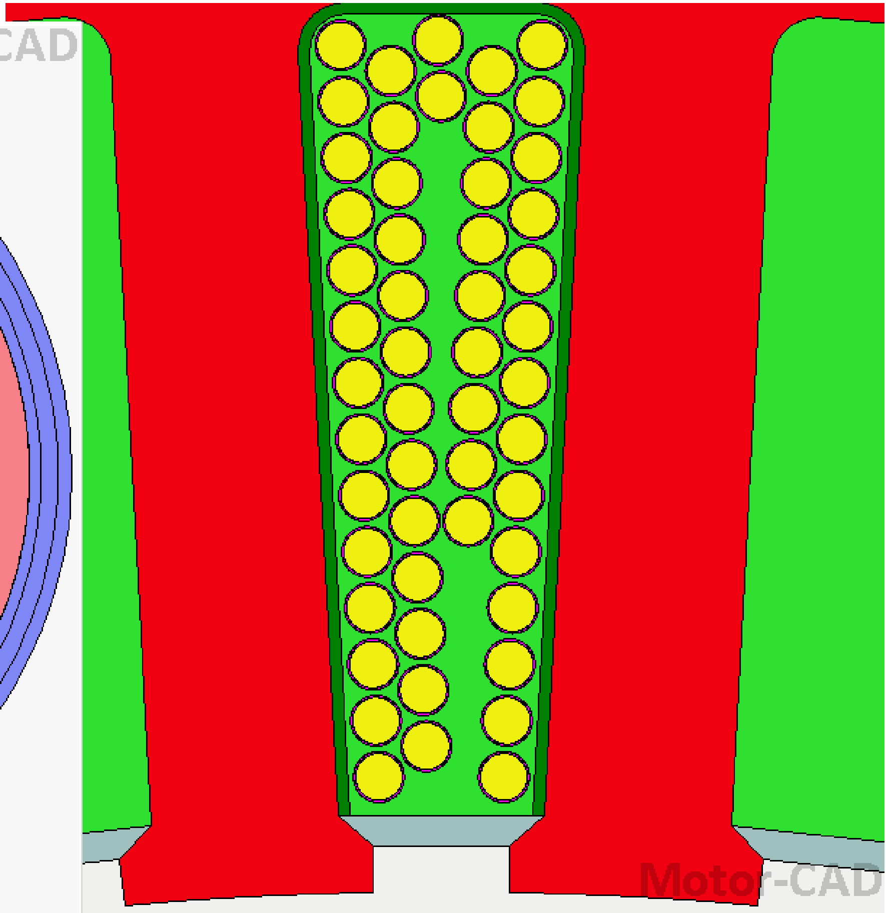


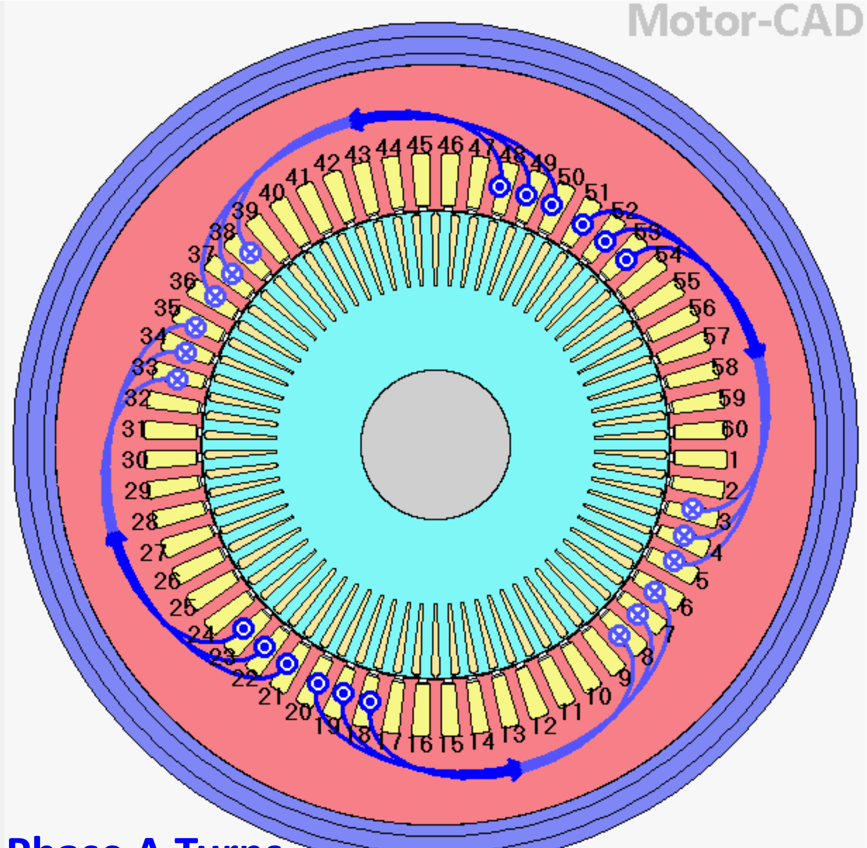
Tesla Model S Winding Design

- 60 slots with distributed winding

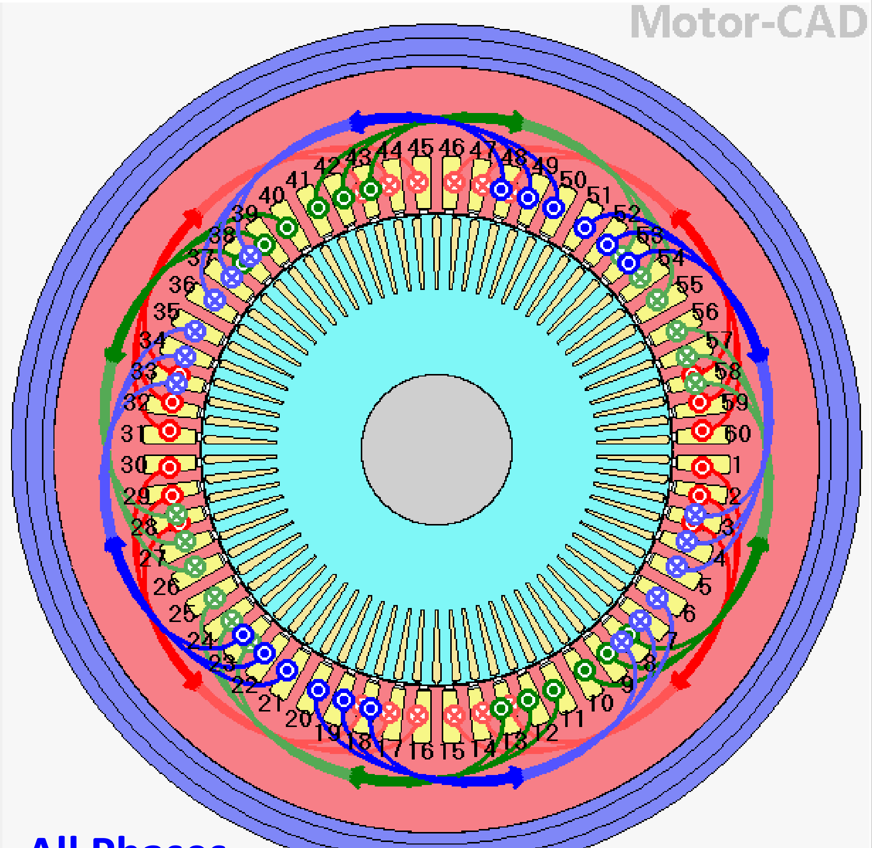
Parameter	Value
Winding layers	2
Parallel branches	2
Conductors per slot	2
Number of strands	26
Wire diameter	1.1Φ
Number of Turns	1

Conductors in Slot





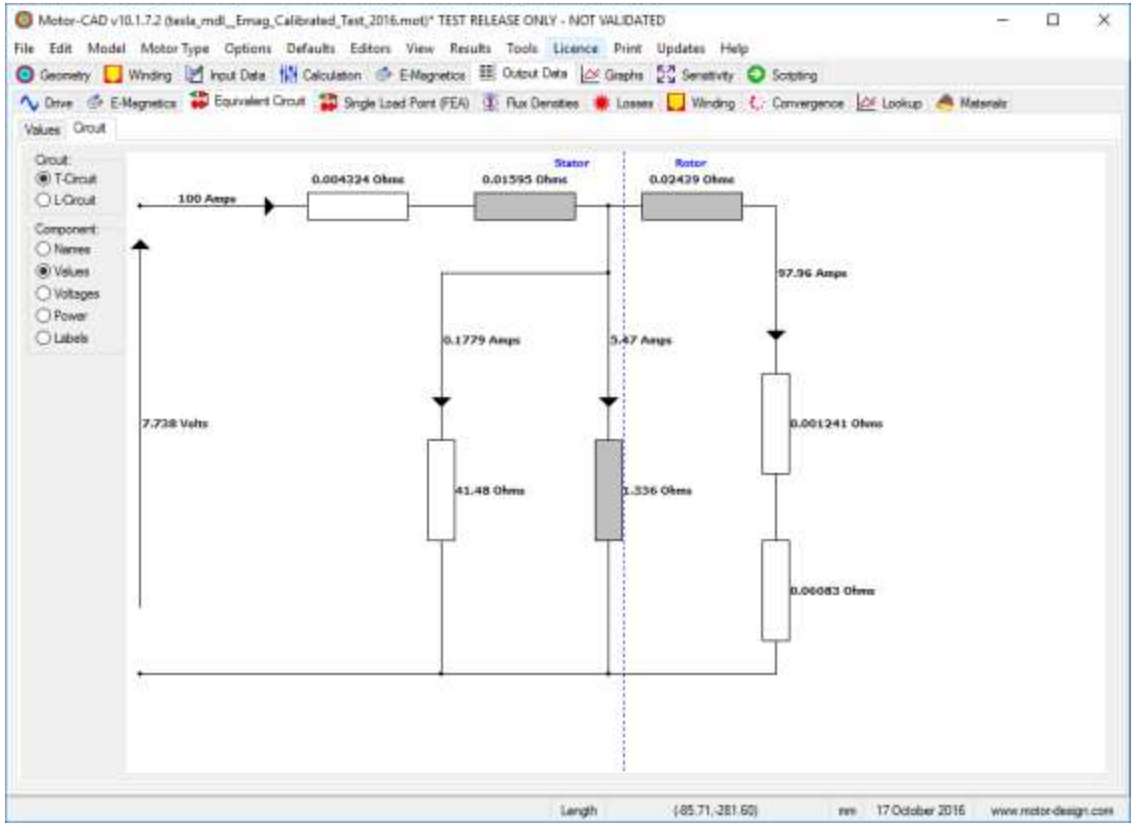
Phase A Turns



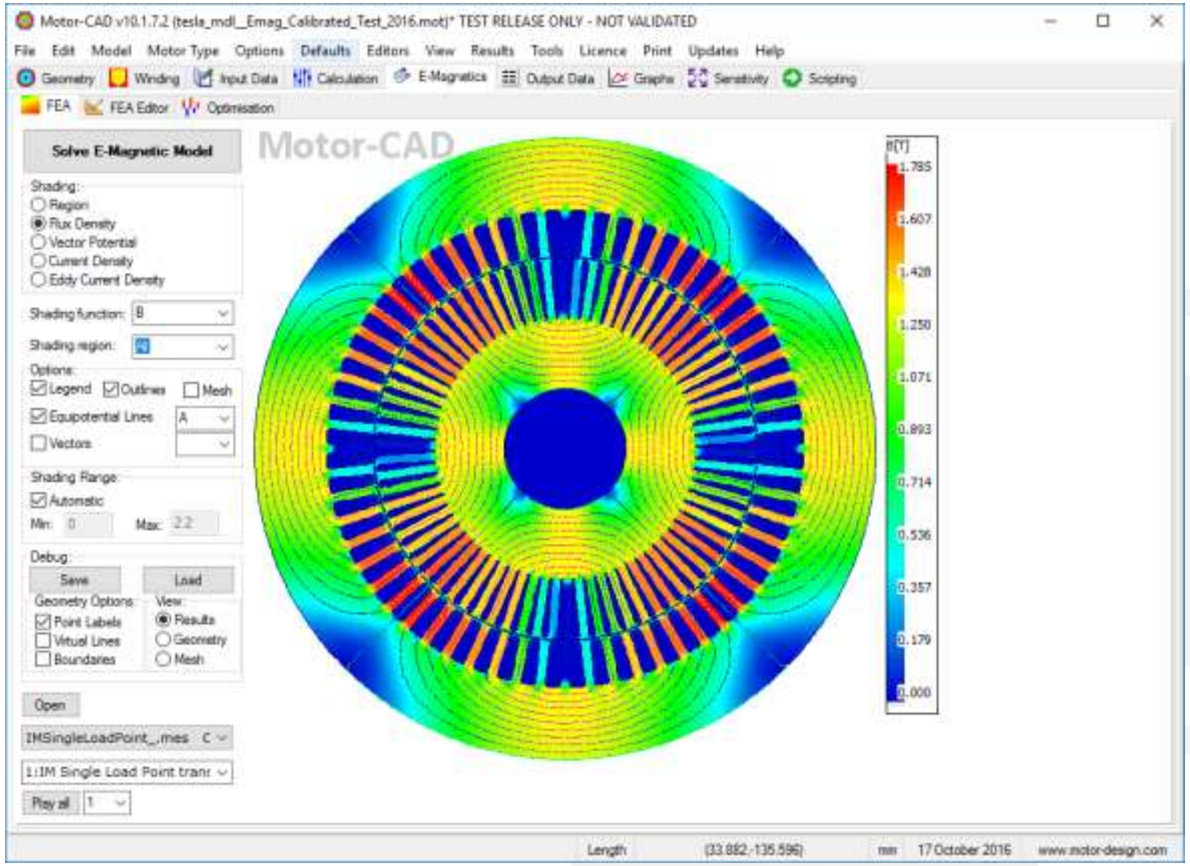
All Phases

Tesla Model S Electromagnetic Analysis

- Calculate the electromagnetic performance using the equivalent circuit
- This can be calibrated using FEA



Induction Motor Equivalent Circuit



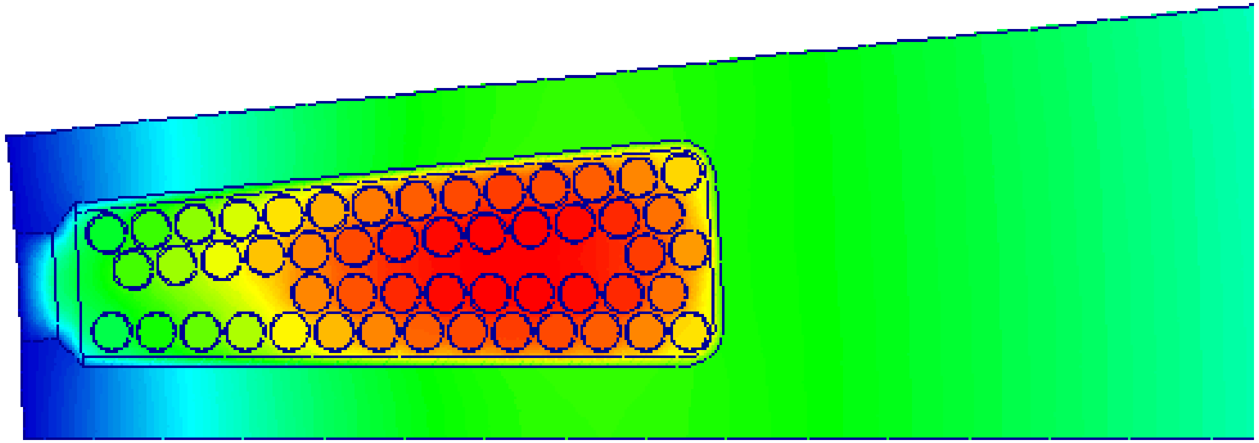
On Load Operation

Tesla Model S Thermal Analysis

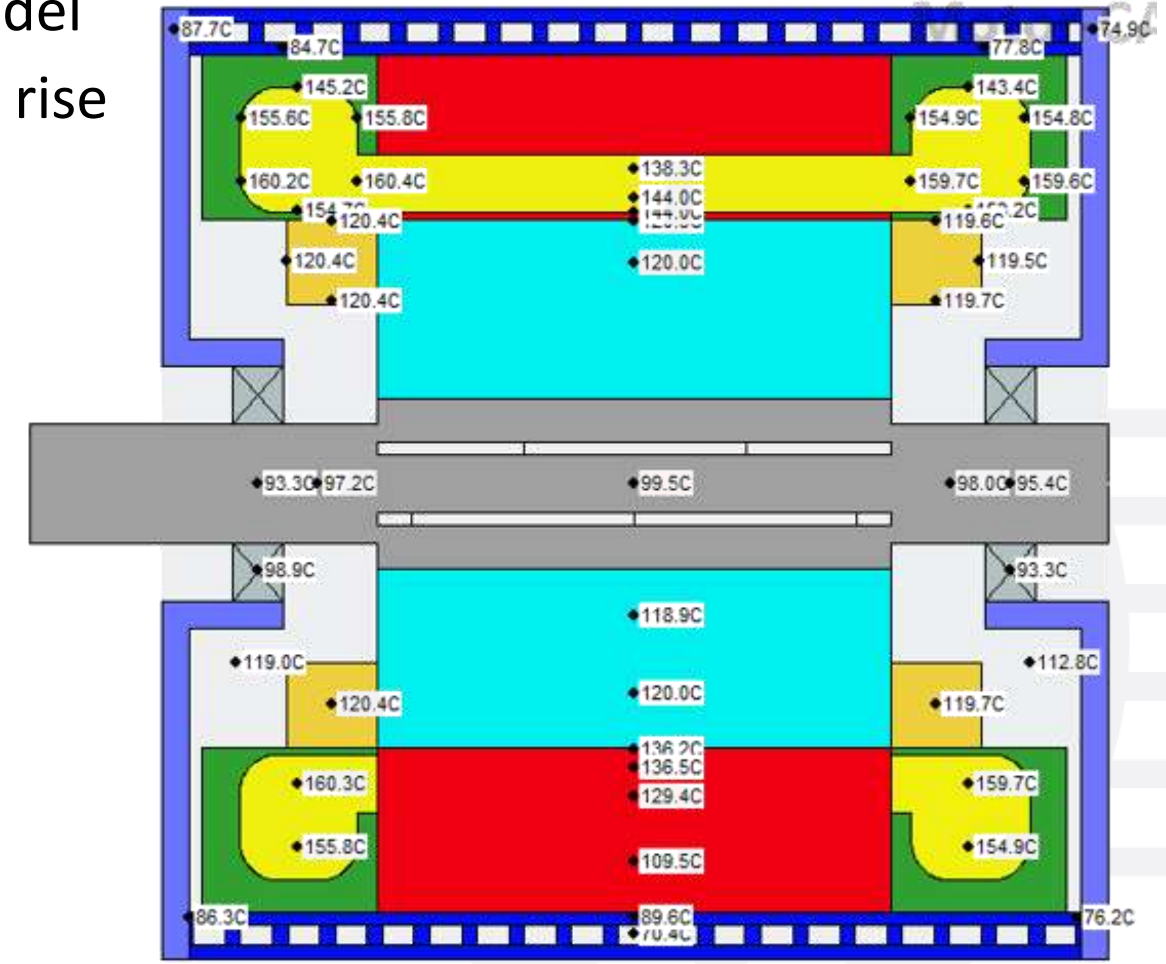
Motor Design Limited

- We can predict the steady-state or transient thermal performance using a lumped circuit thermal model
- For more detail we can predict the temperature rise in the slot using thermal FEA analysis

Motor-CAD



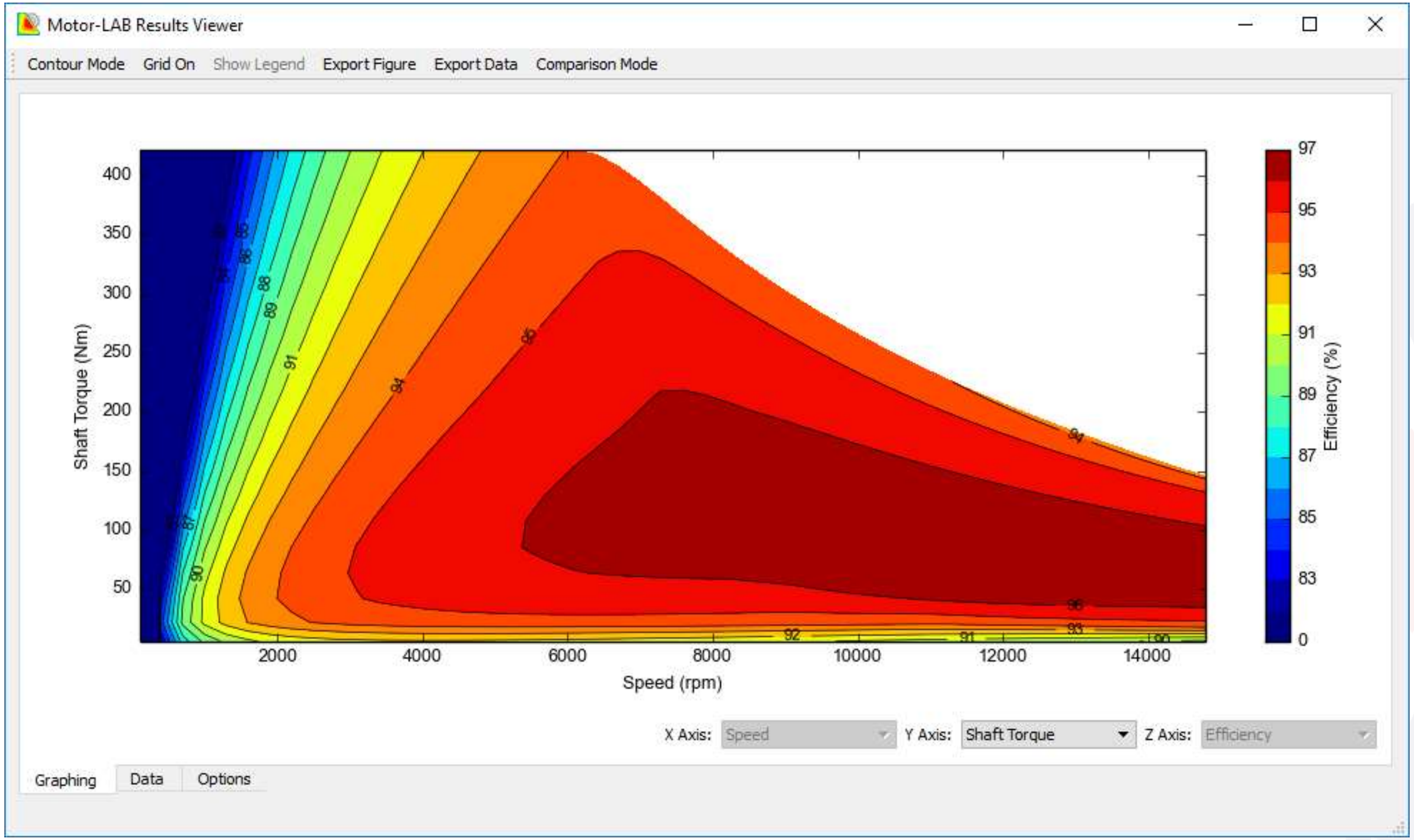
Thermal FEA Analysis for the Slot



Lumped Circuit Nodal Temperatures

Tesla Model S Efficiency Map

- We can calculate the electromagnetic performance at a range of torque and speed values and then plot the efficiency map

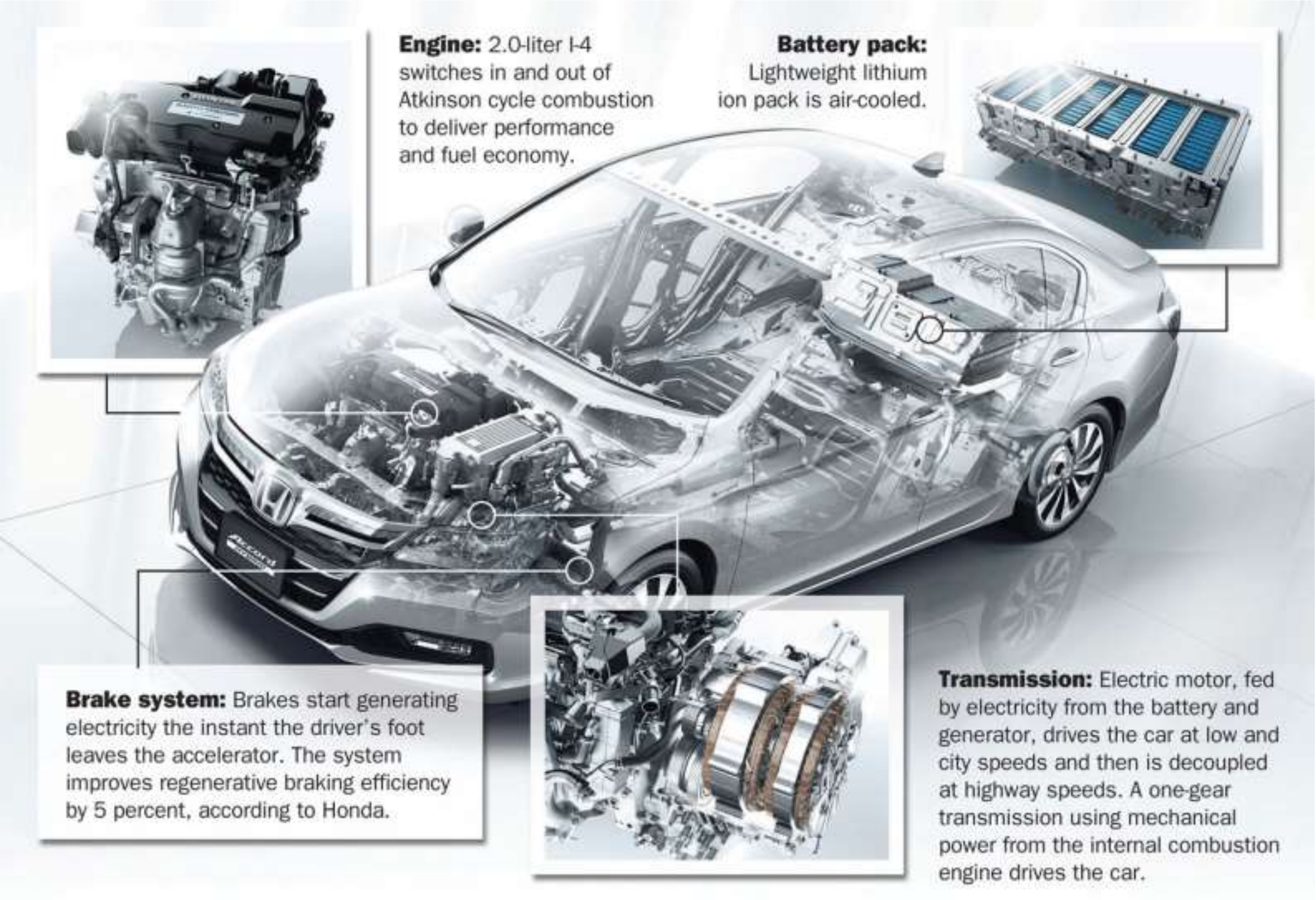


Efficiency Map

- We could now show transient thermal duty cycle analysis if we had time

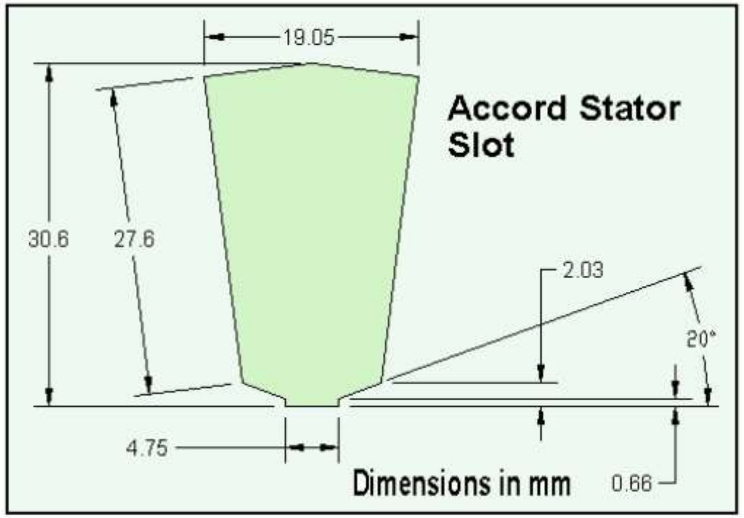
Modelling the Honda 2005 ACCORD Motor

- Much data available on web relating to the Honda ACCORD hybrid electric motor
  - Oak Ridge National Laboratory www.ornl.gov



Published Data for ACCORD Motor

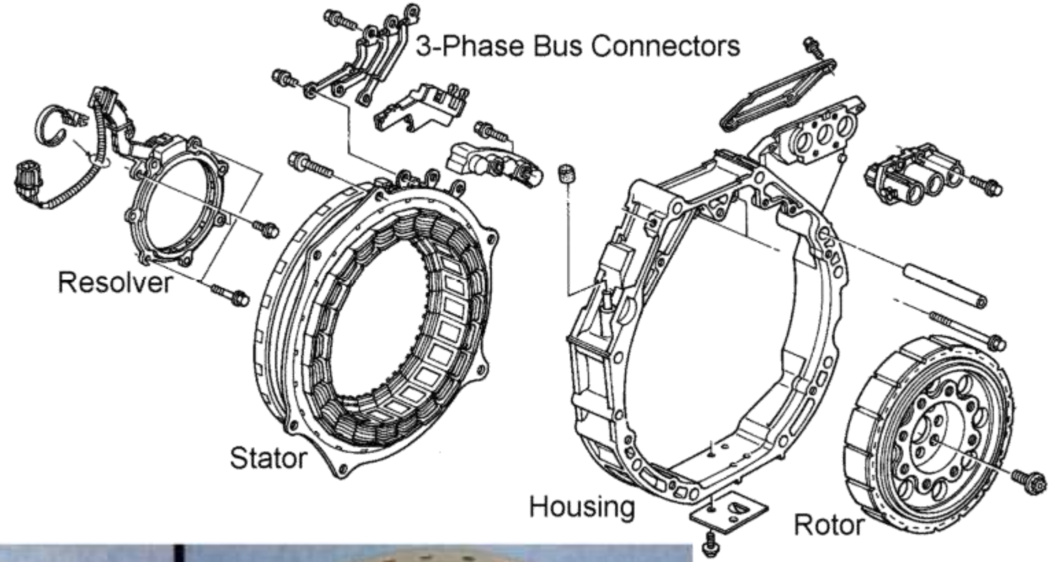
- Oak Ridge National Laboratory www.ornl.gov

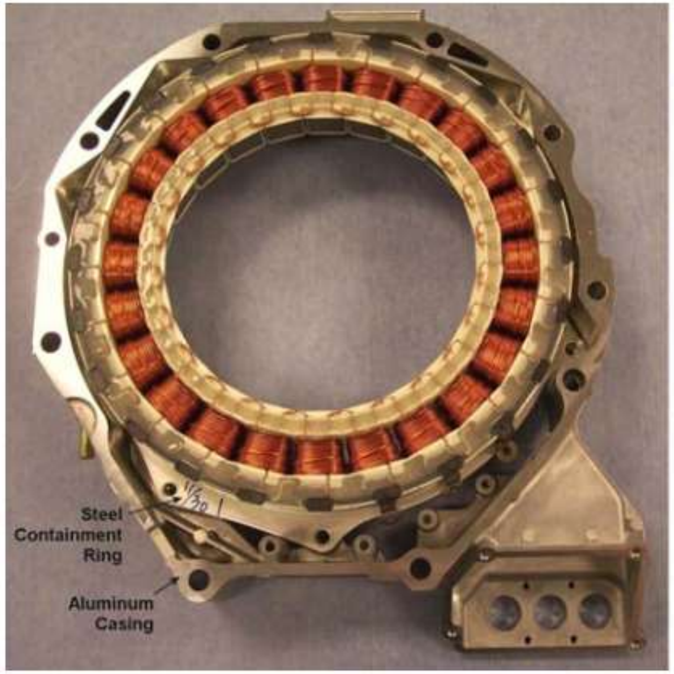


Component/Parameter	Estimated Value for the Accord	Prius (comparison of key parameters)
PMSM radius, mm	191.3	
PMSM thickness, mm	69.0	
PMSM volume, liter (L)	7.93	
Peak power density, kW/L	**1.51**	3.25
Rotor mass, kilogram (kg)	9.99	
Stator and casing mass, kg	12.5	
Bus bar and fastener mass, kg	0.128	
Total PMSM mass, kg	22.6	
Peak specific power, kW/kg	**0.532**	1.11

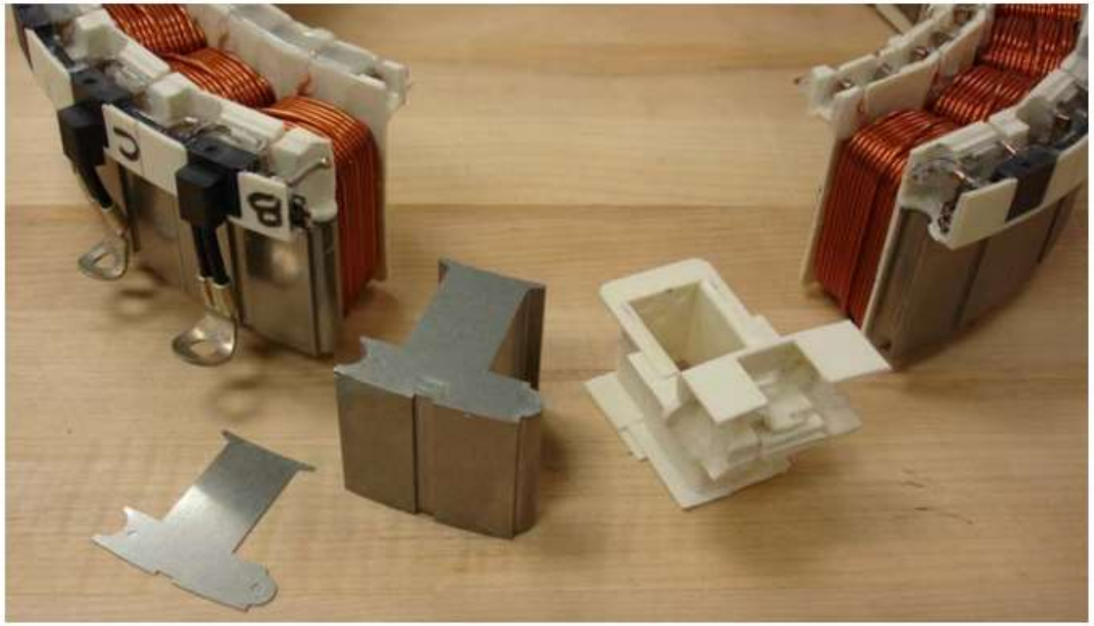
Parameter	Accord	Comments
Stator OD, mm	315.5	
Stator ID, mm	232	
Rotor OD, mm	230	
Rotor ID, mm	188	
Rotor stack length, mm	41.2	Lamination only
Stator stack length, mm	40.1	Lamination only
Air gap, mm	1	
Lamination thickness, mm	0.343	
End-turn length, mm	35	Approx middle line
End-turn length (phase lead side), mm	35	Approx middle line
End turn arc extension, mm	~6.5–10	Perpendicular from lamination
Stator turns per coil	52	
Parallel circuit per phase	8	
Turns in series per phase	0	
Number of poles	16	
Number of stator slots	24	
Number of wires in parallel	0	
Wire diameter	1.55 mm	
Slot depth, mm	30.6	
Slot opening, mm	4.75	
Slot area, mm^2	307	
Phase resistance at 21°C, ohm	0.0097	
Stator winding mass, kg	3.01	
Stator core mass, kg	7.704	Laminations only
Rotor mass, kg	8.02	Without bearings
Magnet width, mm	18.45	Individual magnets (two/pole)
Magnet thickness, mm	4.46	Individual magnets (two/pole)
Magnet length, mm	40.4	Individual magnets (two/pole)
Magnet Volume, mm^3	3320	For a pole, double volumes
Magnet mass, g	25	For a pole, double masses

Published Data for the ACCORD



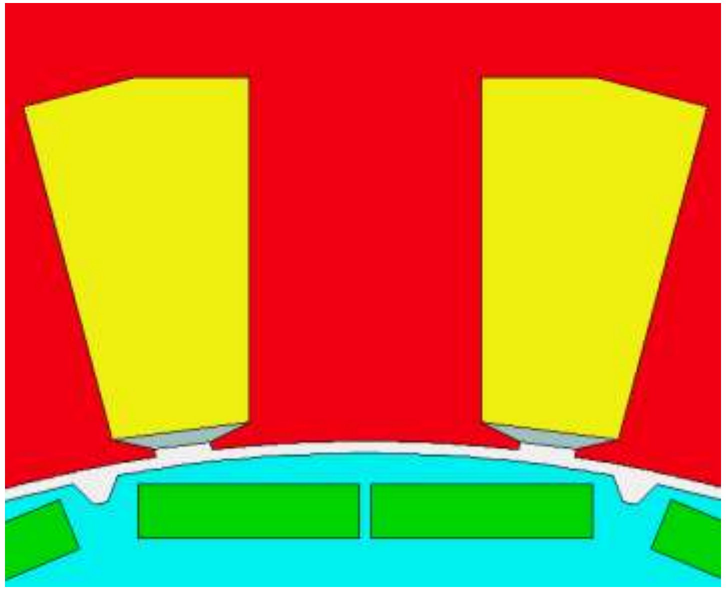


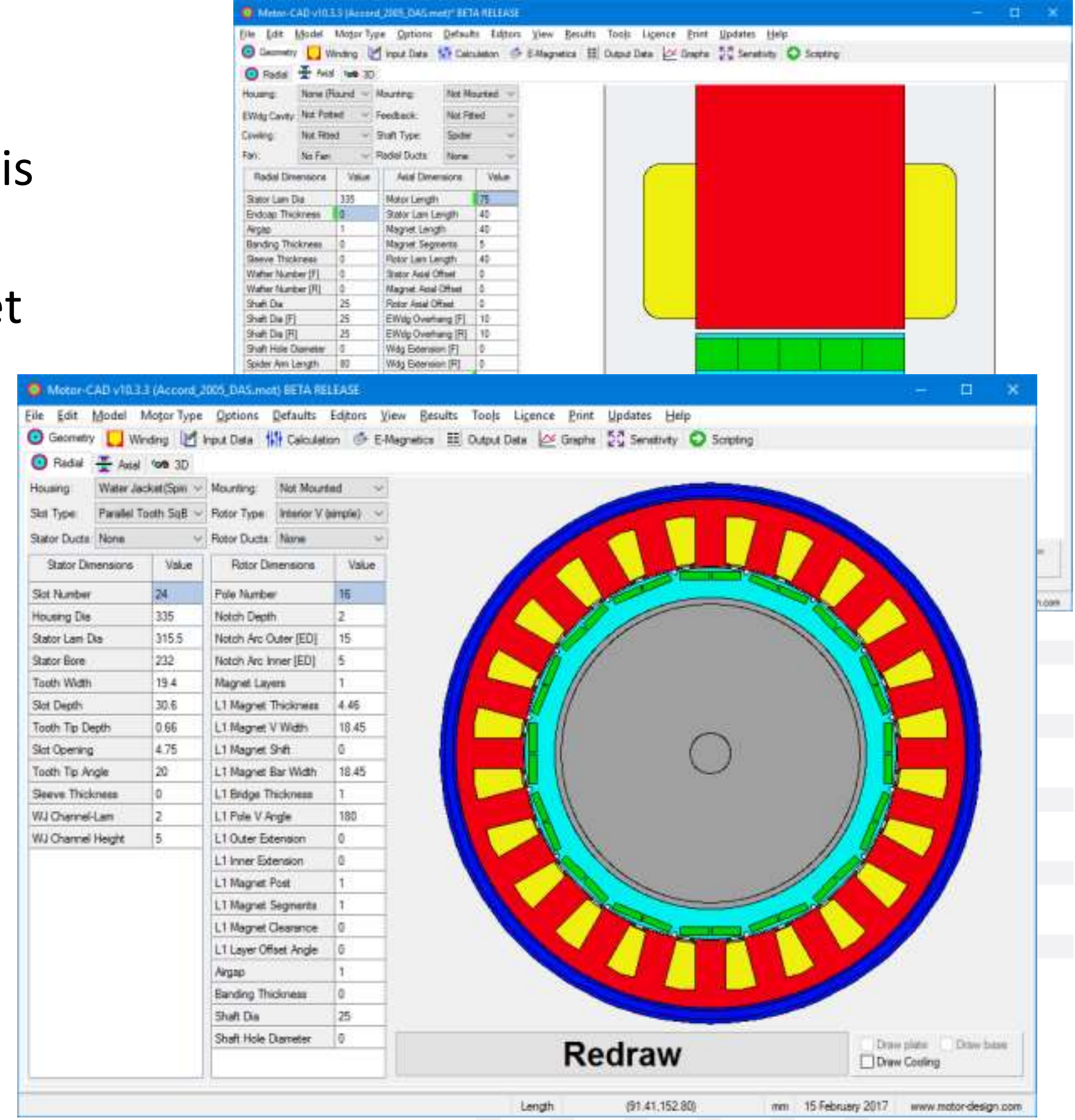
Oak Ridge National Laboratory
www.ornl.gov



Honda ACCORD Geometry

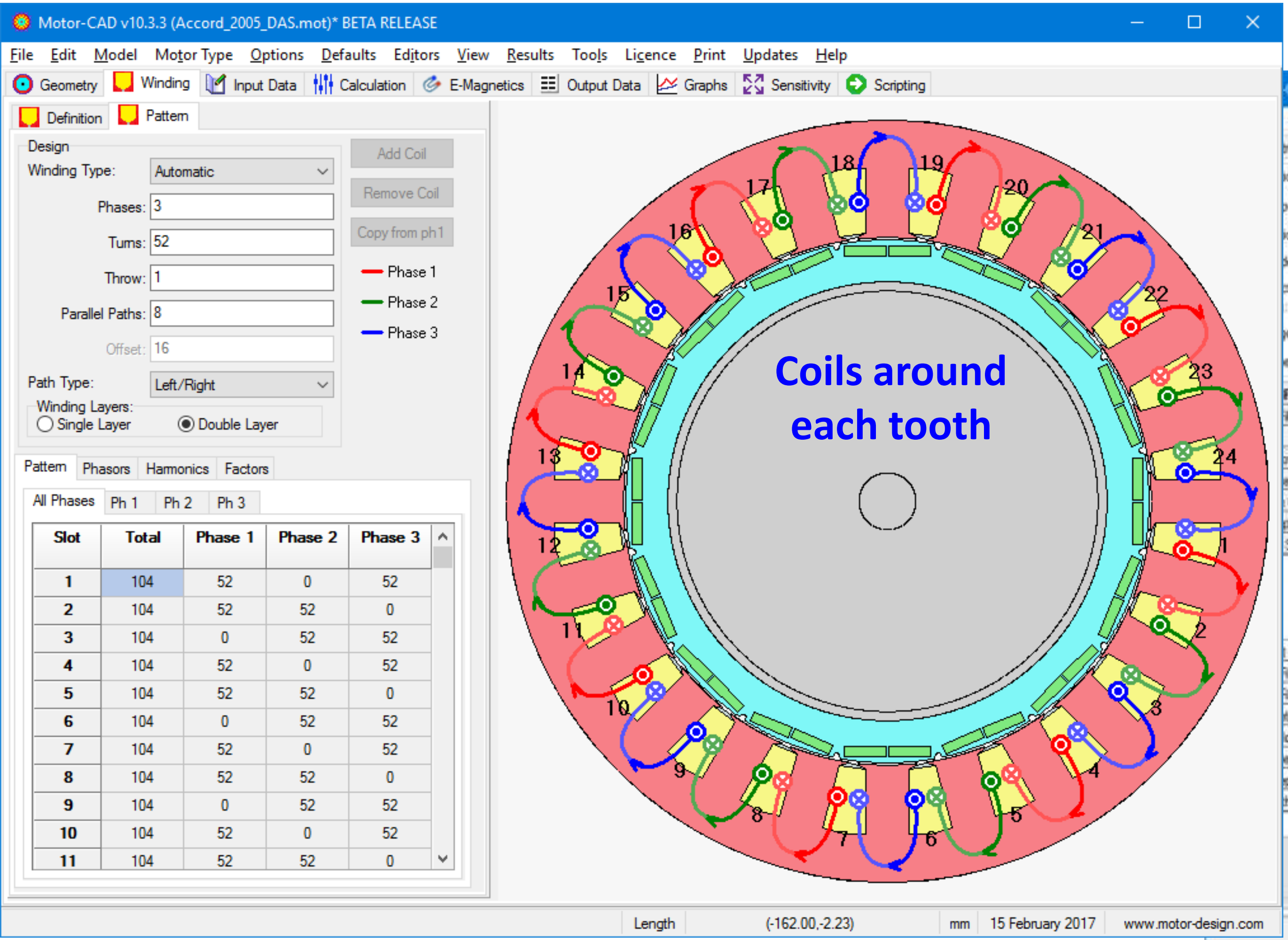
- Put motor dimensions from teardown analysis into the motor model
- 24-slot, 16-pole brushless permanent magnet (BPM) motor design
- Interior permanent magnet IPM with flat magnets
- Passive air cooling



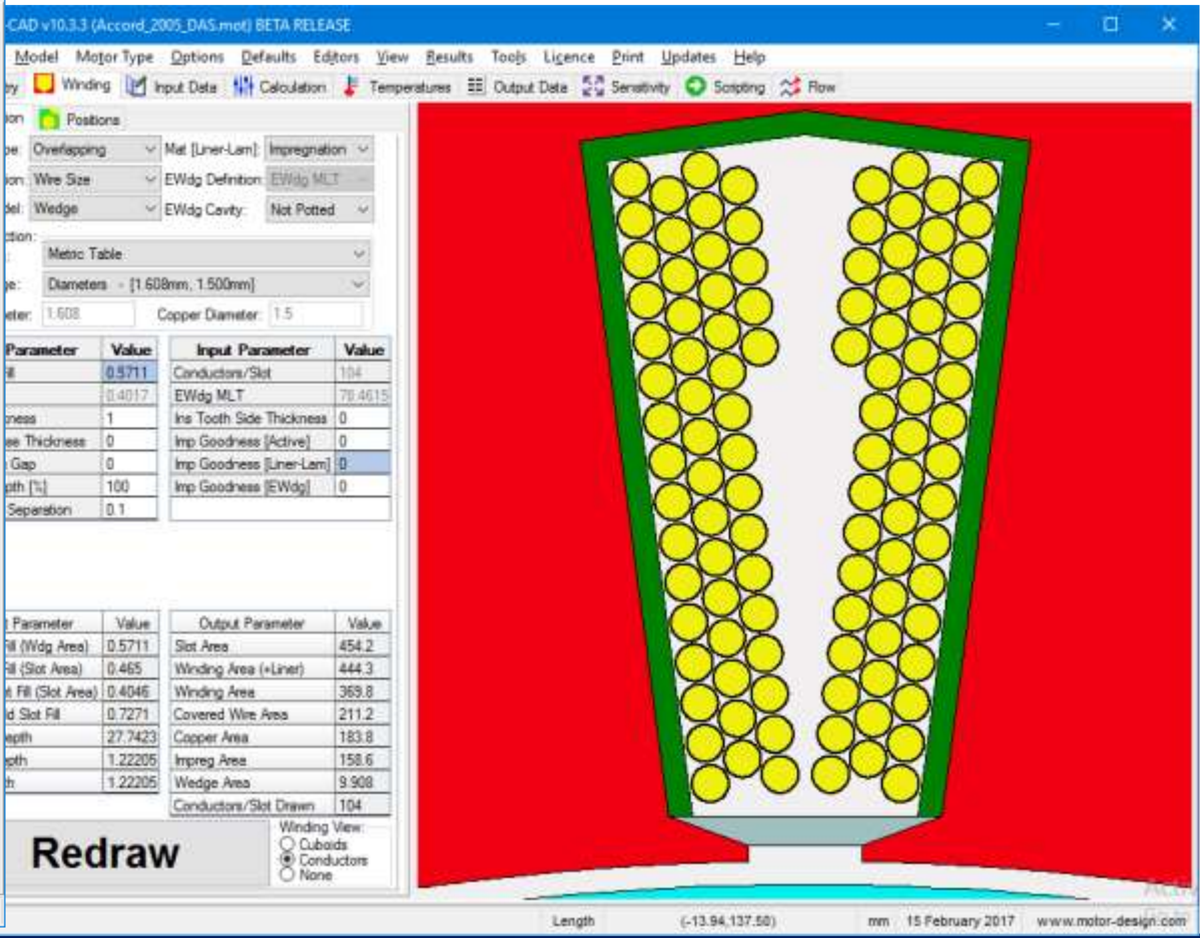


Honda ACCORD Winding Design

- ➢ Segmented stator construction with bobbin wound winding
- ➢ Coils wound around each tooth

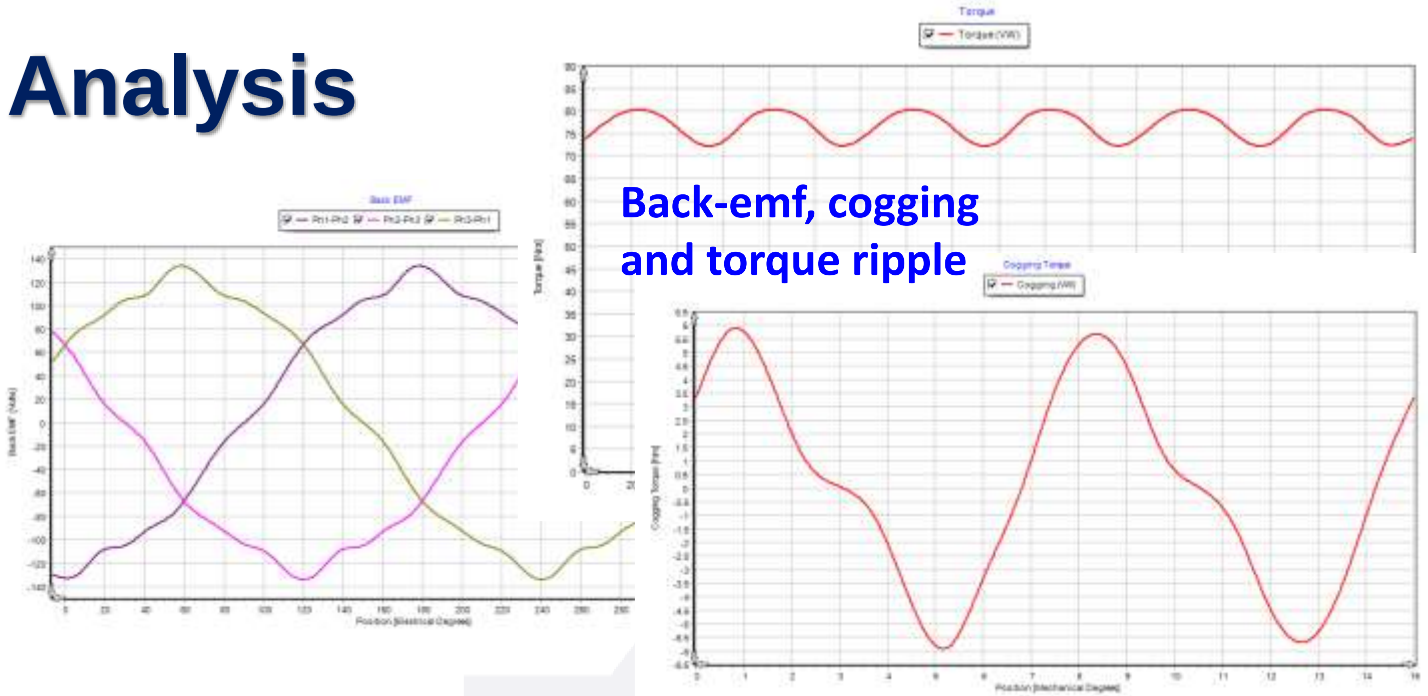


Conductors in Slot with Coil around a Tooth

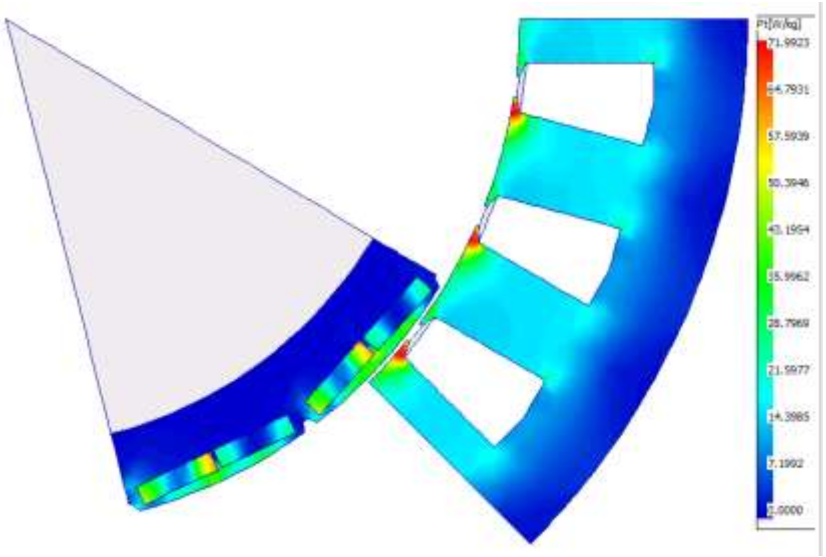


ACCORD Electromagnetic Analysis

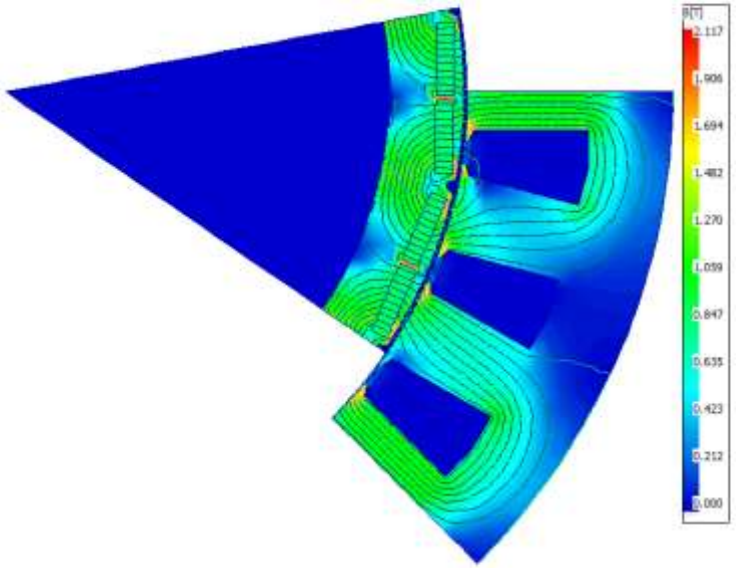
- We can calculate the open circuit and on-load electromagnetic performance



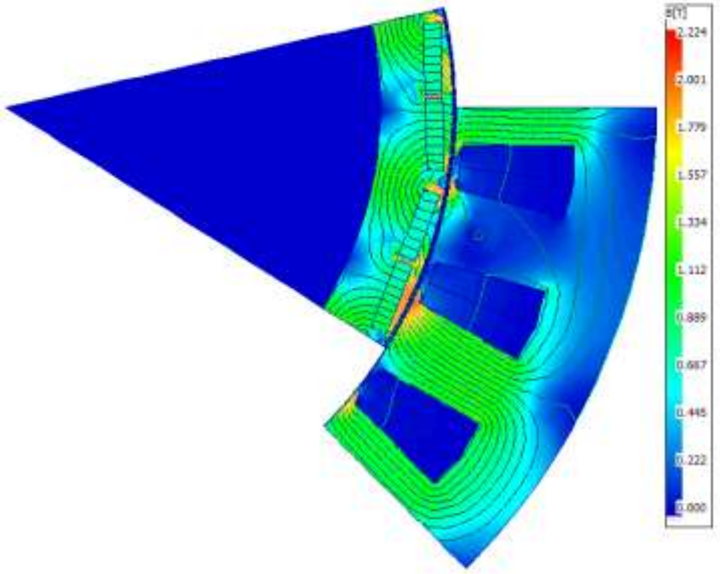
Back-emf, cogging and torque ripple



Loss density plots



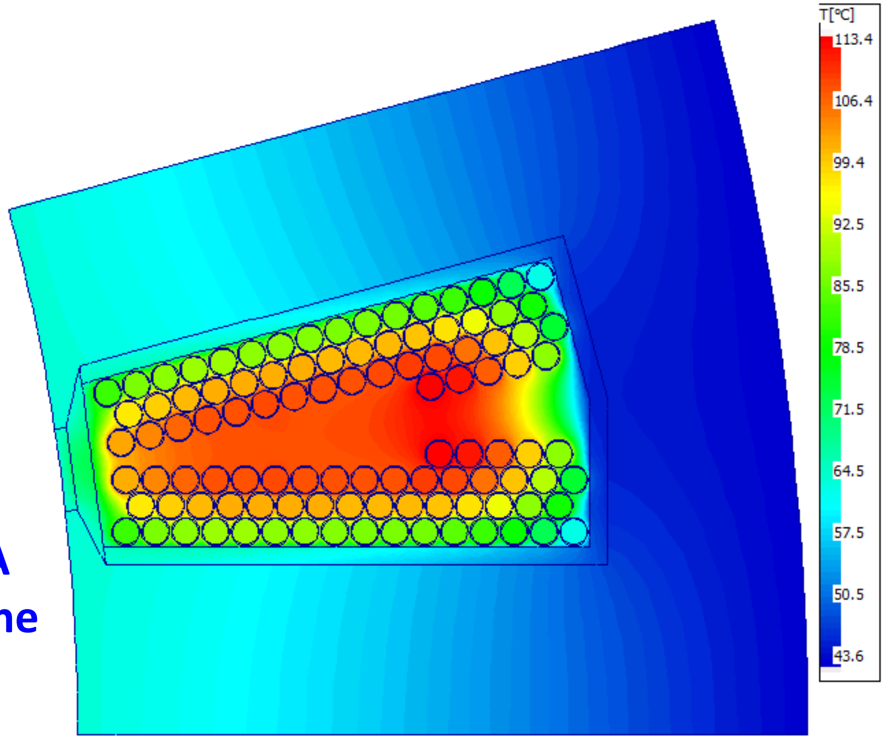
Flux plot (open-circuit)



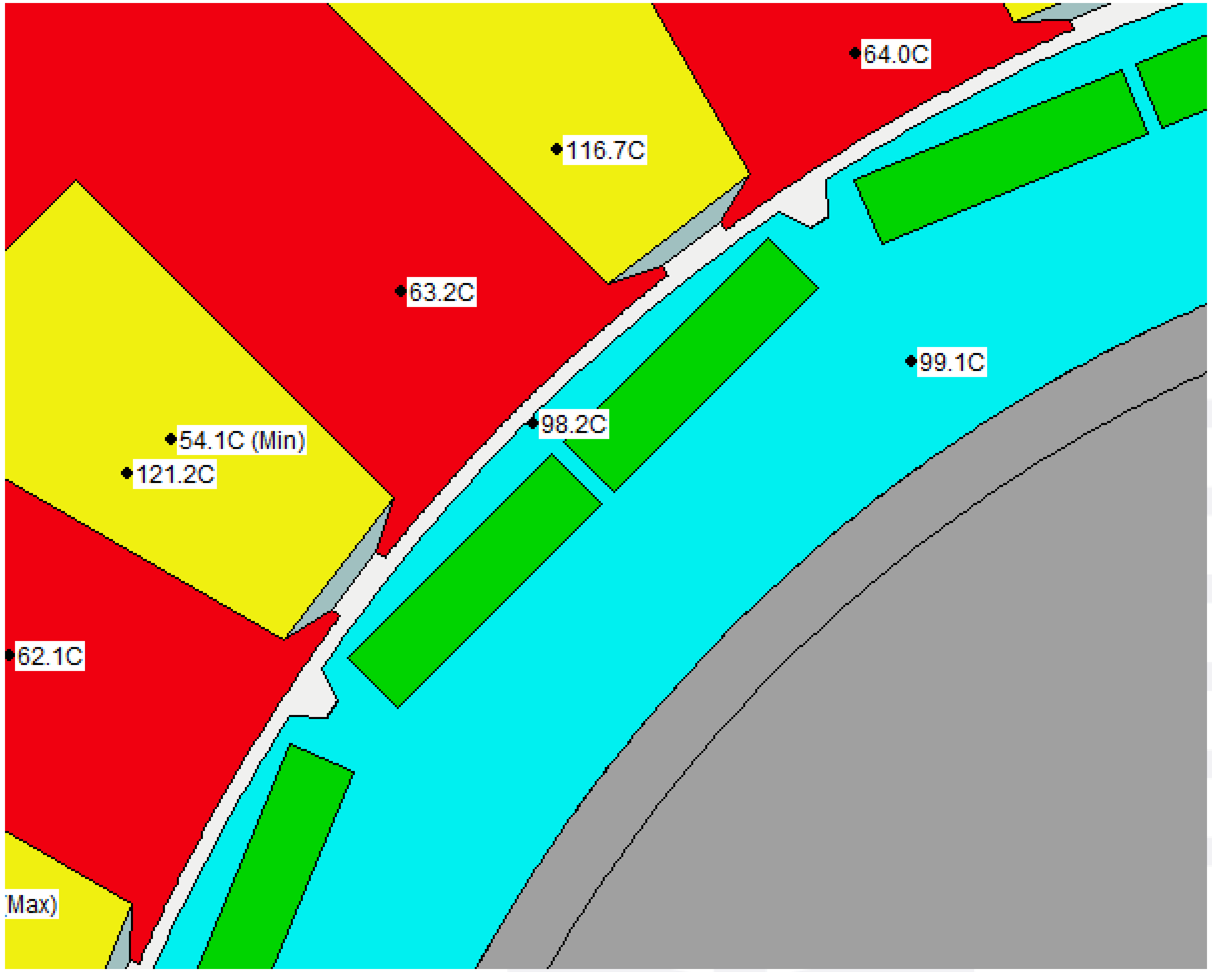
Flux plot (on-load)

Honda ACCORD Thermal Analysis

- We can predict the thermal performance using a lumped circuit thermal model or thermal FEA analysis



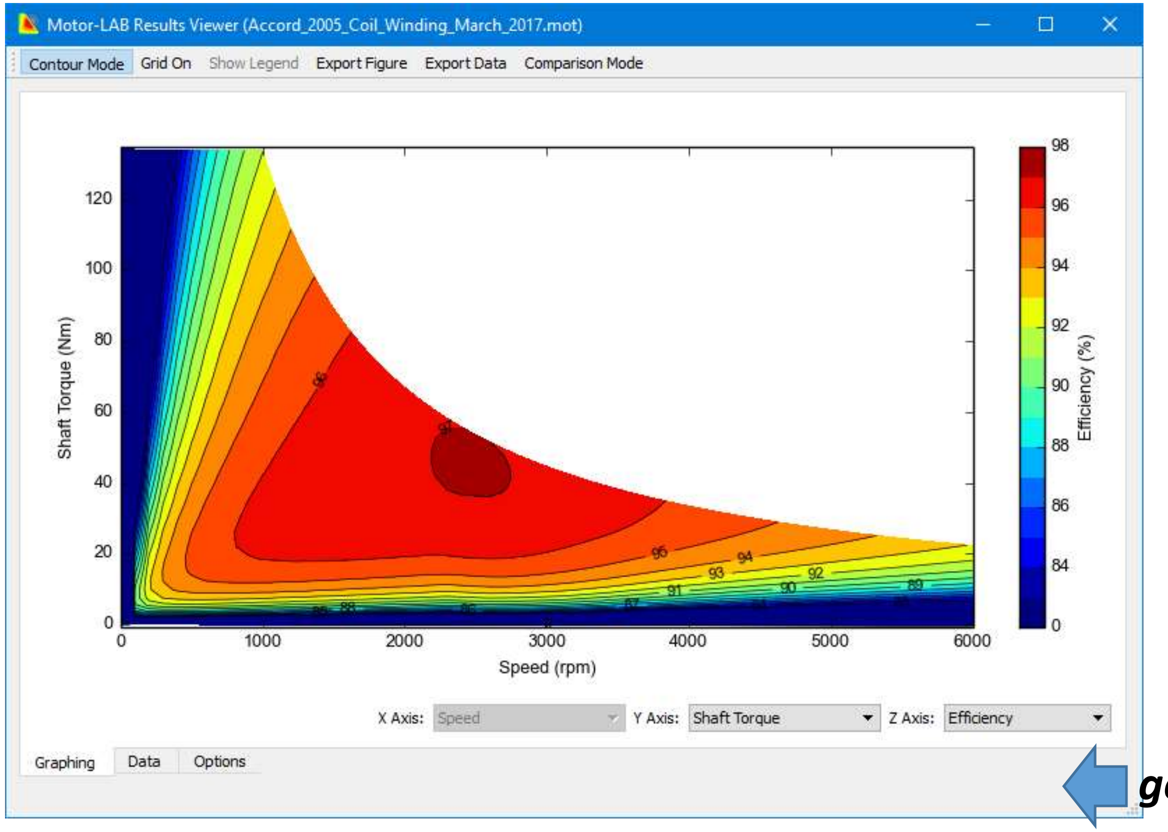
Thermal FEA Analysis for the Slot



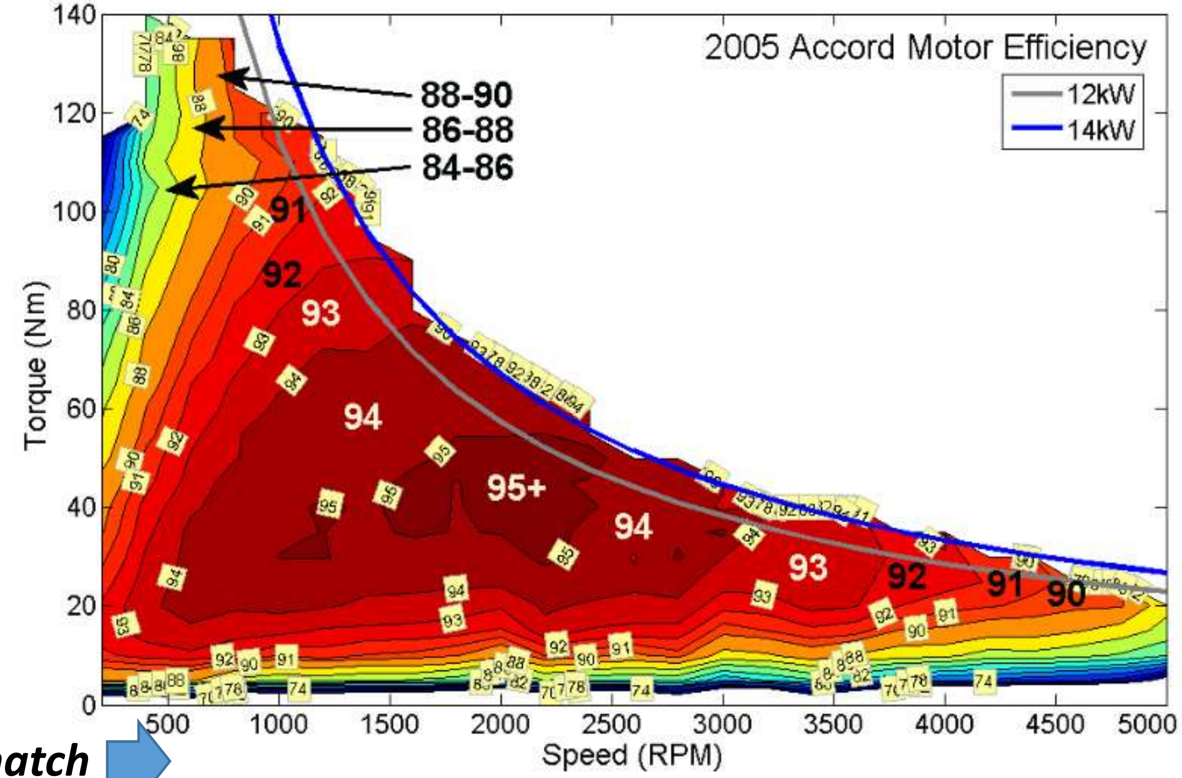
Lumped Circuit Nodal Temperatures

Honda ACCORD Efficiency Map

- We can calculate the efficiency map
- Apply a 14kW maximum power limit in this case
- We can validate the electromagnetic model by comparing with test data



good match



Calculated Efficiency Map **Measured Efficiency Map**

2004 Toyota PRIUS

- Teardown and benchmarking data available on the ORNL web site for Toyota Prius motors (2004 Prius shown here)
- We can use the data to set up electromagnetic and thermal models

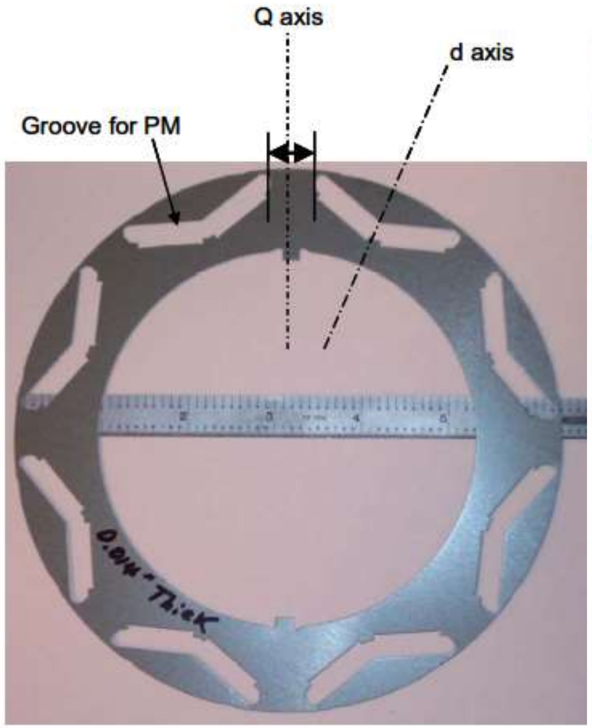
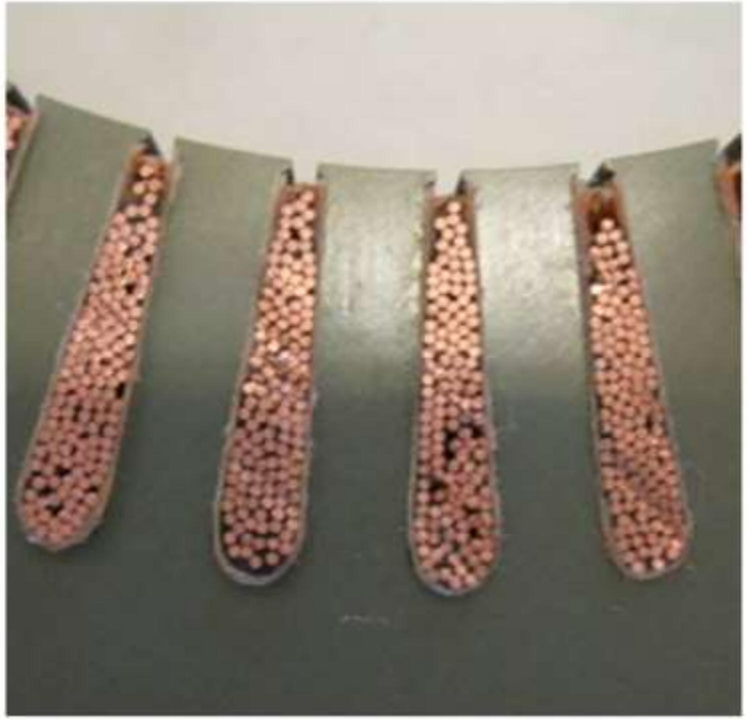
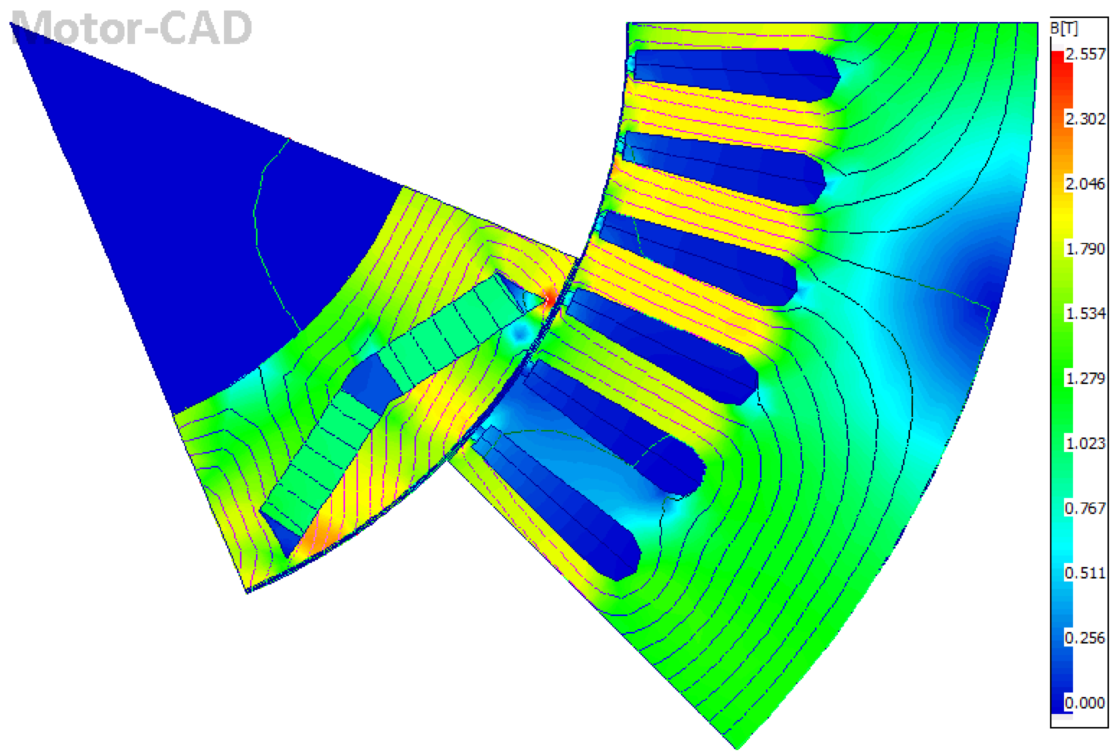


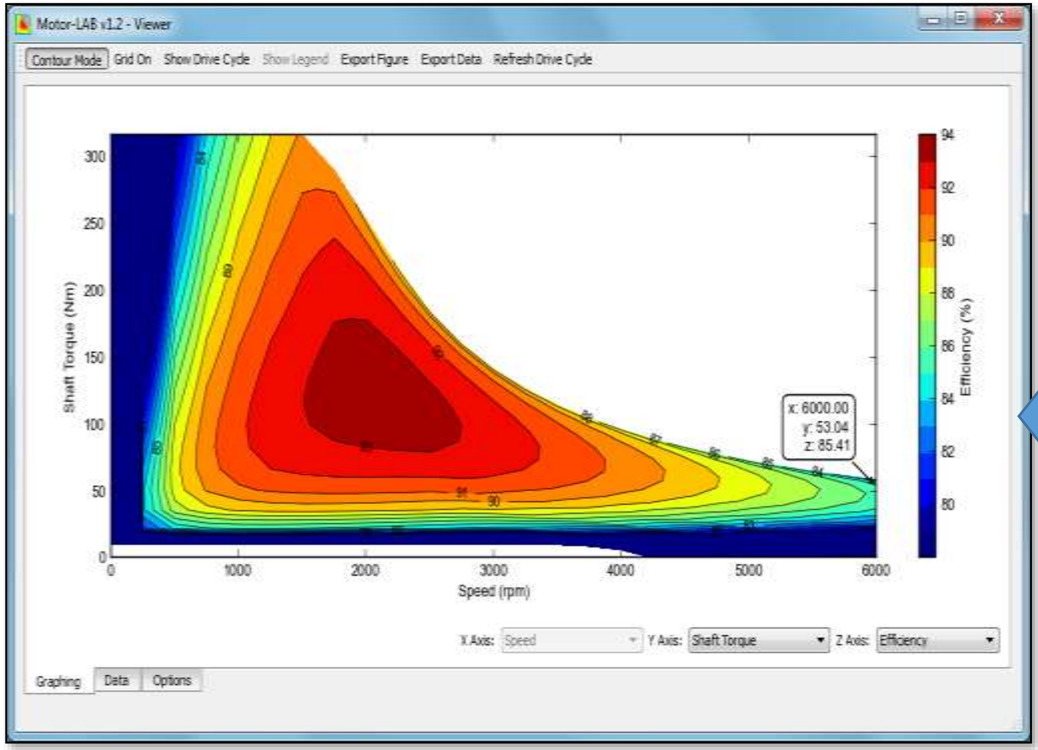
Fig. 12. Prius 2004 rotor punchings.





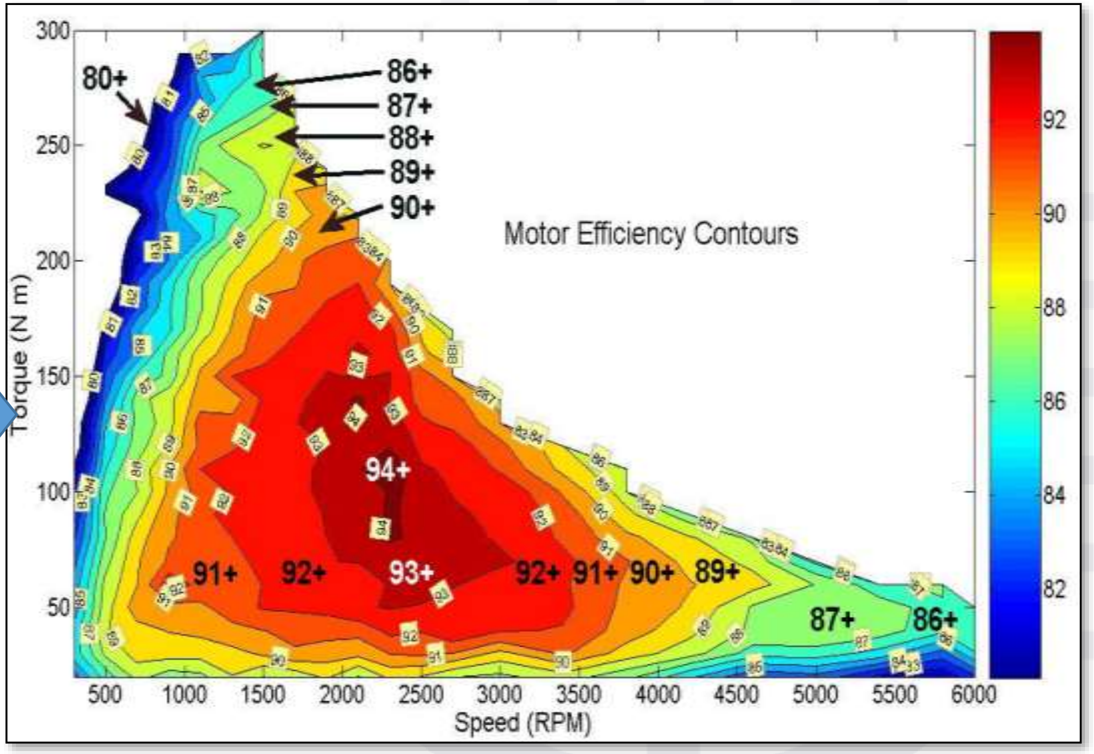
2004 Toyota PRIUS Efficiency Map Validation

- Validation based on Toyota 2004 Prius test data from ORNL published at PEMD 2012
- Excellent match between measured and calculated efficiency map



Calculated Efficiency Map

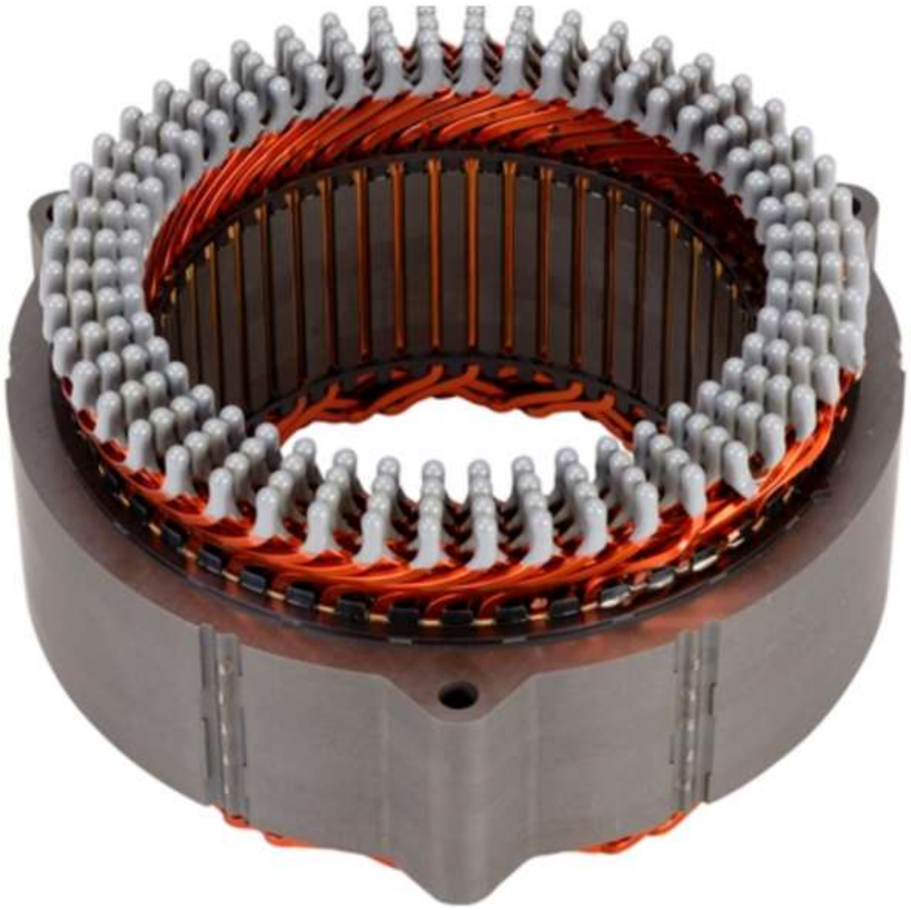
good match



Measured Efficiency Map

2017 PRIUS Plug-in Dual Motor Drive System

- The newest PRIUS now uses a Hairpin winding



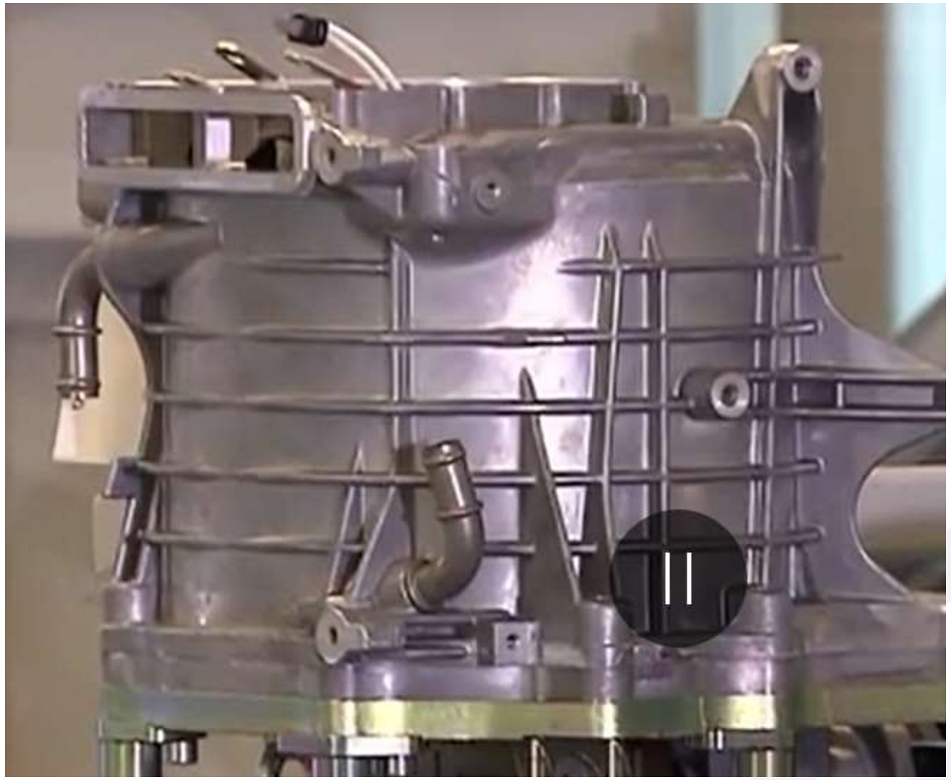
Picture from IEMDC Tutorial by James Hendershot (MotorSolver) and Timothy Burress ORNL, Miami, May, 2017

Chevrolet Volt (Gen 2)

- 50kW Ferrite and 100kW Nd-Fe-B IPM motors
- Hairpin windings
- EV range >50 miles but no fast charge

BMW i3

- 125kW NdFe-B- IPM Motor
- 18.8 kWh lithium iron battery (range extender option)
- Around 80 mile range
- New model has 115m range with larger 33kWh battery
- Video’s online showing motor construction

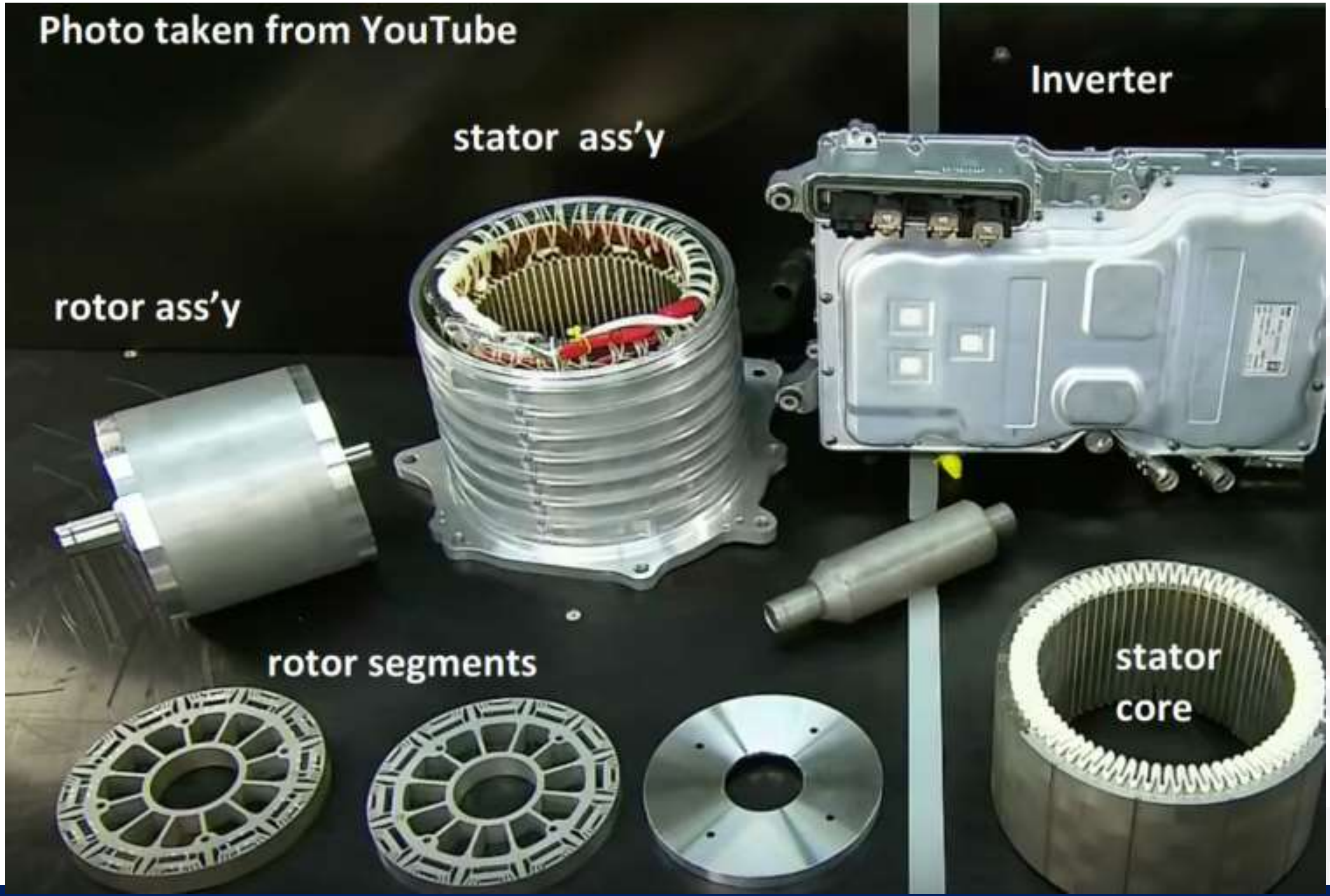


BMW i3 (Manufacturing Videos)

- Several motor manufacturing videos on the internet:
  - https://youtu.be/SWlNpwlq71k
  - http://youtu.be/2uz-Lv2qUA8
  - https://youtu.be/DHRqPT4c2xg

Published Data for the BMW i3 (ORNL)

- Recent tutorial at IEMDC (Miami, May, 2017) by James Hendershot (MotorSolver) & Timothy Burress (ORNL) showing a teardown analysis of the BMW i3



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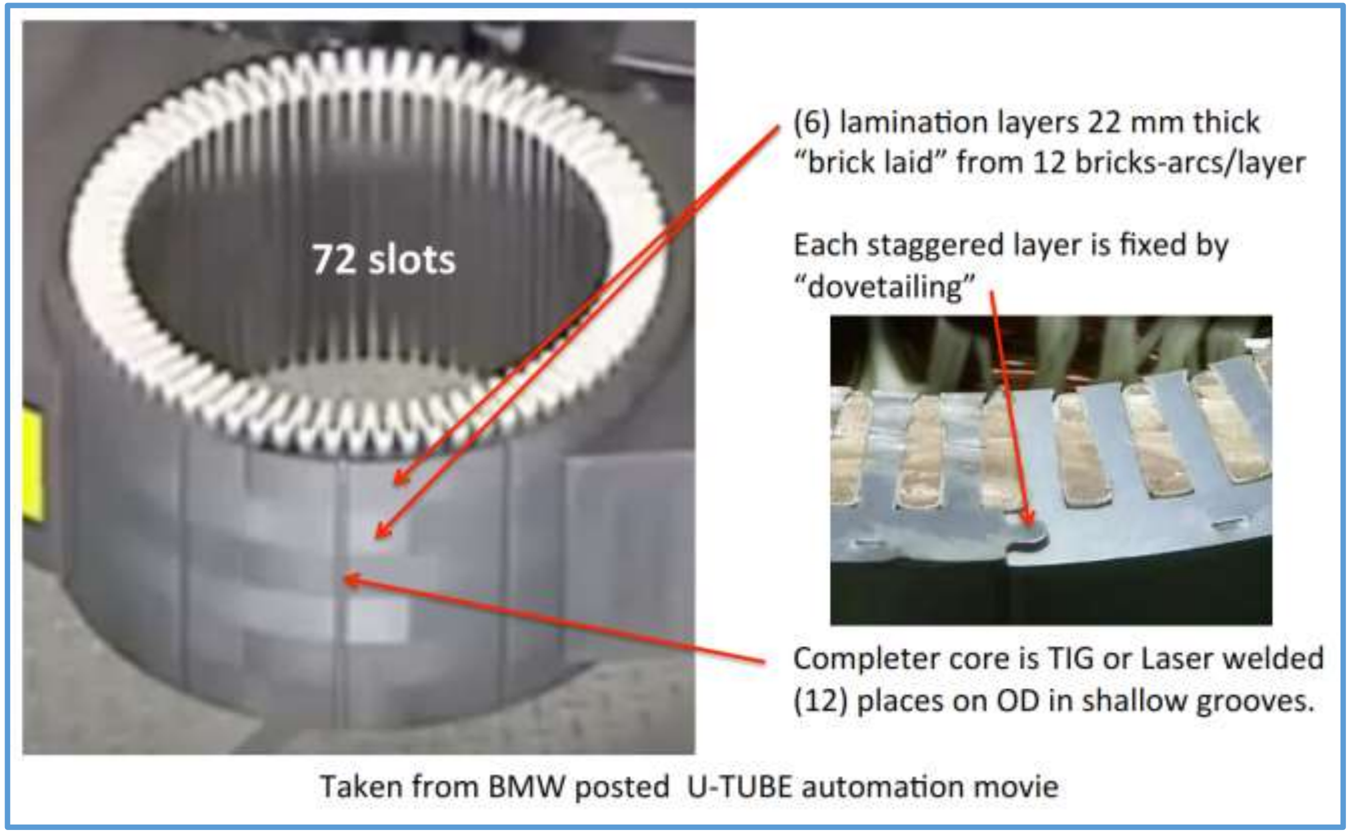


Published Data for the BMW i3

- We will now look at the teardown/benchmarking process that has just been started by Drive Systems Design (DSD) in the UK
- This is on a BMW i3

DRIVE SYSTEM DESIGN

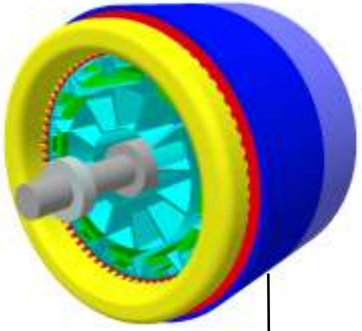
www.drivesystemdesign.com

DSD i3 Motor Benchmarking Study

Expanding e-machine capabilities and providing correlation baseline

DRIVE SYSTEM DESIGN

Motor Design Limited



Stripdown and inspection

- measurement of physical dimensions
- resistance testing
- insulation testing

Modelling

Characterisation

- o/c test for EMF waveform
- friction & windage loss test

Loaded tests

- Efficiency map
- torque vs speed
- torque vs current angle

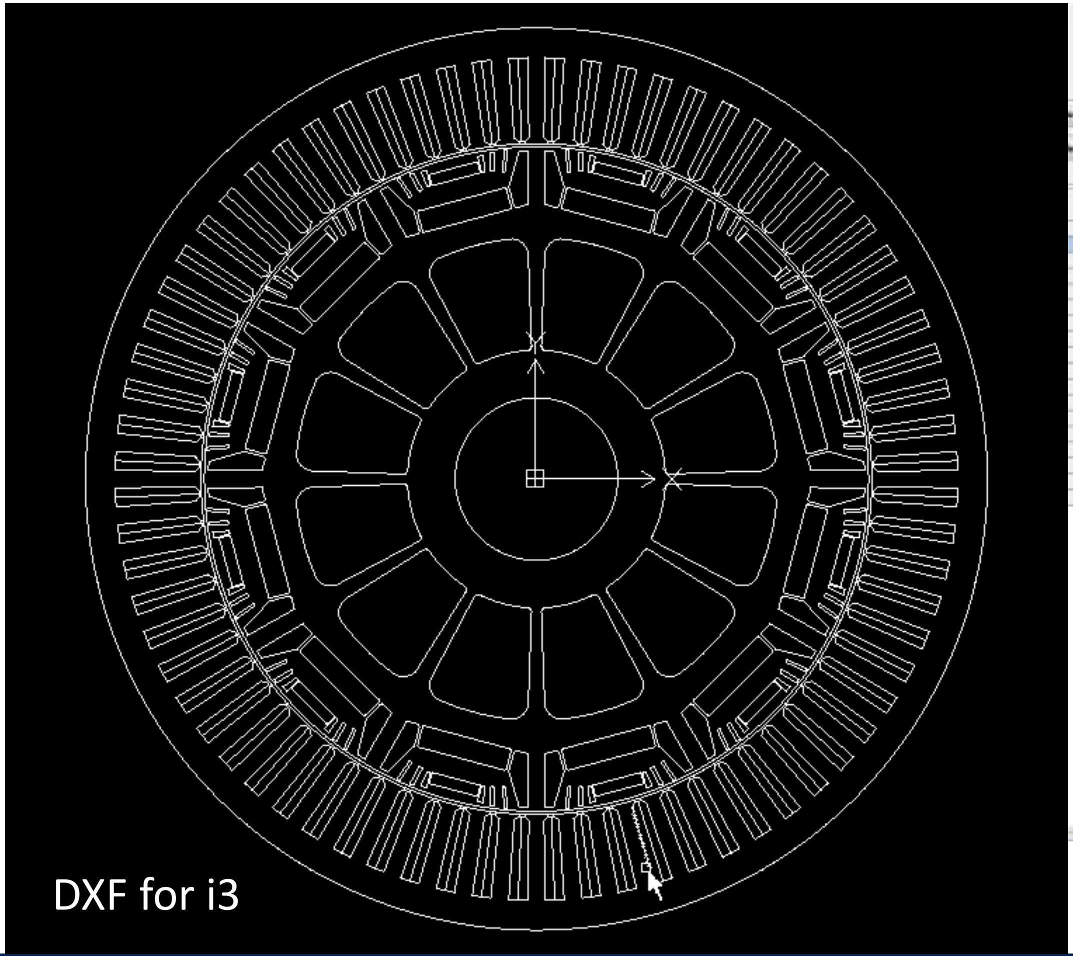
Today

Model correlation

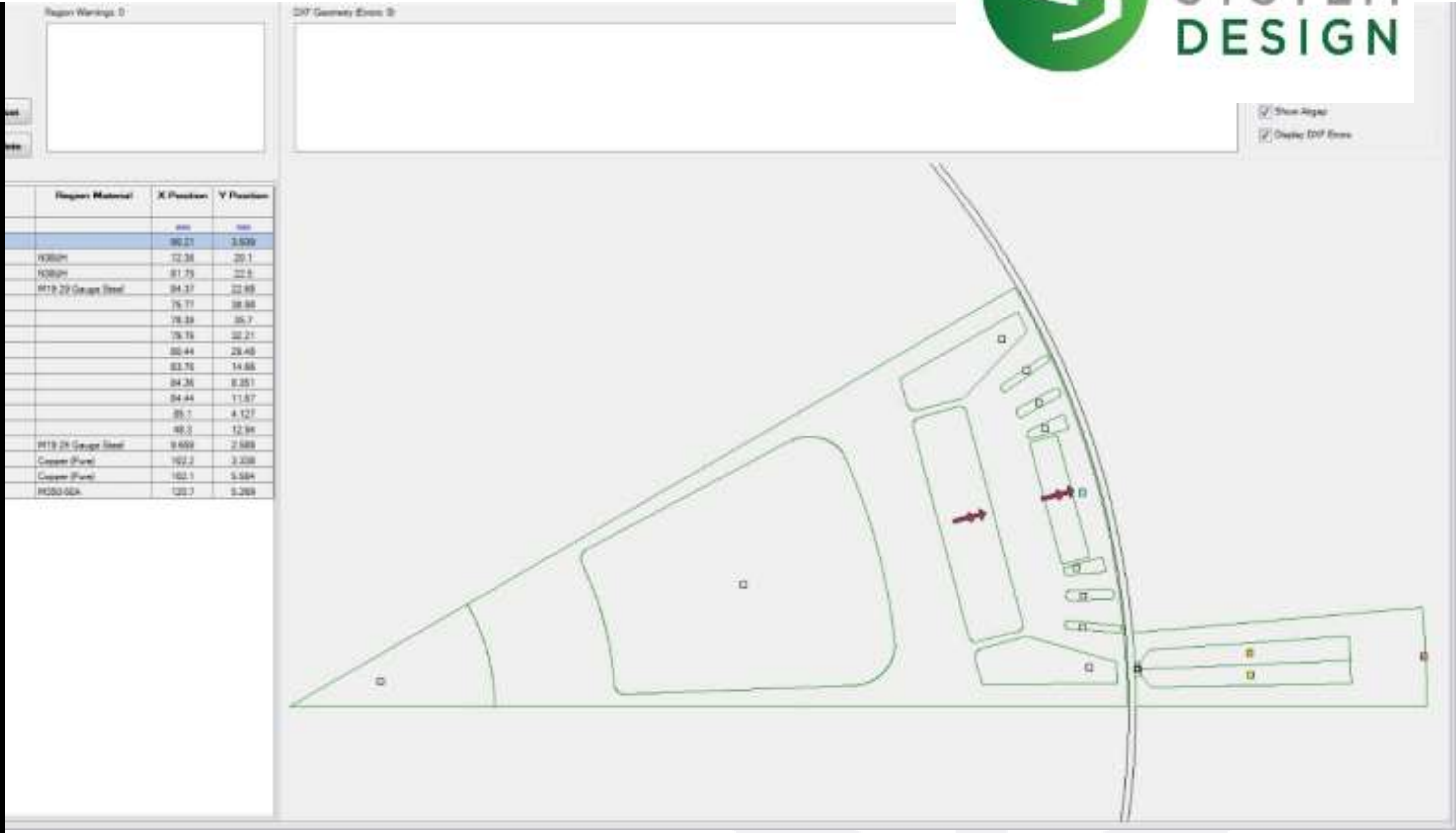
James will review the model correlation process at the end of the presentation

DSD Teardown Analysis of i3 Motor

- After teardown the stator and rotor dimensions are measured and converted into a CAD geometry – these can be used as input for our electromagnetic calculation



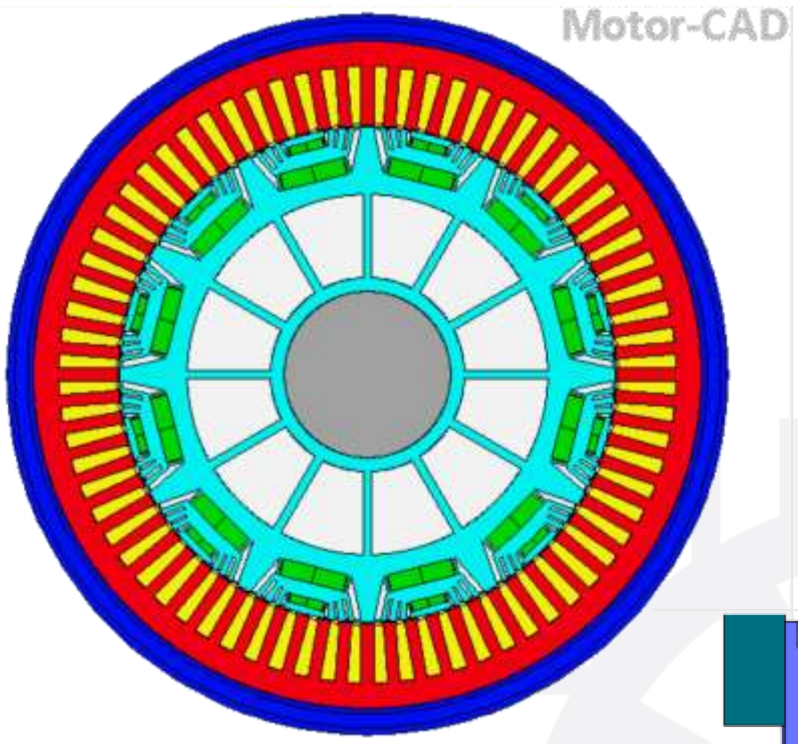
DXF for i3

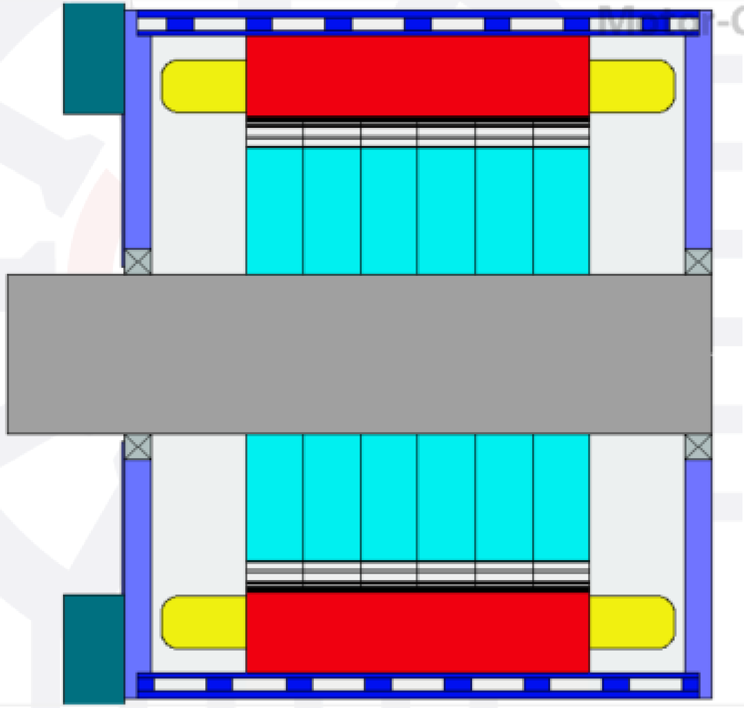


DXF for i3 imported to Motor-CAD to carry out EMag analysis

BMW i3 Motor Geometry

- Rather than use the CAD (DXF) geometry for the EMag calculation we can use a standard template in Motor-CAD software that gives nearly the same geometry and prediction of performance
- Advantage of template geometry is that parameterised so can do parametric studies.
- 72-slot, 12-pole, double layer IPM motor
- We can also see the rotor cooling channels





Motor Design Limited

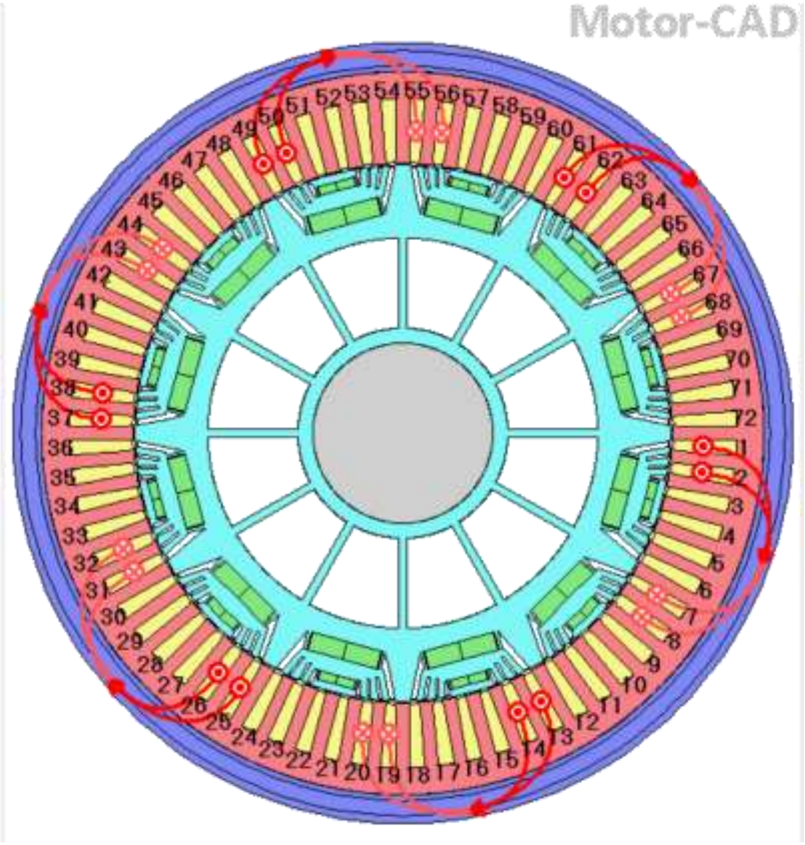
DRIVE SYSTEM DESIGN

BMW i3 Winding Design

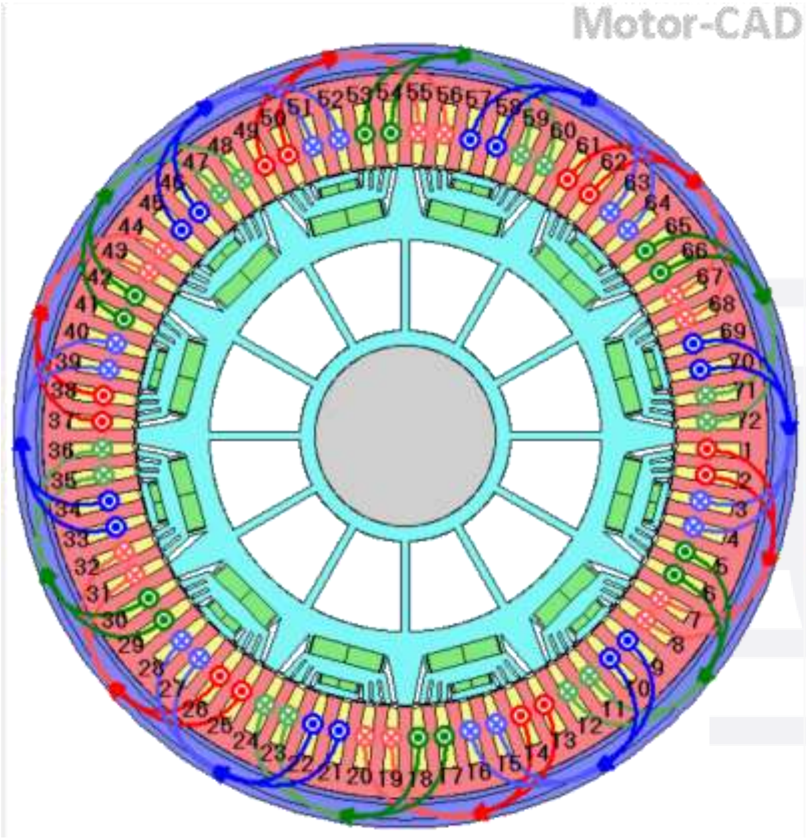
DRIVE SYSTEM DESIGN

Motor Design Limited

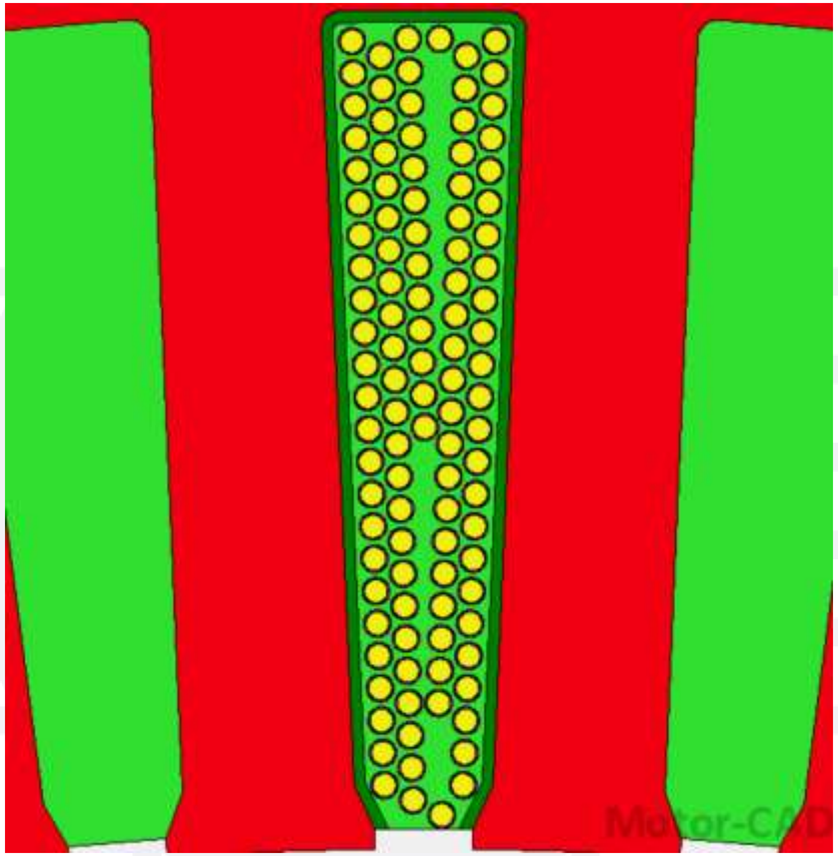
- 72 slots with distributed winding



Phase A Turns



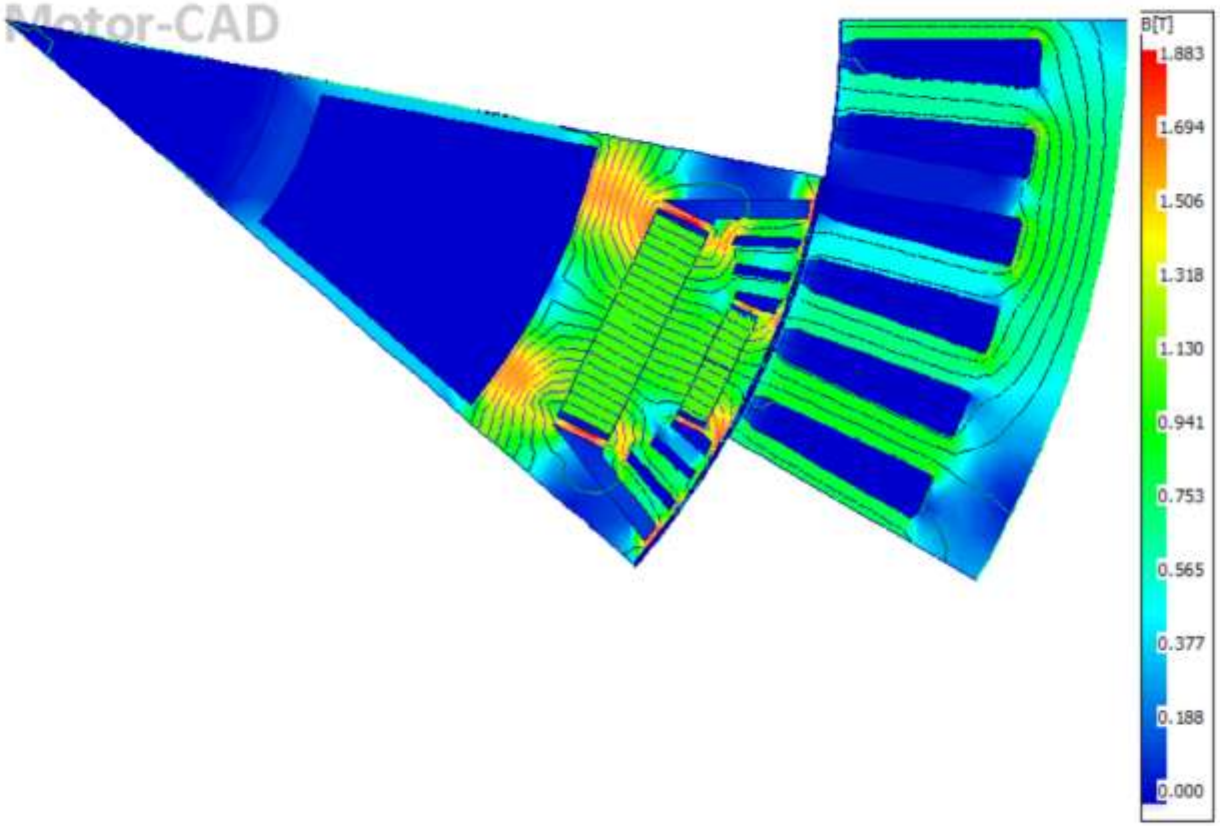
All Phases



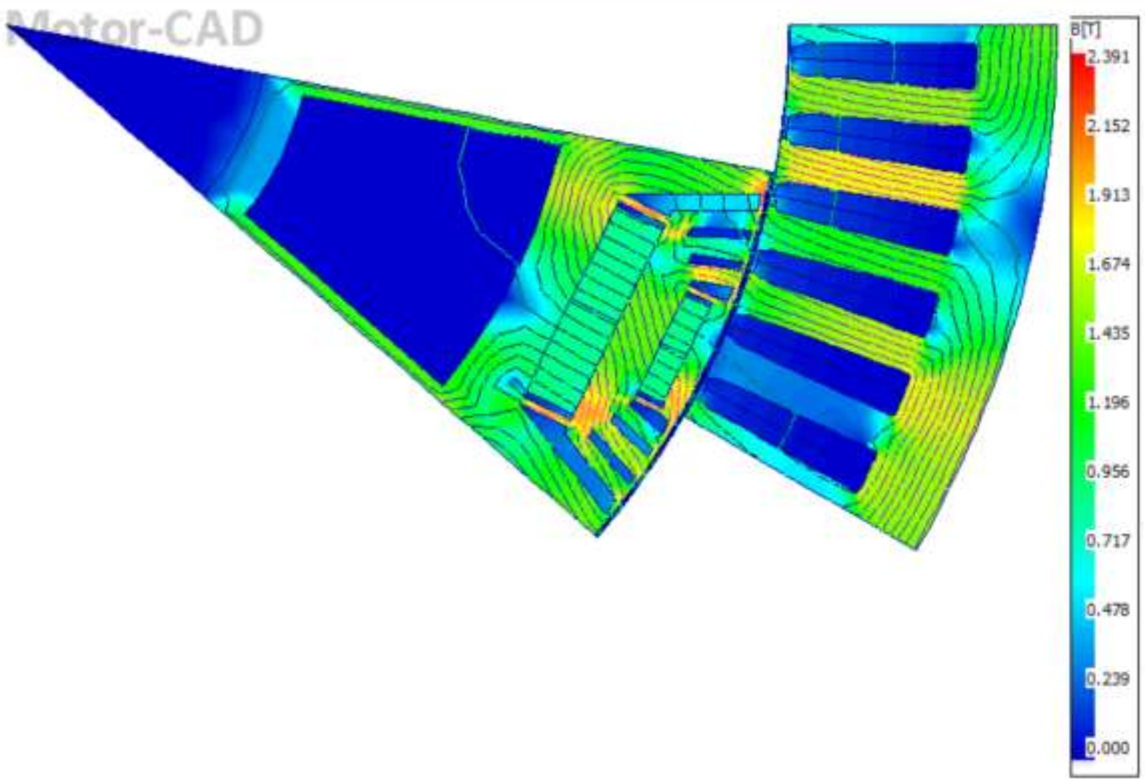
Conductors in Slot

BMW i3 Electromagnetic Analysis

- We can calculate the open-circuit and on-load electromagnetic performance (template geometry)



Open Circuit Flux Plot (Template Geometry)



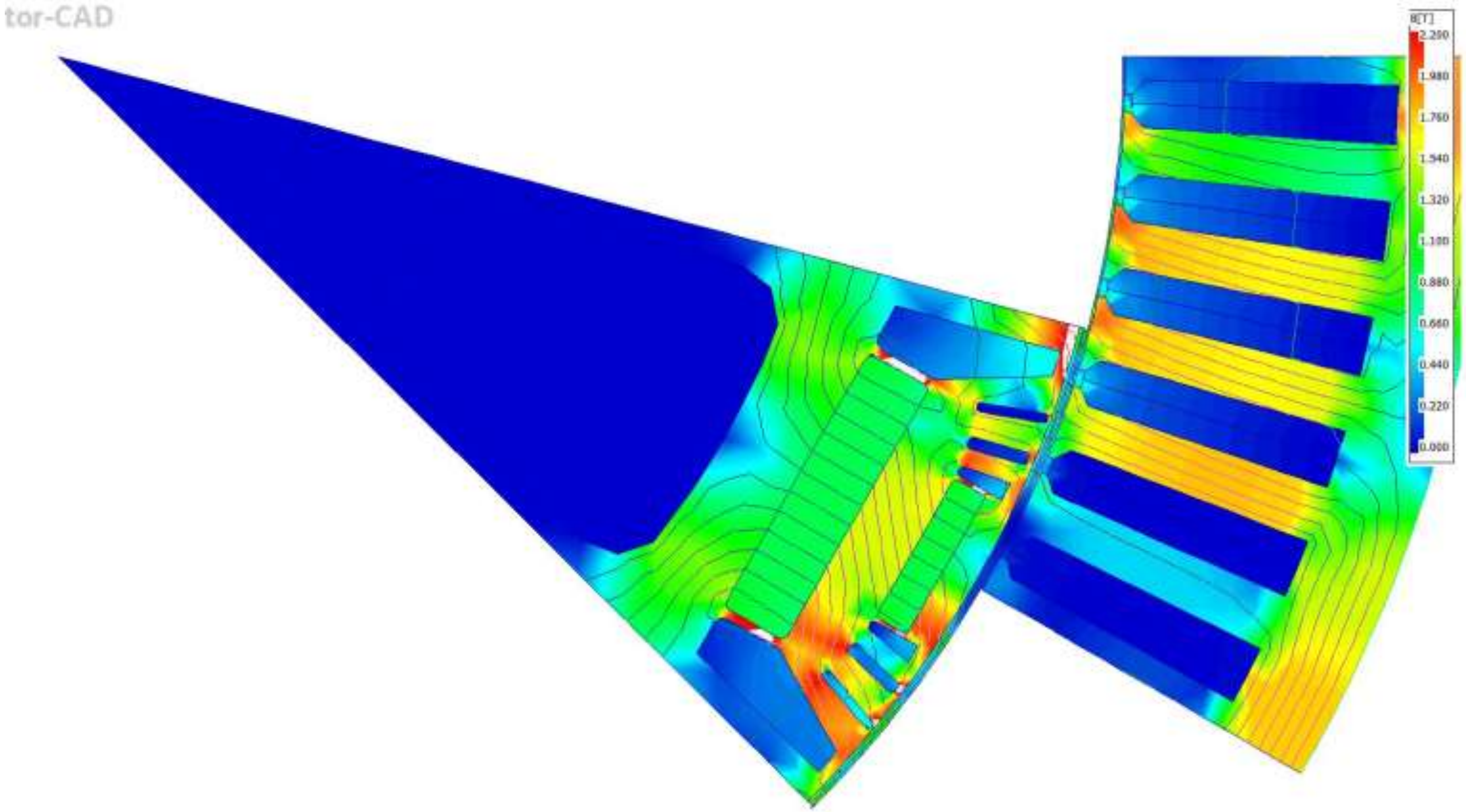
On Load Open Circuit Flux Plot (Template Geometry)

BMW i3 Electromagnetic Analysis

Motor Design Limited

DRIVE SYSTEM DESIGN

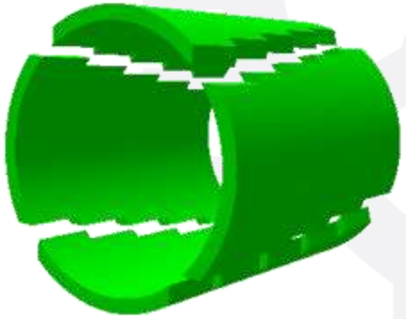
- Electromagnetic calculation based on the CAD (DXF) geometry)



BMW i3 Electromagnetic Analysis

- Due to the 6 slice step skew used on the rotor the back emf has good sinusoidal performance

- Motor-CAD calculates the optimum step skew angles
- An FEA calculation is done for each slice
- The calculation is made faster by using separate treads for each slice



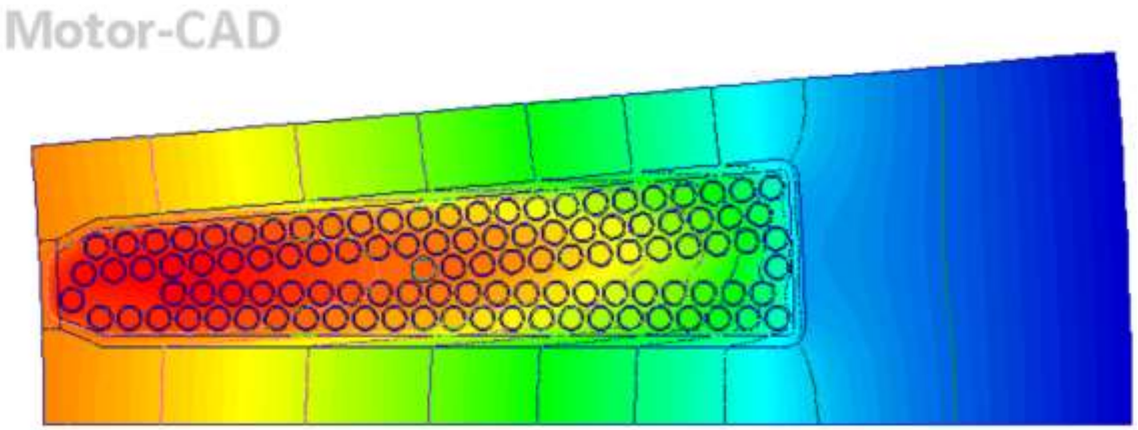
Skew:
Skew Type:
- None (default)
- Stator
- Rotor (selected)

Stator Skew: 0
Rotor slices: 6

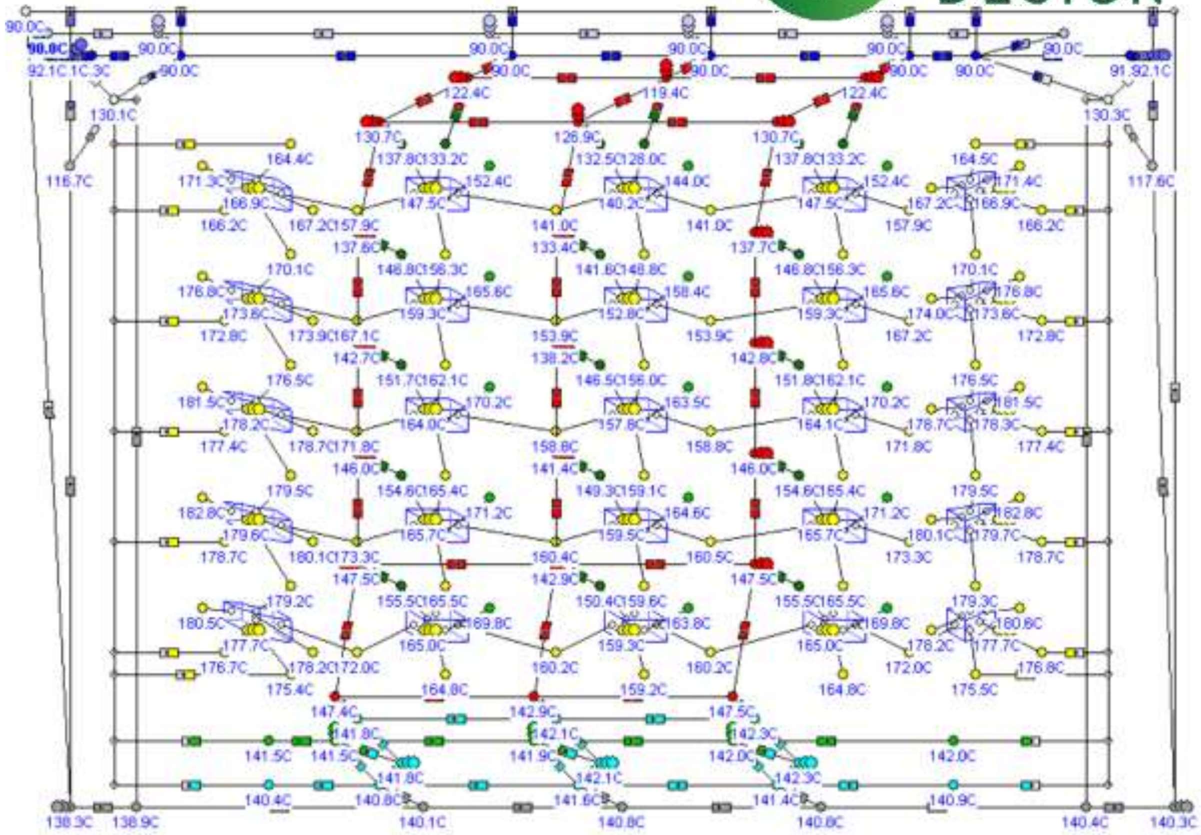
Slice	Proportional Length	Angle
		Mech Deg
1	1	-2.08333
2	1	-1.25
3	1	-0.416667
4	1	0.416667
5	1	1.25
6	1	2.08333

BMW i3 Thermal Analysis

- We can predict the steady-state or transient thermal performance using a lumped circuit thermal model
- We can vary the 3D thermal resistance resolution in both axial and radial directions to capture hotspots
  - Required if large component of ac loss in the winding or improved cooling at one end of the motor



Thermal FEA Analysis for the Slot



Lumped Circuit Nodal Temperatures

Summary:

- Many teardown and benchmarking studied are performed by OEM, Tear 1 and other companies and research institutions
- Some benchmarking studies are made open source
- Modelling a teardown motor assists in understanding why they have certain performance characteristics and helps identify difficult to measure quantities in the teardown analysis
- Benchmarking studies allow comparisons of different technologies and manufacturing processes
- Benchmarking study models can be used as starting point for new designs
- State of the art motor design software allows design variables to be studied very quickly enabling optimal motor design

Electromagnetic and thermal model validation procedure for PMSMs

Outline

- Overview of test procedure
- Electromagnetic model validation example
- Loss model validation example
- Thermal model validation example

Definitions

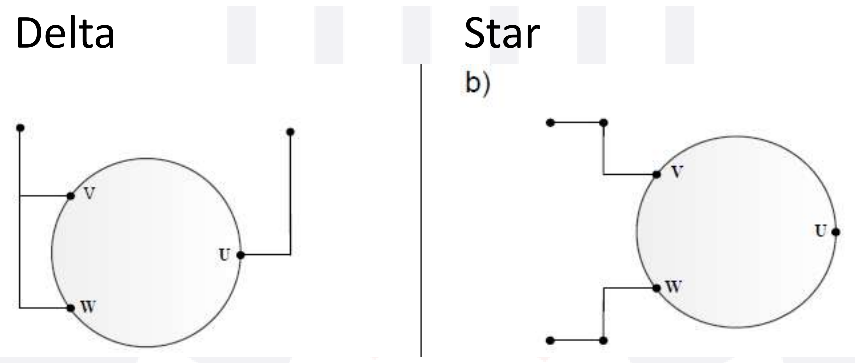
- MUT (machine under test)
- Steady state - <1^{o}C temperature change from ambient in 20 minutes.
- Soaking – Using the coolant temperature to get machine to a consistent temperature before undertaking a test.

Notes on measurement

- Multiple thermocouples in each component of the machine and each phase as well as measurement of the housing, plate, test bed and ambient.
- Torque transducer, high accuracy at low Nm is very useful for measurement of losses.
- Rotor temperature measurement is not often available however can been reasonably well estimated for measurements of open circuit EMF.

Test procedure

1. DC test
   - DC current is applied to the windings of the machine with a static rotor, until steady state is reached. Can be done at different current levels
   - Used for calibration of the thermal model.
   - Ideally all phases can be connected in series to give an equal current in all the slots. Otherwise if star use two phase. If delta shorted phase. Consider where thermocouples are placed.
   - Important to measure voltage drop at the machine terminals not the power supply. Use this with measured current to derive the loss in the machine.
   - If the machine is coupled to a large plate on the rig this test can be done with the MUT and off the rig. This enables calibration of any influence of the rig on cooling. This effect should not be underestimated!



Test procedure

2. Dummy rotor

- Either the rotor is replaced by non-magnetic rotor or magnetic rotor is spun in an empty housing.
- At different speeds torque is measured to calculate friction and windage loss.
- Windage losses are usually small and can be estimated through a simple calculation.
- Frictional bearing losses are very often higher than expected and can contribute to significant unexpected temperature rise in the rotor.
- A high resolution torque transducer is essential, often it's best to use 2 different transducers for the low torque and high torque tests.
- Do the measurement in both rotational directions then average, there is typically a small offset on the torque measurement.

Test procedure

3. Open circuit test (transient)

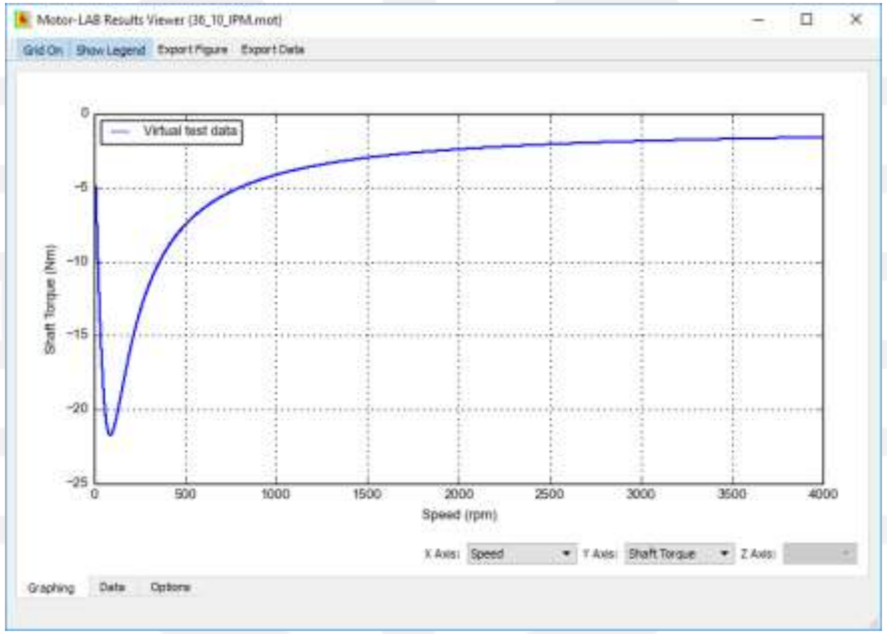
- The machine is spun at different speeds with no inverter connected and the terminals open circuit.
- The test is fast and machine only held at each speed for a few seconds while the measurement is taken.
- The shaft torque is measured to deduce the losses at different speeds.
- The voltage is also measured at the different speeds.
- An oscilloscope can also be used at one low speed condition to measure the shape of the EMF waveform.
- A high resolution torque transducer is essential, often it’s best to use 2 different transducers for the low torque and high torque tests.
- Do the measurement in both rotational directions then average, there is typically a small offset on the torque measurement.
- Smoothing or filtering the torque transducer output can be helpful so that average torque is measured.

Test procedure

4. Short circuit test (transient)

- The machine is spun at different speeds with no inverter connected and the terminals short circuited.
- Again the test is fast and machine only held at each speed for a few seconds while the measurement is taken.
- The shaft torque is measured to deduce the losses at different speeds.
- The current induced in the windings is measured.
- Make sure the cable used to short circuit the windings is not long (ideally <30cm), otherwise it can add extra inductance to the machine terminals.
- A high resolution torque transducer is also useful although the peak torque can be quite high during this test.
- Do the measurement in both rotational directions then average, there is typically a small offset on the torque measurement.
- Take the measurement rapidly to try to avoid significant temperature change during the test. Machine can be soaked beforehand.

Short circuit torque characteristic



Test procedure

5. Torque Vs. Current Angle

- Machine is operated under load. The current is kept steady and phase advance varied from 0-90 degrees in consistent steps. This can be repeated at various current levels.
- Torque is measured.
- Ideally this is automated so the test is done quickly and temperature doesn't vary between points.
- Machine can be soaked to a single temperature before the test.

Test procedure

6. Thermal steady state

- The machine is measured at various on-load points. Different operating speeds and currents. Can also be done at short circuit if machine design is suitable.
- If open circuit losses are high it is also very useful to run to steady state temperature at high speed on open circuit.
- Thermocouples should be sampled regularly and data stored (every 30s for example).
- As with DC test, as well as the machine, the coolant, housing, test bed, mounting bracket and ambient should be measured.

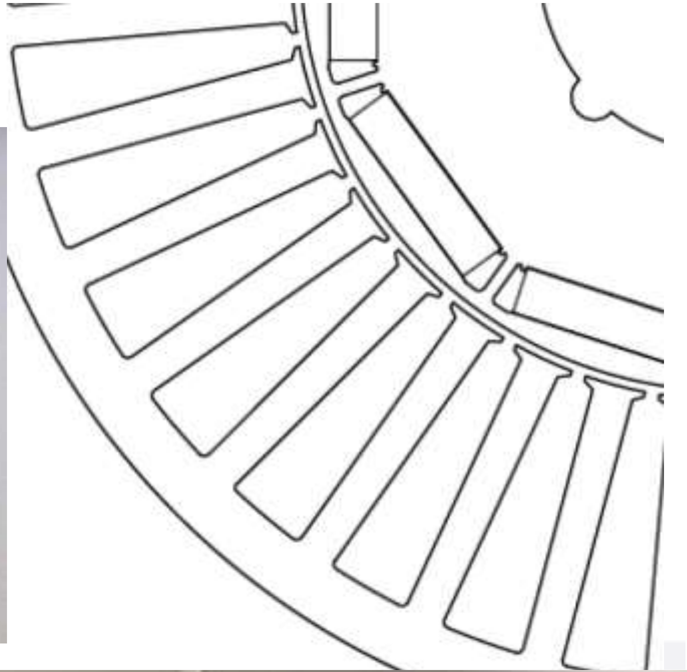
Test procedure

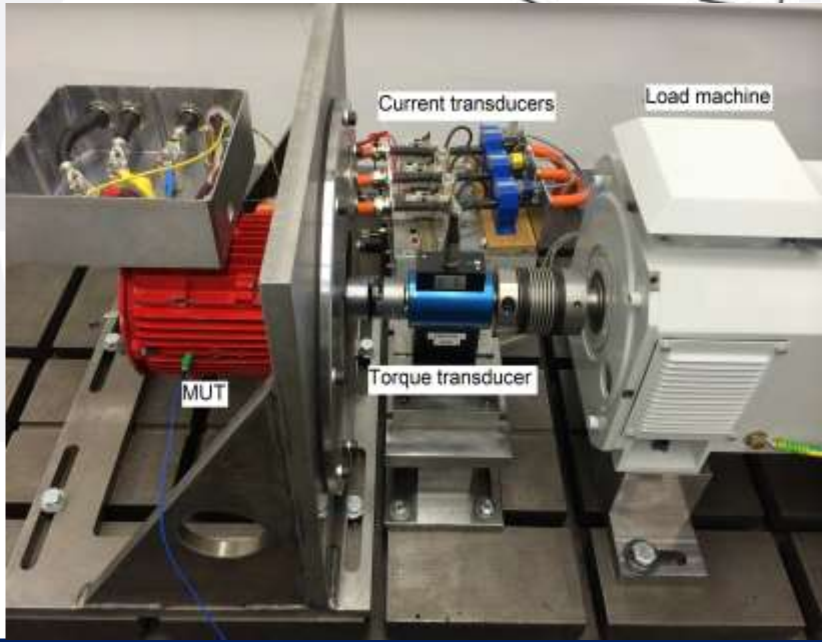
7. Torque/speed curve, Efficiency map measurement

- Many operating points are measured rapidly.
- Again ideal if temperature is consistent between points. This can be achieved with soaking, automation of the rig and modulation between high load, low load and high speed and low speed measurement points.
- Efficiency is notoriously difficult to measure. Smoothing or filtering the torque transducer output so that average torque is measured helps, otherwise peaks and troughs in the torque waveforms cause inconsistent measurements.
- To measure efficiency ideally the electrical input power and mechanical output power measurement should be synchronised.

Example test and validation

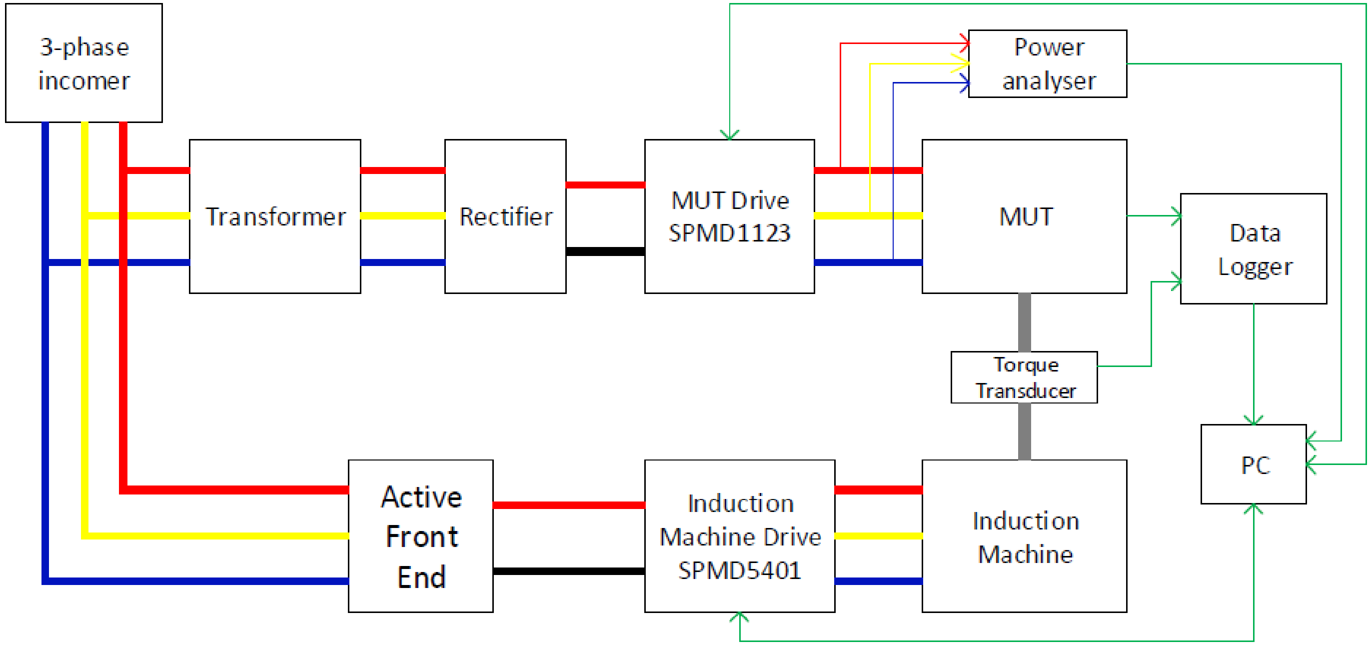
- 36 slot 10 pole machine
- Interior permanent magnet rotor
- Distributed winding
- 70Nm, 20kW peak
- 10,000rpm max. speed.





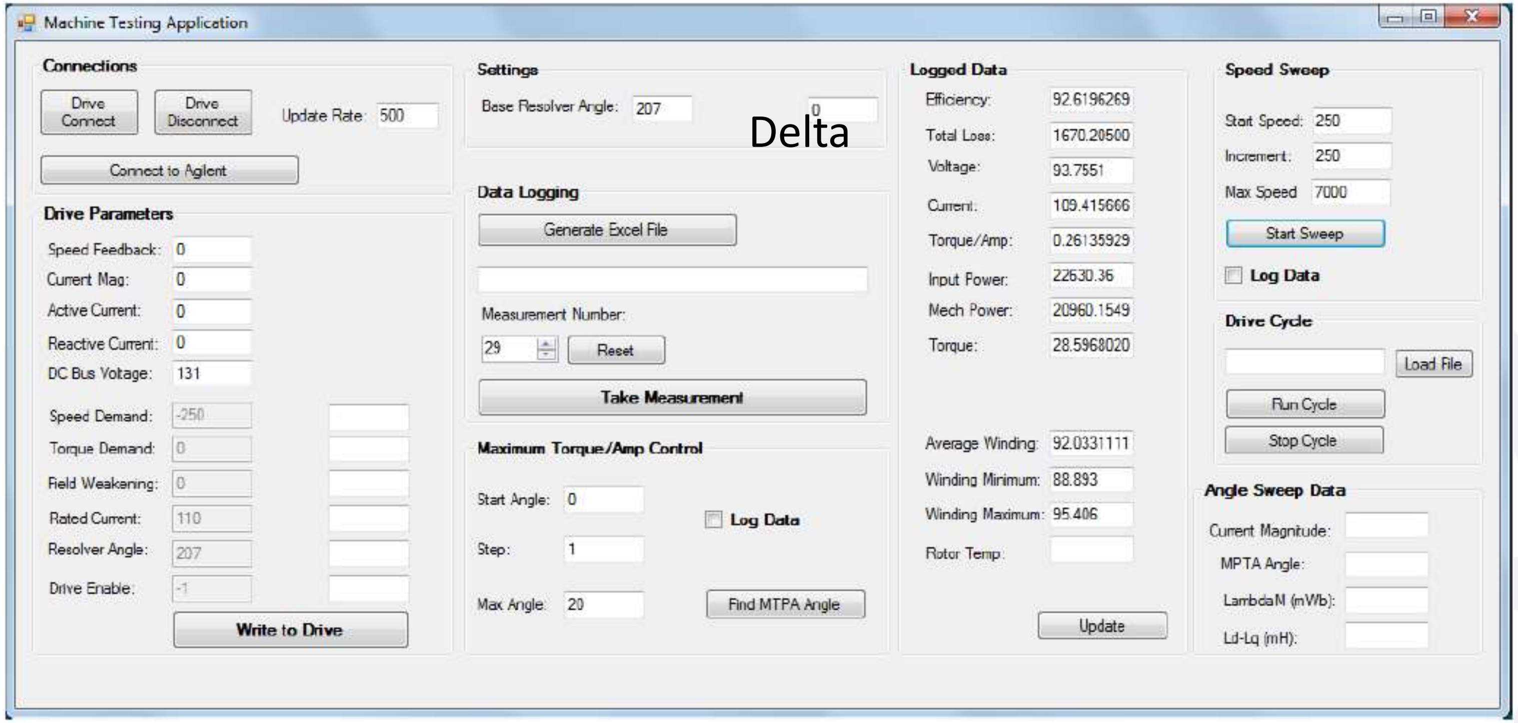
Test rig set-up

- Electrical quantities measured from power analyser
- Torque and speed measured from transducer
- Temperature measured from machine thermocouples
- All data fed into PC, PC also controls machine drives



Automation tool

- Fully automated rig
- Enables fast and accurate measurements
- Ensures repeatability of tests

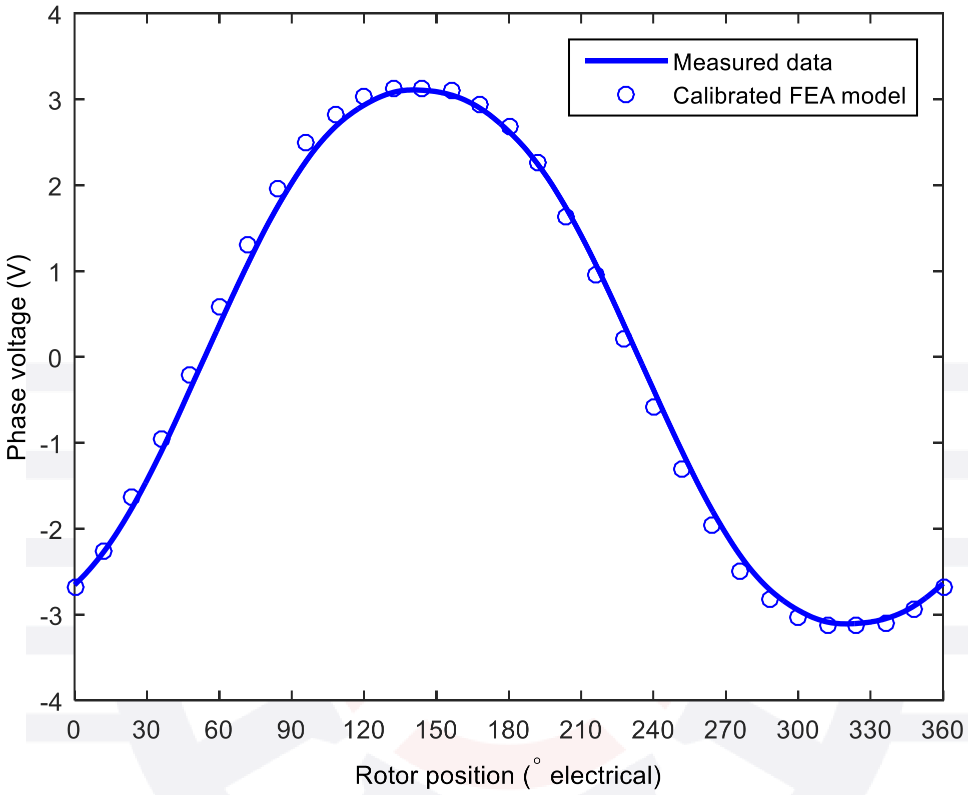


Overview of Validation Process

1. Electromagnetic parameter validation:
   - Back emf
   - Short circuit current
   - Torque production against current magnitude and angle
2. Loss model validation:
   - DC winding loss
   - Friction + windage loss
   - Iron losses
   - AC winding loss + magnet loss
3. Thermal model validation
   - DC static temperature rise
   - On load operation at various load points and frequencies

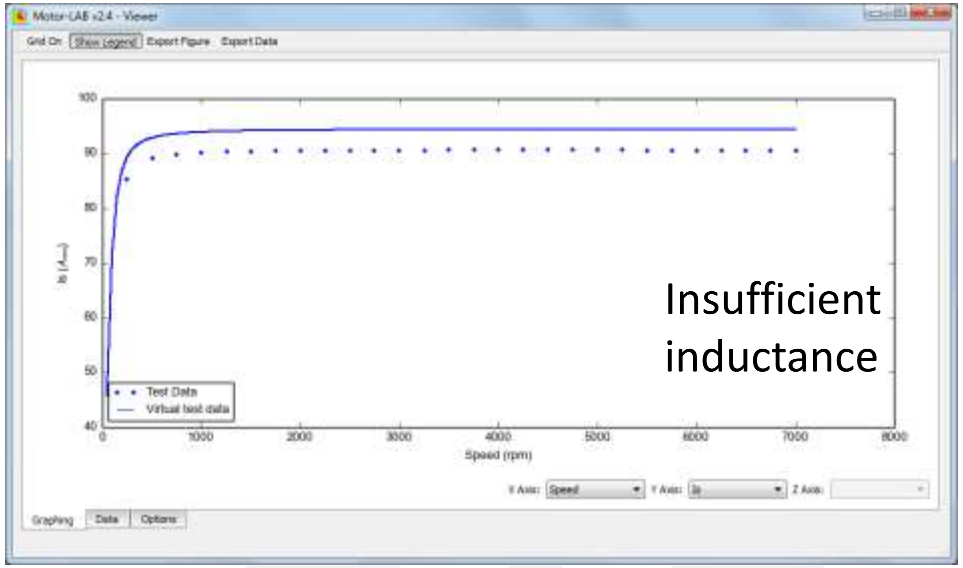
Electromagnetic validation

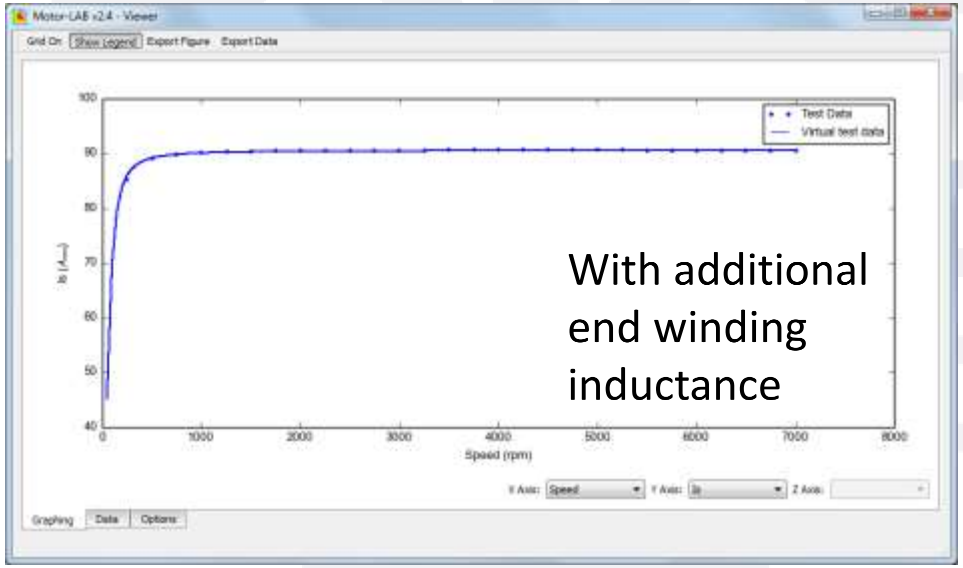
- Open circuit EMF at low speed.
- Validation of FEA modelling and magnet Br.
- Magnet Br can be adjusted, in this case modification wasn't required.



Electromagnetic validation

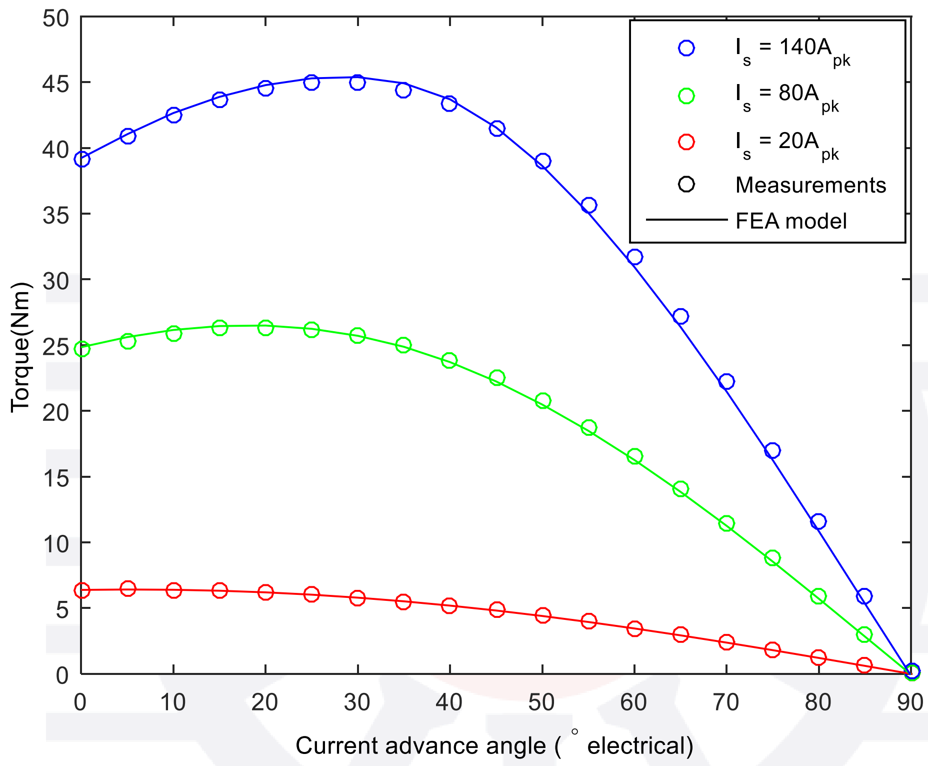
- Steady state short circuit current is measured
- Used to calibrate the end winding inductance
- 0.04mH required here
- Make sure test cable is not adding to inductance here!





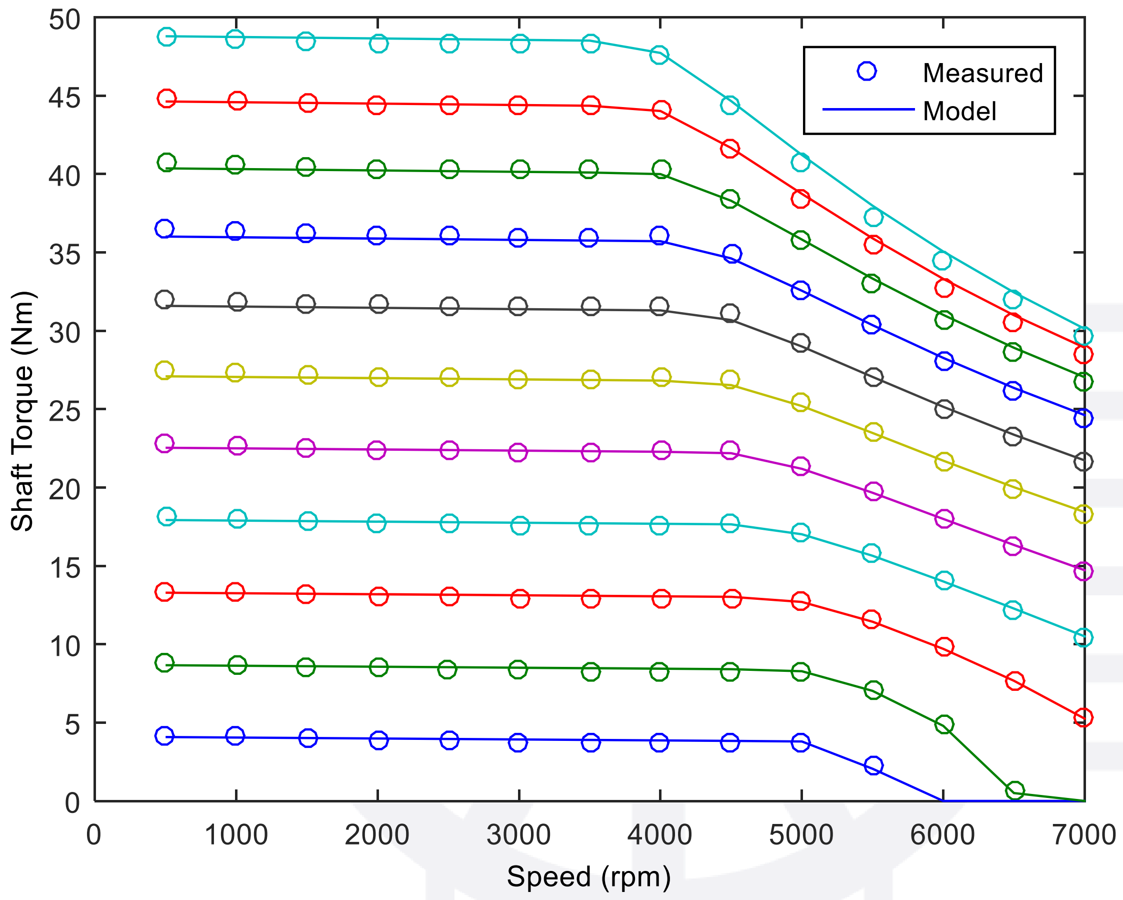
Electromagnetic validation

- Torque per amp and torque vs. current angle
- If BEMF is correct and this isn't then saturation characteristics may be wrong.
- Adjustment of B-H curve may be necessary
- Why?:
  - B-H need information required beyond 1.8T
  - Stacking factor causes increased saturation
  - End leakage effects occur during saturation
  - B-H steel properties affected during manufacturing process



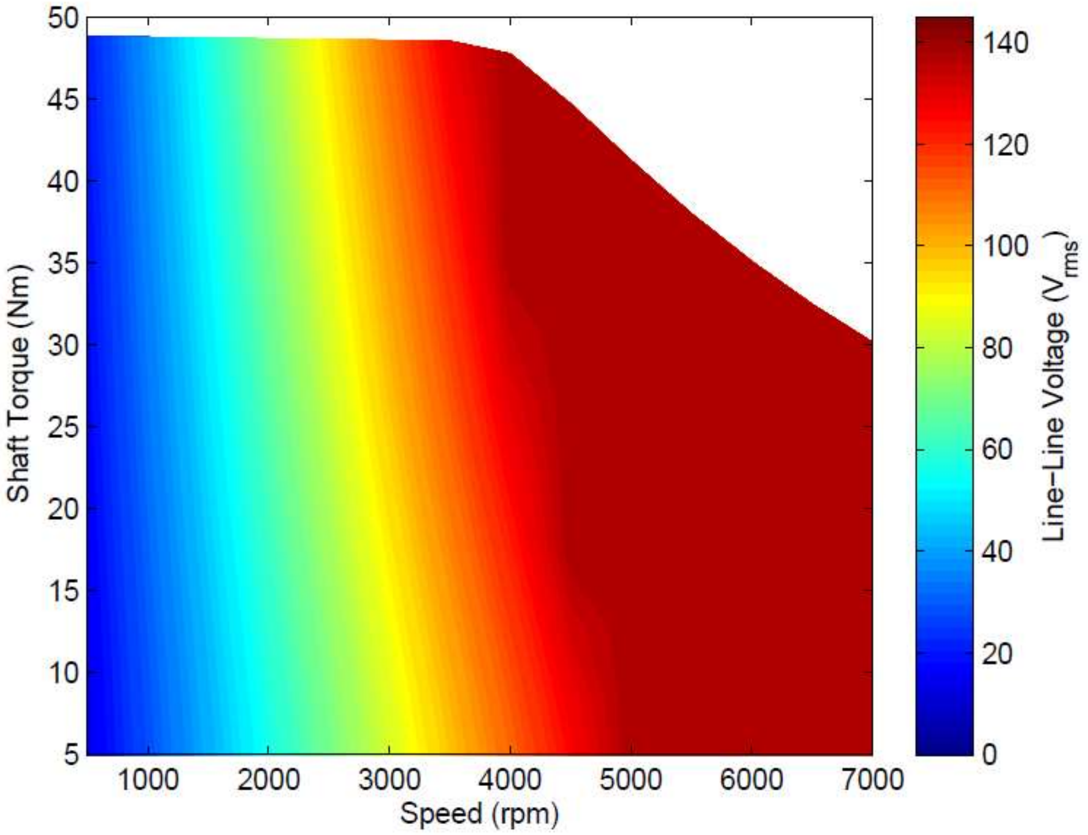
Electromagnetic validation

- Good correlation of torque across the full operating range.
- The MTPA operating points Id/Iq values for this measured map were calculated using the model.

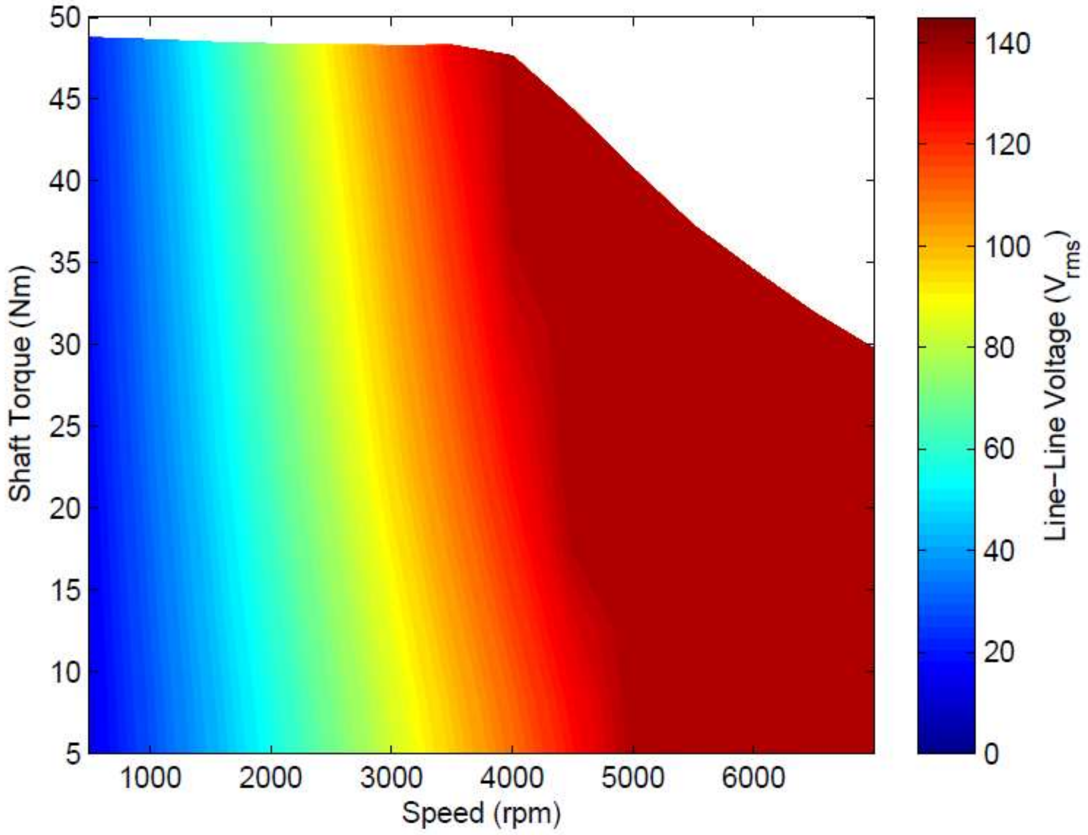


Electromagnetic validation

- Modelled voltage map



- Measured voltage map



Loss model validation –DC resistance

- DC resistance is measured at a known temperature from DC test. The end winding length in the model is then adjusted if necessary to match the resistance.

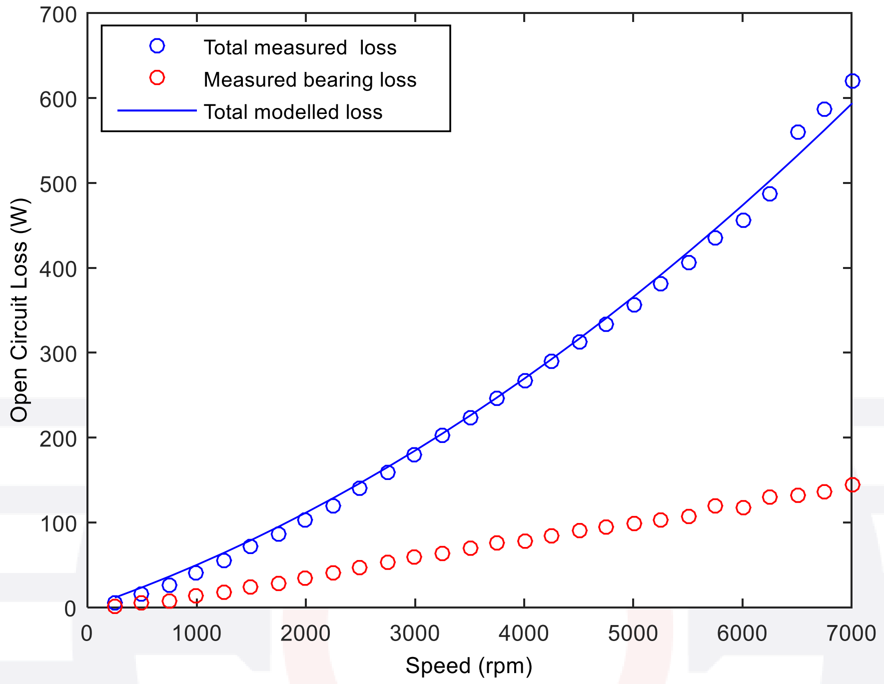
- Software assumes a semi-circular path from one slot to the other, this may not be the case in reality. ->

Manufacturing Factors:

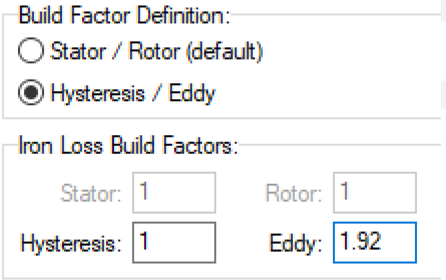
Stator EWdg length multiplier: 2.33

Loss model validation – Dummy rotor and open circuit losses

- In this case rotor is spun in an empty housing without stator and the torque measured
- The open circuit torque is then also measured.
- The difference between the open circuit losses and dummy rotor losses are assumed to be iron losses
- The adjustment of the iron losses in the model to account for manufacturing effects is then based upon this.
- It may be that the modelled hysteresis and eddy current components of the iron losses need to be independently adjusted to match the scaling with frequency

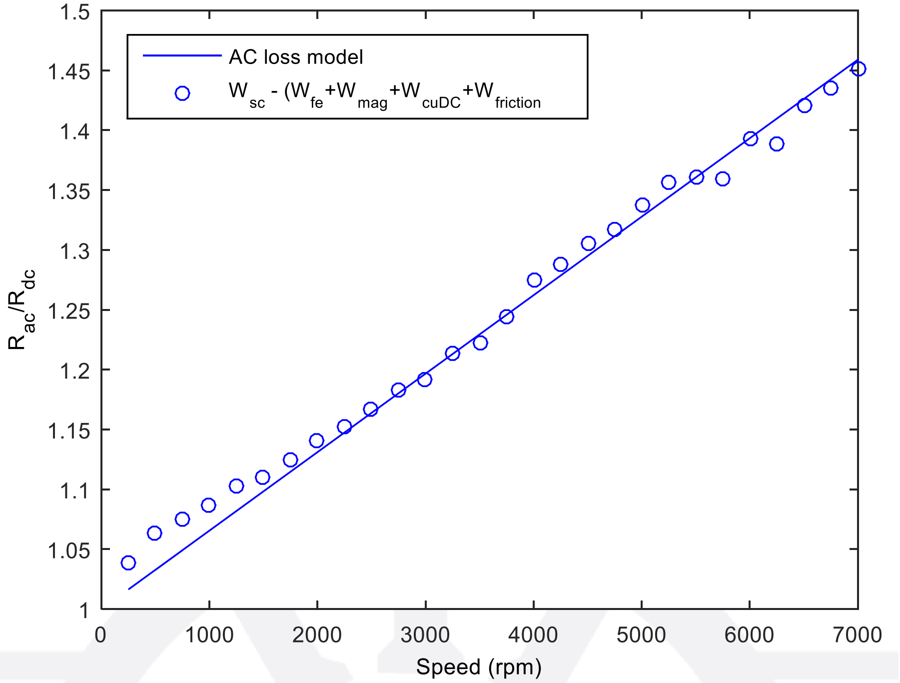


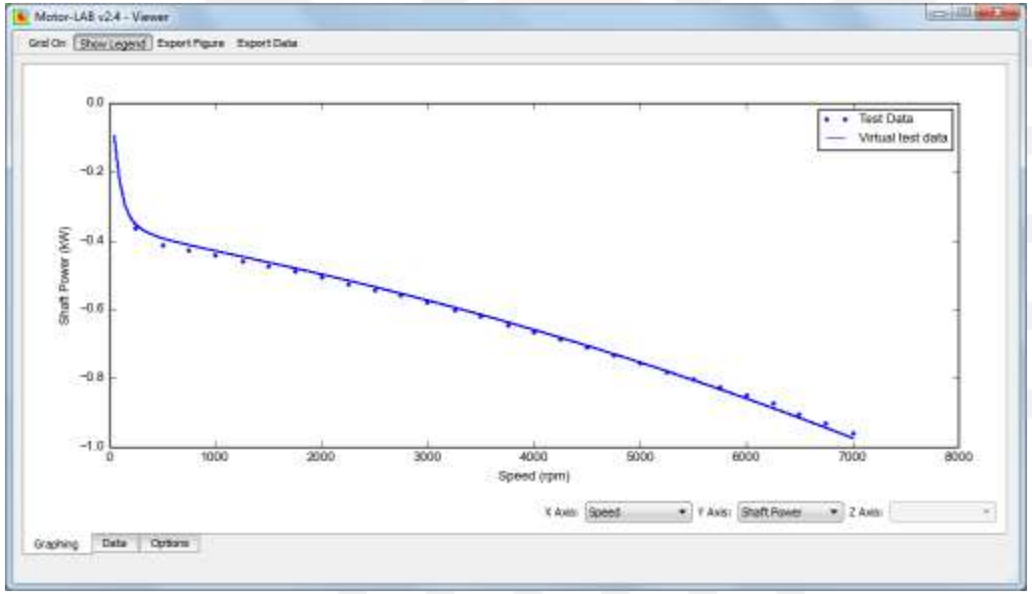
Hysteresis iron loss build factor = 1.0
Eddy iron loss build factor = 1.92



Loss model validation – short circuit losses

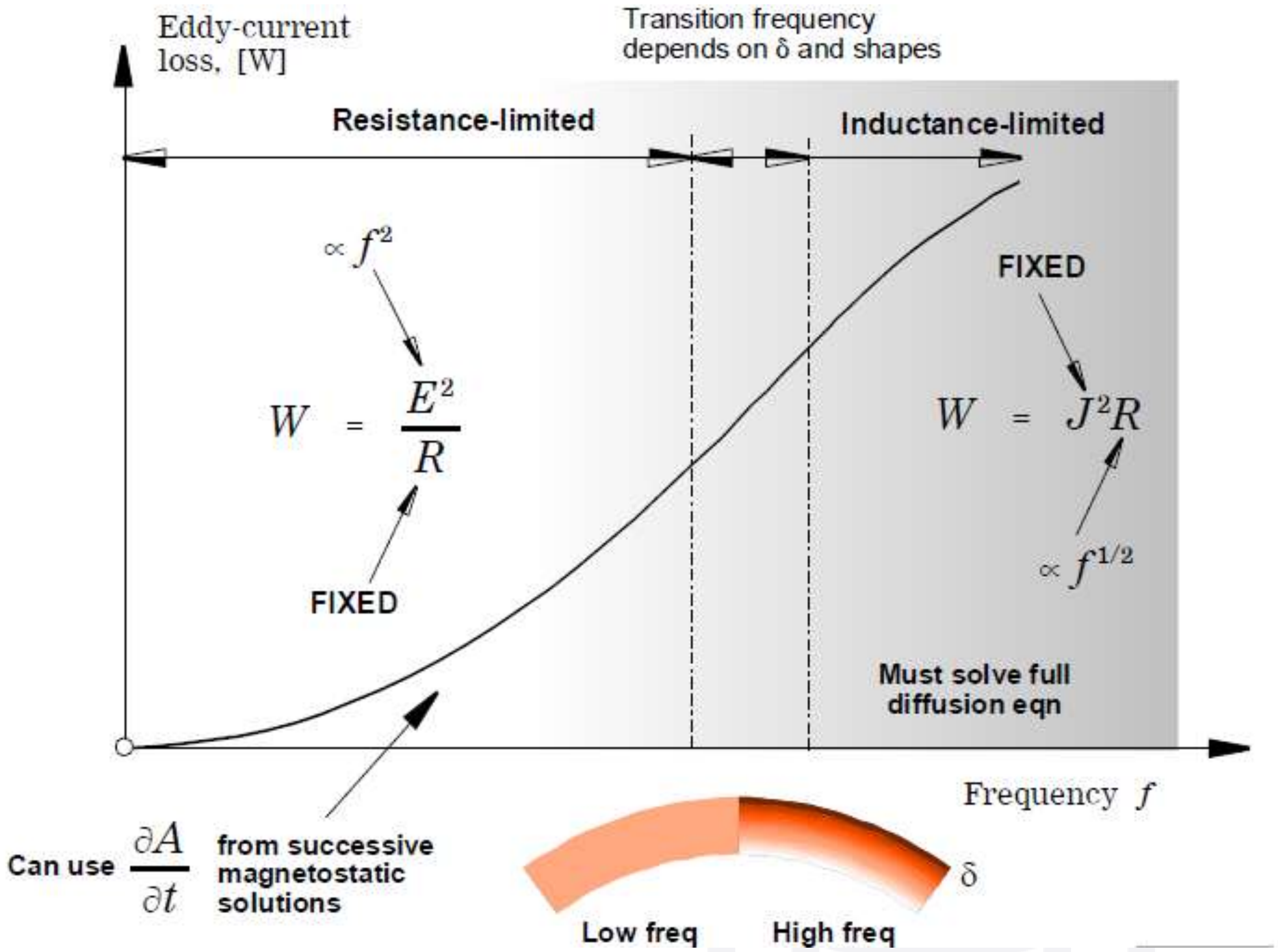
- Short circuit losses are measured across the speed range
- The DC component, iron losses, bearing friction and windage are now accounted for with calibrated models.
- The remaining loss components are AC winding losses and magnet losses.
- Here we have assumed that the magnet losses are correct in the FEA model and used the results to deduce the AC losses
- In this case the AC losses are difficult to model precisely as the windings are made of multi-stranded bundles with a random distribution and no transposition.
- AC losses are proportional to d^4, where d is the bundle height





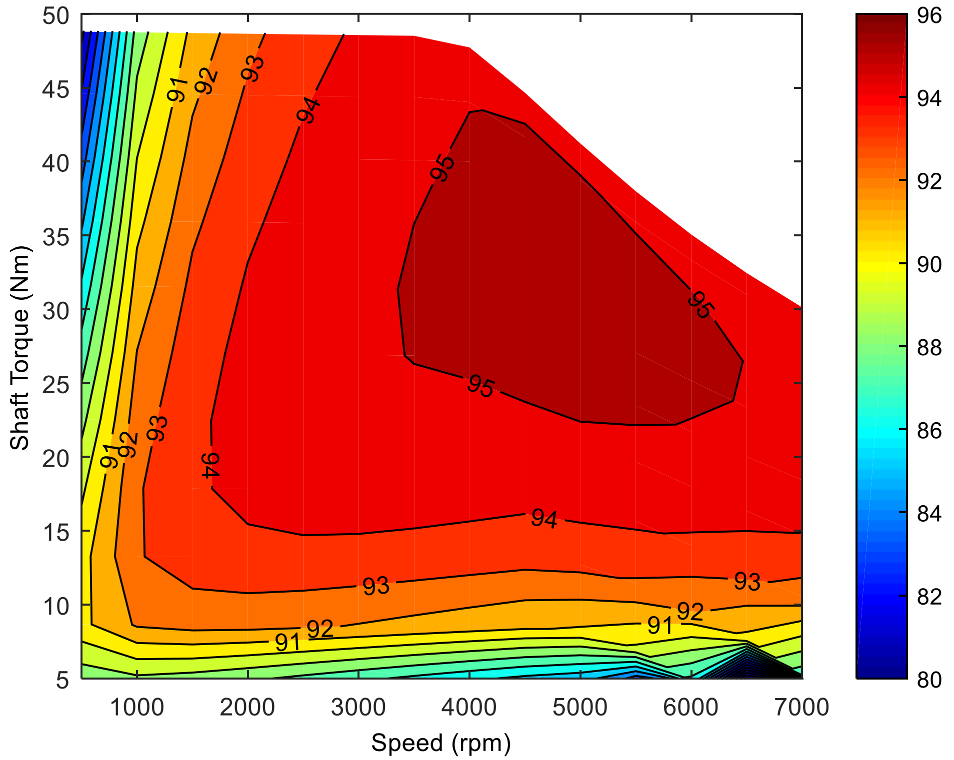
Loss model validation – short circuit losses

- Usually AC losses scale with f^2 at lower speed and become more linear at higher speed when they become inductance limited. In this case they appear to be linear throughout the speed range.

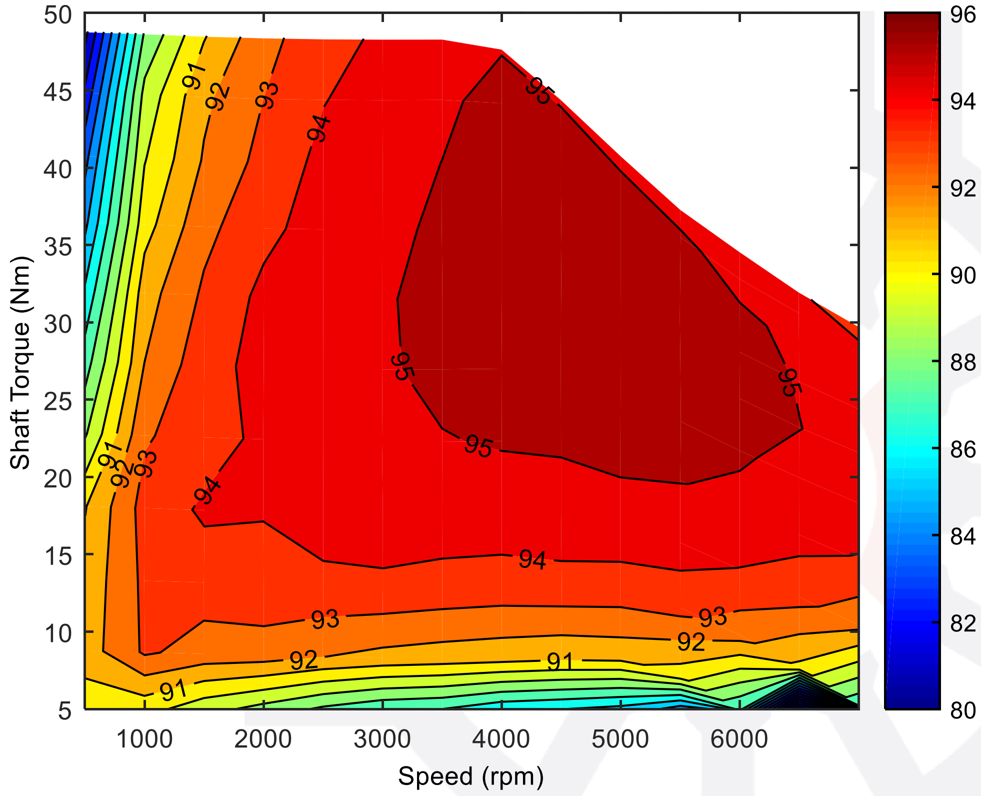


Electromagnetic & Loss model validation

- Modelled efficiency map



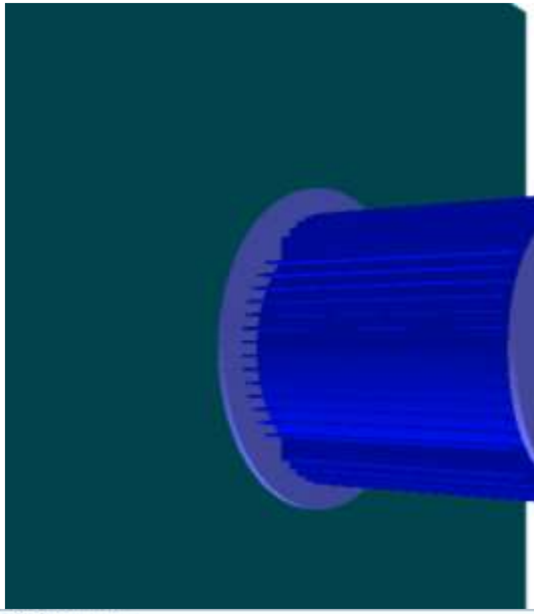
- Measured efficiency map

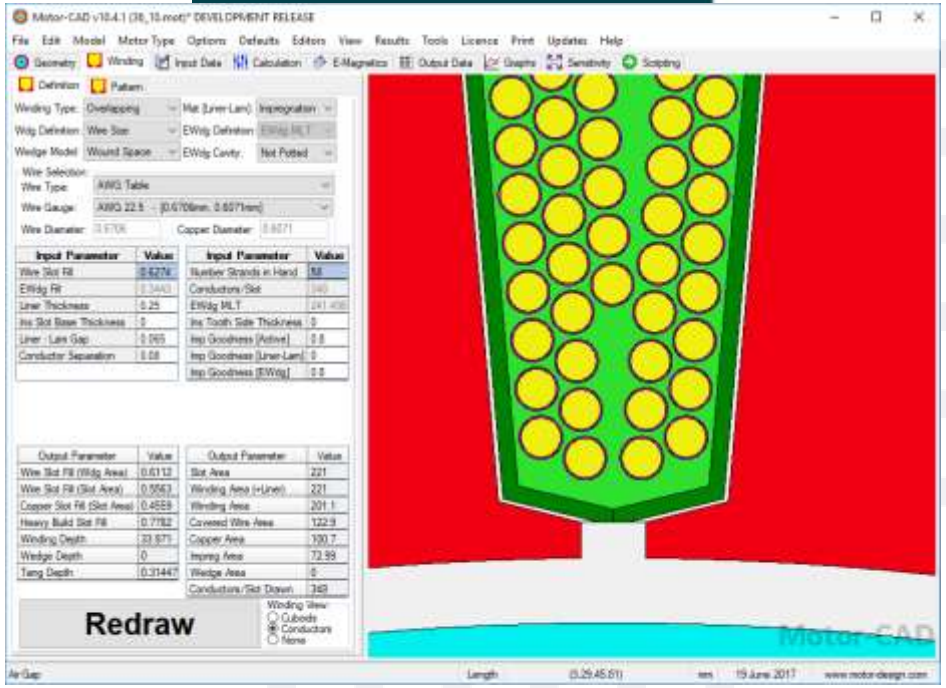


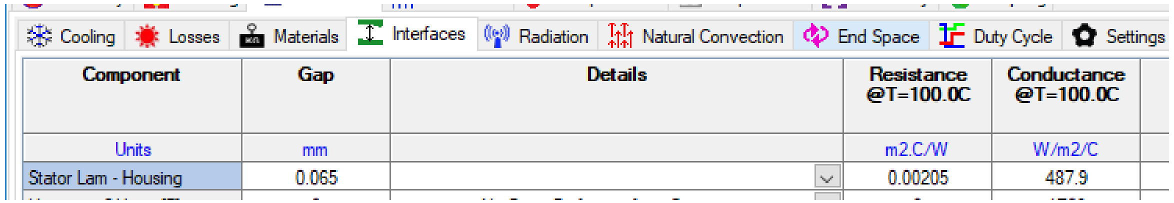
Thermal model validation – DC test

- DC test completed with all phases in series
- Calibrated model parameters:
  - Heat transfer from flange mounting plate
  - Interface gap from stator lamination to housing
  - Interface gap between slot liner and lamination

	Test	Model
DC current (A)	85	
Winding loss (W)	505	
Winding Average (^oC)	150.7	150.6
Housing (^oC)	106.3	106.4
Flange mounting plate (^oC)	59.0	59.2







Component	Gap	Details	Resistance @T=100.0C	Conductance @T=100.0C
Units	mm		m2.C/W	W/m2/C
Stator Lam - Housing	0.065		0.00205	487.9

Thermal model validation – Steady state

- Steady state operation points run at various speeds
- End winding airflow calibrated & division of losses validated.

Cooling | Losses | Materials | Interfaces | Radiation | Natural Convection | End Space | Duty Cycle | Settings

Front End Space:
End Space Velocity Multiplier [Front]: Normal Rotor 0.5
End Space Reference Velocity [Front]: 10.65
End winding roughness [Front]: 1
Endcap Ventilation [Front]: (•) Closed ( ) Vented ( ) Fully Open

Rear End Space:
End Space Velocity Multiplier [Rear]: Normal Rotor 0.5
End Space Reference Velocity [Rear]: 10.65
End winding roughness [Rear]: 1
Endcap Ventilation [Rear]: (•) Closed ( ) Vented ( ) Fully Open

Internal Surface	k1	k2	k3	Air Velocity	Air Velocity	h	Area	Rt
Units				pu	m/s	W/m2/C	mm²	C/W
Housing [Front]	15	0.4	0.9	0.2	2.13	23.2	3.032E04	1.421
Housing [Rear]	15	0.4	0.9	0.2	2.13	23.2	3.032E04	1.421
Endcap [Front]	15	0.4	0.9	0.7	7.455	44.58	2.26E04	0.9926
Endcap [Rear]	15	0.4	0.9	0.7	7.455	44.58	2.26E04	0.9926
Bearing [Front]	15	0.4	0.9	1	10.65	56.54	1276	13.86
Bearing [Rear]	15	0.4	0.9	1	10.65	56.54	1276	13.86
Shaft [Front]	15	0.4	0.9	1	4.712	33.88	2890	10.21
Shaft [Rear]	15	0.4	0.9	1	4.712	33.88	2890	10.21
Rotor [Front]	15	0.4	0.9	1	15.36	73.57	4763	2.854
Rotor [Rear]	15	0.4	0.9	1	15.36	73.57	4763	2.854
Magnet [Front]	15	0.4	0.9	1	20.12	90.23	1341	8.262
Magnet [Rear]	15	0.4	0.9	1	20.12	90.23	1341	8.262
EWdg Bore [Front]	15	0.4	0.9	1	10.65	56.54	1.447E04	1.222
EWdg Bore [Rear]	15	0.4	0.9	1	10.65	56.54	1.447E04	1.222
EWdg Outer [Front]	15	0.4	0.9	0.2	2.13	23.2	2.64E04	1.633
EWdg Outer [Rear]	15	0.4	0.9	0.2	2.13	23.2	2.64E04	1.633

	Test	Model
Operating Point 1		
Speed (rpm)	500	
Torque (Nm)	35.3	
Average winding (°C)	147.6	152.6
Operating Point 2		
Speed (rpm)	2000	
Torque (Nm)	25.4	
Average winding (°C)	109.3	111.8
Operating Point 3		
Speed (rpm)	6000	
Torque (Nm)	15.7	
Average winding (°C)	130.2	131.1

Validation example summary

- Getting very good correlation between simulation and reality is certainly achievable
- However in electrical machines the challenges and uncertainties are typically in the manufacturing processes e.g. electrical steel degradation, interface gaps and layout of conductors.
- This uncertainties are often unknowable at design stage and cannot be solved using more computationally intensive simulation. However through model validation exercises and understanding of your own manufacturing processes high confidence in your simulations be achieved.
- The model validation is often also very useful in highlighting where issues and areas for improvement occur in the machine.

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Motor Design Limited

Motor Design Software by Motor Design Engineers

Motor Design Ltd
4 Scotland Street | Ellesmere | Shropshire | SY12 0EG | UK
Tel. +44 (0)1691 623305