Thermal Modeling & Simulation of a High Performance Electric E-axle

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Topics

1. Marelli’s Vehicle Electrification Business Unit
2. Objectives of Thermal Modeling
3. Case Study – High Performance E-Axle
4. Summary

01

Marelli’s Vehicle Electrification Business Unit

Marelli Electrification... Derived from Motorsport!

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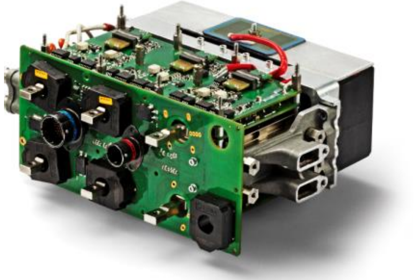
In a race to the future Marelli Motorsport continually develops innovative solutions for hybrid and full electric vehicles, focusing on performance not cost.

From racetrack to road

Formula E motor generator unit

Le Mans 24h, Formula 1 DC-DC converter

Formula E inverter



F1 double inverter

Marelli Electrification Product Range & Recent Customer Applications

PRODUCT RANGE

e-Powertrain Drive System

Inverter

e-Motor

e-Axle

Power Electronics

DC-DC Converter
On Board Charger (OBC)
Power Distribution Unit

Battery System

Battery Management System (BMS)

Chillers

Battery Thermal Plate

RECENT CUSTOMER APPLICATIONS

SF90 STRADALE

- ✓ 400V e-Motor
- ✓ BMS
- ✓ Inverter

Taycan

- ✓ 800V e-Motor

LEAF

- ✓ Inverter
- ✓ OBC
- ✓ DC/DC converter
- ✓ BMS

Livewire

- ✓ e-Axle

- ✓ 800V e-Motor (SOP 2022)

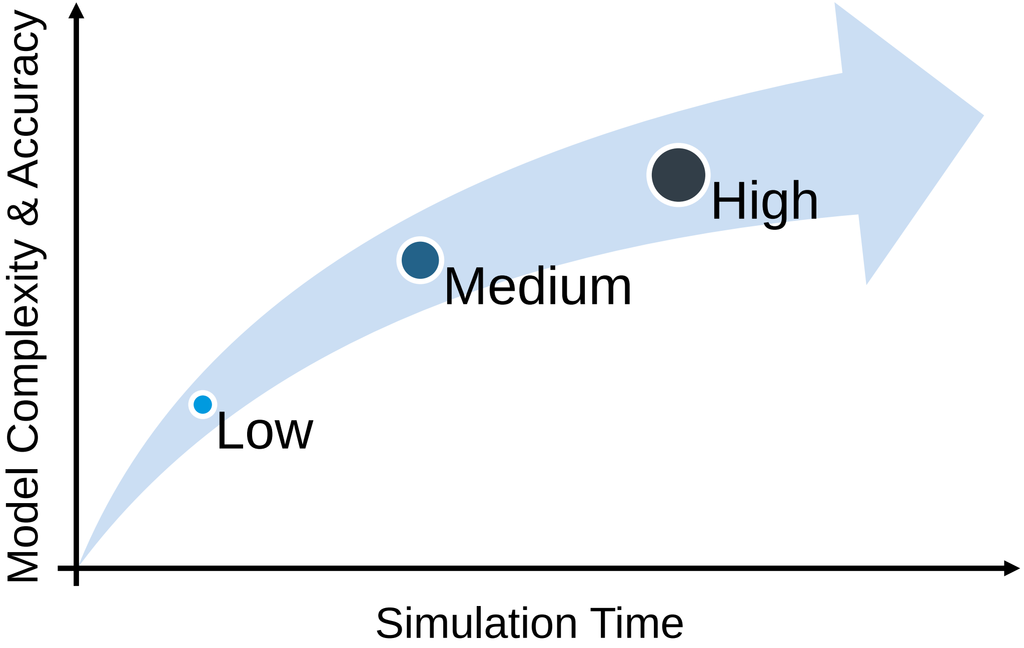
- ✓ Inverter

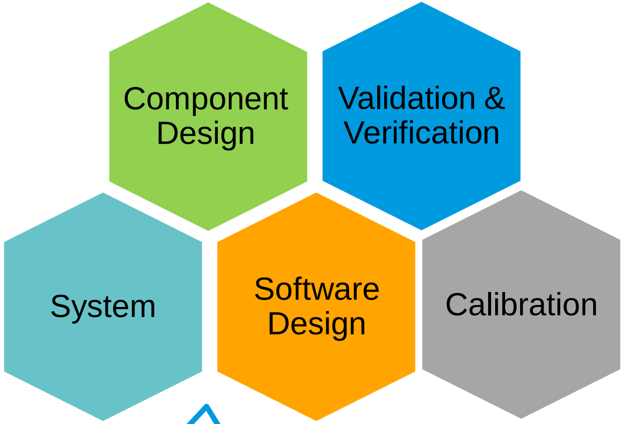
02

Objectives: Thermal Modeling an e-Axle

Product Development Requires Models of Varying Fidelity

- Require models of components characterized by increasing levels of complexity, including thermal behavior
- Leverage differing levels of component model & system fidelity dependent on the simulation requirements





Each application uses different complexity level according to the simulation purposes

High Level Objectives of Modeling and Simulation

1. Expedite development of cost competitive state-of-the-art technologies
    a. *Component design*
    b. *System design & analysis*
    c. *Software design, validation & verification*
    d. *Virtual calibration*
2. Integrate & highly optimize complex multi-physic systems
    a. *Push limits of electromagnetic, thermal, electrical and mechanical performance*
    b. *Optimize for key metrics: Efficiency (%), power density (kW/L), cost ($/kW)*
3. Shorten overall product development time & cost
4. Improve product quality and system/component reliability
5. Mitigate potential risk of a failure or hazard

Key Thermal Modeling Objectives – High Performance e-Axle

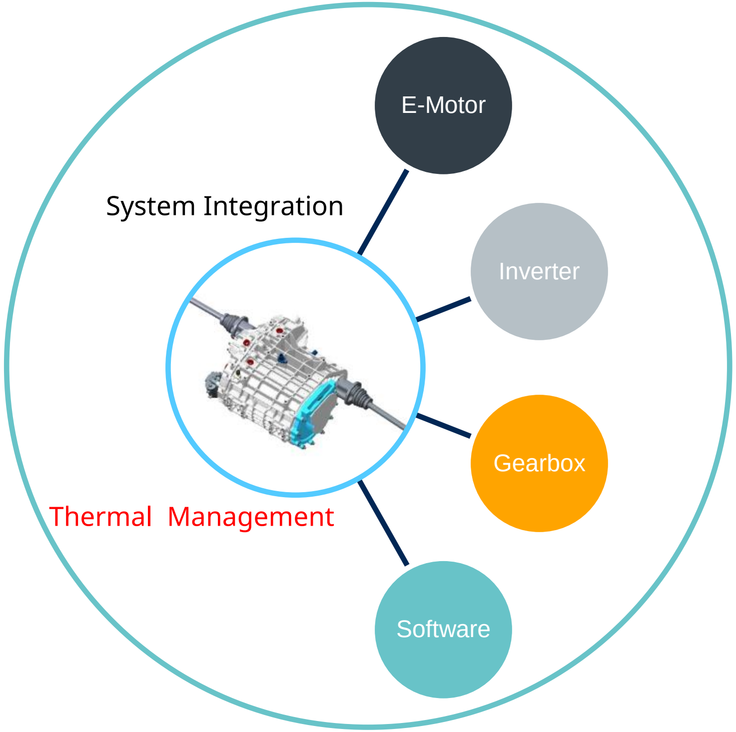
1. Maximise transient & continuous performance of e-axle system
2. Thermal management & component protection
3. Validate system & thermal performance over virtual real world drive cycles
4. Verify & improve accuracy of models by correlating with bench/vehicle test data
5. Development of virtual temperature sensors

03

Case Study – High Performance E-Axle

E-Axle System Complexity – Why Modeling is Needed

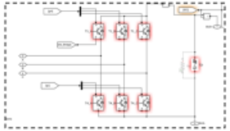
- ❑ e-Motor
- ❑ Inverter
- ❑ Gearbox / Axles
- ❑ Thermal management
- ❑ Embedded Software
- ❑ System Integration



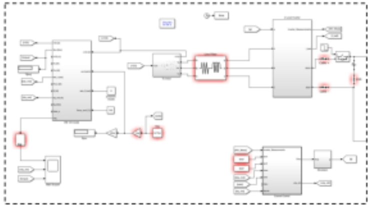
Power Electronics & System Modeling

Matlab & Simulink are used to replicate inverter waveforms for assessing inverter & motor losses and thermal performance. Powersystems libraries are used to evaluate inverter behavior in the whole electric PWT system (inverter+ battery + motor).

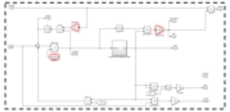
inverter model

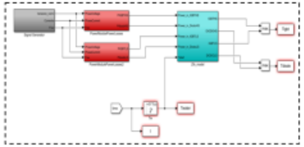


system model

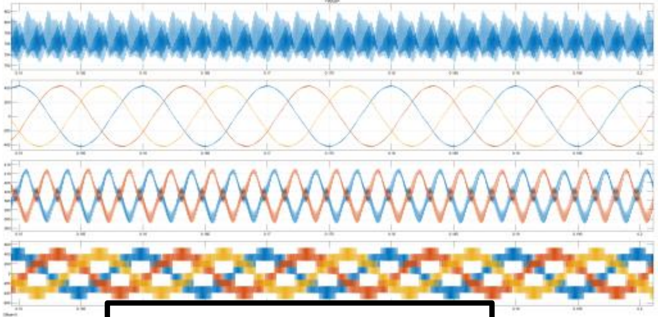


motor model

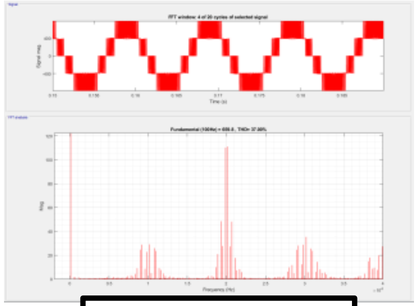




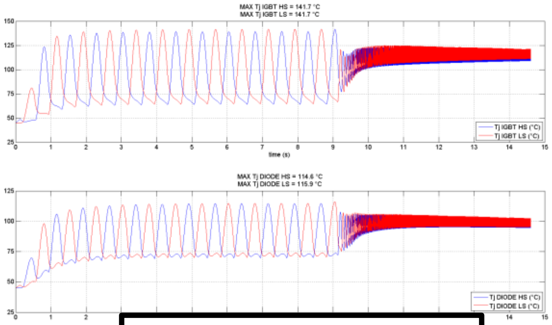
Thermal model



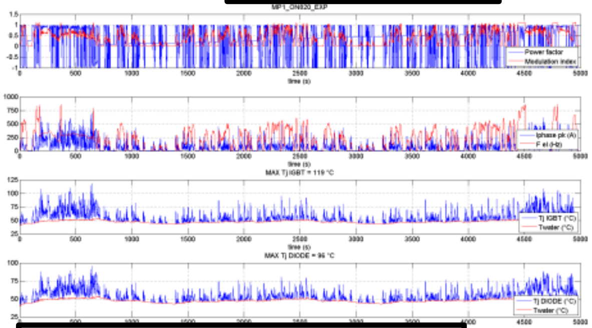
Inverter electrical waveforms



Phase voltage FFT



Junction thermal transient



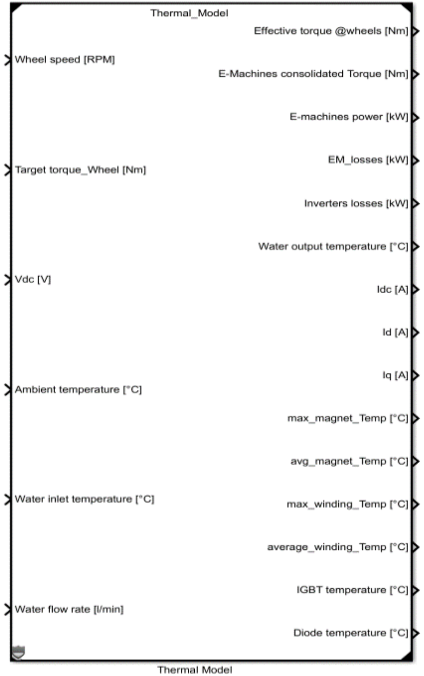
Temperatures over Mission Profile

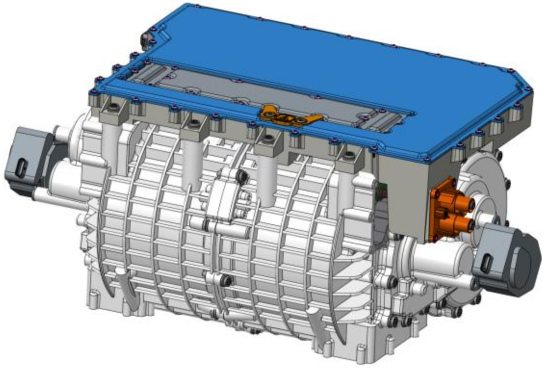
E-Axle Thermal Modeling in Simulink – Phase 1

Phase 1 objective was to develop a lumped mass e-axle thermal model in Matlab/Simulink environment in order to evaluate the thermal behavior of the system under various transient driving conditions, assessing temperature of stator, rotor (magnet), bearings & electronics.

Inputs:
Wheel torque
Wheel speed
Battery voltage Vdc
Ambient Temperature
Water inlet Temperature
Water flow rate

Outputs:
E-machine temperatures
Power module temperatures
E-machine performance





E-Machine Thermal Modeling Options when Integrating with Simulink

EM Thermal Modeling

State Space

- Export the Motor-CAD lumped parameter thermal network
- Import and run as a state-space model

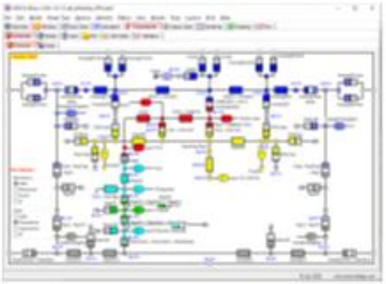
Pros

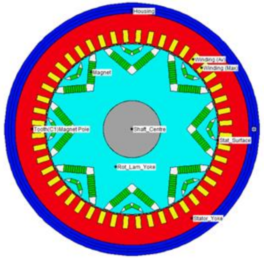
✓ Easy to export and share the thermal model

✓ Maintain design confidentiality

Cons

✓ Needs some time to update the thermal network with, speed, temperature





FMU

Pros

✓ Accurate Models

✓ Thermal model accounts for variable resistances

✓ Accurate mapping and scaling of the losses

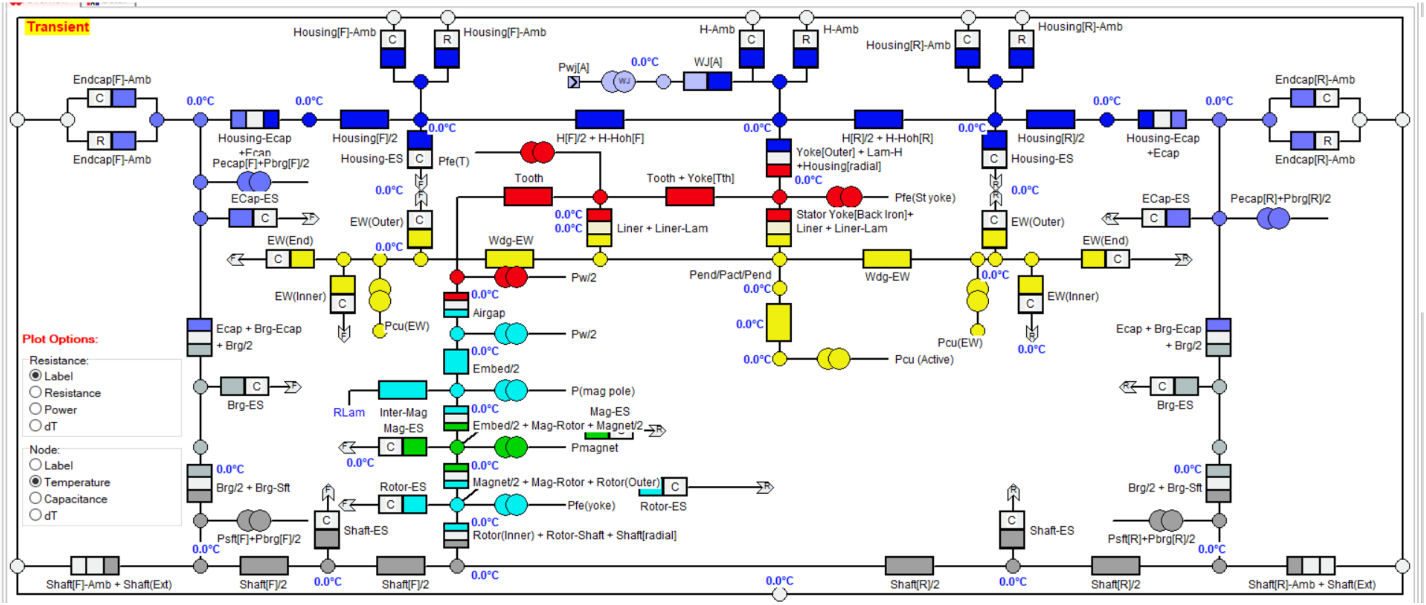
Cons

✓ Currently model can not be shared without design data in .mot file

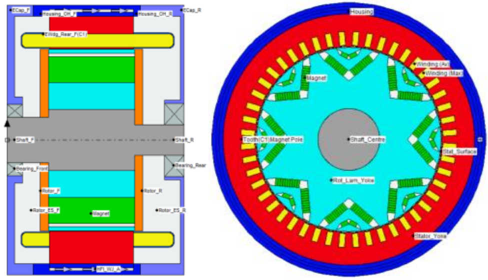
Thermal Lumped Parameter Model - ANSYS Motor-CAD

Lumped parameter thermal networks are exported to generate state-space models to run in Simulink.

winding, stator lamination, magnets, rotor lamination, housing, cooling, ambient etc.

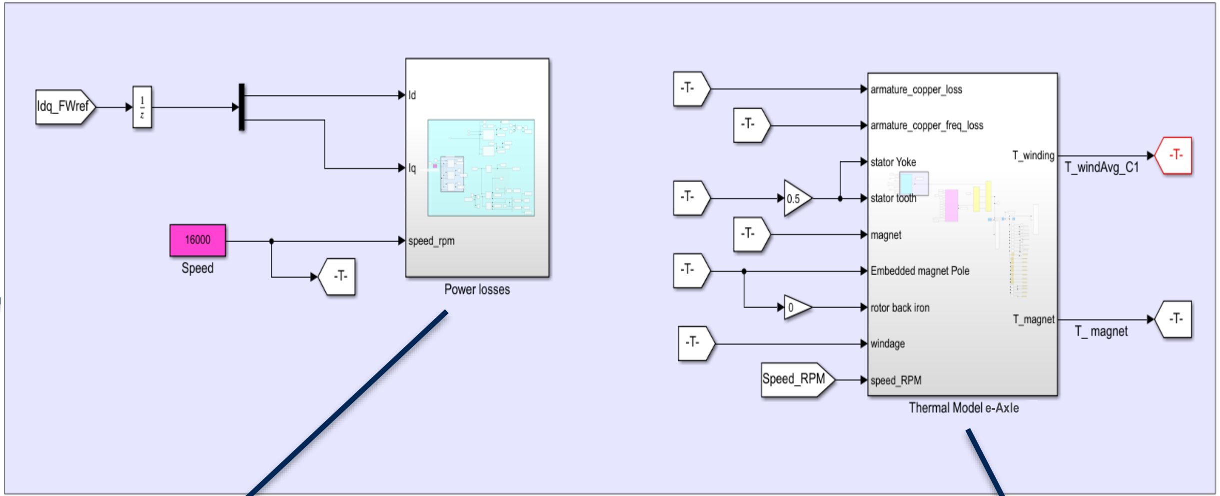


Example illustrating a Motor-CAD lumped parameter thermal network model



2D cross section views of one motor

E-Machine Thermal Model Implementation within Simulink



Operative working point

Power Losses:
- Stator iron loss
- Rotor iron loss
- Magnet loss
- Windage loss
- Armature copper loss (ac, dc)

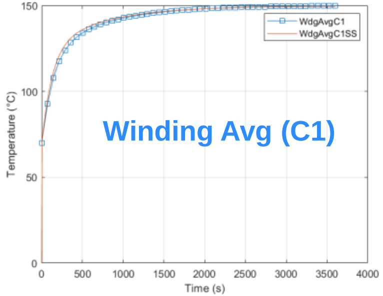
Thermal Model: (State Space)
- Update the power loss matrix for a given operative point
- Recalculate/update the thermal resistances of each component
- Calculate node temperatures

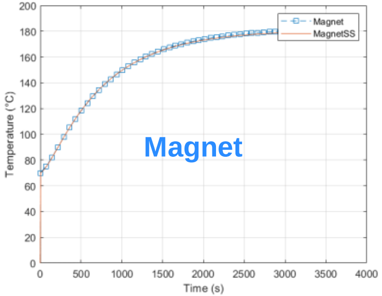
Comparison between Motor-CAD and Simulink : e-Machine

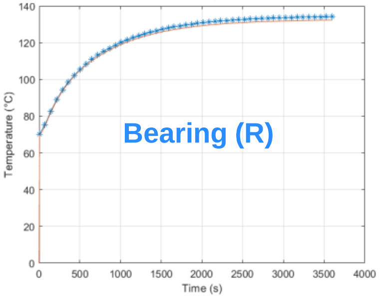
Steady State Comparison

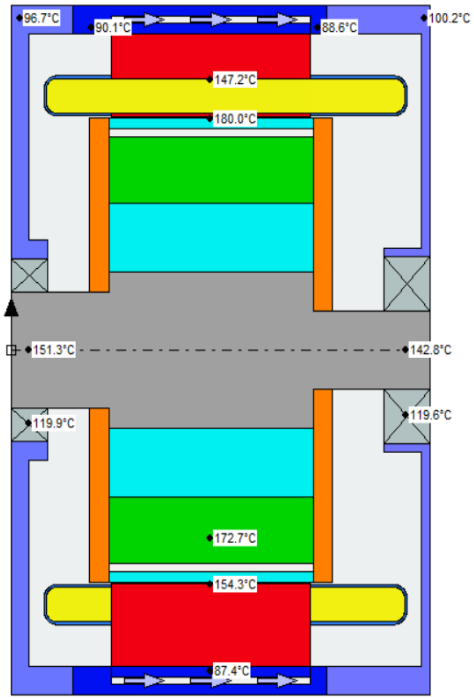
Node name	Motor-CAD (ºC)	Simulink (ºC)	Relative Error (%)
Housing	87.43	86.65	0.89
Housing_OH_F	90.07	88.81	1.4
Housing_OH_R	88.6	87.61	1.12
Stator Surface	154.3	153.8	0.32
Rotor Surface	180	179.1	0.5
EndCap_F	96.67	94.32	2.43
EndCap_R	100.2	97.34	2.85
Bearing_F	119.9	118.1	1.5
Bearing_R	119.6	117.4	1.84
Shaft_F	151.3	149.9	0.93
Shaft_R	142.8	141.1	1.19
Magnet	172.7	171.6	0.64
Wdg_Avg_C1	147.2	147.2	0

Transient Comparison









winding, stator lamination, magnets, rotor lamination, housing

Varying Fidelity of the Thermal Lumped Parameter Model: E-Machine

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EM Thermal Model
168 Nodes

→

EM Thermal Model
29 Nodes

	Detailed Model	Reduced Model
Node Number	168	29
Simulated Time [s]	1800	
Step time [s]	1	
Elapsed Time [s]	152.5	18.55

Each node within the network represents a capacitance, a temperature, and a power source (loss)

Compare e-Machine Temperatures from Detailed & Reduced Models

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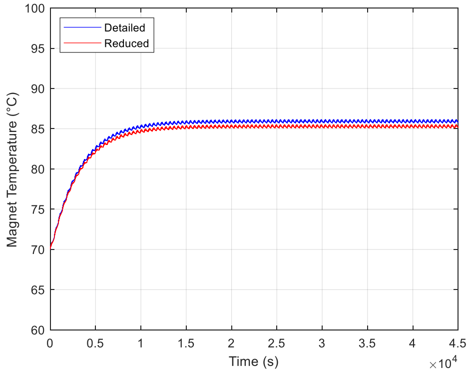
Steady State Comparison

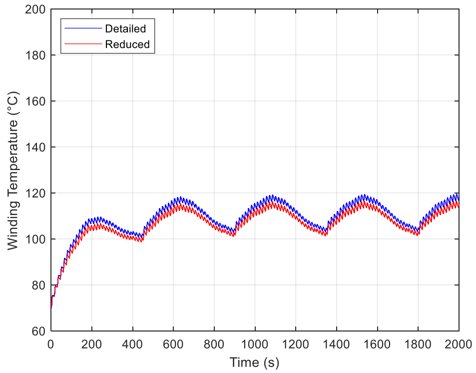
Speed [RPM]	Torque [Nm]	Detailed Model		Reduced Model		Relative Error	
		Twinding (°C)	Tmagnet (°C)	Twinding (°C)	Tmagnet (°C)	Twinding (%)	Tmagnet (%)
2000	113.7	179.9	106.2	172.91	105.82	3.89	0.36
5000	111.8	179.1	119.6	170.43	119	4.84	0.50
8000	103	180.05	127.9	170.38	127.048	5.37	0.67
10000	83	179.7	137.44	169.89	136.31	5.46	0.82
12000	66	180.8	149.7	170.87	148.18	5.49	1.02
14000	52	178.65	160.5	169.01	158.62	5.40	1.17
16000	38.5	174.8	169.25	165.76	169.47	5.17	-0.13

Simulation results: continuous performance for 30 mins, V_{dc}=340v, $T_{inletcoolant}$ = 70°C.

Losses are calculated for T_{magnet} =100°C, T_{stator} =180°C, and 97% gear efficiency.

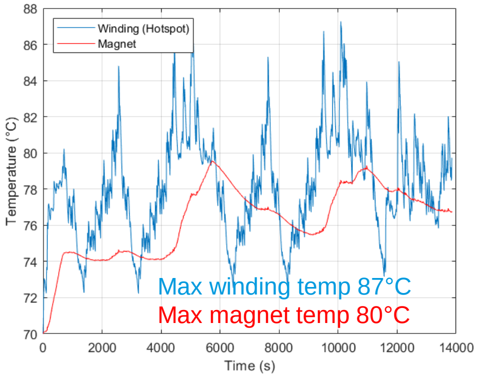
Transient Drive Cycle

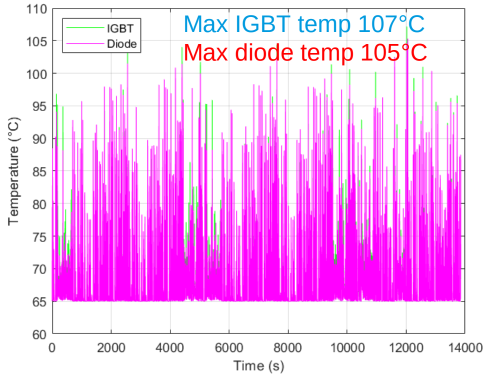


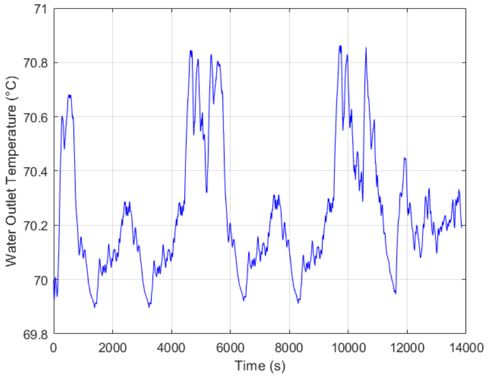


E-Axle Thermal Model Results: Mission Cycle Sensitivity

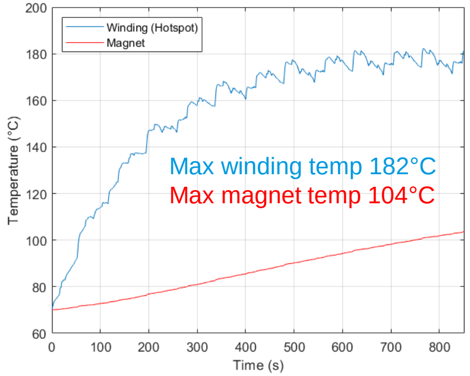
Urban Mission Profile		Units
Cycle Duration	13851	s
Vdc	340	V

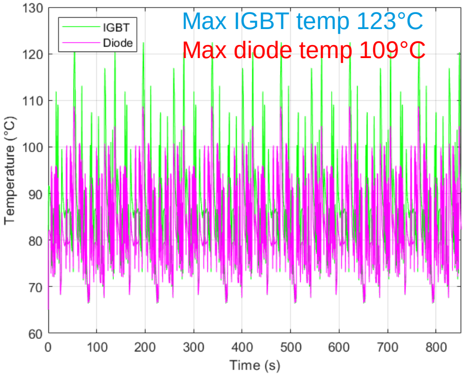


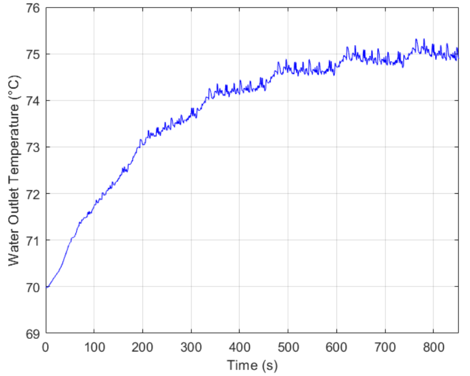




Track Mission Profile		Units
Cycle Duration	852	s
Vdc	340	V



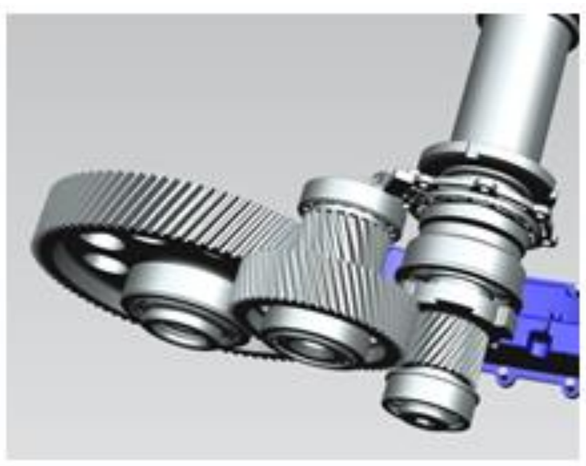


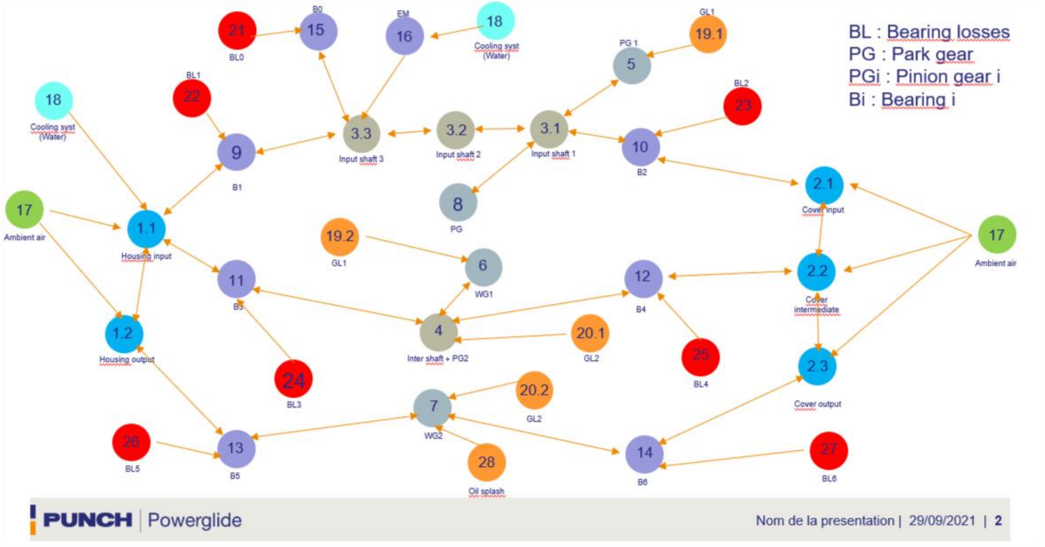


E-Axle Thermal Modeling – Phase 2

Enhanced Reducer Thermal Model

- The lumped parameter thermal network for the reducer is shown below
- This is incorporated with e-machine in Motor-CAD and used to generate updated state space models





E-Axle Thermal Modeling – Steady State Operation Comparison

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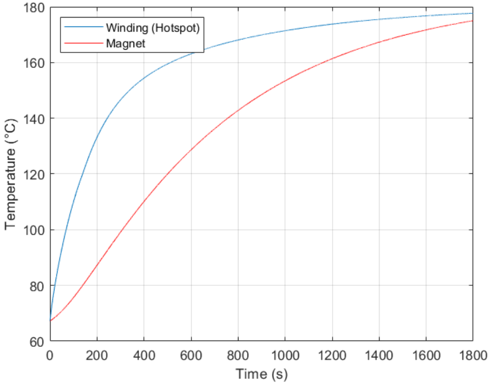
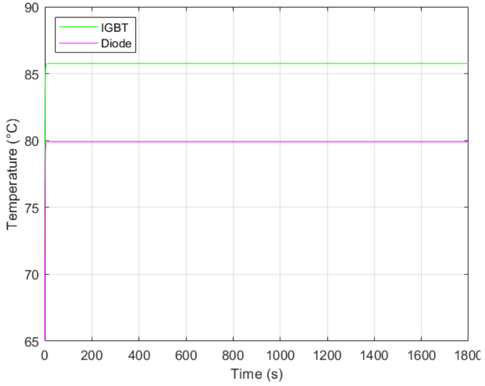
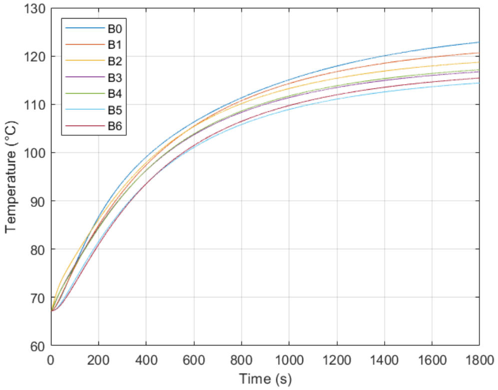
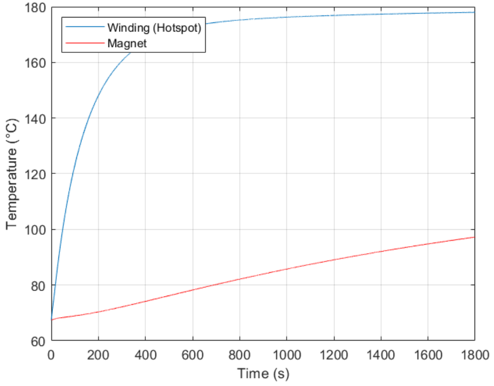
High Speed Low Torque		Unit
E-Axle/ Wheel Speed	1683	rpm
Wheel Torque	360.7	Nm

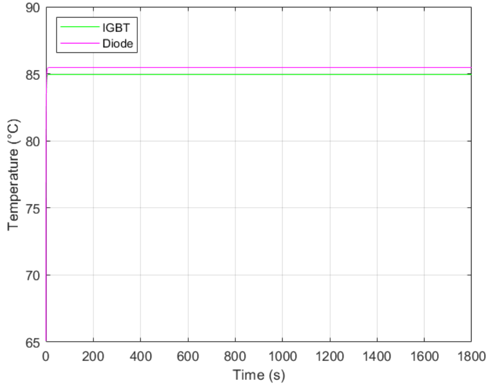


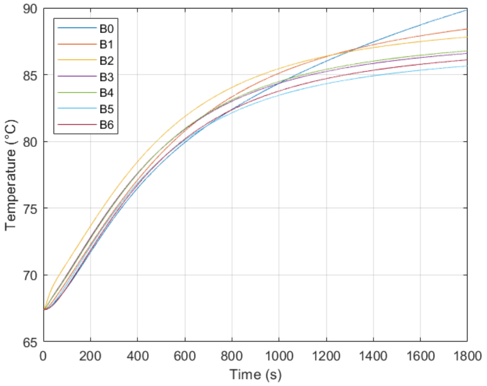




Low Speed Higher Torque		Unit
E-Axle/ Wheel Speed	210.3	rpm
Wheel Torque	1060	Nm







Motor Inverter Axle

Bench Test Comparison: 30 min Continuous Load-Speed Tests

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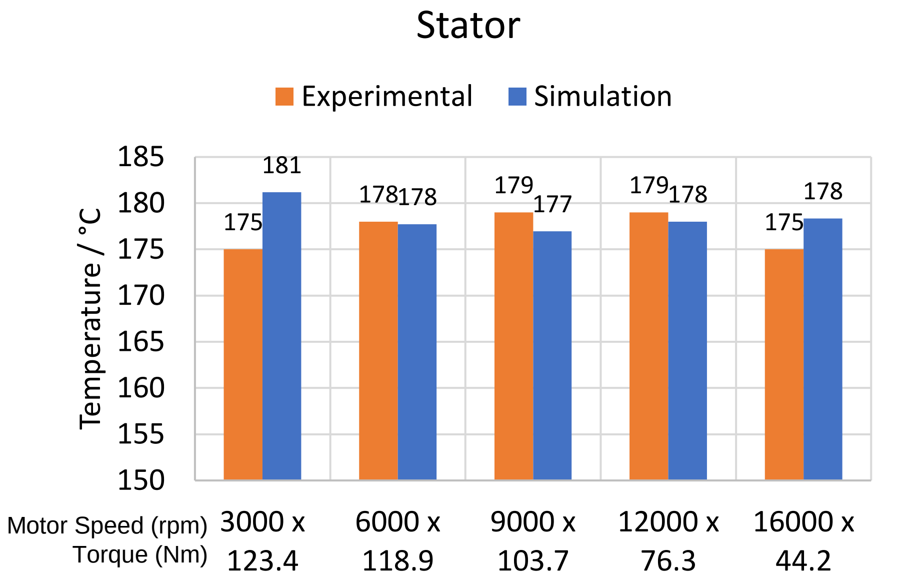
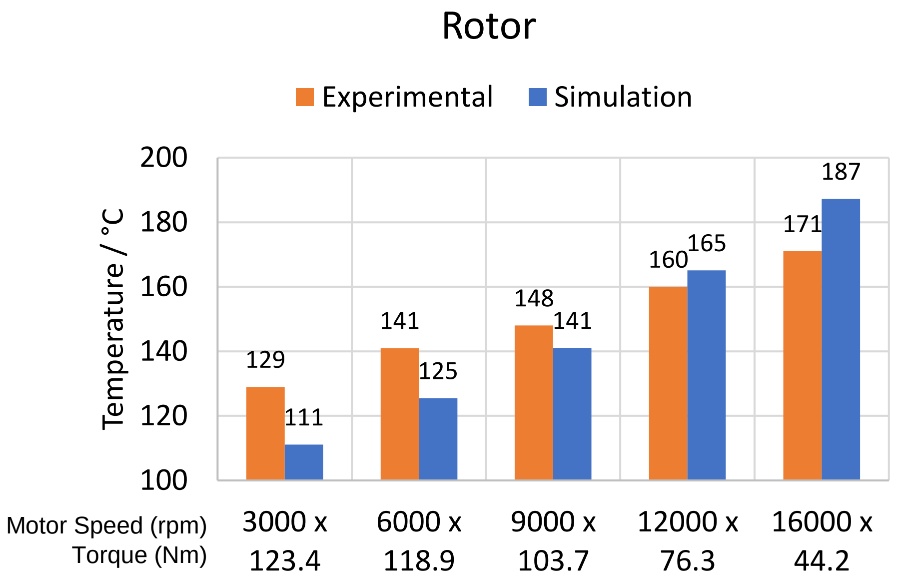
Comparison of test bench performance versus Simulink models correlated using higher fidelity 2D/3D models





- **Stator**: Comparison between experimental and simulation results highlight good agreement (max deviation at 3000 rpm of 3.4%)
- **Rotor**: Comparison highlights temperature underestimation (14% at 3000 rpm) at low speed and overestimation at high speed (9% at 16000 rpm)

04

Summary

Summary

- E-axles development requires design and integration of complex components covering several interacting multi-physics domains that is best undertaken using a digital twin approach from component design through to system analysis
- Modeling system performance and thermal behavior is important to accelerate design development and the Kaizen approach to component and system optimization
- Need to model and assess thermal behavior & system performance over a diverse range of extreme drive cycle scenarios to determine & improve thermal capability/protection
- Corelation of models is necessary once bench or vehicle data is available to improve accuracy although initially one can use data from high fidelity 2D/3D FEM design tools
- Continuous improvement of model based product development tools is needed to further improve the process for developing technology solutions more efficiently and quickly