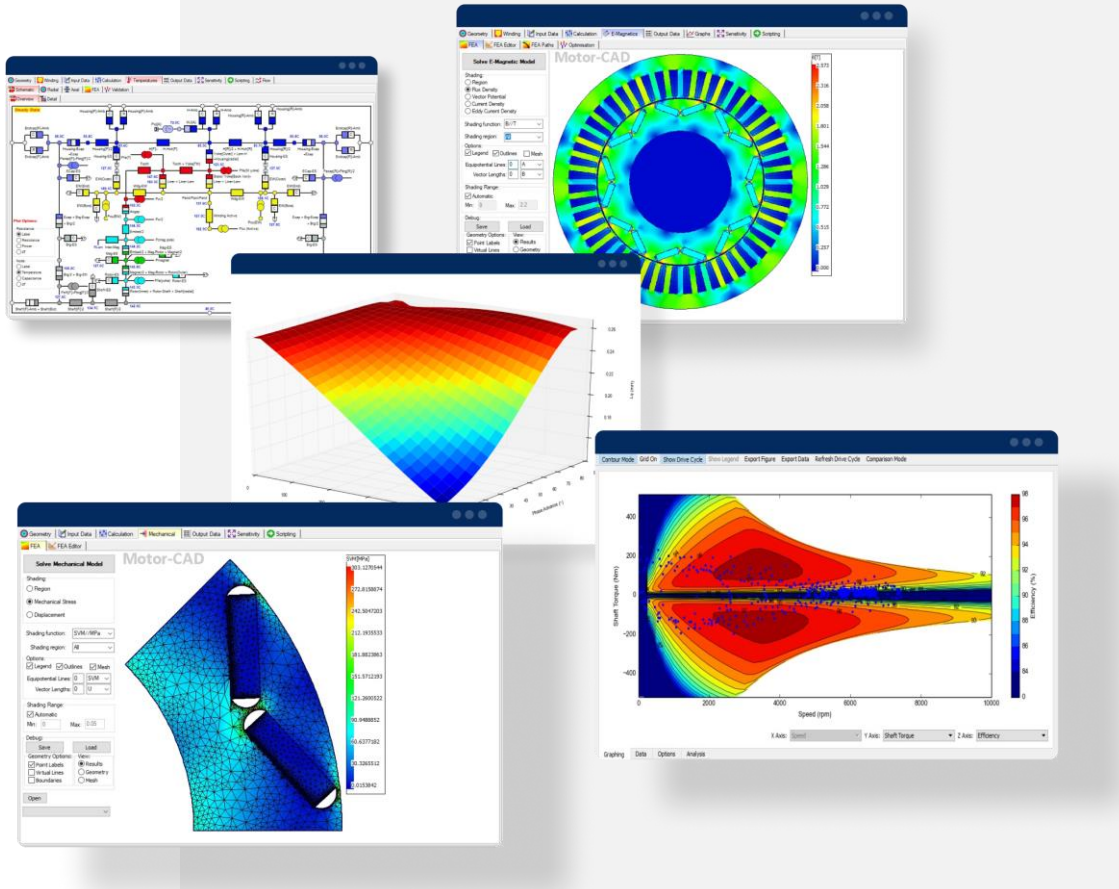
Motor Design Limited

Model Based System Engineering with Ansys Motor-CAD

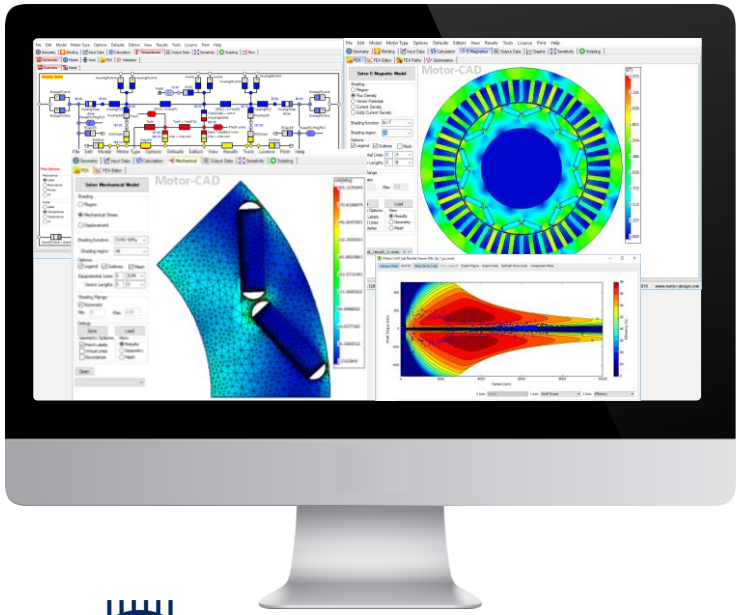


Jonathan Godbehere

20th July 2021

About Motor Design Ltd

- **Software developers: Ansys Motor-CAD**
  - Developers of Ansys Motor-CAD – world-leading tool for the design and analysis of electric motors.
  - High level of customer support and engineering know-how.
  - Developed with expert electric machine designers.
- **Consultancy**
  - Design, analysis & training.
  - Led by motor design experts with significant industry and academic experience.
- **Research**
  - Involved in collaborative government/EU-funded research projects.
  - Collaborate with Universities worldwide to develop electric machine modelling techniques and create validation data.

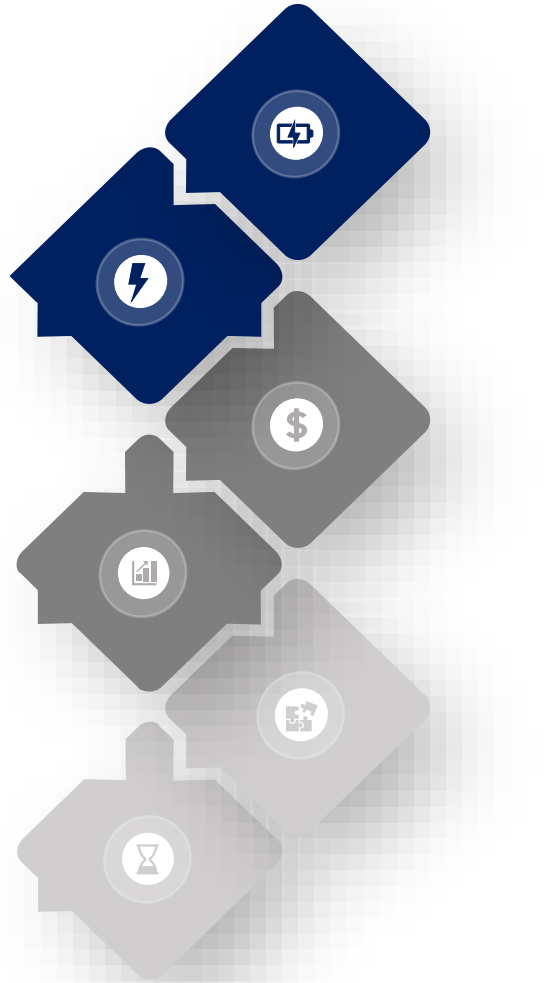


Motor-CAD
MOTOR DESIGN SOFTWARE BY MOTOR DESIGN ENGINEERS

Electric Drive Unit (EDU) design: trends and challenges

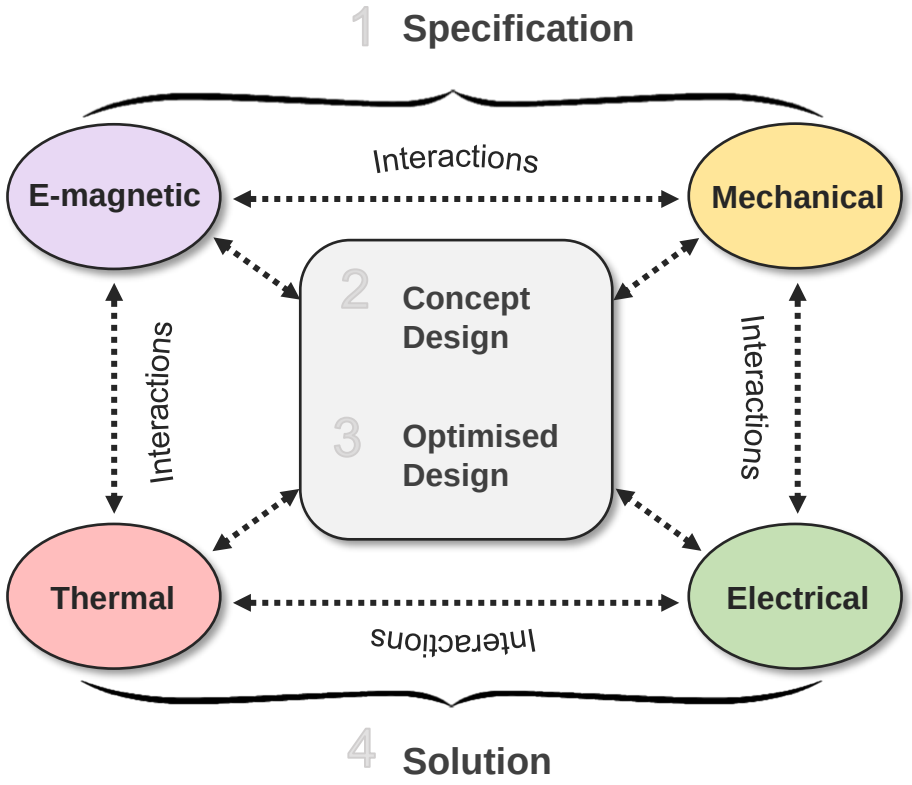
Need for a system led design process

- Higher efficiency (%)
- Increased torque and power density levels (kW/L)
- Reduced costs ($/kW)
- Increasing volumes and mass production
- Increased integration
- Shorter development cycles



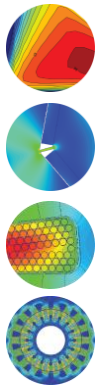
Competitive electric machine design challenges

- Rapid design iterations.
- Pushing boundaries of electromagnetic, thermal and mechanical performance.
- Highly optimised across the full operating range.
- Designed and optimised as part of a wider system.



Evolution of electric machine design

- Single physics
- Fixed operating conditions



- Multiphysics
- Wide torque/speed operating range
- Rapid development cycles
- System integration

Evolution of electric machine design approaches over time

Motor-CAD

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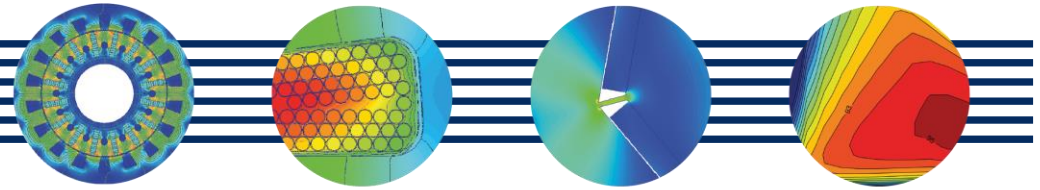
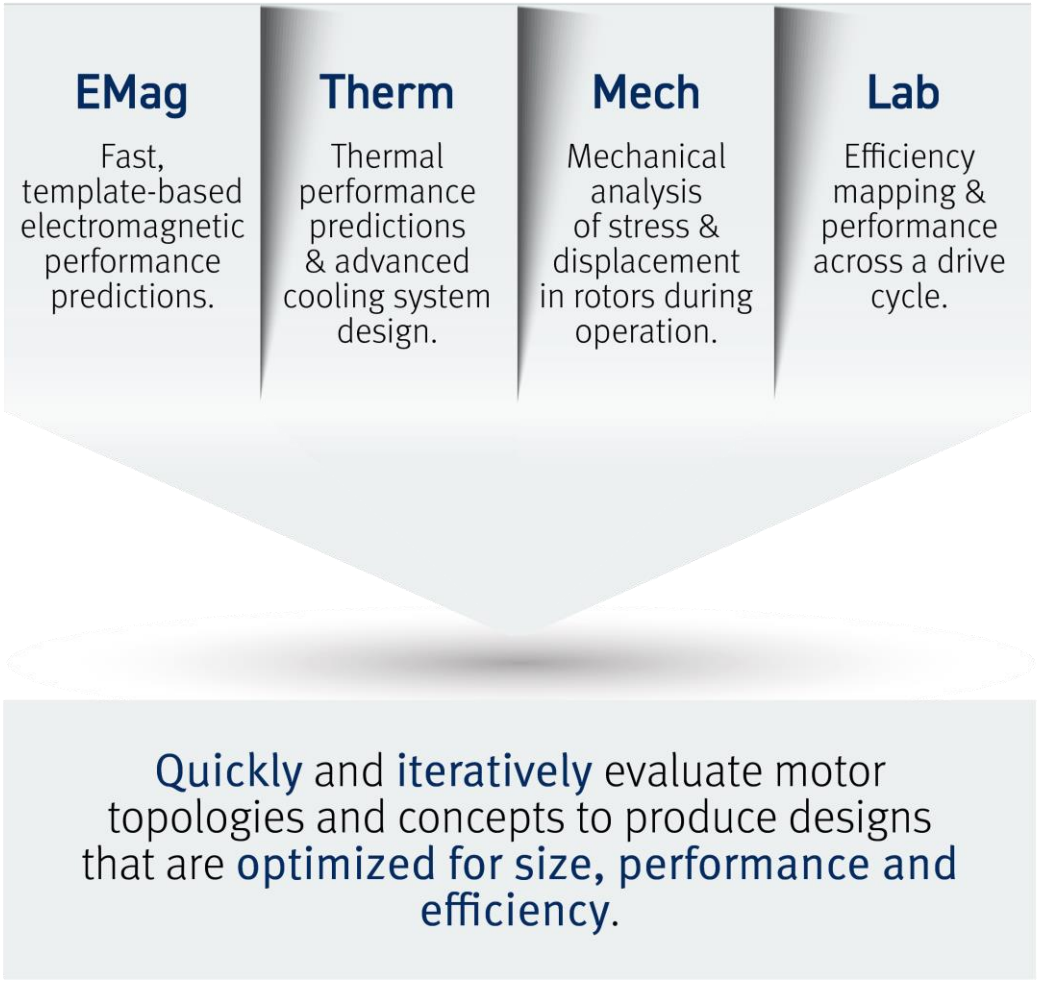


- Ansys Motor-CAD is the market leading tool dedicated to the design and analysis of electric motors.
- Enables rapid and accurate Multiphysics design of electric machines across the full operating envelope.
- Developed by expert electric machine designers.
- Embedded engineering expertise.

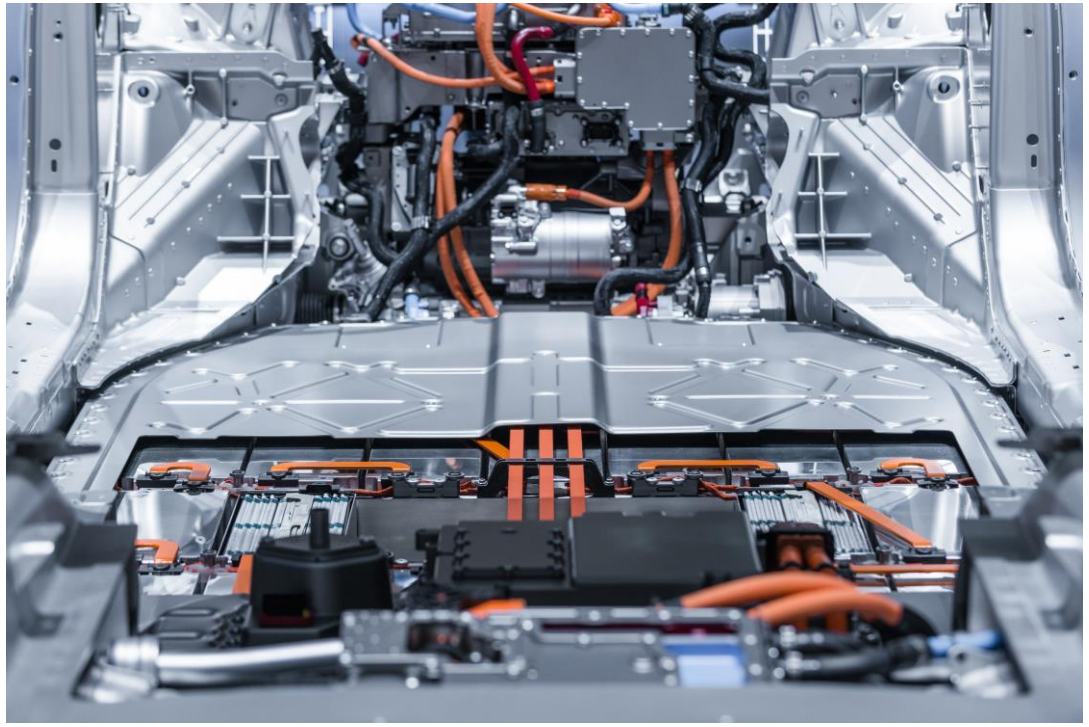


The Need for Systems Engineering

- Increasing demands for high efficiency, high power density, low cost electrified powertrains:
  - Leading to more closely integrated systems and system to system interactions.

- Evaluation of system behaviour throughout the development process:
  - Component performance requirements vs. system performance requirement.
  - Cost of change.

- System level optimisation:
  - An individually optimised motor, inverter and gearbox ≠ optimised system



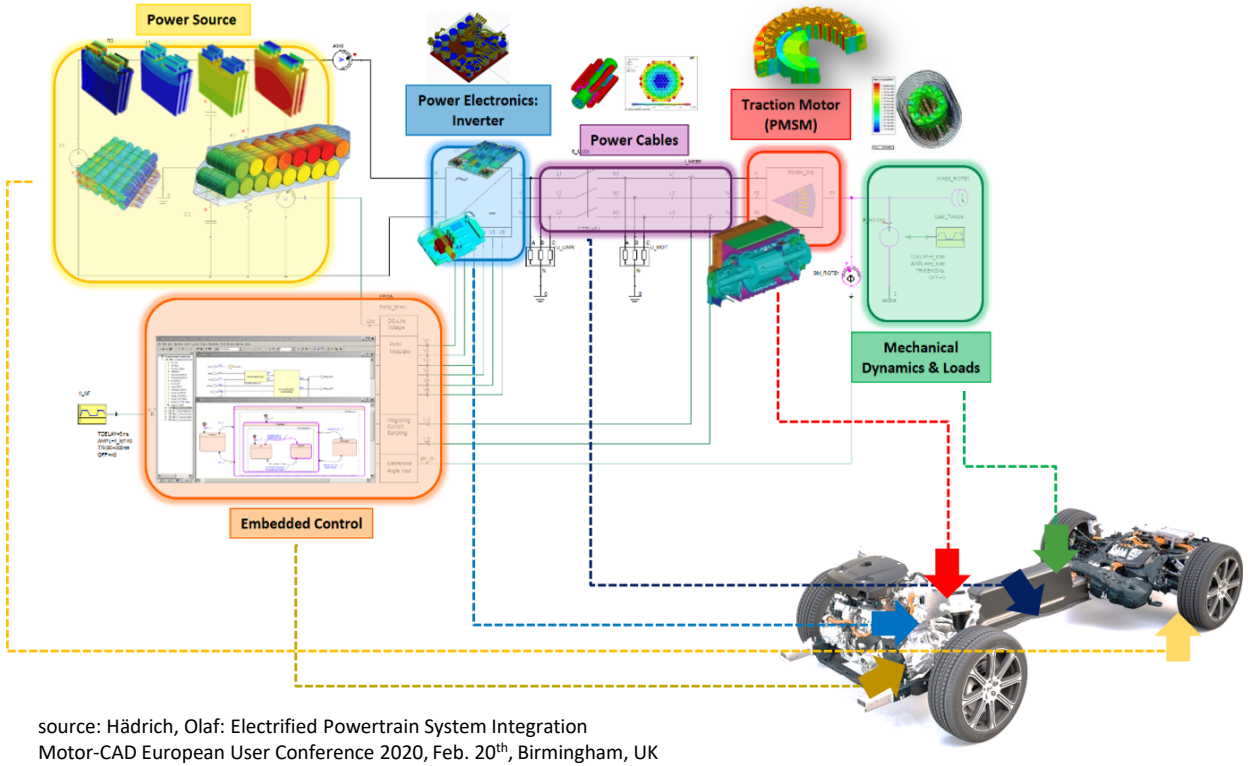
System Simulation Solutions

- Integration of motor models in system simulation environments.

- Multiphysics models:
  - Thermal
  - Electromagnetic
  - Losses
  - Control

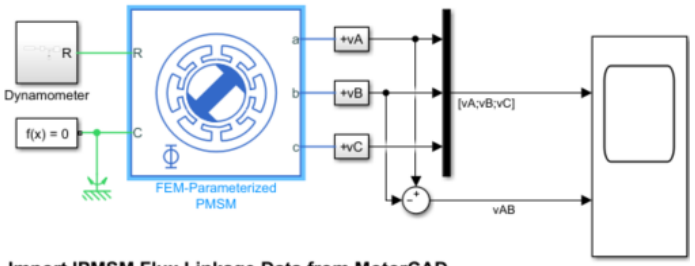
- Varying levels of model fidelity:
  - Reduced order – very fast solving
  - Non-linear variables based on external inputs.
  - Coupled physics models

- Motor-CAD aims to bridge the gap between reduced order and full physics system simulations:
  - More representative models while also keeping the simulation time low.



source: Hädrich, Olaf: Electrified Powertrain System Integration
Motor-CAD European User Conference 2020, Feb. 20th, Birmingham, UK

System Simulation Solutions with Ansys Motor-CAD



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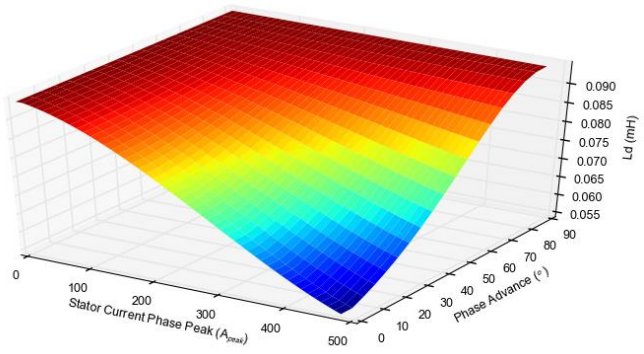

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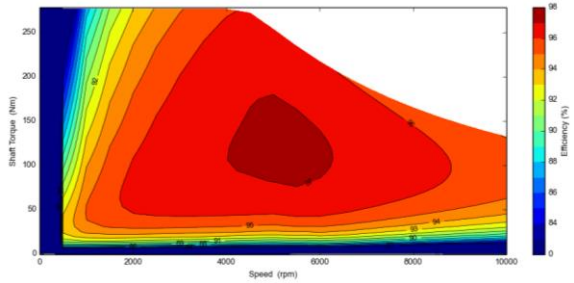

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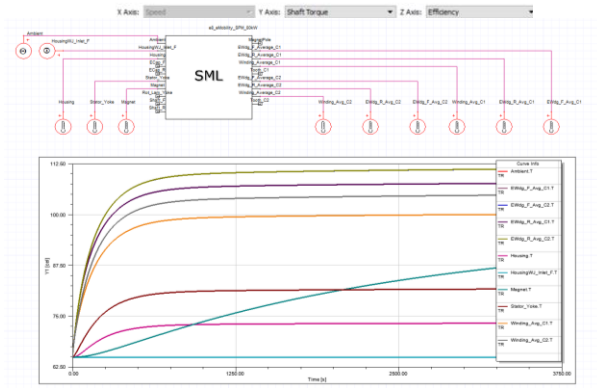

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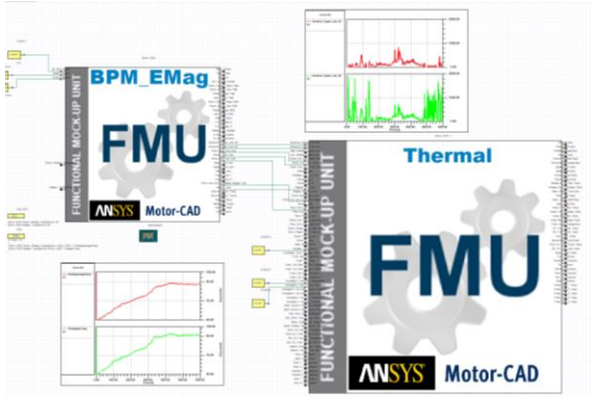
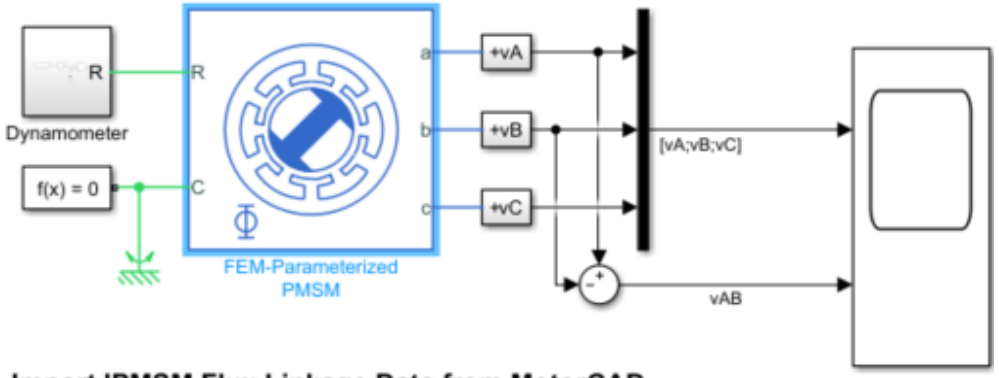


1. **Electromagnetic D/Q Flux Linkage model export (ECE model).**
2. Electromagnetic/Loss/Control Model export, efficiency/loss map export.
3. Thermal model export, fixed resistance network. Full or reduced order.
4. Electromagnetic/Loss/Control Co-Simulation, FMU interface.
5. Thermal model Co-Simulation, FMU interface.

Ansys Twinbuilder & Simscape, Ansys Motor-CAD Flux Linkage export

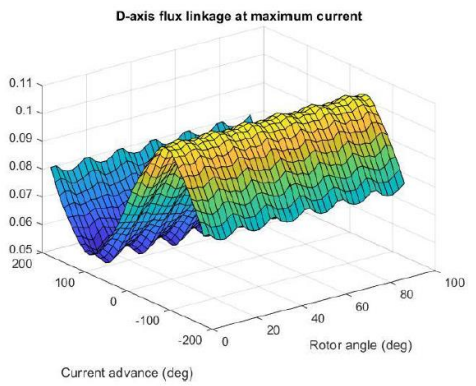
- Export the D/Q flux linkage and torque data from Ansys Motor-CAD.
- Import into the Matlab / Simscape / Twinbuilder E-machine model.
- In-corporate non-linear flux linkage characteristics into a system model.
- Ansys Motor-CAD tutorial and example script available, to automate the extraction process.

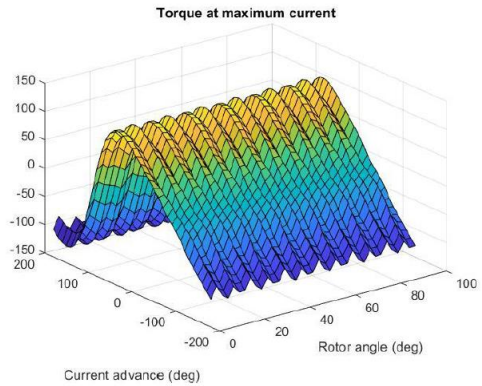
- **Pros:**
  - Significant improvement over a simple E-machine model
  - Conversion into the electrical domain, machine model can be used within a circuit simulation
- **Cons:**
  - No (or very basic) machine loss modelling
  - Machine model is at a fixed temperature



Import IPMSM Flux Linkage Data from MotorCAD

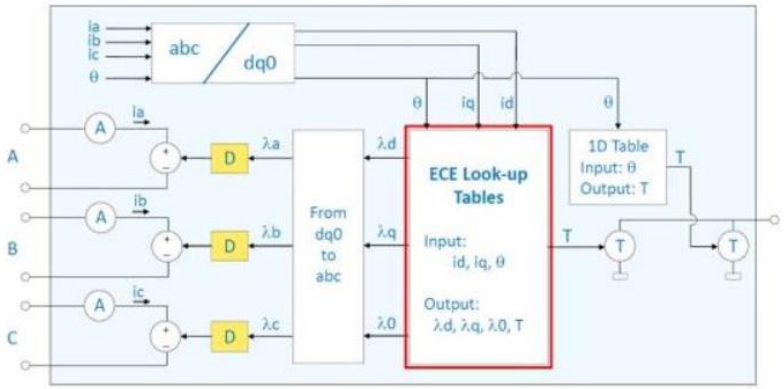
1. Motor data: Open MATLAB script
2. Plot voltages in motor windings (see code)
3. Explore simulation results using sscexplore
4. Learn more about this example



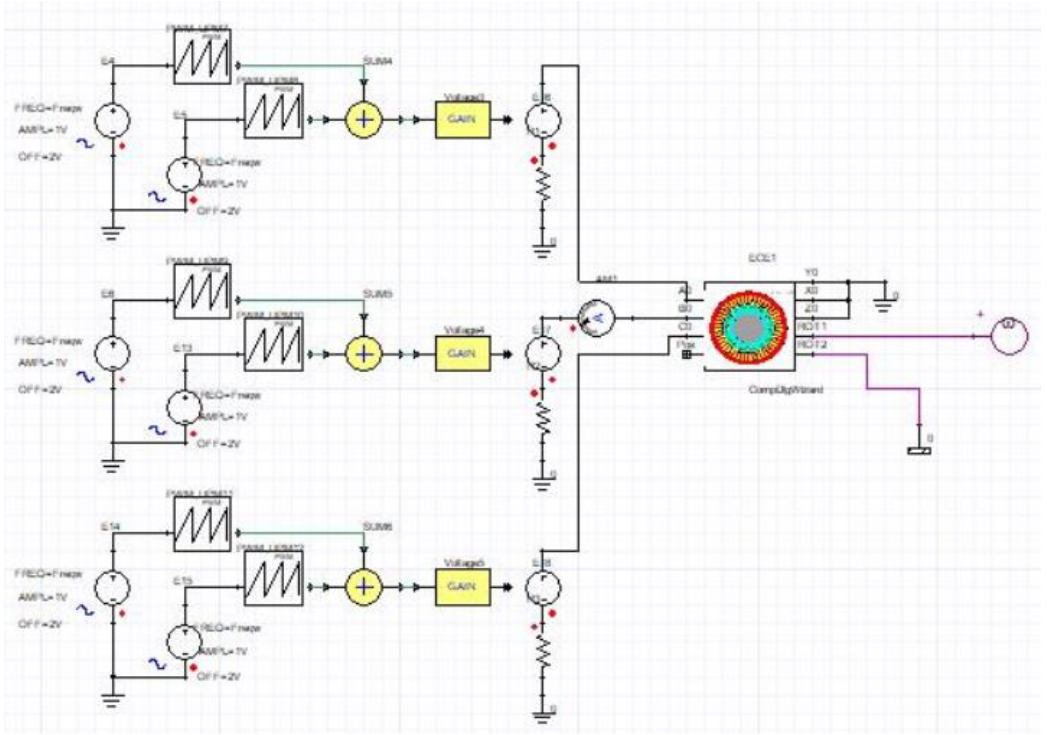


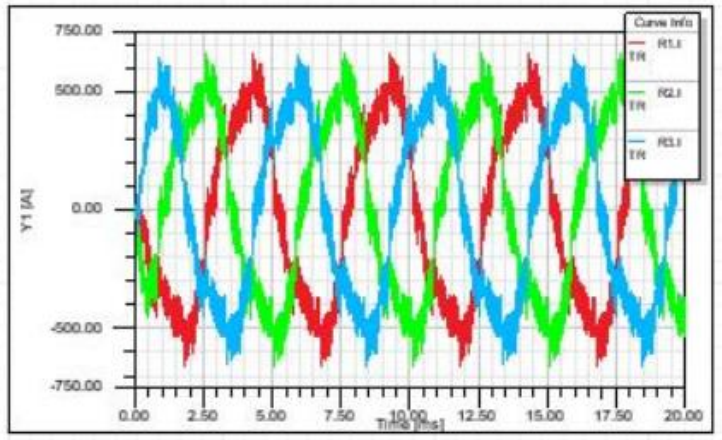
Anys Twinbuilder ECE Model

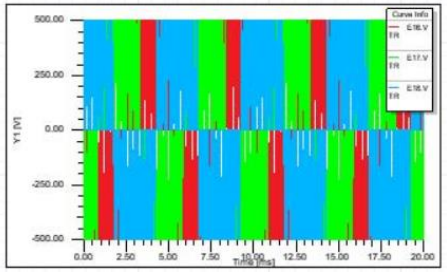
- The Ansys Twinbuilder ECE model is a circuit model based on a combination of motor equations, circuit components and look up tables for flux linkage and torque, obtained from Ansys Motor-CAD.



- This can be used to setup a Pulse Width Modulated voltage source simulation, using built in circuit models.
- A 3-phase current waveform with PWM induced harmonic content is produced, and could be imported into Motor-CAD for loss analysis.

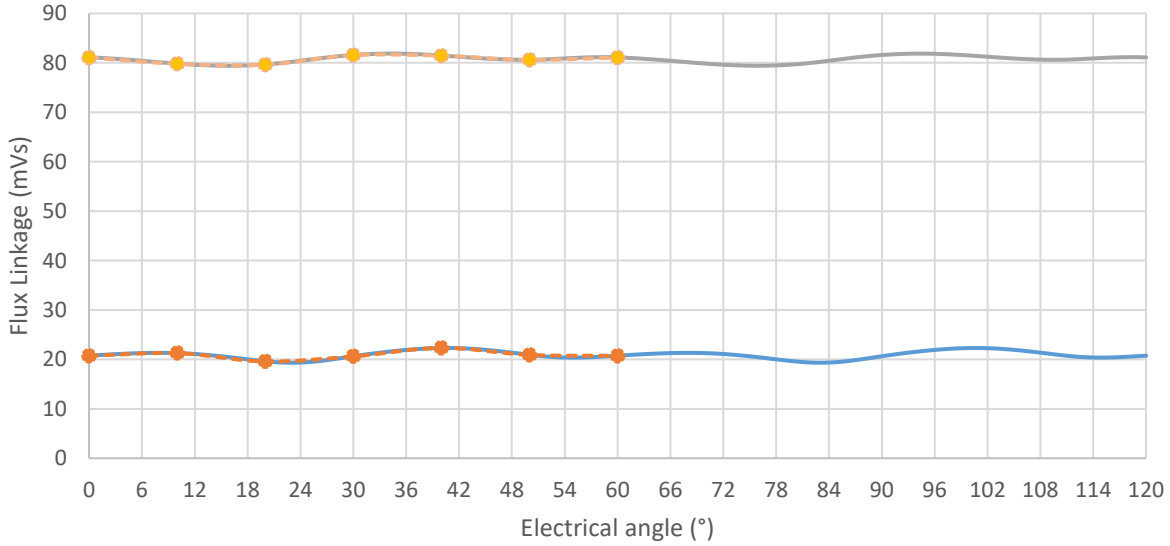


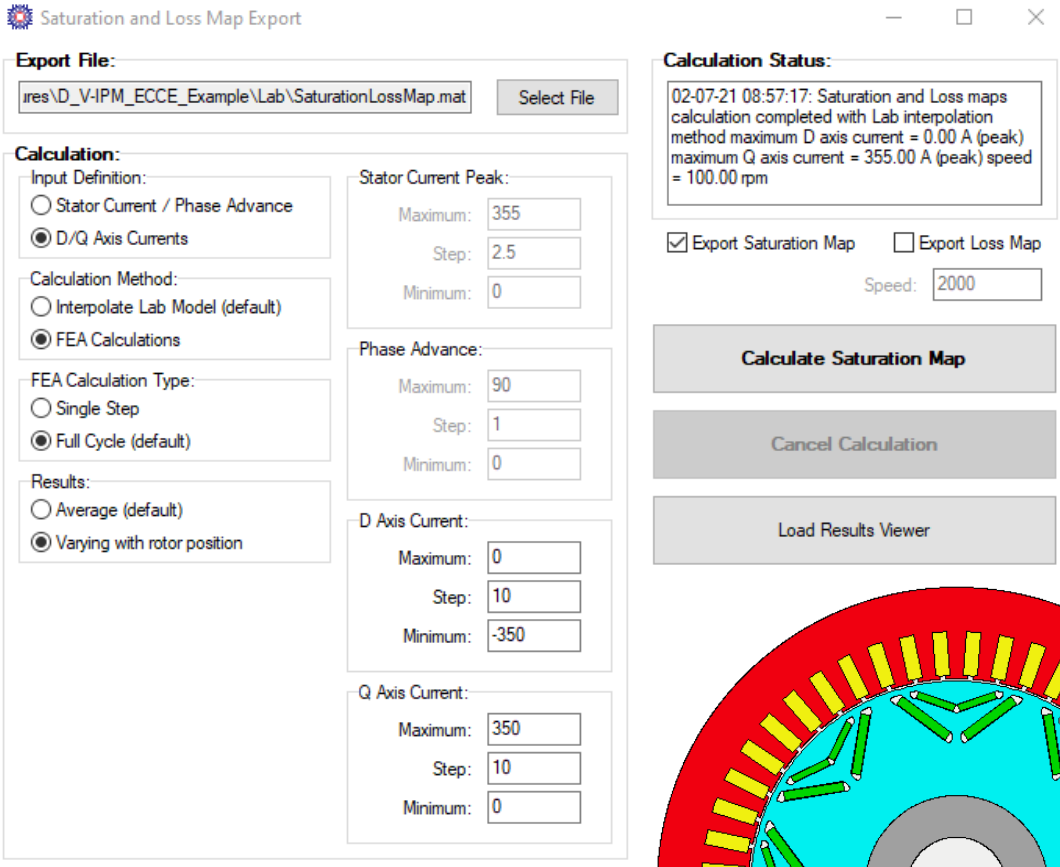


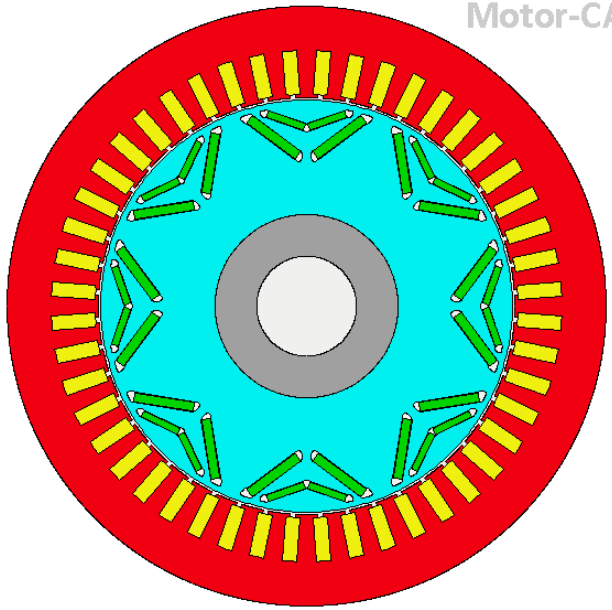


ECE Model Data Extraction

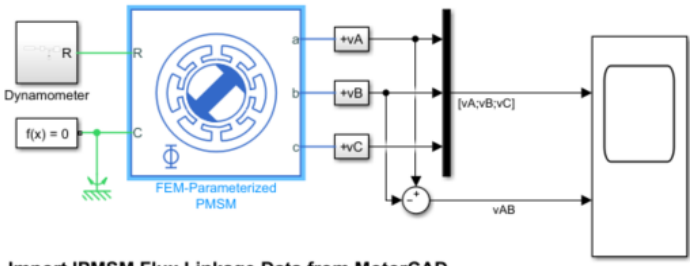
- The Ansys Twinbuilder ECE model requires flux linkage and torque, varying with rotor position.
- A Saturation Map export tool is included within Ansys Motor-CAD to automate and simplify this export process:
  - Just set the current range and resolution to include
  - Simulation strategy is optimised; 6 sims per operating point and parallel computation
  - Available for all Synchronous machine types







System Simulation Solutions with Ansys Motor-CAD



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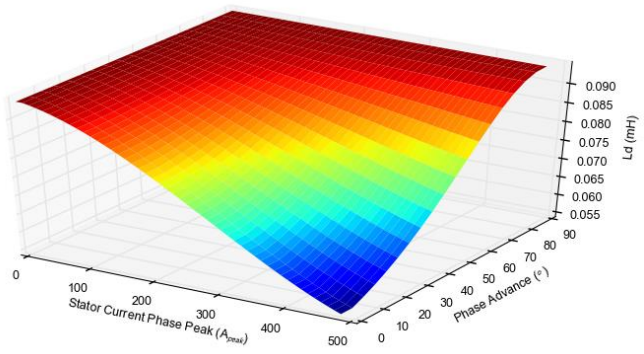

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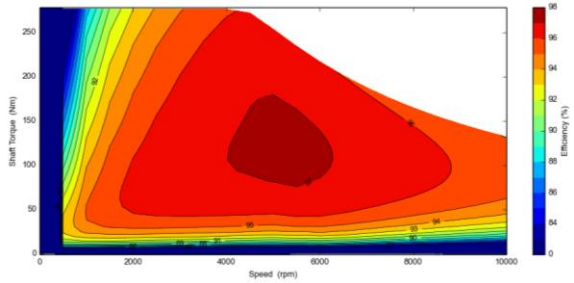

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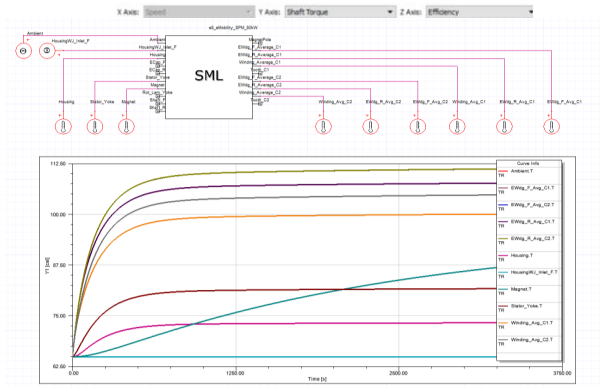

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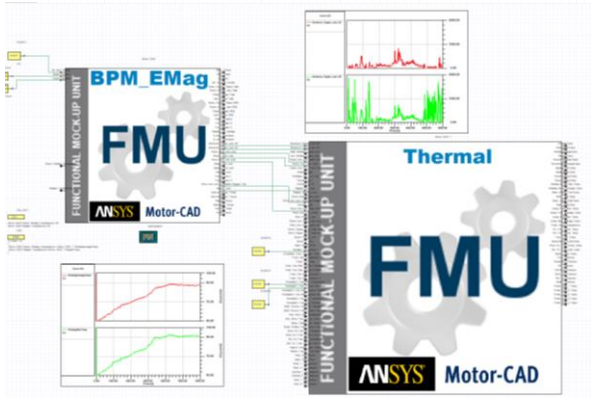

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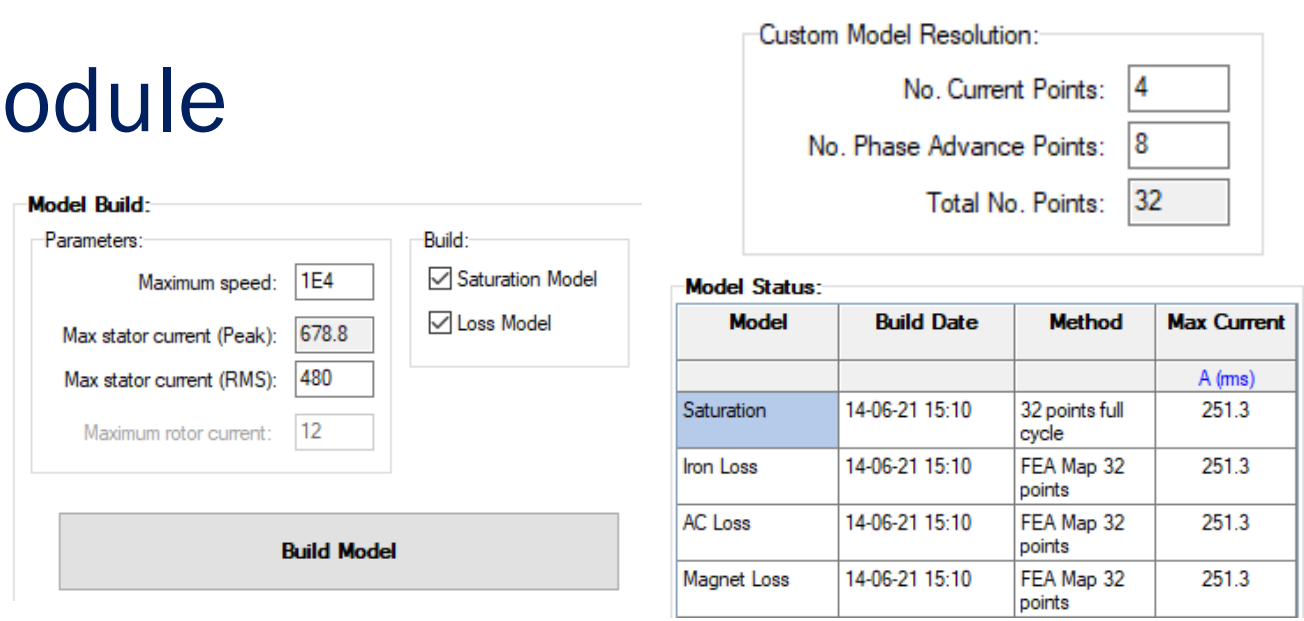
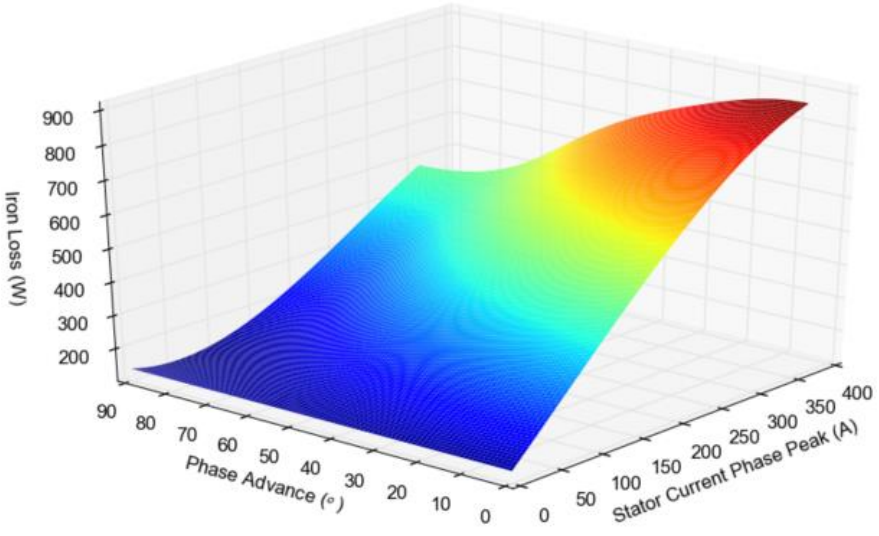
Ansys Motor-CAD Lab Module

- FEA and analytical E-Mag solvers are used to build up inductance and loss maps of the machine design.
- This provides numerous advantages:
  - D/Q axis flux linkage with temperature scaling
  - Inverter model:
    - Account for DC bus voltage & modulation index
    - Enforce common or custom control strategies: e.g. MTPA & ME
  - Loss modelling, including:
    - DC & AC winding loss, with temperature scaling
    - Iron & magnet loss, with current & frequency scaling
    - Mechanical loss (windage and bearing) with speed scaling
  - Fast simulation, fully optimised FEA routine
- Fast calculation of saturation maps, maximum torque/power and efficiency plots.
- Flux linkage, torque, power factor, loss etc. data can be exported.



Model build interface in Ansys Motor-CAD Lab

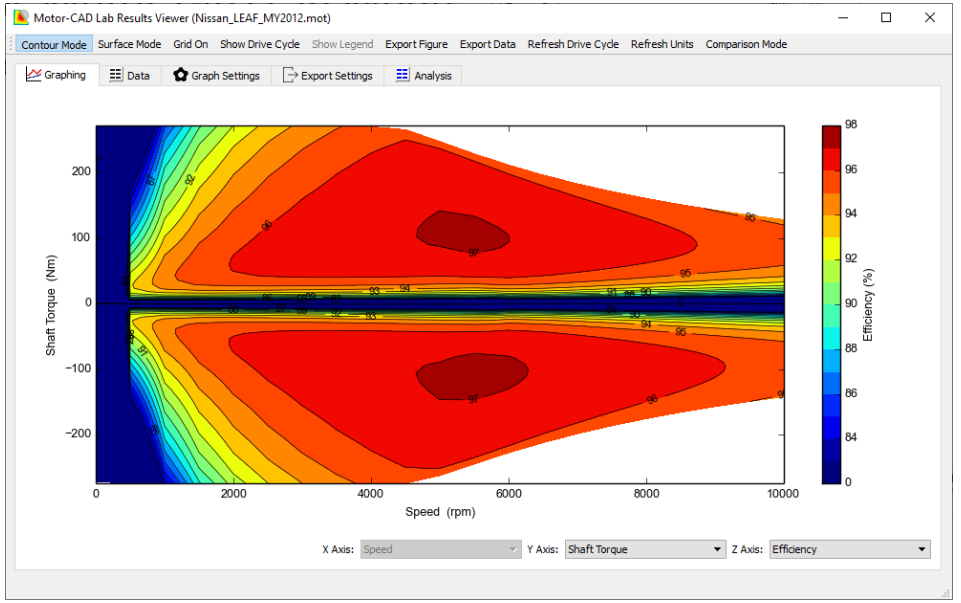


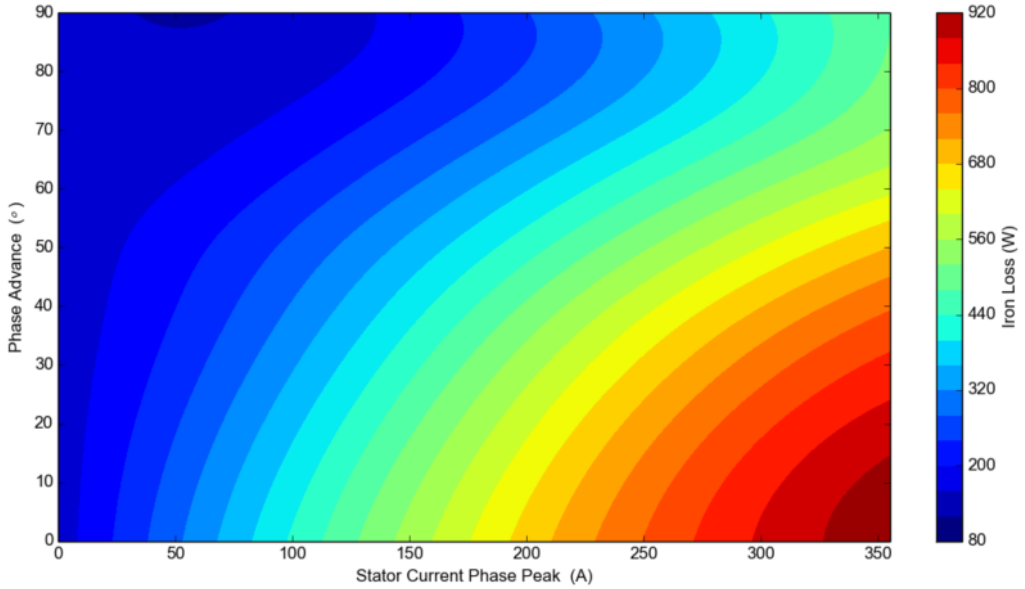
Response surface of iron loss vs current magnitude and angle, calculated using the FEA solver

Loss map export

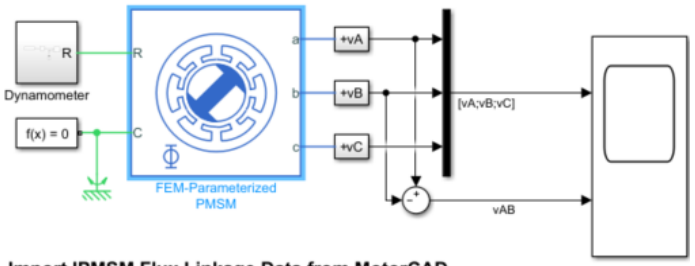
- **Tables of losses against torque and speed.**
  - Using Lab module inverter model
  - Can be easily generated at different temperatures and voltages/modulation index
  - Maximum torque/amp or maximum efficiency control strategy available
- **Tables of losses versus current, at specific shaft speeds**
  - Saturation and loss map export tool
  - Interpolate using the Lab module

- **Pros:**
  - Fast
  - Generates losses to feed into thermal model
  - Data can be spaced by even torque steps
- **Cons:**
  - Inverter-motor control is simplified: average flux linkage and sinusoidal D/Q axis voltage and current phasors





System Simulation Solutions with Ansys Motor-CAD



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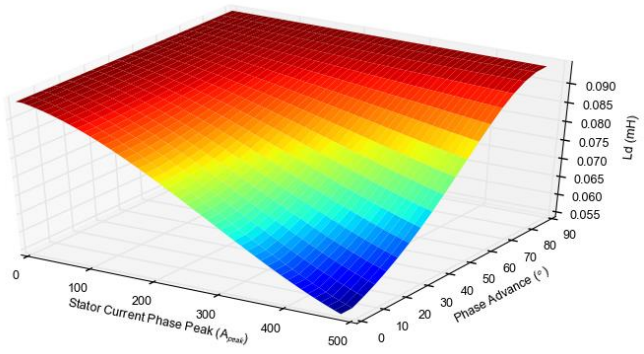

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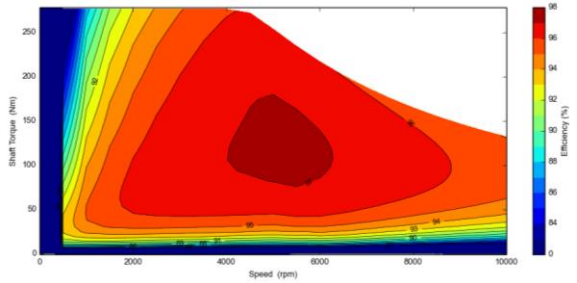

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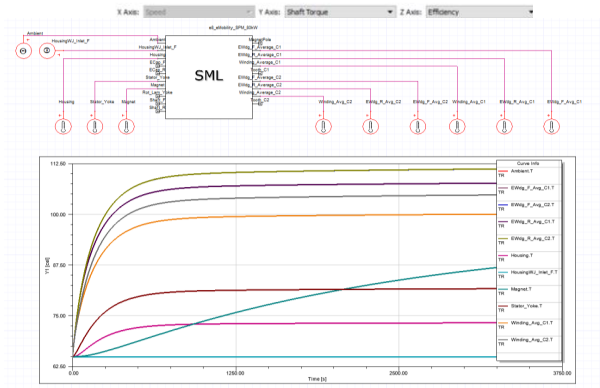

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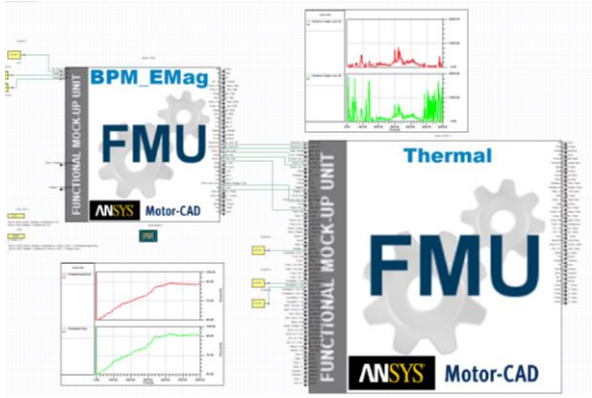

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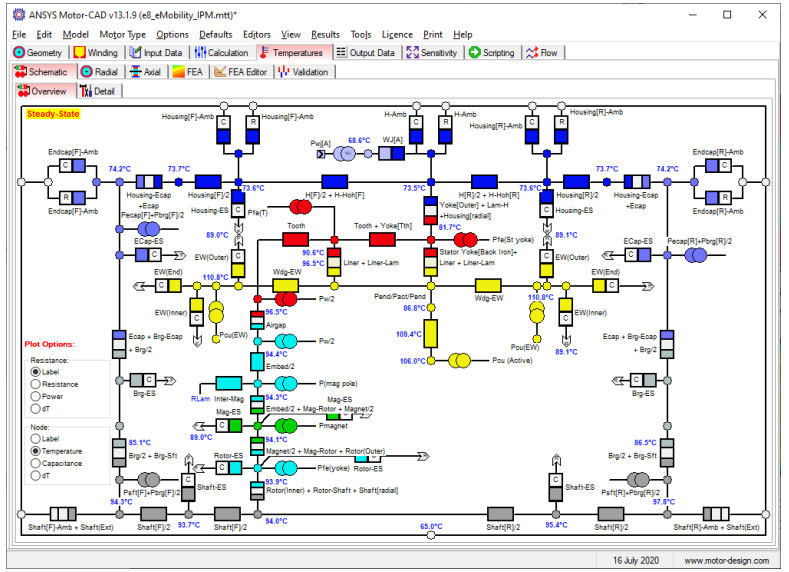
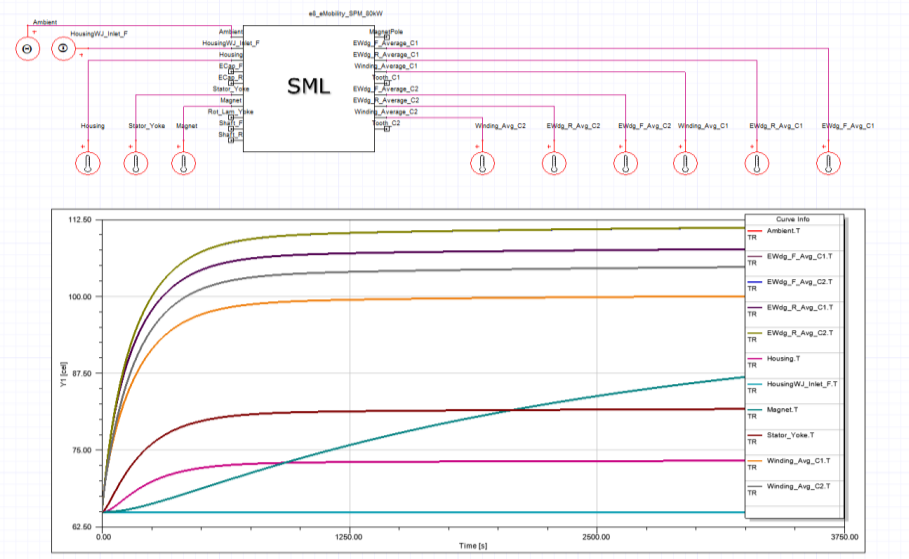
Ansys Motor-CAD Thermal Network Export

- Export the Ansys Motor-CAD lumped parameter thermal network for use in system simulations.
- Import and run as a state-space model.
- Full or reduce order thermal networks possible.
- Ansys Motor-CAD tutorial and example script available, to drive the state space simulation.

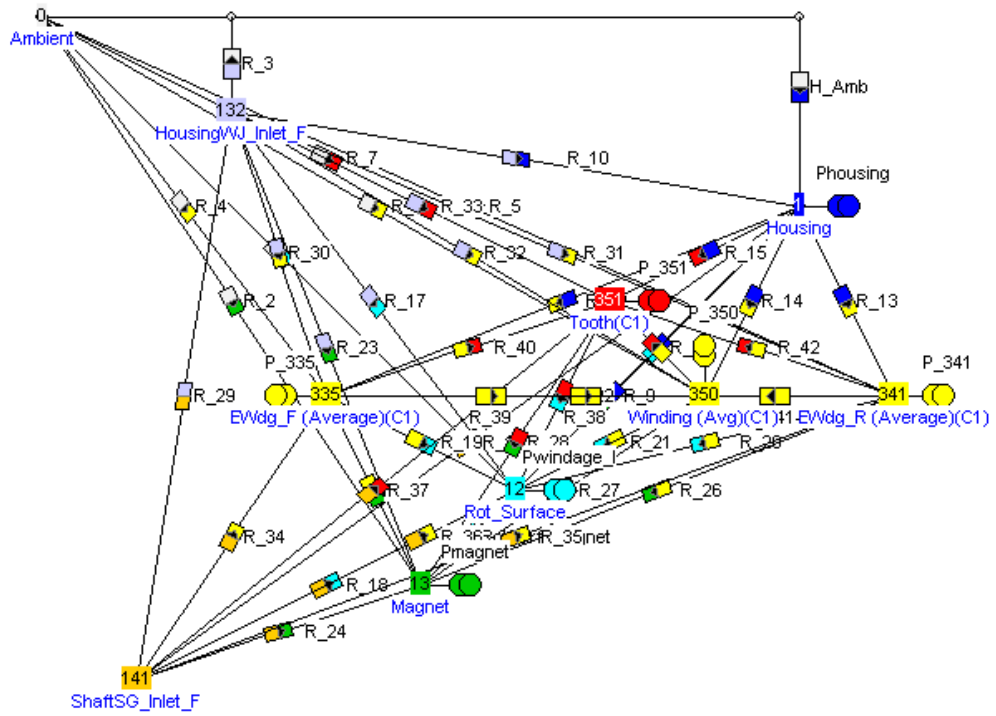
- **Pros:**
  - Easy to export and share the thermal model
  - Maintain design confidentiality
- **Cons:**
  - Thermal network is fixed when exported:
    - Flow, speed, temperature and loss dependencies cannot be updated
    - Valid only for a single operating point or simple transient
    - Other operating points will require further thermal network exports

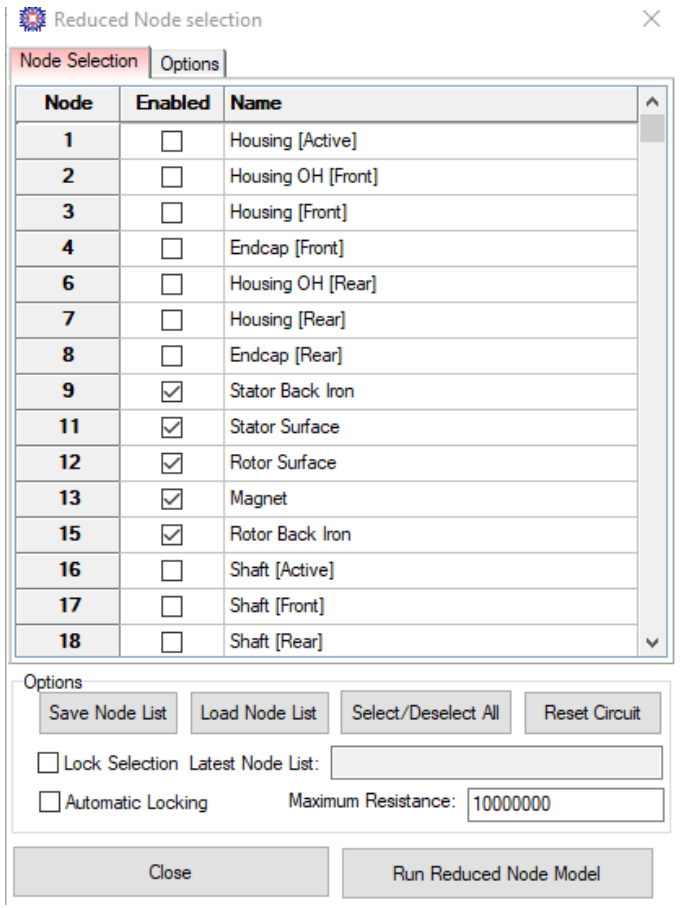


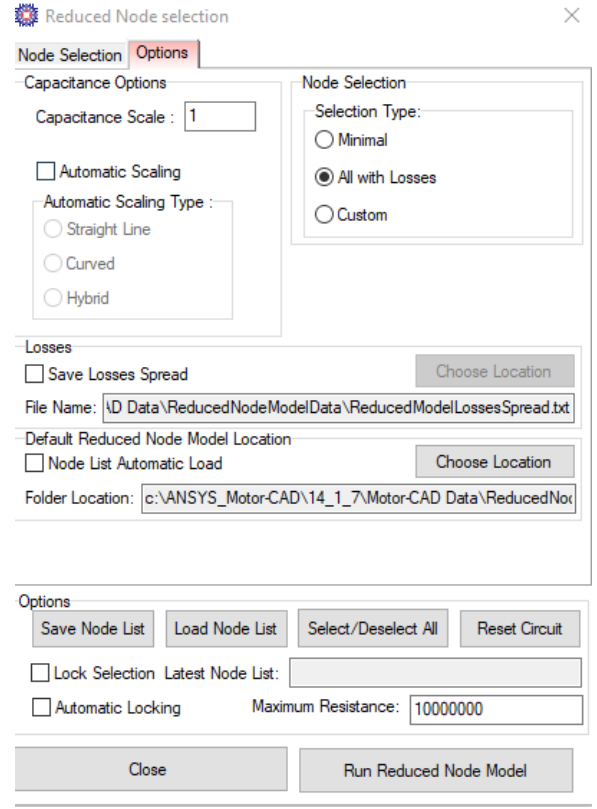


Motor-CAD Reduced Node Thermal Model

- Built in tool for reducing the thermal model
- Several pre-set options: all nodes with losses and minimal
- Functionality to compare with the full thermal model
- Tutorial is available







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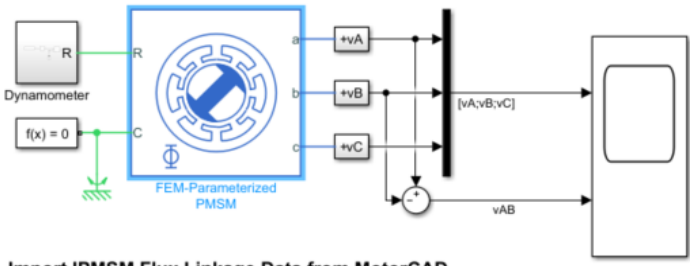

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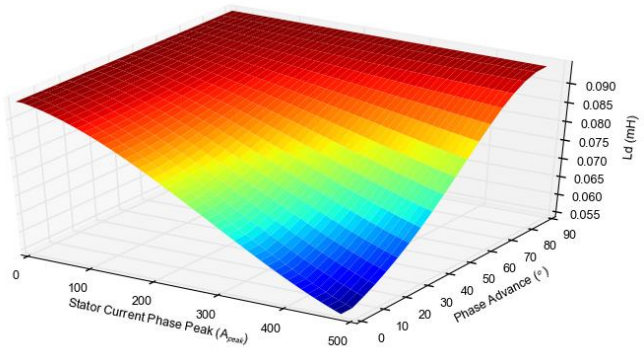

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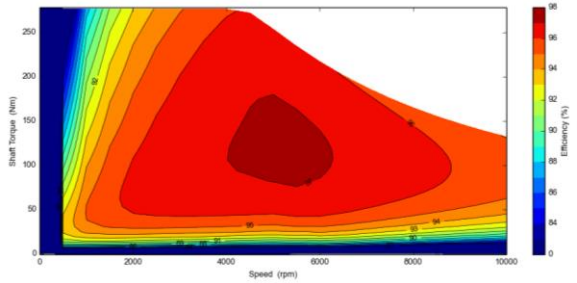

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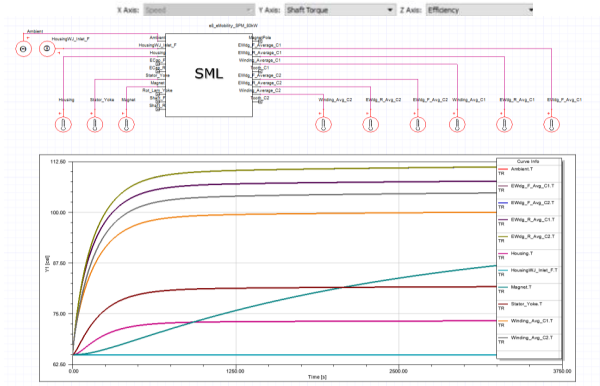

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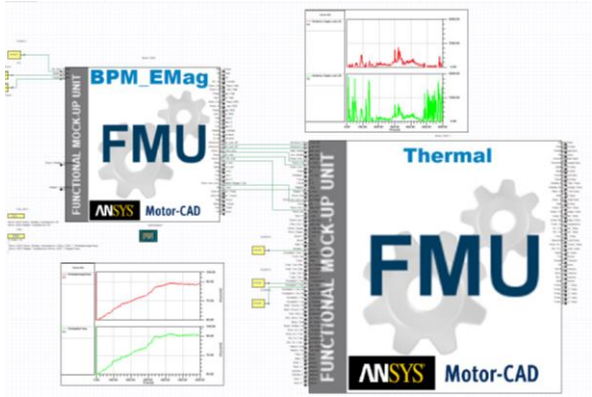
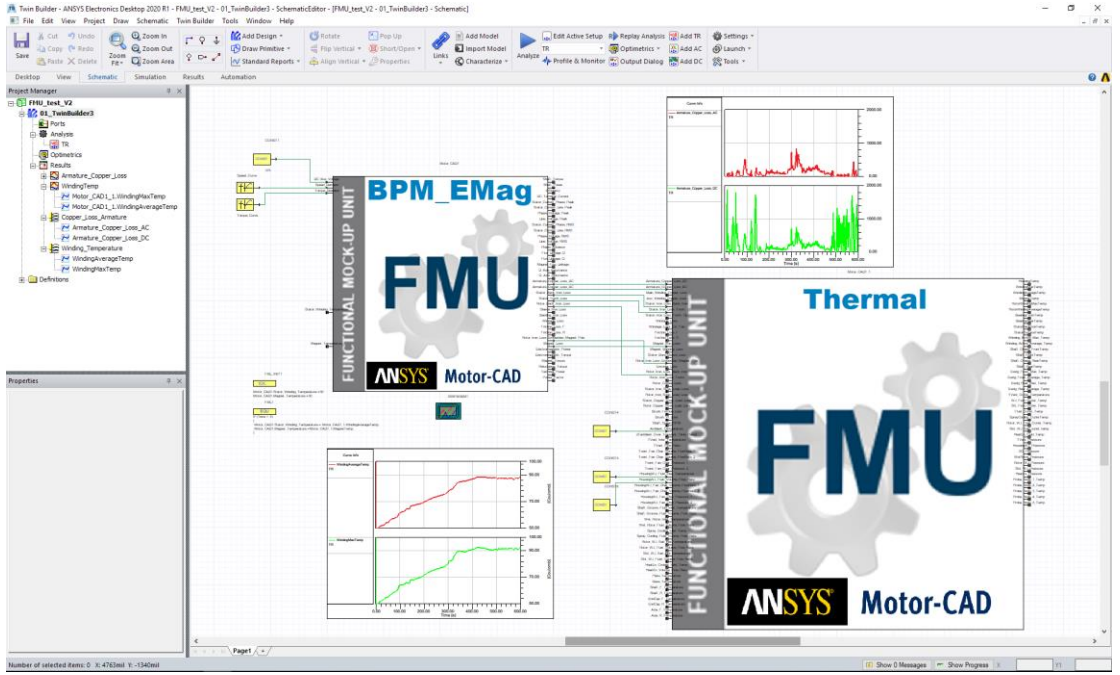


1. Electromagnetic D/Q Flux Linkage model export (ECE model).
2. Electromagnetic/Loss/Control Model export, efficiency/loss map export.
3. Thermal model export, fixed resistance network. Full or reduced order.
4. **Electromagnetic/Loss/Control Co-Simulation, FMU interface.**
5. **Thermal model Co-Simulation, FMU interface.**

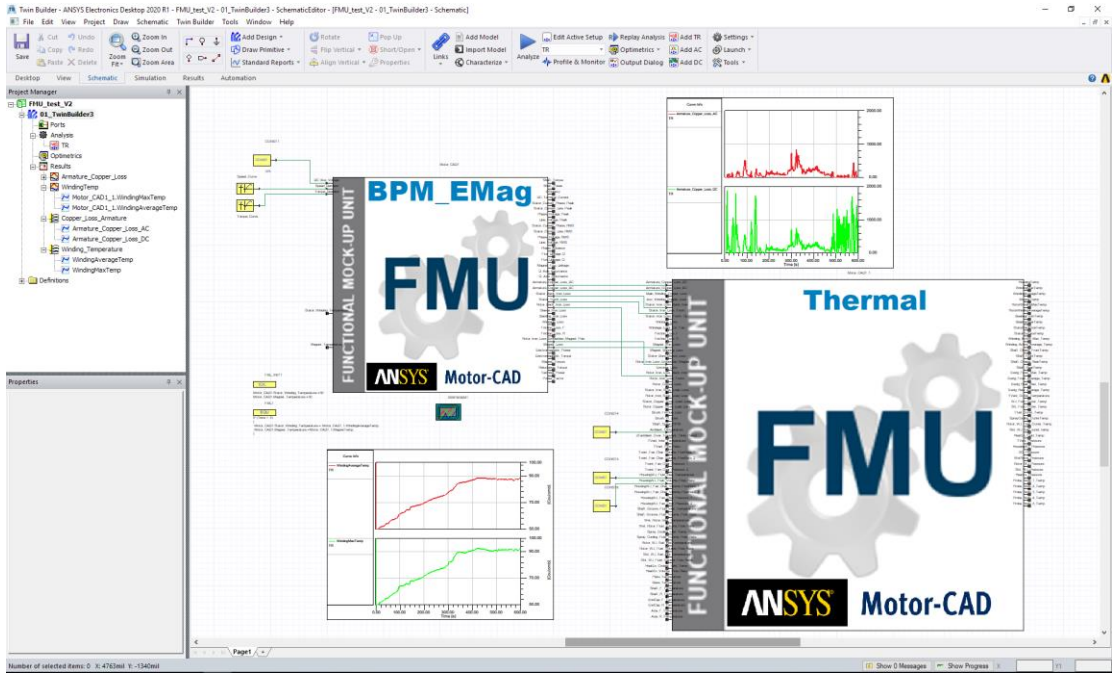
Multiphysics system simulation: Functional Mock-up Interface

- System level co-simulation of Ansys Motor-CAD models.
- Runs the Ansys Motor-CAD Lab and thermal modules within the system simulation.
- Three options available:
  - **Electromagnetic only model** (torque / speed, max. current, DC bus voltage, temps)
    - Runs the Lab module: analytical (fast), but FEA informed (accurate)
  - **Thermal only model** (losses, coolant flow rates, speed)
    - Transient lumped parameter thermal simulation
  - **Combined Electromagnetic and Thermal model:**
    - Connecting the two modules together



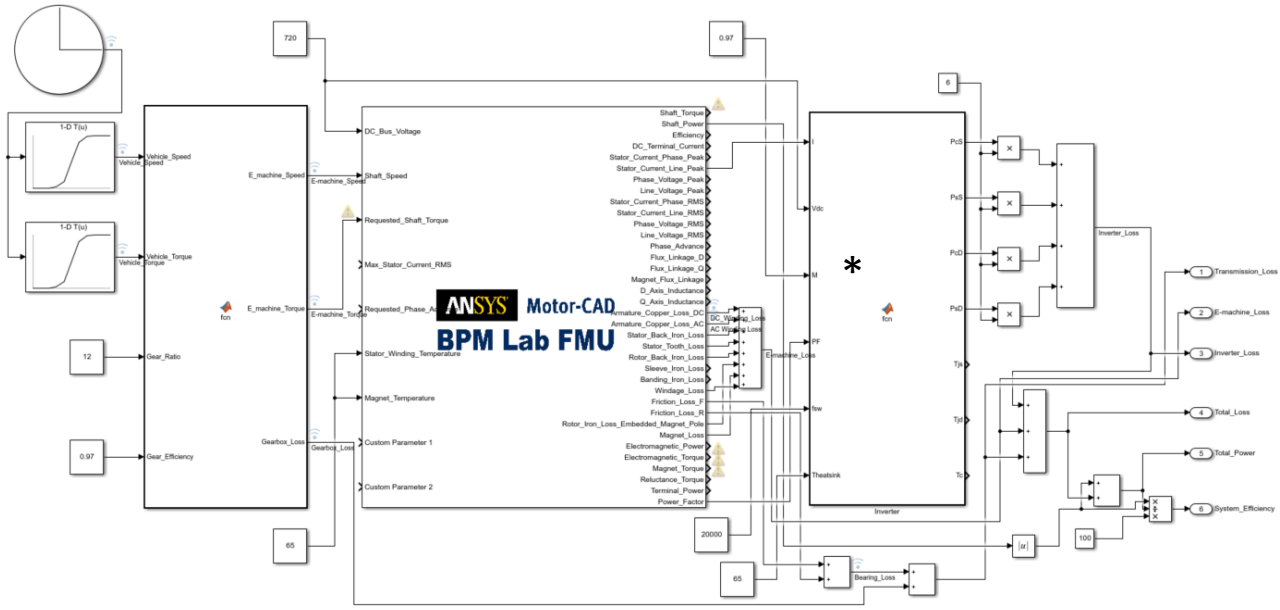
Multiphysics system simulation: Functional Mock-up Interface

- **Pros:**
  - Accurate models
  - Thermal model accounts for variable resistances
  - Accurate mapping and scaling of the losses for the thermal model
  - Fast
  - Open – can be easily coupled with other system components
- **Cons:**
  - Currently model can't be shared without design data in .mot file



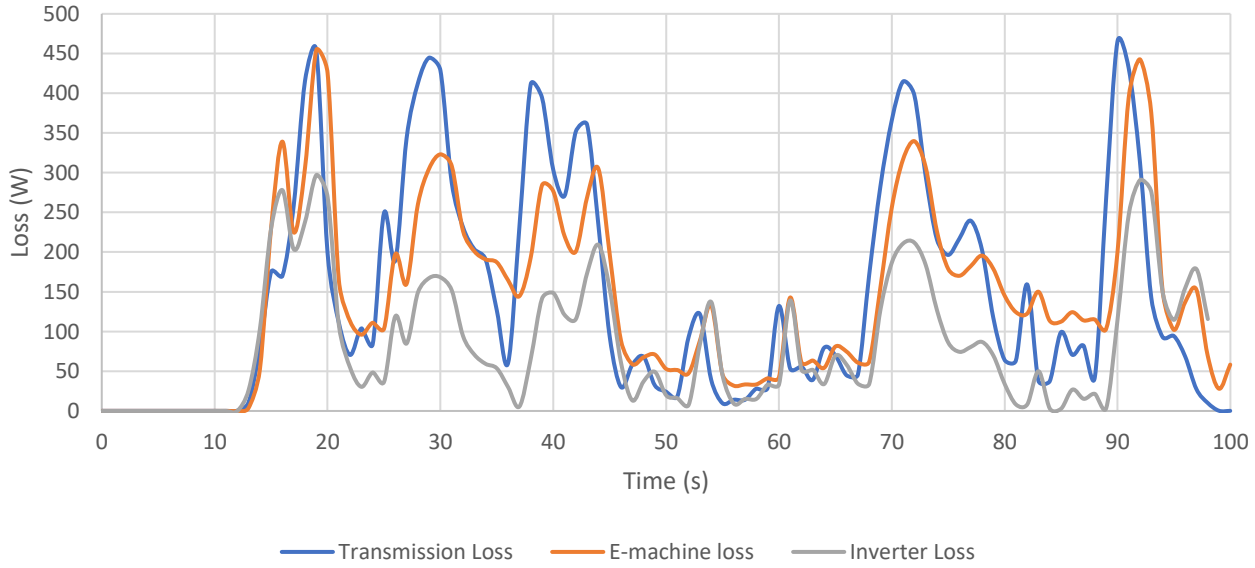
Ansys Motor-CAD Lab FMU

- **Example PM traction application using only the Ansys Motor-CAD Lab FMU:**
  - System inputs = Torque & speed demand or phase current & advance, temperature and DC bus voltage
  - BPM Lab FMU:
    - Calculates optimal phase current and advance to meet torque demand
    - Outputs = voltage/current/power factor, achieved torque/power and losses
  - Inverter loss model:
    - Calculates losses from E-machine operating condition
- **Result = corresponding, transmission, E-machine and inverter losses over the WLTP class 3 drive cycle.**



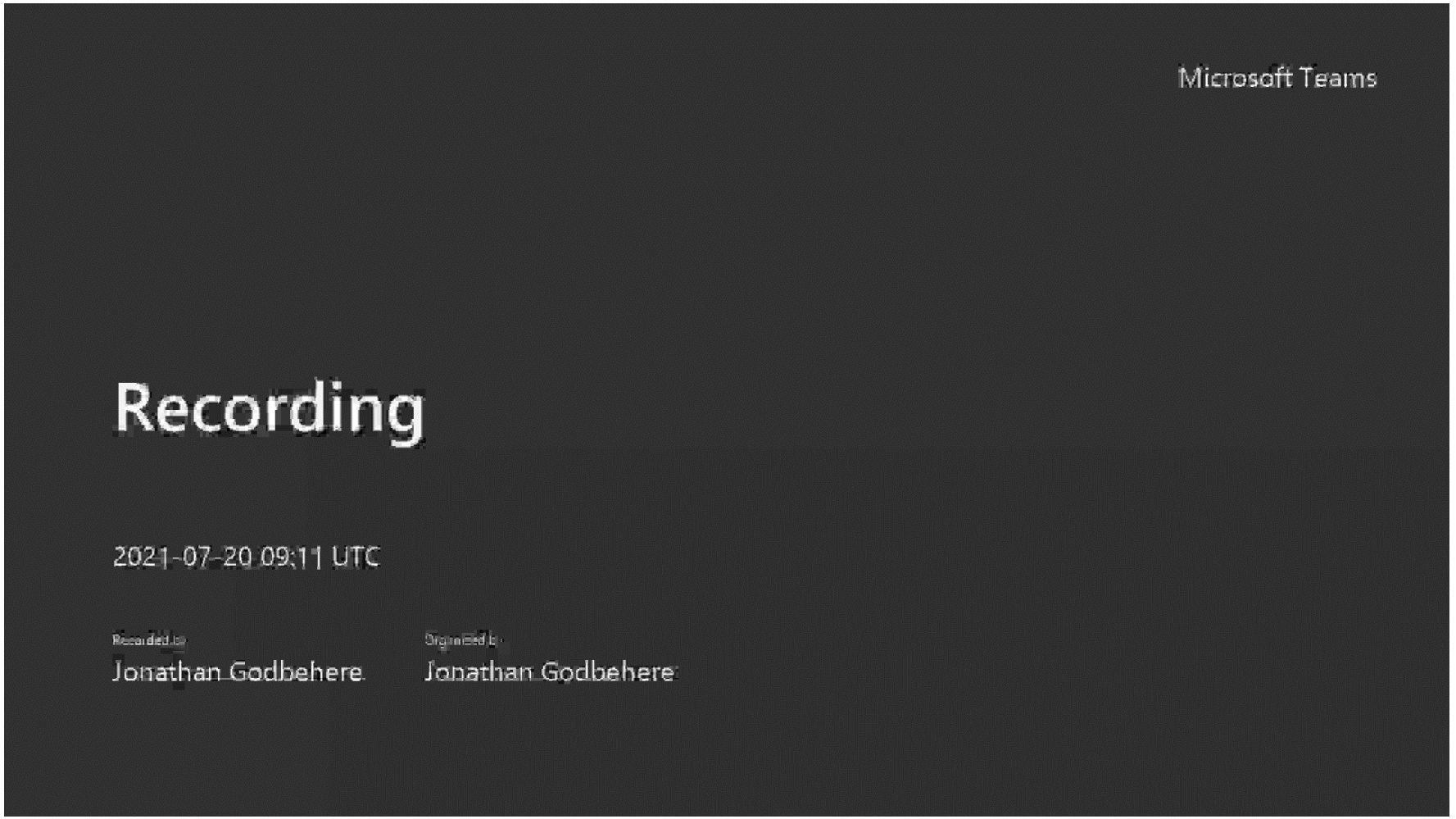
1800 data points in 2 mins, 30 seconds

*Model developed by University of L'Aquila



Ansys Motor-CAD Lab FMU Demo

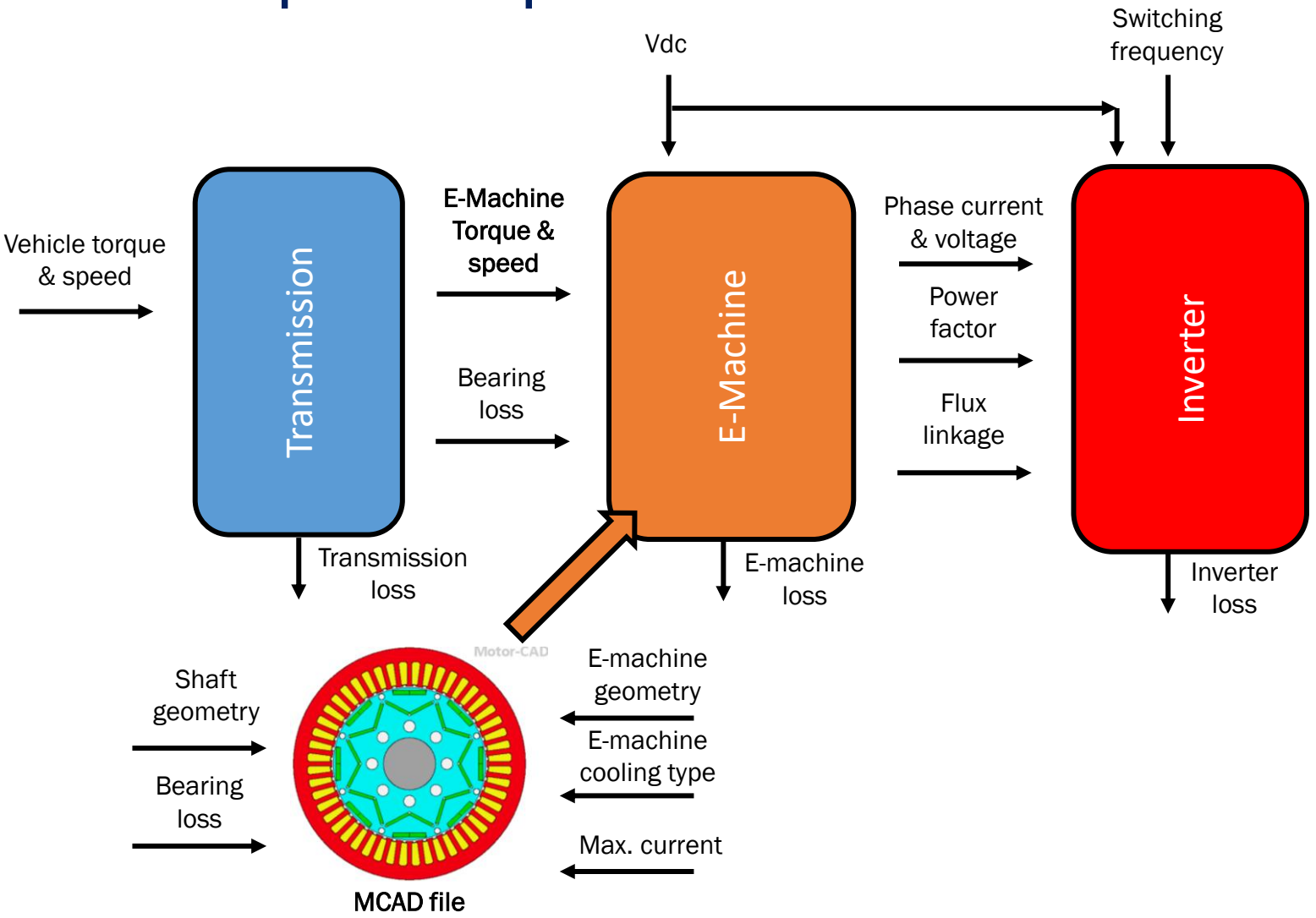
- Point the FMU to the Motor-CAD file you wish to run.
- Most time-efficient, when the Lab models have been pre-simulated.
- An instance of Motor-CAD is opened, file is loaded and it moves to the Lab module.
- Works well with a Motor-CAD blackbox license, which are a separate license pool.
- FMI simulation took 30s to do 500 operating points



Automotive system example – Option 1

Transmission -> E-machine -> Inverter

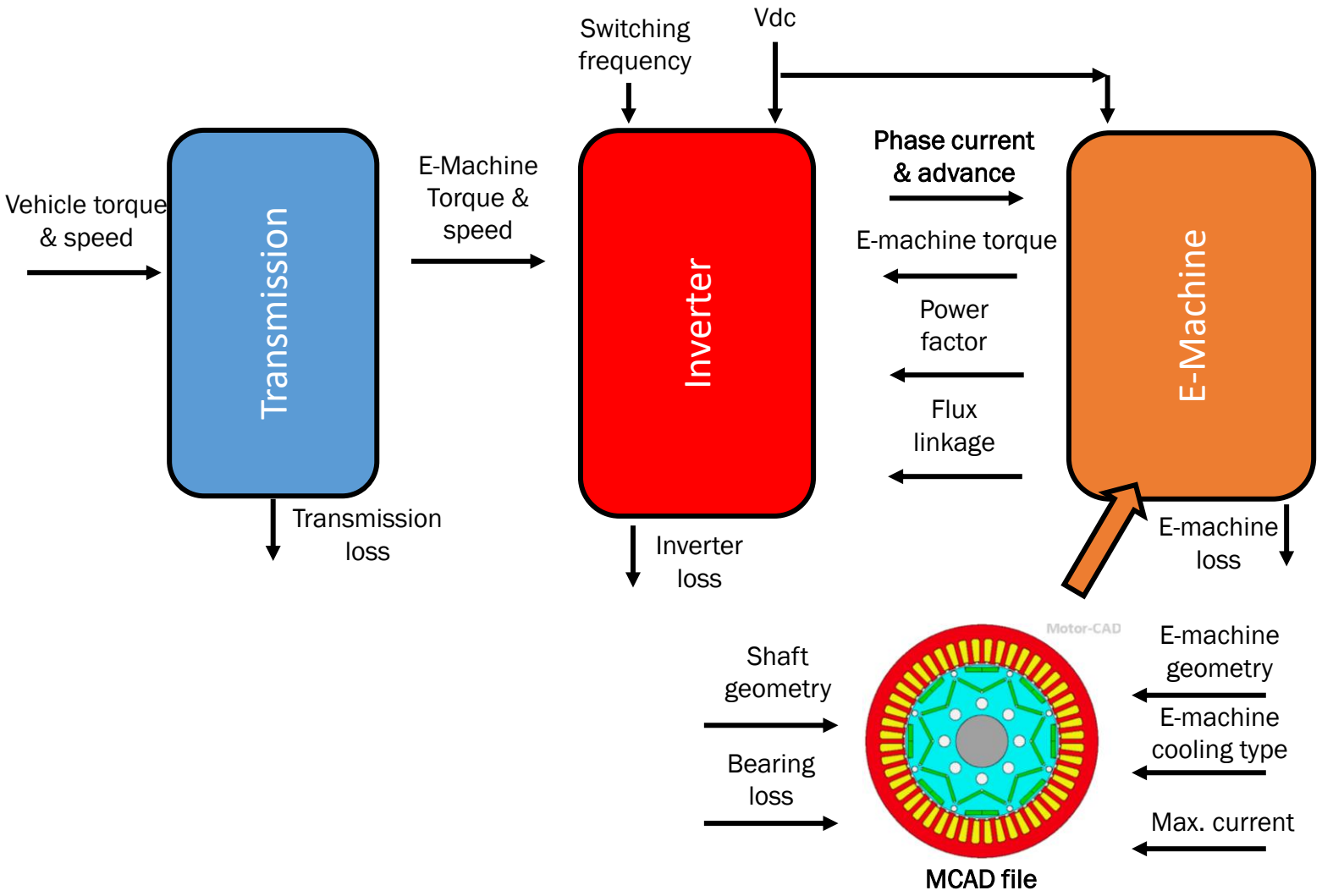
- FMU inputs = torque and speed demand
- Transmission block takes vehicle requirements and converts to E-machine
- Uses Motor-CAD integrated inverter control model within E-machine block
  - Maximum torque per amp or maximum efficiency
  - Space vector control
  - Sinusoidal components
  - Must be pre-built up to the maximum current required
- Previous application example is this topology
- Mechanical losses could be directly integrated in MCAD file, if useful



Automotive system example – Option 2

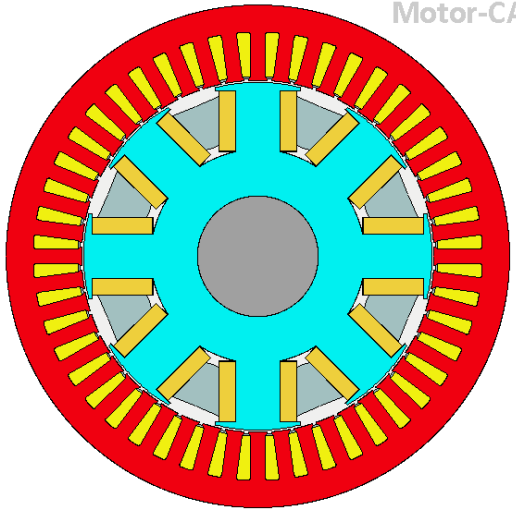
Transmission --> Inverter -> E-machine

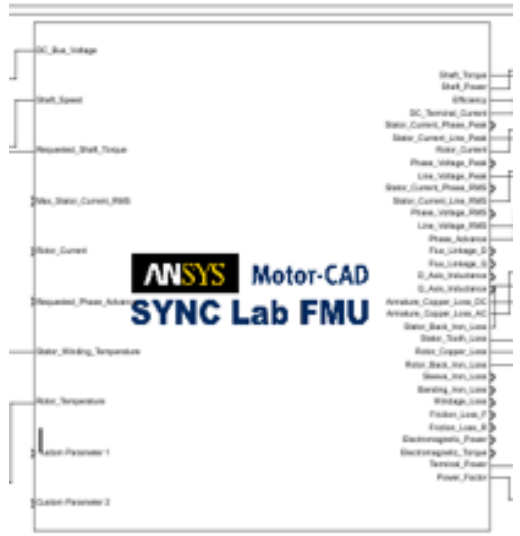
- FMU inputs = current and phase advance
- Transmission block takes vehicle requirements and converts to E-machine
- Inverter takes torque & speed demand, calculates necessary E-machine current & phase advance
  - Control is included within inverter block
  - Inverter may require power factor, flux linkage & output torque from E-machine model
  - Some internal iterations between inverter & E-machine will be necessary, to ensure output torque is achieved
  - Possible with DQ current transformations

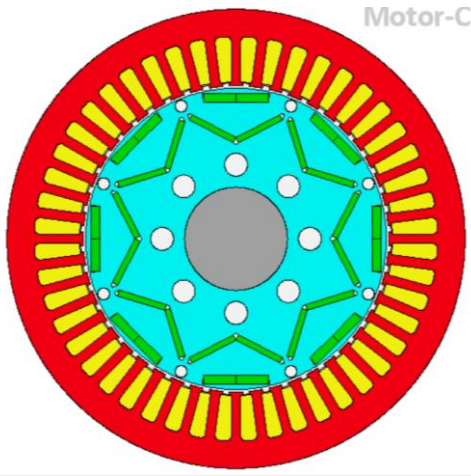


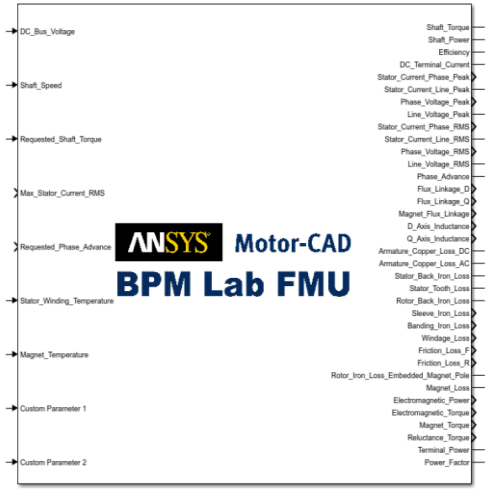
Ansys Motor-CAD FMU – V. 14.1

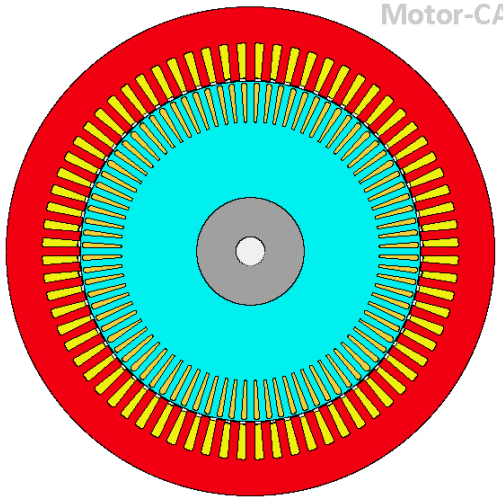
- **V14.1 updates**
  - Induction Machine (IM) Lab FMU
  - Synchronous Machine (Wound Rotor & Synchronous Reluctance) Lab FMU
- **New motor types added alongside Permanent Magnet machines, released in V13 of Ansys Motor-CAD**
- **Lab and Thermal FMU blocks available**

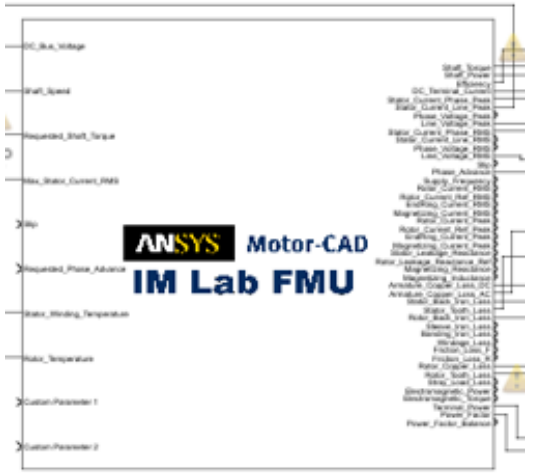






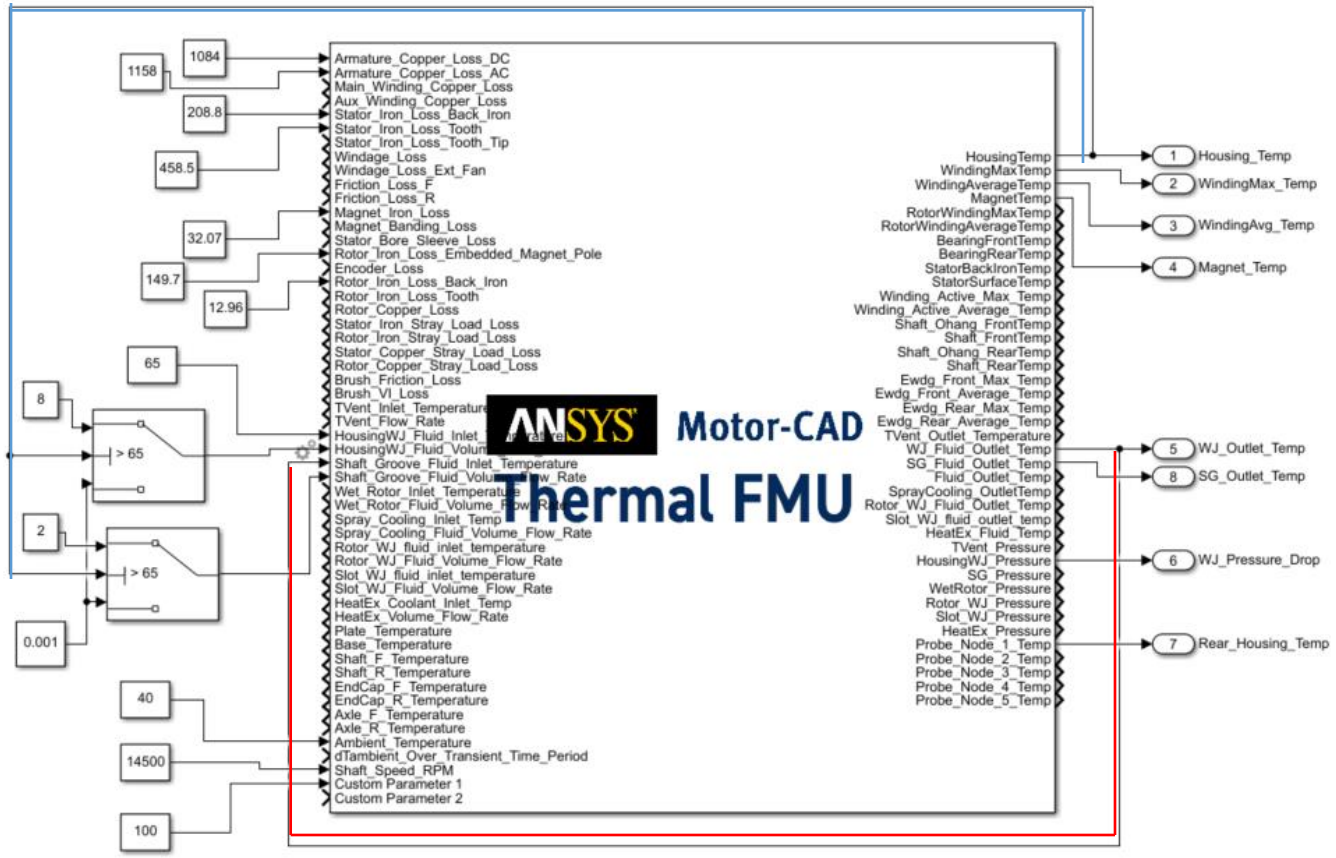






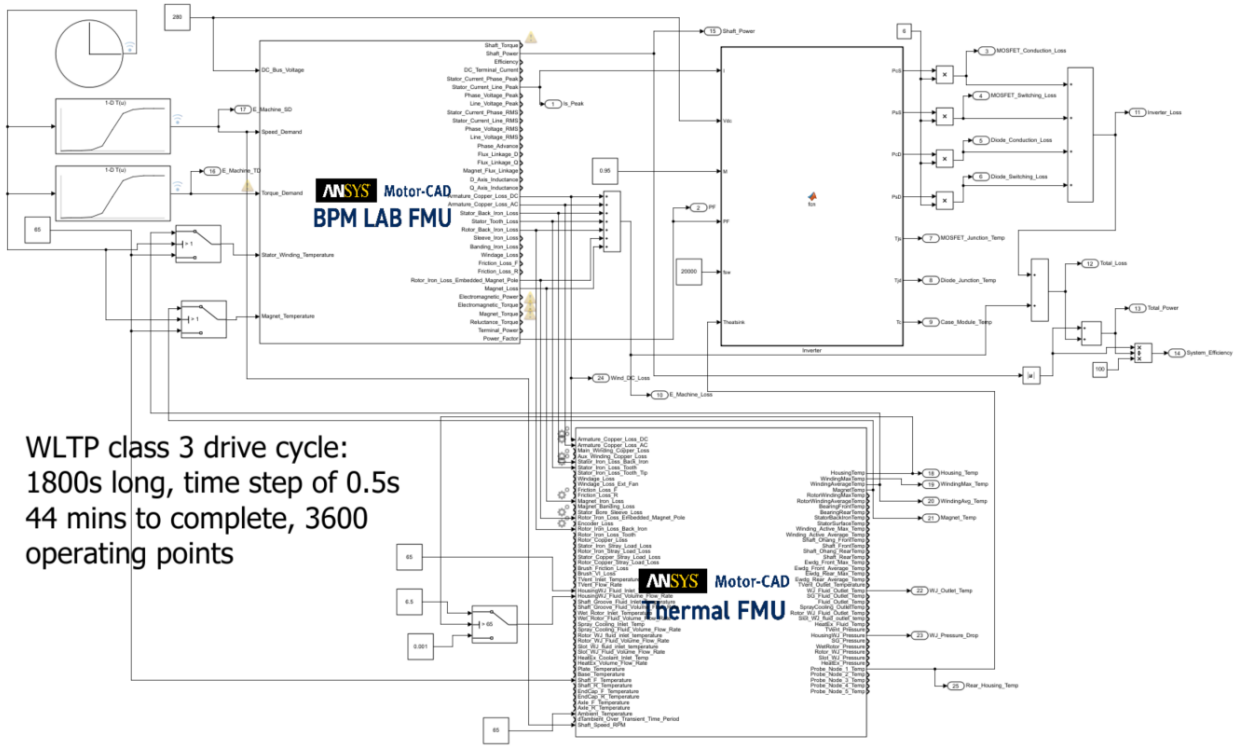
Ansys Motor-CAD Thermal FMU

- **Can be run as a stand-alone FMU**
  - Transient thermal simulation
  - Full functionality of the thermal module:
    - Full model resolution
    - Lumped parameter thermal model updates with coolant input, temperature and speed
- **Losses are input as a parameter**
  - For example: from test results
  - Losses split into regions: e.g. stator tooth iron loss and stator back iron loss
  - Winding loss will be scaled with temperature,
- **Potential customisations to the cooling circuit**
  - Allow coolant to be turned “on” once the motor reaches a certain temperature
  - Connect two active cooling components in series
  - Possible within Motor-CAD with scripting or customisation of the thermal circuit, but the FMU is an easy to use alternative

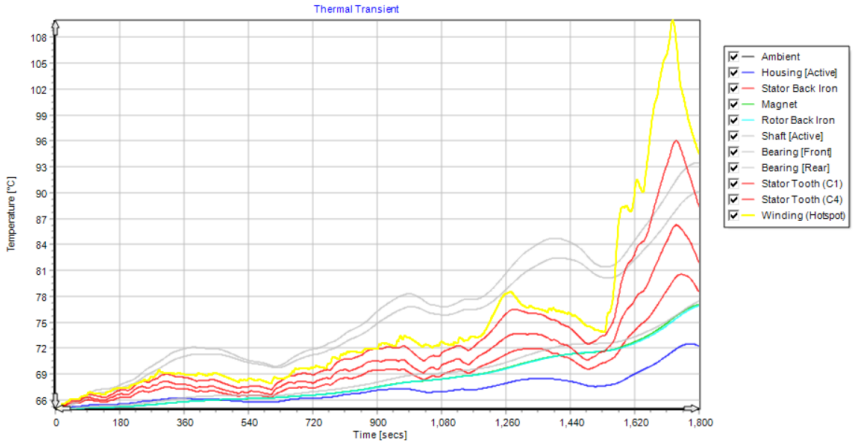


Ansys Motor-CAD Thermal FMU

- When combined with the Lab FMU:
  - Losses are input from the Lab FMU
  - Resultant temperature is fed back into the Lab FMU
  - Inverter model compensates for temperature, losses scale with temperature, current and speed
  - Still uses one instance of Motor-CAD
- Potential system simulation uses:
  - Add external loss sources or temperature boundaries into the Motor-CAD thermal model
  - Add the Motor-CAD thermal FMU into a wider system cooling flow



WLTP class 3 drive cycle:
1800s long, time step of 0.5s
44 mins to complete, 3600 operating points



Summary

- System engineering is crucial to the managing the complexity in electrified powertrain development.
- Systems modelling and design can lead to faster, lower cost development processes as well as better overall performance of the developed system.
- Utilising standardised interface technology is a key enabler for this and is now being built in as a core feature of application specific design and development tools such as Ansys Motor-CAD.
- Having native support of the FMI interface in Motor-CAD enables accurate and fast solving models to be integrated into any systems modelling environment.

Motor Design Software by Motor Design Engineers