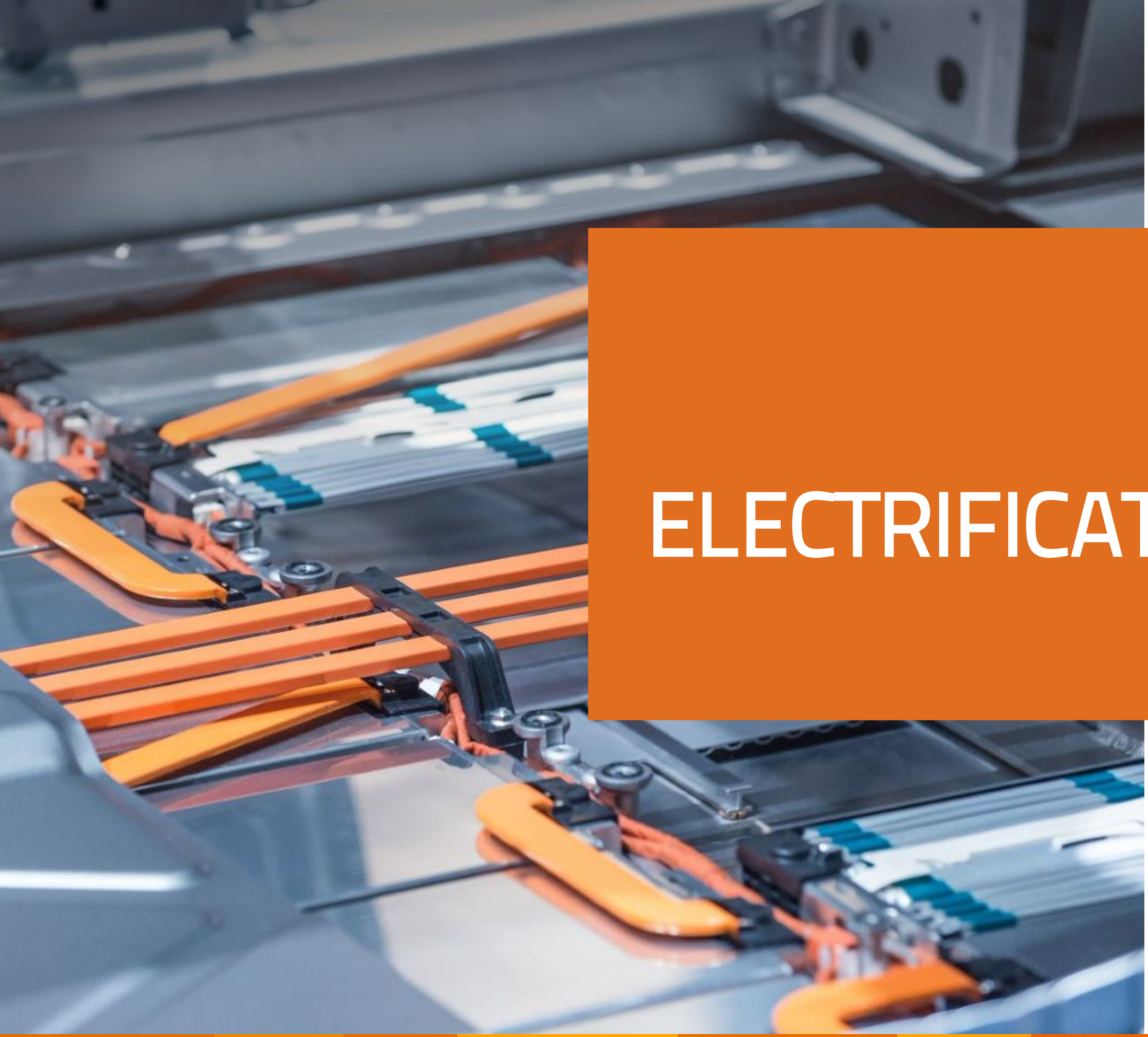


ELECTRIFICATION LIBRARY

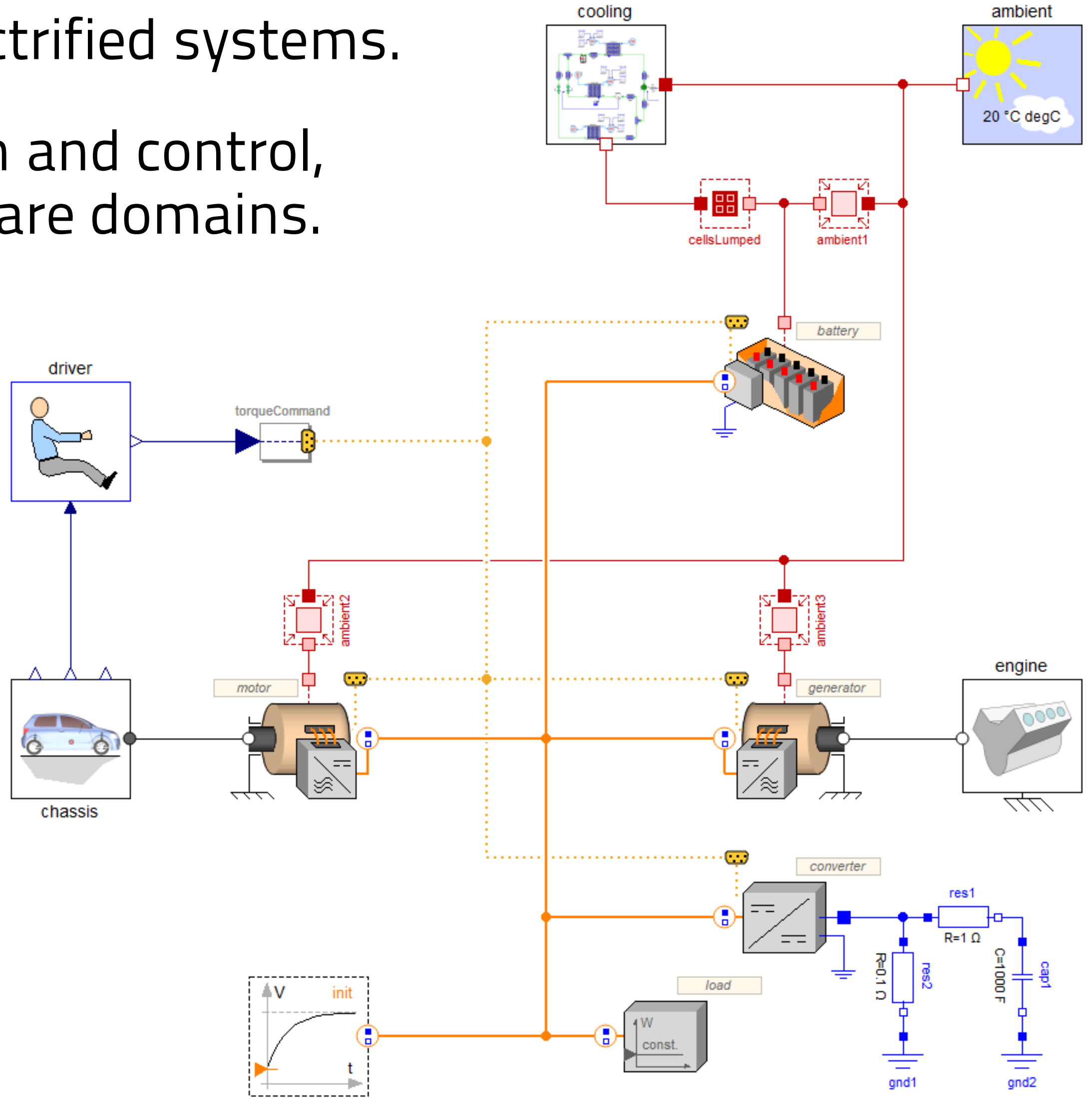
Overview

AGENDA

- ❑ About
- ❑ Key Benefits
- ❑ Key Capabilities
- ❑ Key Applications
- ❑ Library Contents
- ❑ Modelon Compatibility
- ❑ Latest Release

ABOUT ELECTRIFICATION LIBRARY

- Modelica library for multi-purpose modeling of electrified systems.
- A common solution for design, analysis, verification and control, spanning electrical, thermal, mechanical and software domains.
- Suitable for a wide range of applications, including:
  - Automotive
  - Aerospace
  - Personal mobility
  - Auxiliary power electric storage
  - Industrial systems



KEY CAPABILITIES

KEY CAPABILITIES

- **Scalable architecture** with compatible component models for systems modeling
  - Multi-purpose: different simulation use cases within the same model framework
  - Scalable fidelity levels
  - Thermal support for all components
- **Multi-physics** component models
  - Batteries
  - Machines
  - Power converters
  - Loads
- Object-oriented, **modular** library with re-usable components
  - Reusable components
  - Streamlined variant handling

KEY CAPABILITIES

- **Extendable**
  - Adapts to customer specific interfaces
  - Allows implementation of custom implementations and IP that plug into system architecture
  - Supports integration of models from 3rd party libraries
- **Adaptable**
  - Model topology that can reflect customer system topology and decomposition

KEY BENEFITS

KEY BENEFITS

- Accurate, computationally-efficient representation of electrical, mechanical, thermal, and control (software) dynamics
- Support for a wide range of electrification applications with a common, collaborative approach
- Native configuration management to handle multi-purpose use cases (different systems, applications, level of detail, computational requirements, interfaces, etc.)
- Streamlined modeling with reusable components and flexible architecture
- Robust model architecture for users to focus on application-specific modeling
- Extendable models for user customization and IP
- Standard interfaces to support integration with other models

KEY APPLICATIONS

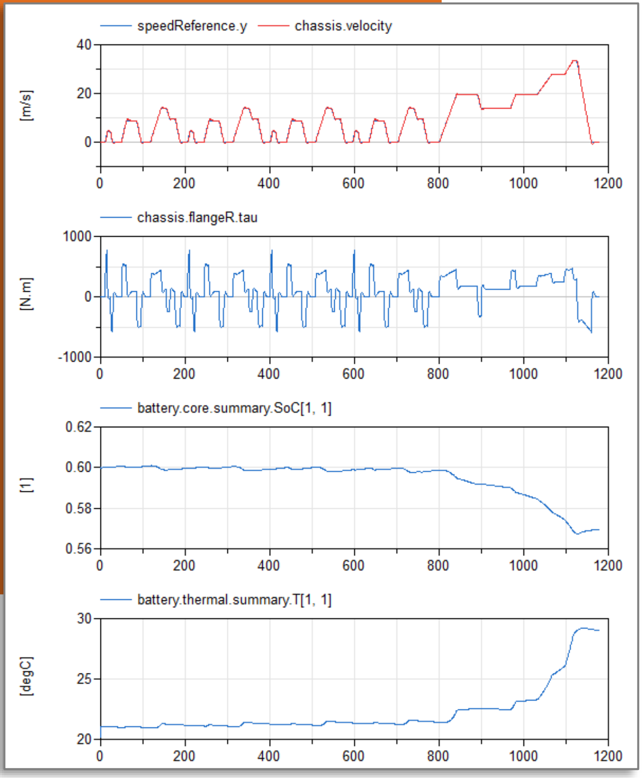
KEY APPLICATIONS

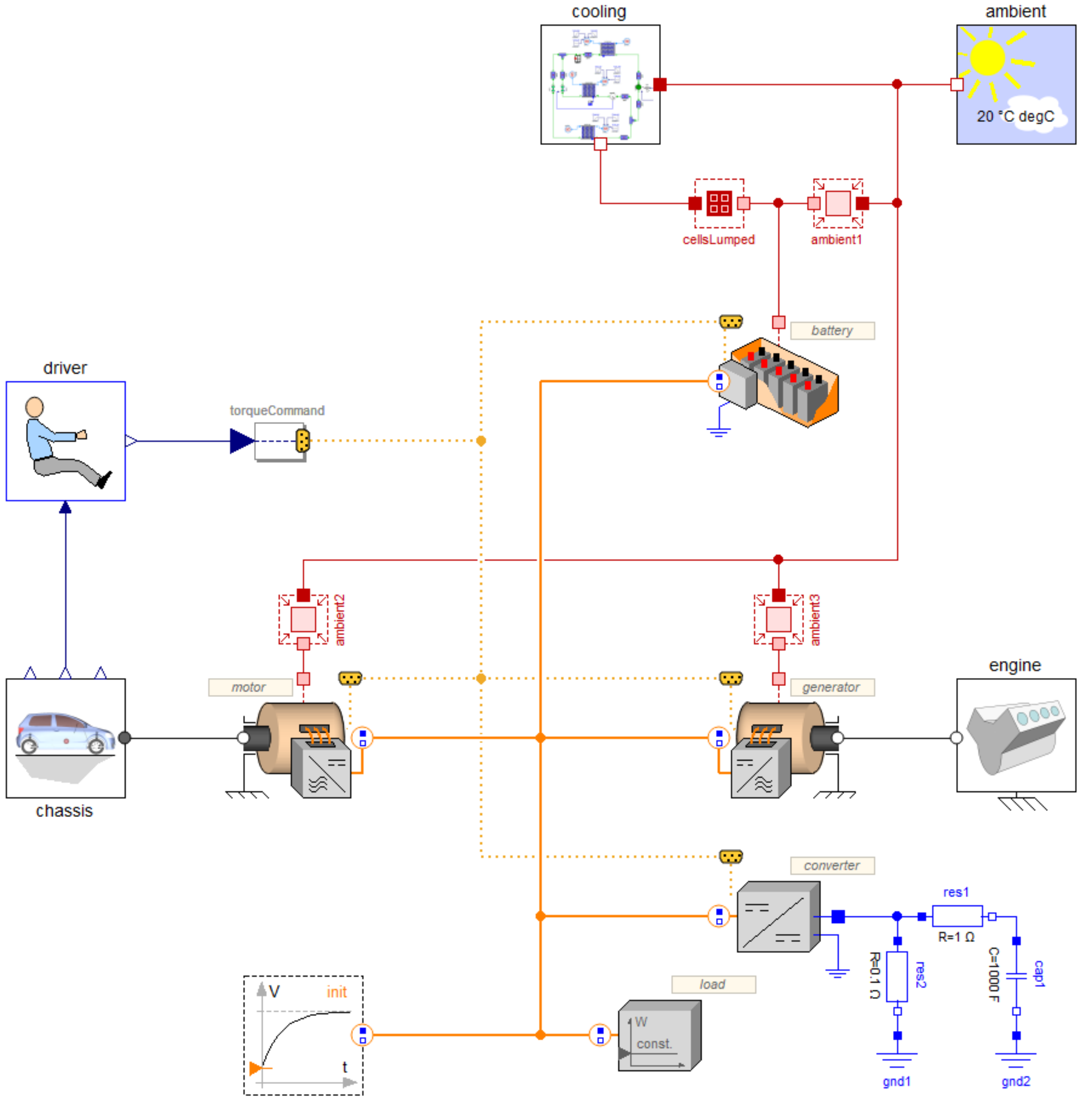
- Virtual system design and validation
- Predicting component usage for system sizing
- Predicting system performance,
  and evaluating component limits
- Predicting system efficiency and energy consumption
- Thermal management
- Analyzing transient dynamics,
  including normal and off-design operation
- Software/control verification and validation (MIL/SIL/HIL)
- Analyzing sensitivity to electrical disturbances (EMC)

EXAMPLE: HYBRID VEHICLE DRIVE CYCLE

Series hybrid vehicle with integrated cooling

- System sizing
- Component usage
- Energy losses
- Thermal management
- System limits and control
- Long drive cycles

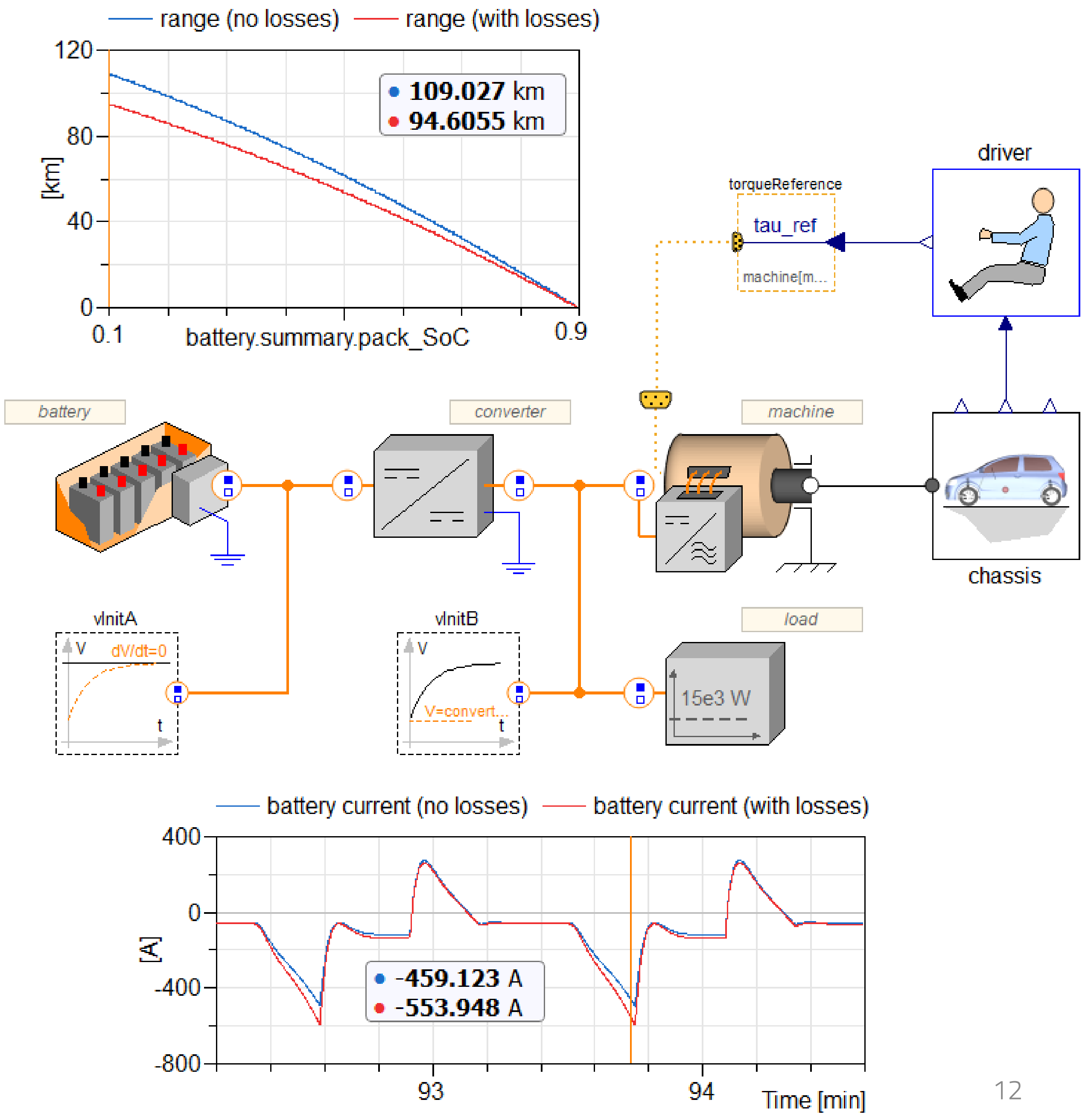




EXAMPLE: ELECTRIC VEHICLE RANGE

Maximum range of a battery electric vehicle

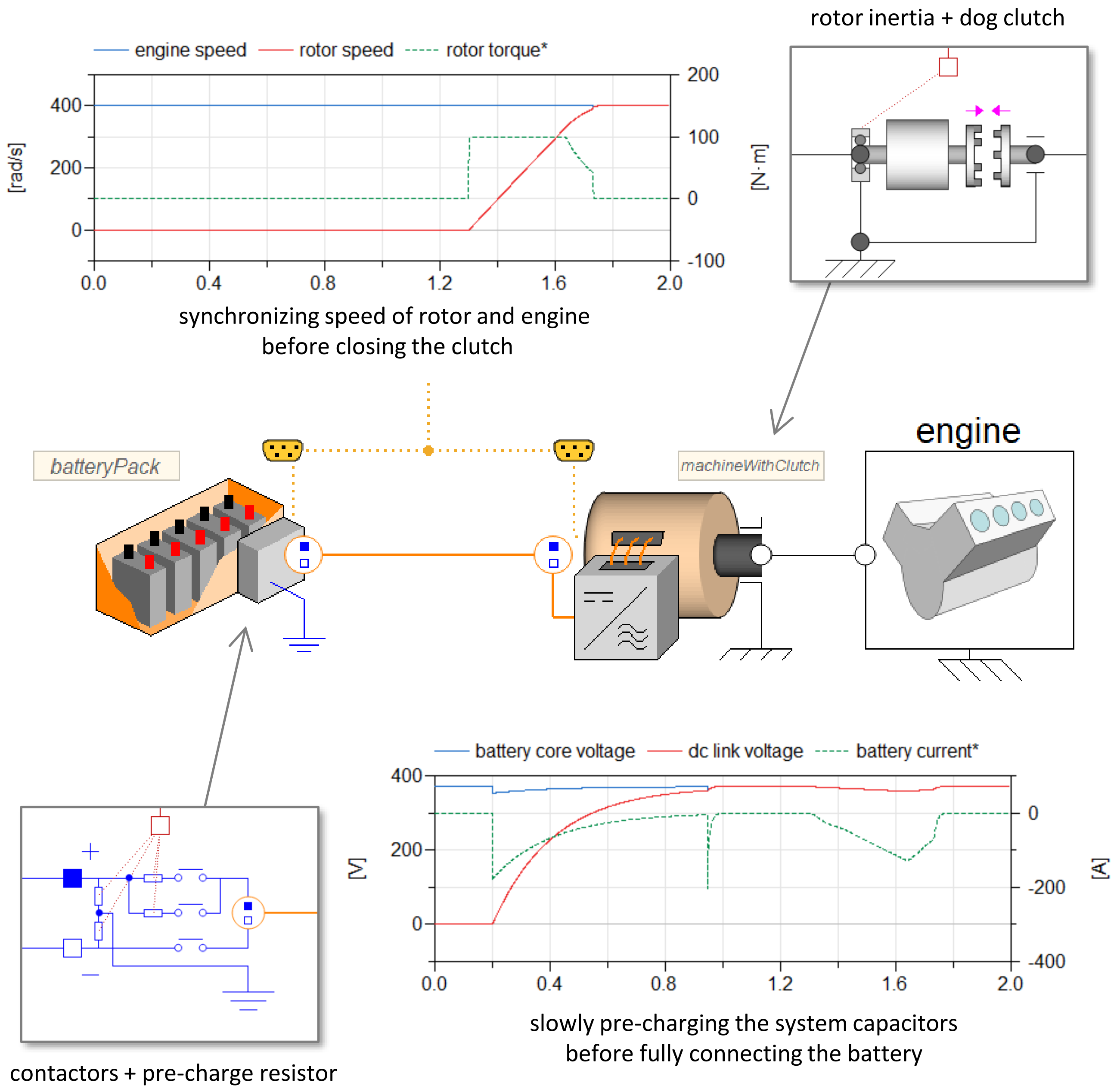
- Energy efficiency
- Long drive cycles
- Boundary conditions



EXAMPLE: ELECTRIC POWERTRAIN START-UP CONTROL

1. Battery pack voltage pre-charge
2. Machine clutch speed synchronization

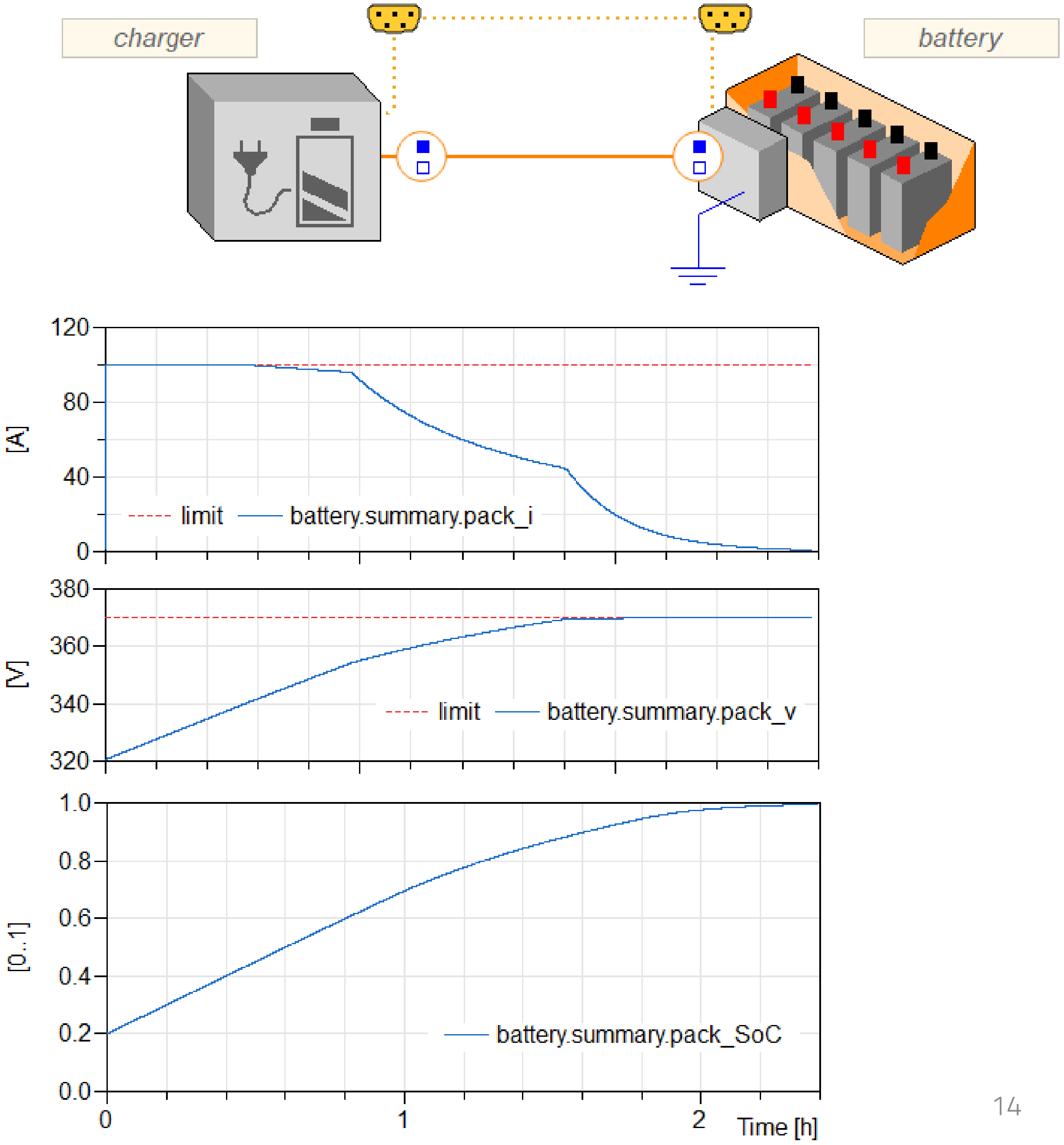
- Verify control functions (Model-in-the-Loop)
- Robust transient dyanamics
- Custom controller models
- Actuator and sensor signals



EXAMPLE: BATTERY CHARGING

Charger respecting limits reported by battery

- Battery management
- Battery power limits
- Communicating between controllers
- Robust load models (charger)
- Thermal power de-rating

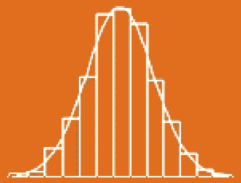


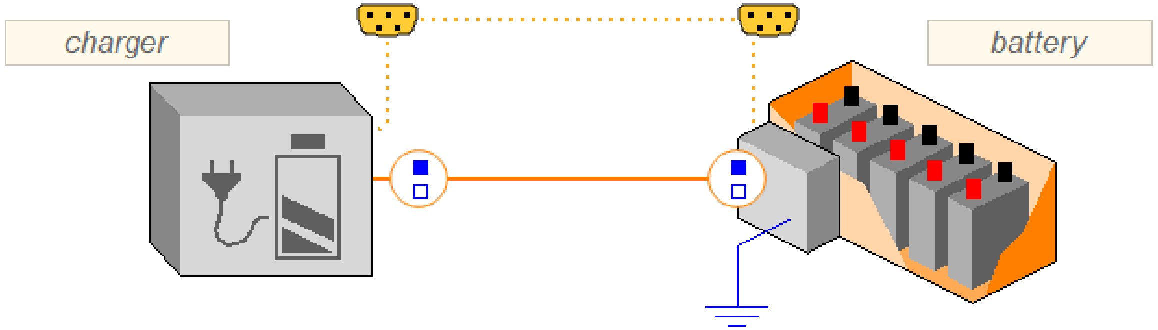
Modelon

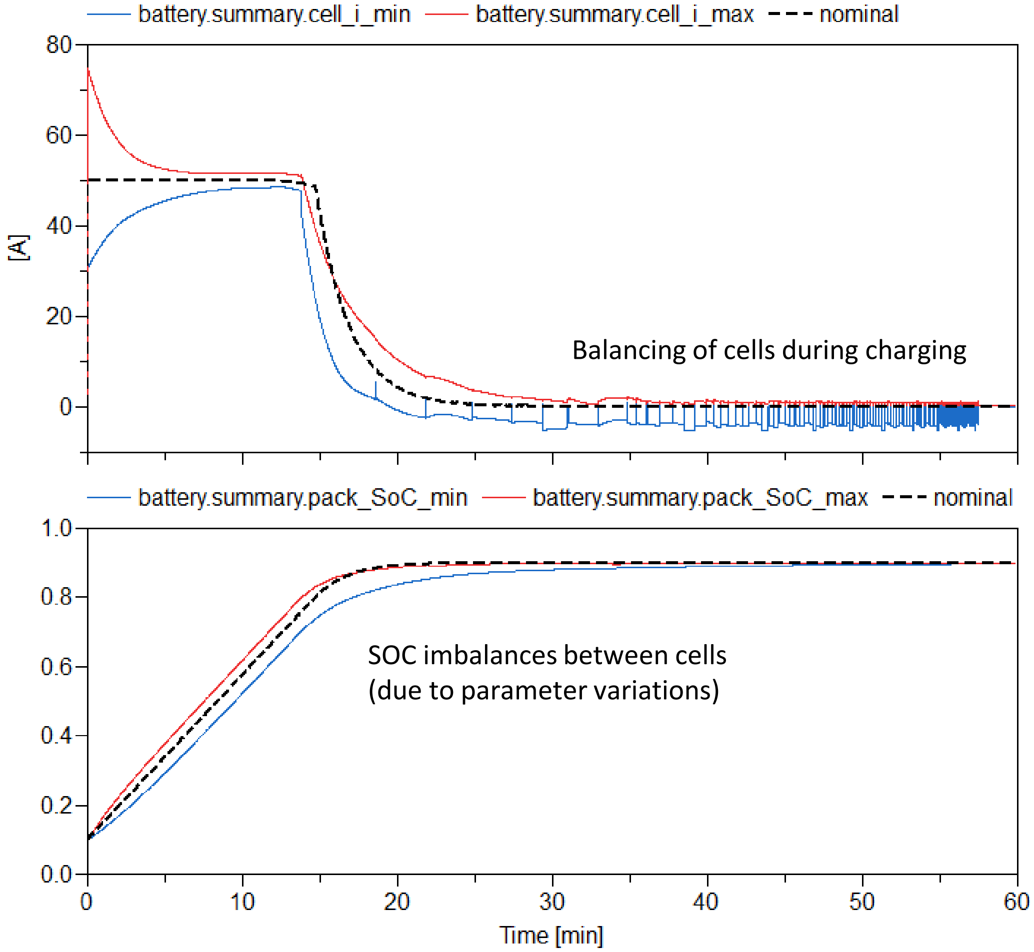
EXAMPLE: BATTERY IMBALANCES

Imbalances between cells in a battery pack:

- Impedance
- Charge capacity
- State of charge (SOC)
- Thermal
- Random imbalances as statistical distributions
- Balancing circuits and control (BMS)





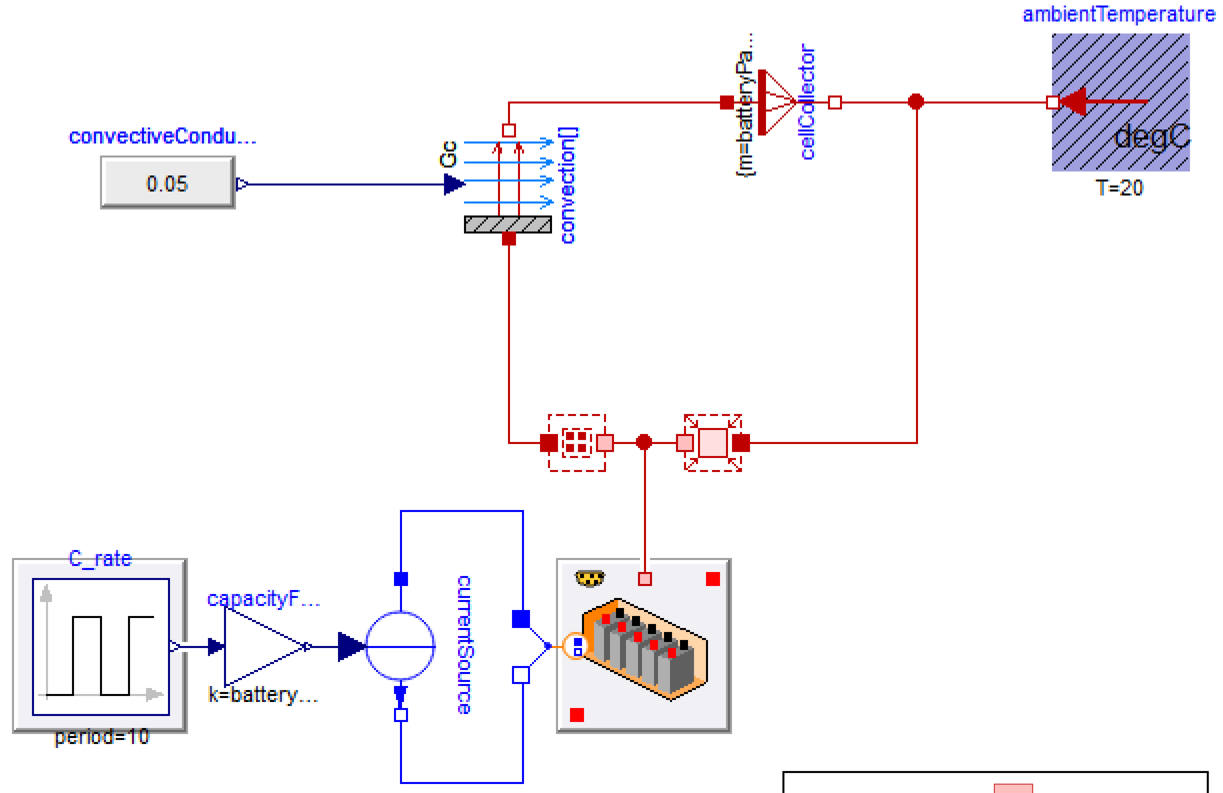


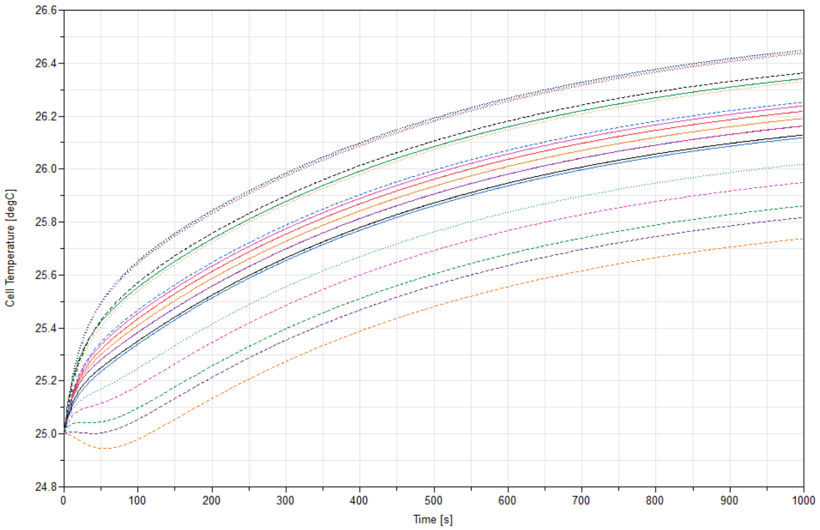
Modelon

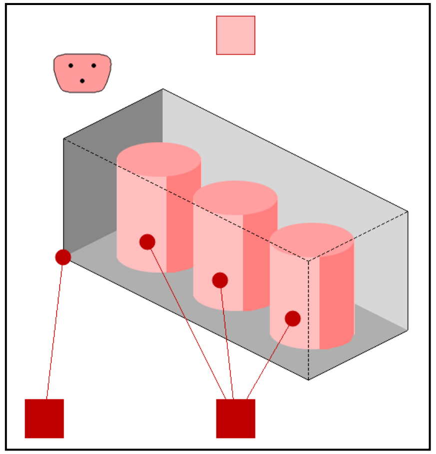
EXAMPLE: BATTERY (THERMAL)

Battery pack with individual cylindrical cells and passive cooling

- Thermal management
- Imbalances between cells
- Controls



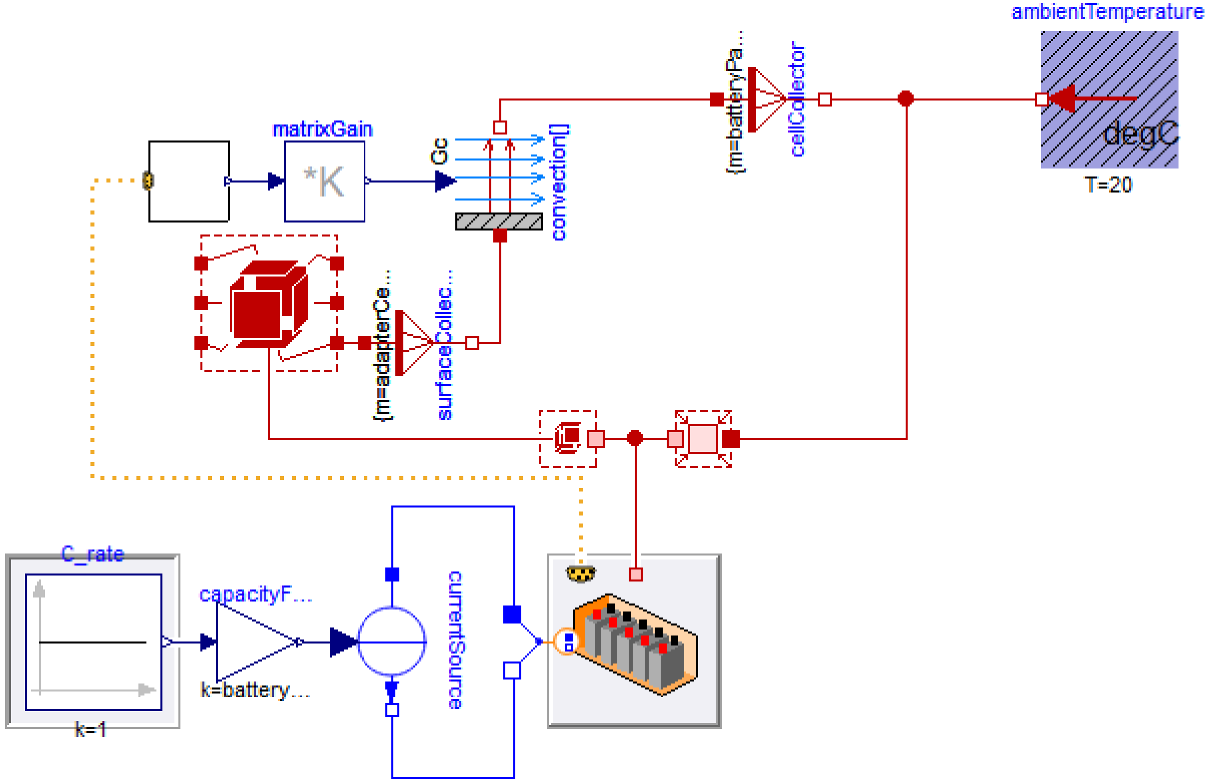


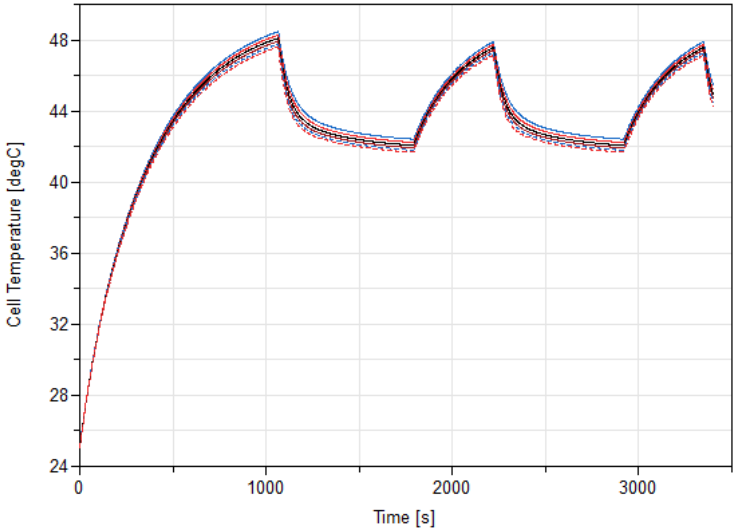


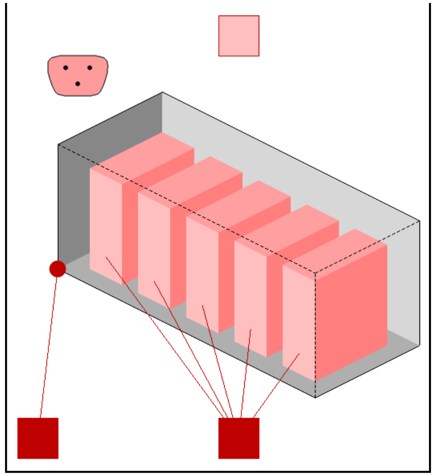
EXAMPLE: BATTERY (THERMAL)

Battery pack with individual prismatic cells and active cooling

- Thermal management
- Imbalances between cells
- Controls



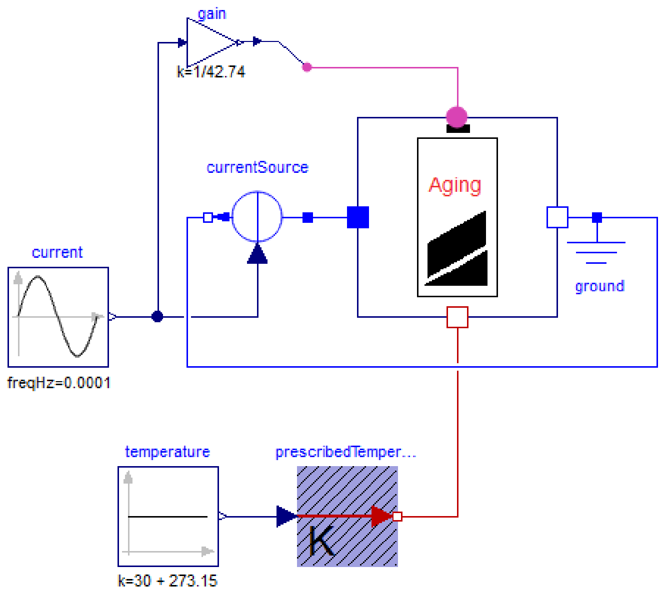


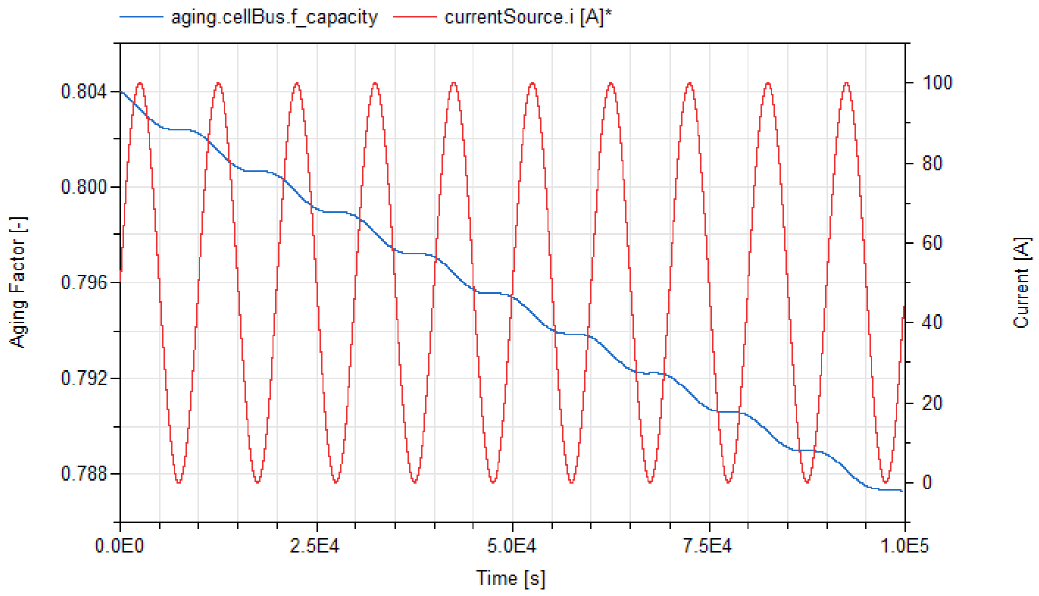


EXAMPLE: BATTERY (AGING)

Battery aging model (both calendar and cyclic)

- Cell capacity degradation
- Aging of battery physical parameters (resistance, capacitance)

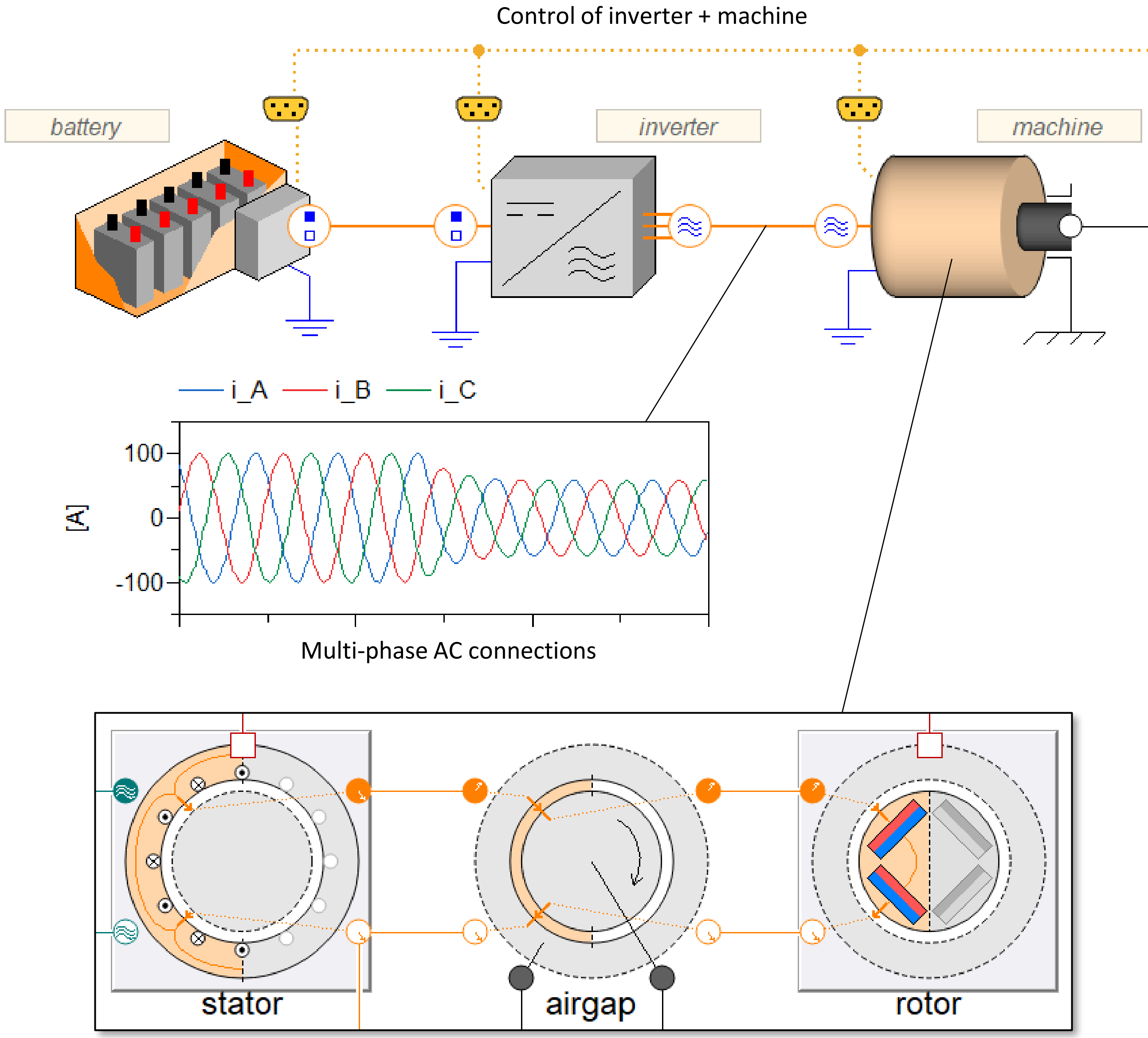




EXAMPLE:
AC MACHINES
AND INVERTERS

Detailed electrical simulations of three-phase machines and inverters

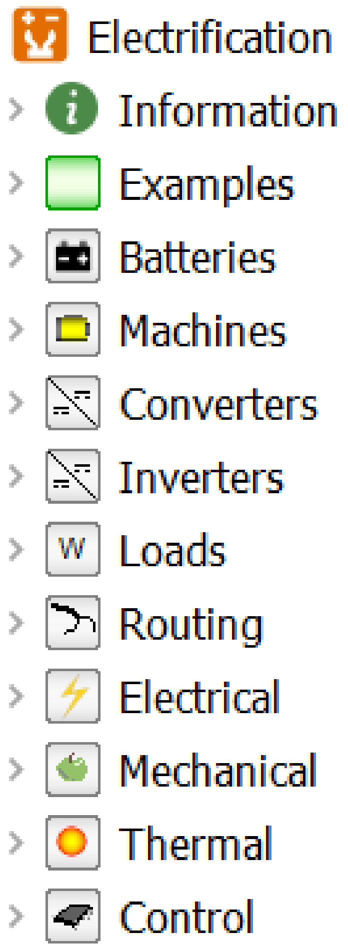
- Electro-magnetic circuit models
- Examples of common machine types (PMSM, SynRM, AIM)
- Different phase representations (abc vs dq0)
- Inverter models of different fidelity (transistors/diodes or averaged dynamics)



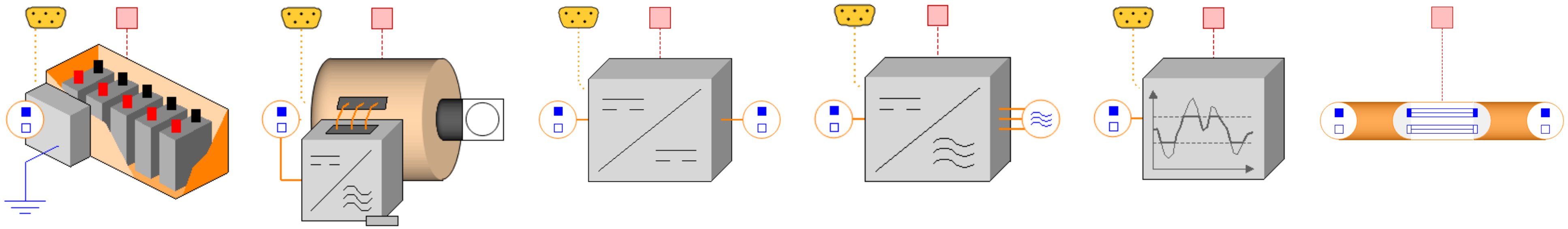
Modular electro-magnetic circuit of a permanent-magnet synchronous machine (PMSM)


LIBRARY CONTENTS

LIBRARY

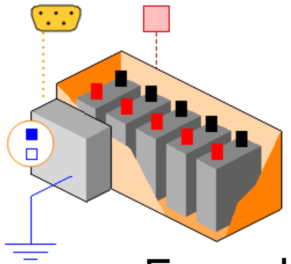


- Suite of components for electrification systems:



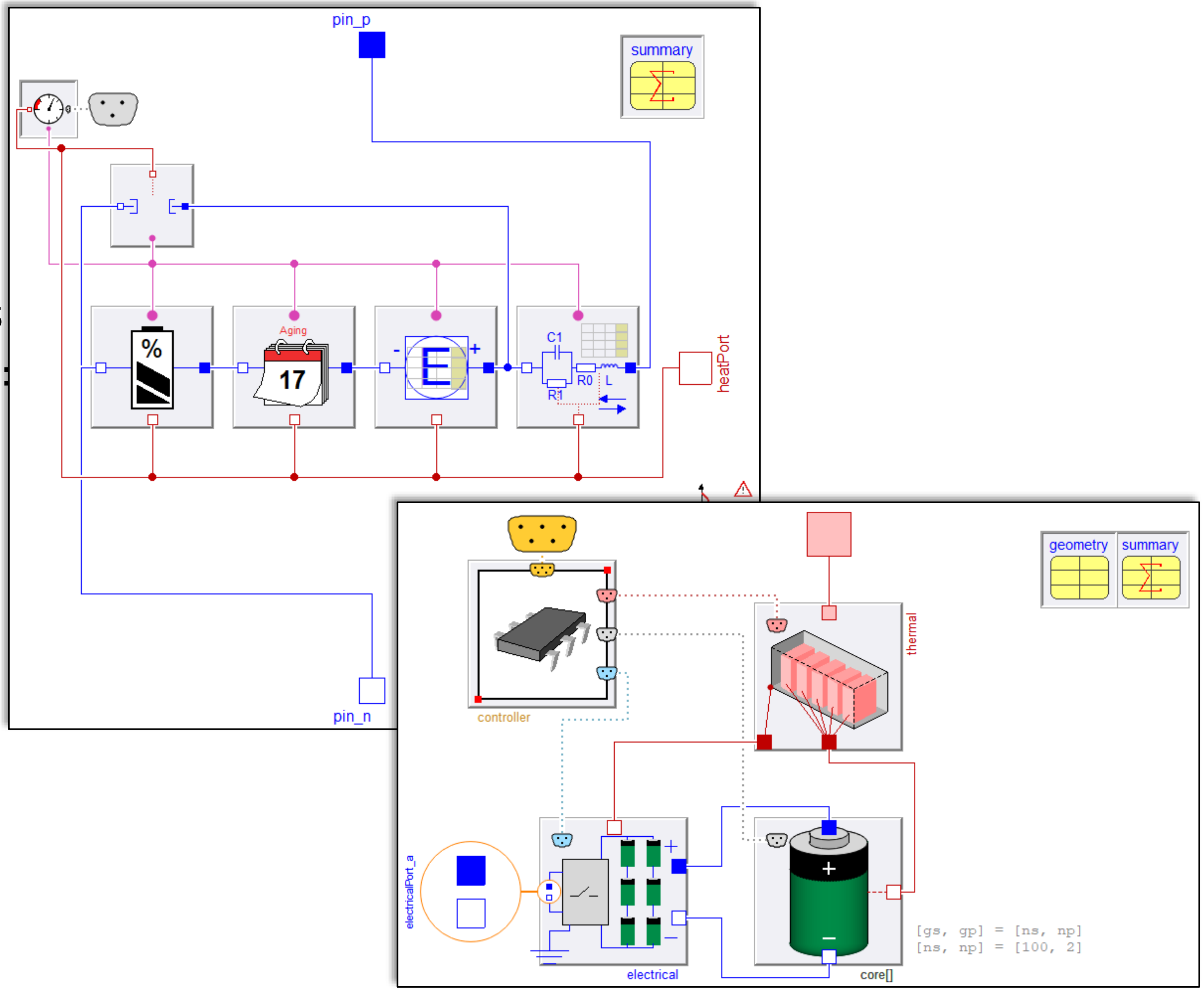
Batteries **Machines** **Converters** **Inverters** **Loads** **Routing**

- The components cover multiple physical domains: electrical, thermal, mechanical and controls (software)



BATTERIES

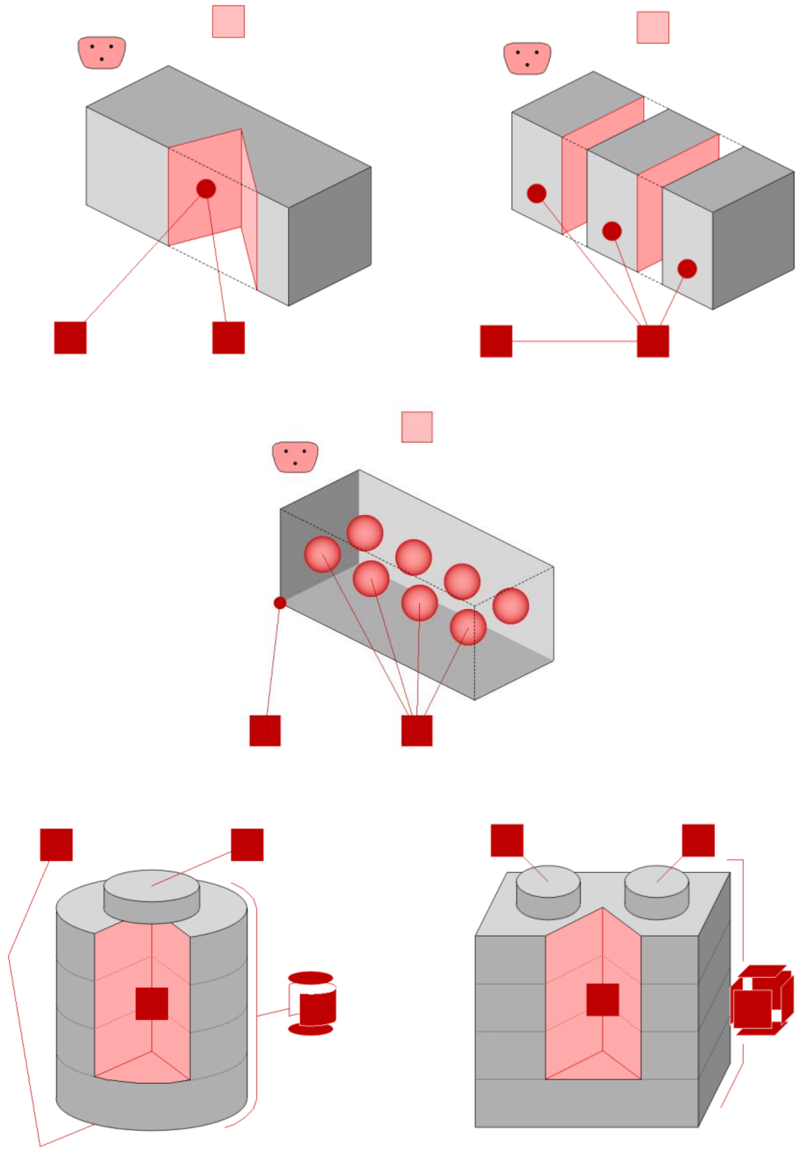
- From battery cell to module to pack
- Scalable fidelity:
  from lumped packs to individual cells
- Separate scaling of physical domains:
  core battery, thermal dynamics,
  electrical connections, controls
- Modular core battery models
  - Charge capacity
  - Voltage
  - Impedance
  - Self discharge
  - Aging
- Battery management control
- Cell imbalances

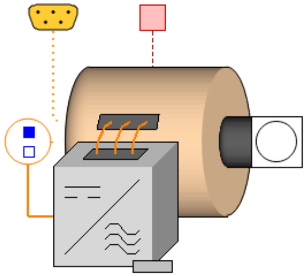


Component architecture with separation of domains:

BATTERY THERMAL

- Scalable discretization: Individual cells to full pack
- Example thermal models
  - Lumped pack
  - Discretized pack (3 nodes)
  - Multi-node (individual cells)
  - Cylindrical (discretized cells)
  - Prismatic (discretized cells)
- Create custom thermal models
  based on common templates/interfaces
- Scalable fidelity of external interface (thermal nodes)
- Controls interface for thermal management

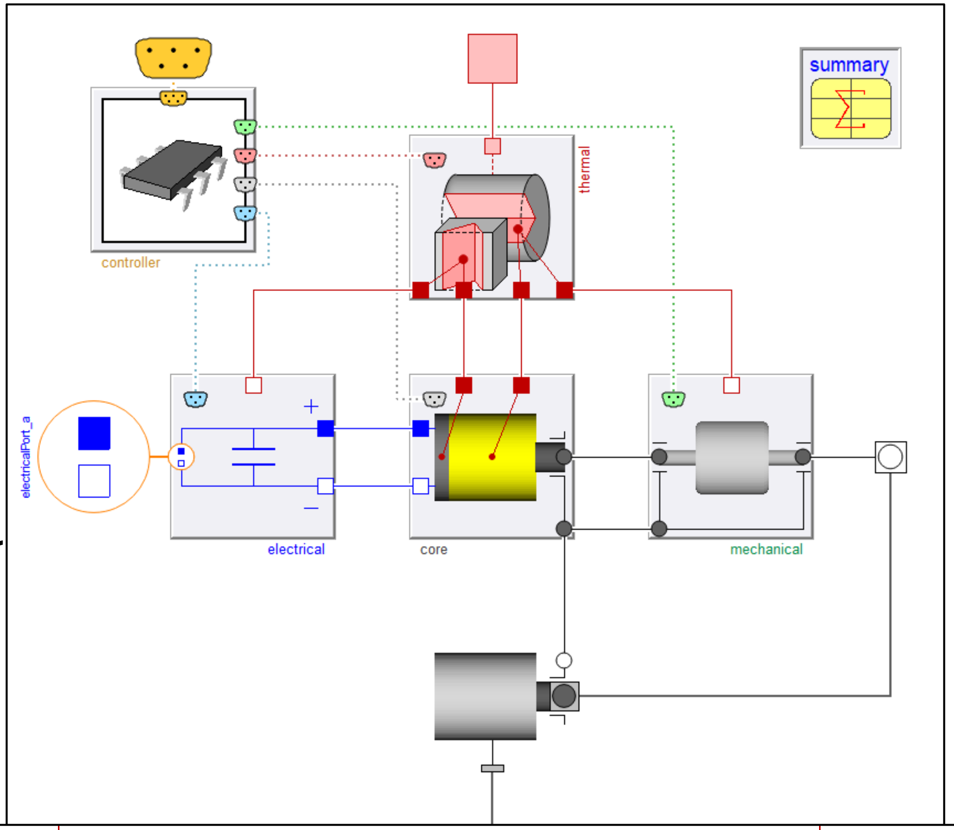


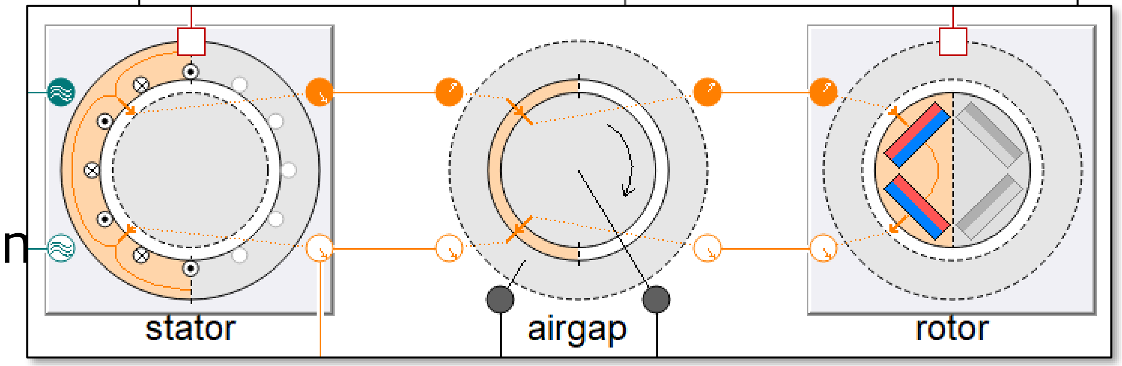


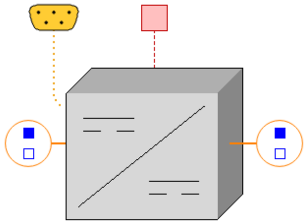
MACHINES

- Models of different levels of fidelity:
  - **Generalized machines**
    (ideal power flow, robust limits, empirical losses)
  - **Electro-magnetic circuits (multi-phase AC)**
    (detailed dynamics that scale with physical parameter
- Examples of common machines (PMSM, SynRM, AIM)
- Separation of domains (electrical, mechanical, thermal).
- Scalable thermal fidelity (lumped or discretized)
- Example controllers with multi-mode operation
  (torque, speed, position, power, voltage control)
- Supports both 1D rotation and MultiBody3D systen

Component architecture with separation of domains:



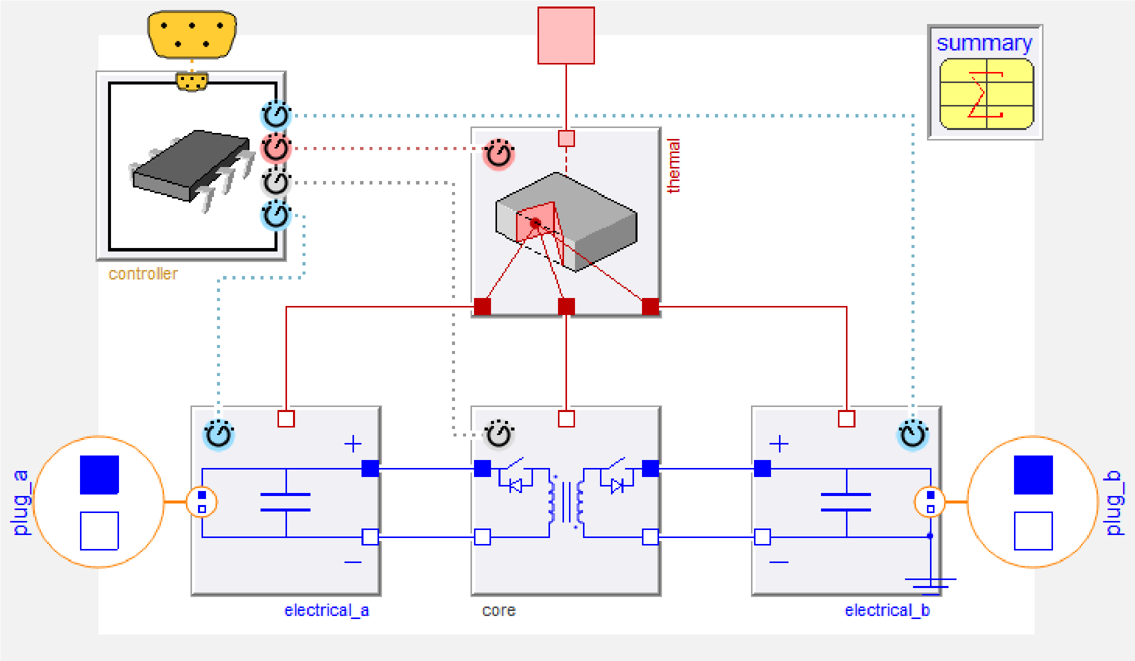




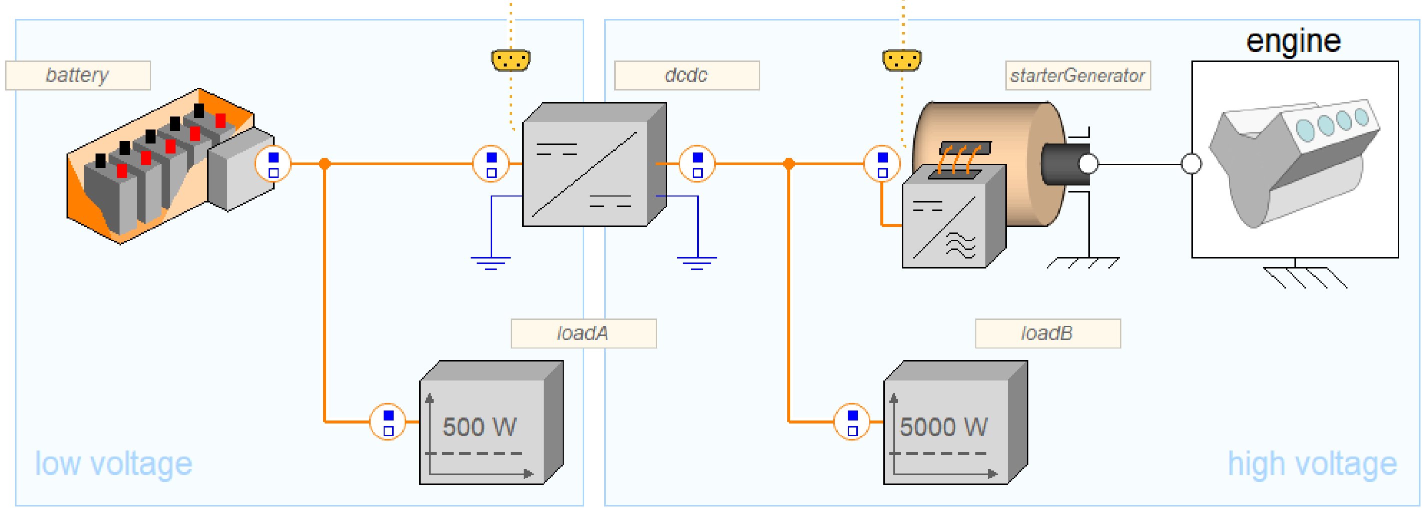
CONVERTERS

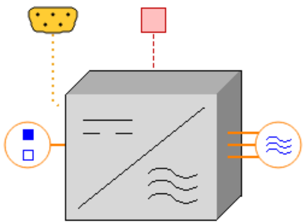
- Modular converters with separation of domains: core, electrical, thermal, controller.
- Averaged and switched DCDC converter models:
  - Averaged: for fast and robust simulations
  - Switched: with detailed high frequency dynamics
- Bi-directional conversion
- Isolated and non-isolated
- Ideal or with heat losses
- Multi-mode control:
  - Voltage or current control
  - Primary or secondary side control
  - Change mode during simulation

Component architecture with separation of domains:



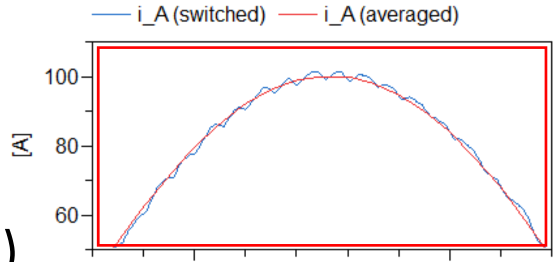
Example: System with bi-directional DCDC converter boosting the battery voltage



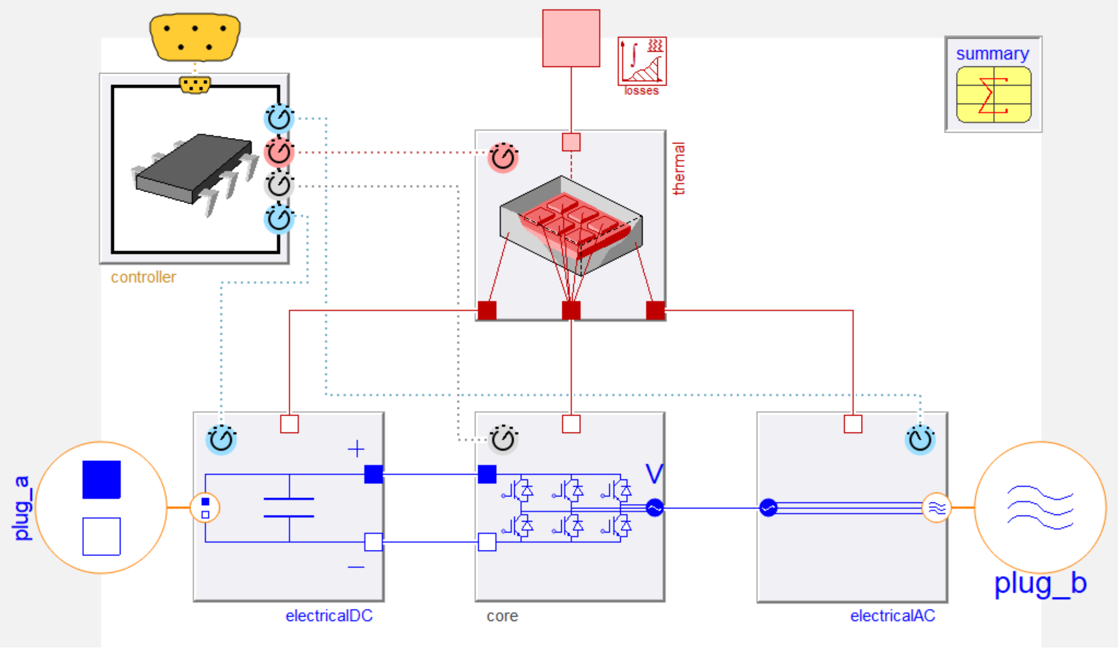


INVERTERS

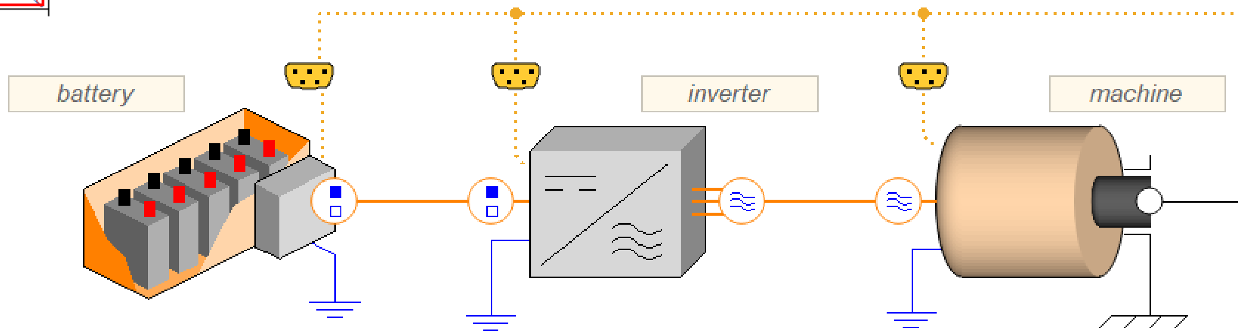
- Modular inverters with separation of domains: core, electrical, thermal, controller.
- Averaged and switched inverter models:
  - Averaged: for fast and robust simulations
  - Switched: with detailed high frequency dynamics
- Ideal or with heat losses
- Cascaded control stack:
  - AC machine control (torque, speed, position)
  - Field oriented torque control
  - Current control
  - Control of switching (transistors)

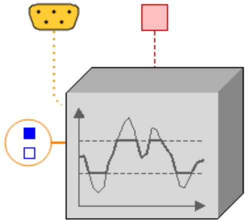


Component architecture with separation of domains:



Example: An inverter driving a three-phase AC machine from a battery

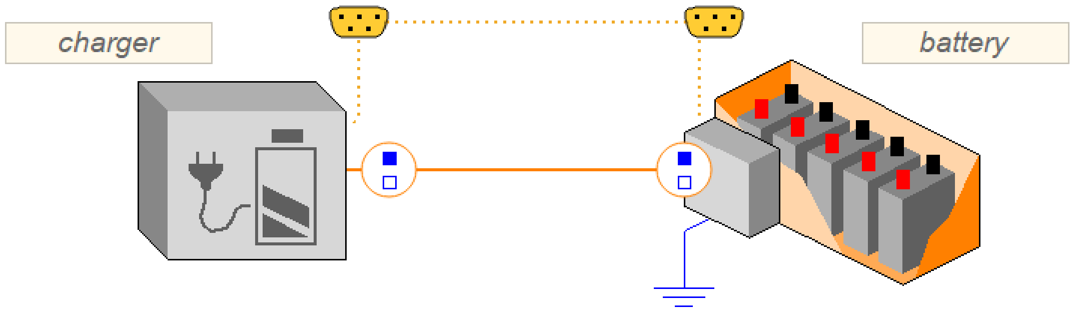


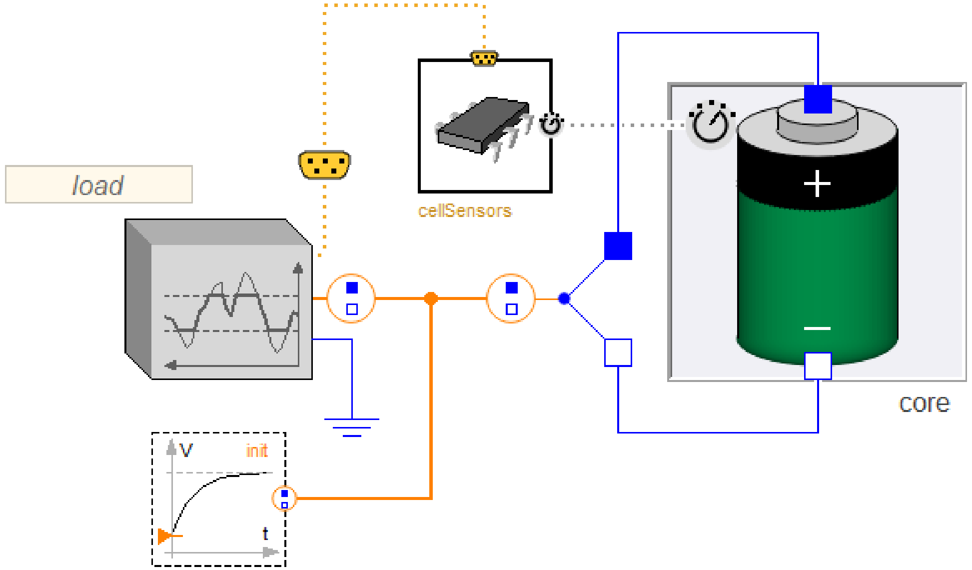


LOADS

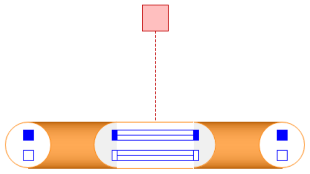
- General-purpose electrical loads:
  - Constant power loads
  - Dynamic and time series loads
  - Battery charger
  - Battery cycler (power de-rating)
- Possible to control via external signals and limits
- Support for thermal dynamics

Example: Charger load “listens” to limits reported by battery via control bus



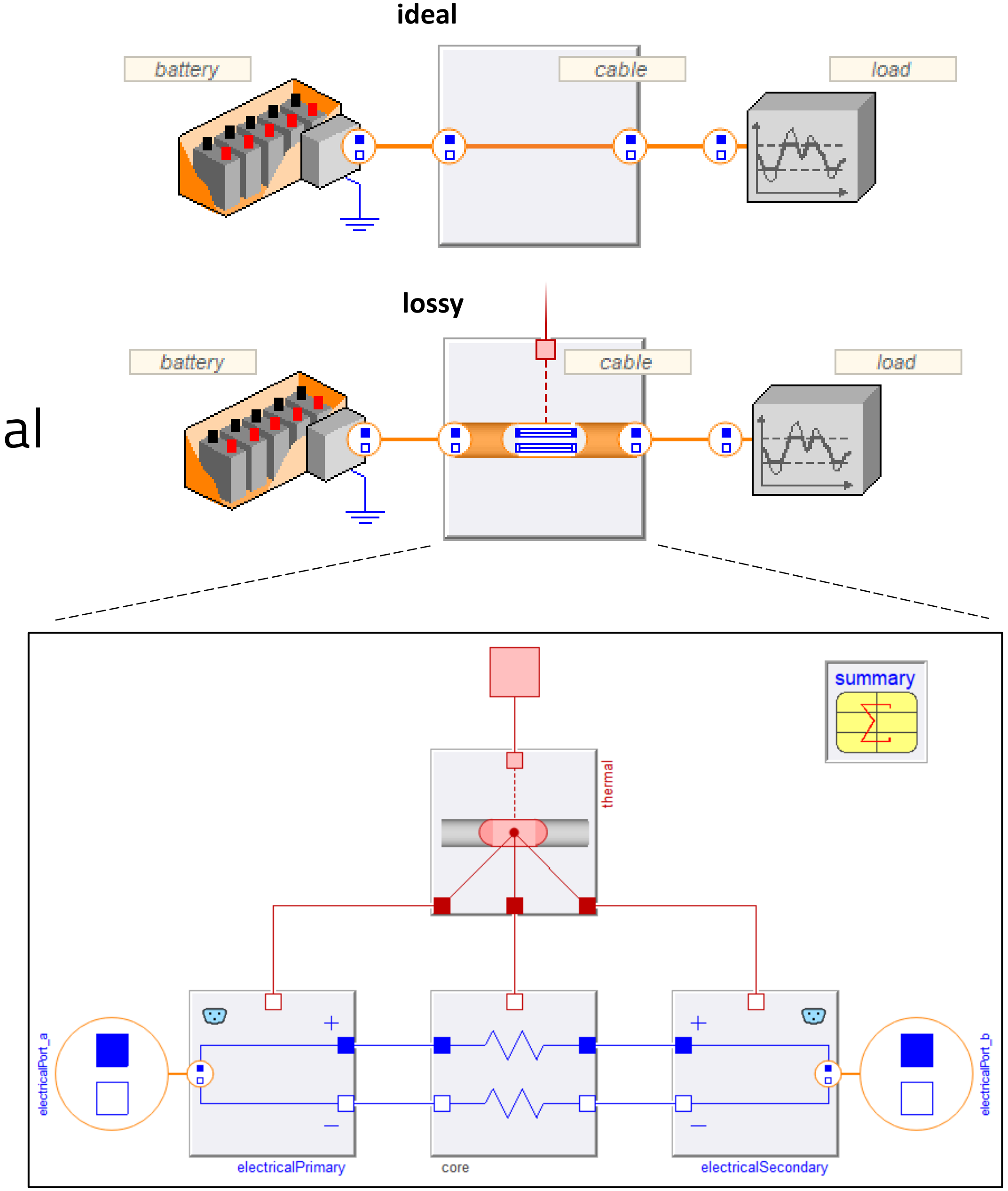


Example: Discharge battery cell according to time-series load power (with de-rating of power based on cell sensors)



ROUTING

- Represent cables in systems with scalable fidelity
- Modular architecture support separation of electrical cable model, connector model, and thermal model.
- Example cable model with geometry based losses.
- Extendable with custom cable models, based on common interfaces/templates.



Component architecture with separation of domains:

MODELON COMPATIBILITY

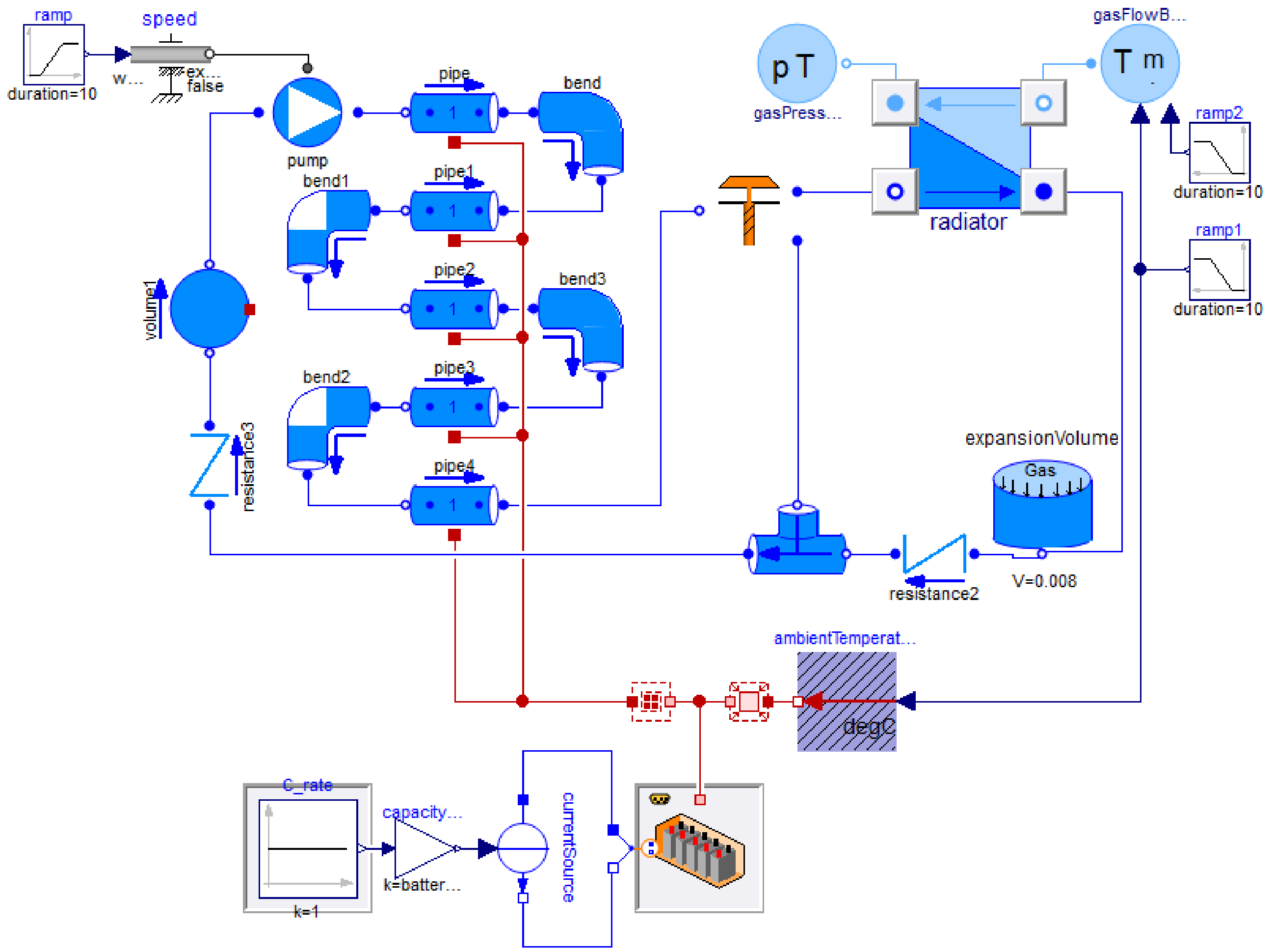
RECOMMENDED MODELON LIBRARY COMPATIBILITY

- Electrification Library integrates with the Modelon Library Suite
  - Vehicle Dynamics Library
  - Aircraft Dynamics Library
  - Liquid Cooling Library
  - Heat Exchanger Library
  - Vapor Cycle Library
  - Air Conditioning Library
  - Fuel Cell Library
  - Electric Power Library
  - Thermal Power Library

EXAMPLE: BATTERY THERMAL MANAGEMENT

Battery integrated with Liquid Cooling Library

- System sizing
- Cooling concept development
- Thermal constraints
- Thermal-electrical interactions
- BMS development

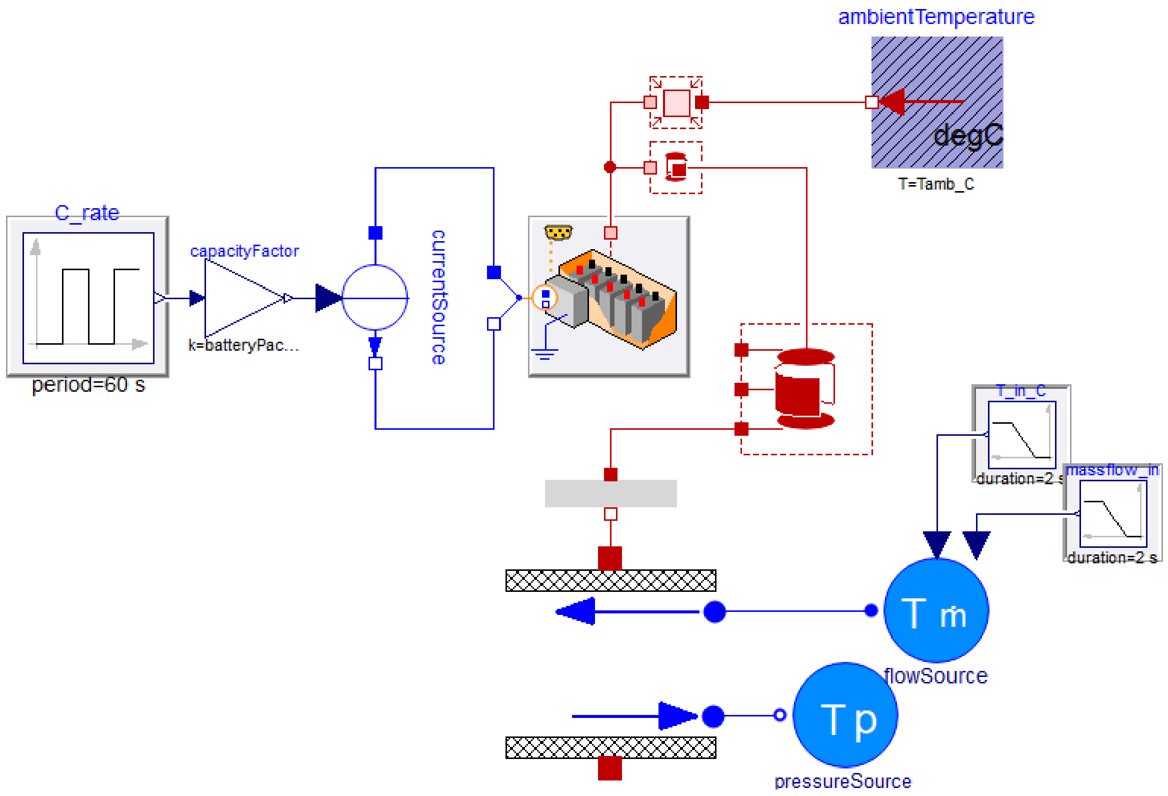


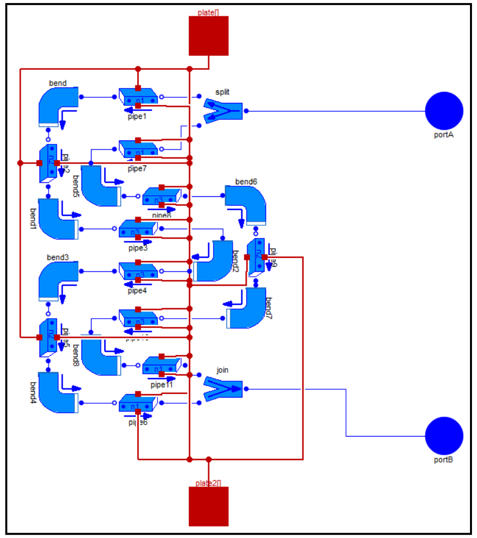
Modelon

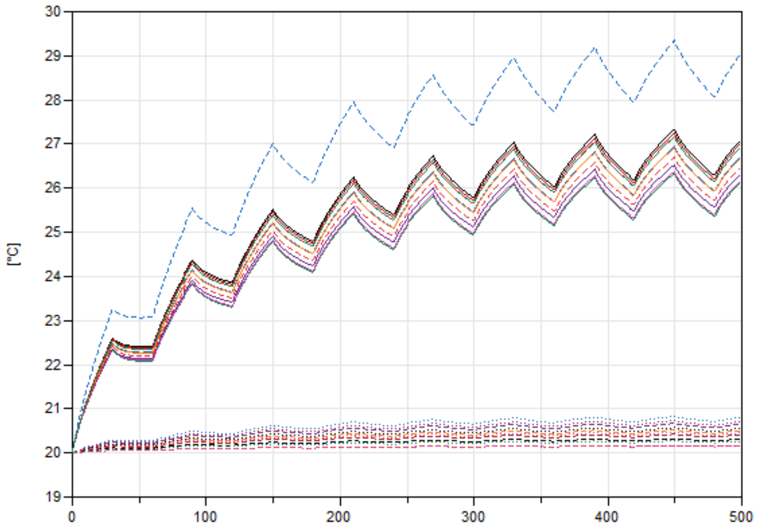
EXAMPLE: BATTERY WITH COLD PLATE

Battery integrated with Liquid Cooling Library

- Cooling concept design
- Thermal constraints
- Thermal-electrical interactions
- BMS development







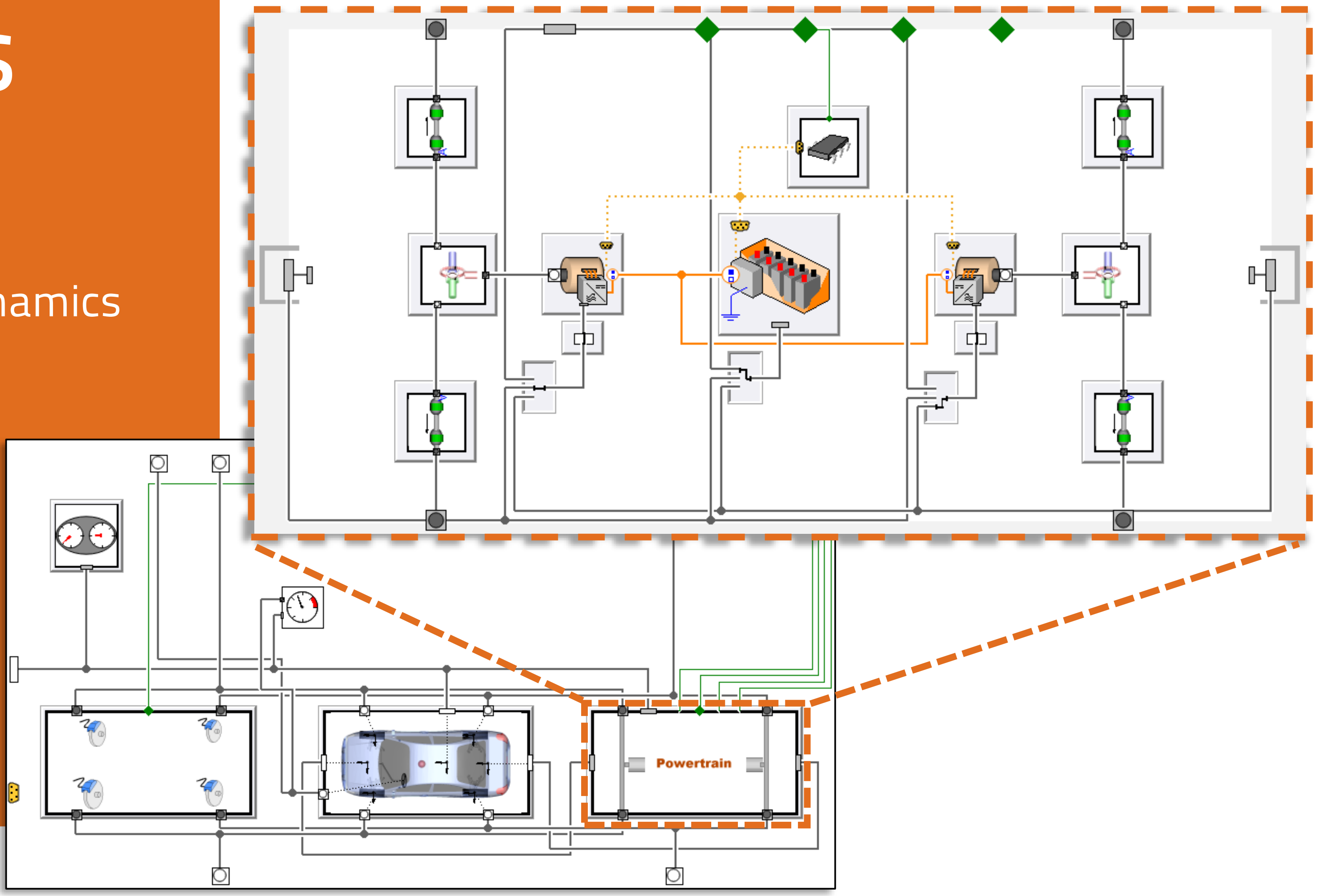
Modelon

EXAMPLE: VEHICLE DYNAMICS

Electrified powertrains with the Vehicle Dynamics Library

- Co-simulation of powertrain dynamics with chassis dynamics.
- Electric powertrain with mechanical 3D reaction forces.
- Simulate handling and performance including both mechanical and electrical limits
- Applications: torque vectoring, acceleration performance, …

MultiBody3D powertrain with a battery and two electric machines

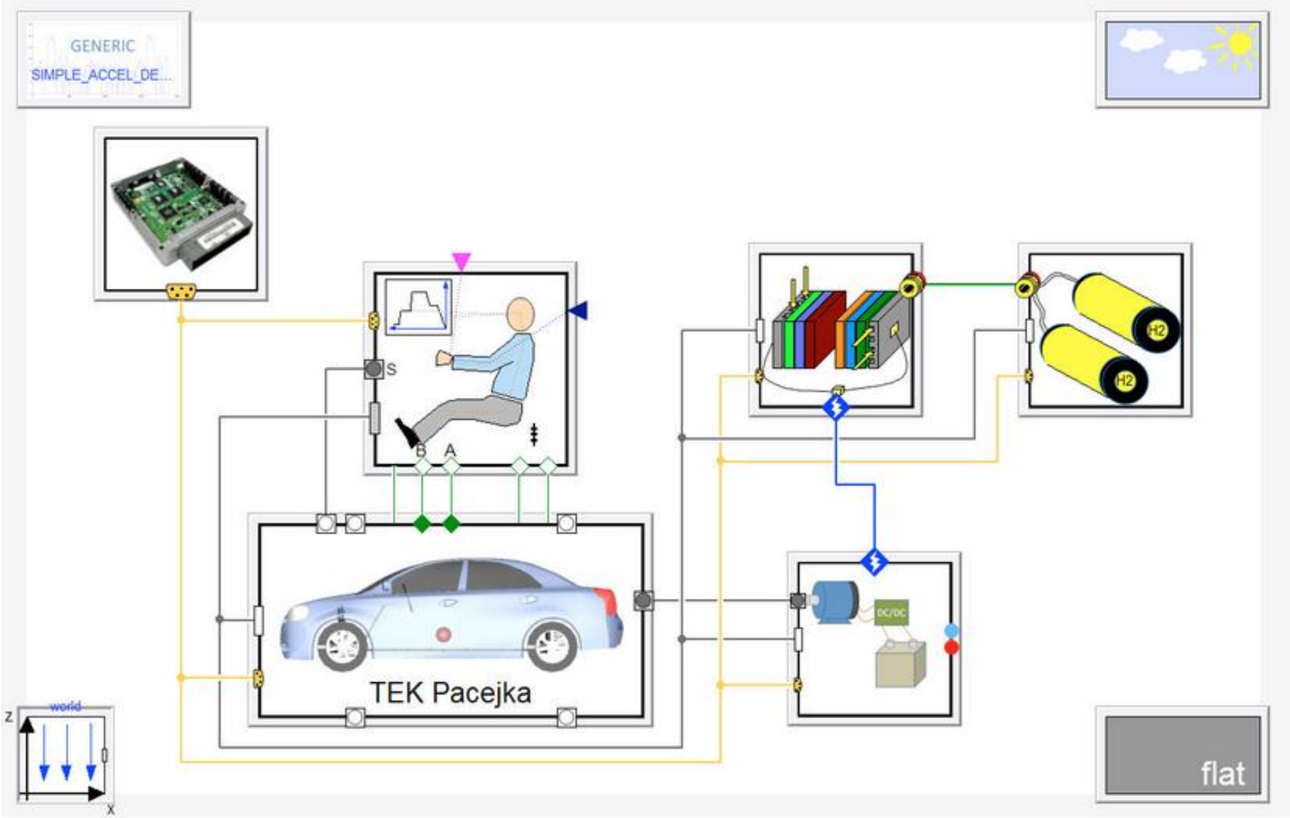


Integration with the Vehicle Dynamics Library

EXAMPLE: FUEL CELL VEHICLE

Electric powertrain integrated with
Fuel Cell Library and Vehicle Dynamics Library

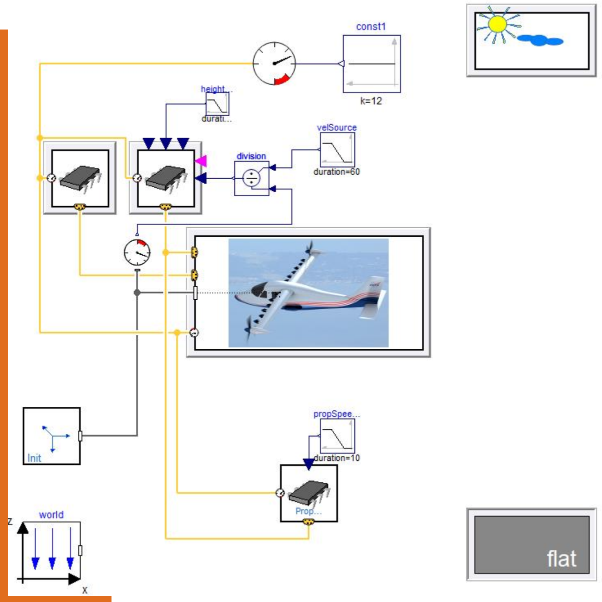
- Powertrain concept development
- System sizing
- System efficiency and range

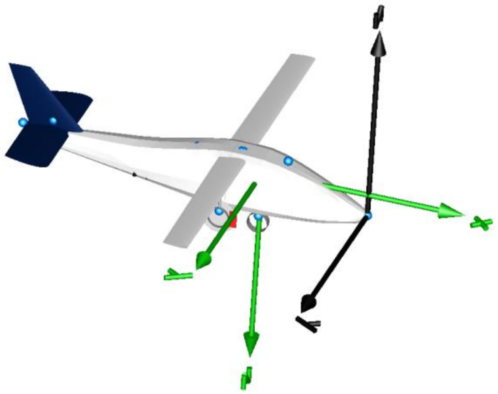


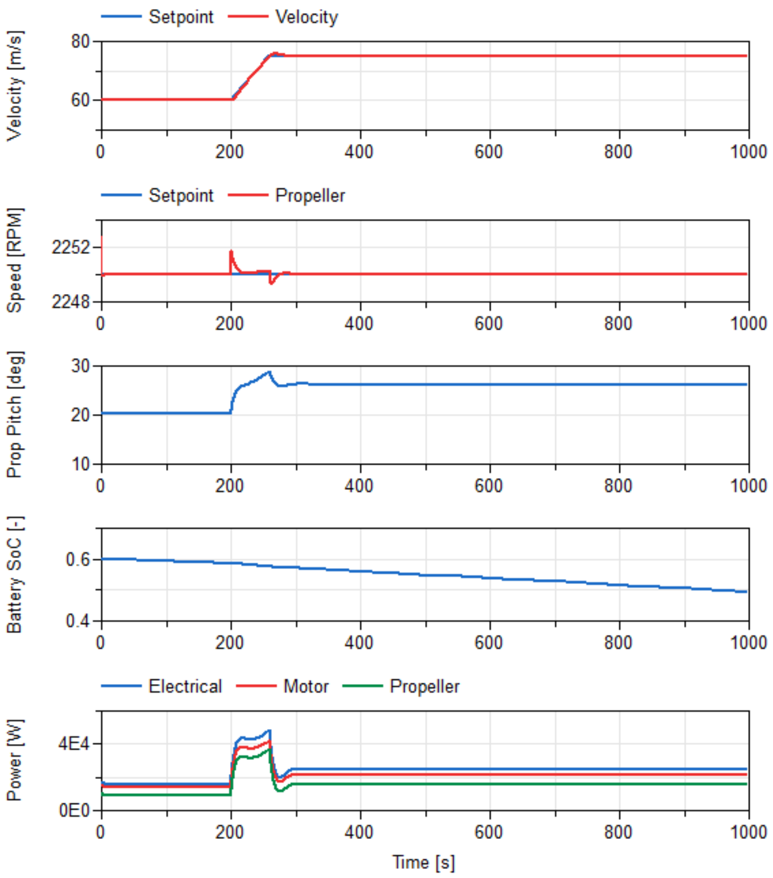
EXAMPLE:
NASA X-57 ELECTRIC AIRCRAFT

Electric powertrain integrated with Aircraft Dynamics Library

- Powertrain concept development
- System sizing
- System efficiency and range



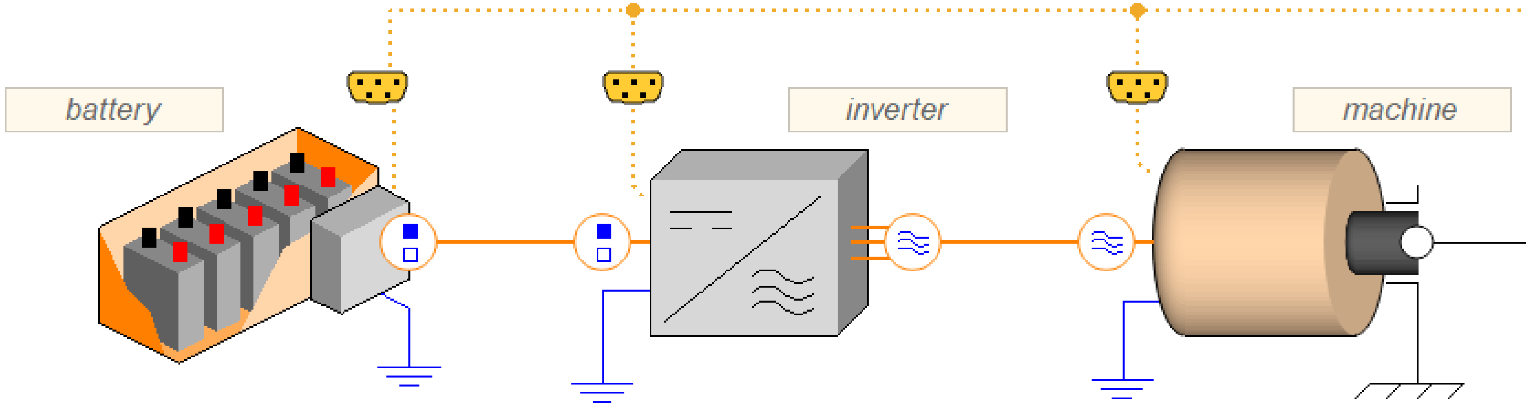





LATEST RELEASE

RELEASE: 2021.2

NEW FEATURES



Separate inverter and machine with AC interface

AC machines and inverters

- Electro-magnetic models of common three phase AC machines.
- Discrete and switched models of DC/AC inverters.
- AC interface with individual phases or Park/Clarke (dq0).
- Modular cascaded controllers (speed, torque, current, voltage, switching).

Imbalances in battery packs

- Example battery with imbalances using stochastics parameters dedicated for sizing / optimization
- Active cell balancing example

Modelon