MATLAB EXPO

Electric Mobility & Future Grids: Accelerating the Transition towards Net-Zero Emissions

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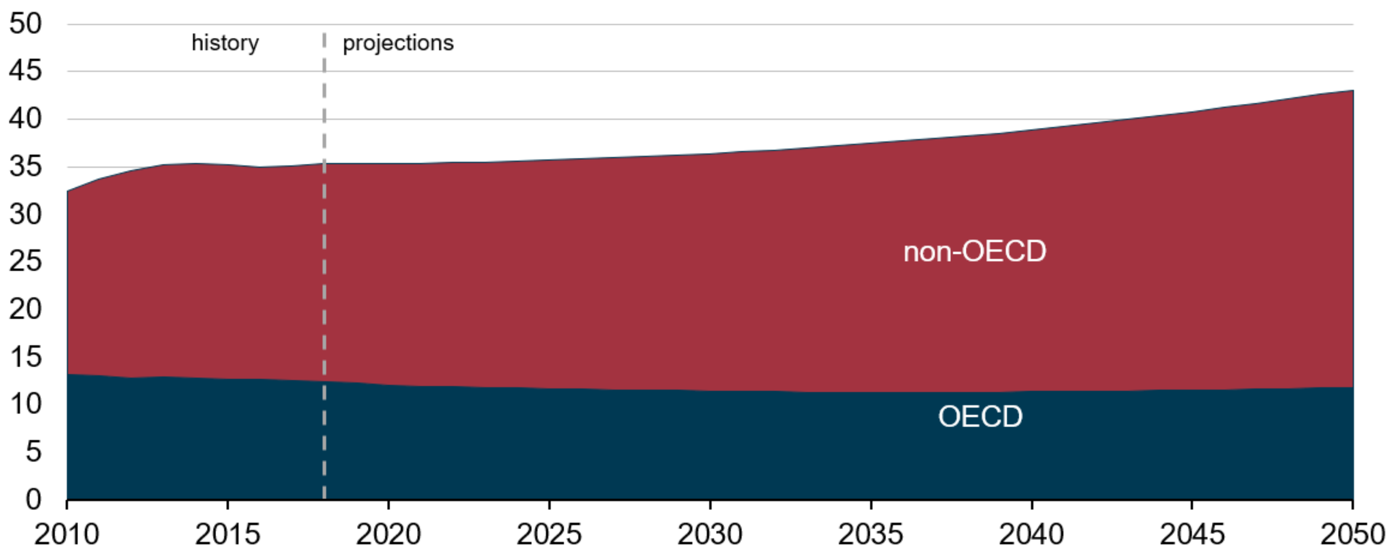
MathWorks

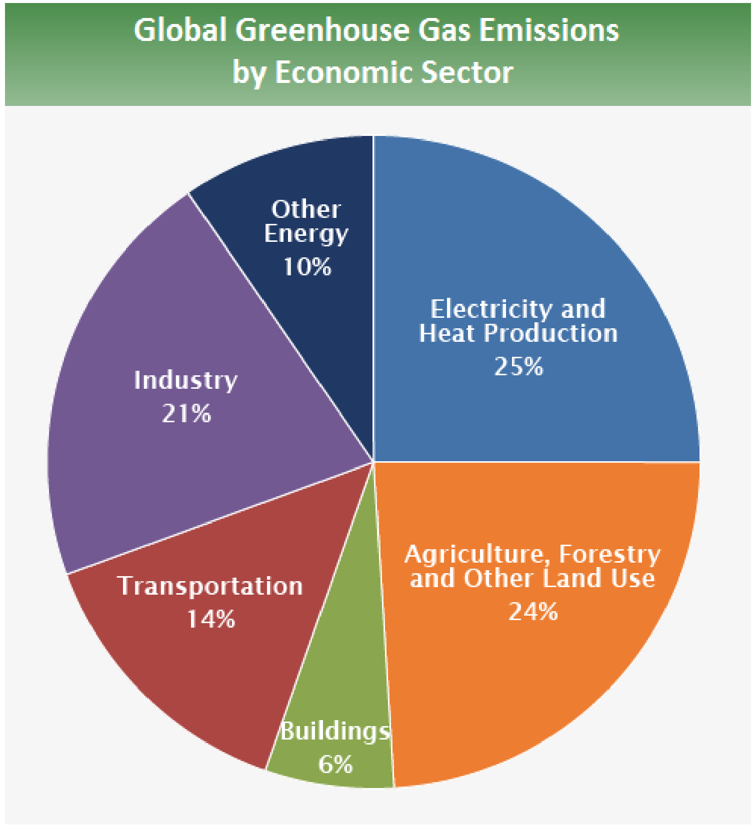
Global Greenhouse Gas Emissions

Energy-related carbon dioxide emissions
billion metric tons



OECD: Organization for Economic Cooperation and Development

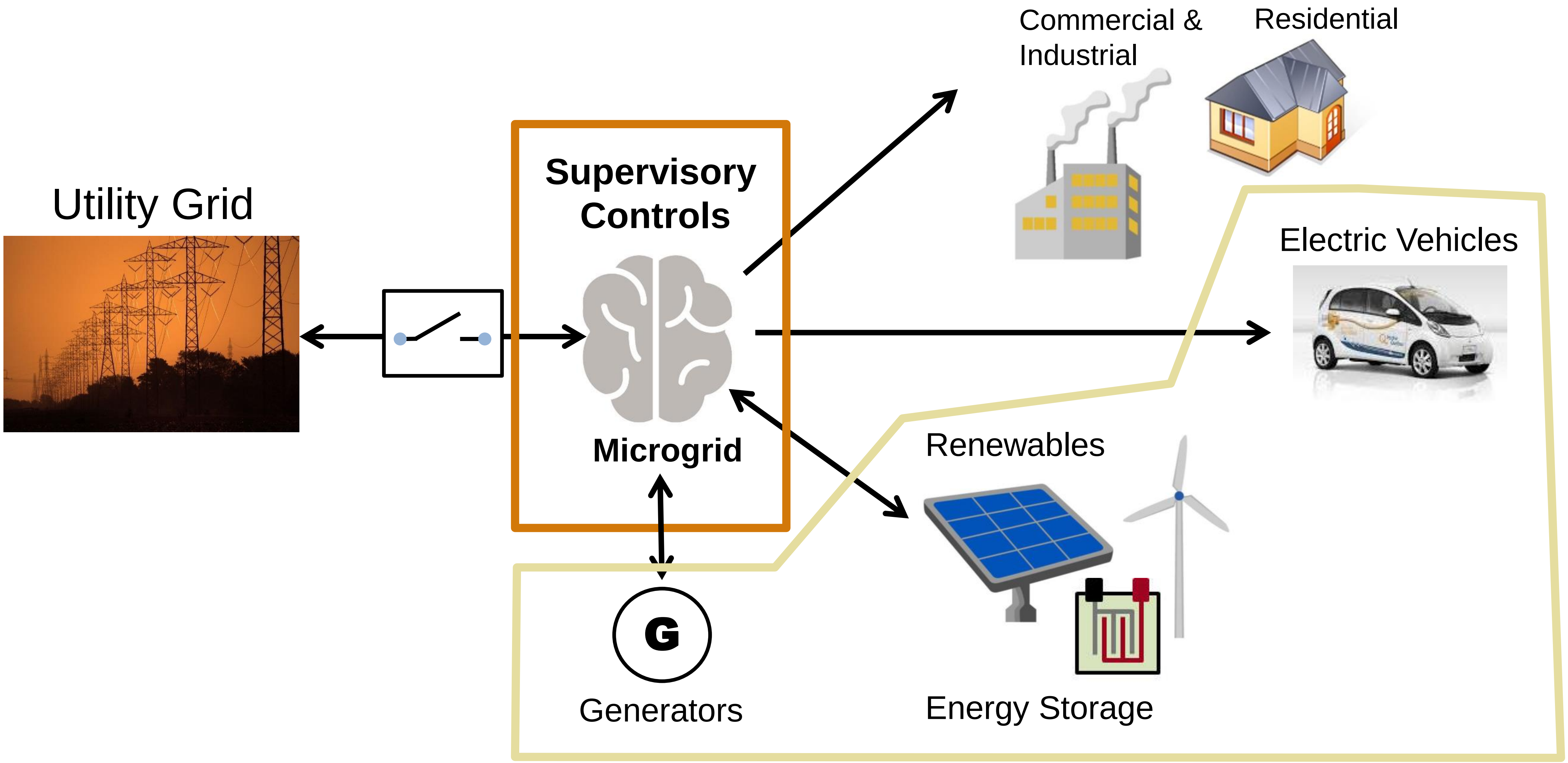
International Energy Outlook 2019
https://www.eia.gov/outlooks/ieo/pdf/ieo2019.pdf



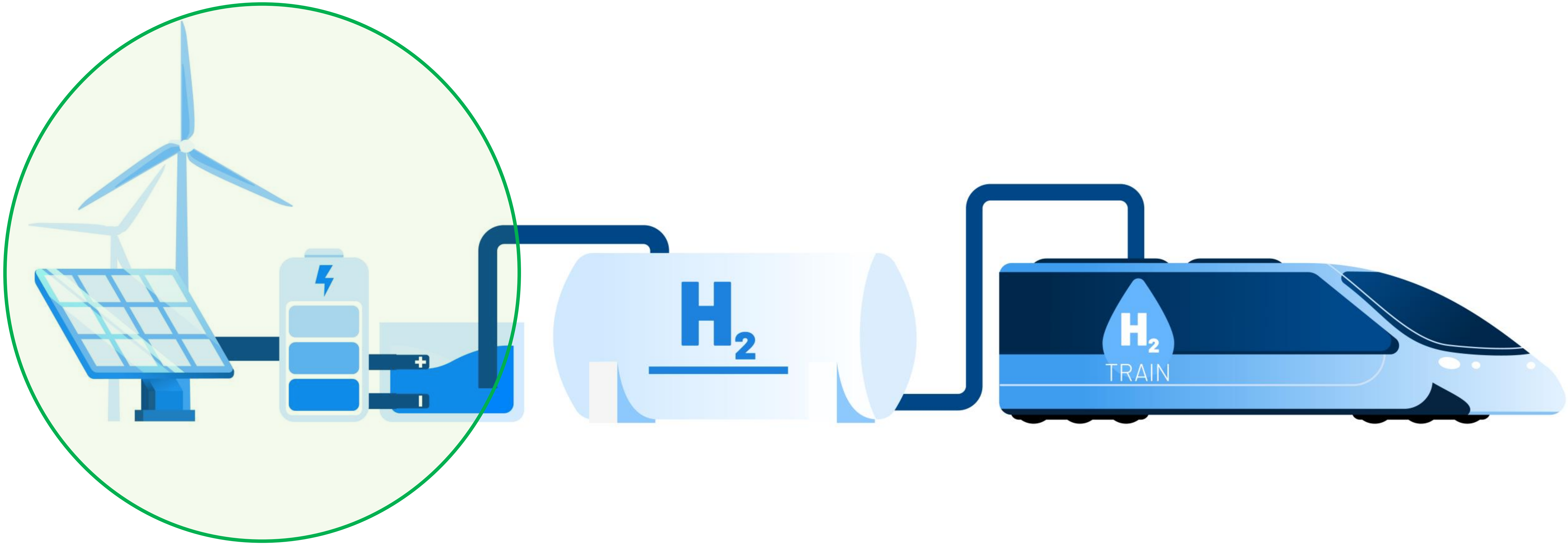
United States Environmental Protection Agency
https://www.epa.gov/ghgemissions/global-greenhouse-gas-emissions-data#Sector

Megatrend: Electrification of Everything

Grid Modernization: New Grid Paradigm



Enabling Green Hydrogen



Green Hydrogen Production

Design Challenges

Component Level

Component Design

- electrolyzer
- energy storage
- power converter unit
- generator

Asset Digitalization

- anomaly detection
- lifetime estimation
- prognostics development

System Level

Plant Design

- concept evaluation
- physical requirements
- energy balance

High-Level Algorithmic Design

- supervisory logic
- setpoint definition

Addressing Model Fidelity

milliseconds (ms)
microseconds (us)

seconds
minutes

months
years

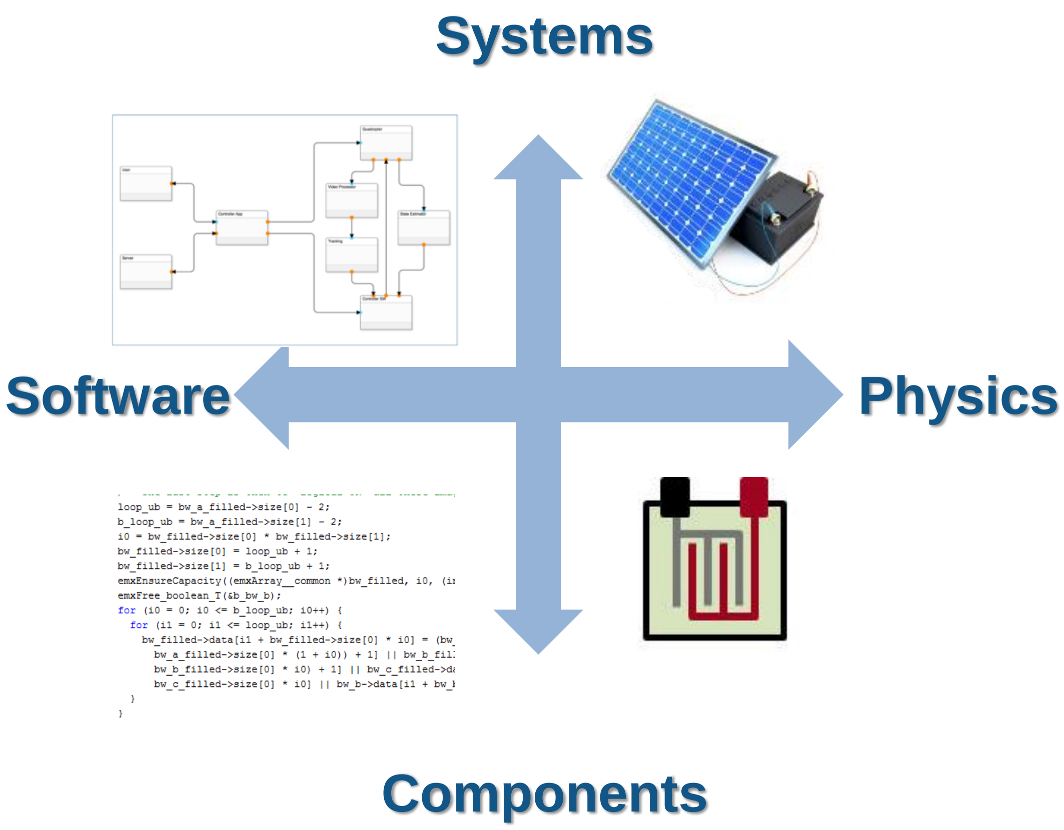
Embedded development (component) → **High fidelity**

Key performance assessment (system) → **Medium fidelity**

Techno-Economic Analysis → **Low fidelity**

Quasi-steady (8760) simulations

Addressing Model Fidelity



- **Add fidelity based on your needs**
  - Model what you need
  - Maintain architectural consistency

- **Choose the right integration platform**
  - Interface with different tools
  - Co-simulate

Electric Mobility: User Stories

Tesla Tells Us How It Keeps Beating Nearly Everyone in the Range Game

Ather Energy Develops Electric Two-Wheeled Scooter and Charging Stations

Tesla: System Optimization

Tesla Tells Us How It Keeps Beating Nearly Everyone in the Range Game

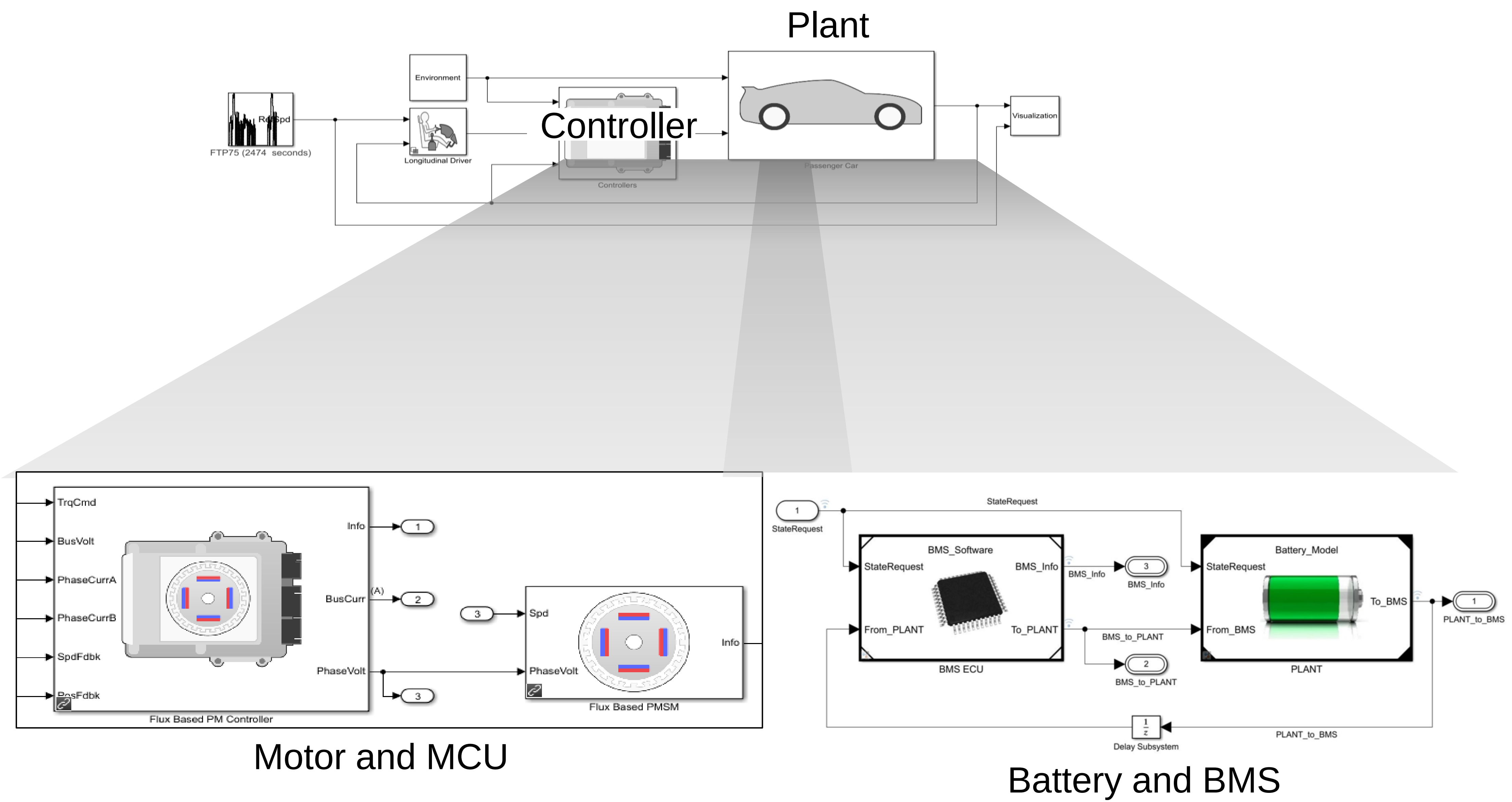
- Alleviate customer range anxiety
- Need to get the maximum efficiency from existing components
- How can we design components and do architecture tradeoff without building prototypes?

Ather Energy: BMS Design

[Ather Energy Develops Electric Two-Wheeled Scooter and Charging Stations]

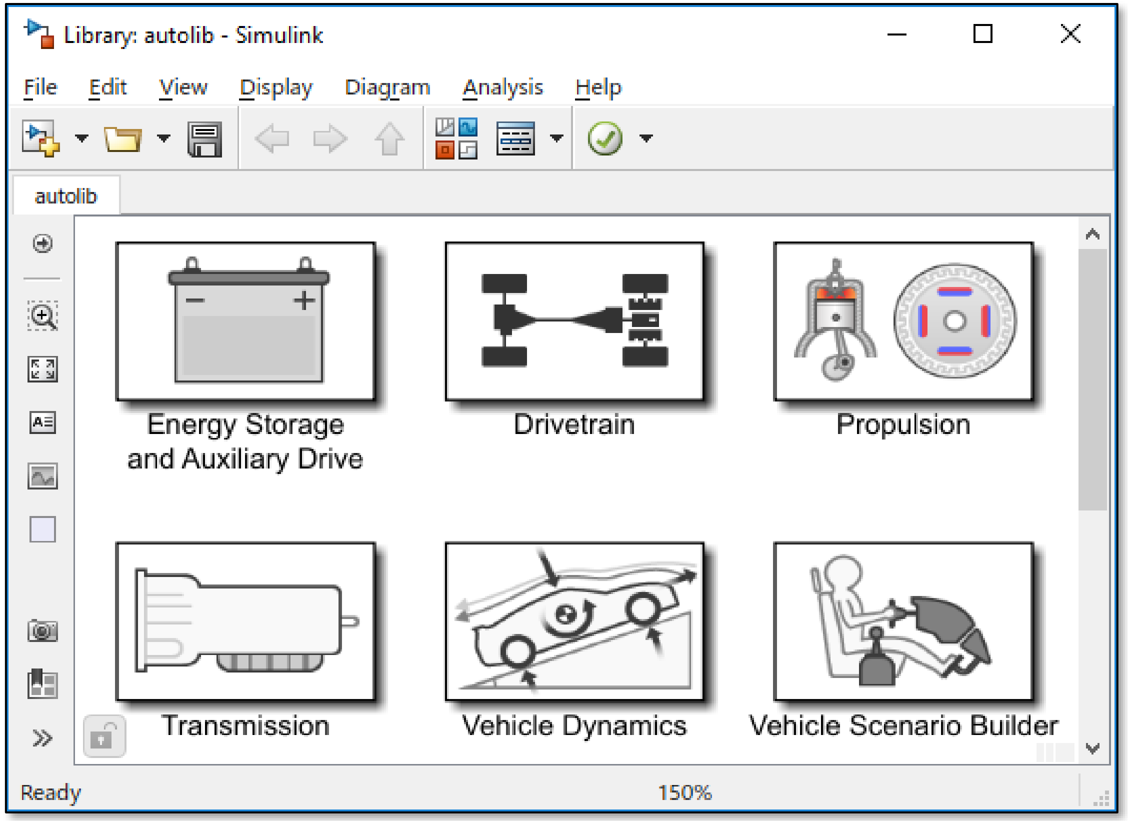
- How to explore promising Ideas against constraints of time to market and costs
- Gain maximum from Automation?
- How to gain the required competency rapidly?

Electric Vehicle: Building System Level Simulation Models

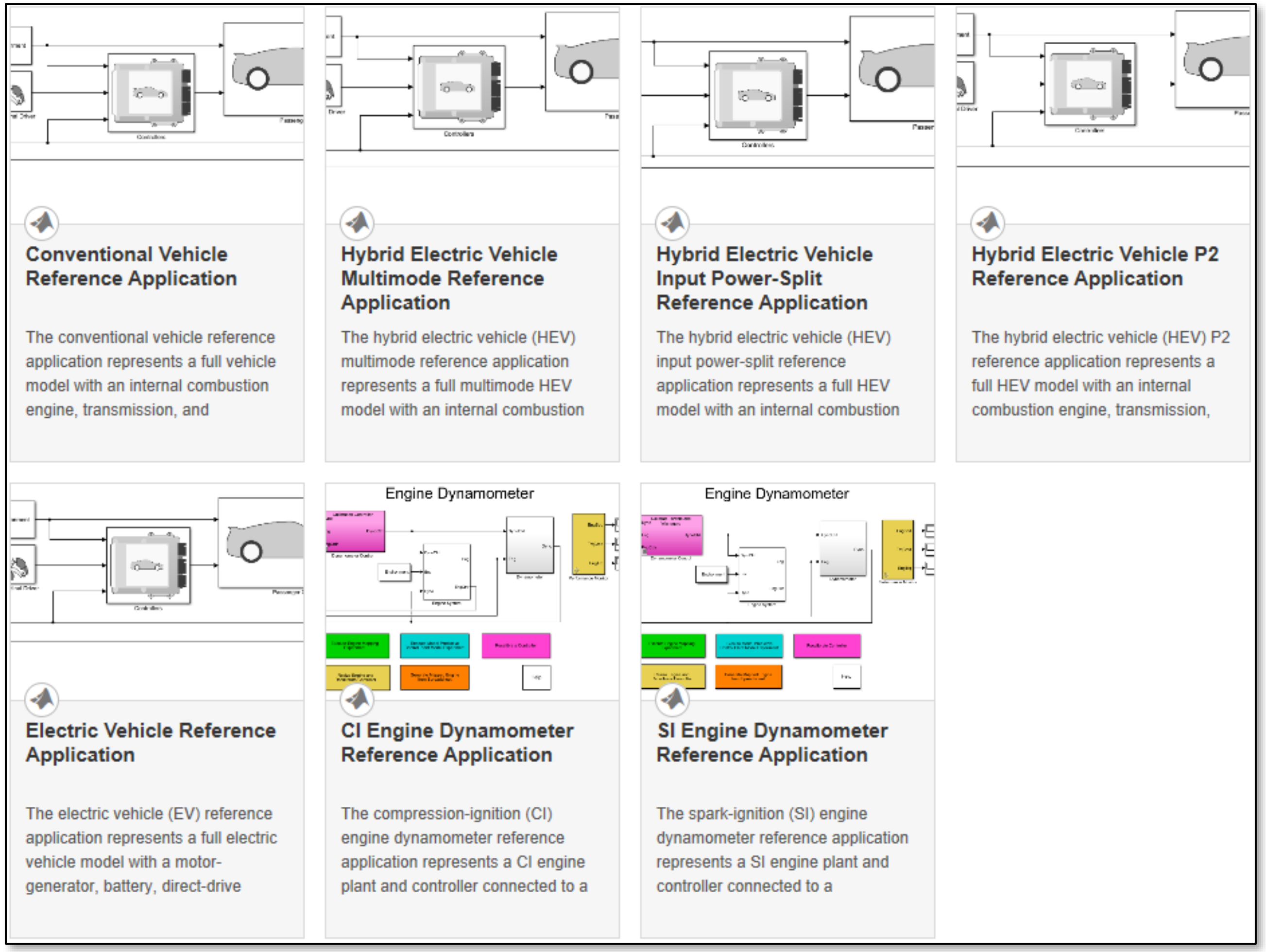


Powertrain Blockset: Pre-built Reference Applications

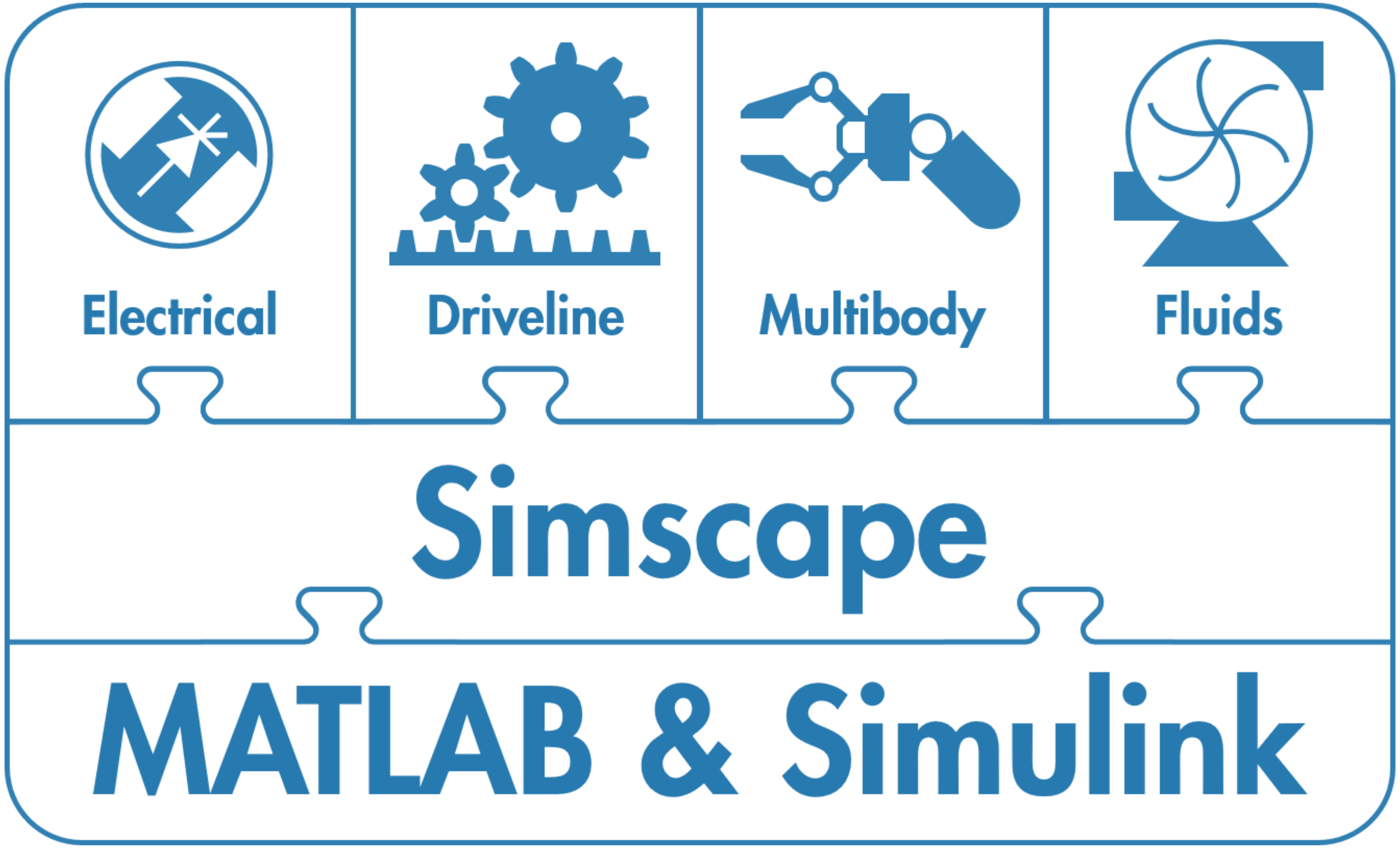
Library of blocks



Pre-built reference applications



Simscape: Multi-Domain Physical Modelling Libraries

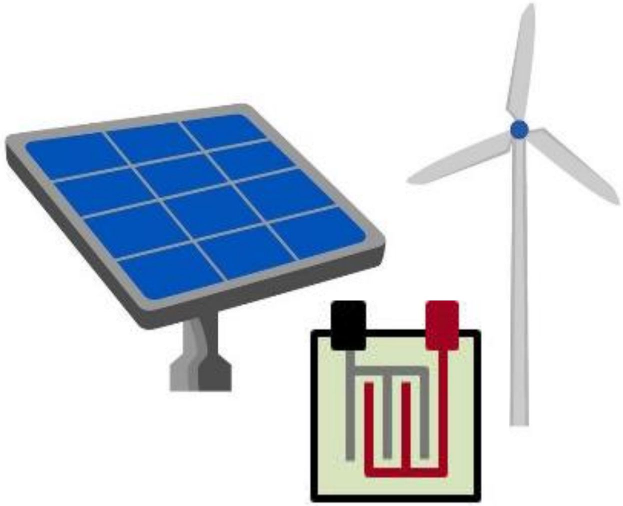


What’s next in this session?

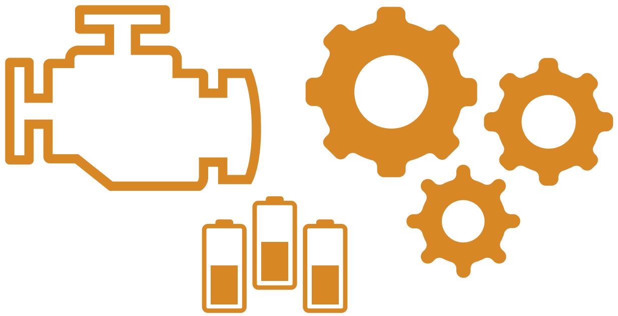
- **Battery & Motor Modelling**
  - Cell to Module to Pack
  - Thermal Analysis
  - Cooling Circuit Design

- **EV Charger Design**
  - AC/DC Charging
  - Power Electronics & Control

- **Microgrid Simulations**
  - System Level Simulation
  - Real-time Testing

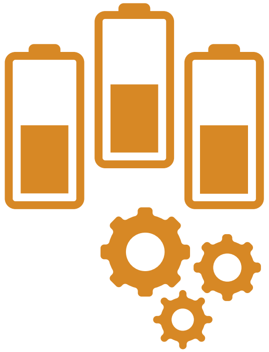


Personal Mobility Solutions
Hybrids, Pure Electric, or Fuel Cells ?



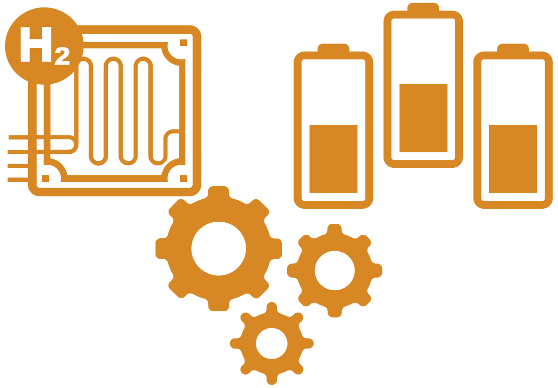
Hybrids (HEV, PHEV)
+ Lower emissions than ICE vehicle
+ No range anxiety

- Complex Controls



Pure Electric (BEV)
+ Fewer components
+ Simpler Controls (compared to HEV)

- Cost
- Safety (Battery fires)



Fuel Cells (FCEV)
+ Clean Energy source
+ Quick refill and longer range

- Cost
- Safety (H2 tank)

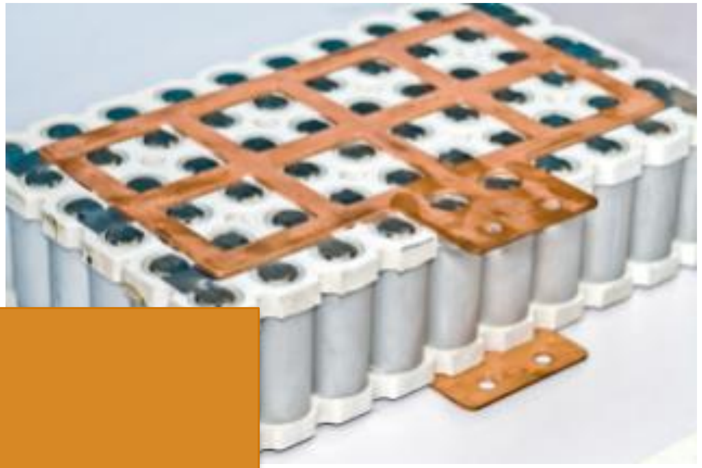
Personal Mobility Solutions
Requirements Analysis

Safety
- No Fire outside and occupant must have ~5 mins to exit the vehicle cabin
- Safe during service and handling

Cost
- Lower the Better, $/kWh
- Over 8 years of Battery, Motor, and Inverter warranty
- DoD 70% at EOL

Comfort
- Ride Quality (motor torque ripple, noise), Power deliverable (-30 to 50 degC)
- Single Charge Range – higher the better
- Charging Options & Time – Fast Charge capability

Battery & e-Motor Design
Key Design Questions



- Impact of battery design on it's safety and performance
  - Is my battery safe from a Thermal runaway perspective ?
  - How robust is my thermal management strategy ?
  - How to I model large battery packs ? How to I characterize a Li-ion cell ?
  - What should be my cell balancing strategy ? How robust is my BMS design ?
  - How do I reduce my overall battery pack cost ?

- Impact of motor design in controls and performance (Ride quality, NVH)
  - How does motor design impact overall vehicle performance ?
  - NVH issues arising out of, say, torque ripple ?
  - What size e-motor is required to meet operational requirements?
  - How can I optimize the motor controller ?
  - How does machine design affect power electronic losses ?

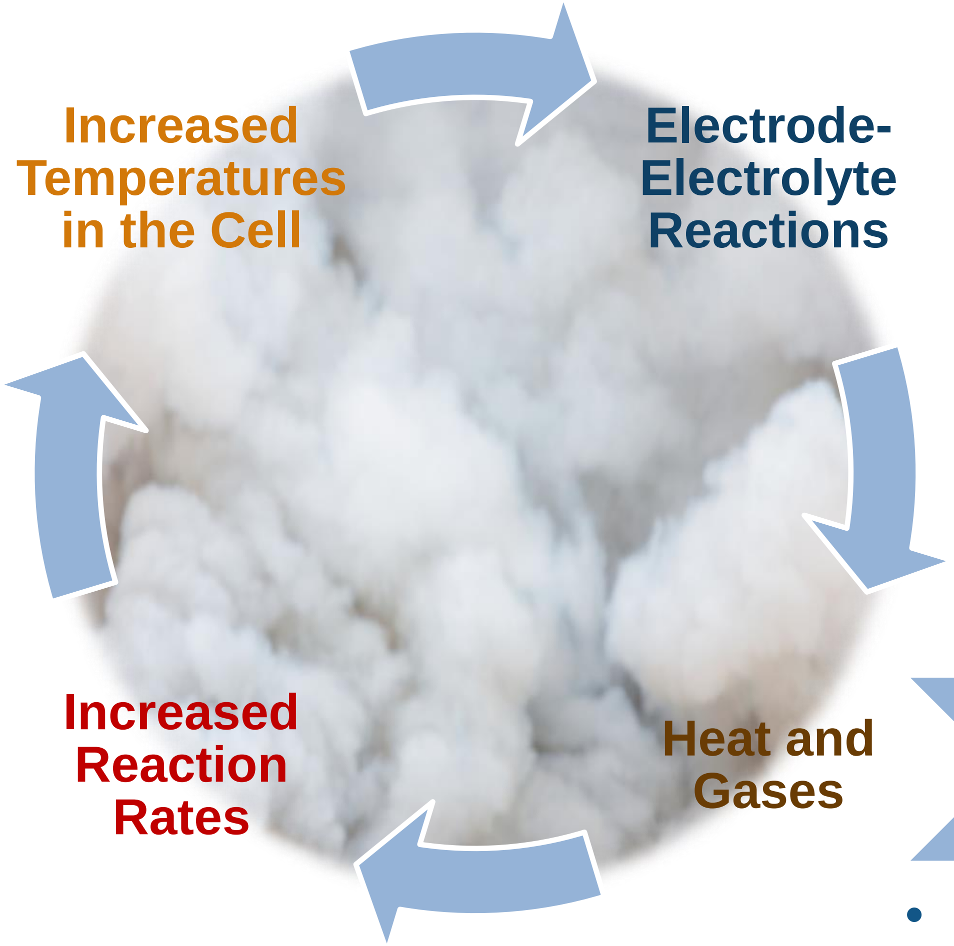
Safety of HV Battery Packs

Is my battery safe from a thermal runaway perspective ?

Safety of HV Battery Packs
Thermal Safety

Trigger

- Short Circuit
- Crash, crush
- Cooling failure



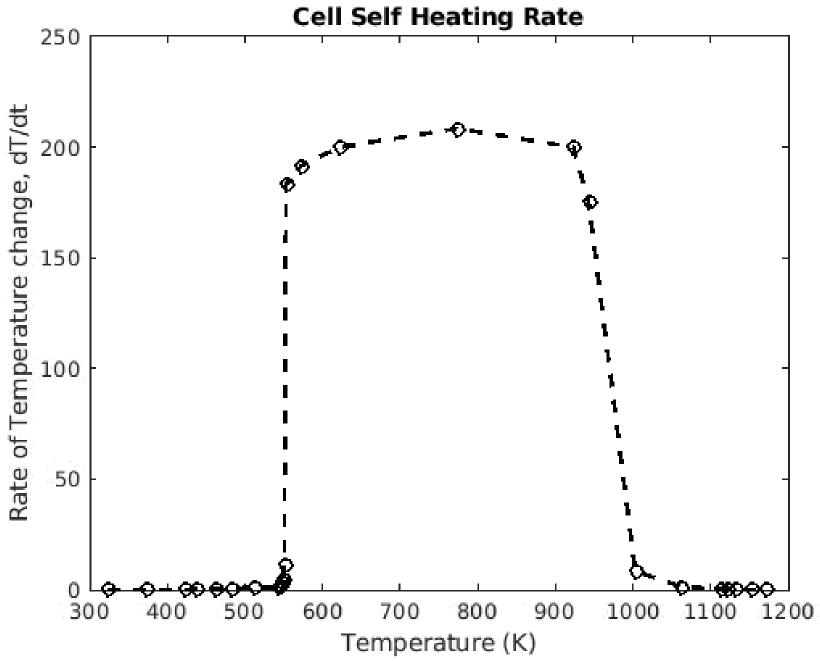
~ 150^{O}C, Electrolyte-Anode
~ 220^{O}C, Cathode decomp.
~ 250^{O}C, Electrolyte decomp.

Cell Vent

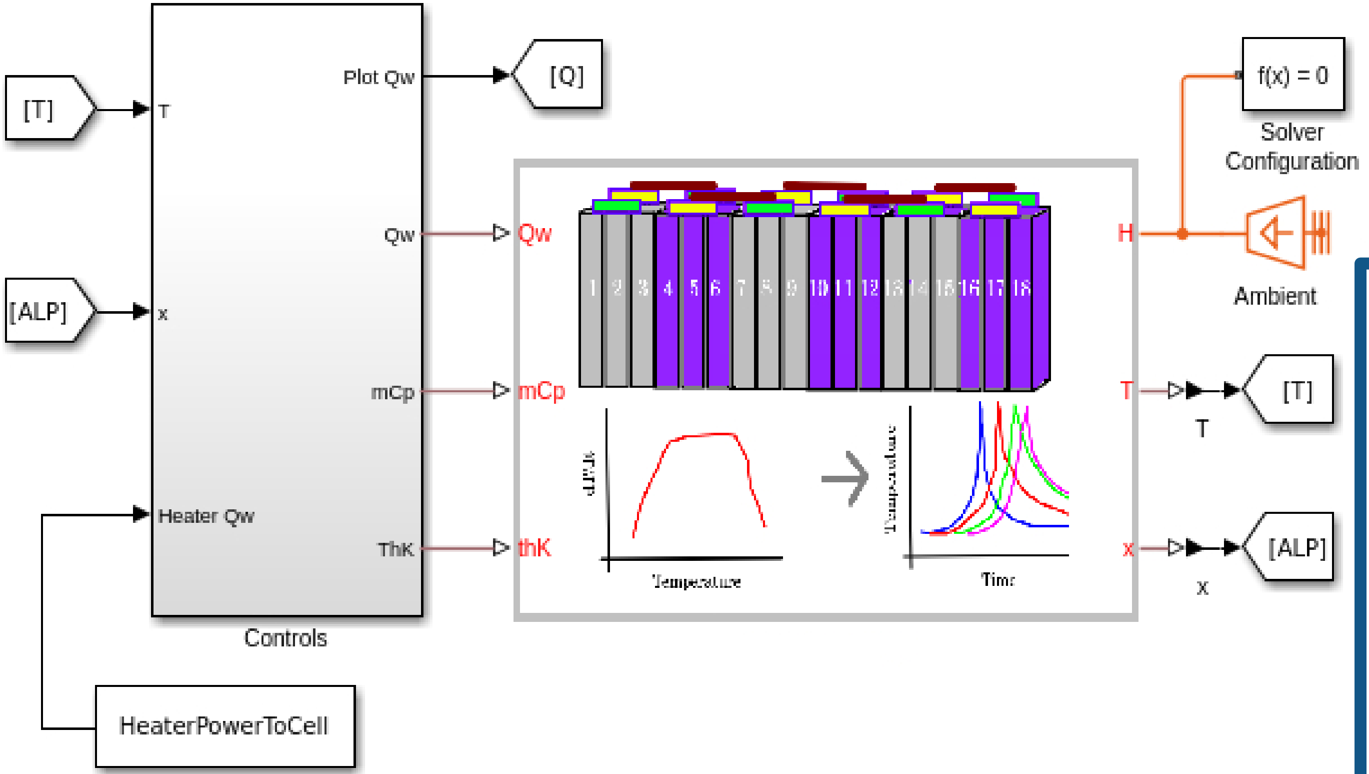
- Combustion
- Fire

Example – Thermal Runaway
Modelling

- Computationally expensive to model all reaction kinetics in a runaway reaction
- Strategy – fit lumped reaction rates for electrode-electrolyte reaction based on measured cell abuse test data (cell self-heating rates)
- Assume – all cell heat generation due to anode-electrolyte reaction (initially)



Example – Thermal Runaway
Simscape Component



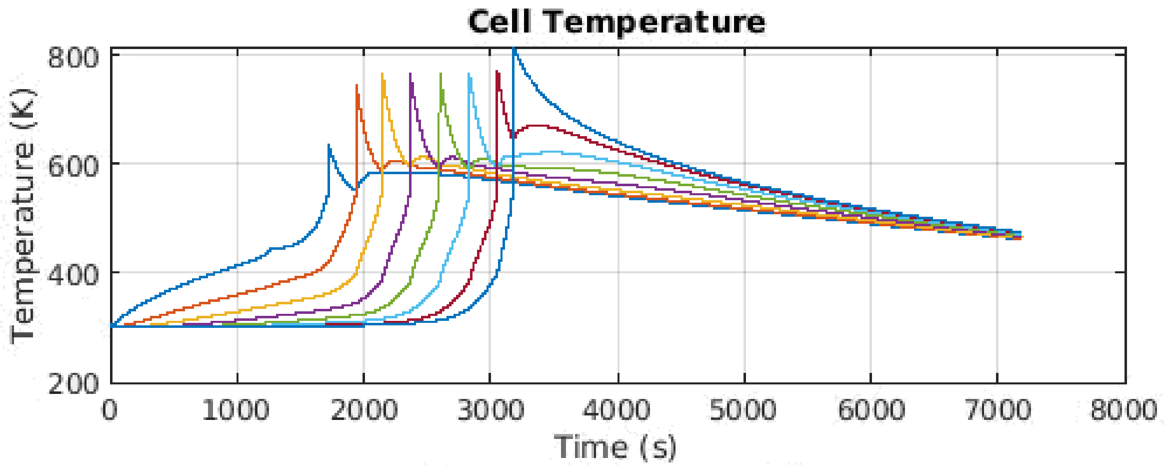

```
let
    % Check if temperature limit for thermal runaway initation reached
    % If reached, calculate cell abuse heat
    triggerTcrossed = (T>=triggerT); % 0 or 1 (Qabuse valid)
    Qabuse = triggerTcrossed*mass*sp_heat*tablelookup(cell_Tvec,...
        cell_dTdt,T,interpolation=linear,extrapolation=nearest);
    % Check if all reactants in cell have been consumed
    % If yes, no more abuse heat generation
    % No burning or phase change of cell material considered
    cellDead = (alpha>=maxAlpha);
    alphaRate = (unityDummy-cellDead)*(Qabuse/(rxnHeat*activeMass));
in
    % Calculate extent of reaction and cell abuse heat
    alphaRate == alpha.der;
    Q + (unityDummy-cellDead)*Qabuse == frac * mass * sp_heat * T.der;
end
```

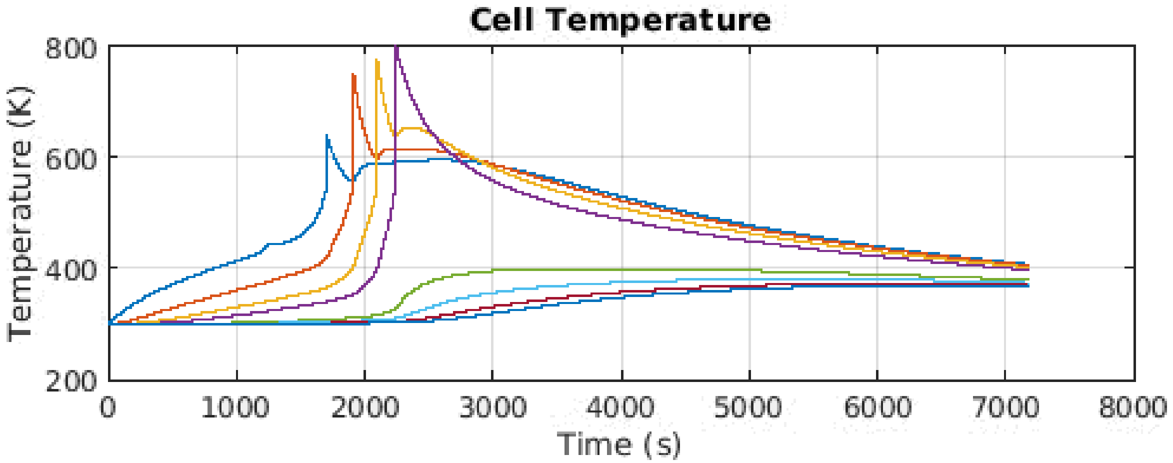
Energy Balance Equations

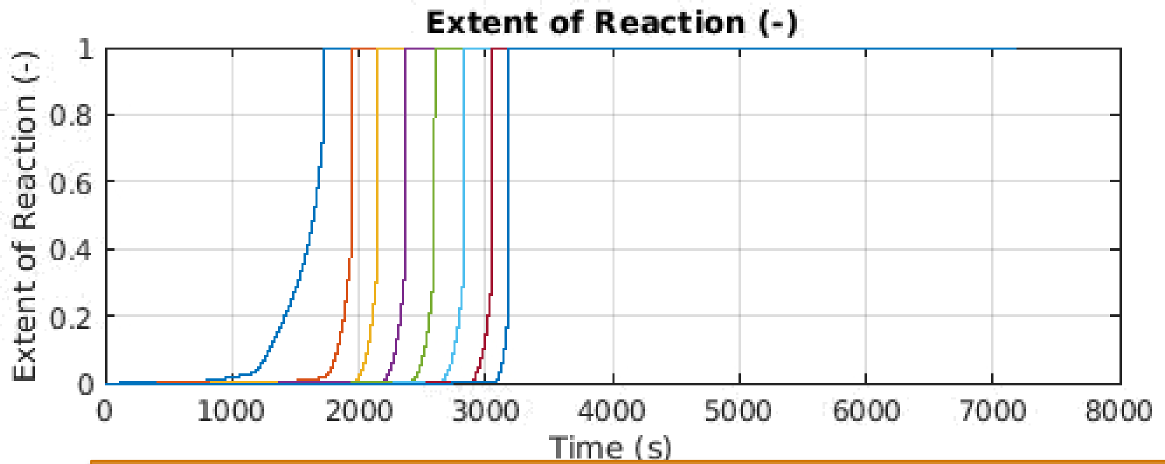
Calculate heat load due to cell abuse reactions

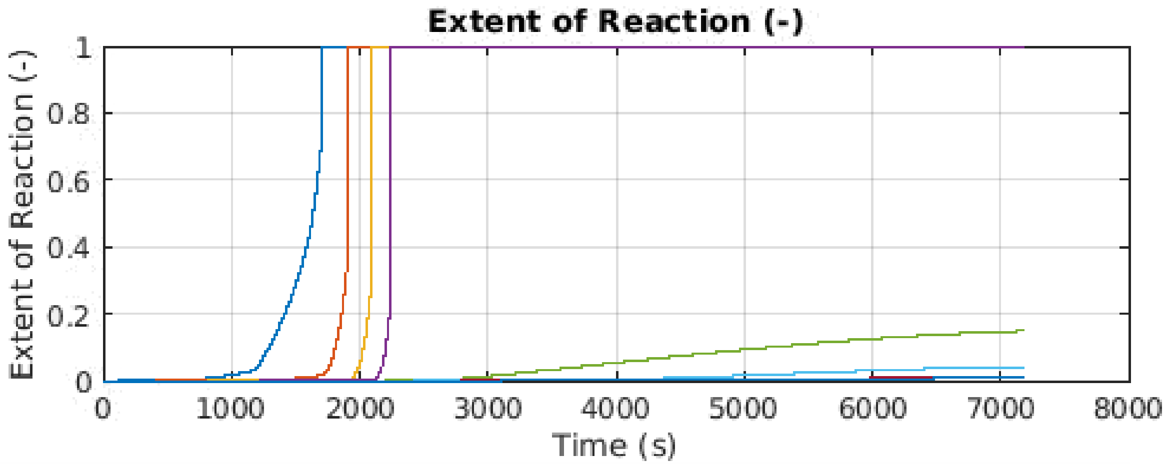
Example – Thermal Runaway

Results – with/out Thermal Barrier



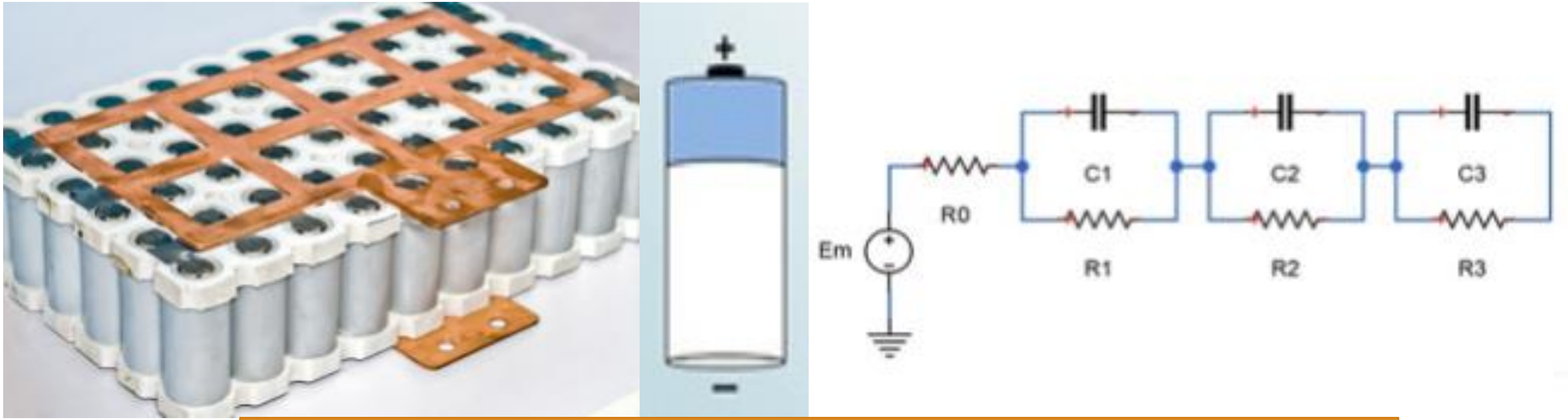






The energy released during a thermal runaway in a module can be reduced by placing thermal barriers, at the cost of spacing (and weight); this also favorably impacts the specs. for sealing design (pack enclosure).

Battery Pack Design for Performance

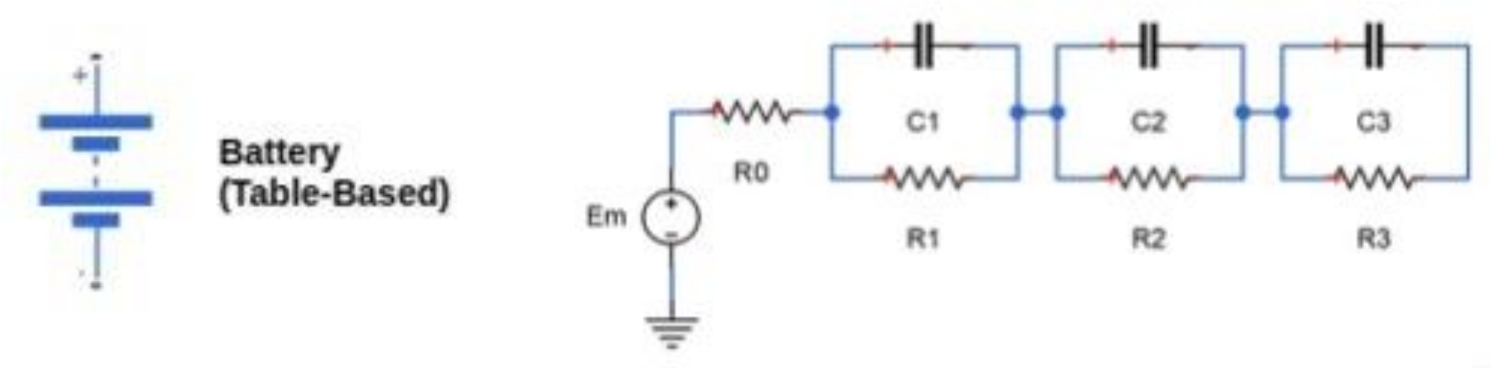


How robust is my thermal management strategy ?
How do I model large battery packs ? How do I characterize a Li-ion cell ?

Battery Pack Design
Cell Model

- Simscape™ Electrical™ provides capable cell level modelling capabilities including cell aging and pre-parameterized cells

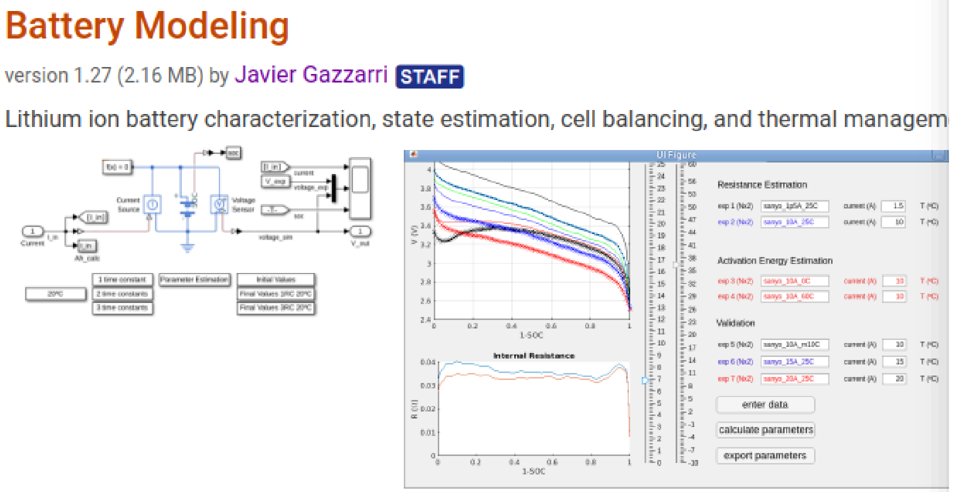
- Equivalent-circuit-based cell models, upto 5RC pairs

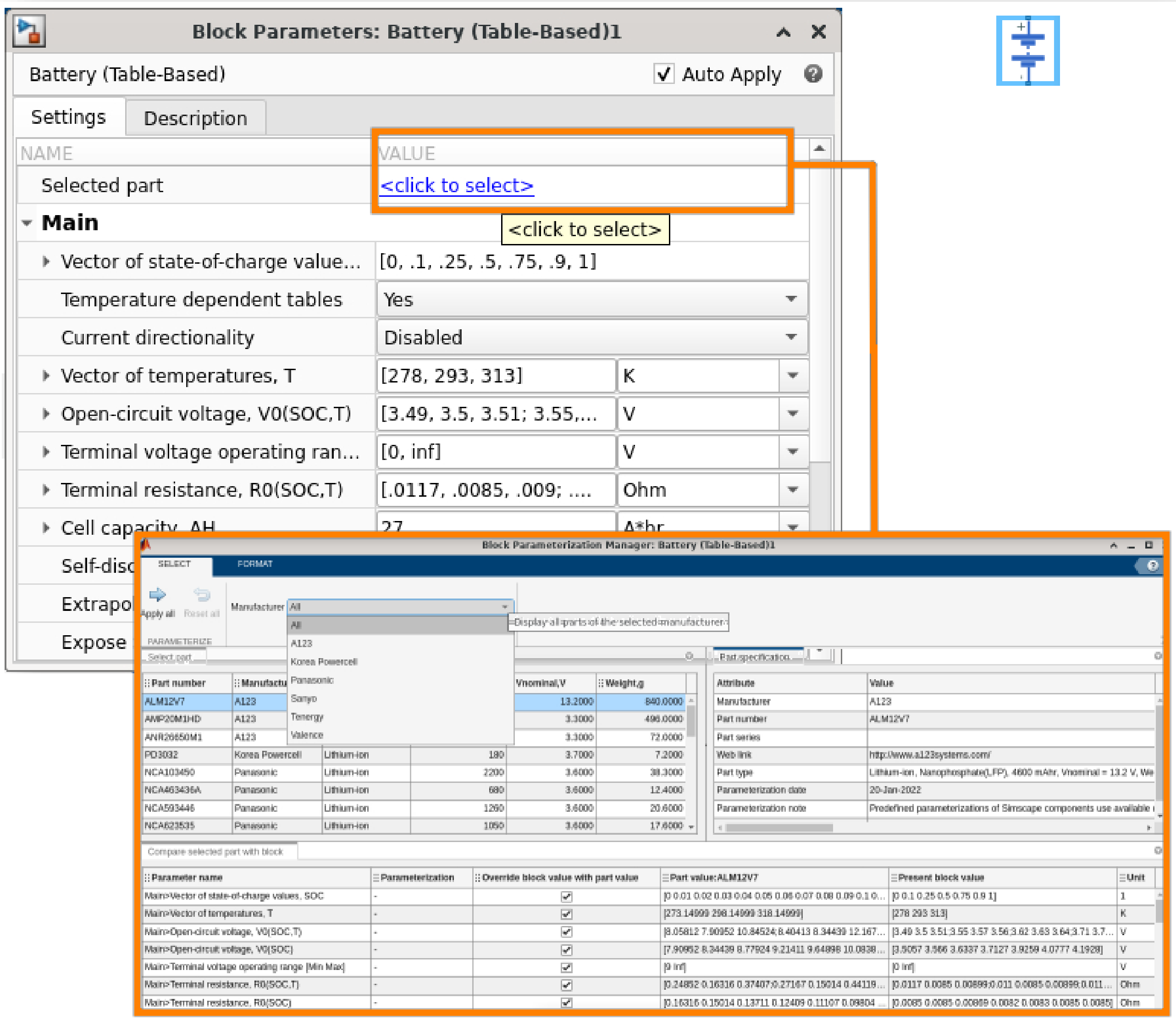


Battery Pack Design
Cell Characterization

- Use pre-parameterized battery cell data

- Cell characterization using test data (HPPC), upto 5RC pairs





Battery Pack Design
Cell Aging

- Cell Fade – impact of charge-discharge cycle on changes in OCV, cell ohmic resistance, and capacity
  - Semi empirical, tabulated, equations
  - Included in battery pre-parameterized data

$$v_{0,\text{fade}} = v_0\left(1 + \frac{\delta_{v_0}}{100}\frac{n}{N}\right)$$

$$q_{nom,\text{fade}} = q_{nom}\left(1 + \frac{\delta_{AH}}{100}\sqrt{\frac{n}{N}}\right)$$

$$R_{i,\text{fade}} = R_i\left(1 + \frac{\delta_{R_i}}{100}\sqrt{\frac{n}{N}}\right)$$

- Calendar aging – impact on ohmic resistance
  - Semi empirical, tabulated

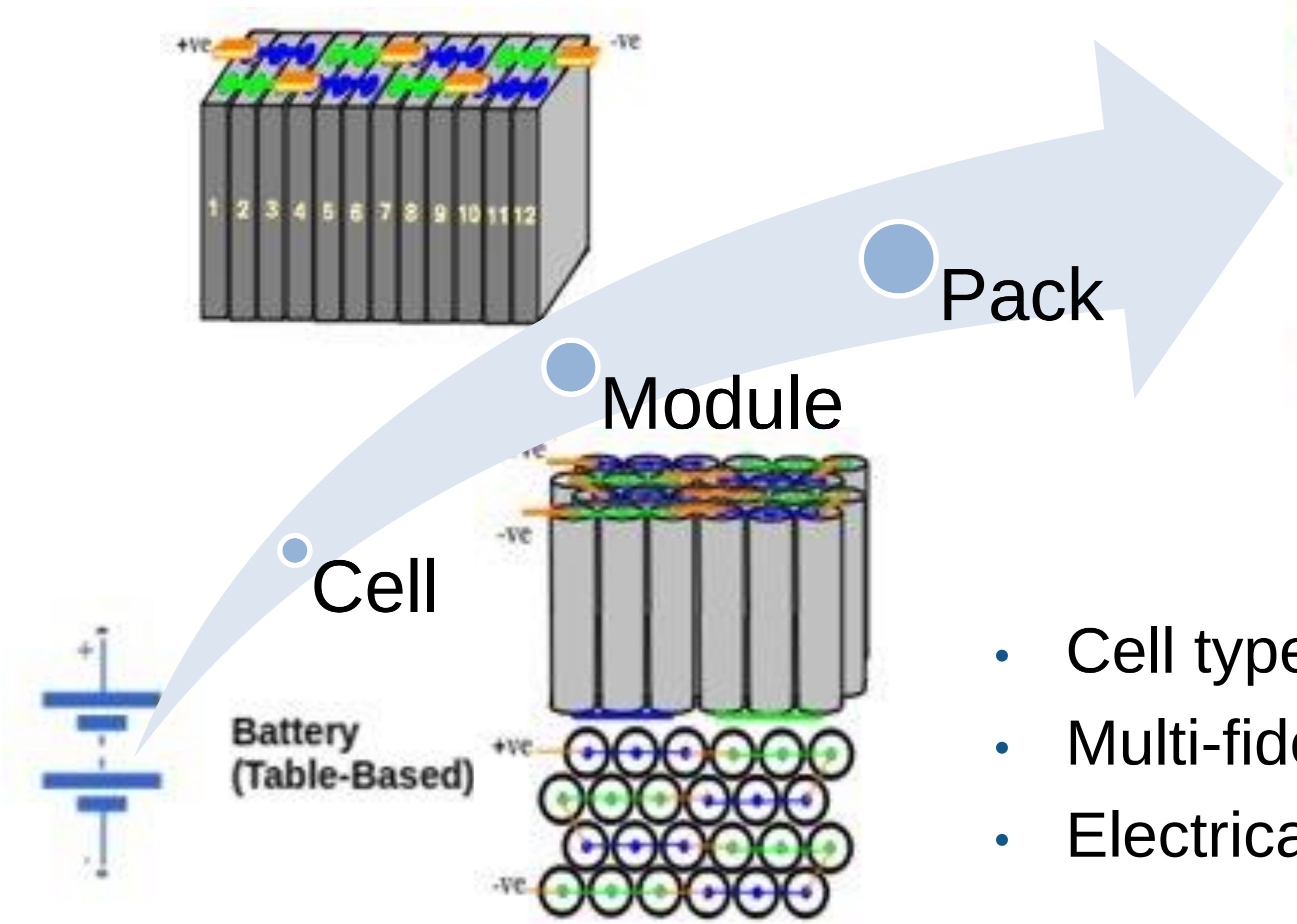
$$\alpha_r(T, V_{oc}) = (bV_{oc} - c)e^{-\frac{qd}{kT}},$$

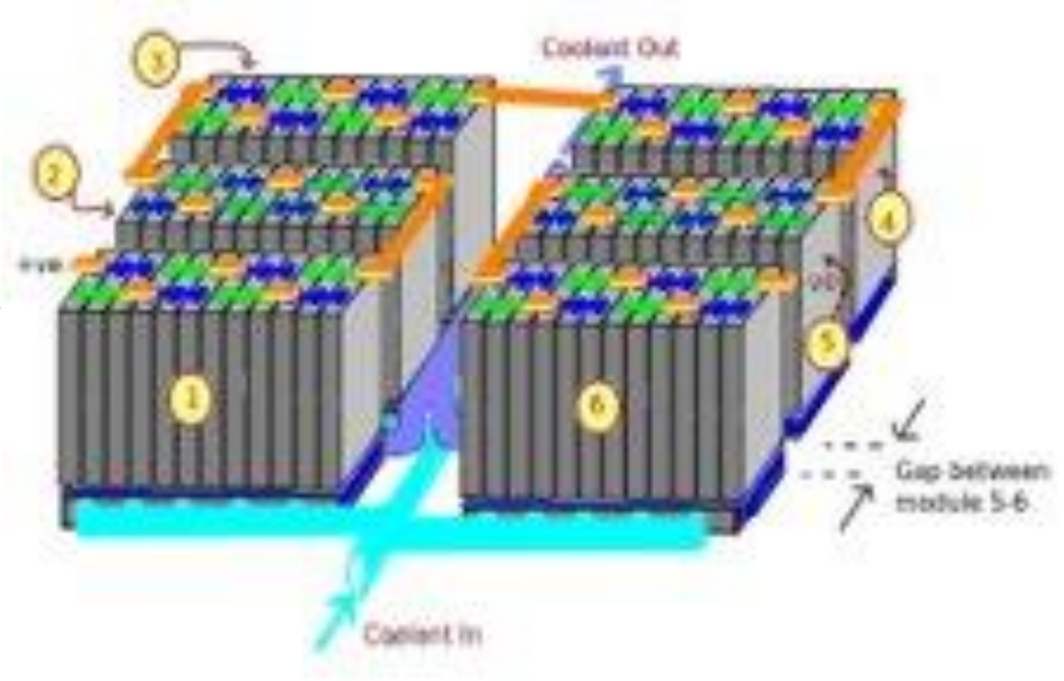
$$R = R_0\left(1 + \sum_{i=1}^{i=n} \alpha_r(T_i, V_{oc})\left(t_i^a - t_{i-1}^a\right)\right),$$

$$\alpha_c(T, V_{oc}) = (bV_{oc} - c)e^{-\frac{qd}{kT}},$$

$$C = C_0\left(1 - \sum_{i=1}^{i=n} \alpha_c(T_i, V_{oc})\left(t_i^a - t_{i-1}^a\right)\right),$$

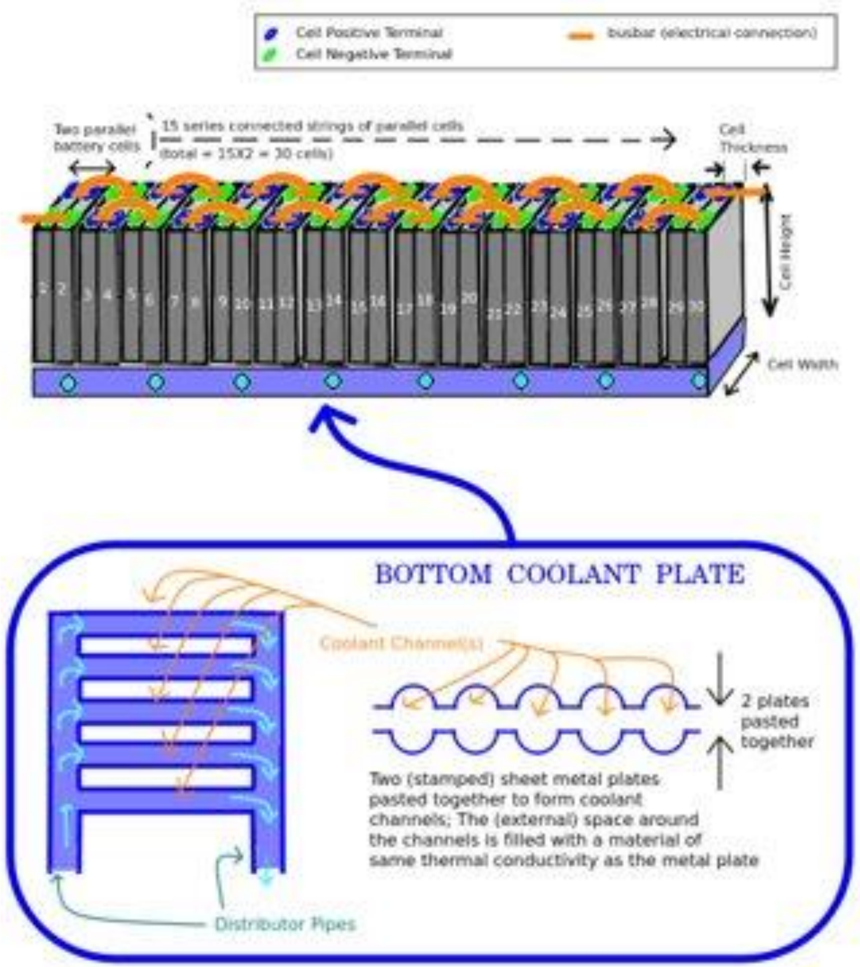
Battery Pack Design
Simscape Workflows



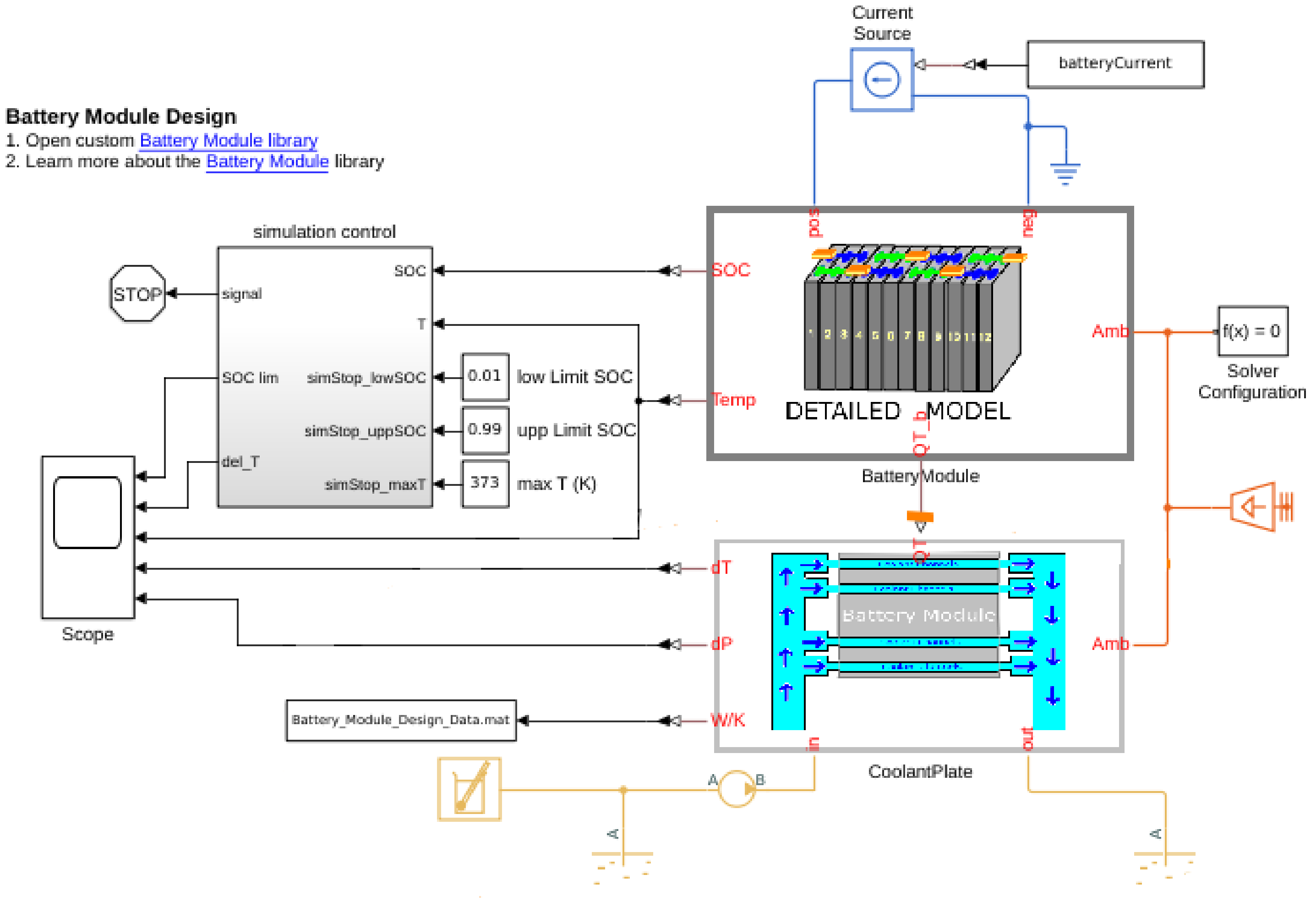


- Cell type – pouch, prismatic, and cylindrical
- Multi-fidelity – detailed, grouped, and lumped
- Electrical & thermal response

Battery Pack Design
Electrical & Thermal



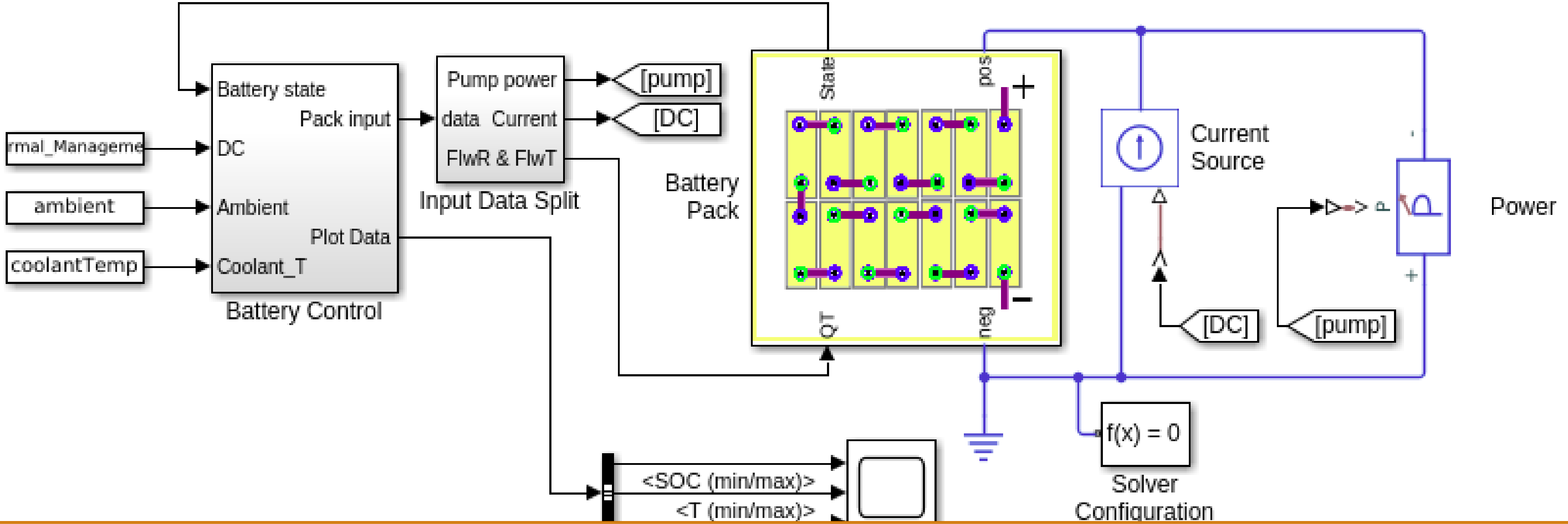
Physical Layout



Simscape Implementation

Battery Pack Design Examples
Thermal Management

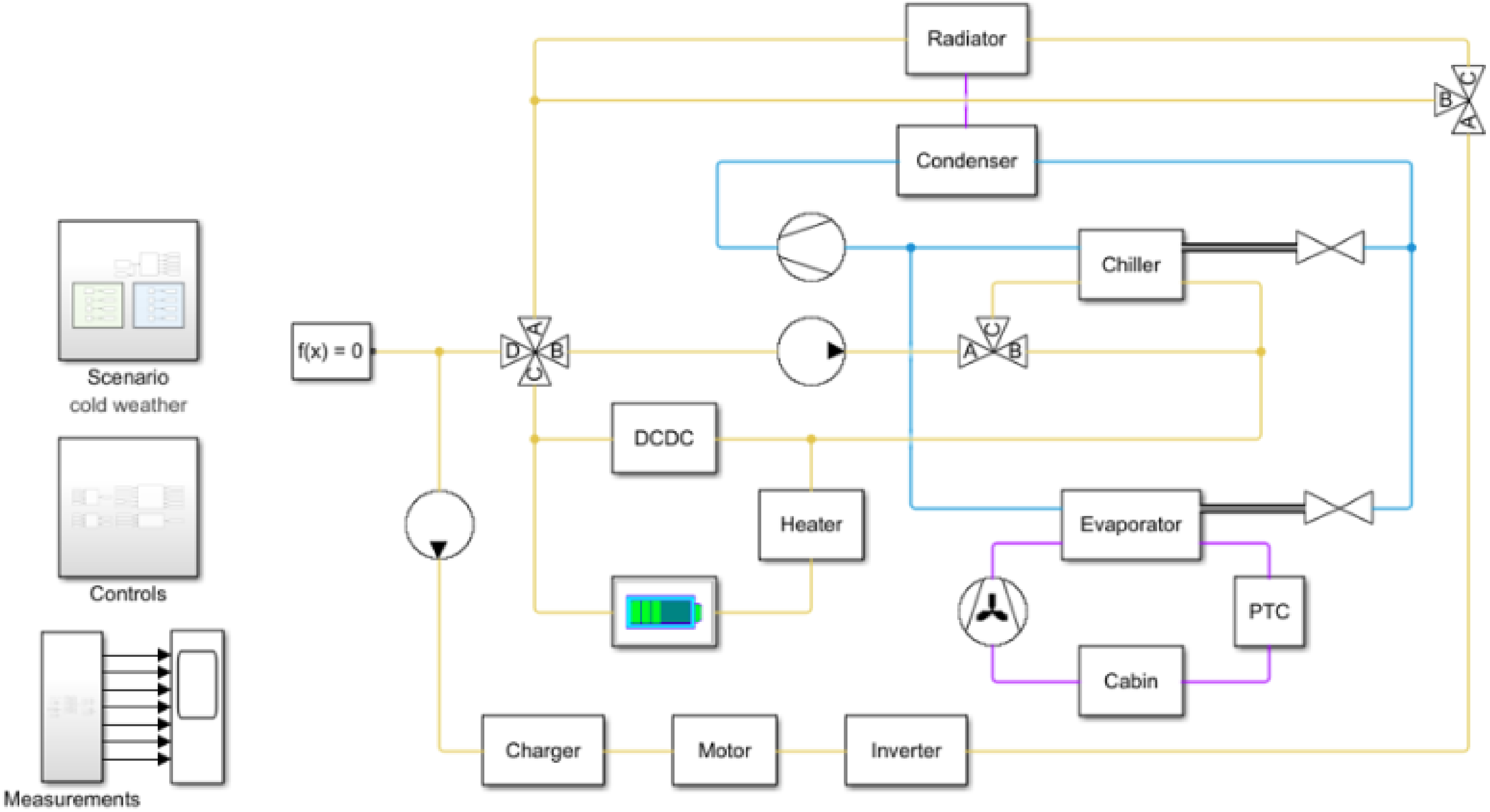
- Analyze cell-to-cell temperature gradient and devise thermal management strategies, robust BMS



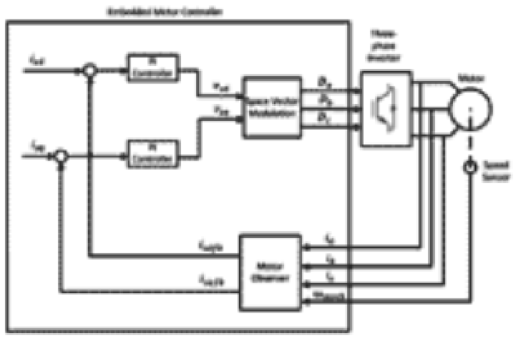
Ability to track different weak/strong cells in the entire pack and design robust strategies for managing temperature, electrical safety, and pack utilization from a range perspective.

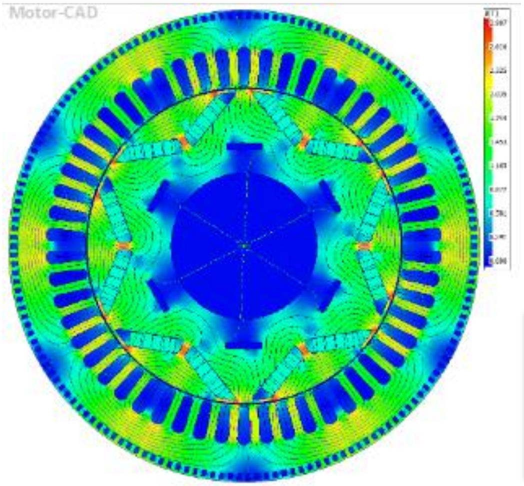
Battery Pack Design Examples
Thermal Management for BEVs

- Battery pack cooling strategy – single or separate cooling systems



Motor Design for e-Mobility





What size e-motor is required to meet operational requirements?
How can I optimize the motor controller ?

Electric Motor Design
Detailed Design Process

Motor Design Engineer

Motor Design
- Pole/slot design
- Sizing, windings

Performance
- Thermal
- Losses

Validate
- Simulate with actual waveforms, losses

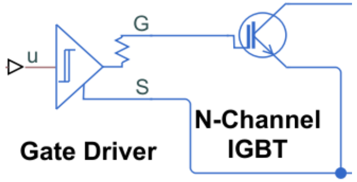
Flux linkage & winding configuration

Feedback control

Steinmetz coefficients & efficiency map

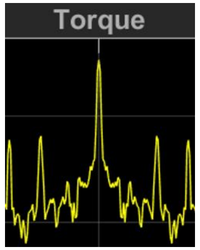
$$i_{ds}^{ref} = g_1\left(T_e^{ref}, n, V_{dc}\right)$$
$$i_{qs}^{ref} = g_2\left(T_e^{ref}, n, V_{dc}\right)$$

Op. point management



Drive electronics

Current waveforms and/or harmonics



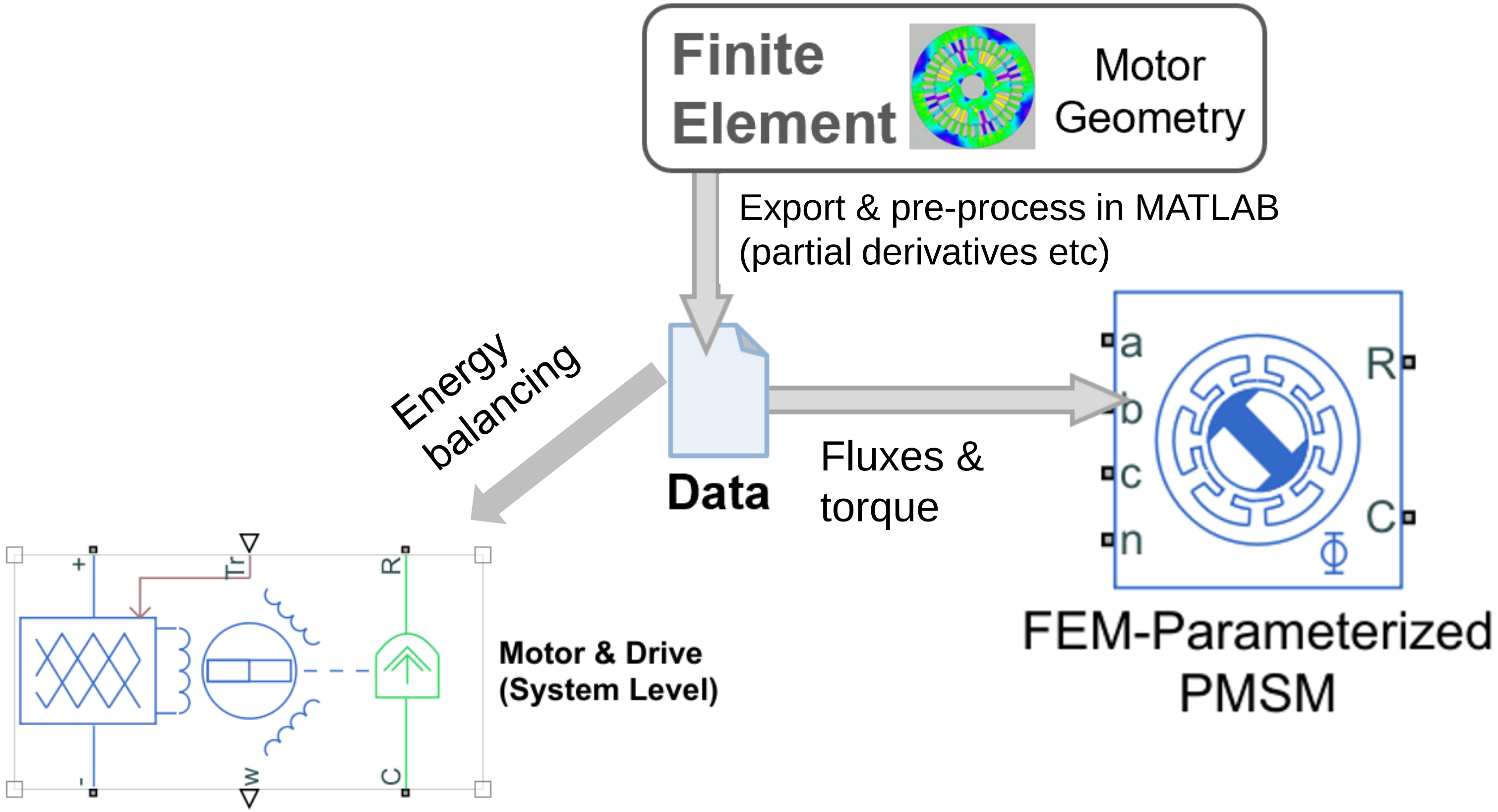
System simulation-> drive efficiency & harmonics

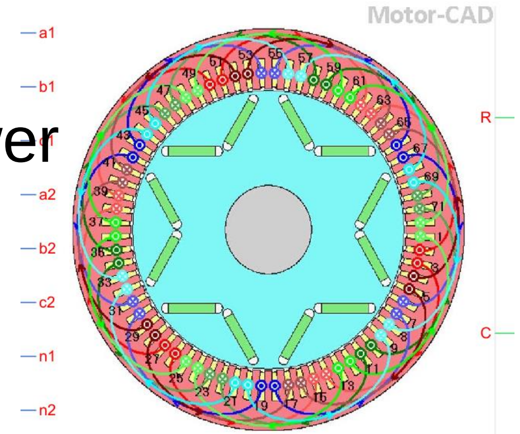
Systems and Controls

Electric Motor Design
Design to System Model

- Import flux for 3-phase PMSMs from FE design tools like JMAG, ANSYS-Maxwell, and Motor-CAD

- Enables design and optimization of the complete e-drive system (motor, power electronics, and controller)



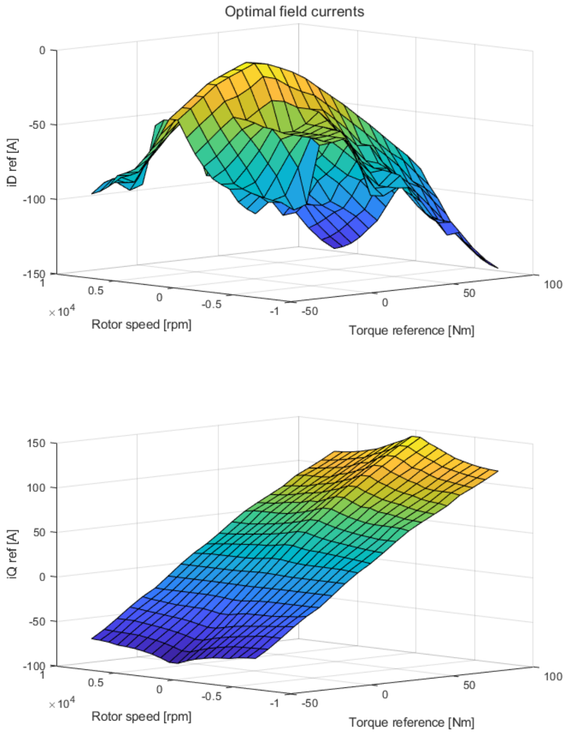


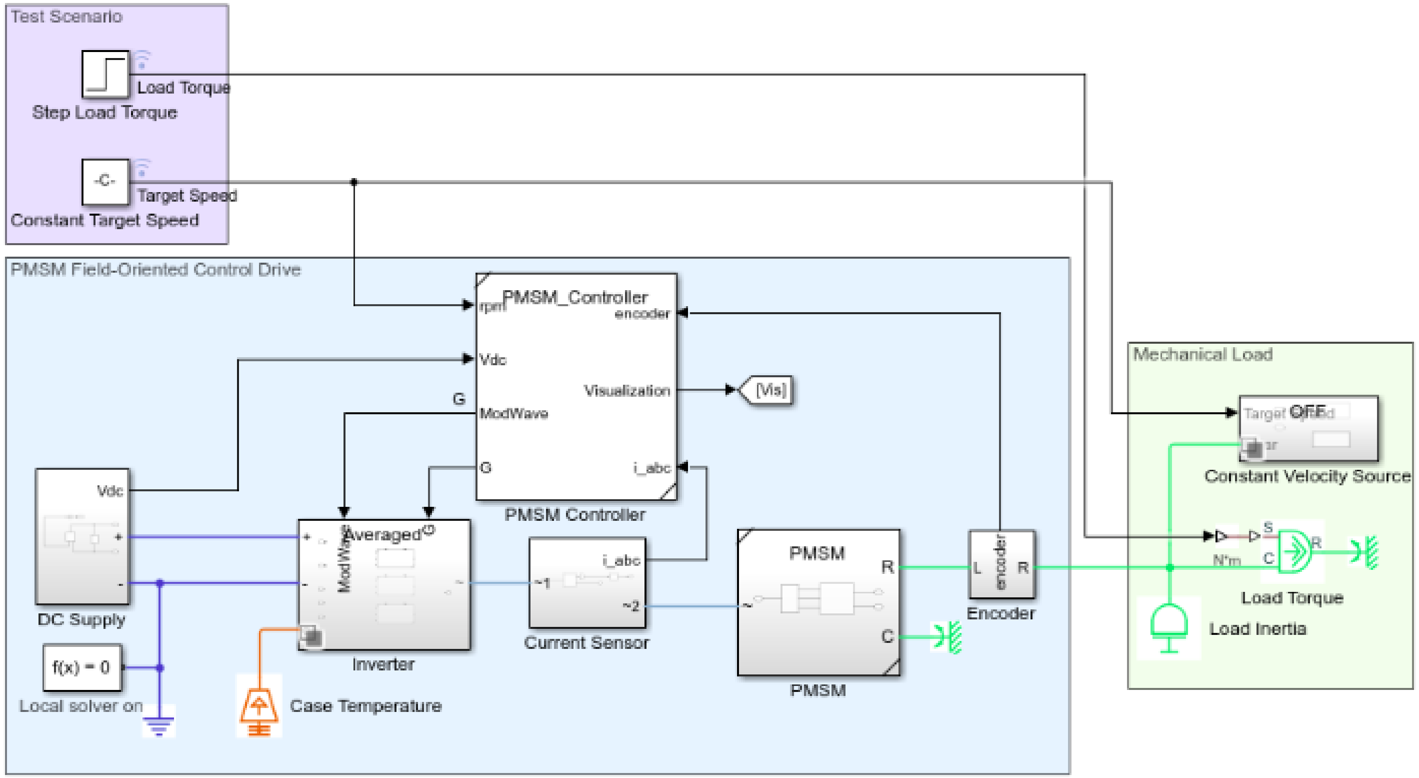

```
mcad = actxserver('motorcad.appautomation'); % Start MotorCAD ActiveX server
invoke (mcad,'LoadFromFile','IPMtraction6phase.mot' )
for i = 1:nMag
    for j = 1:nGamma
        invoke(mcad,'SetVariable','PeakCurrent',magVec(i));
        invoke(mcad,'SetVariable','PhaseAdvance',gammaVec(j));
        invoke(mcad,'DoMagneticCalculation');
        for m = 1:nX % Loop over rotor angles
            xe = N*angleVec(m)*pi/180; % Electrical angle in radians
            [~, ~, torque] = invoke(mcad, 'GetMagneticGraphPoint', 'TorqueVW',m-1);
            [~, ~, fluxA]  = invoke(mcad, 'GetMagneticGraphPoint', 'FluxLinkageLoadP
            fluxAmat(i,j,m)  = fluxA;
            torqueMat(i,j,m) = torque;
        end
    end
end
```

Electric Motor Design Example

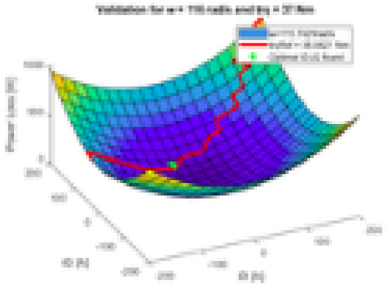
Control Strategies for BEV Motor Design

- PMSM using imported FEM data & optimized Field-Oriented Control (FOC)
- Simscape Electrical nonlinear motor model in the form of tabulated flux linkages and Steinmetz coefficients





Electric Motor Design Example
Component, Controls, and System



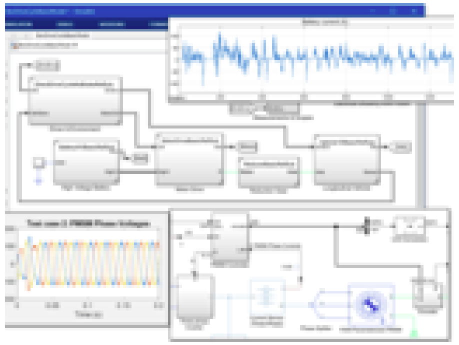
Motor Efficiency Improvements With Tuned Control Parameters

version 21.2.1.1 (1.88 MB) by Angel Gonzalez Llacer STAFF

PMSM drive using imported FEM data and optimized Field-Oriented Control (FOC) parameters.

https://github.com/mathworks/pmsm-drive-optimization

Simscape enables detailed motor design along with it's power electronics & provides workflows to integrate component model into system level models



Battery Electric Vehicle Model in Simscape

version 1.2.1 (9.08 MB) by Isaac Ito STAFF

A Battery Electric Vehicle (BEV) model in Simscape

https://github.com/mathworks/Simscape-Battery-Electric-Vehicle-Model

Learn More

More on Simscape Electrical, Fluids, and Driveline examples

Selected Examples in Simscape Product Family

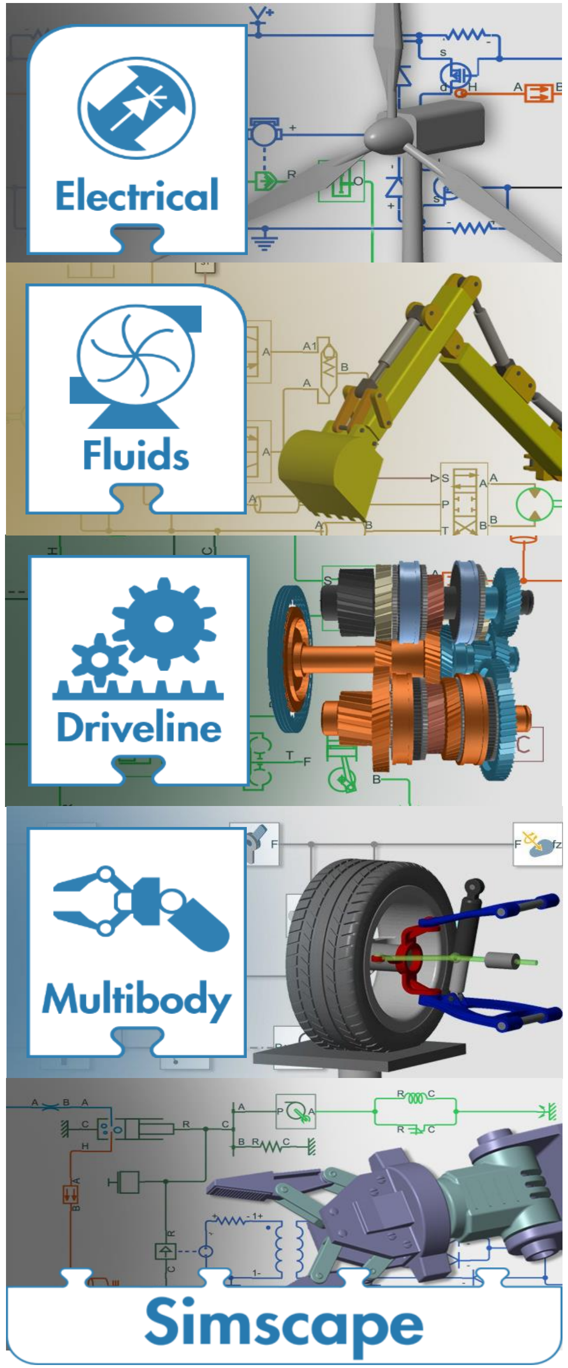
- Battery Thermal Management : ee_lithium_pack_cooling
- Battery Thermal Runaway : ssc_lithium_pack_thermalRunaway
- Fuel cells from a Detailed Chemistry perspective : ssc_fuel_cell
- Fuel cells from a Systems perspective : ee_fuel_cell
- PMSM electrothermal : ee_pmsm_drive_thermal
- PMSM faults : ee_motor_pmsm_faulted

Selected Examples on MATLAB Central

- Battery Electric Vehicle model in Simscape
- Hybrid Electric Vehicle model in Simscape
- Battery pack design solutions for BEVs in Simscape
- Motor efficiency improvements with tuned control parameters

Webinars

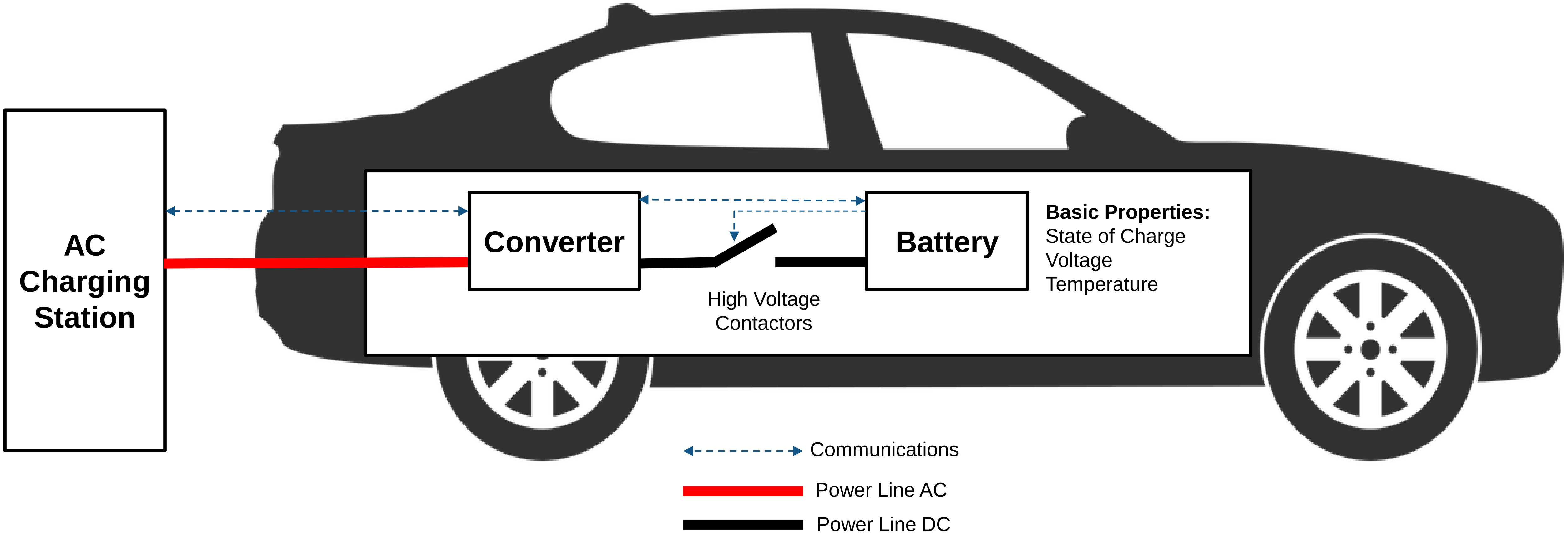
- Integrating FEM motor data into Simscape Electrical
- Fuel cell integration for electrified propulsion



Coming-up Next...

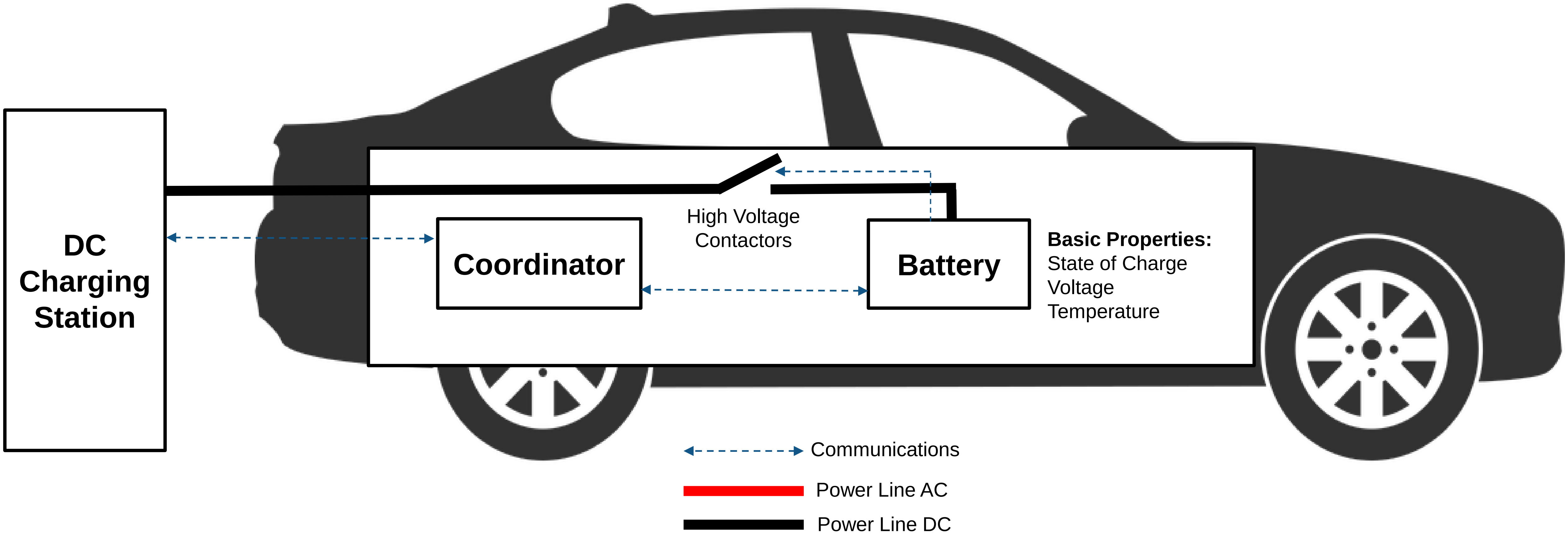
AC Charging

- EVSE delivers low/medium AC power to the vehicle
- Vehicle coverts AC power to DC power for battery charging



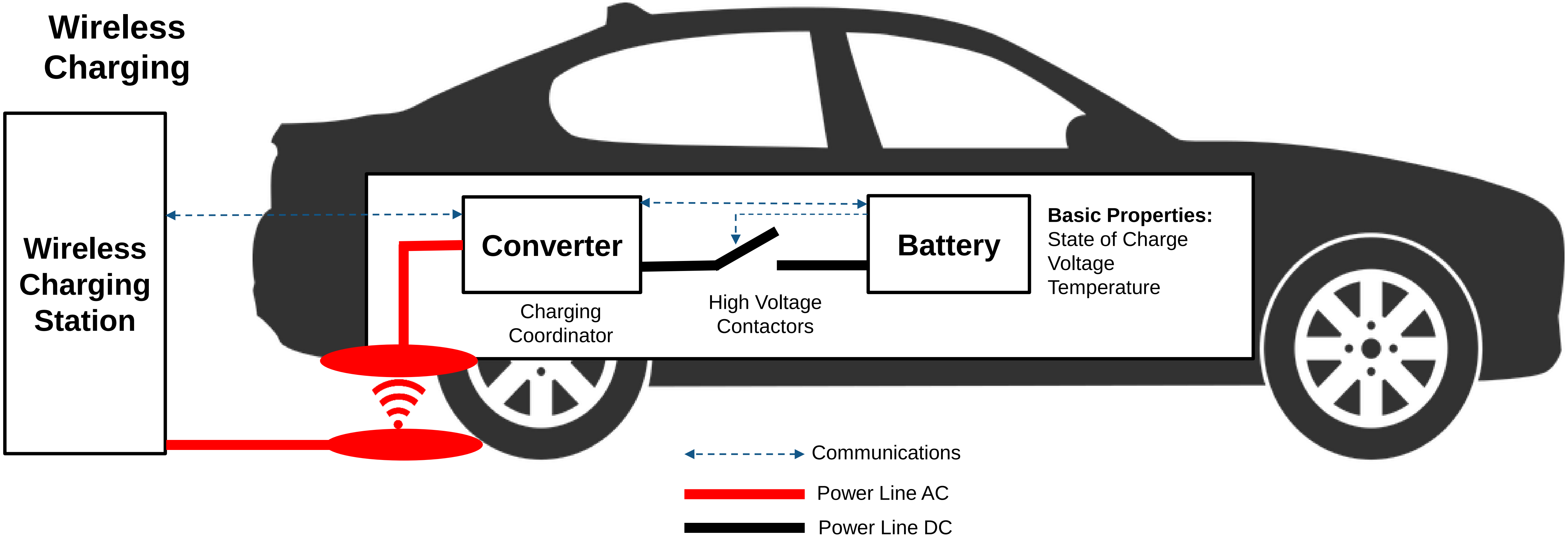
DC Charging

- EVSE delivers high DC power to the vehicle
- Vehicle directly uses the DC power for battery charging.



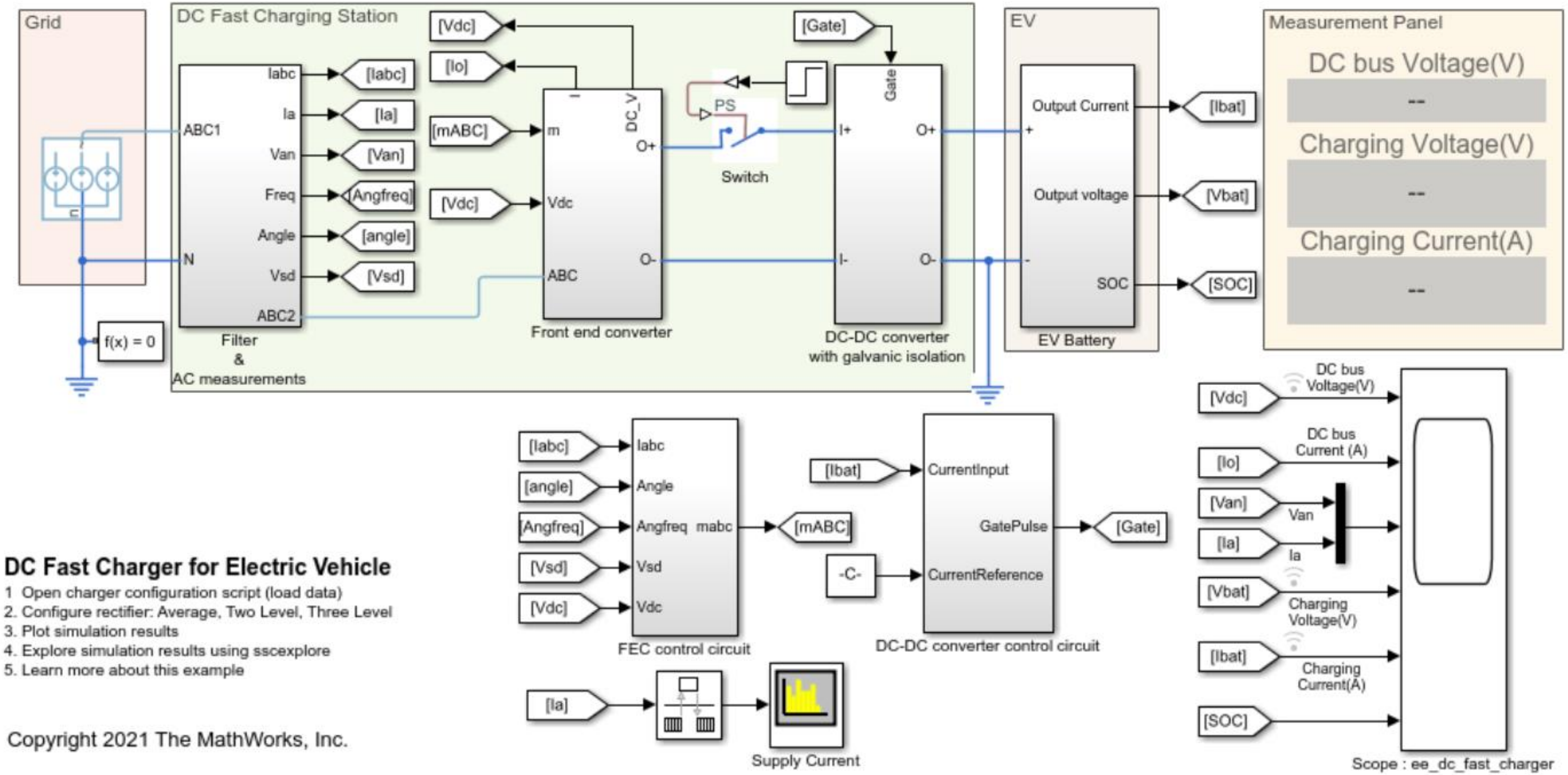
Wireless Charging

- EVSE induces low/medium AC power on the vehicle
- Vehicle converts AC power to DC power for battery charging

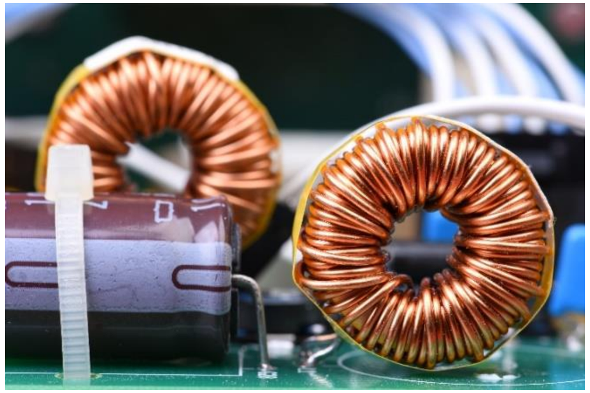


Example: DC Fast Charger

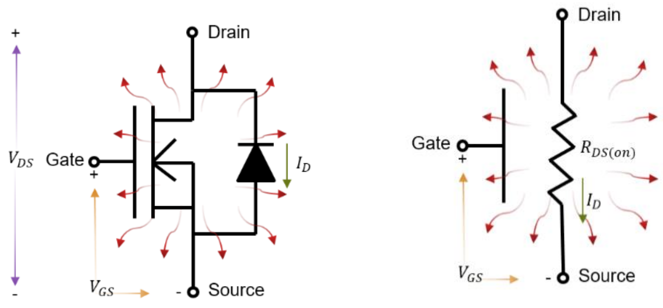
Model Overview



Power Converter Control Design: Workflow Tasks



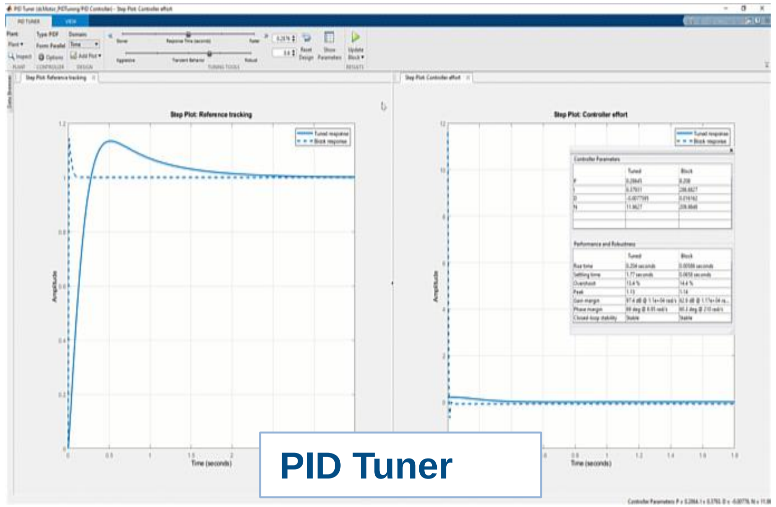
Size Components



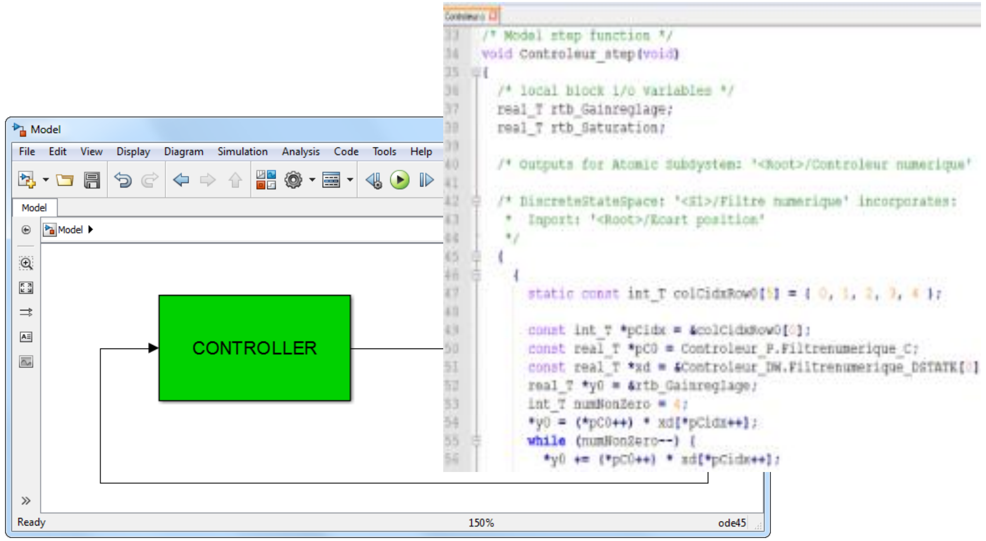
Switching loss

Conduction loss

Loss Analysis

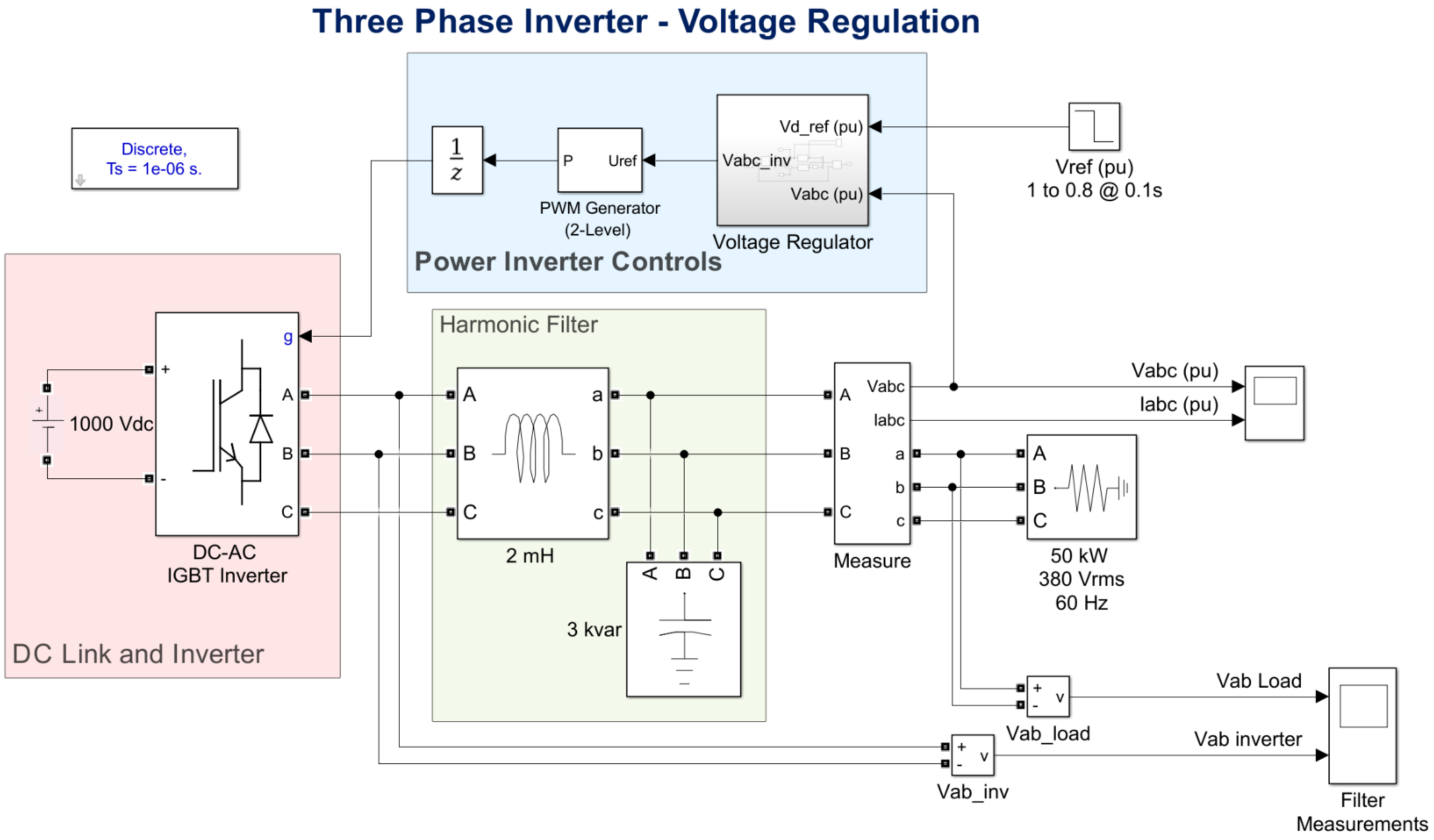


Controller Design



One-Click Embedded Deployment

Modeling and Controlling DC-AC Grid-Tie Inverters



Automatic Code Generation

Microcontroller

- **Use Embedded Coder and C2000 hardware support package**

Combine Simulink Algorithms with C2000 IO Blocks	Auto-generate C code	Build and Implement using CCS	Operation Check with TI C2000

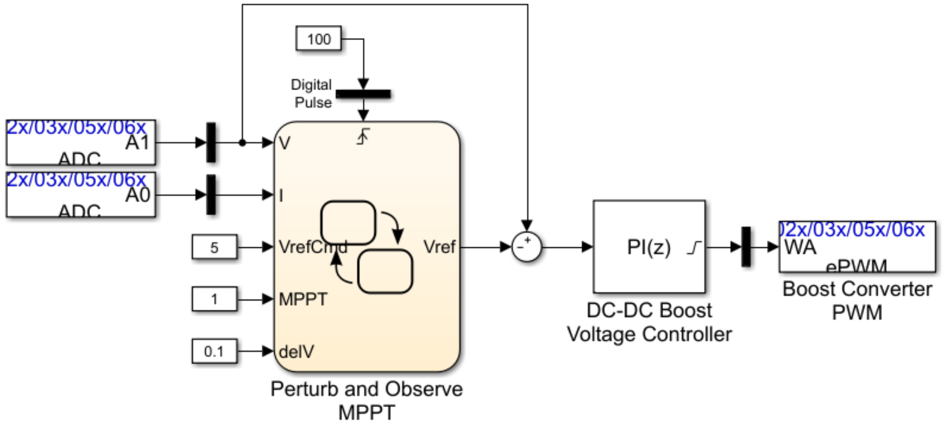


ABB Accelerates the Delivery of Large-Scale, Grid-Connected Inverter Products with Model-Based Design

A cabinet of Power Electronic Building Blocks (PEBBs).

Challenge

Accelerate the design and delivery of large, grid-connected power inverter products

Solution

Use Model-Based Design to model, simulate, and generate control software for modular, scalable power electronic building blocks

Results

- Prototypes delivered in two weeks, not three months
- Defect-free, optimized code generated
- Potential damage to test equipment mitigated

"Simulink and Embedded Coder enabled us to open the door to new markets. With increased productivity from extensive simulation and efficient code generation, we have confidence in our ability to produce the systems that larger customers are asking for in the time frames they want."

- Dr. Robert Turner, ABB

SuperGrid Institute: An efficient and compact power converter to enable the supergrids of the future

Challenge
Design and implement a DC-DC power converter using SiC transistors that would operate at 20kHz

Solution
Model-Based Design with Simulink and HDL Coder to model, verify, and implement the controller on a Speedgoat real-time target

Results
- Less than 12 months to test a compact 1 kV, 100 kW DC-DC power converter with an efficiency of 98%
- Fast design iterations using HDL code generation from model to FPGA

"The transition from design model to real-time software was very fast thanks to the complete compatibility between MATLAB & Simulink and Speedgoat. The Speedgoat target machine provides fast and robust control of the switching semiconductors in a difficult electromagnetic environment."

\- Piotr Dworakowski, Power Converters team leader

Sandia National Laboratories Simulates Hawaii Microgrid and Photovoltaic Systems

Challenge

Evaluate the battery capacity and control systems required for reliable operation of a new solar power generation facility

Solution

Use Simulink and Simscape Electrical to model and simulate microgrid distribution systems with photovoltaic sources

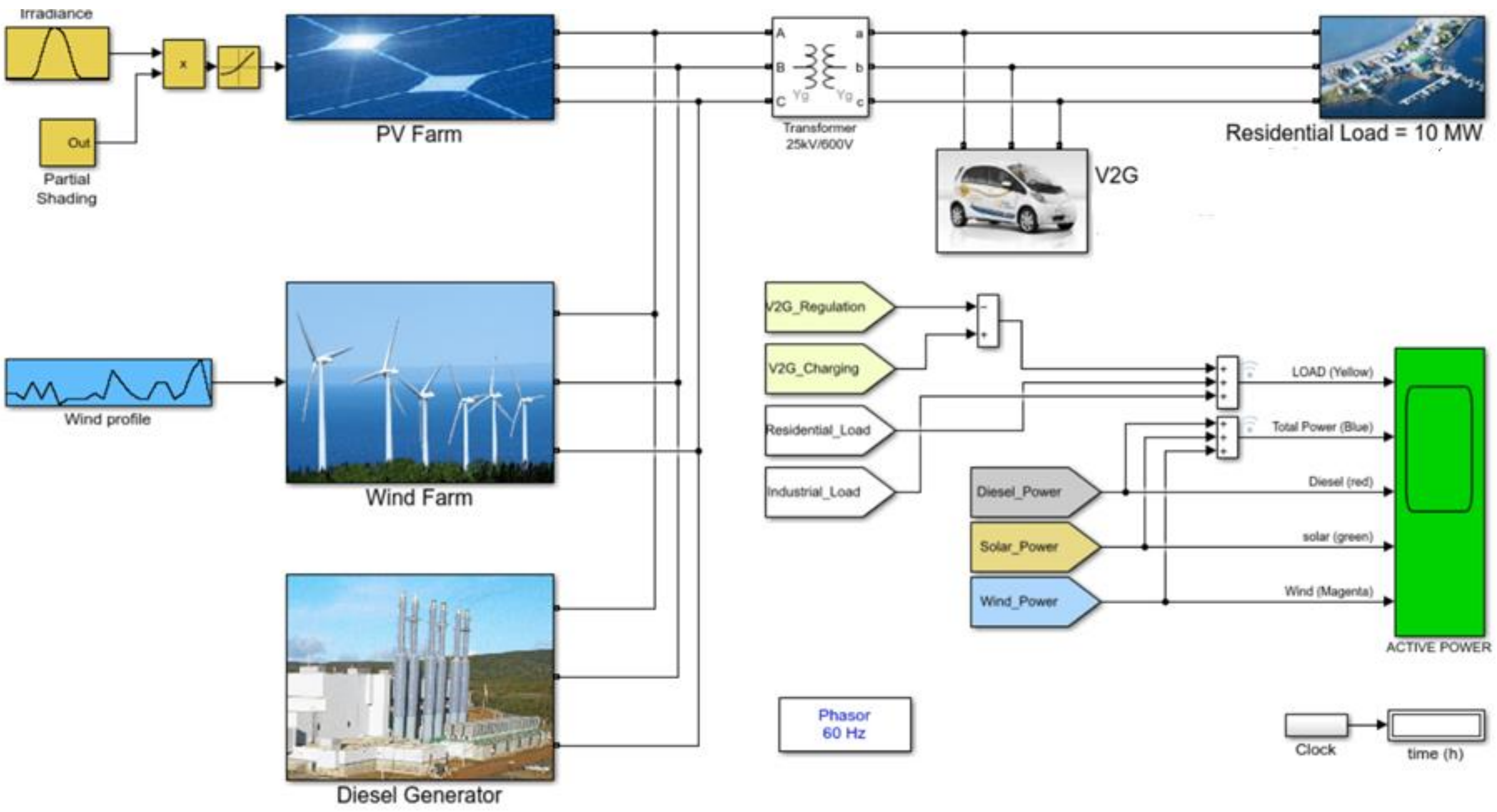
Results

- Model development time cut by 80%
- Costs reduced through battery right-sizing
- Simulation accuracy verified with real data

"MATLAB, Simulink, and Simscape Electrical enable mechanical, power, and controls engineers to work together using the same tools, which helps in a multidisciplinary environment like ours."

- Ben Schenkman, Sandia

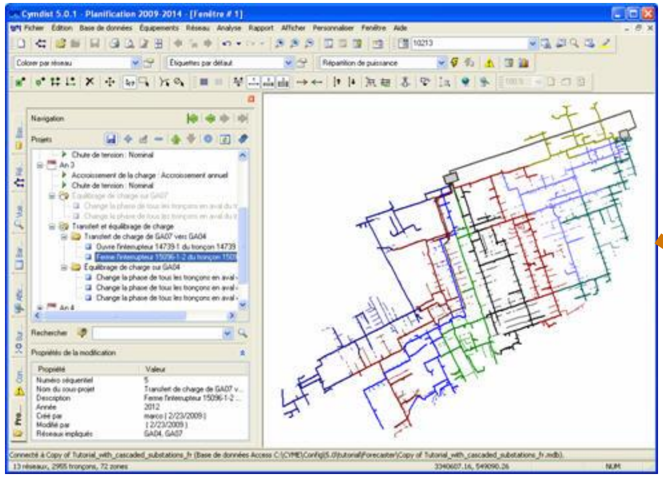
Microgrid System Level Simulation



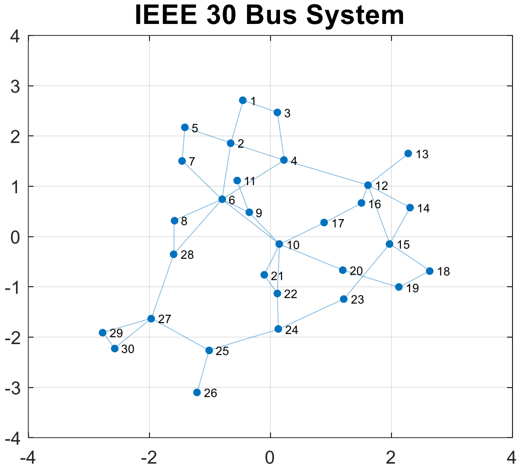
Large Scale Power Grid Simulations

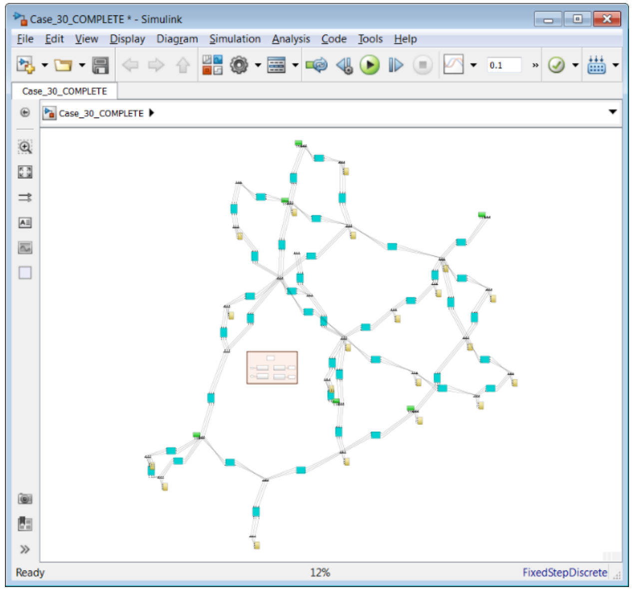
Leveraging MATLAB Scripting

CYME, OpenDSS, etc.



GIS Data





Layers of Control in Microgrids Applications

Control Transients

Hours

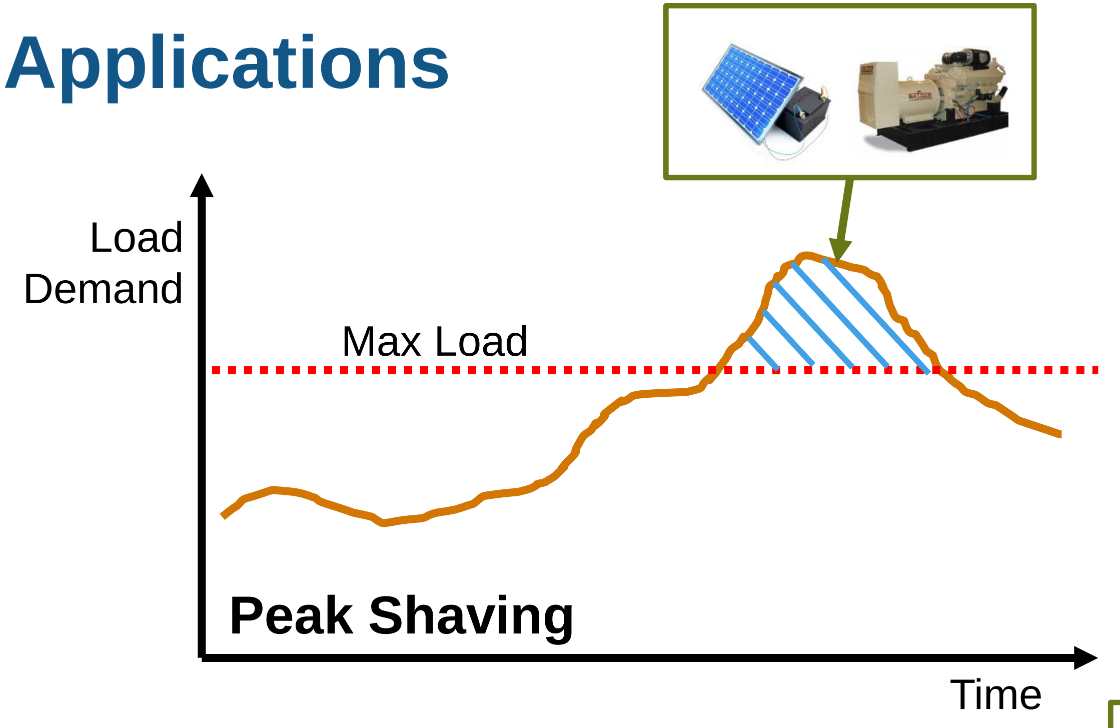
- Peak Shaving/Load Leveling
- Energy Markets
- Integration of Renewables
- Islanding Operation

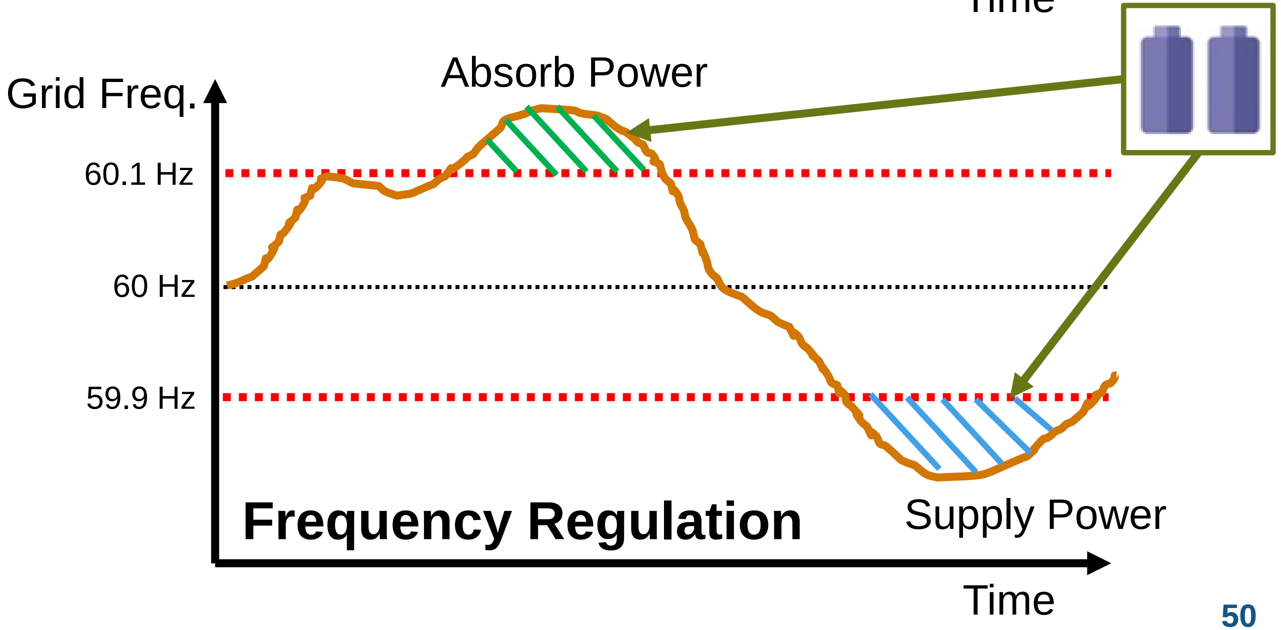
Seconds

- Voltage/Frequency Regulation
- Transient Smoothing
- Reactive Power Control

m/µ-Seconds

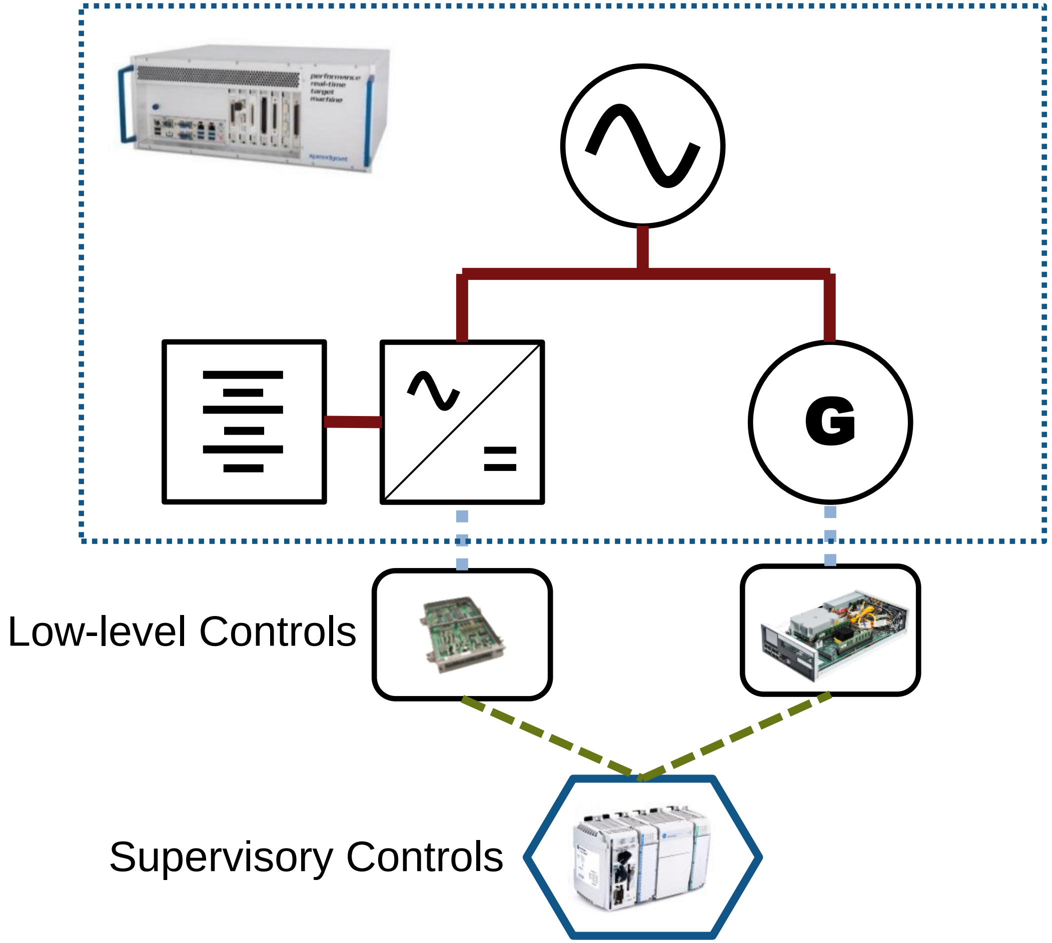
- Switched-Mode Control
- Harmonic Analysis



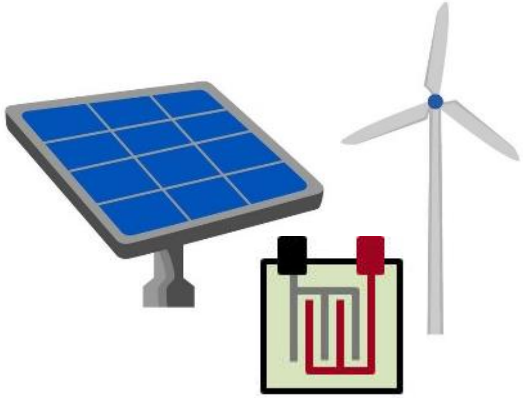


Real-Time Simulation for Microgrids

Hardware-in-the-Loop (HIL)



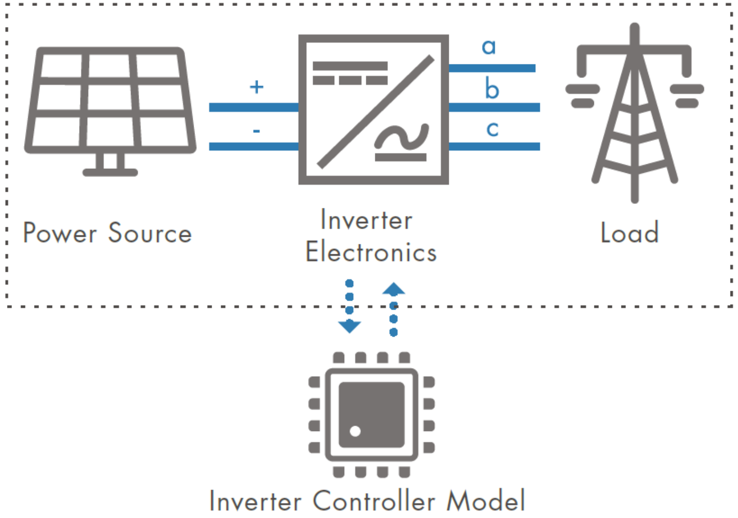
Test before Grid Integration



From Desktop to Real-time

Model Based Design with Simulink

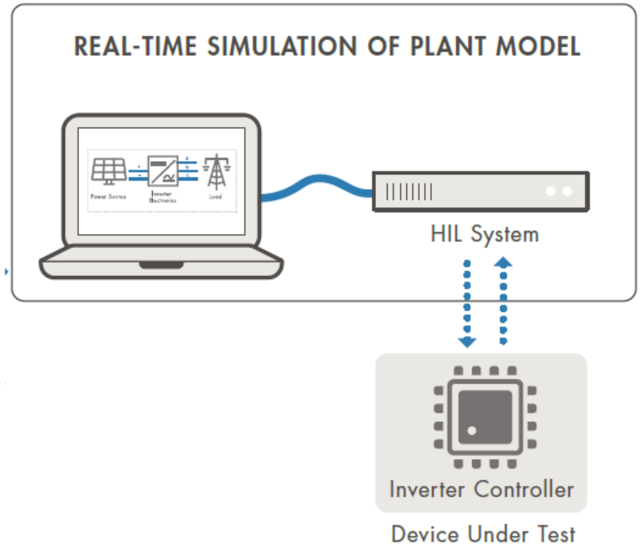
Design and optimize controls using electrical systems simulation



Generate code for the plant

and the controller

Test the control hardware using HIL simulation



Key Takeaways

- **Speeding up journey from an idea to implementation!**
- **Iterating on new ideas faster using Model Based Design**
  - Design with simulation
  - Prototype on real-time hardware
  - Generate code for production
- **Varying model fidelity based on your needs**
- **Assessing technology readiness**
  - Solar, Wind, Energy Storage
  - Power Electronics & Control Architectures
  - Energy Management Systems, Economic Dispatch

Model-Based Design Adoption

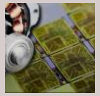
	Modeling and Simulation	*Real-Time Simulation and Testing*	*Production Code Development*
Systematic Testing of Algorithms	System Verification	Automated Real-Time Testing	Certification
Simulating Algorithms with System Models	System Simulation	Hardware-in-the-Loop (HIL) Simulation	Software- and Processor-in-the-Loop (SIL, PIL) Simulation
Developing Algorithms	Algorithm Modeling	Rapid Prototyping	Embedded Code Generation

Model Usage

Code Generation

MATLAB Expo Technology Booths

Electrification - From Prototyping to Production

- Simscape Vehicle Templates
-  Electric Two-Wheeler Development
-  Embedded Software Development for Motor Control
-  Power Conversion Application Deployment on STM32 Processors
- Deploying Motor Control Algorithms to a TI C2000 Dual-Core Microcontroller & Infineon AURIX TC4x

2W EV Webinar Series

Sept. 20, 21, 22

Date	Topic
20 Sep 2022	**System Modelling & Simulation of an Electric Two-Wheeler: A Journey from Virtual Prototyping to Production** Speakers: Abhisek Roy, *MathWorks*, Prasanna Deshpande, *MathWorks*
21 Sep 2022	**Addressing Challenges Involved in EV Battery Modelling, its Thermal Analysis and BMS Design** Speakers: Abhisek Roy, *MathWorks*, Shripad Chandrachood, *MathWorks*
22 Sep 2022	**Designing Motor Control Algorithms for Optimum Performance and Efficient Operation of an Electric Two-Wheeler** Speakers: Rahul Choudhary, *MathWorks*, Ananth Kumar Selvaraj, *MathWorks*

Self-Paced Online Training

MATLAB Onramp	Simulink Onramp	Stateflow Onramp	Control Design Onramp	Circuit Simulation Onramp
Machine Learning Onramp	Deep Learning Onramp	MATLAB for Data Processing and Visualization	Machine Learning with MATLAB	Deep Learning with MATLAB

matlabacademy.mathworks.com

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Thank you

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