Modeling and Simulation of Photovoltaic Solar Power Vehicle Systems using MATLAB and Simulink

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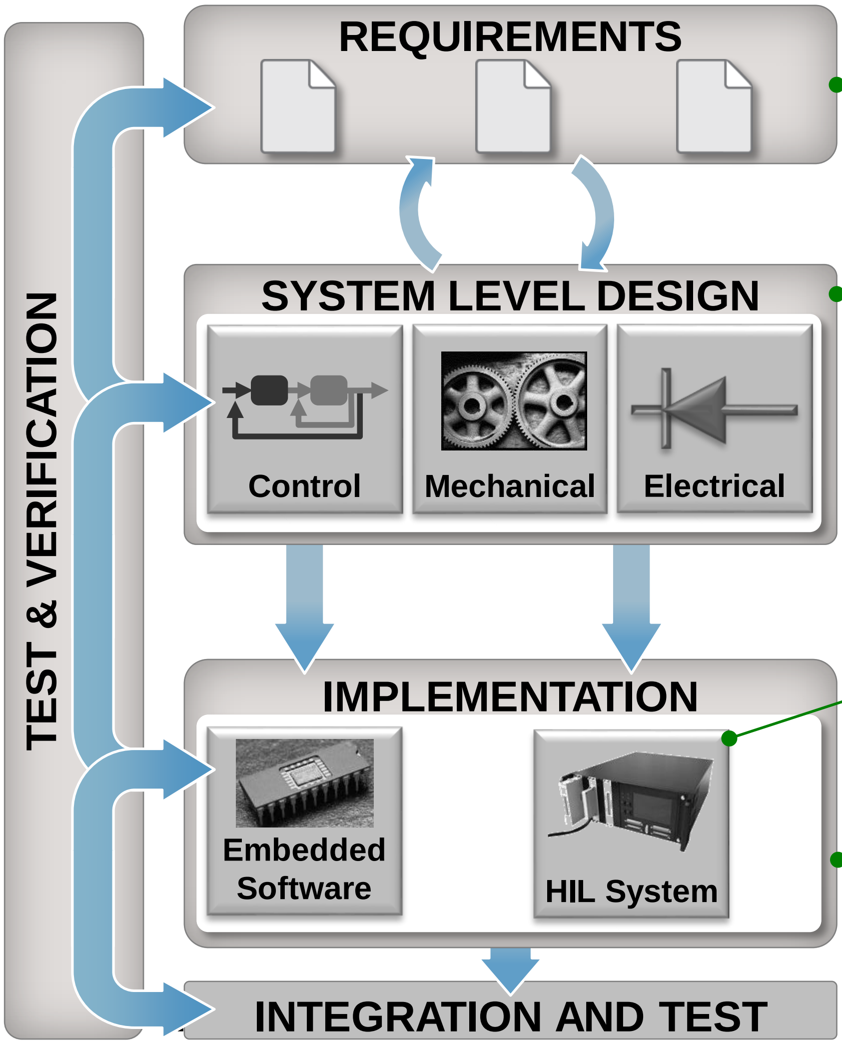
Model-Based Design Process



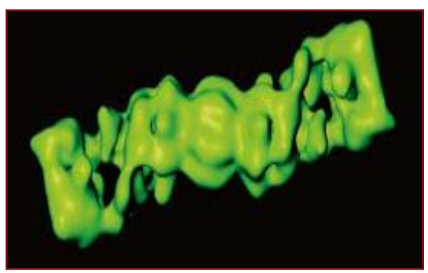
- Produce better designs by continuously comparing design and specification
- Optimize system performance by developing in a single simulation environment
- Lower costs by using HIL tests
- Save time by automatically generating embedded code

Customer Successes
with Model-Based Design

Lockheed Martin
F-35 flight control

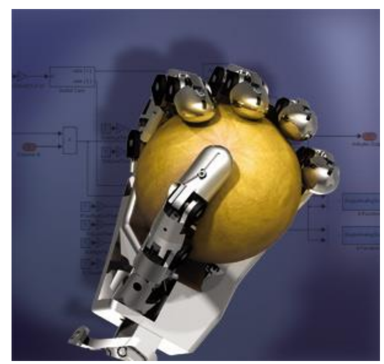
Horizon Wind
forecasting & risk analysis

General Motors
Two-Mode Hybrid powertrain

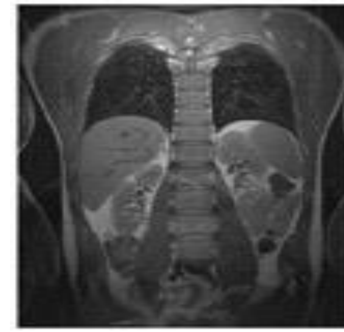


Max Planck Institute
protein structure analysis

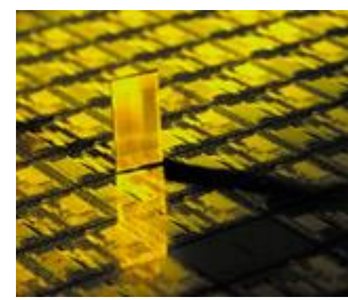
EIM Group
hedge fund management



Johns Hopkins University APL
prosthetic arm development

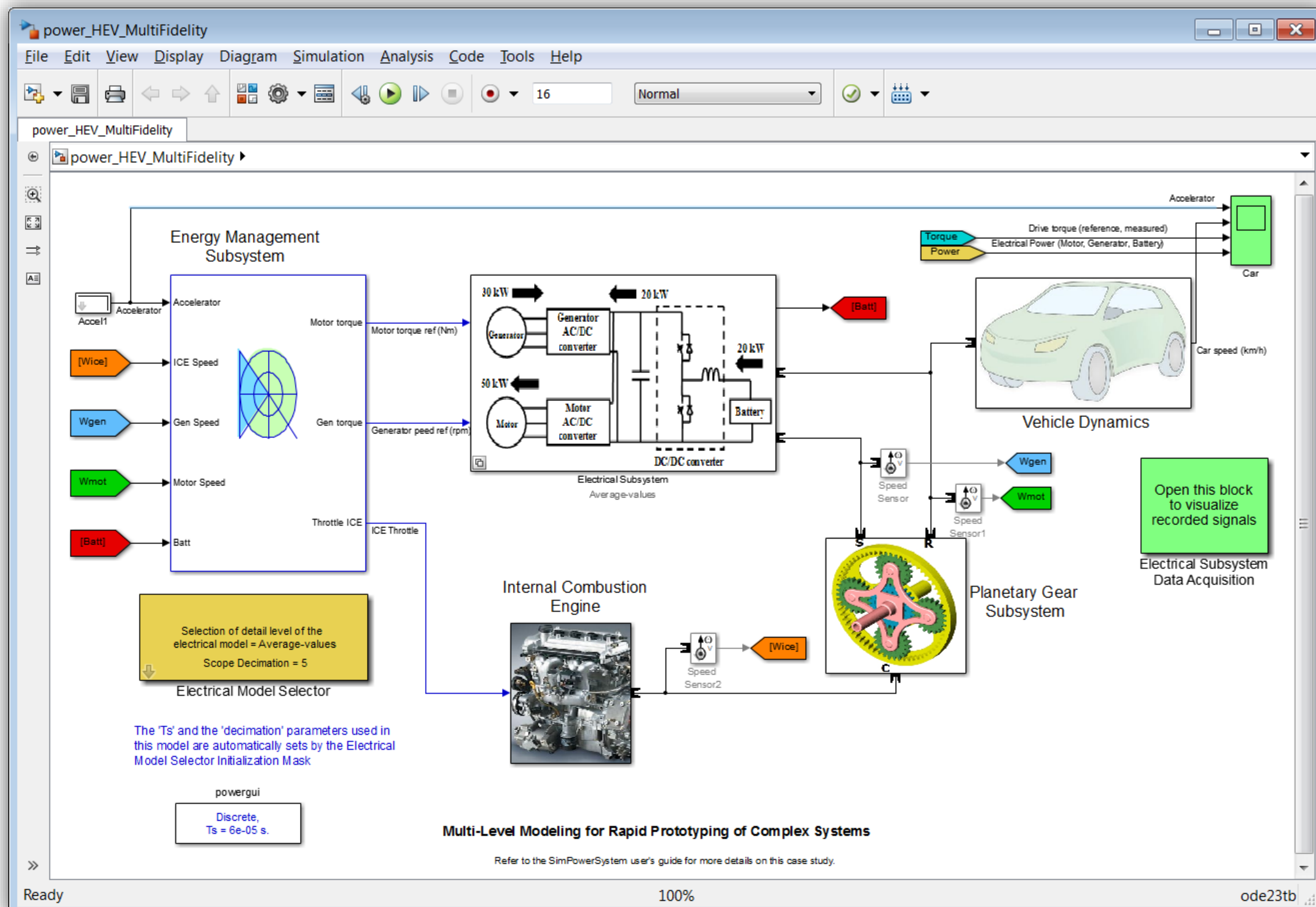


Beth Israel Deaconess Medical Center
improved MRI accuracy

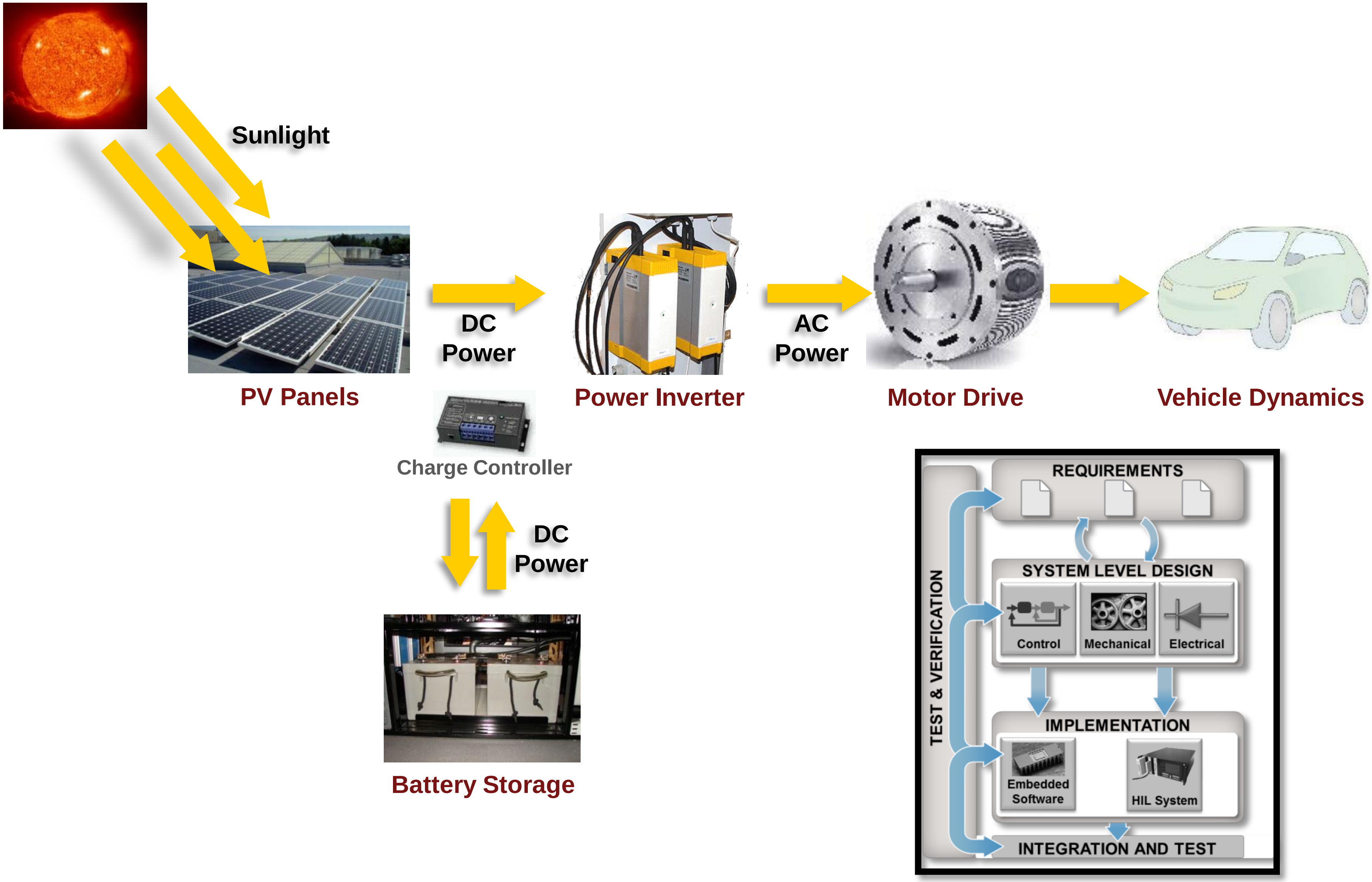


Texas Instruments
advanced DSP design

HEV: System-Level Design & Optimization



Photovoltaic Solar Power Vehicle Systems

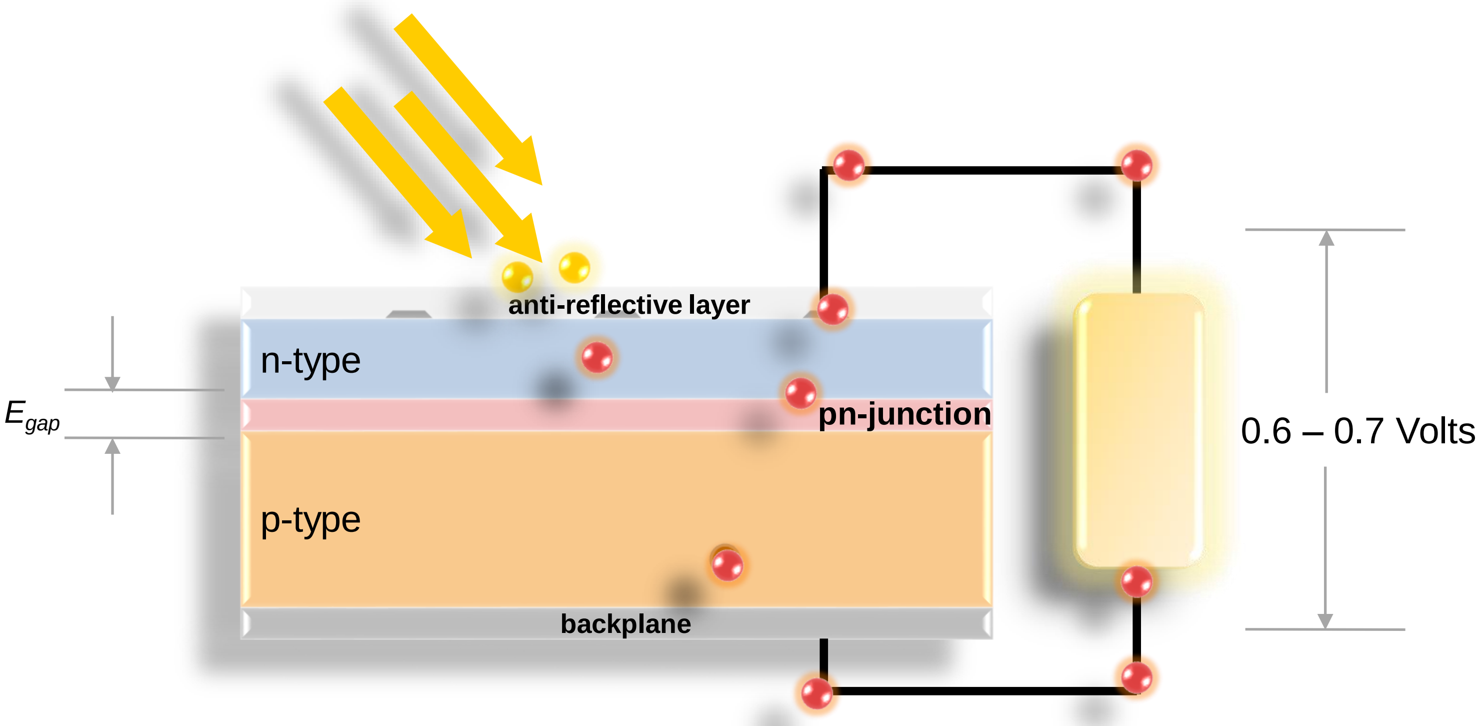


Agenda

- Model-Based Design: System-Level Context
- Modeling electrical and electronic components
  - PV cells, panels, arrays and batteries
  - Power converters and inverters
- Designing control algorithms for power electronics
  - Voltage and current regulation
  - Maximum power point tracking (MPPT)
- Modeling vehicle dynamics and mechanical components
  - Transmission, clutches and tires
- Support for Student Competitions
  - Software
  - Learning Resources

How does a PV cell work?

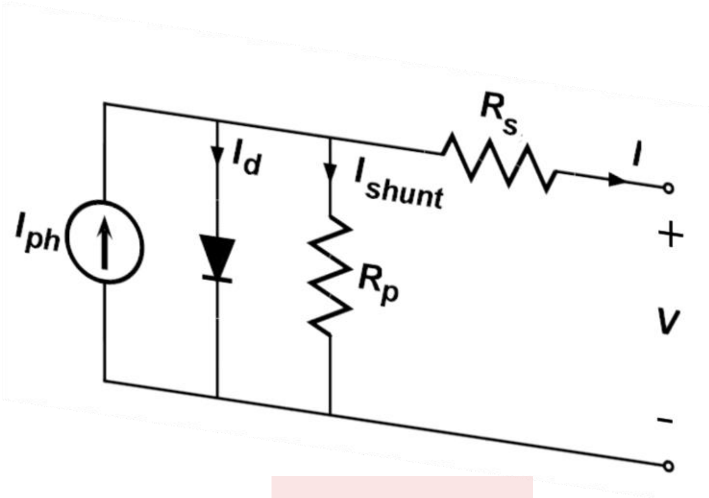
Anatomy of a PV cell



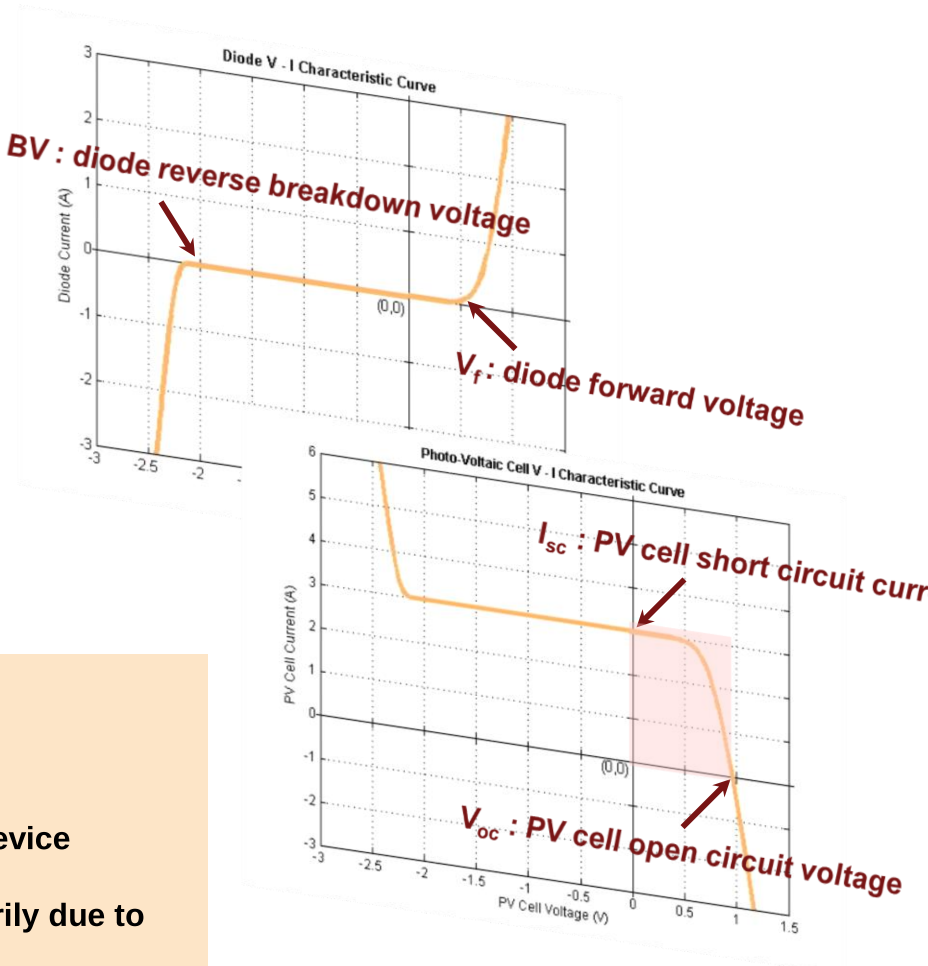
- Photogeneration: Short circuit current I_{sc} is proportional to the number of absorbed photons that cross the *pn-junction* (when photon energy $h_n > E_{gap}$).
- Charge separation: Open circuit voltage V_{oc} depends on the *pn-junction* diode-like characteristics, $V_{oc} < E_{gap}/q$ (where q is the elementary charge on an electron).

How does a PV cell work?

PV Cell Equivalent Circuit



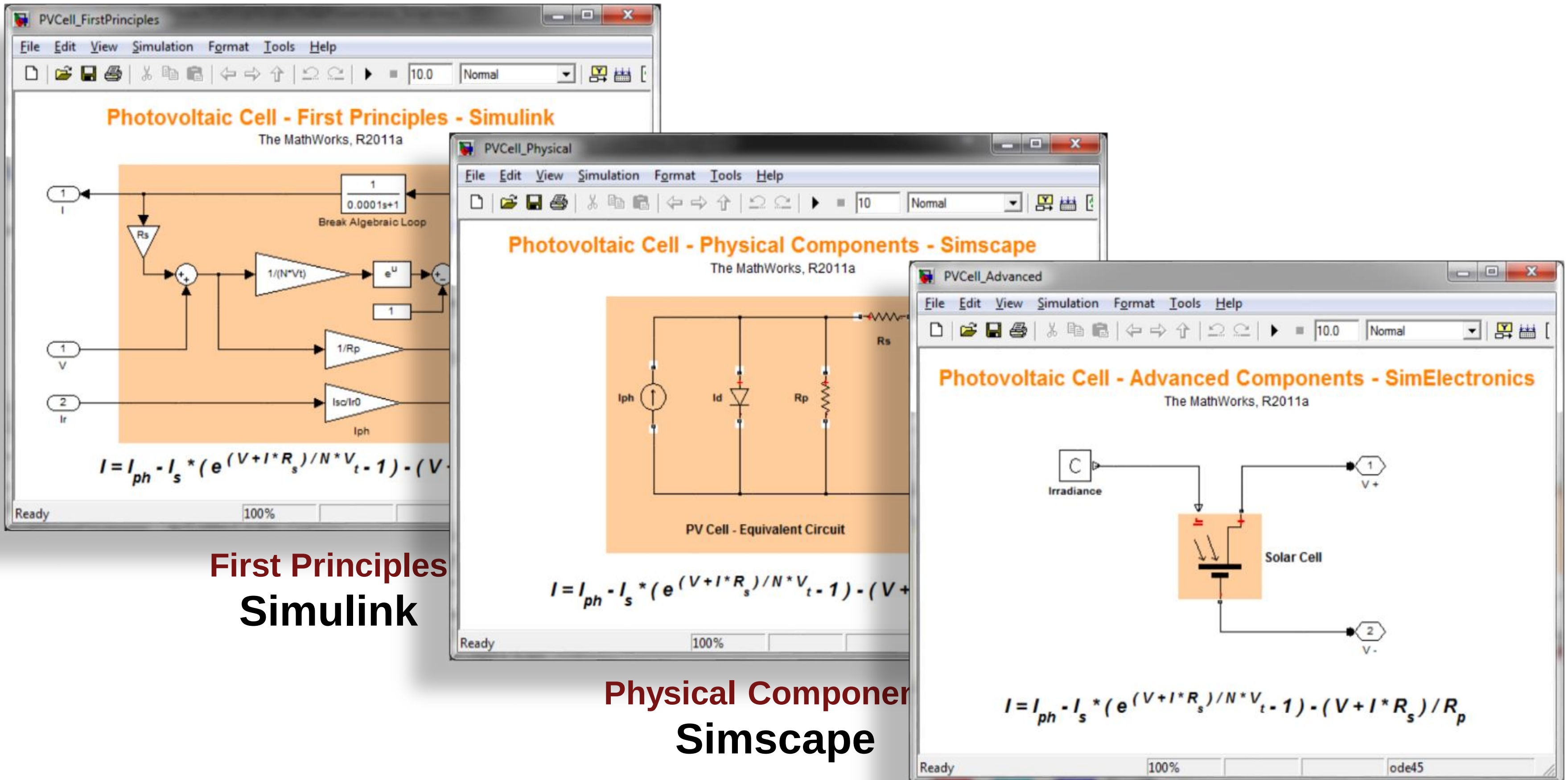
$$I = I_{ph} - I_s\left(e^{\frac{V+IR_s}{NV_t}} - 1\right) - \frac{V + IR_s}{R_p}$$



Where:

- I_{ph} **Solar induced current (proportional to irradiance)**
- I_s **Diode saturation current (exponential behavior)**
- N **Diode quality factor (emission coefficient)**
- V_t **Thermal voltage** kT/q **(**k**: Boltzmann constant,** T**: device temperature)**
- R_p **Shunt resistance (models leakage currents, primarily due to defects)**
- R_s **Series resistance (models bulk and contact resistances)**

Model Using Fundamental Approaches



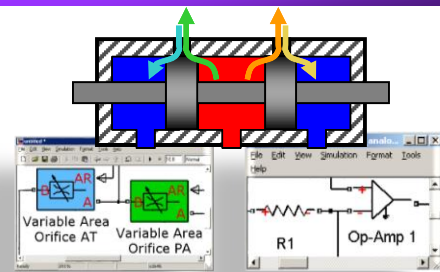
First Principles
Simulink

Physical Components
Simscape

Advanced Components Library
SimElectronics

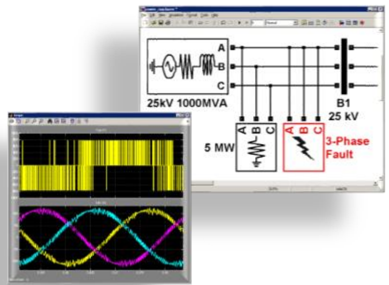
Physical Modeling in Simulink®

Simscape™



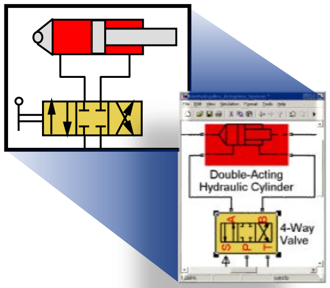
Multi-domain physical systems

SimPowerSystems™



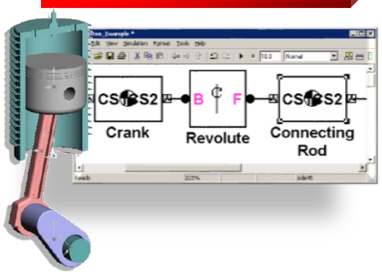
Electrical power systems

SimHydraulics®



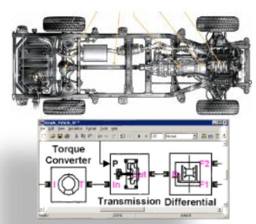
Fluid power and control

SimMechanics™



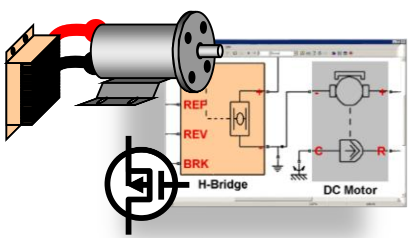
Mechanical dynamics (3-D)

SimDriveline™



Drivetrain systems (1-D)

SimElectronics™



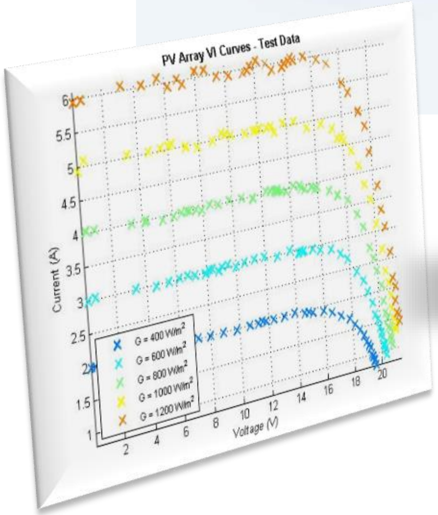
Electromechanical and electronic systems

Model using experimental test data

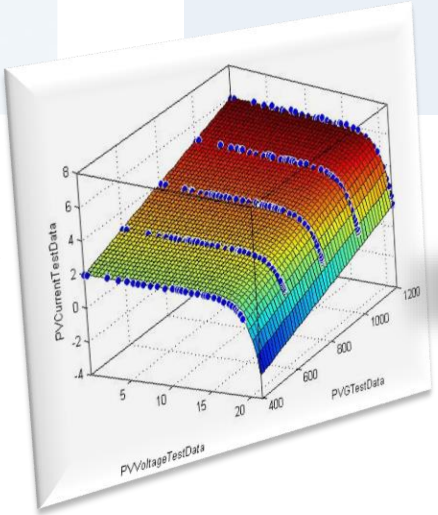
Programmable Solar Array Simulator
i.e. **Agilent E4360A**

or

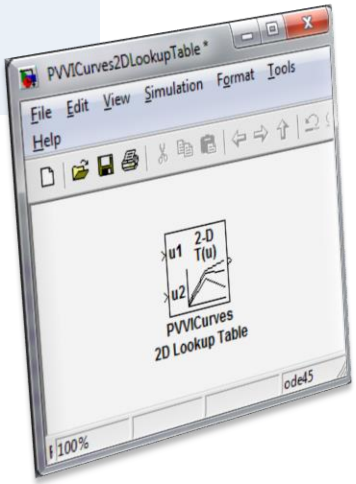
PV panels under test



Import your test data



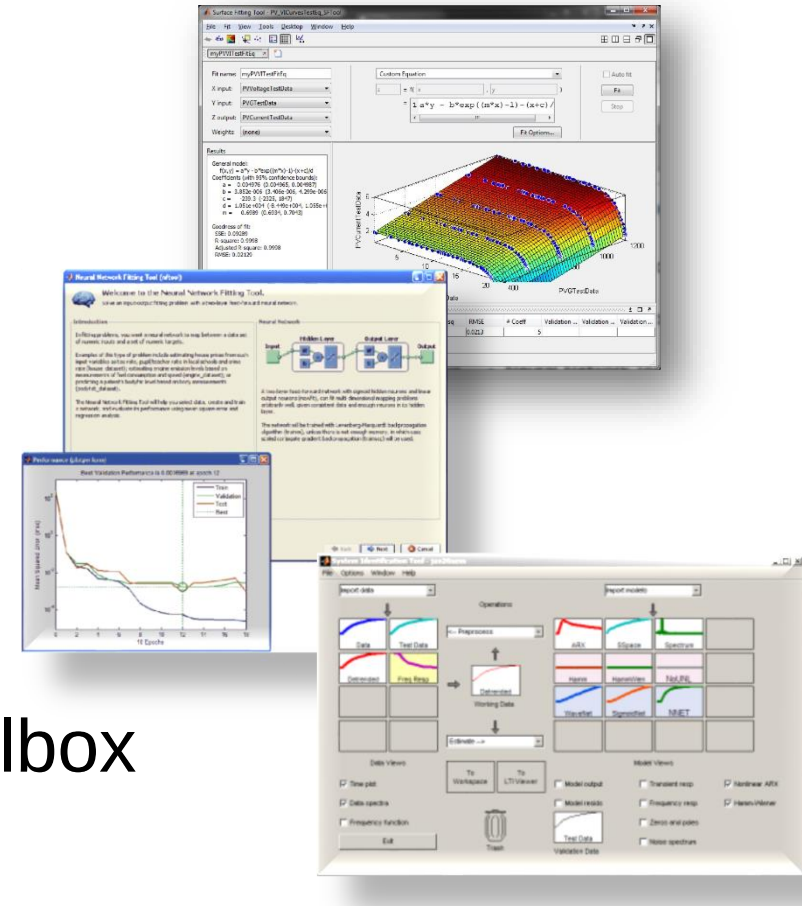
Generate surface fit for experimental V-I curves



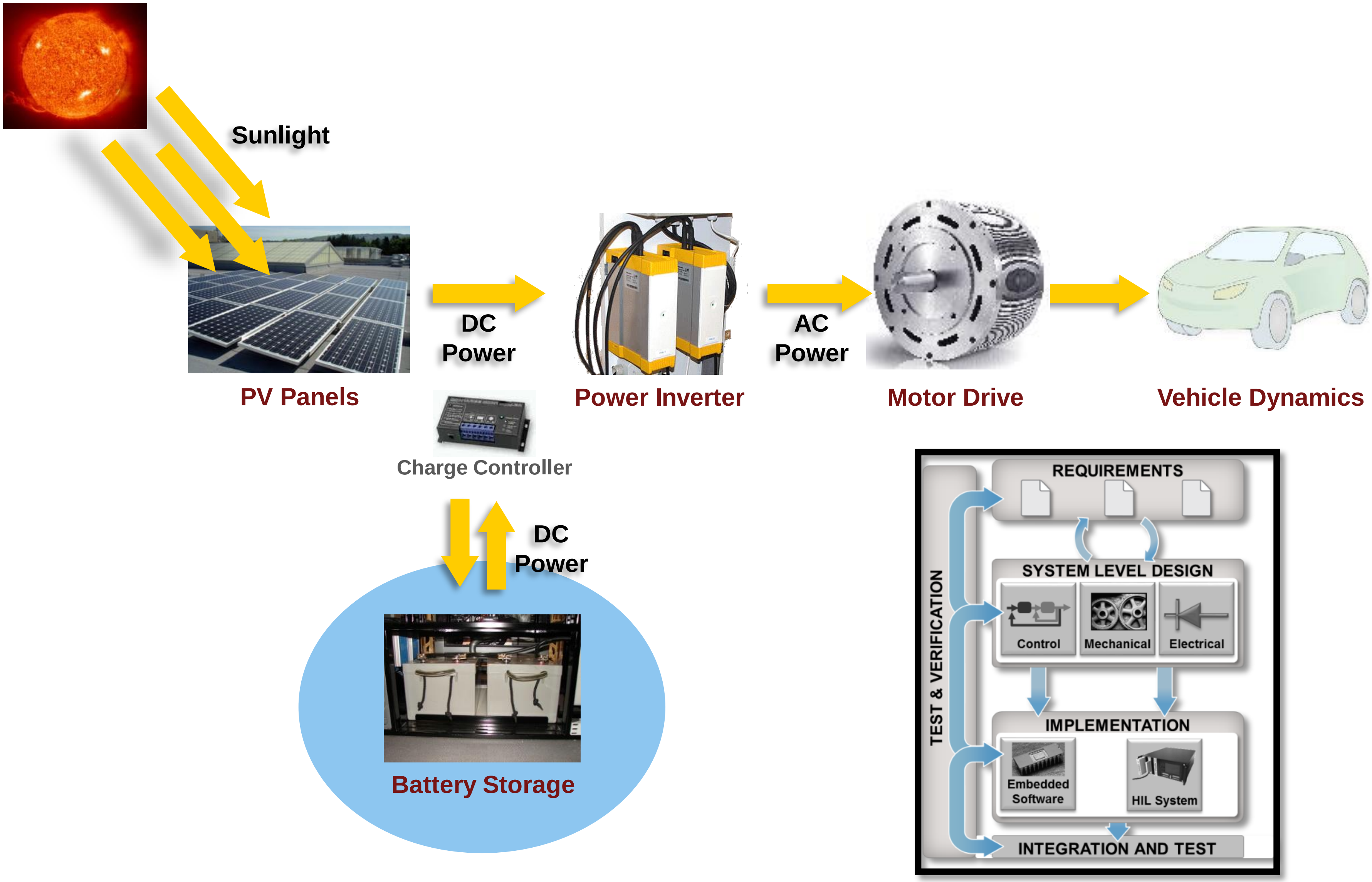
Use 2D Lookup Table model in simulation

Data Driven Modeling in Simulink®

- Curve Fitting Toolbox
- Optimization Toolbox
- Neural Network Toolbox
- System Identification Toolbox

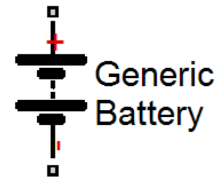


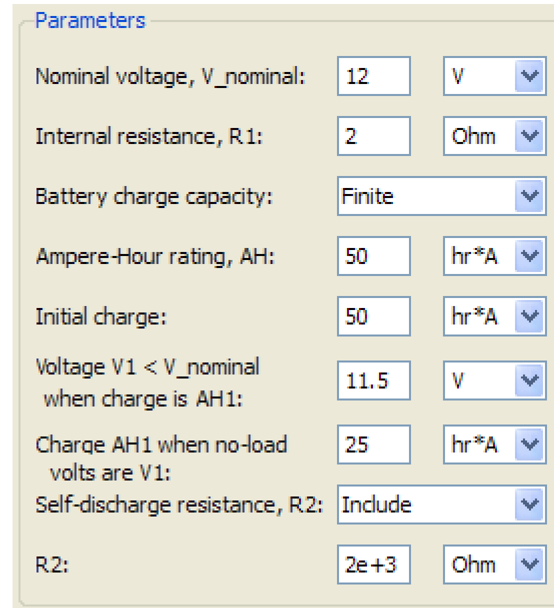
Photovoltaic Solar Power Vehicle Systems



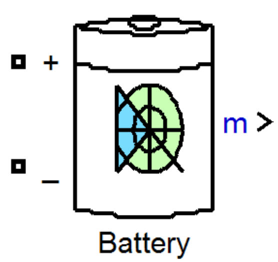
Battery Models: Generic, Pre-Defined

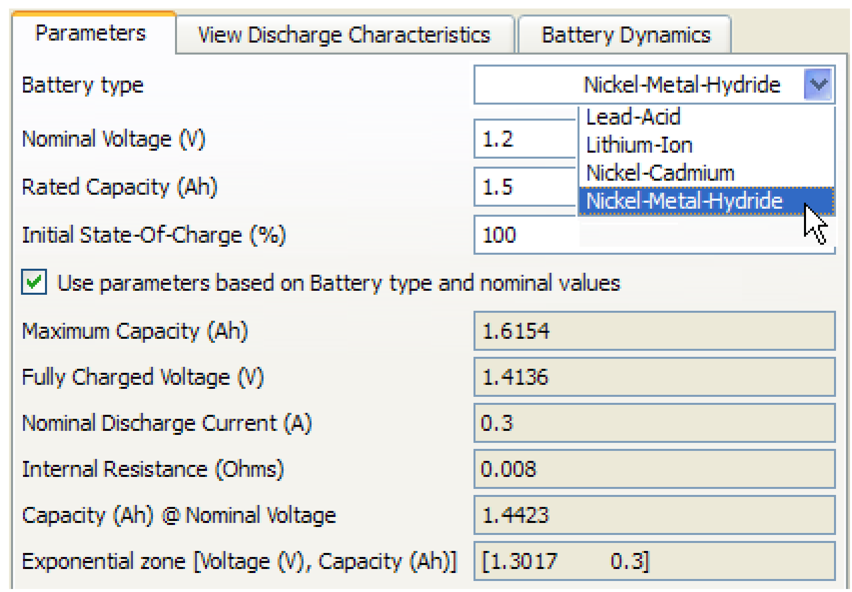
- Generic: SimElectronics
  - Charge-dependent voltage source
  - Parameters found on data sheets





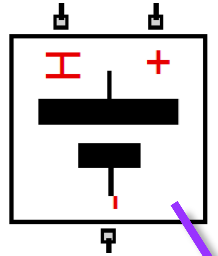
- Pre-Defined: SimPowerSystems
  - Several pre-defined models
  - Full parameterization
  - Documentation provides extensive detail





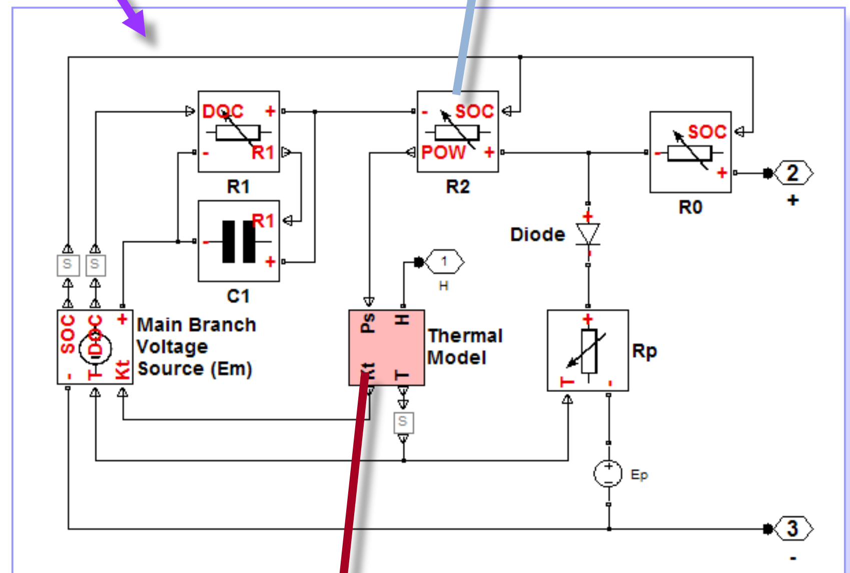
Battery Models: Custom Cell

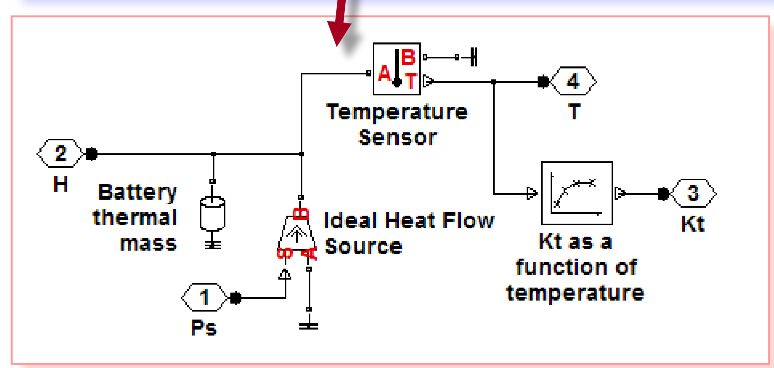
- Use supplied component build new components via Simscape language

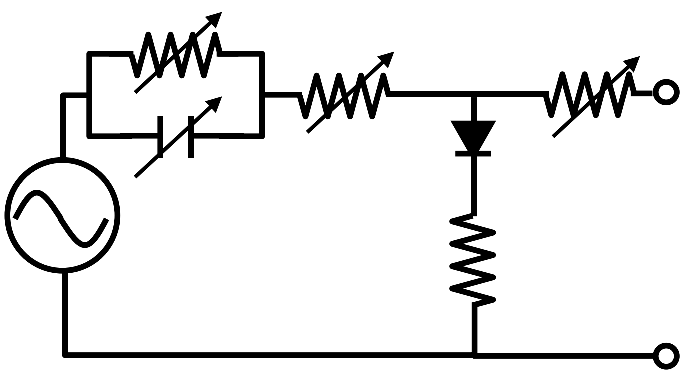


Battery cell

```
equations
   v == i*R20*exp(A21*(1-
   pow == v*i;
end
```





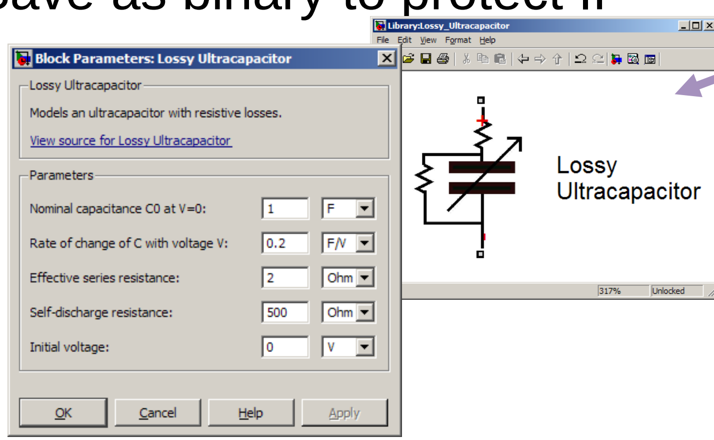


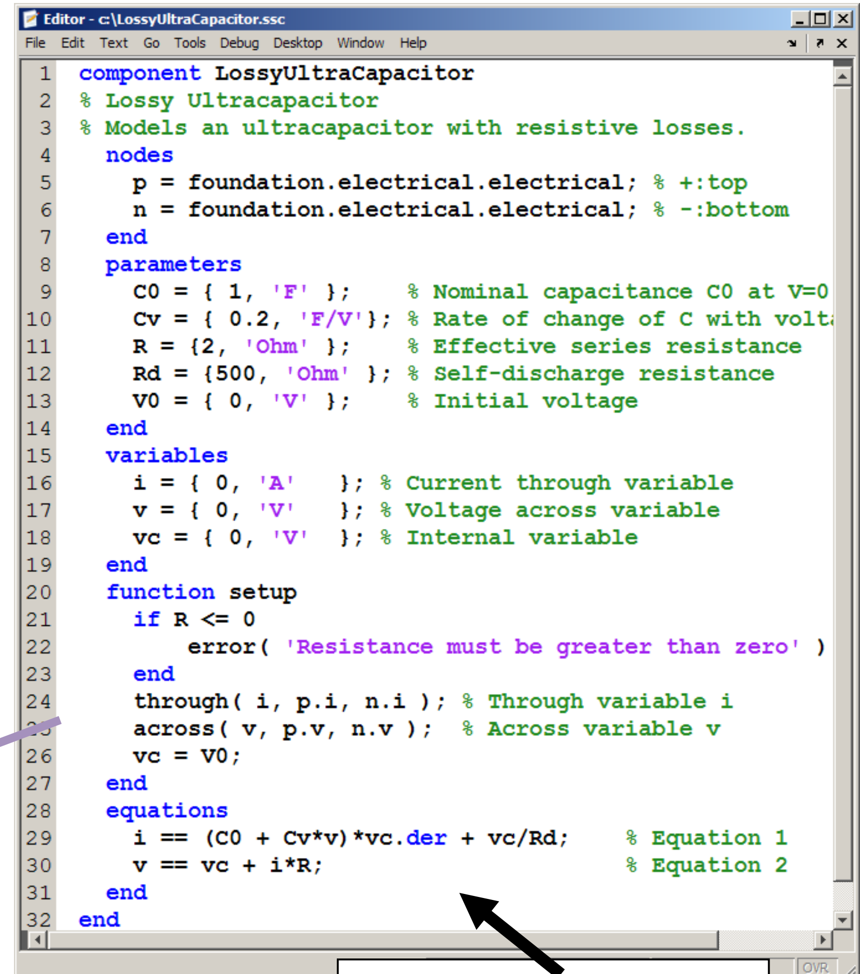
Battery cell equivalent discharge circuit

Resistors, capacitor, and voltage source are dependent upon SOC, DOC, and temperature

Simscape Language For Modeling Custom Components

- MATLAB-based language, enabling text-based authoring of physical modeling components, domains, and libraries
  - Leverages MATLAB
  - Object-oriented for model reuse
  - Generate Simulink blocks
  - Save as binary to protect IP

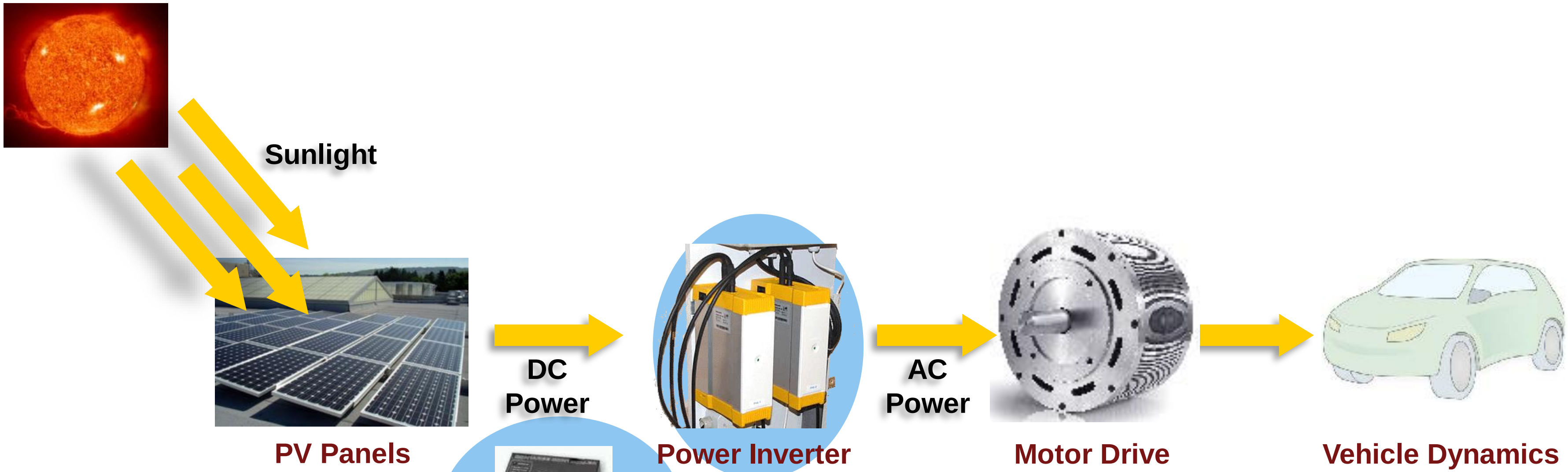


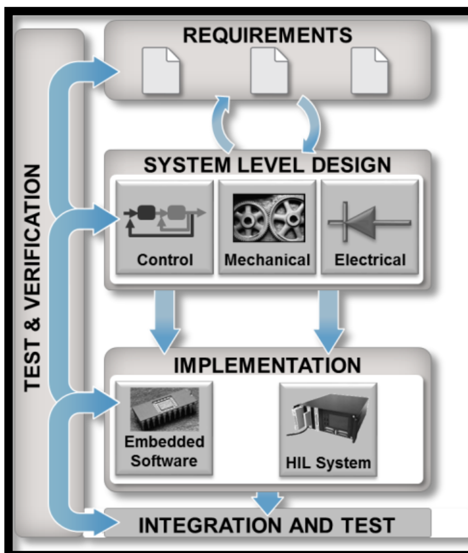



```
component LossyUltraCapacitor
% Lossy Ultracapacitor
% Models an ultracapacitor with resistive losses.
  nodes
    p = foundation.electrical.electrical; % +:top
    n = foundation.electrical.electrical; % -:bottom
  end
  parameters
    C0 = { 1, 'F' };     % Nominal capacitance C0 at V=0
    Cv = { 0.2, 'F/V'}; % Rate of change of C with volt
    R = {2, 'Ohm' };    % Effective series resistance
    Rd = {500, 'Ohm' }; % Self-discharge resistance
    V0 = { 0, 'V' };    % Initial voltage
  end
  variables
    i = { 0, 'A'   }; % Current through variable
    v = { 0, 'V'   }; % Voltage across variable
    vc = { 0, 'V'   }; % Internal variable
  end
  function setup
    if R <= 0
        error( 'Resistance must be greater than zero' )
    end
    through( i, p.i, n.i ); % Through variable i
    across( v, p.v, n.v );  % Across variable v
    vc = V0;
  end
  equations
    i == (C0 + Cv*v)*vc.der + vc/Rd;    % Equation 1
    v == vc + i*R;                      % Equation 2
  end
end
```

$$i = (C_0 + C_v v)\frac{dv}{dt} + \frac{v}{r_d}$$

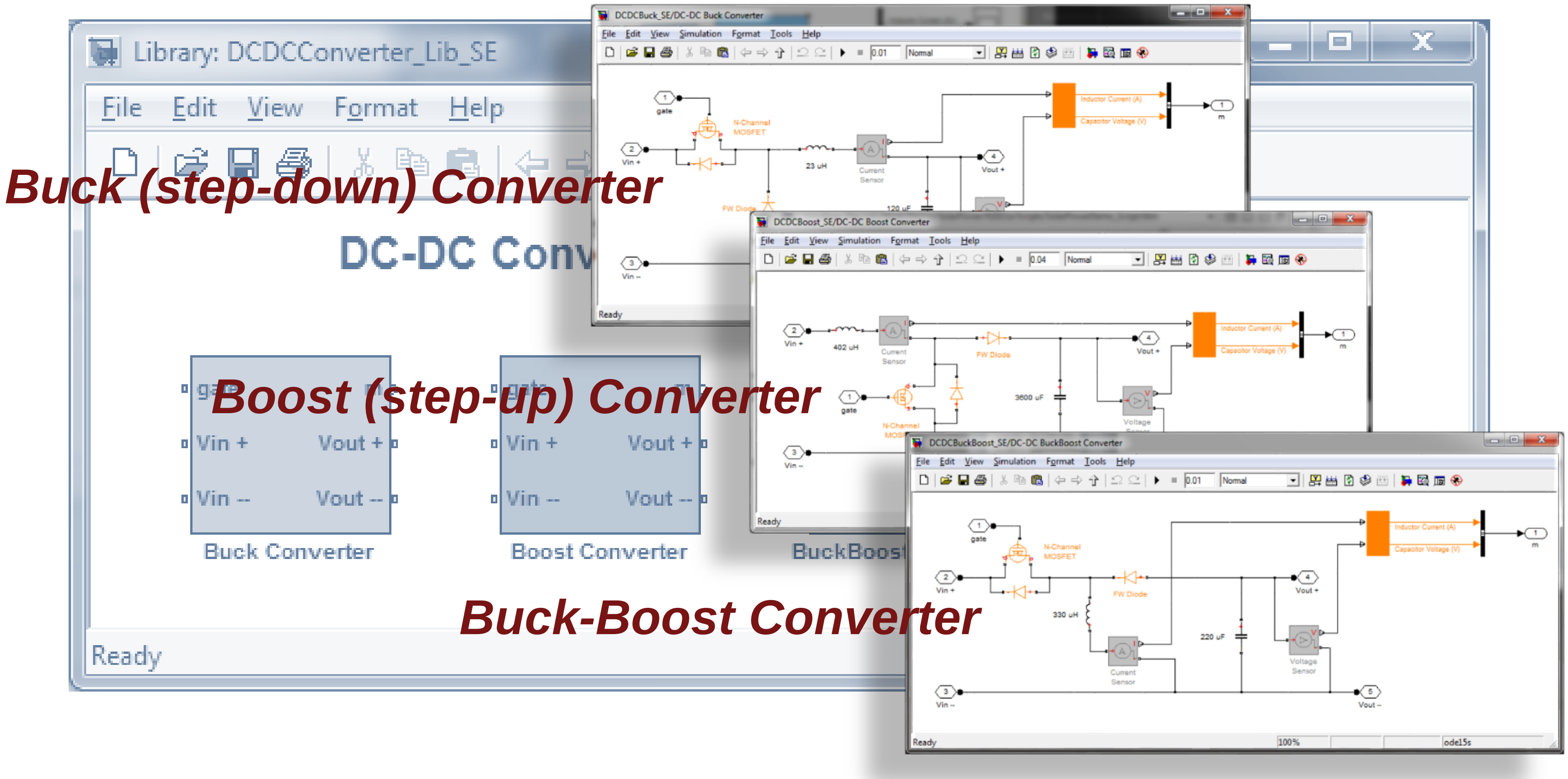
Photovoltaic Solar Power Vehicle Systems





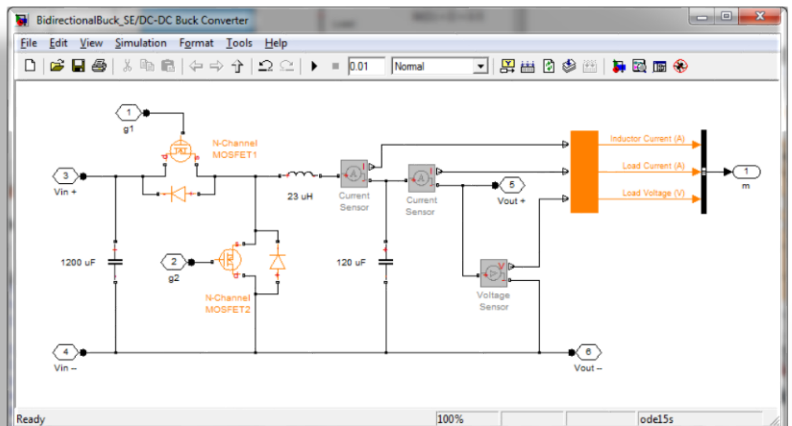
Model DC to DC Power Converters

- Construct, test and re-use multiple power electronic converter topologies quickly and efficiently



Model DC to DC Power Converters

- Balance model fidelity and simulation speed according to your needs

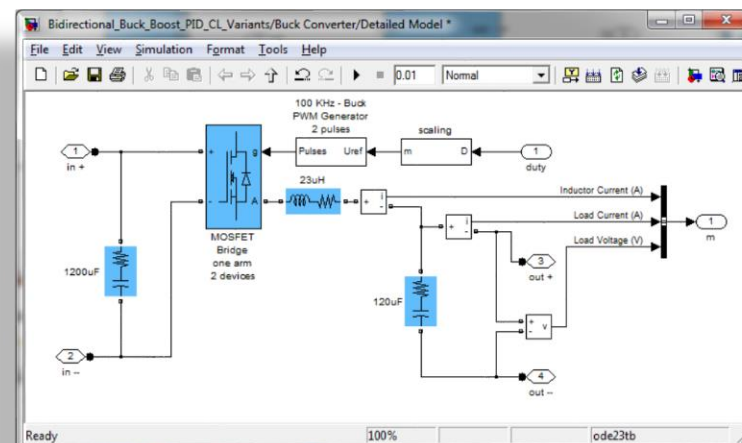


SimElectronics

Nonlinear simultaneous equations solution
Include temperature effects
SPICE level switching device models
Detailed simulation

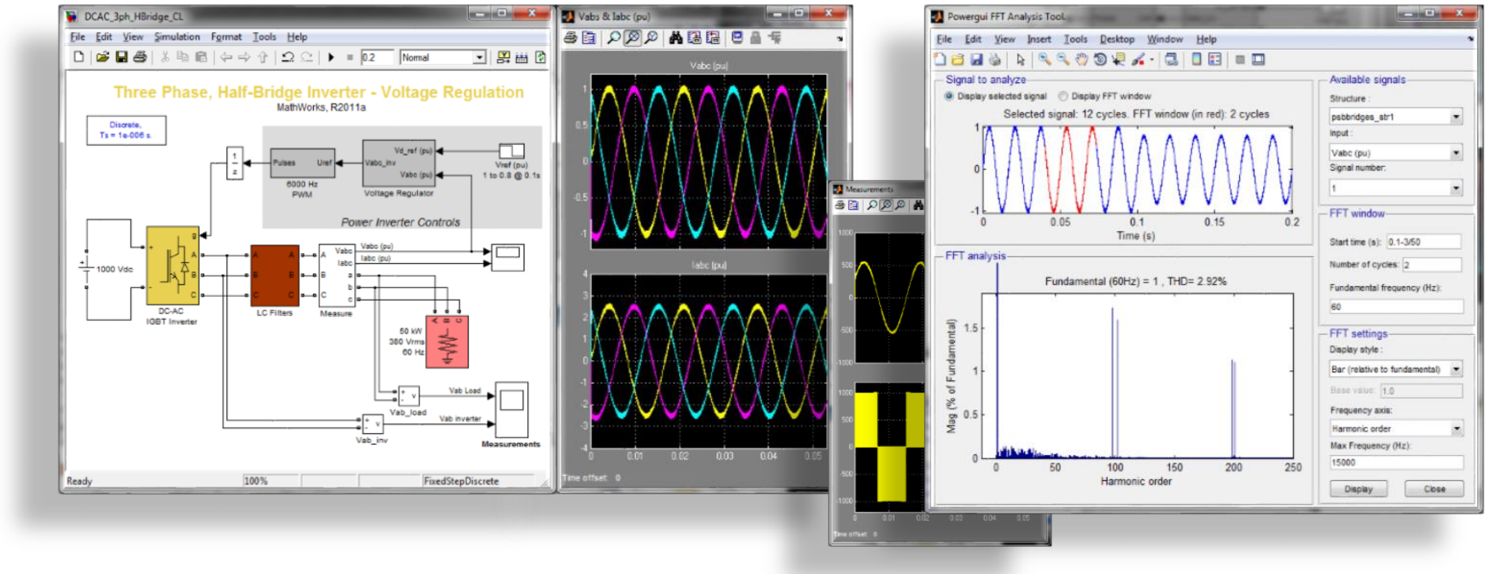
SimPowerSystems

Piecewise linear systems solution
Multiphase bridges and pulse generators
Transient and harmonic analysis
Faster simulation



Model DC to AC Power Inverters

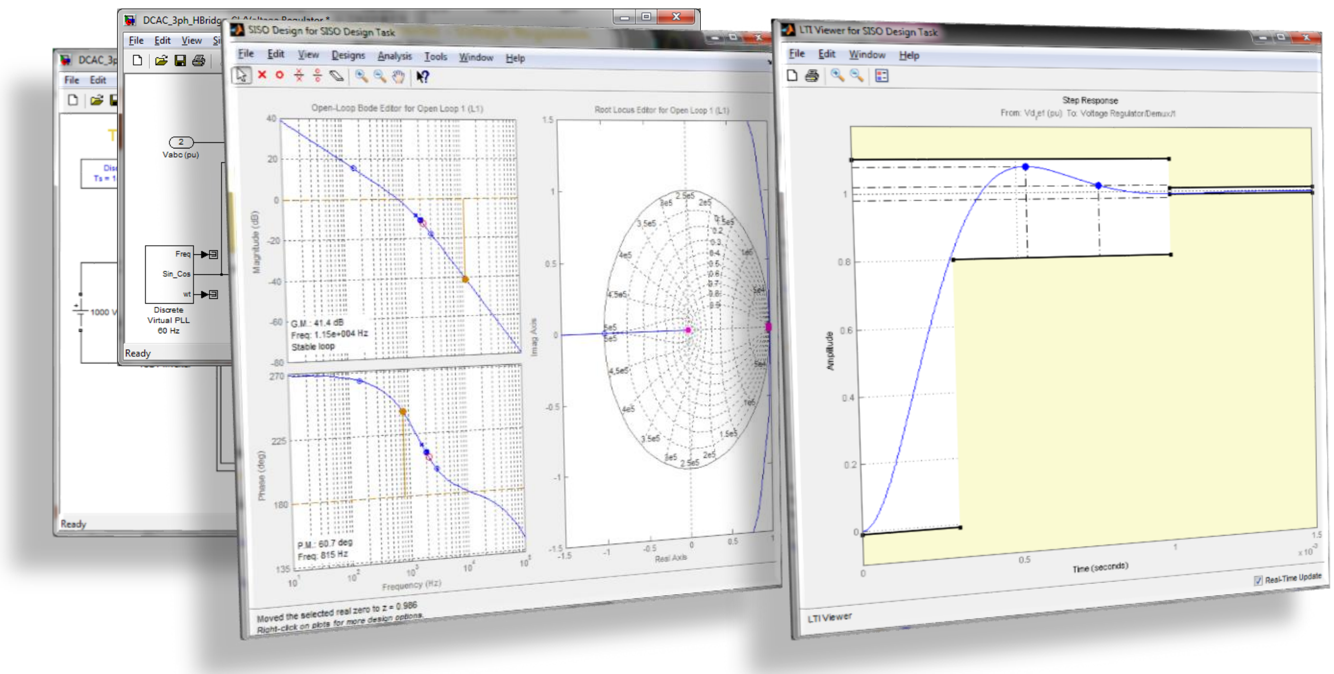
- Build complex, multi-phase, multi-level inverter circuits using the Universal Bridge from the SimPowerSystems library



- Use the built-in tools in SimPowerSystems to perform harmonic analysis directly on your simulation model
- Use average voltage models or ideal switching algorithms for control design and faster simulation

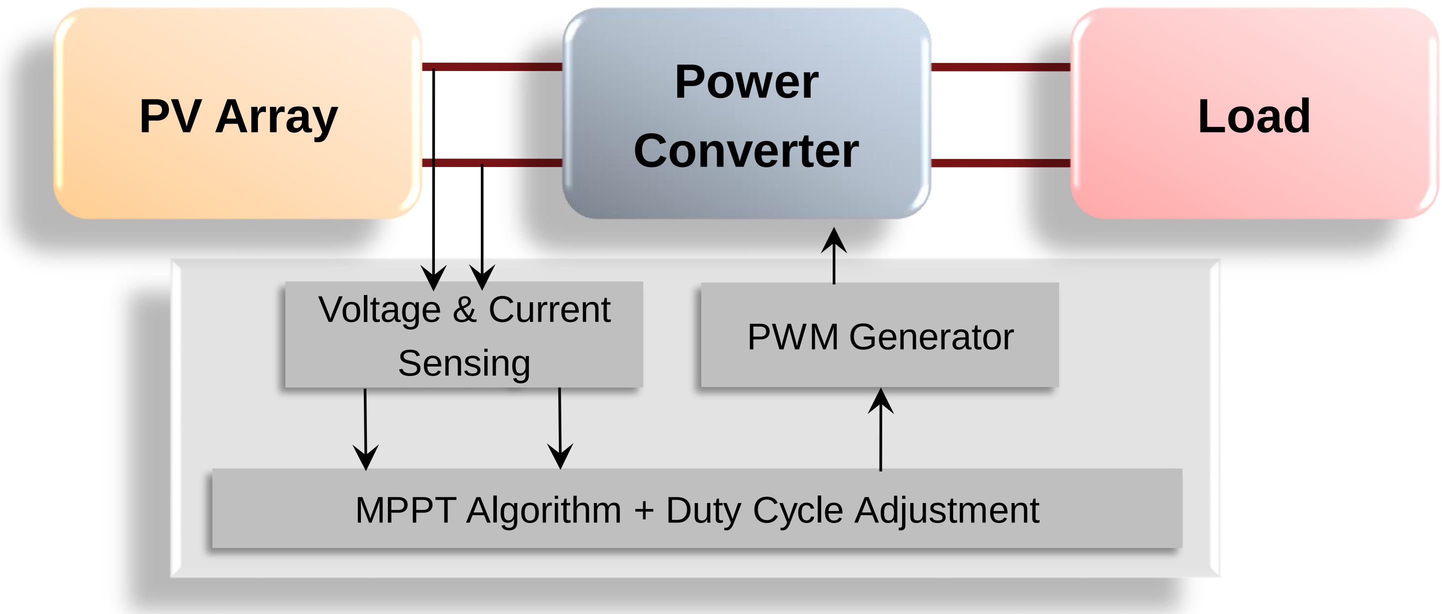
Voltage or Current Regulation

- Use ***Simulink Control Design*** and the ***Control System Toolbox*** to linearize your model and interactively design controllers against requirements in the time and frequency domain



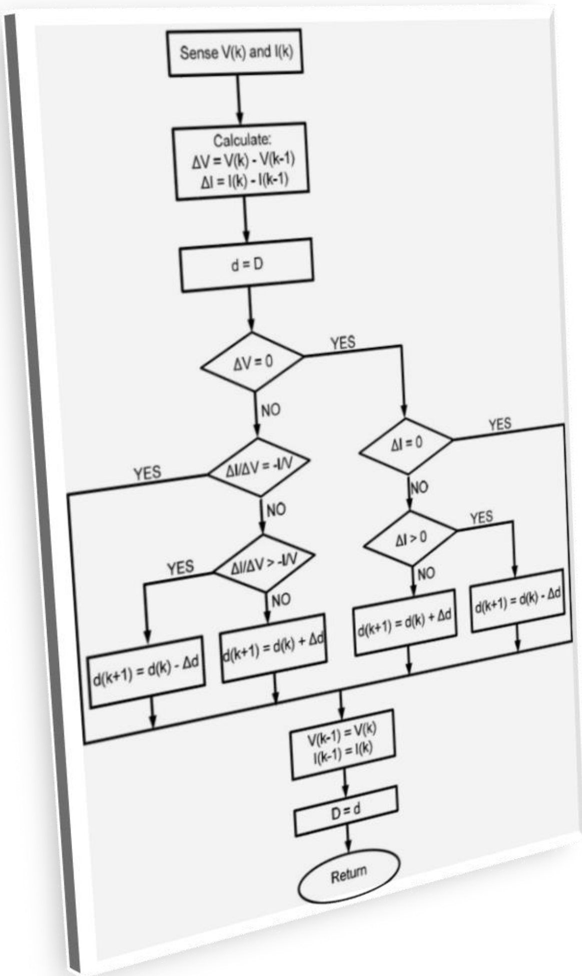
- Once designed, test and verify the performance of your controller against the nonlinear model

Maximum Power Point Tracking



- In general, when a module is directly connected to a load, the operating point is seldom the MPP
- A power converter is needed to adjust the energy flow from the PV array to the load
- Multiple well-known direct control algorithms are used to perform the maximum power point tracking (MPPT)

Maximum Power Point Tracking



Flowchart of the Incremental Conductance MPPT Algorithm

Incremental Conductance Algorithm

- Based on the differentiation of the PV array power versus voltage curve:

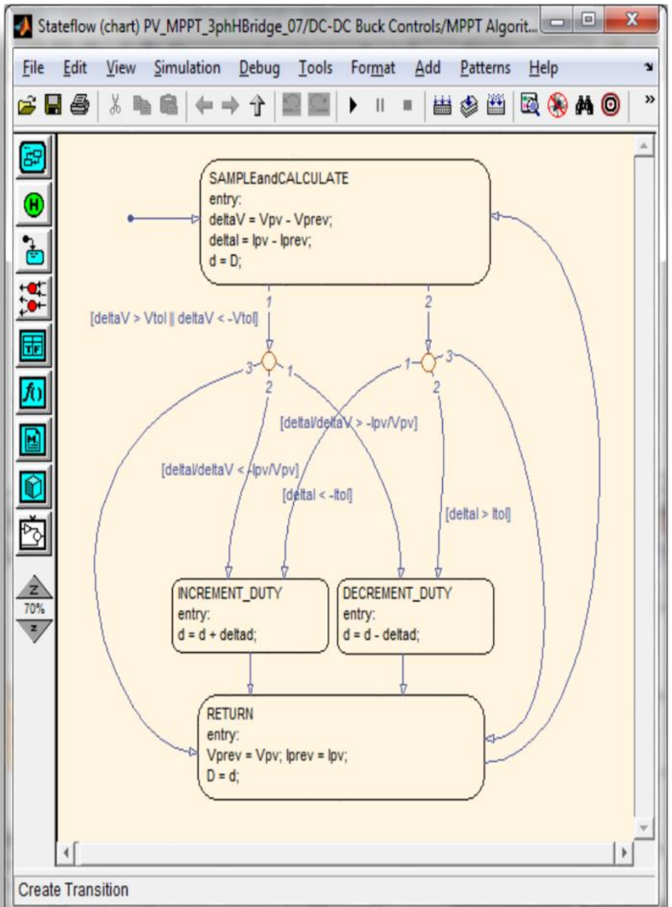
$$\frac{dP}{dV} = \frac{d(VI)}{dV} = I\frac{dV}{dV} + V\frac{dI}{dV} = I + V\frac{dI}{dV}$$

- The MPP will be found when:

$$\frac{dP}{dV} = 0 \Rightarrow I + V\frac{dI}{dV} = 0 \Rightarrow -\frac{I}{V} = \frac{dI}{dV}$$

- Where I/V represents the instantaneous conductance of the PV array and dI/dV is the instantaneous change in conductance.
- The comparison of those two quantities tells us on which side of the MPP we are currently operating.

Maximum Power Point Tracking



STATEFLOW Chart

Incremental Conductance Algorithm

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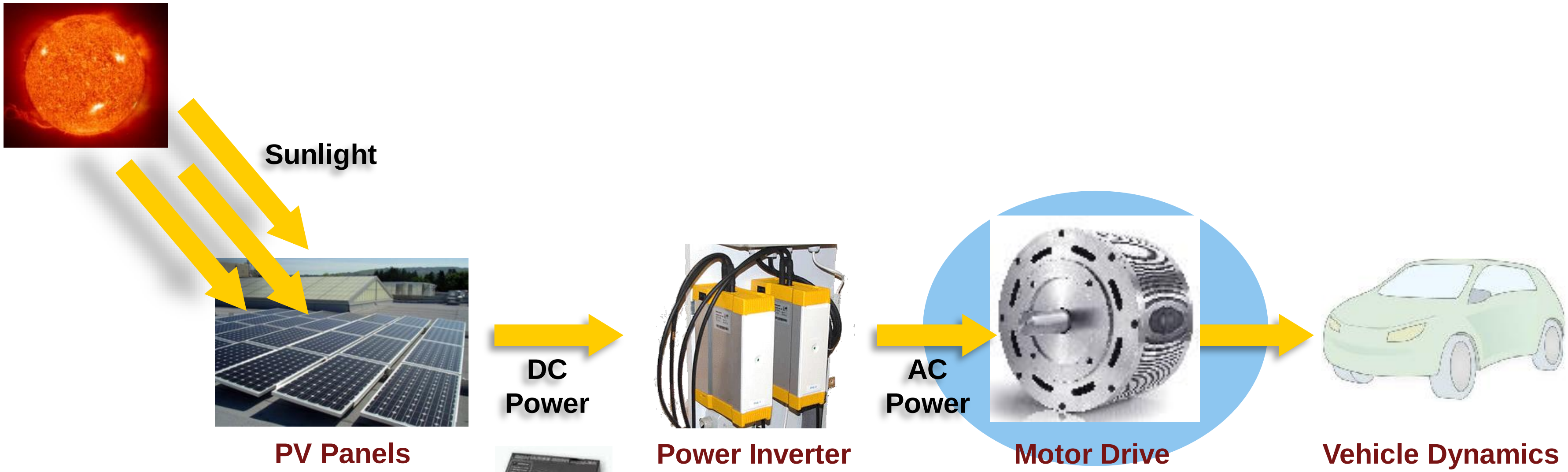

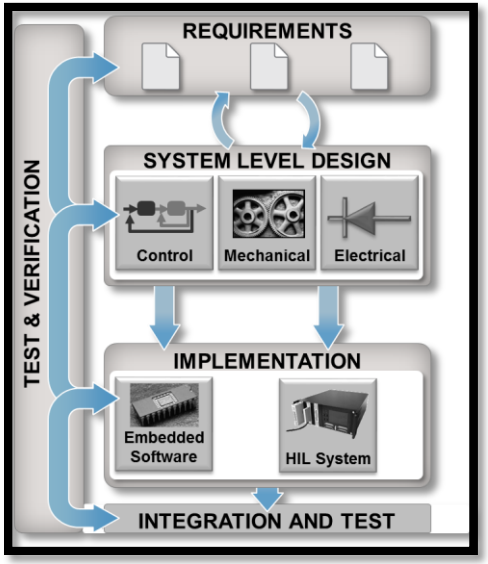

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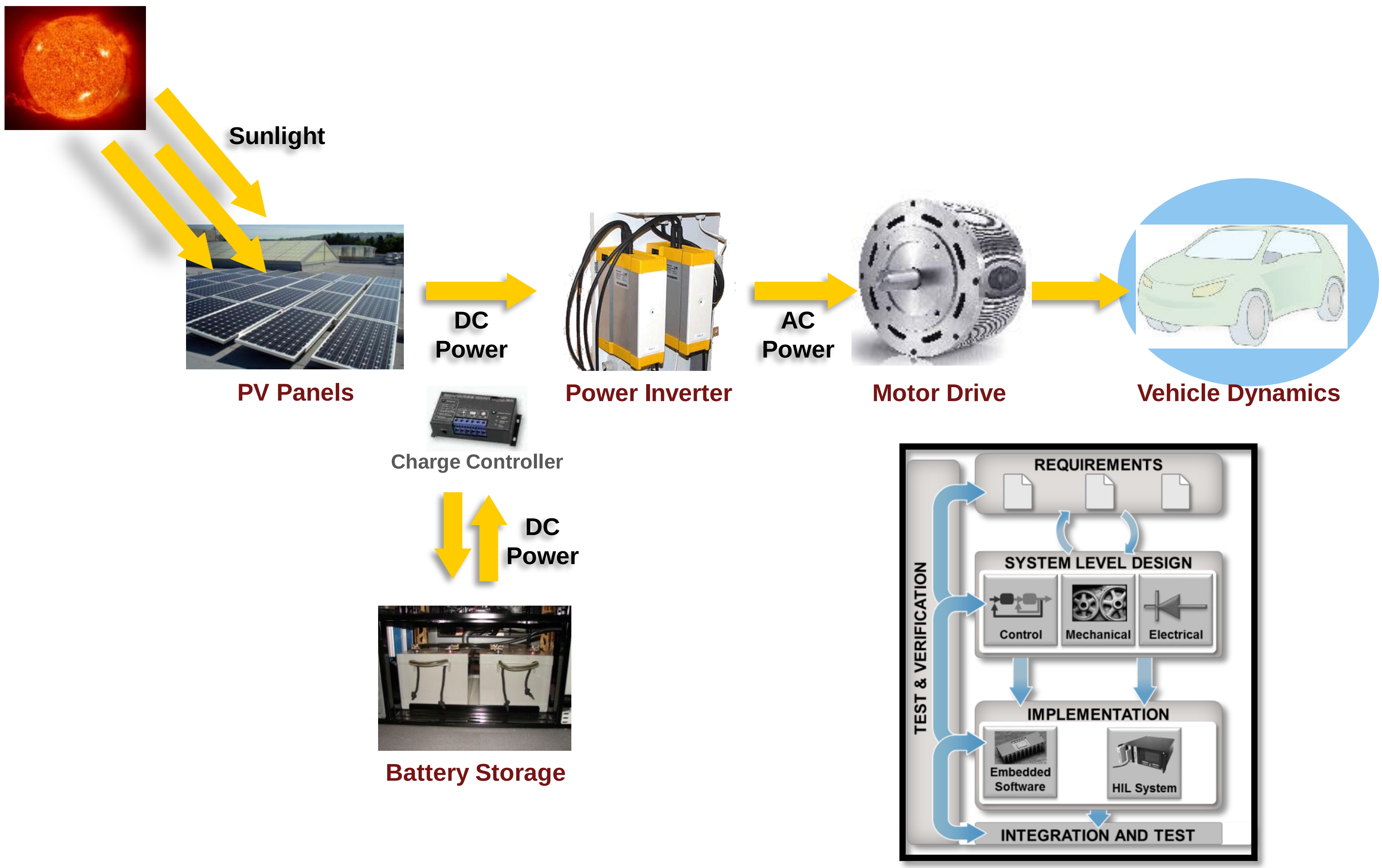
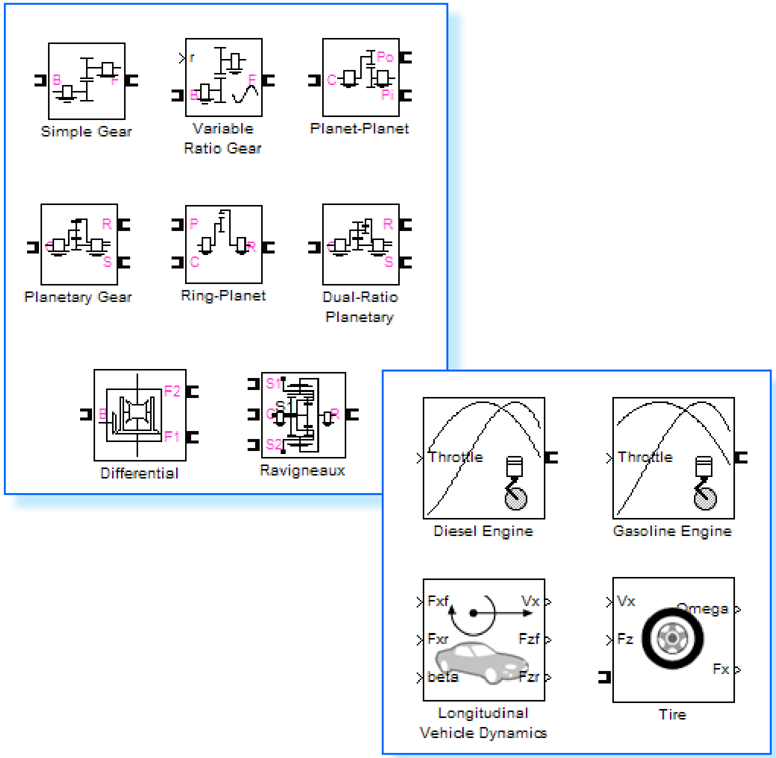


Mechanical Drivetrain: SimDriveline

- Power Split Device
  - Planetary gear, from gear libraries in SimDriveline
- Full Vehicle Model
  - Tire models
    - Transient and steady-state dynamics
  - Longitudinal dynamics
    - Relevant for fuel economy studies
- Engine Model
  - Lookup-table relating speed to available power
- Extend models using Simscape language or Simulink



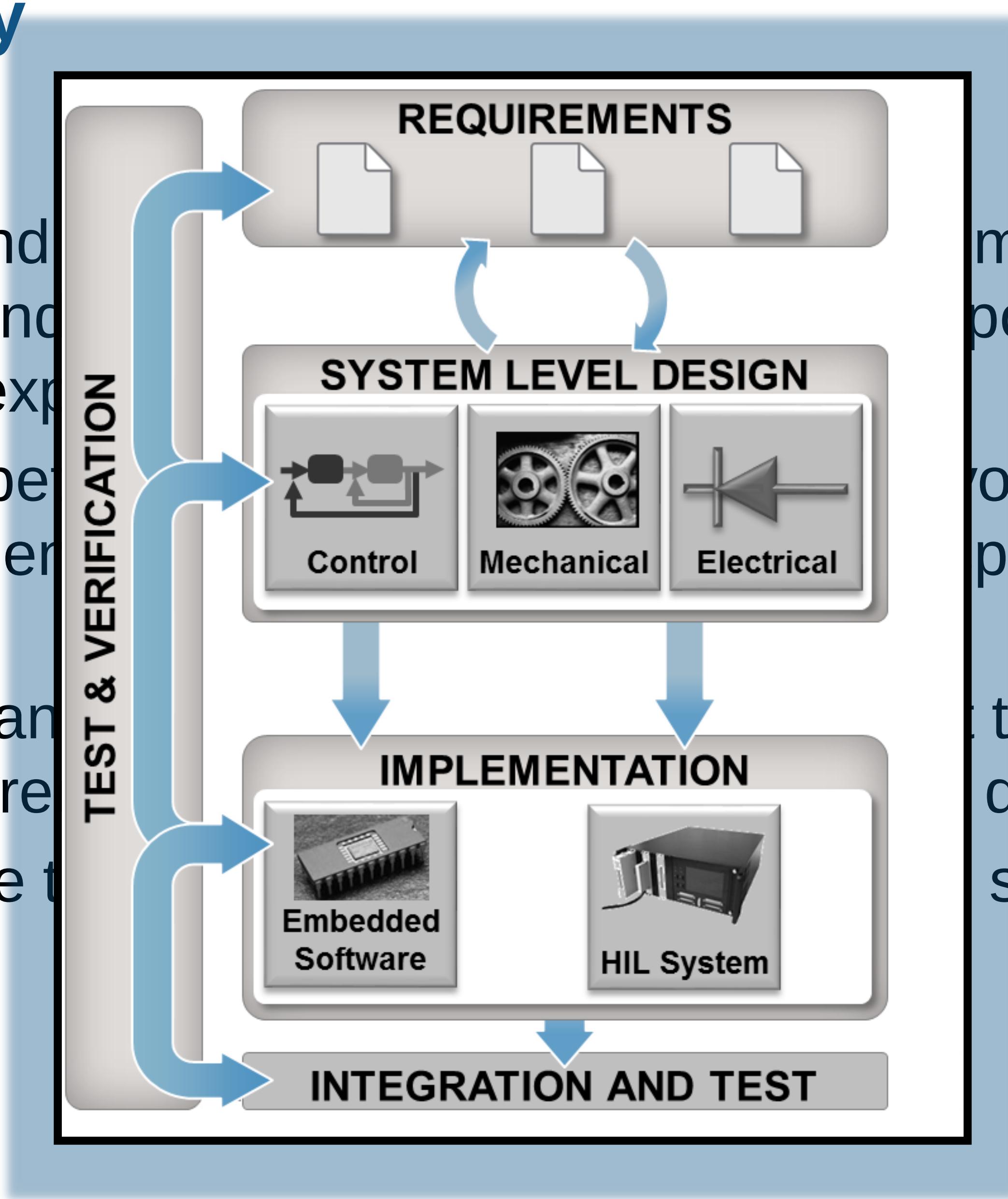
MathWorks Support for American Solar Challenge

- Complimentary Software for teams to use for the competition
- On-demand webinars
- Free MATLAB and Simulink Tutorials

[Learn More: American Solar Challenge Resource Page on MathWorks Website]

Summary

- Model ind mponents
  using fun ponents
  and/or exp
- Switch be your
  componen peed as
  needed
- Design an them
  against re domain
- Optimize simulation



Q&A