"In The Loop" Testing for Power Electronic Systems

IEEE PELS Raleigh Chapter Presentation

electrical engineering software

IEEE POWER ELECTRONICS SOCIETY
Powering a Sustainable Future

Presentation Outline

- Company background
  - System-level power conversion design and test tools
- Leveraging system models for control systems development
  - General concepts, Model-In-the-Loop (MIL) and Software-In-the-Loop (SIL)
- Processor-In-the-Loop co-simulation (PIL)
  - High fidelity testing at all switching frequencies
  - Software test points
  - Demo
- Hardware-In-the-Loop simulation (HIL)
  - Plant code generation from simulation environment
  - Specialized computer to provide real-time testing harness
  - Demo

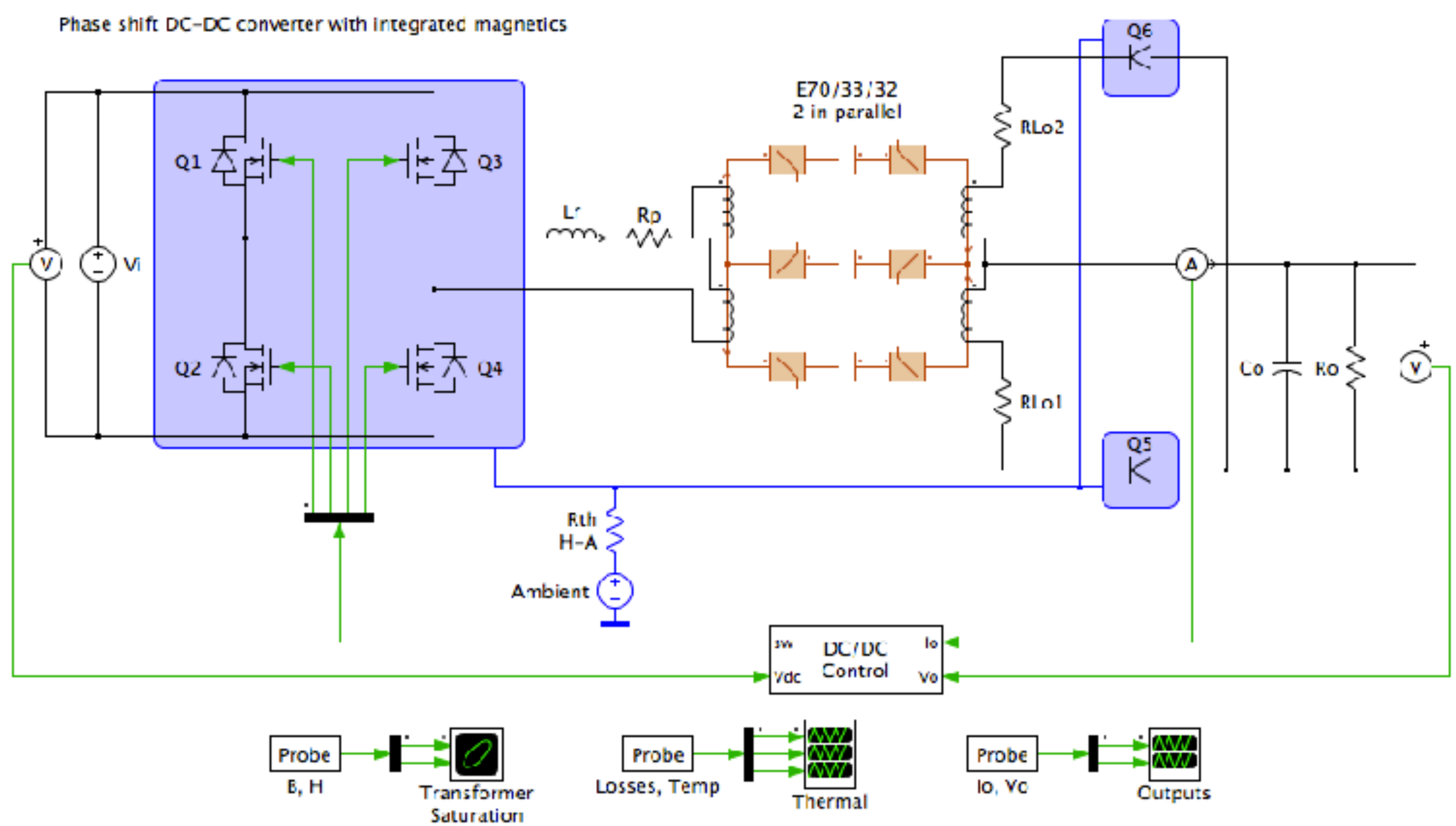
Who We Are

- Plexim was started by 2 power electronics Ph.D. students in 2002
- Independent company, spun-off from ETH Zürich, Switzerland
- Privately owned by founders with headquarters still in Zürich
- US offices in Cambridge, MA and Seattle, WA
- PLECS simulation platform includes:
  - PLECS Blockset and PLECS Standalone as flagship software tools
  - PLECS Coder and PLECS Processor-in-the-Loop available as add-ons
  - PLECS RT Box real-time simulator (2016) and hardware interfaces
- Customers in ~50 countries
- Academic users for coursework and research purposes

Our Offerings

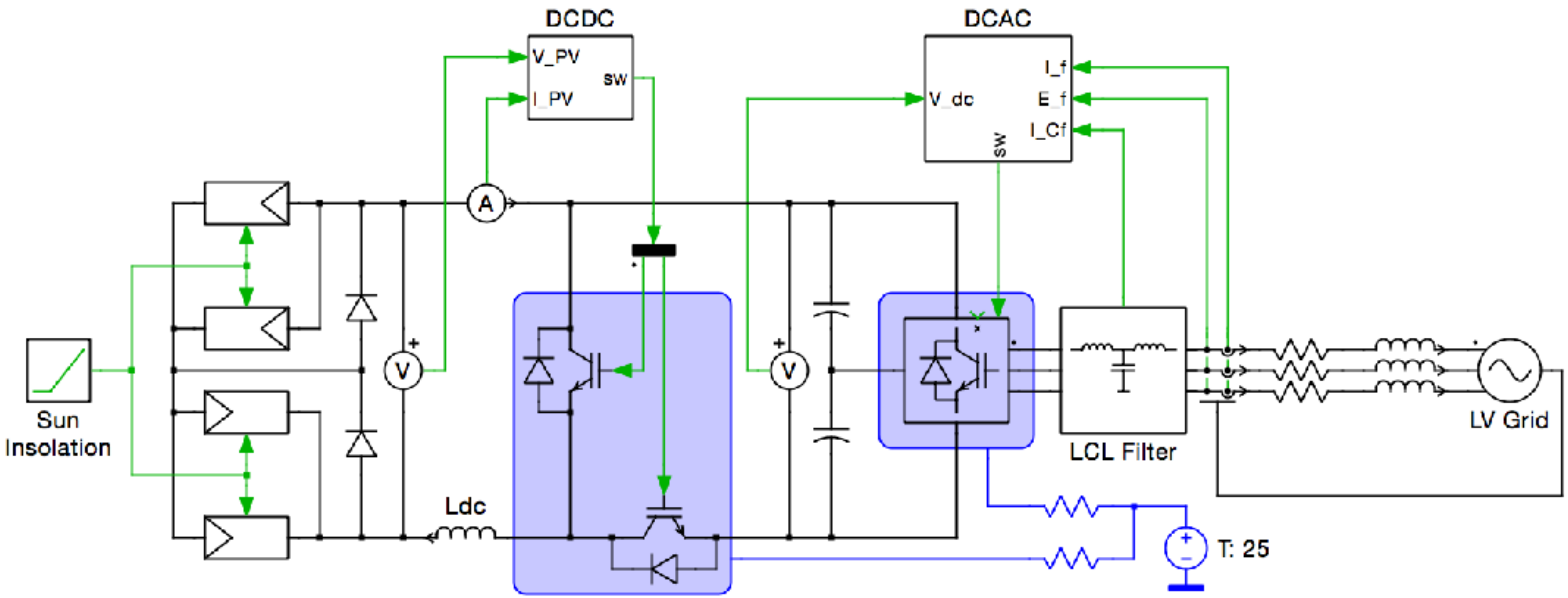
- PLECS Blockset and PLECS Standalone
  - Complete multi-domain modeling environments
- PLECS PIL (Processor-In-the-Loop)
  - Co-simulate embedded control code
- PLECS Coder
  - Auto-generation of code for controls and real-time plant models (HIL)
- PLECS RT Box
  - Real-time hardware platform for controller development and validation
- Custom development services
  - Turnkey models, interface hardware, software target packages
- PLECS WBS
  - Teaching and marketing

Telecom - Power Supply

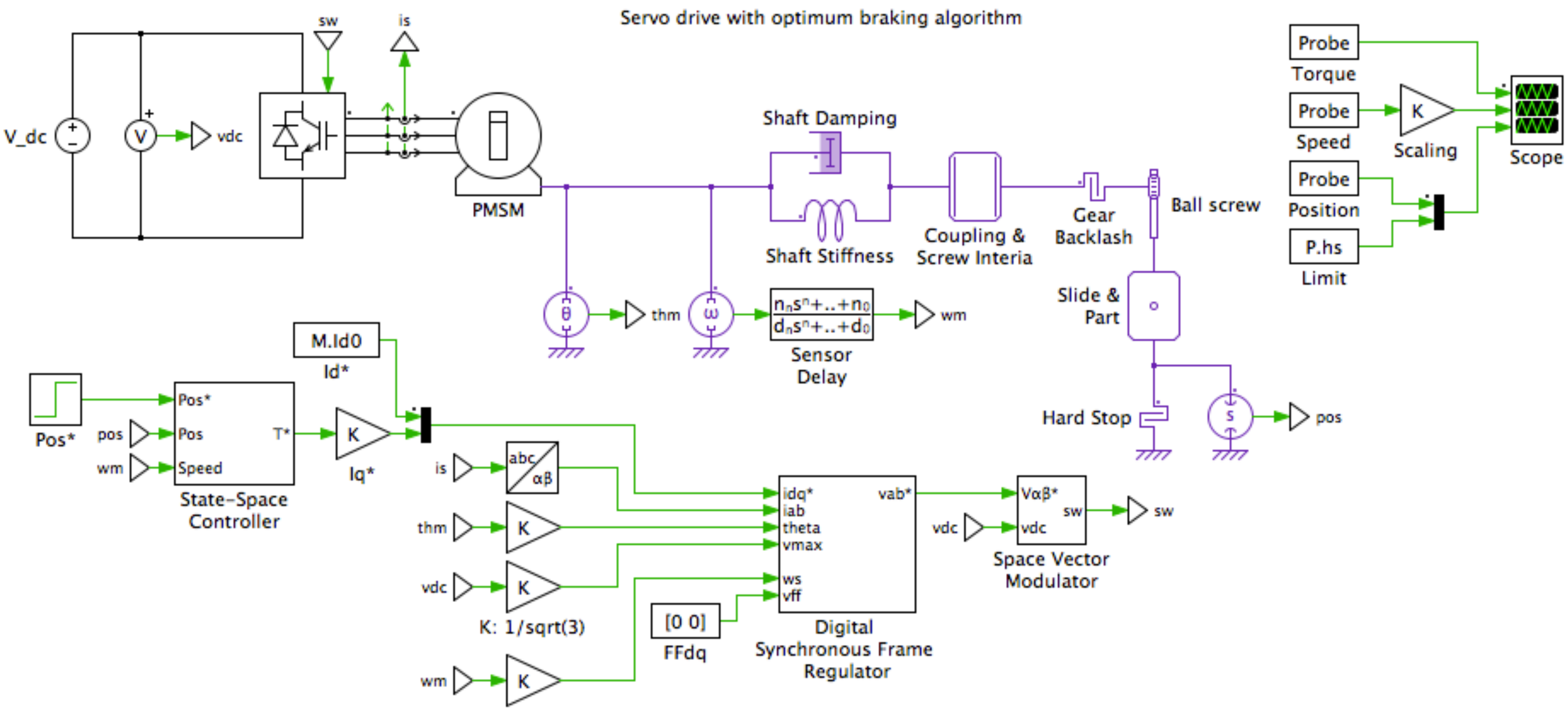


Power Electronic Systems

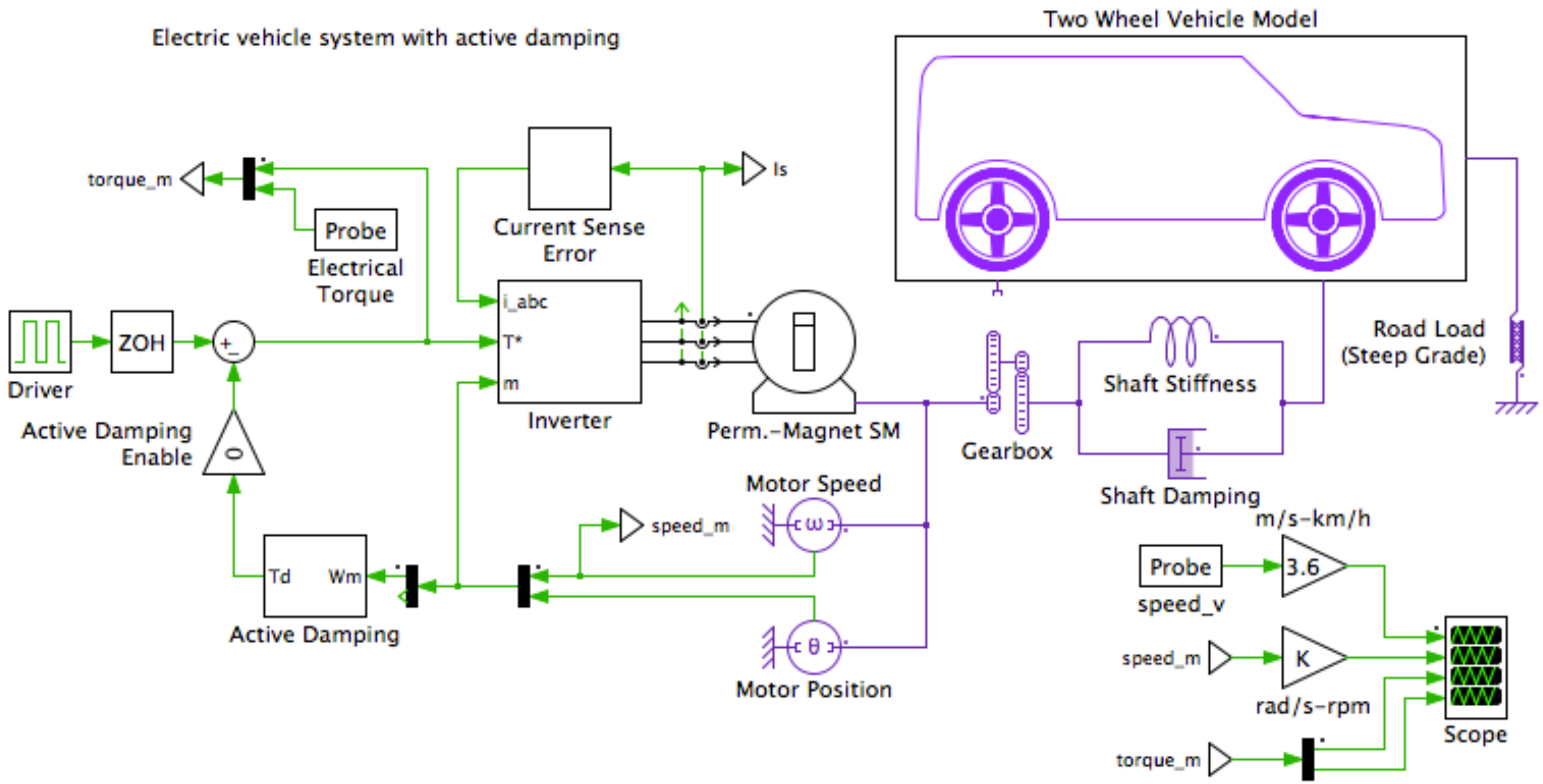
Solar Power



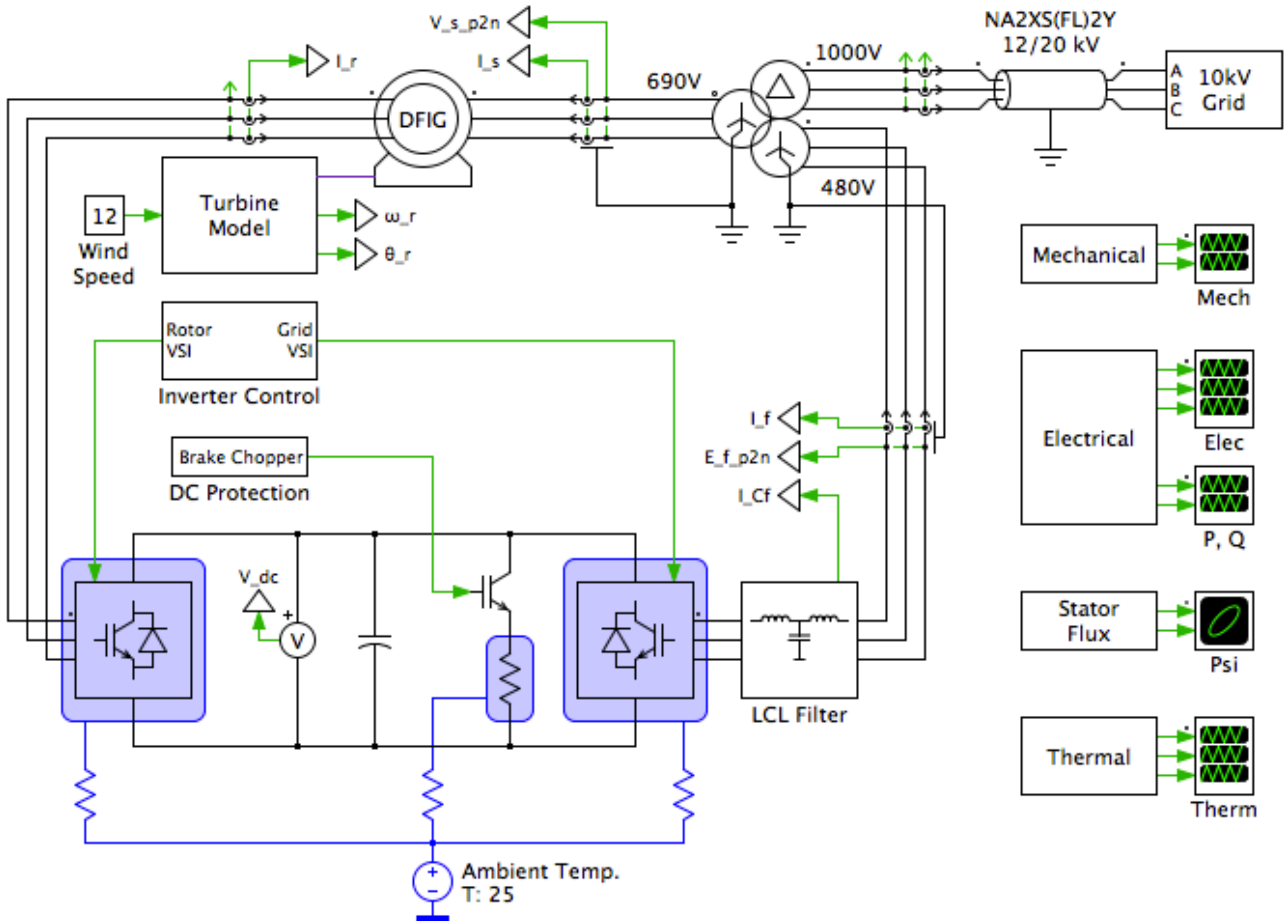
Industrial Control - Servo Drive



Automotive - Electric Vehicle



Wind Power



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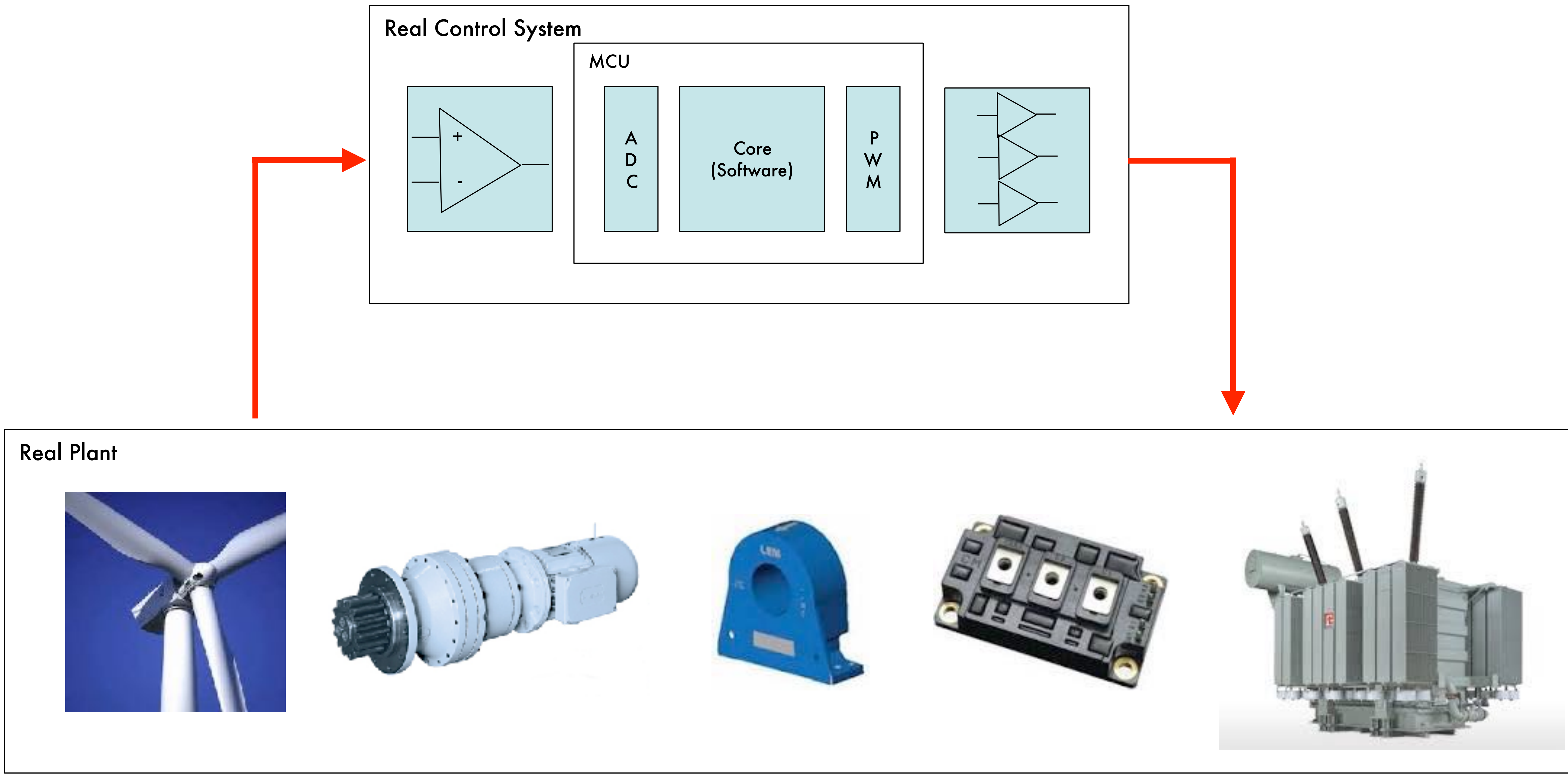
Leveraging System Models for Control Systems Development

System models:

- Create the framework in which control systems are developed
  - Quick prototyping of control methods
  - Definition of subsystem requirements (e.g. sensor bandwidth and accuracy)
- Facilitate bottom-up software design and validation
  - Provide a platform for developing and testing control software
  - Permit placing software modules “in-the-loop” (SIL, PIL)
  - Allow “in-the-loop” testing of an entire control unit (HIL)

"In-the-Loop" Development & Testing



Controller Design: Conventional Model Analysis

End goal:

Converter
(Power hardware)

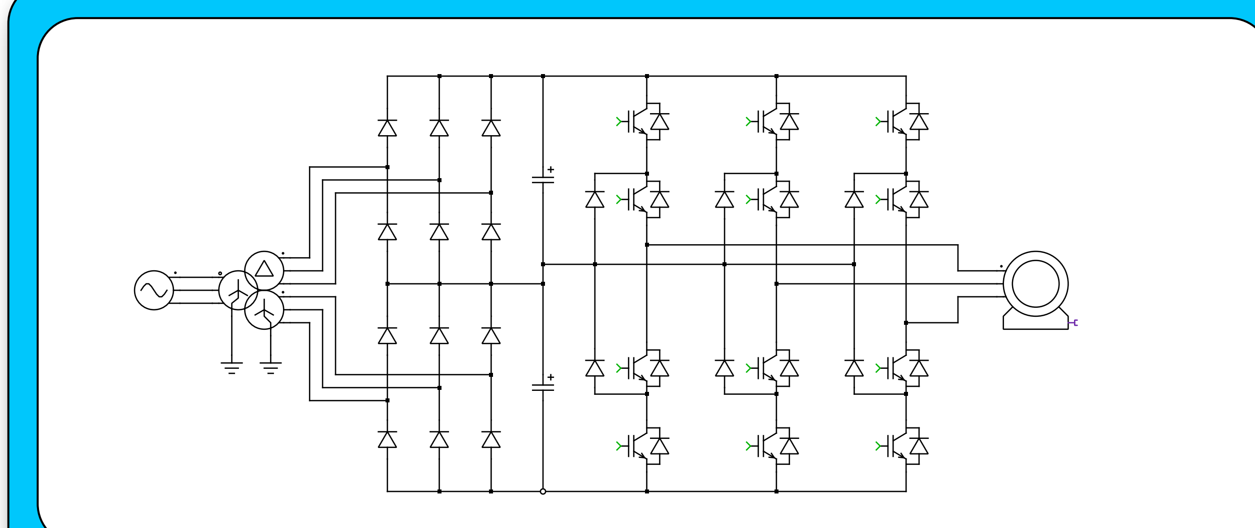
Measurements

Control Signals

MCU
Control

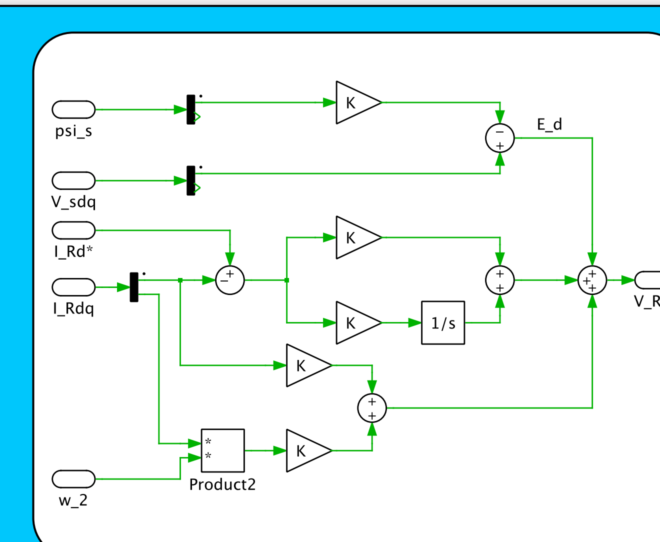
Initial prototyping:

Converter
(Model)



Measurements

Control Signal

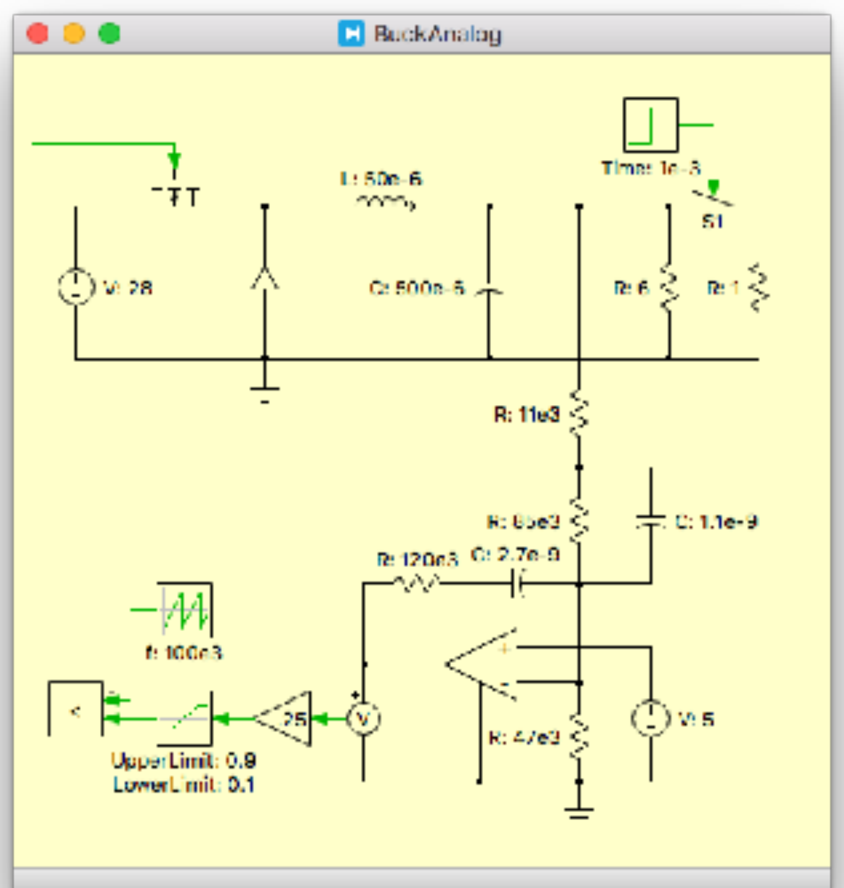


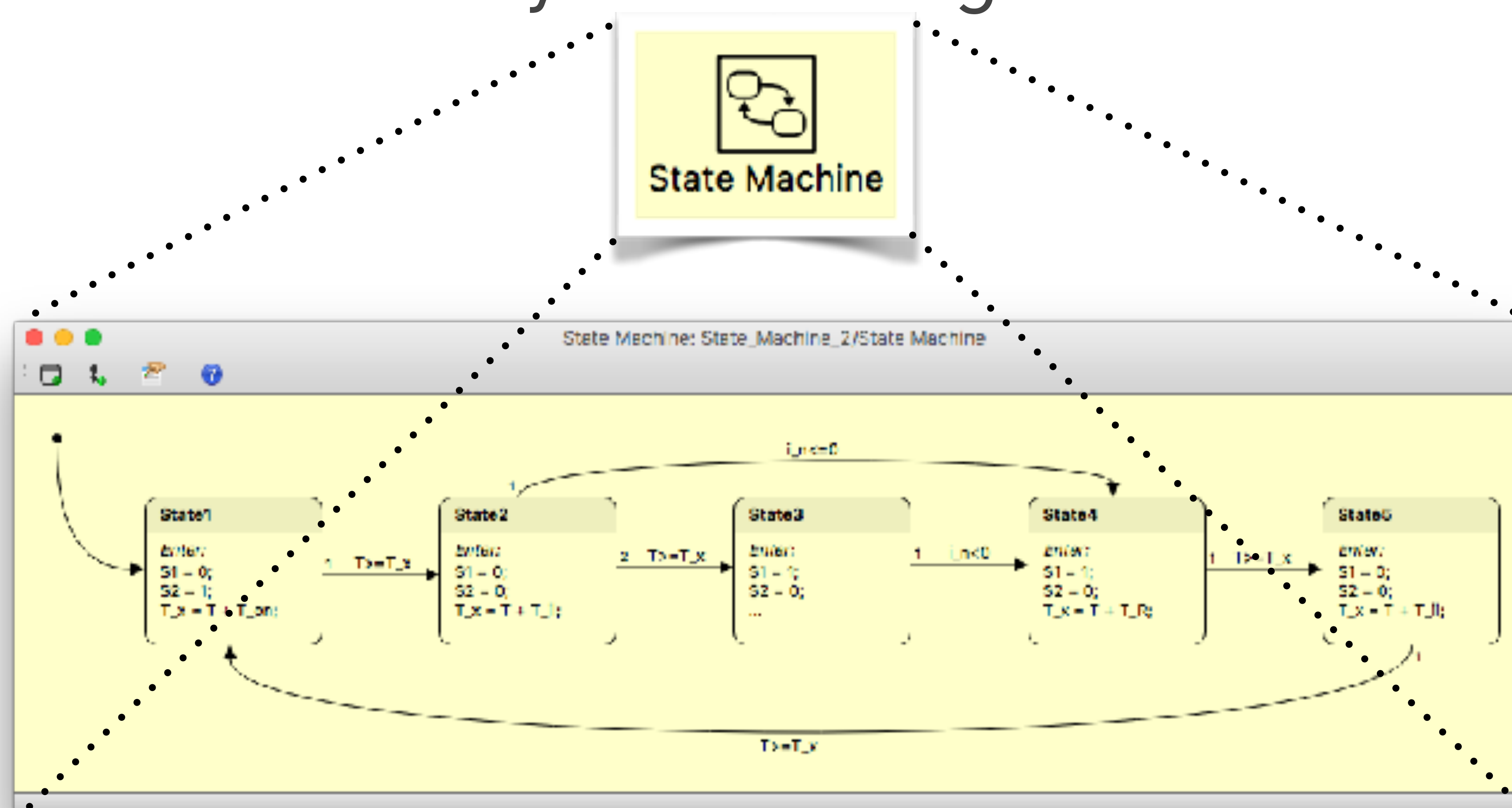
MCU
(Model)

All built in
PC software

Model-In-the-Loop (MIL) Control Implementation Options

- Analog controllers with op-amp circuits and transfer functions
- Continuous and discrete signal processing blocks
- Flexible pulse width modulators included
- State machine block for event driven system design





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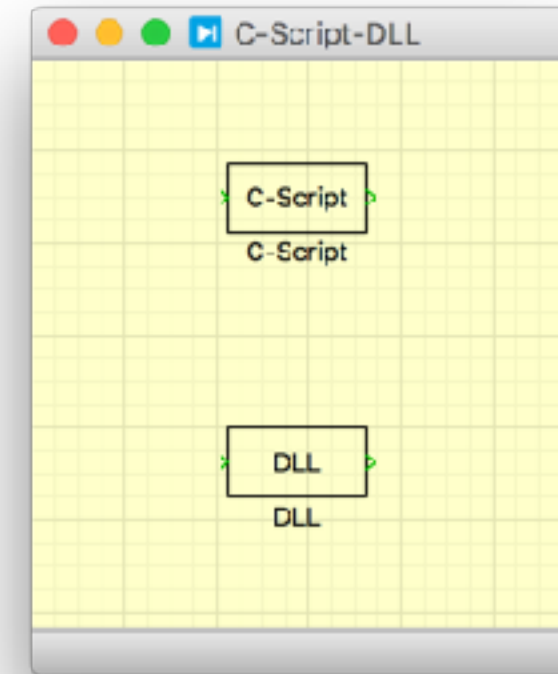
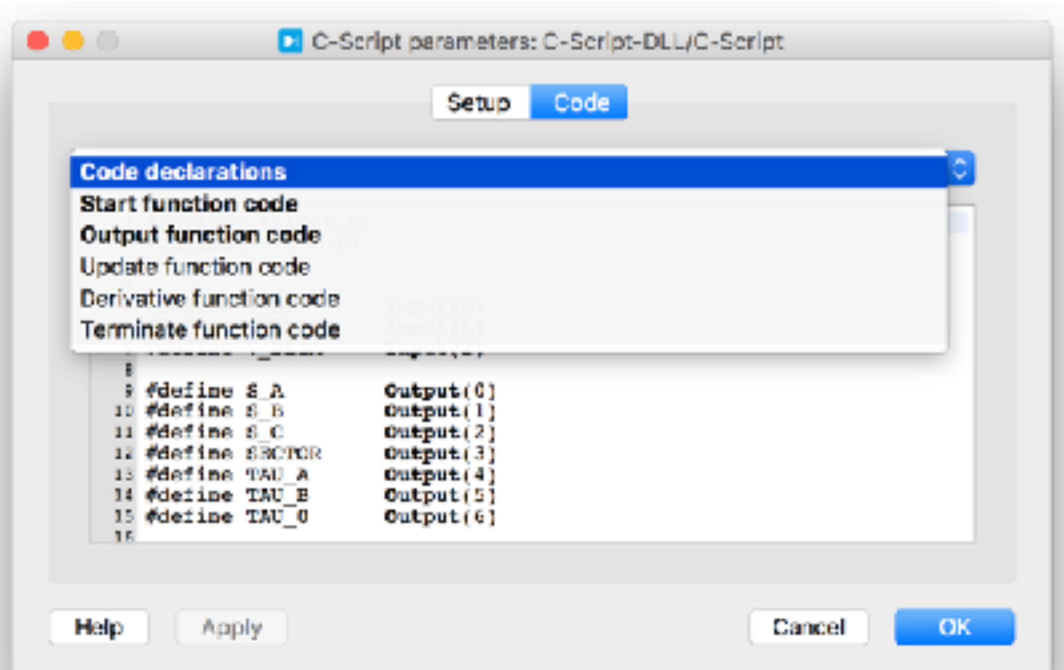
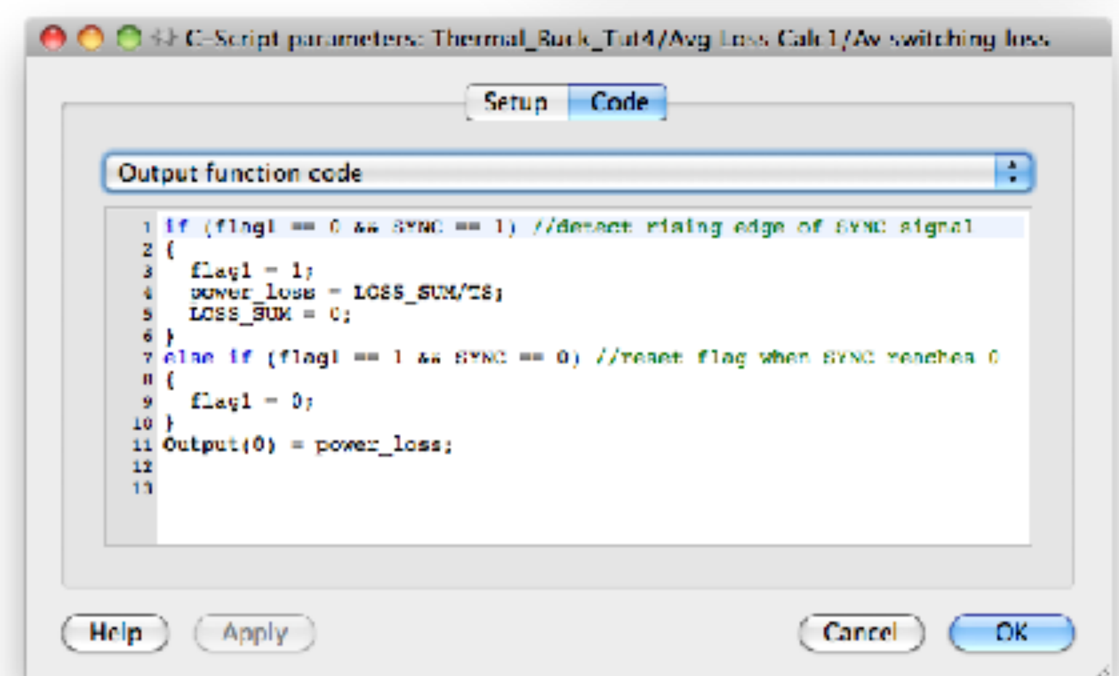
Control Code Integration/Software-In-the-Loop (SIL)

- **C-Script block in library**
  - Custom C code entry and inbuilt compiler
  - Advanced functionality and interaction with solver
- **DLL block for loading compiled object code**
  - Use external IDE and compile for native simulation host
  - Share control logic without disclosing source code







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Simulation and Modeling of Power Converters

	Circuit Simulator		Finite Element Analysis
	Behavioral Models	Physical Models	
Idea/Concept	Topology evaluation and comparison **Control algorithm prototyping** Estimation of efficiency and cooling requirements Refinement of system requirements Subsystem specifications Component pre-selection Cost estimation		Creation of equivalent models for magnetic and thermal components
Design	Detailed power converter design **Control software design and tuning** **SIL and PIL testing** Refined subsystem specifications Cost estimation Drive cycle simulations (efficiency, reliability) FMEA Monte Carlo Analysis	Subsystem design (e.g. gate driver) Refinement of semiconductor loss estimations EMC prediction	PCB layout Semiconductor packaging Busbar design Detailed design of magnetics and thermal management EMC prediction
Testing and Launch	**HIL testing** **Code coverage testing** **Calibration and commissioning**		
Continuous Improvement	Assistance with 8Ds FMEA maintenance **Software regression testing**		Cost-reduction of magnetic and thermal components

Controller Design: PIL

Converter
(Power Hardware)

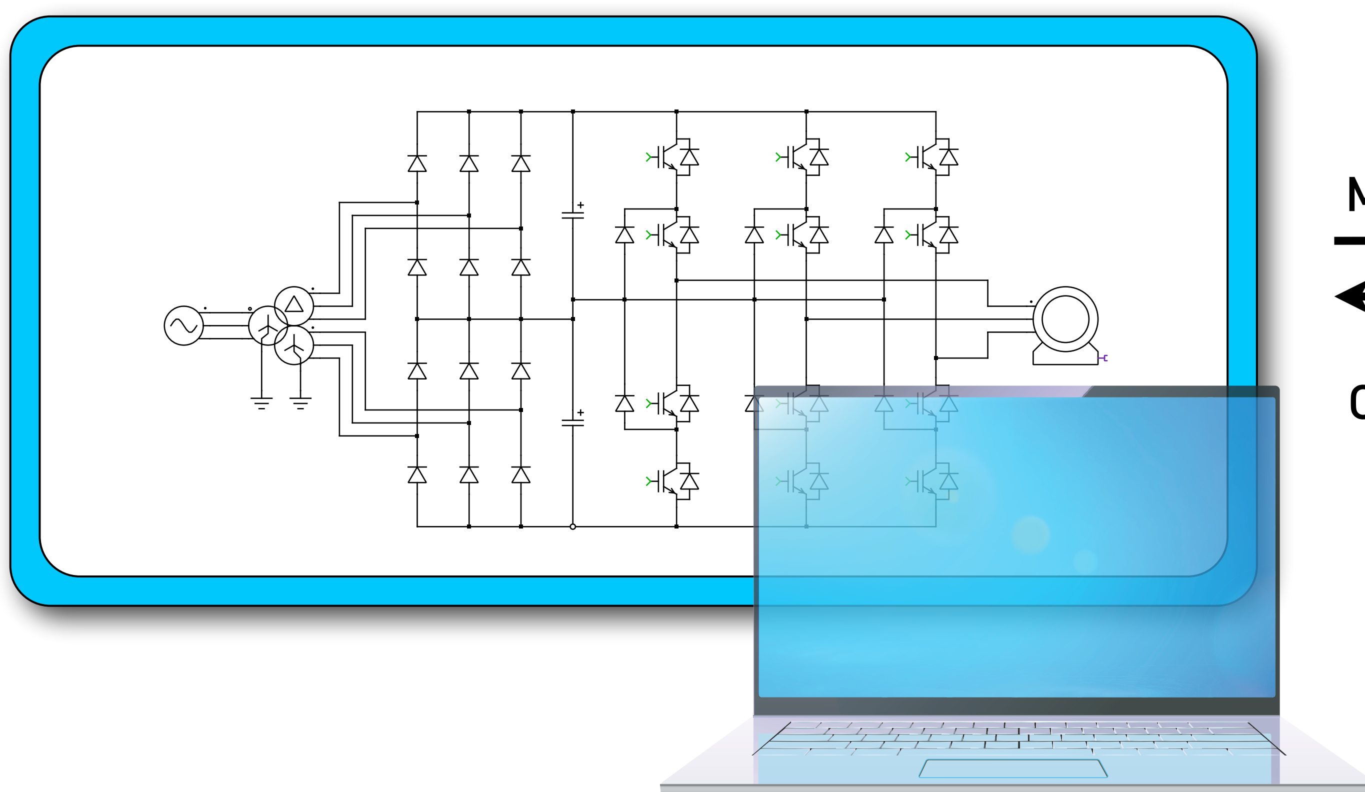
Measurements

Control Signals

MCU
(Ctrl Hardware)

Converter
(Model)

Psuedo-Realtime Simulation



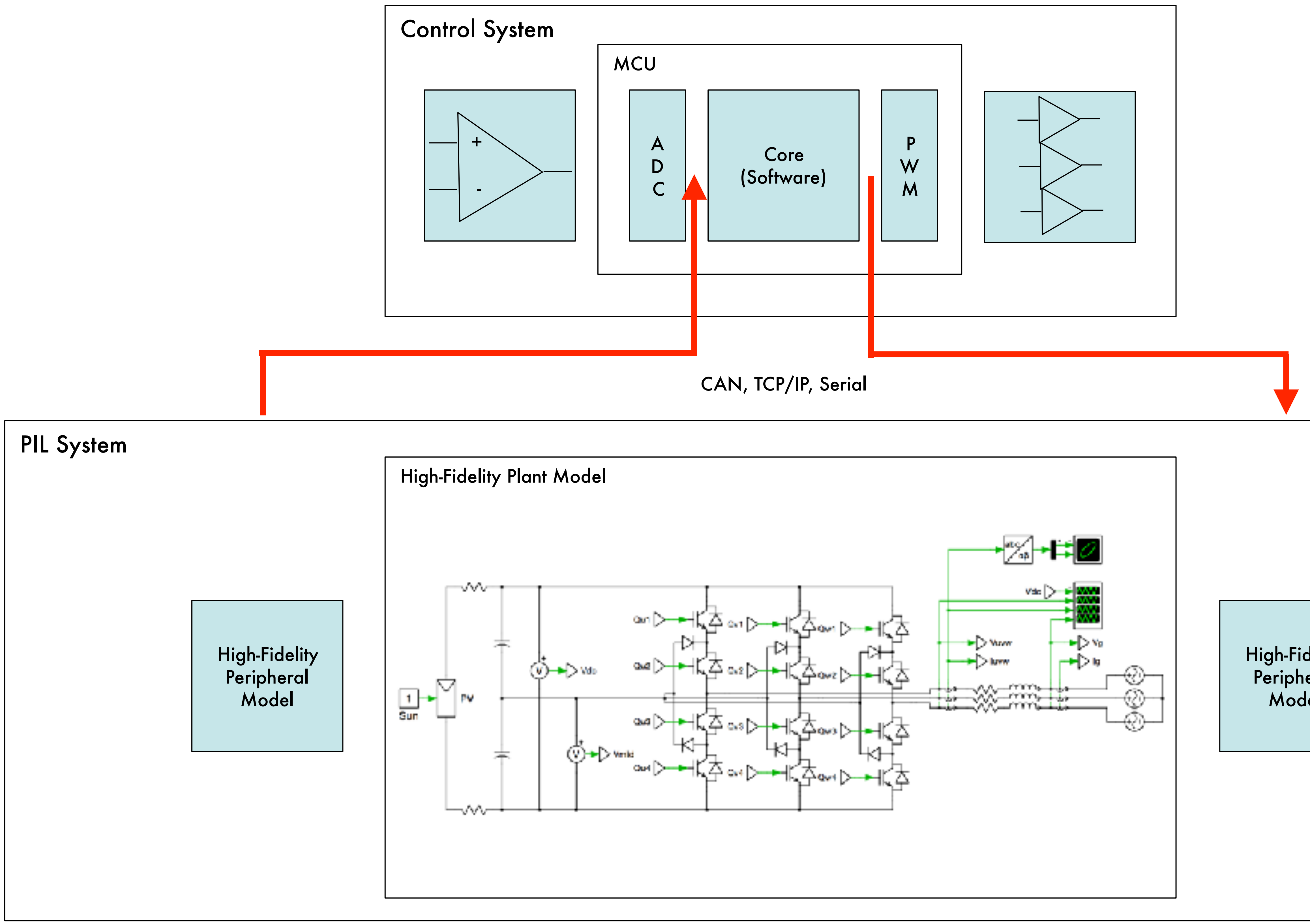
Simulated Measurements

Simulated Control Signals

MCU
(Ctrl Software)

Figure “Power converter” from Semikron product datasheet

PIL Visual

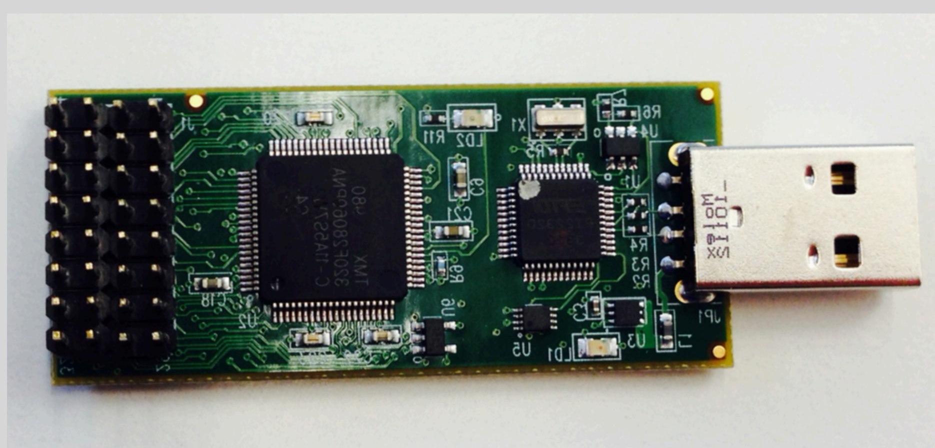


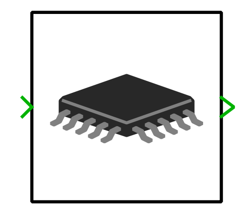
Read and Override Probes

PLECS PIL Workflow

Idea of PLECS Processor-In-the-loop simulation

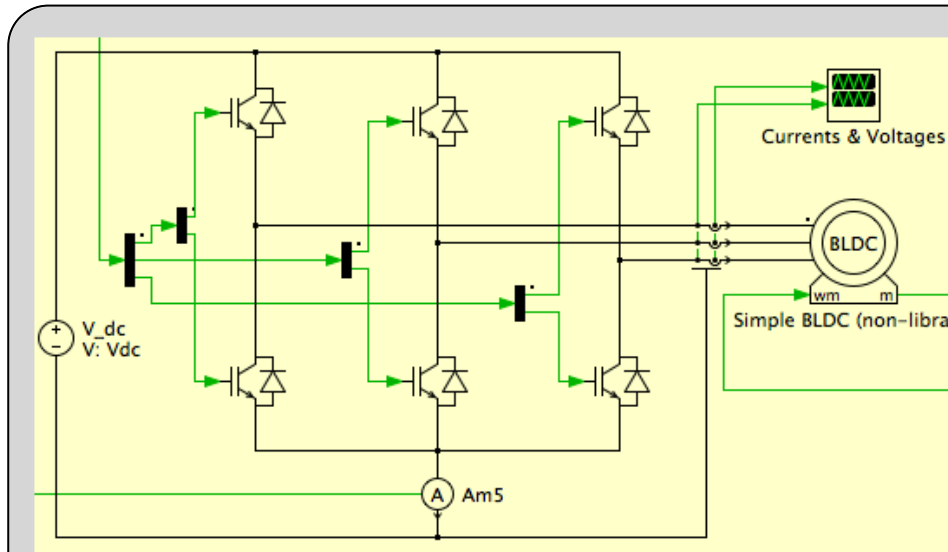
- Control code developed in µC-programming environment (i.e. TI's Code Composer Studio) or auto-generated
- Controller running on real processor in stepped mode
- Control code tested with plant simulated in PLECS





Interface via PIL block

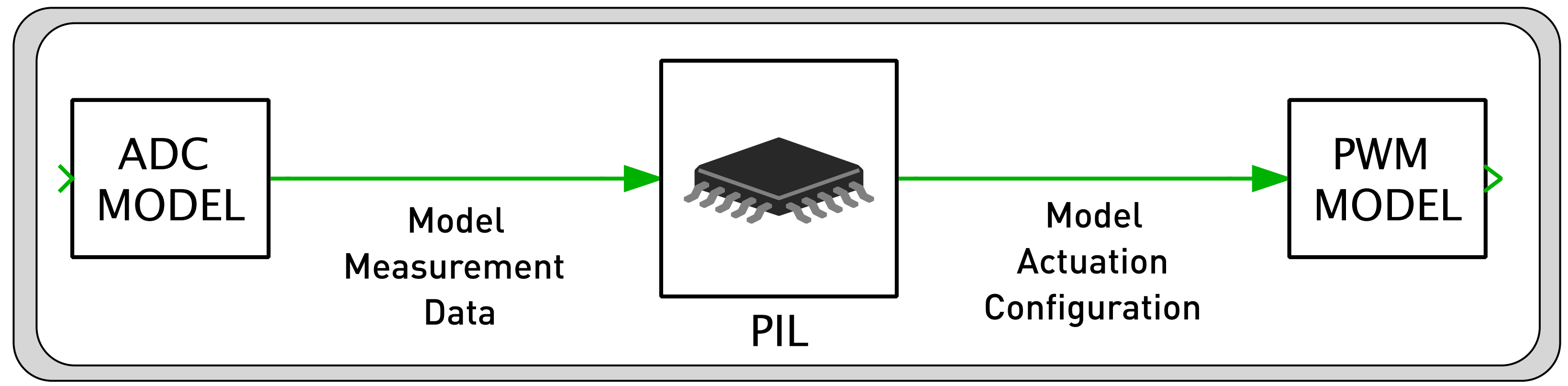
Serial or Parallel Communication



- Real controller
- Plant simulated in PLECS

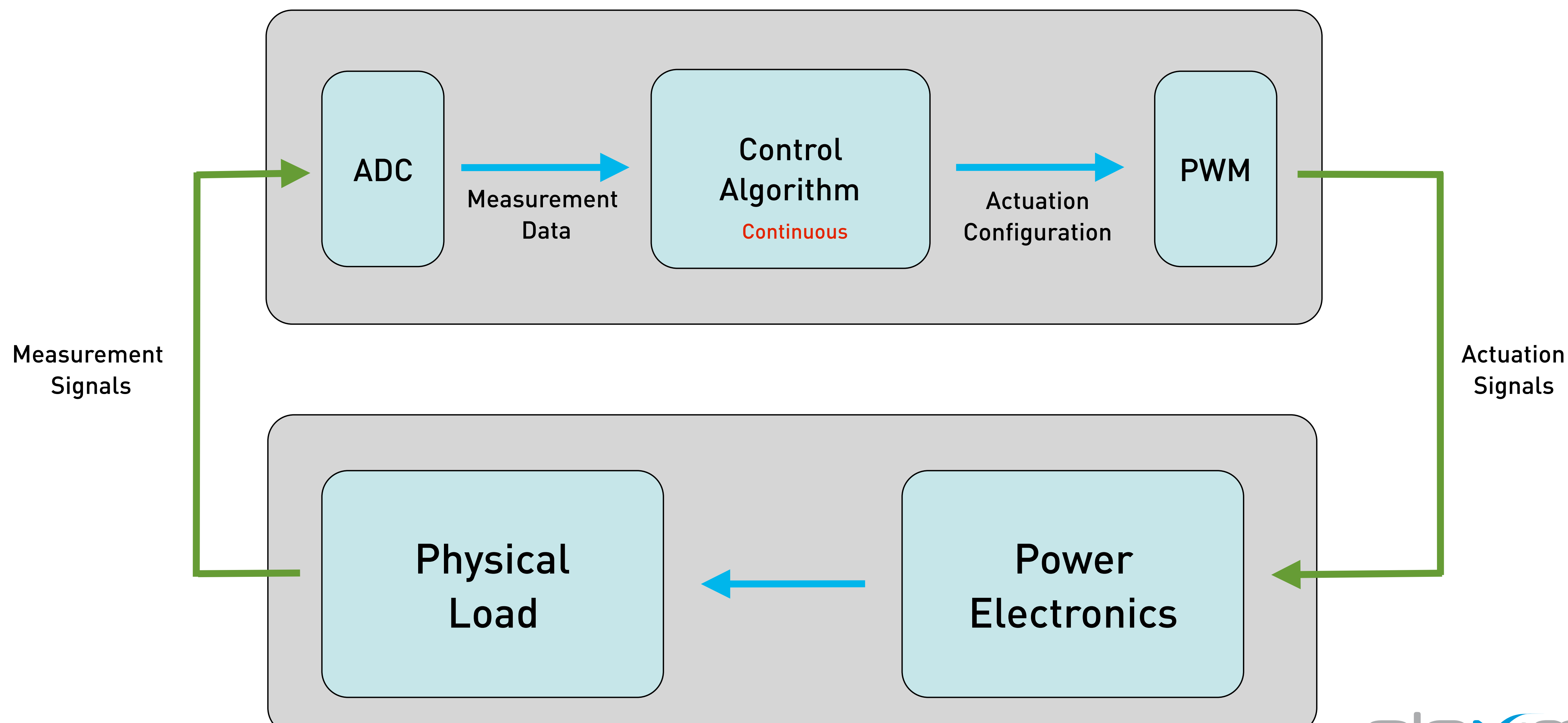
Principle of a PIL Simulation - Without Integration

PLECS Model

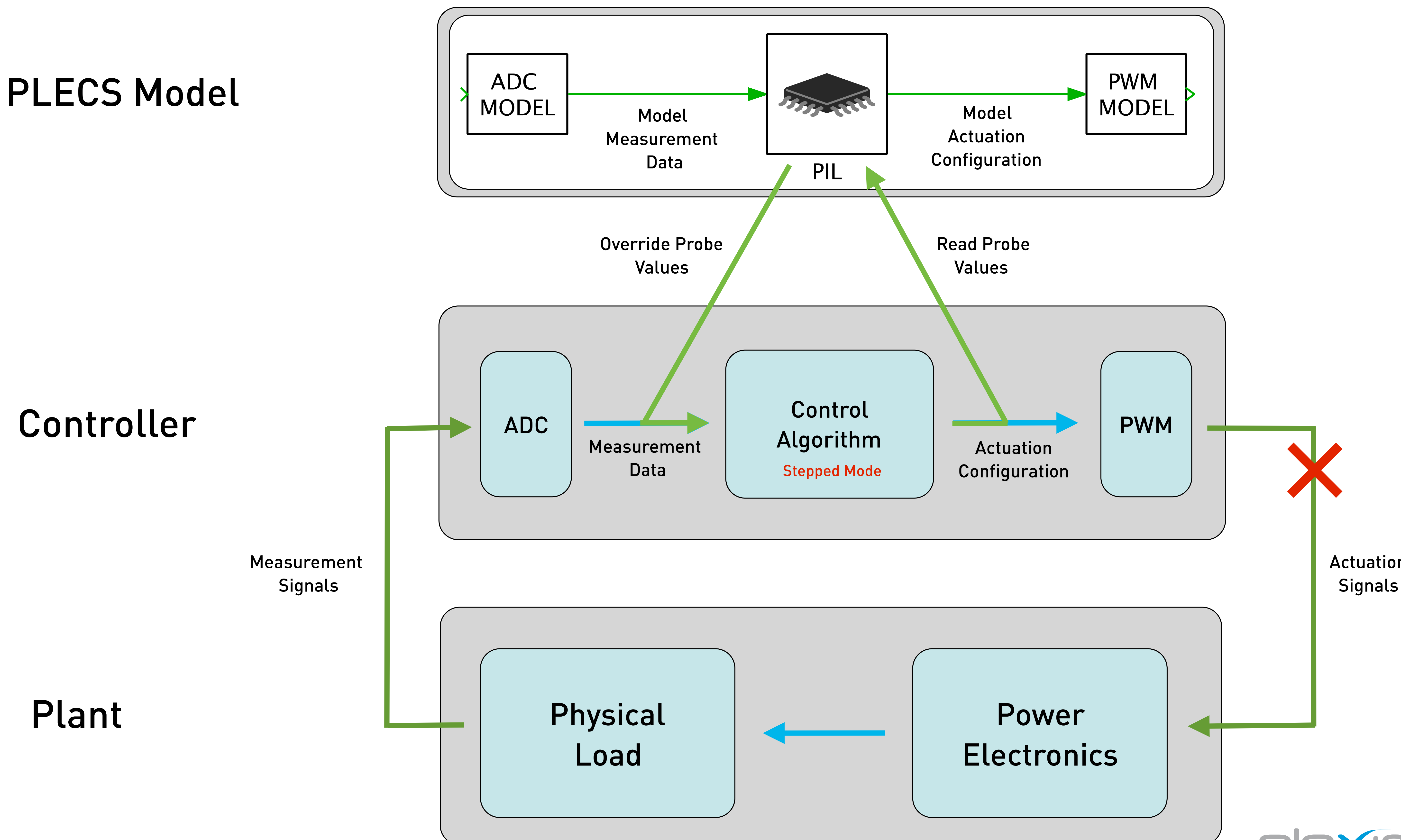


Controller

Plant

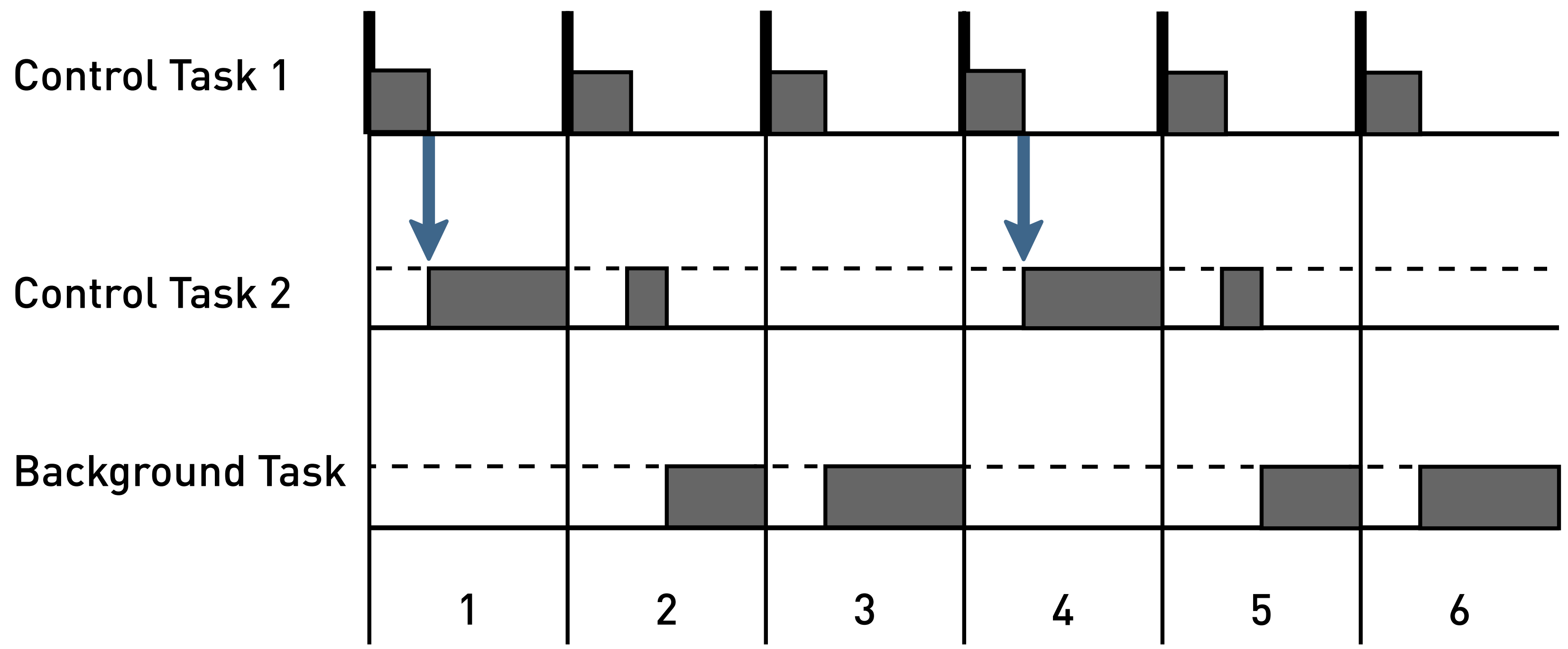


Principle of a PIL Simulation - With Integration



Principle of a PIL Simulation - Real-Time Operation

Embedded controls often use nested tasks

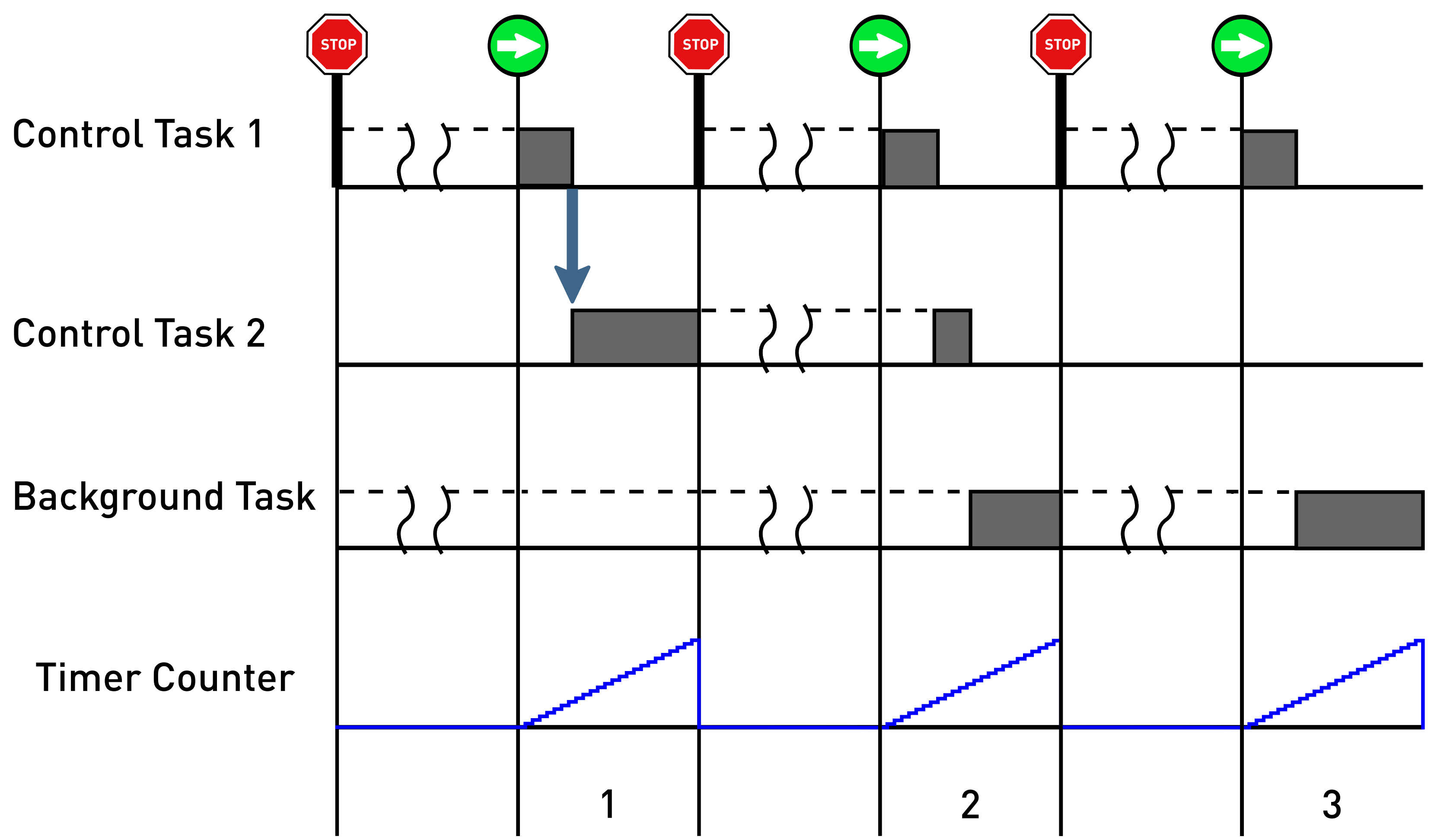


Task dispatching synchronized with PLECS in PIL mode

- Task synchronization with model calculation
- Communication time needed for data exchange between PLECS and Processor

Principle of a PIL Simulation - Pseudo Real-Time Operation

- Co-simulation of PLECS and MCU in PIL mode



- Control frozen while PLECS model updates and data is exchanged
- Control timing preserved during synchronization

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Characteristics of PIL Testing

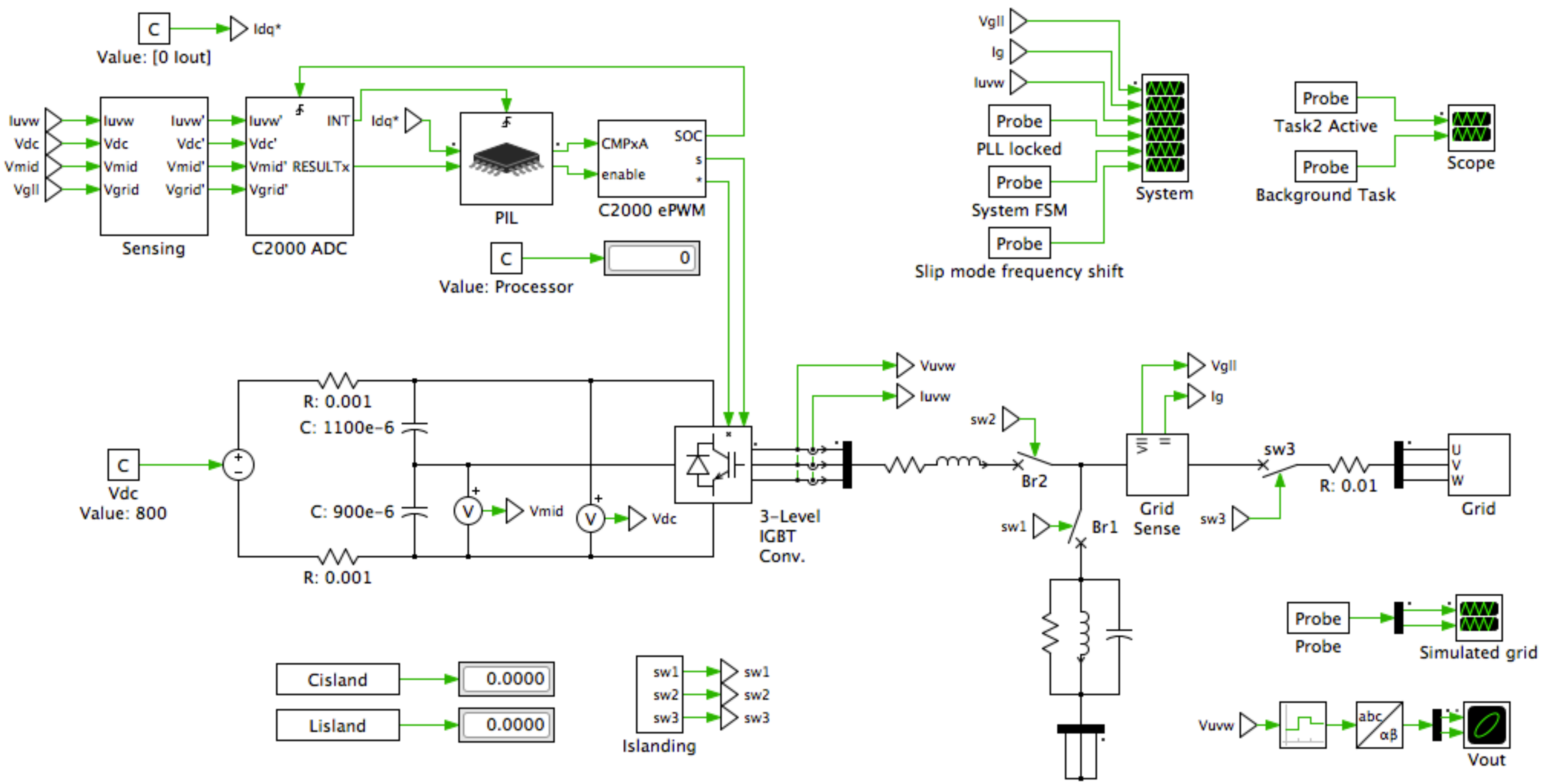
Benefits

- Low cost and barrier to entry
- Allows for arbitrary software test points
- Full fidelity of embedded algorithms at any switching frequency
- High fidelity plant model
- Effects of fixed point calculation in code, controller multithreading
- Facilitates "One Code" approach (same code used for PIL simulation and deployment)
- Reusable plant model
- Pseudo real-time execution facilitates debugging

Challenge

- Test only covers software and CPU

Grid-tied 3-Level Inverter



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Controller Testing: HIL

Converter
(Power Hardware)

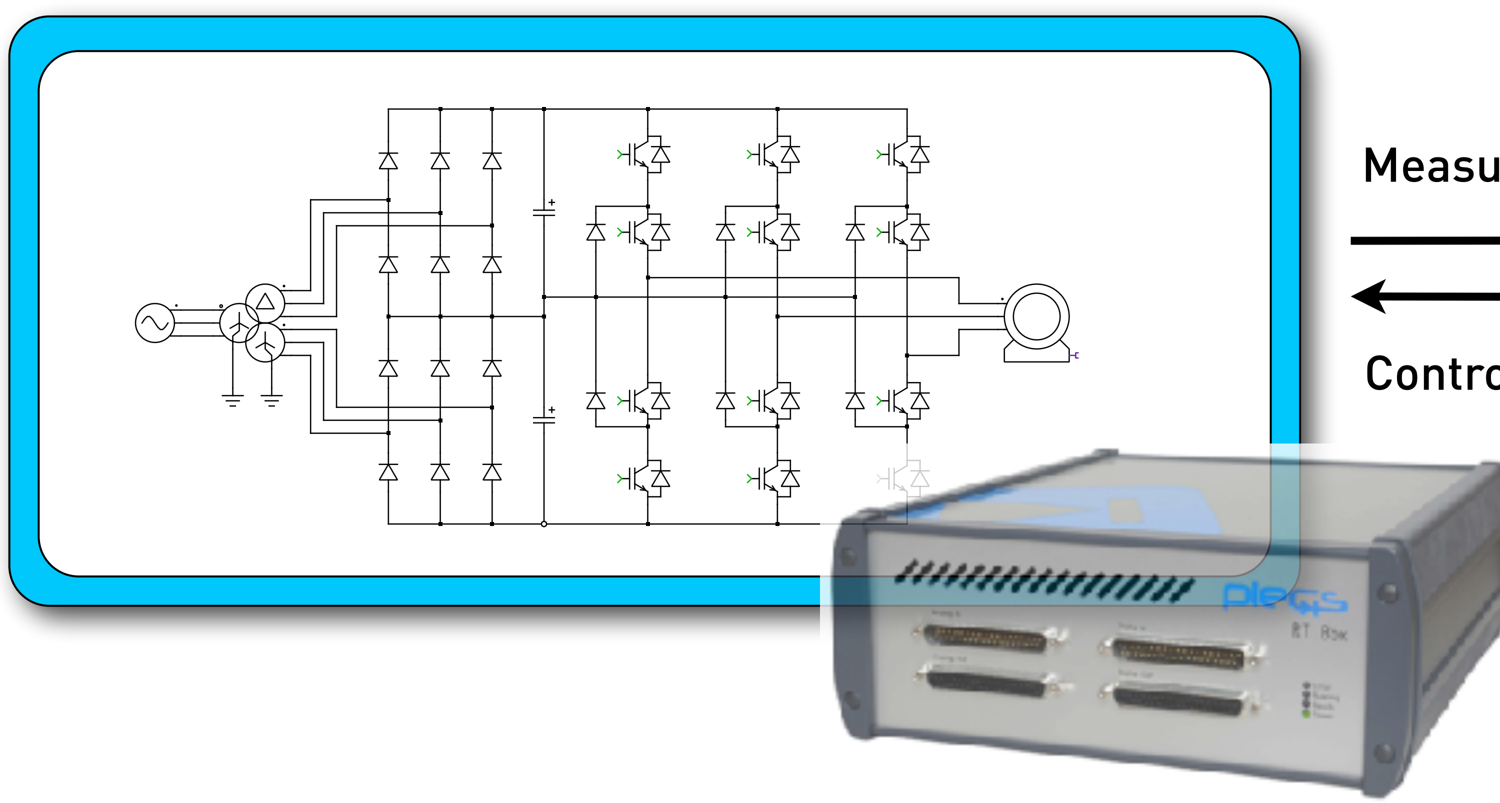
Measurements

Control Signals

MCU
(Ctrl Hardware)

Converter
(Model)

Real-Time Simulator



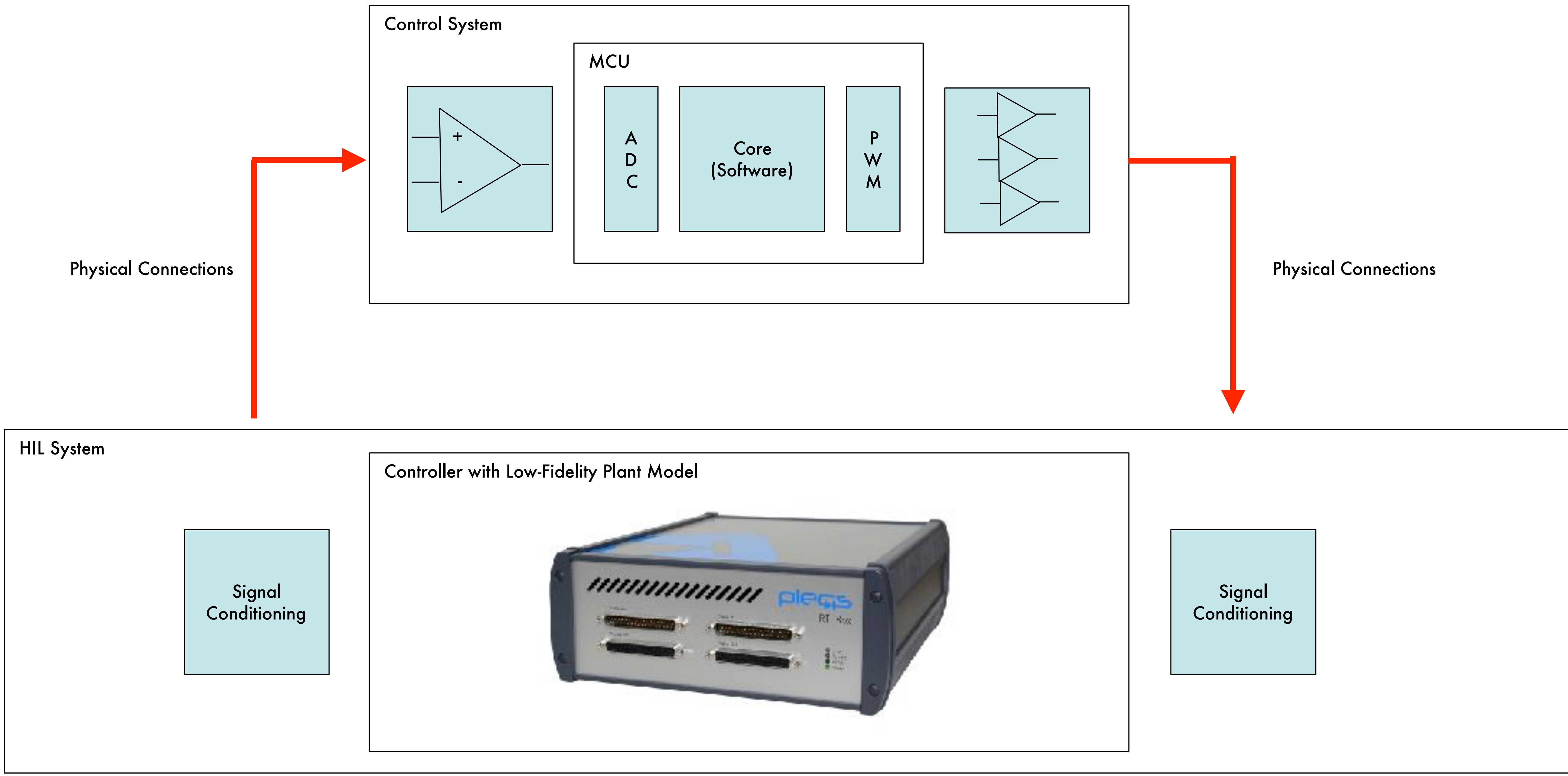
Measurements

Control Signals

MCU
(Ctrl Hardware)

Figure “Power converter” from Semikron product datasheet

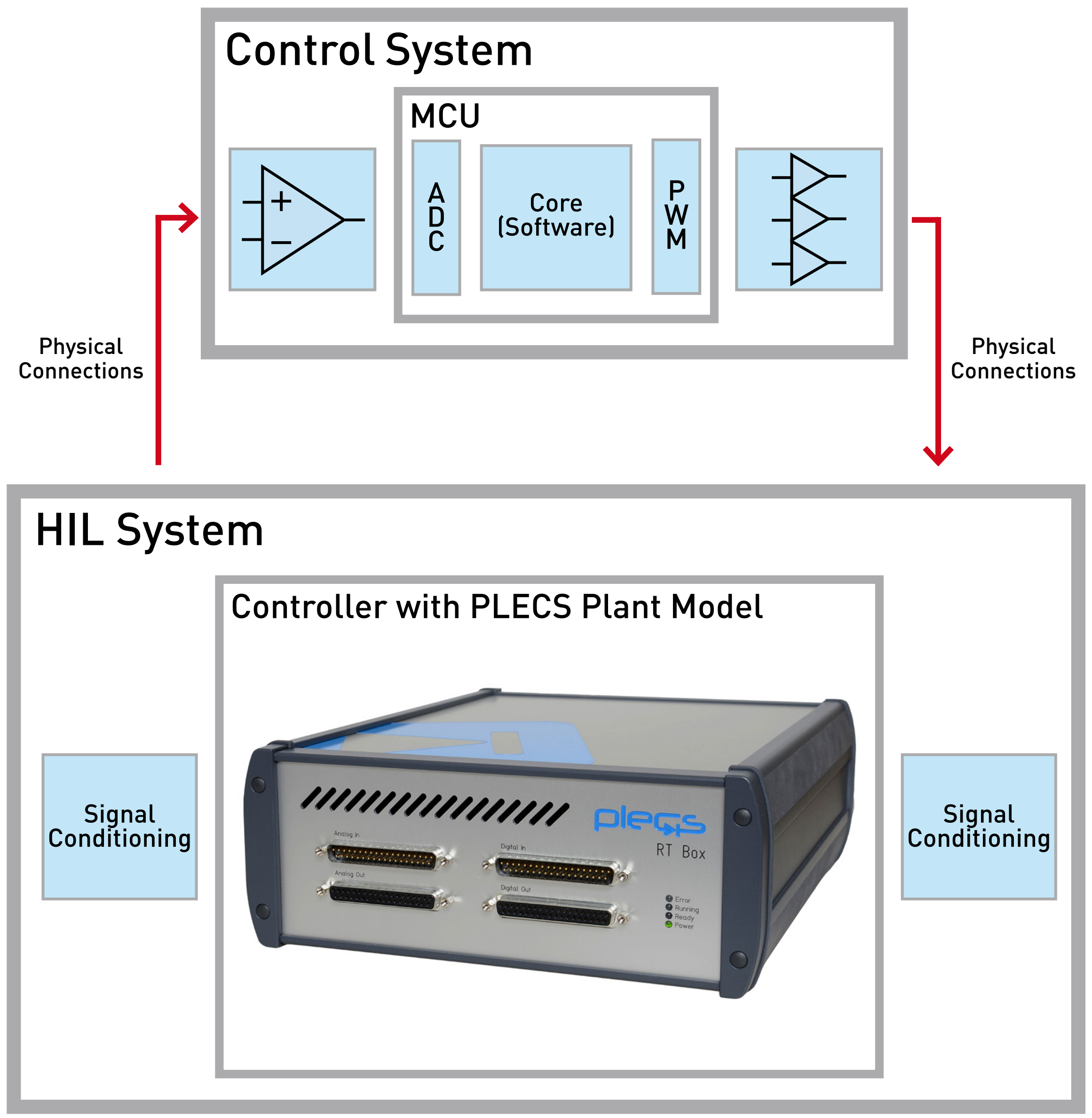
HIL Visual



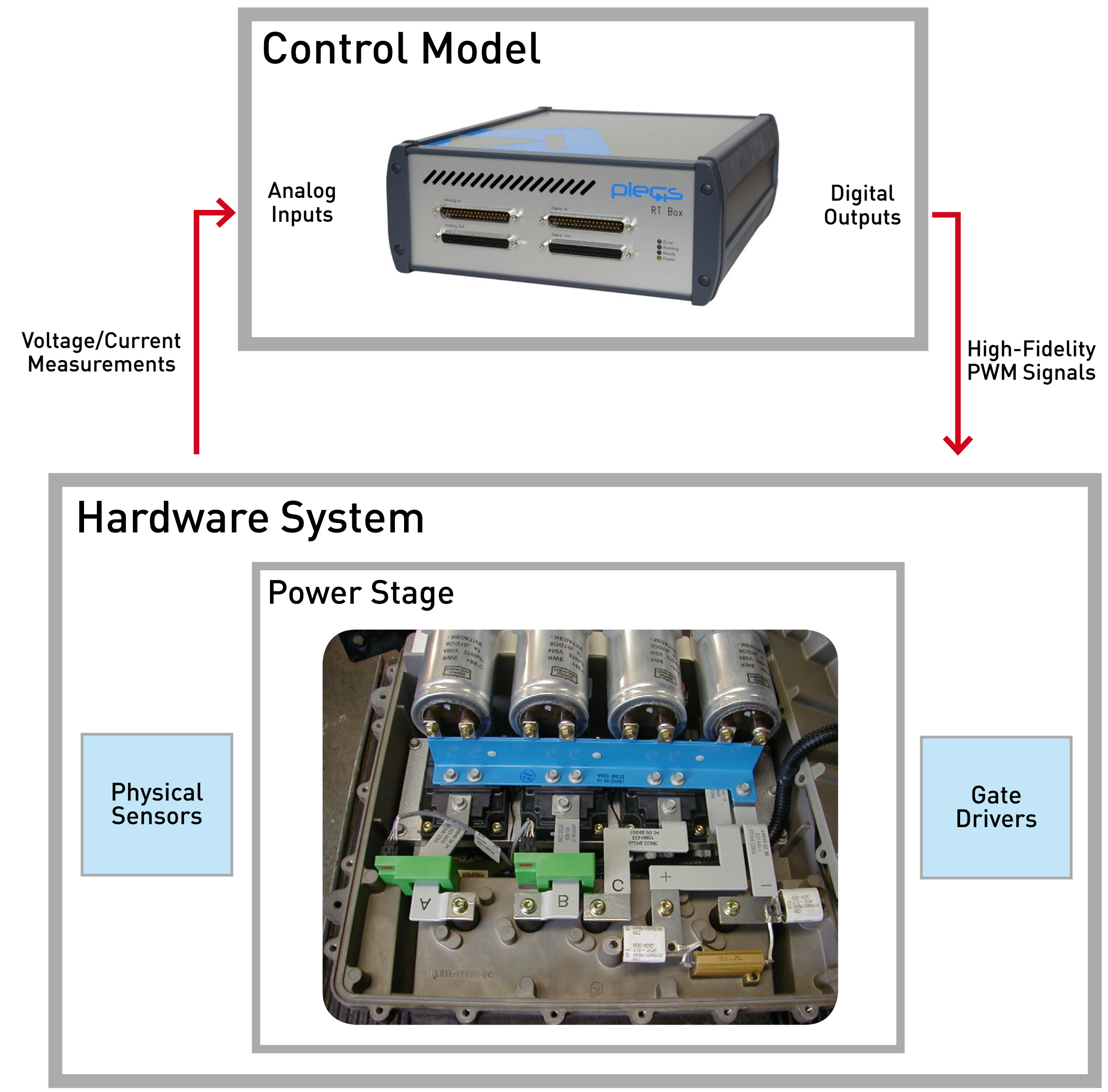
Control System
MCU
+
-
A
D
C
Core
(Software)
P
W
M
Physical Connections
Physical Connections
HIL System
Controller with Low-Fidelity Plant Model
Signal
Conditioning
Signal
Conditioning

PLECS RT Box Applications

Hardware-in-the-Loop



Rapid Control Prototyping



PLECS Code Generation Principle

Circuit in continuous State Space

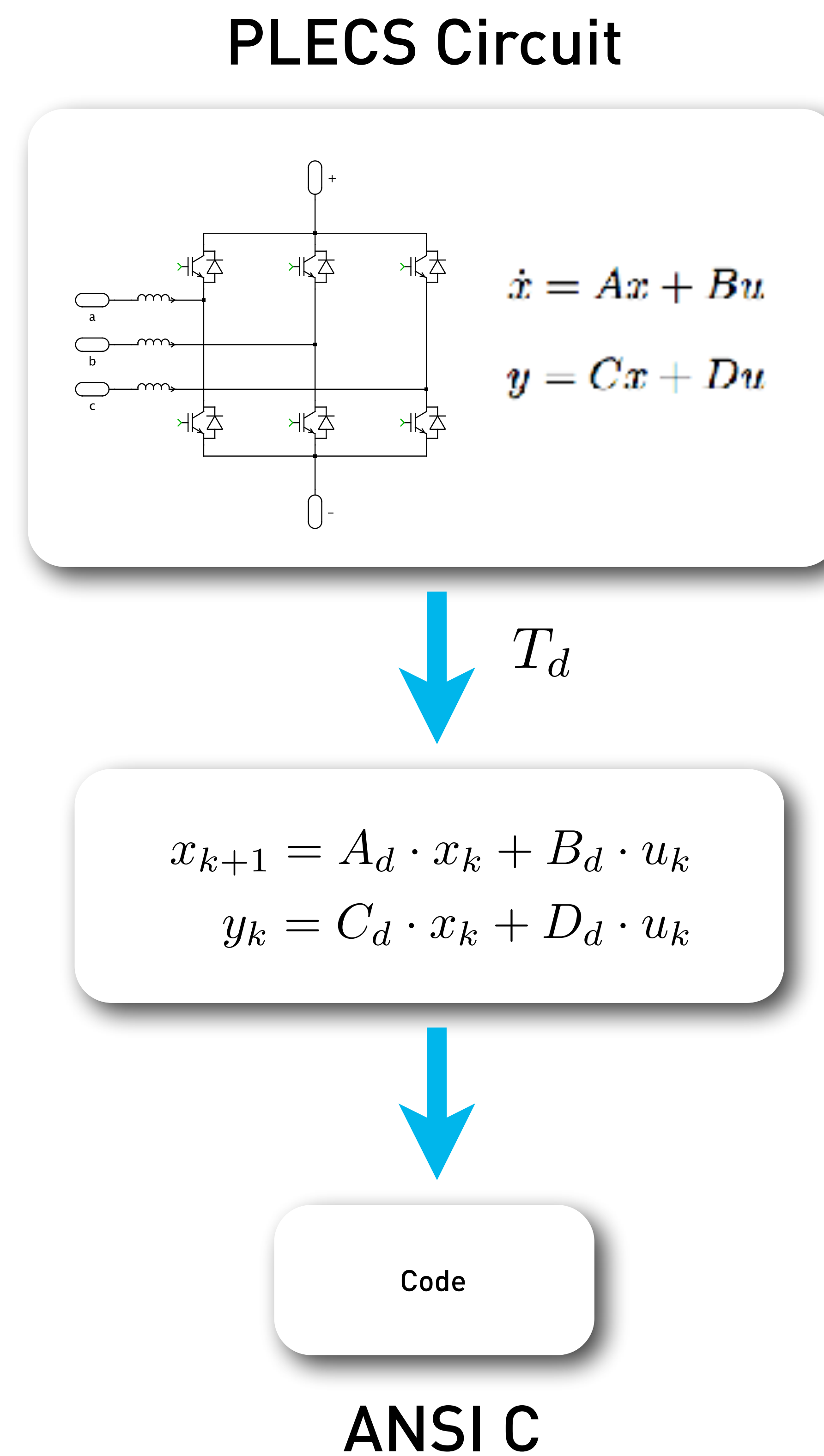
- One set of matrices per switch combination

Discretization to discrete State Space

- Model depends on step size T_d
- Physical model states discretized with Tustin method
- Integrators discretized with Forward Euler method

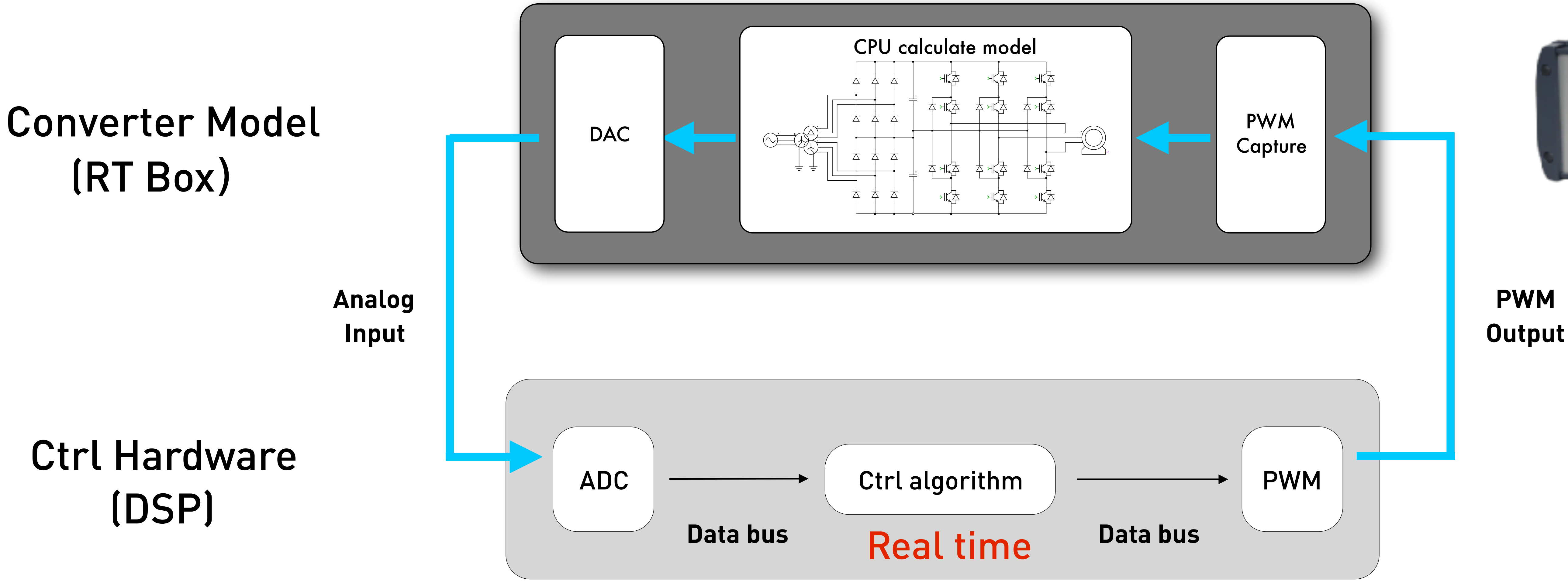
Integration into ANSI-C

- Generic C-Code
- Platform and solver dependent code



RT Box HIL Workflow

Run generated model code with physical controller



Characteristics of Real-Time Testing with the PLECS RT Box

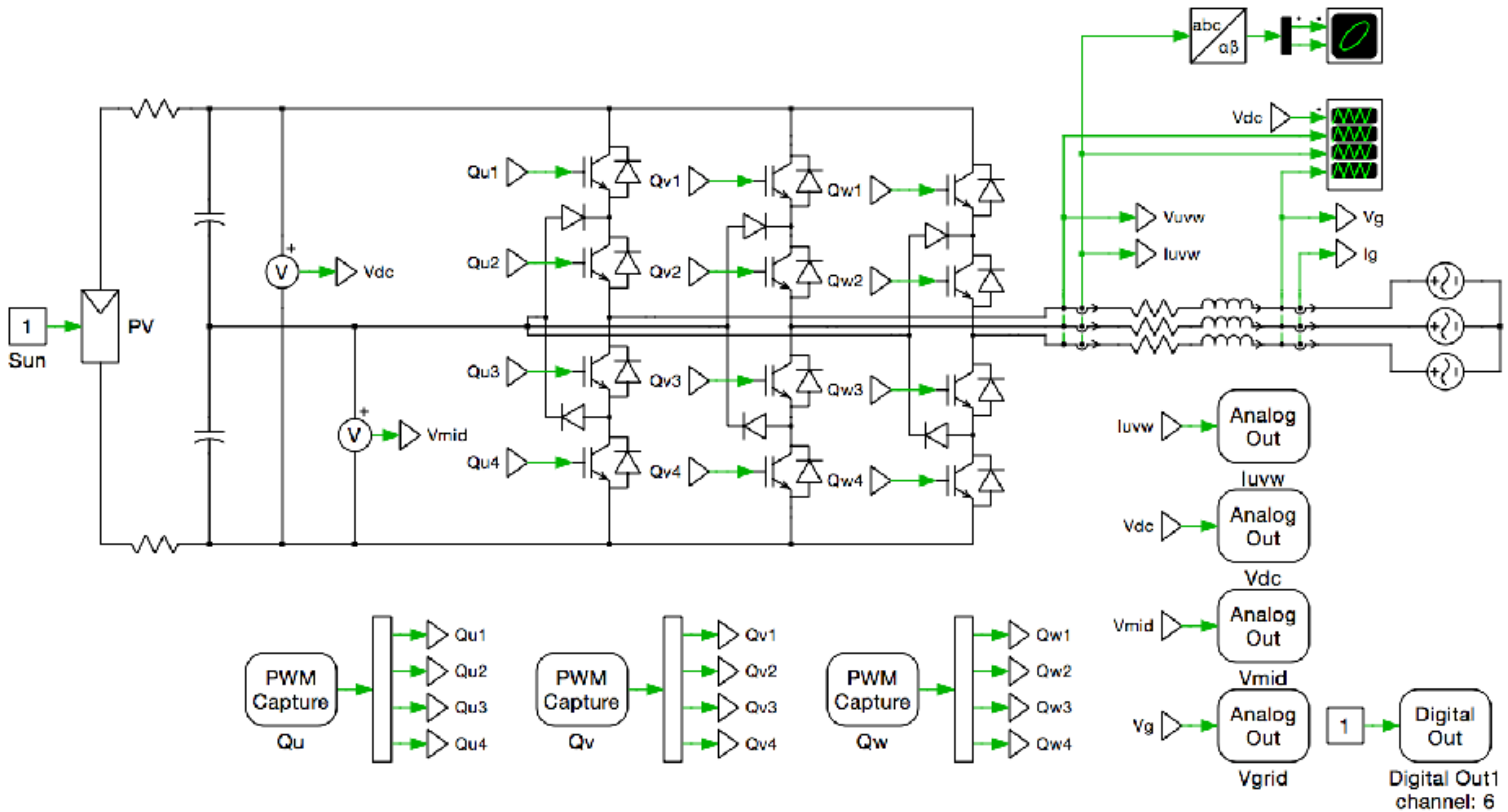
Benefits

- Test entire controller unit including software and hardware
- Plant model derived from offline simulation environment (reusable again)
- Intuitive code generation and workflow routine
- Visualize simulation results in the and tune model parameters on the fly

Challenge

- Possible limits on complexity of plant model, switching speed

Grid-tied 3-Level Inverter



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Summary of PIL vs. HIL Testing

- PIL benefits (as compared to HIL)
  - Much lower cost
  - No limitations on complexity of plant model
  - Controls at any switching frequency
  - Pseudo real-time execution facilitates debugging
  - Suited to software development and testing
- HIL benefits (as compared to PIL)
  - Required for testing complete controller
  - Provides safe alternative to high-power hardware testing
  - Can’t destroy actual devices and components
  - Suited for final verification and validation

electrical engineering software

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