MATLAB EXPO

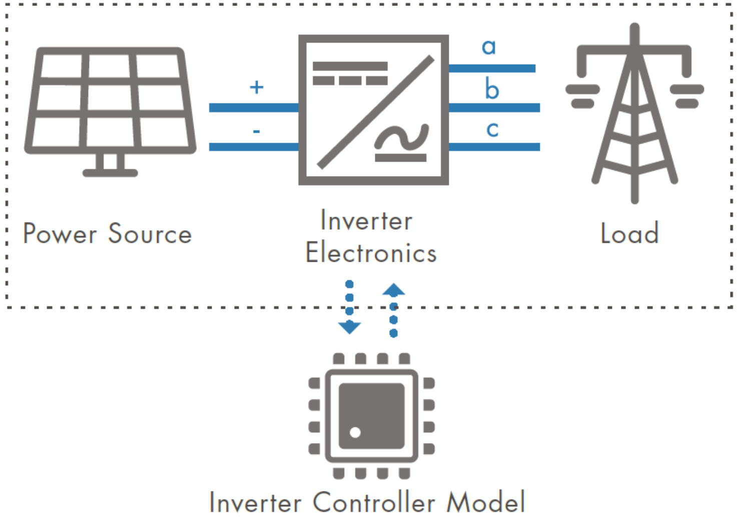
Implementing and Real-Time Testing of a Grid-Tied Solar Inverter Controller

Rahul Choudhary and Shripad Chandrachood

MathWorks®

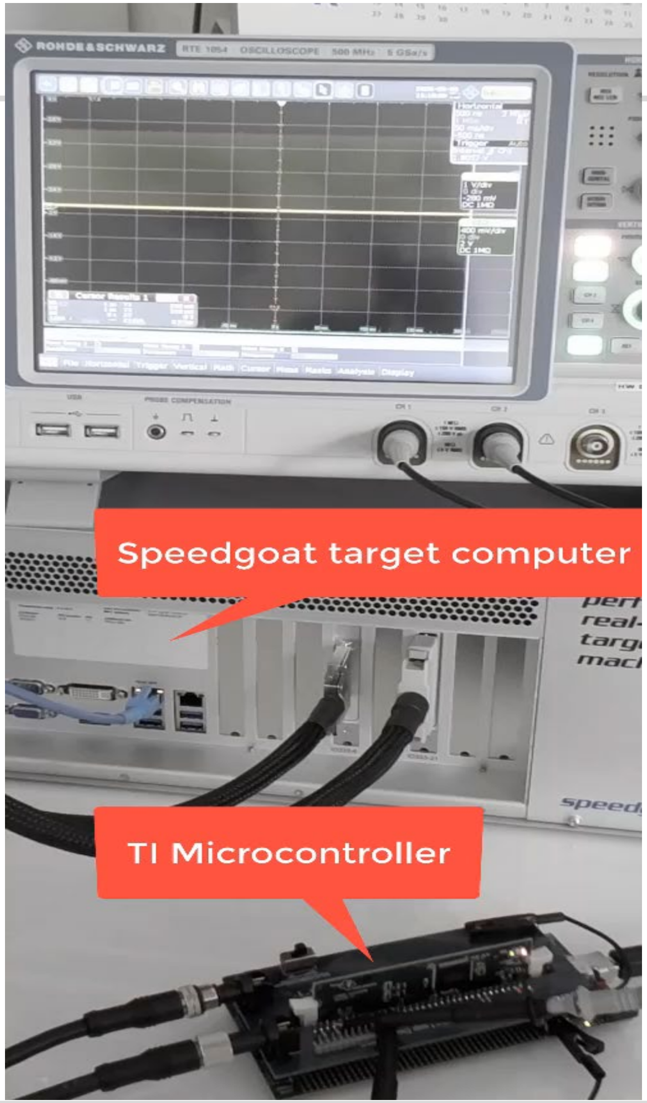
Simulink and Speedgoat are a common platform for control design and testing

Design and optimize controls using electrical systems simulation



Generate code for the plant

and the controller



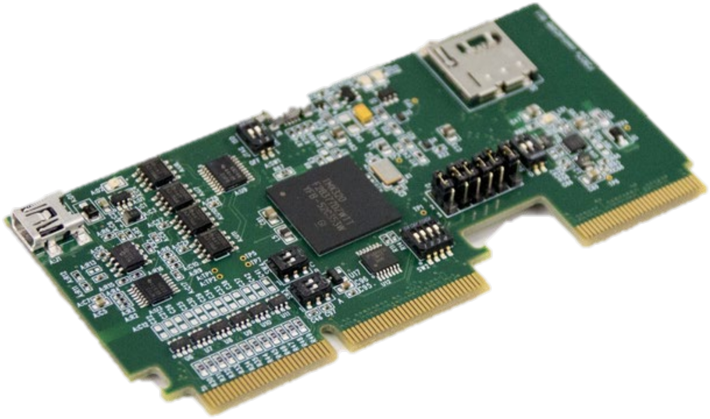
Key Takeaways

- Simplify control development for power electronics using Simscape Electrical and Speedgoat hardware
- Automatically generate C and HDL code for plant simulations and production code from Simulink and Simscape Electrical
- Use hardware-in-the-loop to test normal operation and fault conditions such as Fault-Ride Through

What is Our Goal?

- Primary goal is to design power electronics hardware and controllers

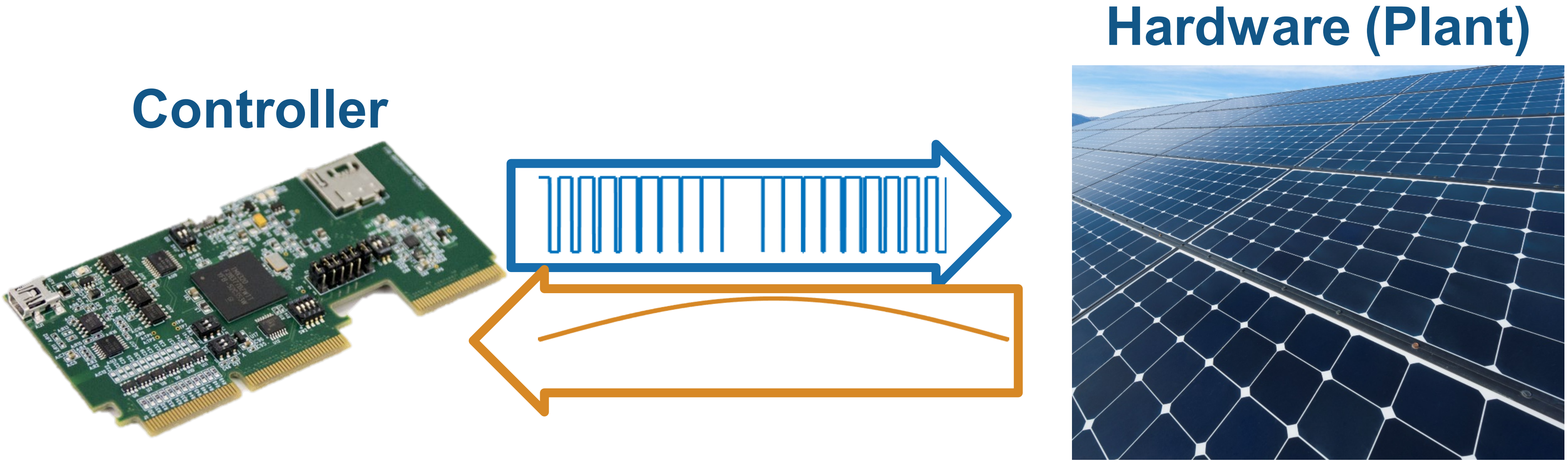
Controller



Hardware (Plant)

What is Our Goal?

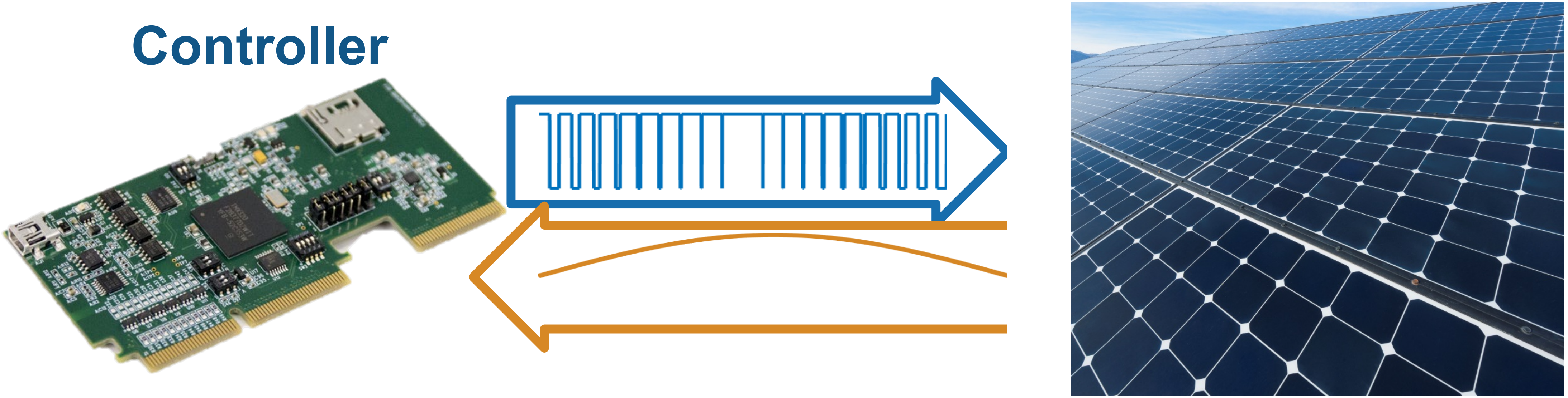
- Primary goal is to design power electronics hardware and controllers
  - Hardware in the loop (HIL) testing can improve this process



What is Hardware in the Loop (HIL) Testing

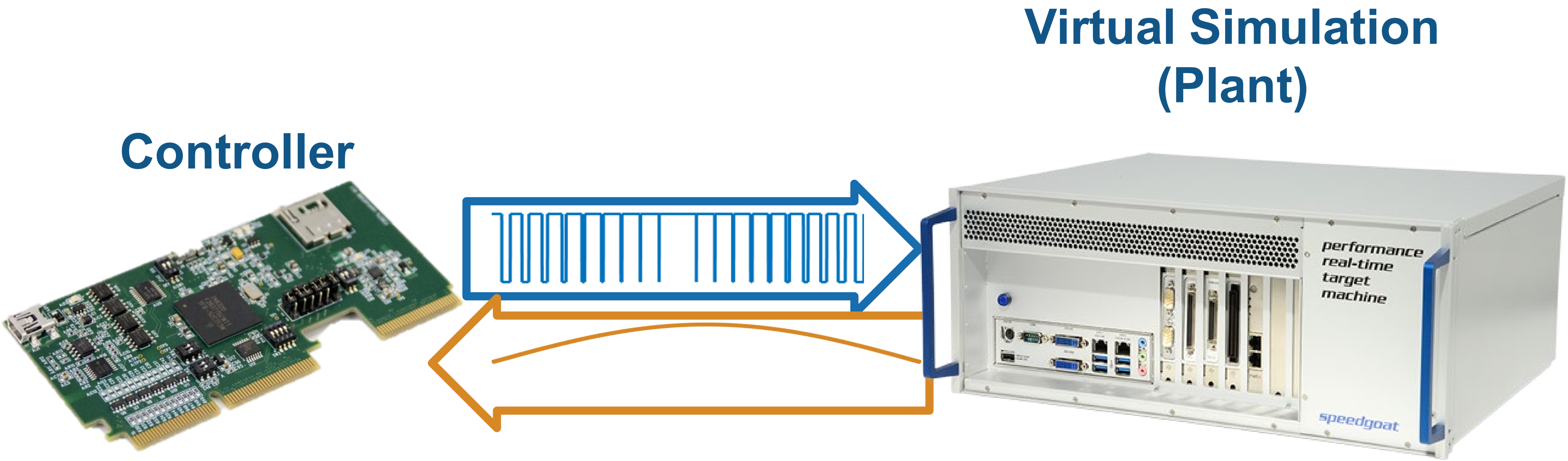
- HIL replaces the power electronics hardware with a virtual simulation

Controller



What is Hardware in the Loop (HIL) Testing

- HIL replaces the power electronics hardware with a virtual simulation
  - Controller can operate as if in the real system

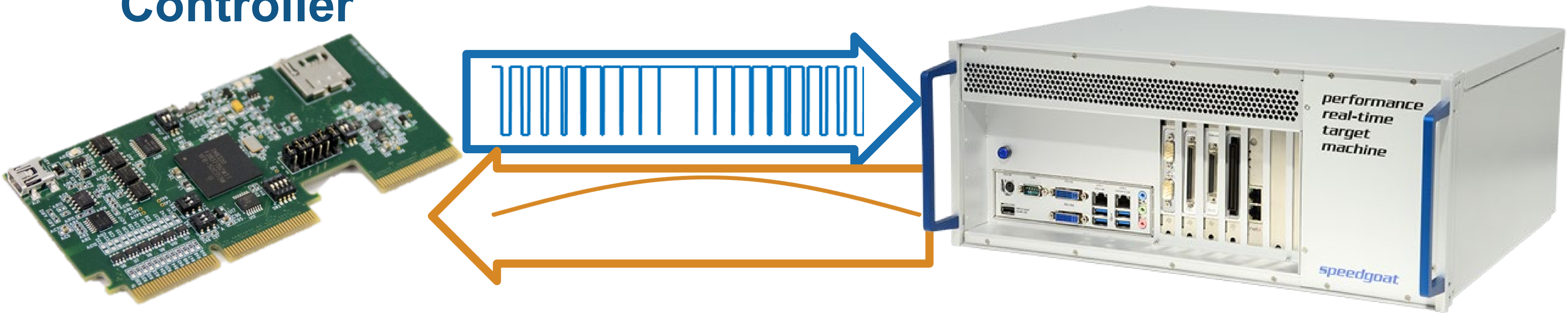


Advantages of Hardware in the Loop (HIL) Testing

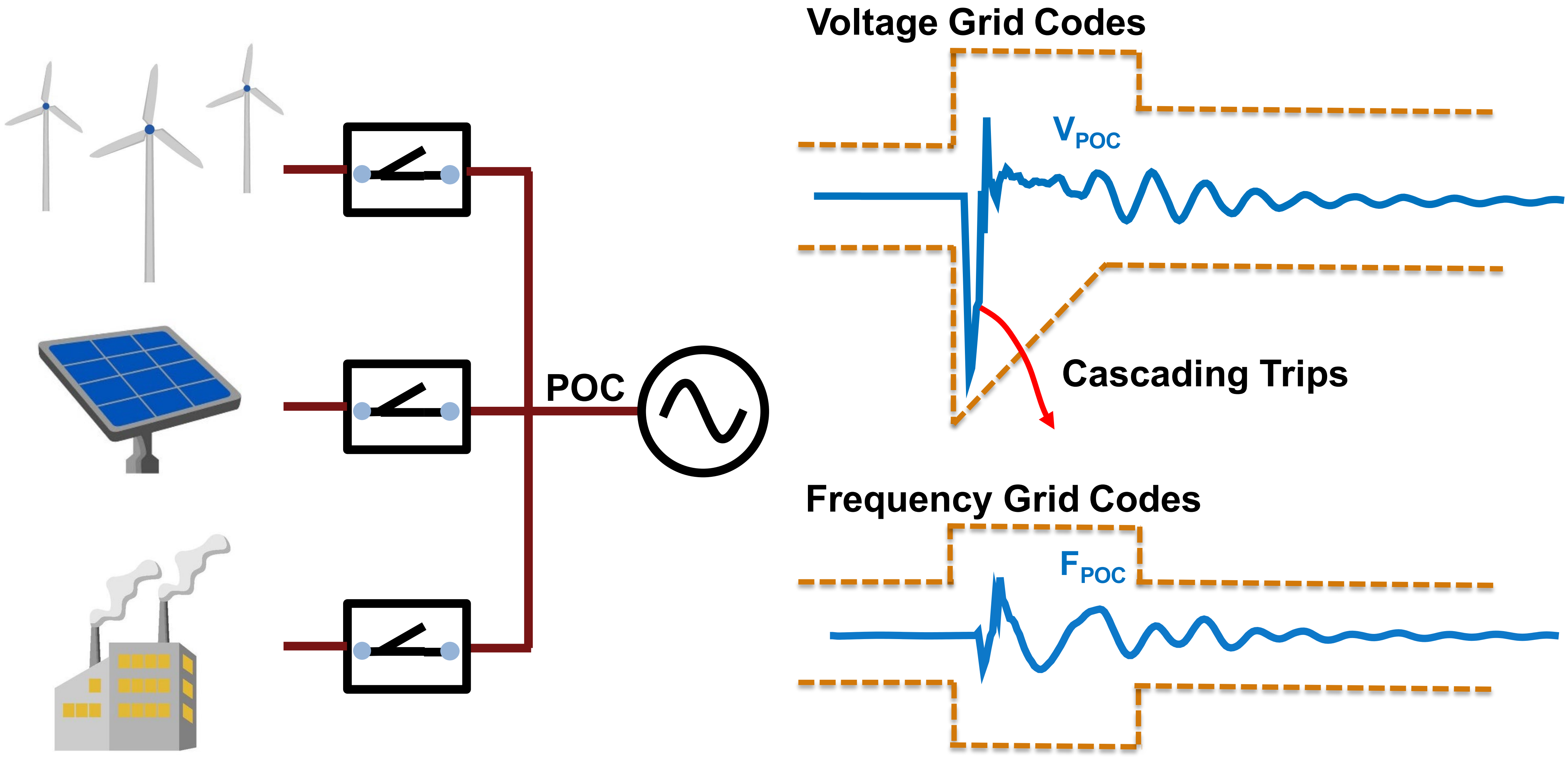
- Can replace prototypes or production hardware with a real-time system
- Easier to automate testing and **test grid code fault scenarios**
- Safer than most power electronics hardware
- Start many design/test tasks earlier

Virtual Simulation (Plant)

Controller



Protecting the Utility Grid



Model Based Design for Power Electronics

REQUIREMENTS

C or HDL Code generated from plant model

DESKTOP SIMULATION

PLANT
Load, power supply, power electronics, batteries, passive circuit components

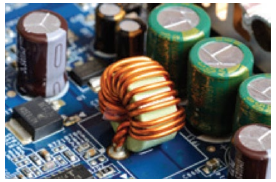
SYSTEM MODEL

CONTROLLER
Algorithms for power electronics control

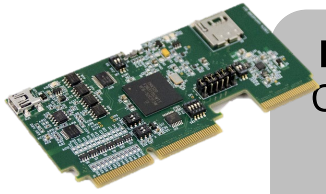
REAL-TIME SIMULATION

HARDWARE PROTOTYPE
Power electronics, battery packs, power supplies, electrical loads

HARDWARE-IN-THE-LOOP SIMULATION
Behavioral model running on a real-time computer



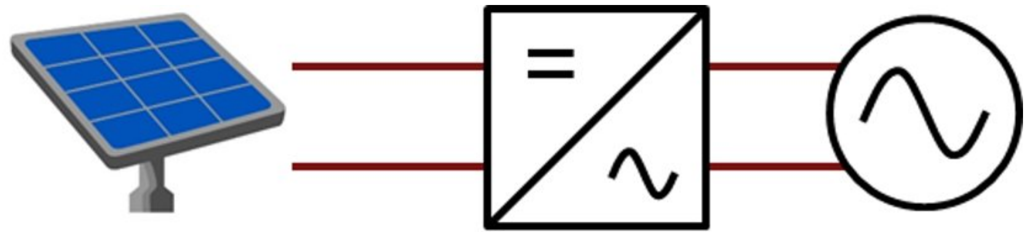
Real-time communication

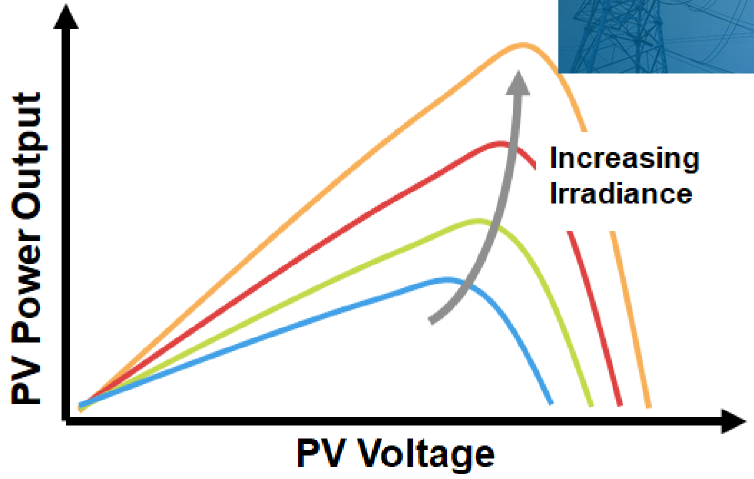


RAPID CONTROL PROTOTYPING
Control algorithms running on a real-time computer, microcontroller, or Simulink-programmable FPGA

C or HDL Code generated from controller model

Overview of Solar Inverter Control Development

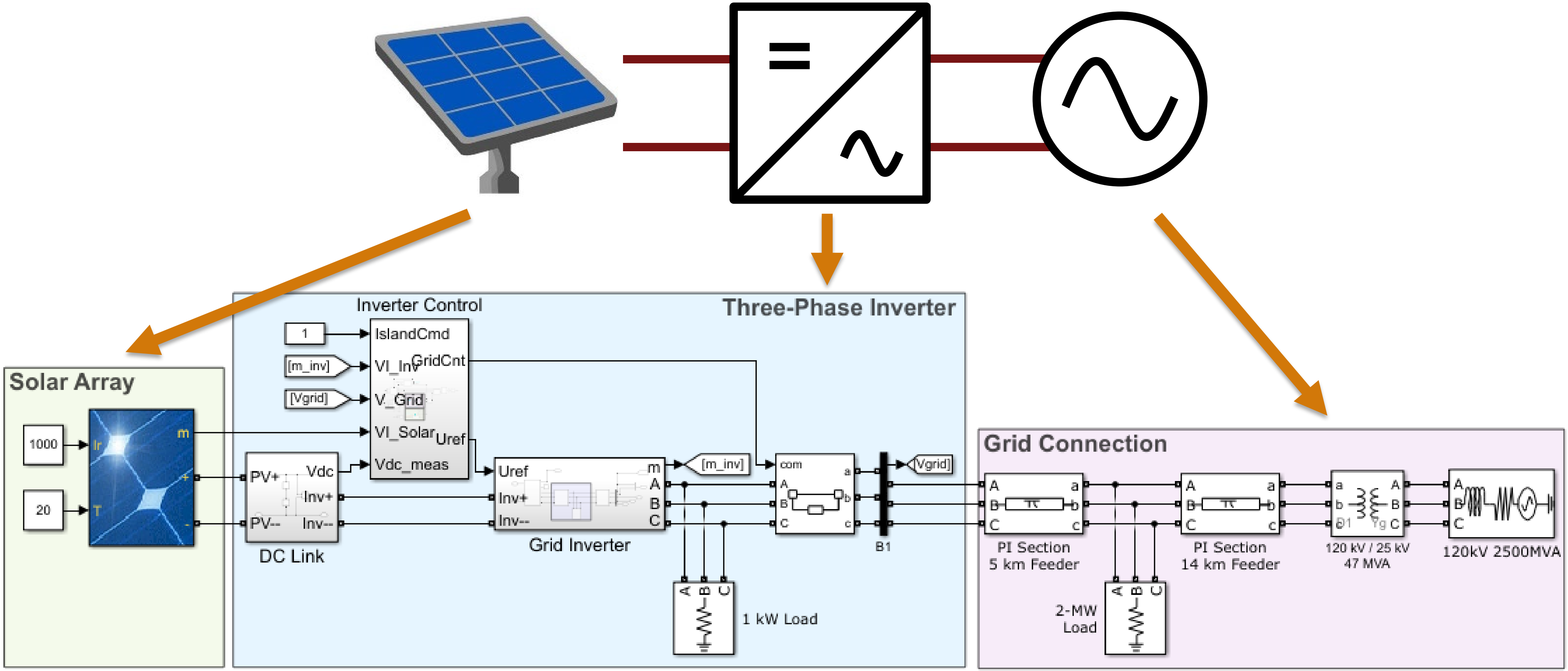


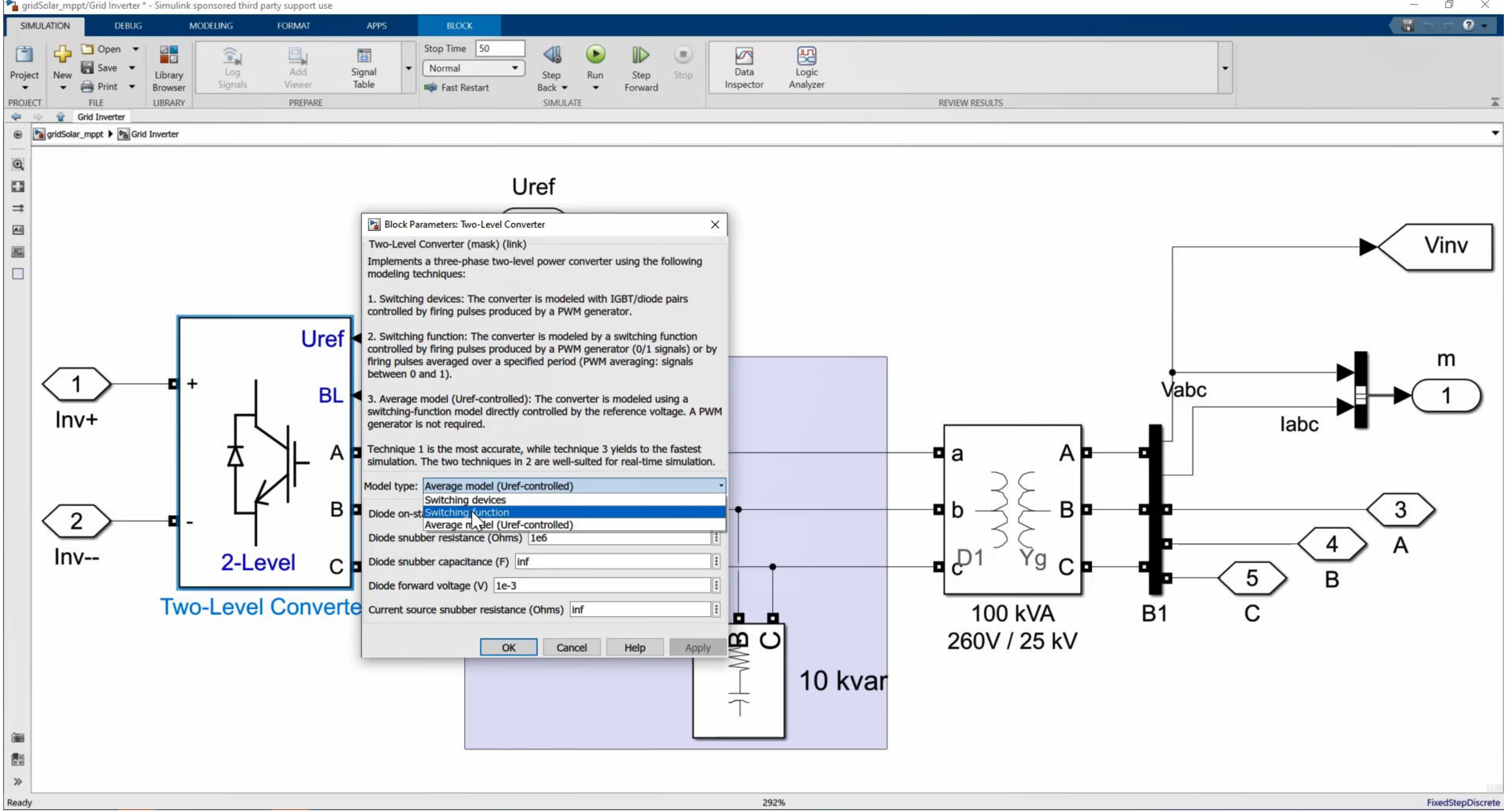


1. **Plant Modeling**
   (Photovoltaic plant, Inverter, Grid)
2. **Control Design**
   (Grid synchronization, MPPT algorithm)
3. **Automatic Code Generation**
   (Deploy code to TI C2000 and Speedgoat hardware)
4. **Hardware-in-the-Loop Testing**
   (Controller verification with Speedgoat hardware)

1 Plant Modelling

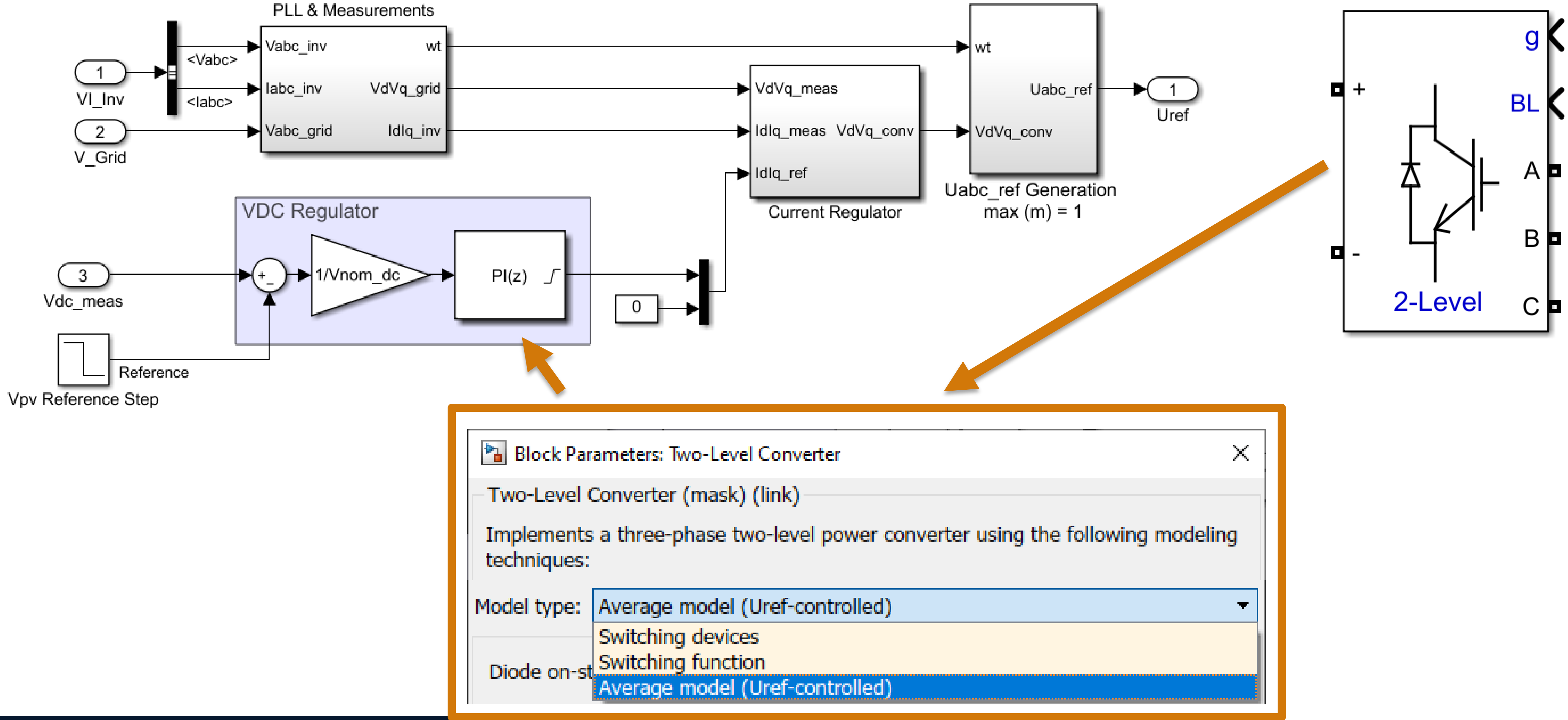
Schematic-based modeling with common power electronics topology

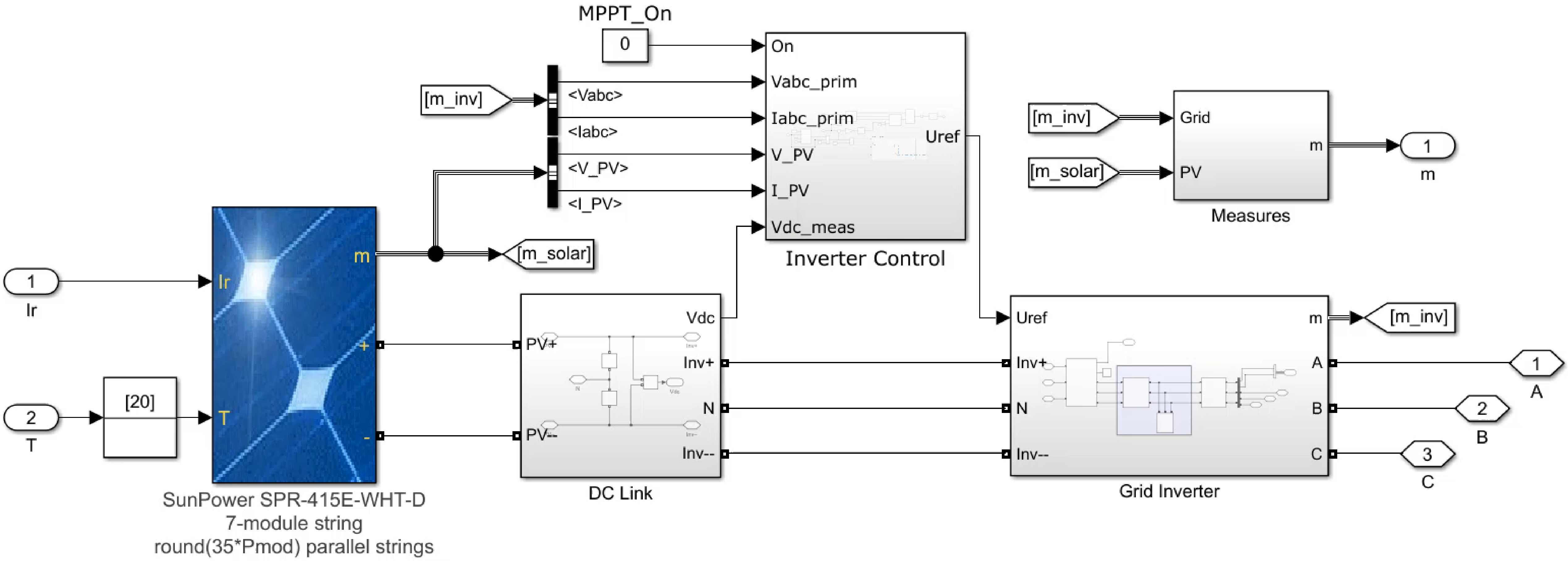


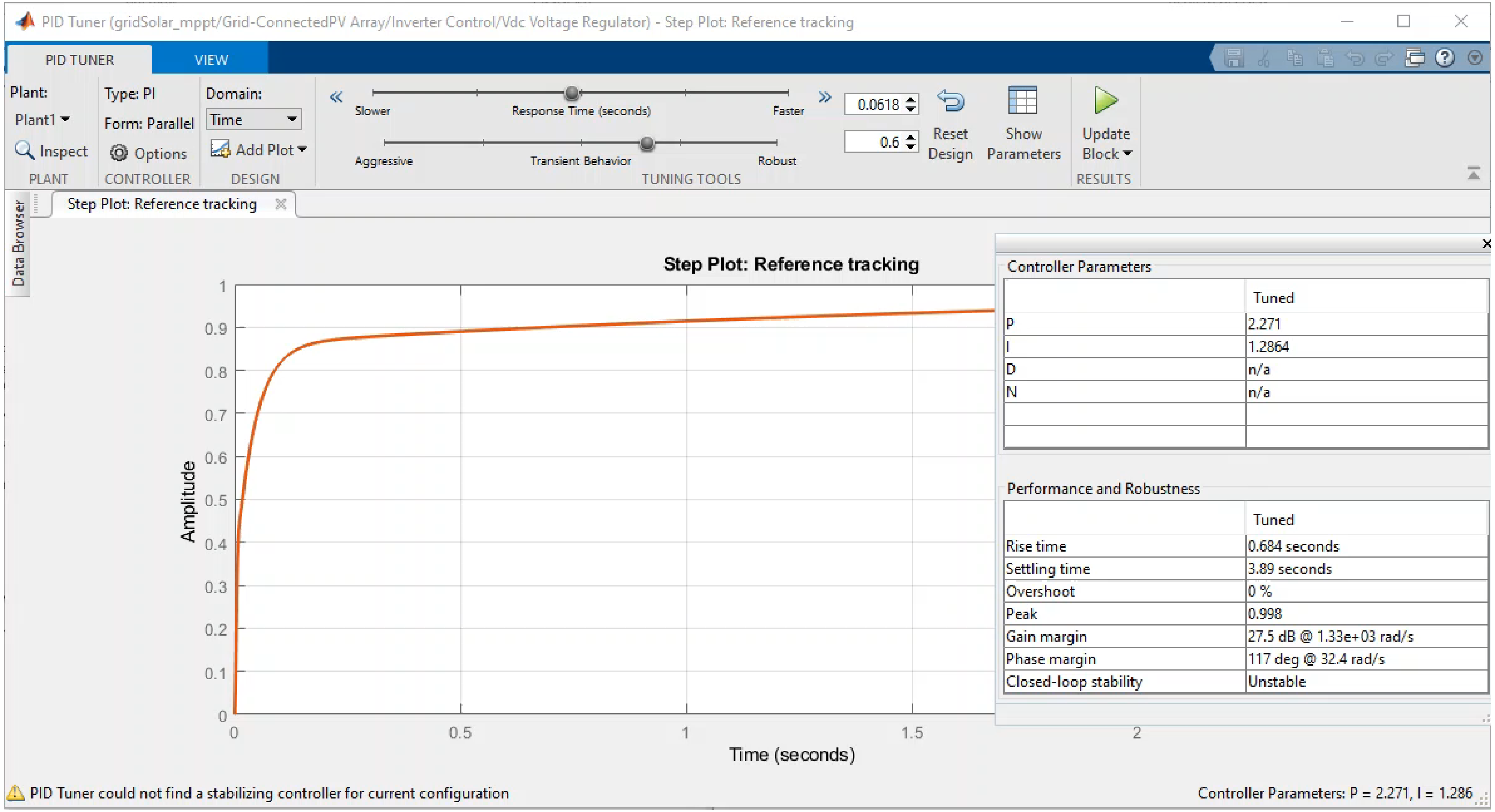

gridSolar_mppt/Grid Inverter * - Simulink sponsored third party support use
SIMULATION
DEBUG
MODELING
FORMAT
APPS
BLOCK
Project
New
Open
Save
Print
Library Browser
Log Signals
Add Viewer
Signal Table
Stop Time 50
Normal
Fast Restart
Step Back
Run
Step Forward
Stop
Data Inspector
Logic Analyzer
PROJECT
FILE
LIBRARY
PREPARE
SIMULATE
REVIEW RESULTS
Grid Inverter
gridSolar_mppt
Grid Inverter
Uref
Block Parameters: Two-Level Converter
Two-Level Converter (mask) (link)
Implements a three-phase two-level power converter using the following modeling techniques:
1. Switching devices: The converter is modeled with IGBT/diode pairs controlled by firing pulses produced by a PWM generator.
2. Switching function: The converter is modeled by a switching function controlled by firing pulses produced by a PWM generator (0/1 signals) or by firing pulses averaged over a specified period (PWM averaging: signals between 0 and 1).
3. Average model (Uref-controlled): The converter is modeled using a switching-function model directly controlled by the reference voltage. A PWM generator is not required.
Technique 1 is the most accurate, while technique 3 yields to the fastest simulation. The two techniques in 2 are well-suited for real-time simulation.
Model type: Average model (Uref-controlled)
Switching devices
Switching function
Average model (Uref-controlled)
Diode on-st
Diode snubber resistance (Ohms) 1e6
Diode snubber capacitance (F) inf
Diode forward voltage (V) 1e-3
Current source snubber resistance (Ohms) inf
OK
Cancel
Help
Apply
1
Inv+
2
Inv--
+
-
Uref
BL
A
B
C
2-Level
Two-Level Converte
10 kvar
a
b
c
A
B
C
D1
Yg
100 kVA
260V / 25 kV
B1
Vinv
Vabc
Iabc
m
1
3
4
5
A
B
C
Ready
292%
FixedStepDiscrete

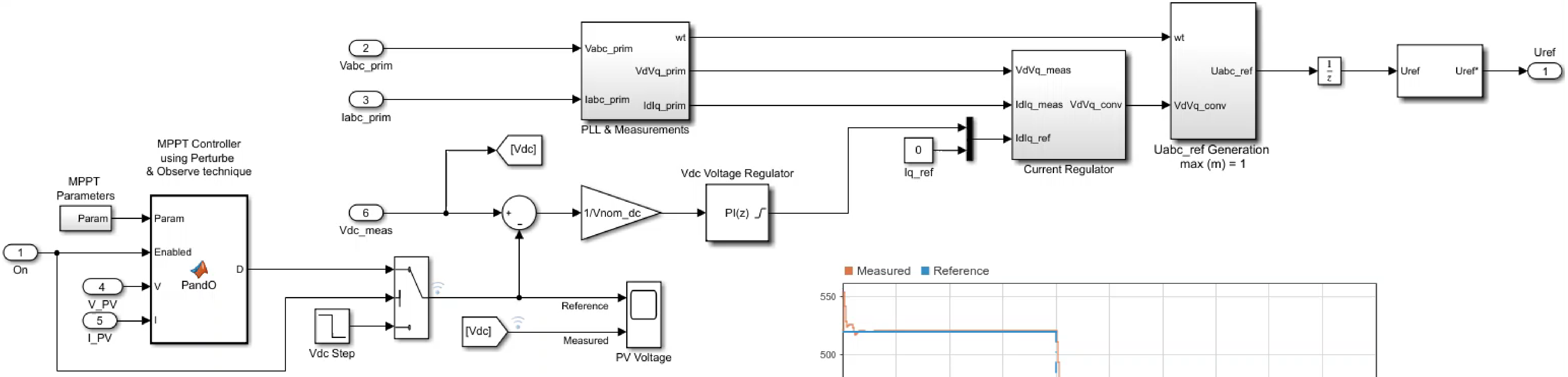
2 Control Design

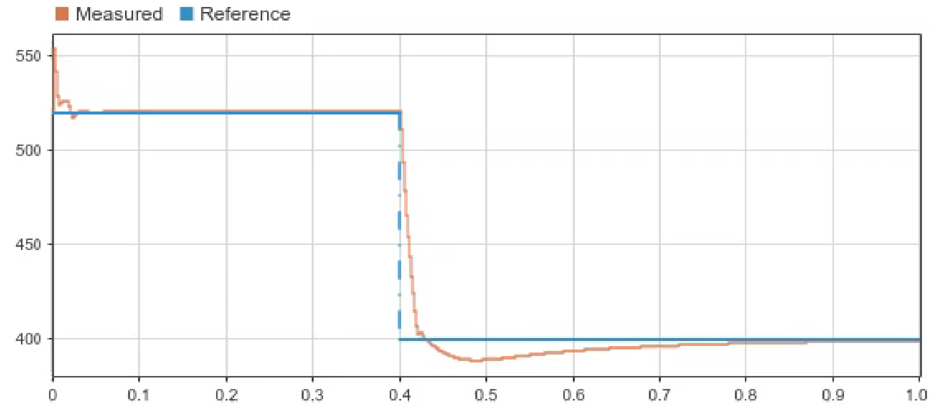
PID Tuning of Power Electronics – Leverage Average-Value Models




MPPT_On
0
On
Vabc_prim
Iabc_prim
V_PV
I_PV
Vdc_meas
Uref
Inverter Control
[m_inv]
<Vabc>
<Iabc>
<V_PV>
<I_PV>
[m_inv]
[m_solar]
Grid
PV
m
Measures
1
m
[m_solar]
1
Ir
2
T
[20]
Ir
T
m
+
-
SunPower SPR-415E-WHT-D
7-module string
round(35*Pmod) parallel strings
PV+
PV-
Vdc
Inv+
N
Inv-
DC Link
Uref
Inv+
N
Inv-
m
A
B
C
Grid Inverter
[m_inv]
1
A
2
B
3
C


PID Tuner (gridSolar_mppt/Grid-ConnectedPV Array/Inverter Control/Vdc Voltage Regulator) - Step Plot: Reference tracking
PID TUNER
VIEW
Plant:
Plant1
Inspect
PLANT
Type: PI
Form: Parallel
Options
CONTROLLER
Domain:
Time
Add Plot
DESIGN
Slower
Response Time (seconds)
Faster
Aggressive
Transient Behavior
Robust
TUNING TOOLS
0.0618
0.6
Reset Design
Show Parameters
Update Block
RESULTS
Data Browser
Step Plot: Reference tracking
Step Plot: Reference tracking
Amplitude
Time (seconds)
Controller Parameters
Tuned
P 2.271
I 1.2864
D n/a
N n/a
Performance and Robustness
Tuned
Rise time 0.684 seconds
Settling time 3.89 seconds
Overshoot 0 %
Peak 0.998
Gain margin 27.5 dB @ 1.33e+03 rad/s
Phase margin 117 deg @ 32.4 rad/s
Closed-loop stability Unstable
PID Tuner could not find a stabilizing controller for current configuration
Controller Parameters: P = 2.271, I = 1.286

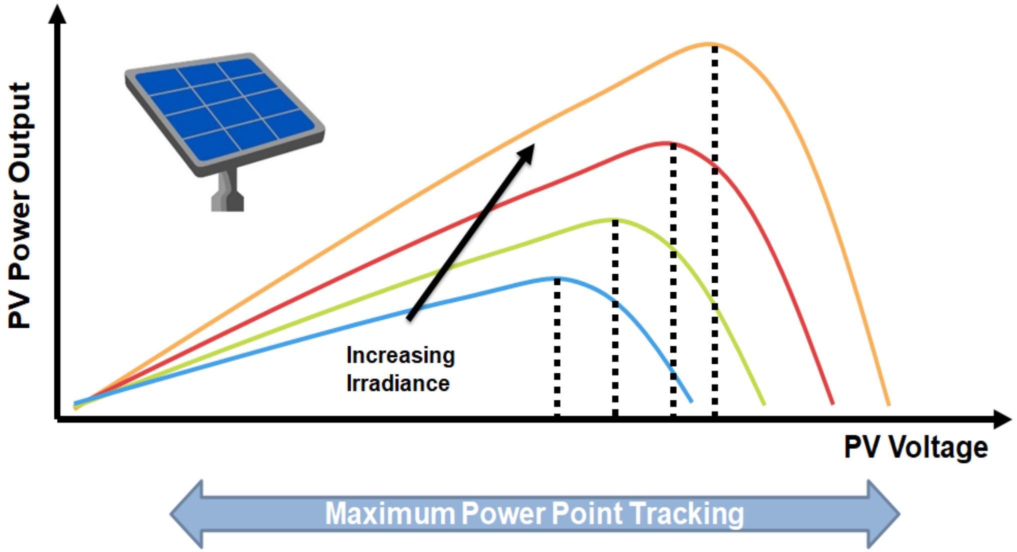




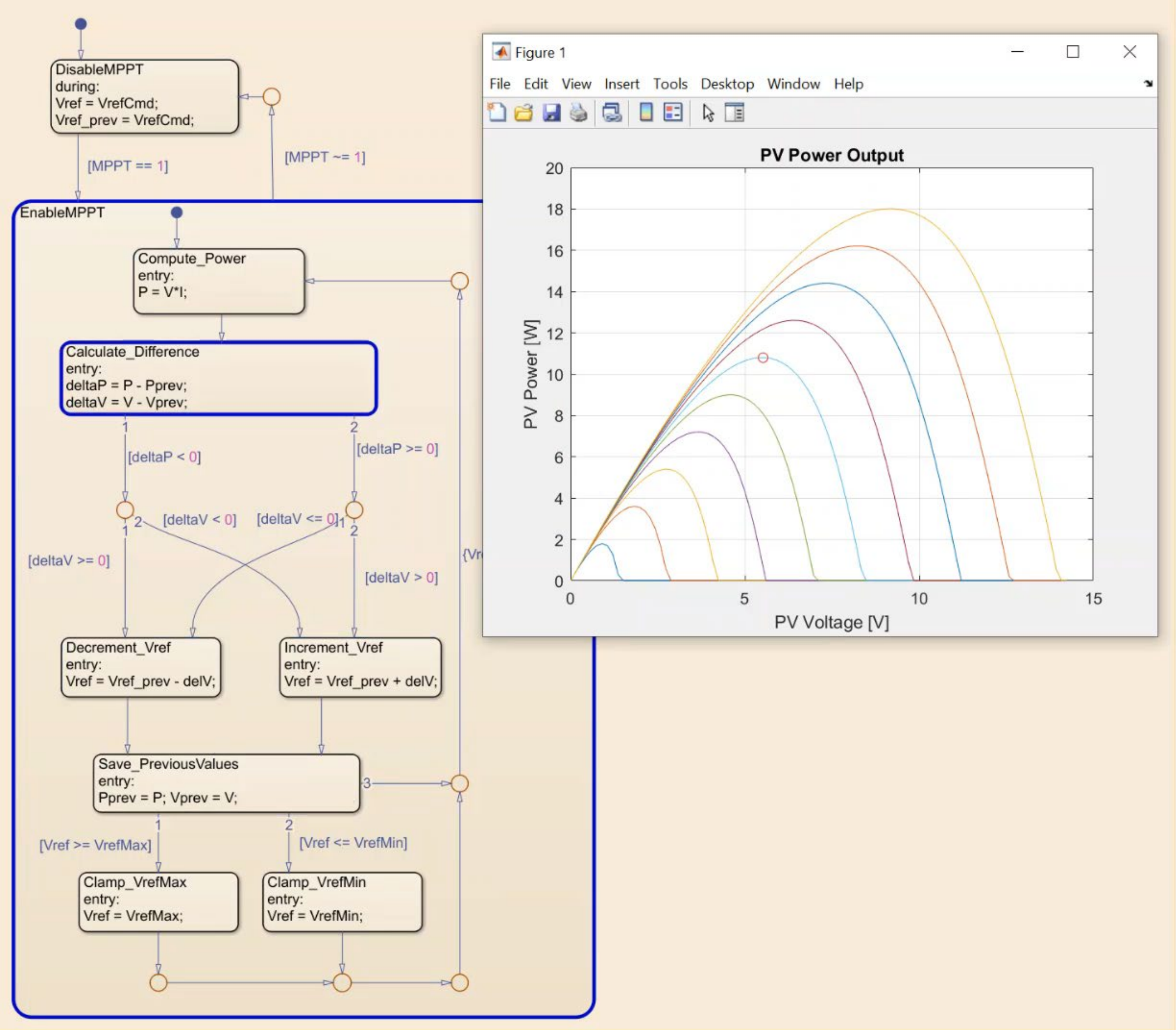
DC Voltage Control - PV Array

2 Control Design - MPPT

- **Using inverter control to track maximum power point**



Automatically adjust desired PV Voltage to find Peak Power Output at any Operating Condition

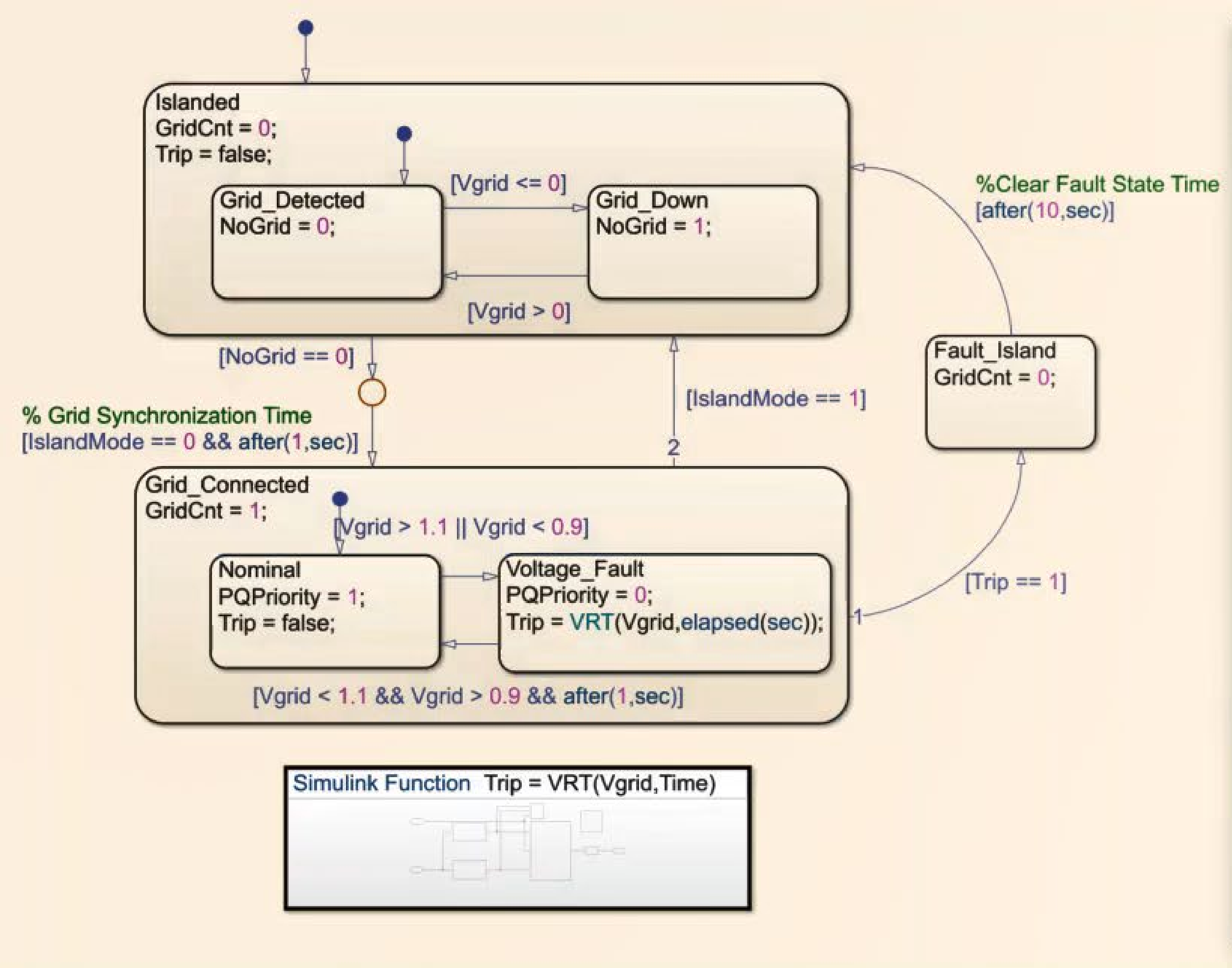


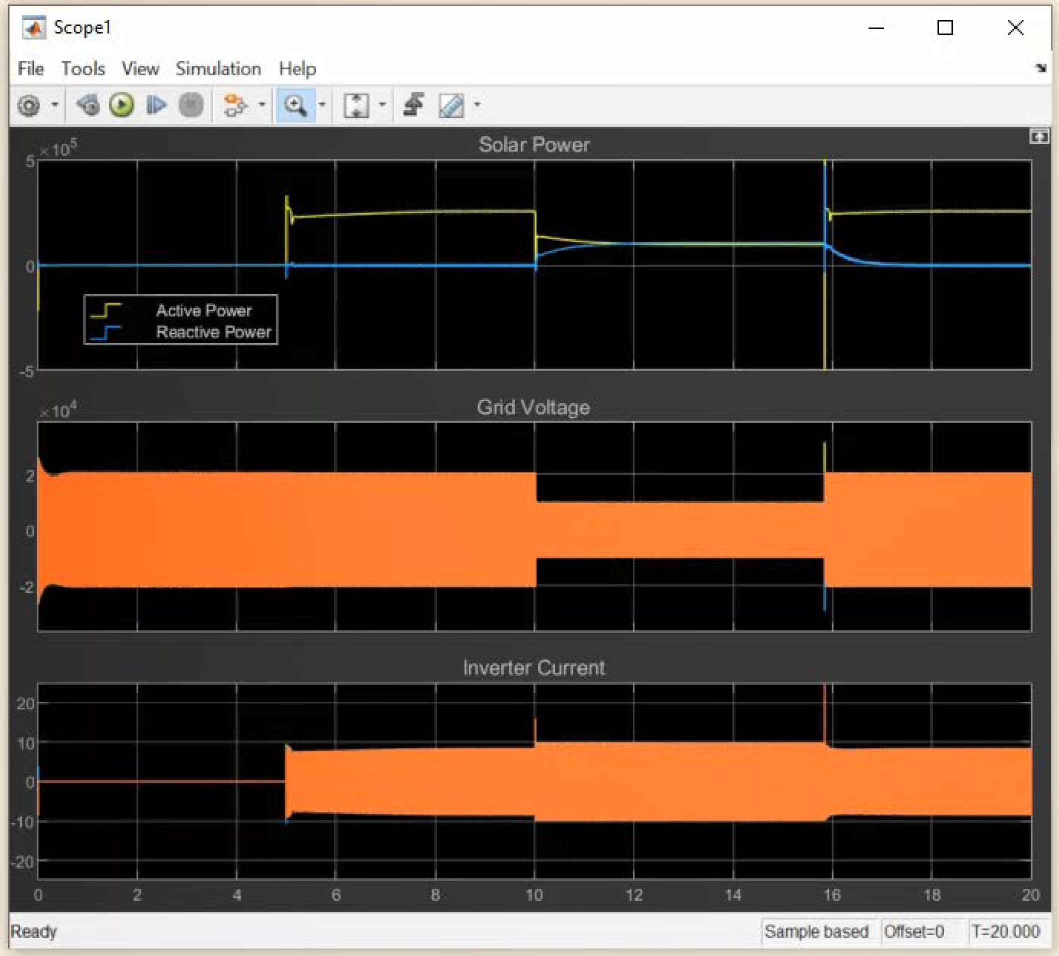
Learn more: [Webinar on Modeling, Simulating, and Generating Code for a Solar Inverter]

2 Control Design

Designing Fault-Ride Through Algorithms

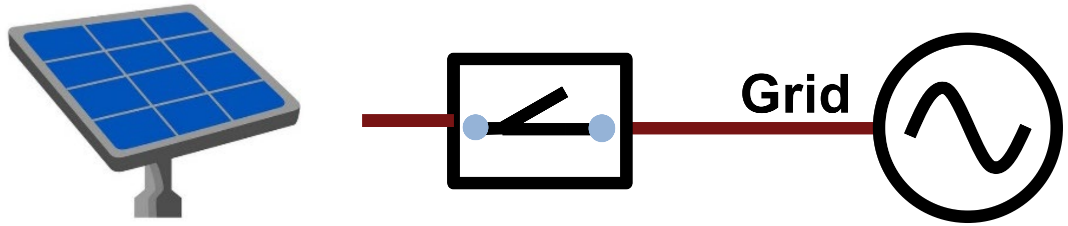
- **Reactive power support during low voltage fault**

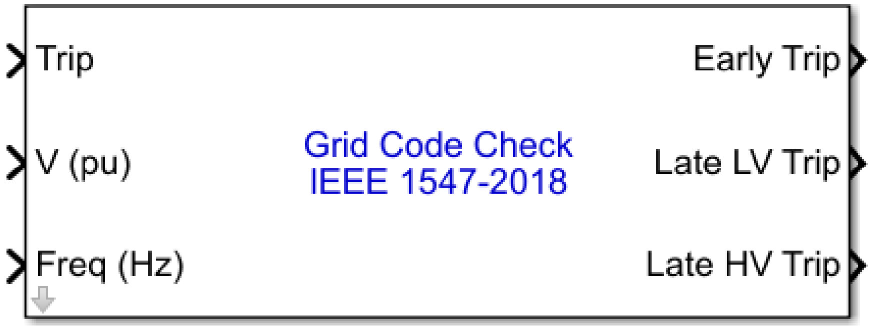




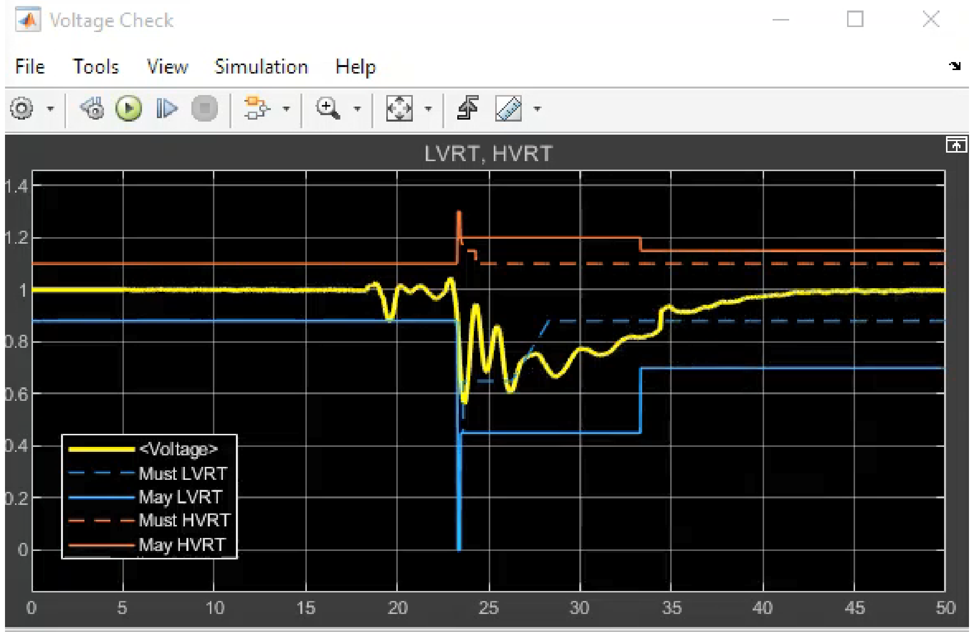
2 Control Design
Fault-Ride Through

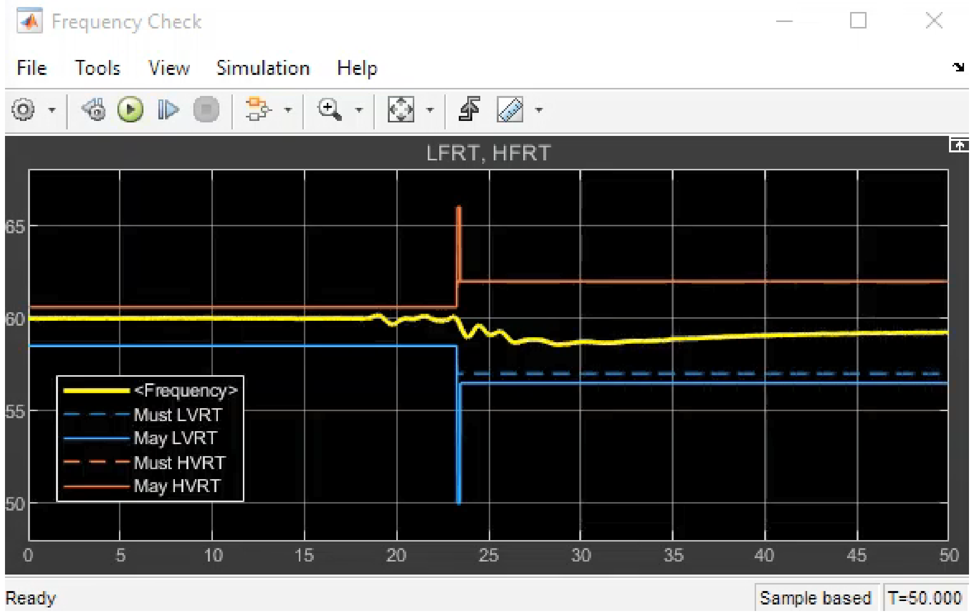
- **Testing Fault-Ride Through against Grid Codes such as IEEE 1547-2018**



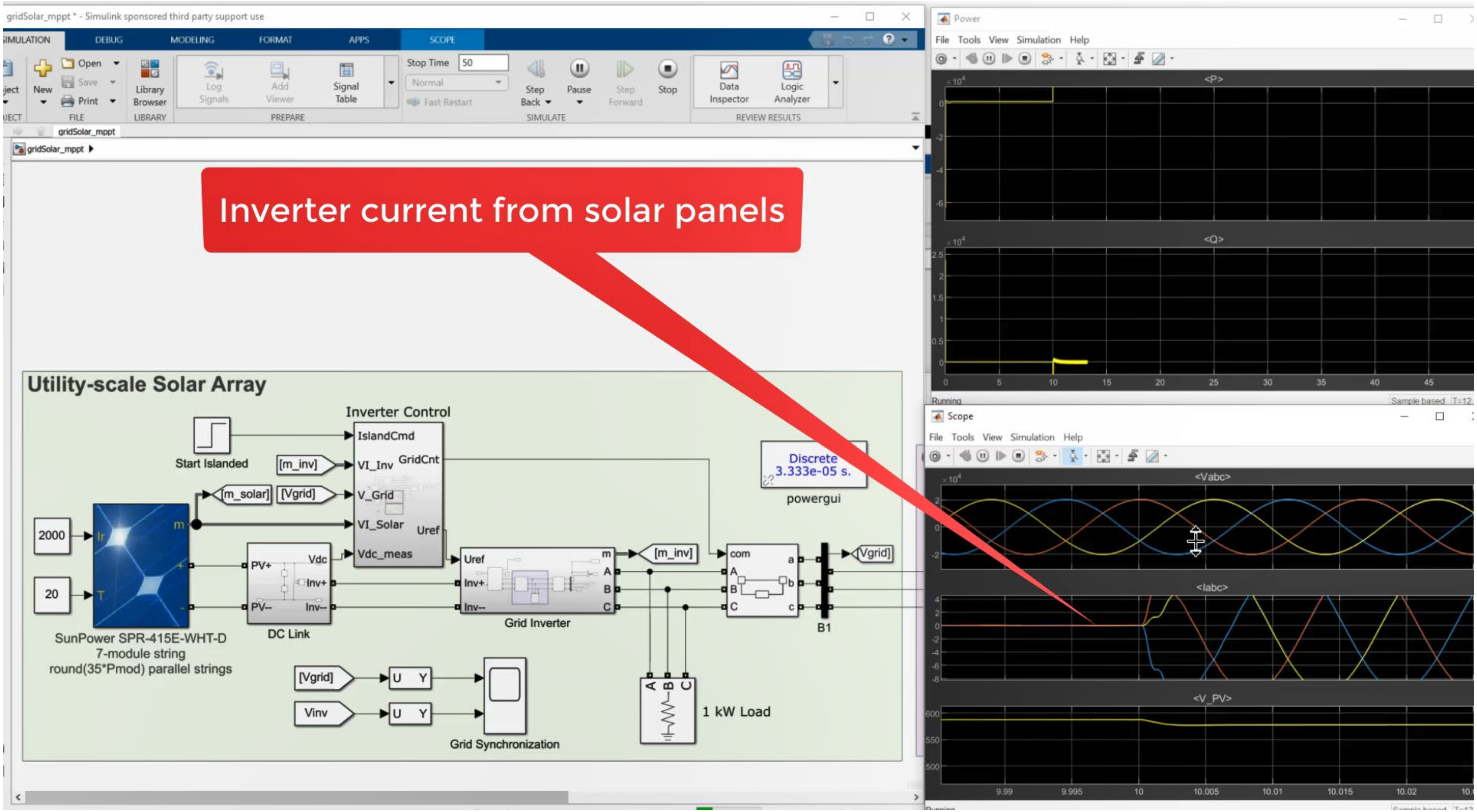


Grid
Code Check





Learn more: Webinar on Renewable Grid Integration Studies

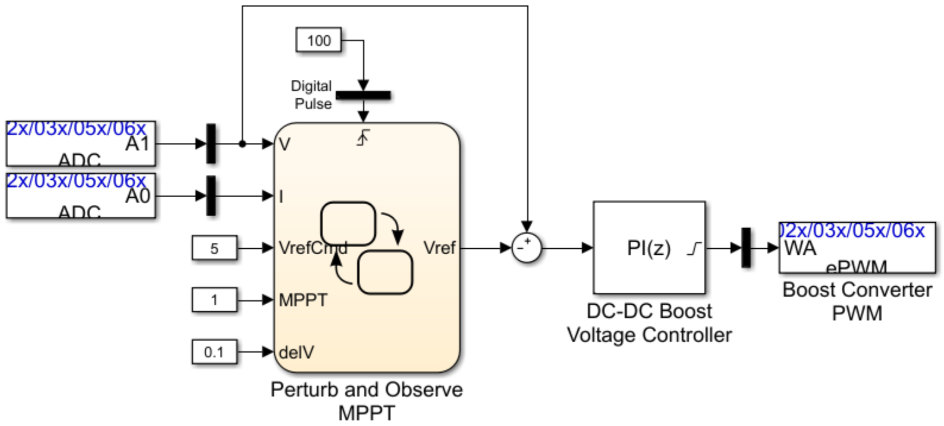


Inverter current from solar panels
Utility-scale Solar Array
Inverter Control
IslandCmd
VI_Inv
GridCnt
V_Grid
VI_Solar
Uref
Vdc_meas
Start Islanded
[m_inv]
[m_solar]
[Vgrid]
2000
20
SunPower SPR-415E-WHT-D
7-module string
round(35*Pmod) parallel strings
DC Link
Grid Inverter
Discrete
3.333e-05 s.
powergui
B1
1 kW Load
Vinv
Grid Synchronization
Power
<P>
<Q>
Scope
<Vabc>
<Iabc>
<V_PV>

3 Automatic Code Generation
Microcontroller

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

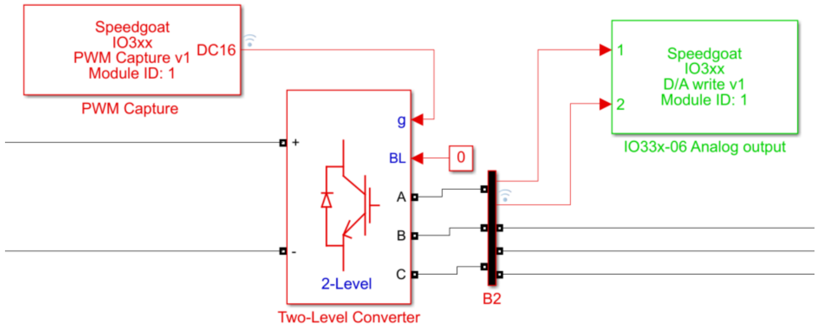
Combine Simulink Algorithms with C2000 IO Blocks	Auto-generate C code	Build and Implement using CCS	Operation Check with TI C2000



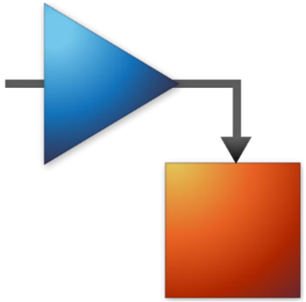
3 Automatic Code Generation
Speedgoat Real-Time Simulator

- **Use Simulink Real-Time and HDL Coder for C and HDL code generation**
- **Deploy to multi-core CPUs or multiple FPGAs**
- **Wide range of I/O connectivity, communication protocols and I/O functionality**

Combine Simulink Model with Speedgoat Driver Blocks	Auto-generate C code or HDL Code	Build using Simulink Real-Time	Operation with Speedgoat Target Computer



VHDL



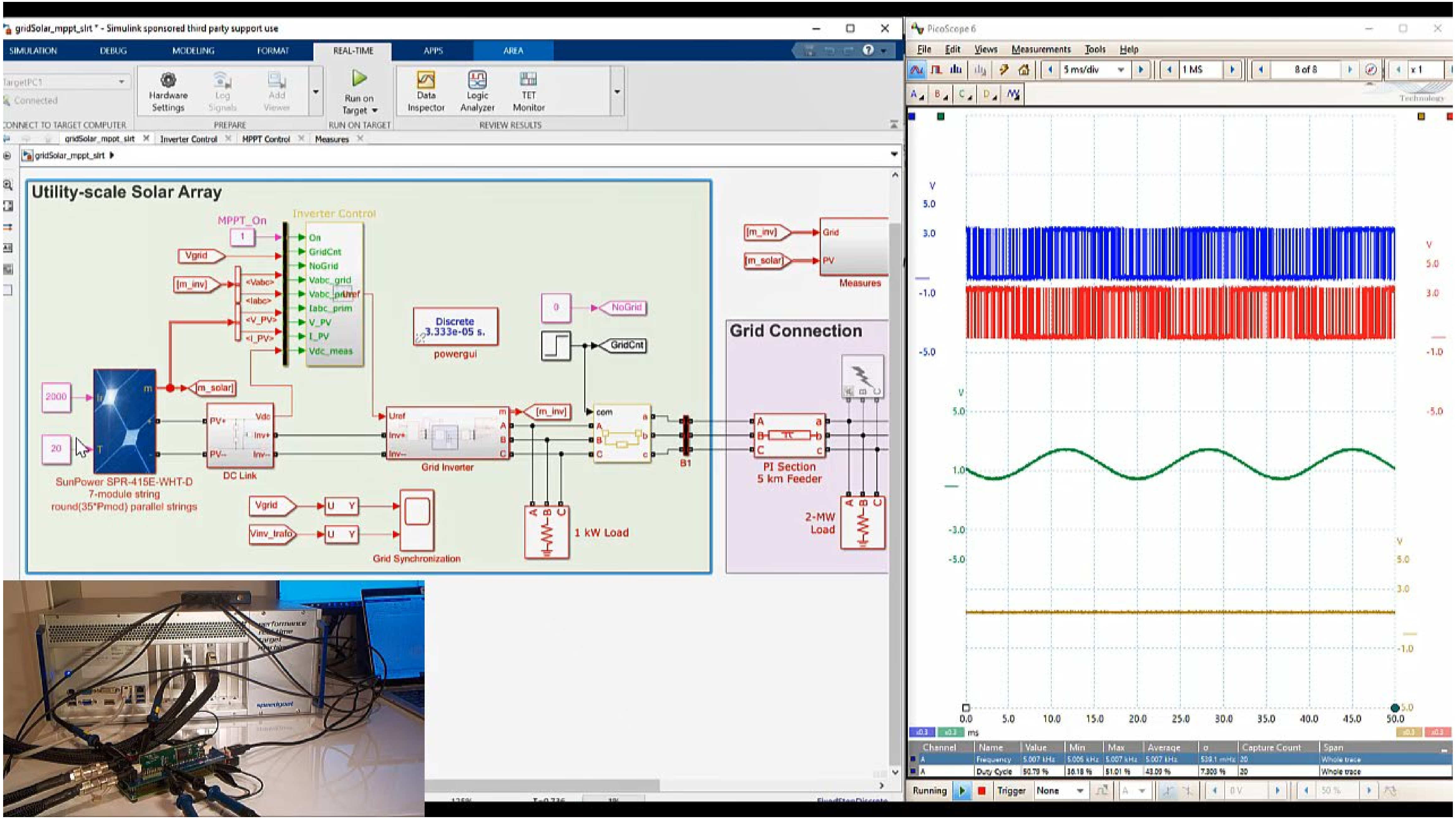
4 Hardware-in-the-Loop Testing

- **Reuse models at different levels of fidelity in CPUs and FPGAs**

- **Automatic code generation**
  - **Multi-core CPUs using Simulink Real-Time**
  - **Simulink-programmable FPGAs using HDL Coder**

- **Compatibility of Simulink, V&V tools and Speedgoat hardware**

- **HIL simulation with switching dynamics**
  - CPU workflow up to around 5 KHz switching
  - FPGA workflow up to around 100 kHz switching


gridSolar_mppt_slrt * - Simulink sponsored third party support use
SIMULATION
DEBUG
MODELING
FORMAT
REAL-TIME
APPS
AREA
Hardware Settings
Log Signals
Add Viewer
Run on Target
Data Inspector
Logic Analyzer
TET Monitor
PREPARE
RUN ON TARGET
REVIEW RESULTS
Utility-scale Solar Array
MPPT_On
Inverter Control
Discrete 3.333e-05 s.
powergui
Grid Connection
SunPower SPR-415E-WHT-D
7-module string
round(35*Pmod) parallel strings
DC Link
Grid Inverter
Grid Synchronization
1 kW Load
PI Section
5 km Feeder
2-MW Load
Measures
PicoScope 6
File
Edit
Views
Measurements
Tools
Help
5 ms/div
1 MS
8 of 8
Channel
Name
Value
Min
Max
Average
Capture Count
Span
Frequency
Duty Cycle
Whole trace
Running
Trigger
None

Conclusion

- Simplify control development for power electronics using Simscape Electrical and Speedgoat hardware
- Automatically generate C and HDL code for plant simulations and production code from Simulink and Simscape Electrical
- Use hardware-in-the-loop to test normal operation and fault conditions like Fault-Ride Through

Call to Action

- Developing Solar Inverter Control with Simulink – video series
- HIL for Power Electronics -whitepaper
- Detailed Model of 100 kW Grid-Connected PV Array - example
- MPPT Algorithm – webpage
- www.speedgoat.com – Speedgoat real-time solutions

Advance your skills with MATLAB and Simulink courses

Get started for free with MATLAB Onramp, then build your skills with our self-paced trainings and instructor-led courses.

Flexible Training

- Over 50 courses available
- Virtual and in class offerings available
- Private customized events

Proven Methods

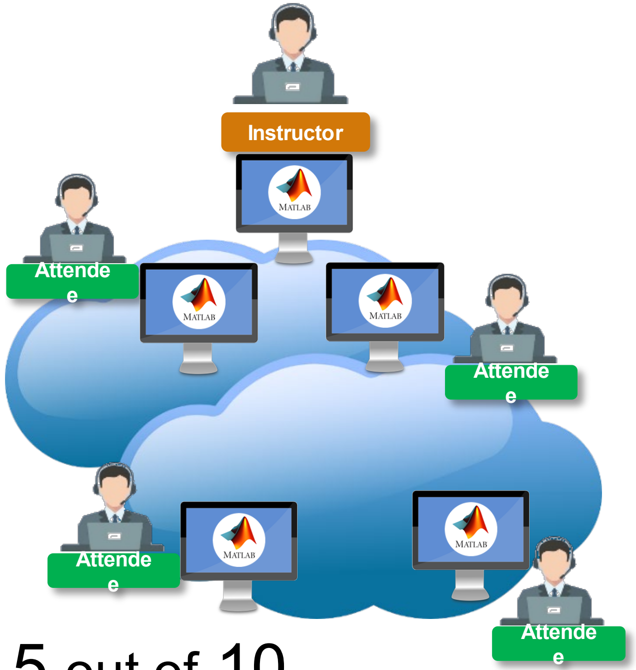
- Hands-on instructions
- Use of Adult Learning Principles
- 95% rated real-world application to their jobs
- 104% average increase in productivity
- 144% average increase in competence

Expert Trainers

- MS and PhD degrees
- Unparalleled products knowledge
- 98% rating as subject matter experts
- 96% of attendees recommend to others

Take Your Training Virtually

- Attend training from anywhere
- Flexible class times with multiple time zones
- Virtual classroom provides interactive learning experience
- Preinstalled software on virtual machines
- Over 40 courses available
- Overall customer satisfaction similar to in class training of 8.5 out of 10



"I attended two online trainings hosted by MathWorks. I was impressed with the virtual learning format. The instructor did an outstanding job presenting course material and facilitating attendee understanding."

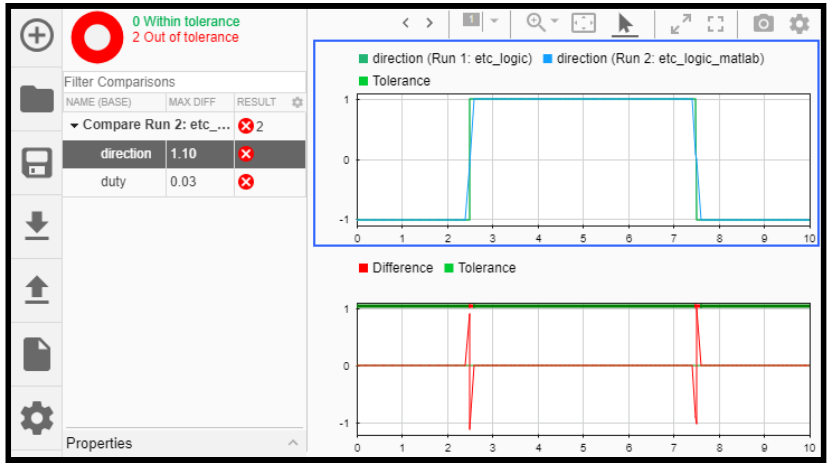
Matt Fisher, Ultradent Products, USA

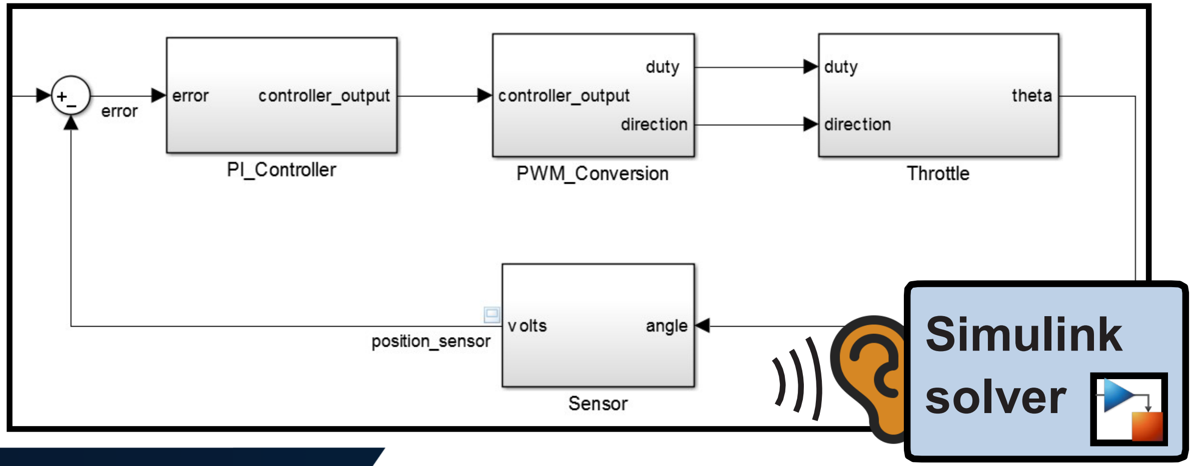
Simulink for System and Algorithm Modeling

After this 2-day course you will be able to:

- Create graphical models of continuous and discrete systems
- Configure solver settings for accuracy and speed
- Design hierarchical models for readability and reusability

[See detailed course outline](#)

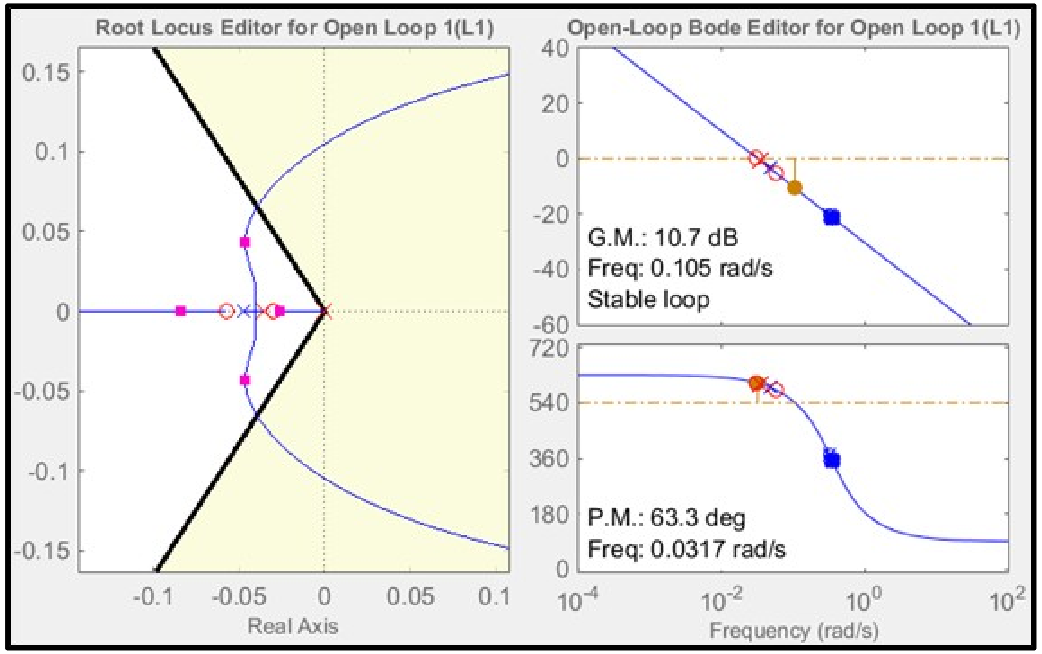




Control System Design with MATLAB and Simulink

Topics included in this 2-day course:

- Control system design, modeling and analysis
- System identification
- Parameter estimation
- Response optimization
- Linearization
- Controller implementation



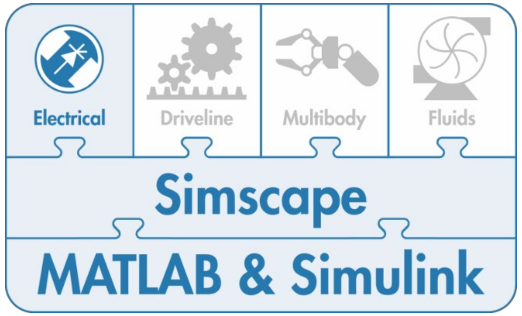
See detailed course outline

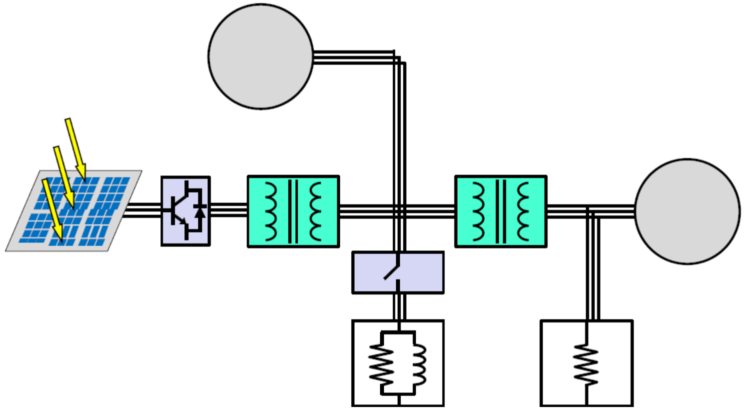
Modeling Electrical Power Systems with Simscape

Topics included in this 1-day course:

- Creating three-phase systems with passive elements
- Creating three-phase systems with electrical machines
- Analyzing and controlling electrical power systems
- Modeling power electronic components
- Speeding up simulation of electrical models

See detailed course outline





Stateflow for Logic-Driven System Modeling

Topics included in this 2-day course:

- Flow charts
- State machines
- Hierarchical and parallel states
- Event and function
- Truth tables and state transition tables
- Component-based modeling

[See detailed course outline]