MATLAB EXPO

并网逆变器设计与实时测试

周前程

MathWorks®

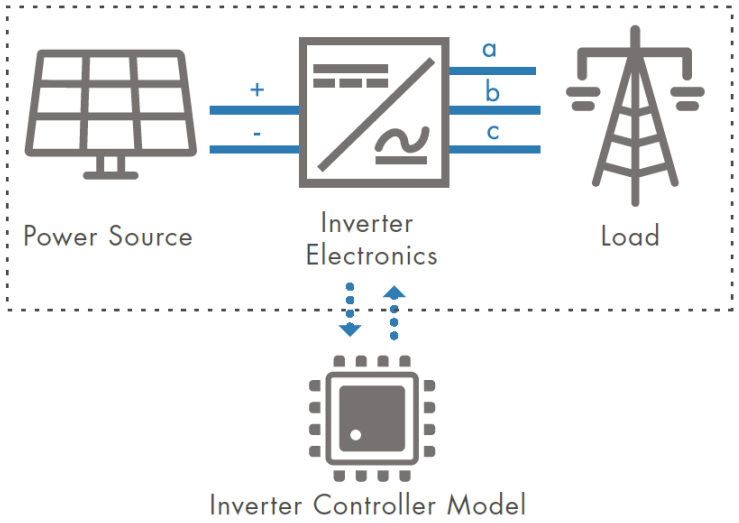
speedgoat
real-time simulation and testing

Key Takeaways

- 利用Simscape Electrical 和 Simulink Real-Time 简化电力电子控制开发
- 自动生成 C 和 HDL 代码，用于控制器和实时仿真
- 使用实时仿真测试运行和故障工况，如低电压穿越

Simulink 构建控制设计平台

利用仿真进行电气系统设计和优化



被控对象代码生成

控制器算法代码生成

我们今天的目标?

- 电力电子硬件与控制设计

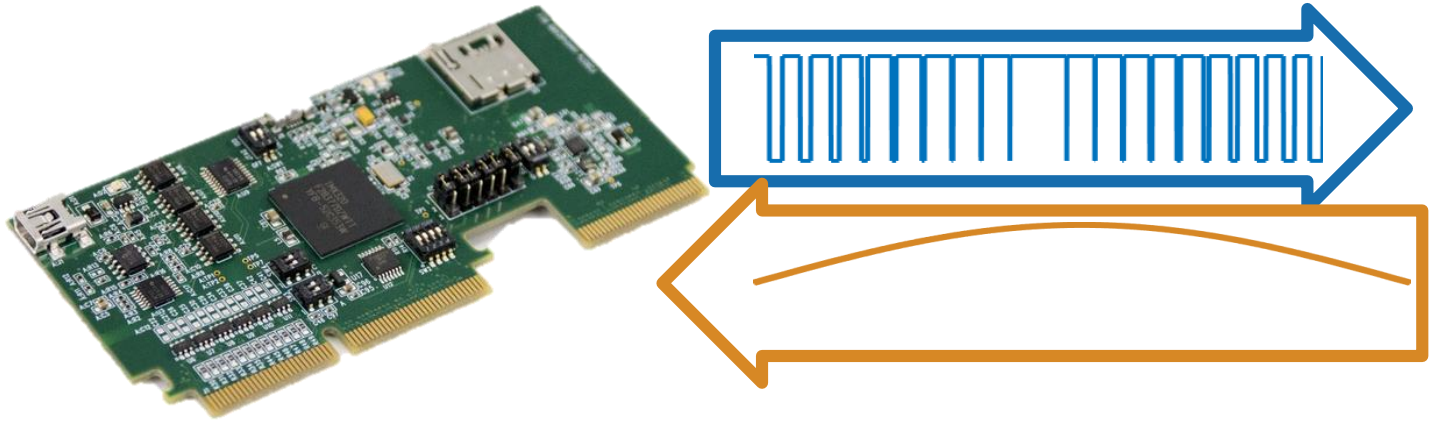
控制器

物理对象

我们今天的目标?

- 电力电子硬件与控制设计
  - 硬件在环技术可以帮助我们改进开发流程

控制器

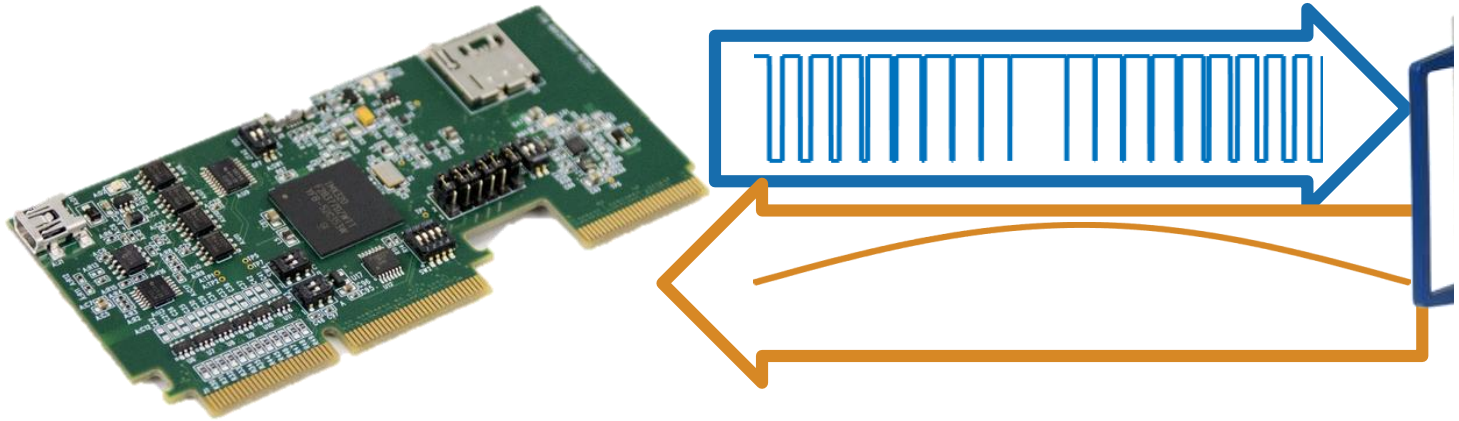


物理对象

什么是硬件在环（HIL）

- 利用HIL虚拟模型代替电力电子硬件

控制器

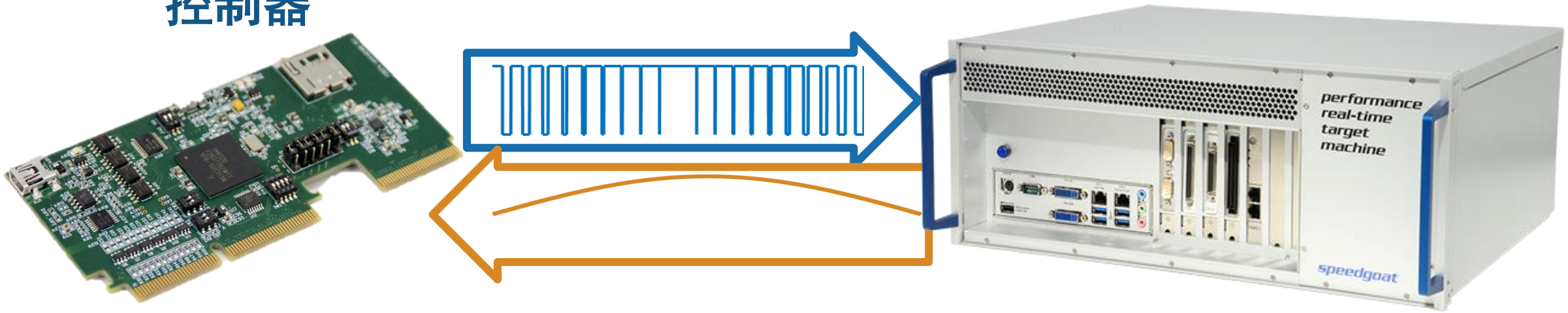


什么是硬件在环（HIL）

- 利用HIL虚拟模型代替电力电子硬件
  - 控制器像连接到真实系统一样工作

虚拟对象

控制器



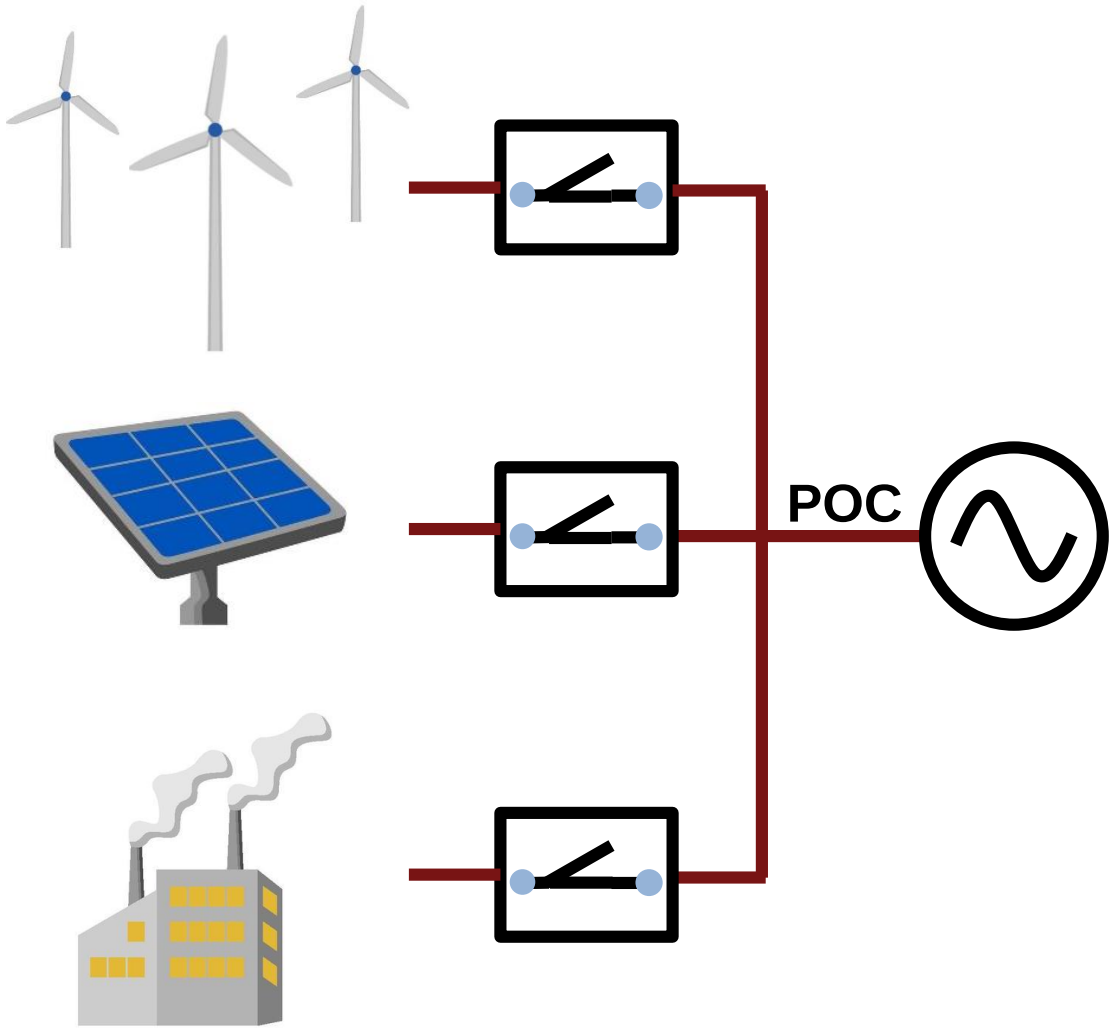
硬件在环的优势

- 利用实时仿真系统代替硬件原型
- 容易实现测试自动化和**电网故障模拟**
- 相对电力电子硬件更安全
- 方便尽早开展设计和测试

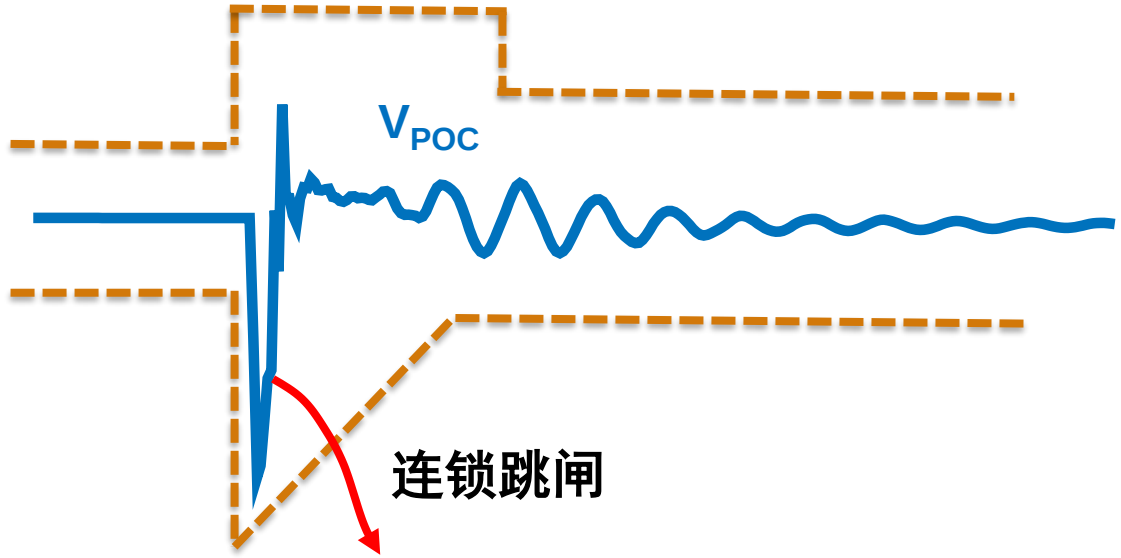
控制器

虚拟对象

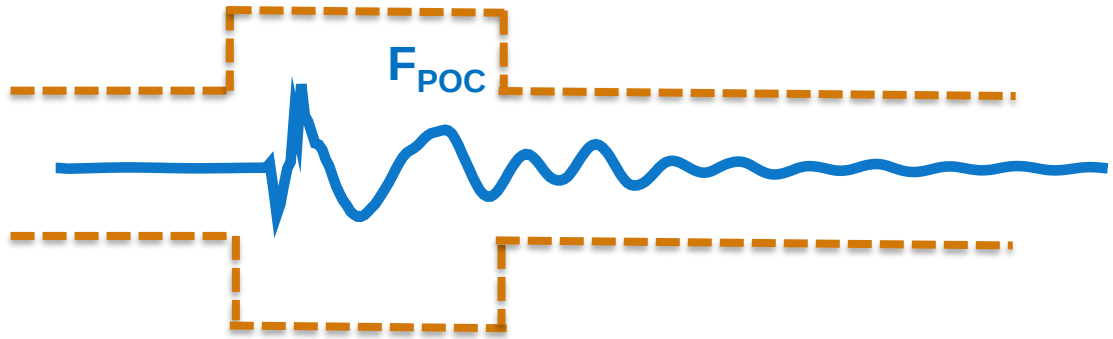
硬件在环测试



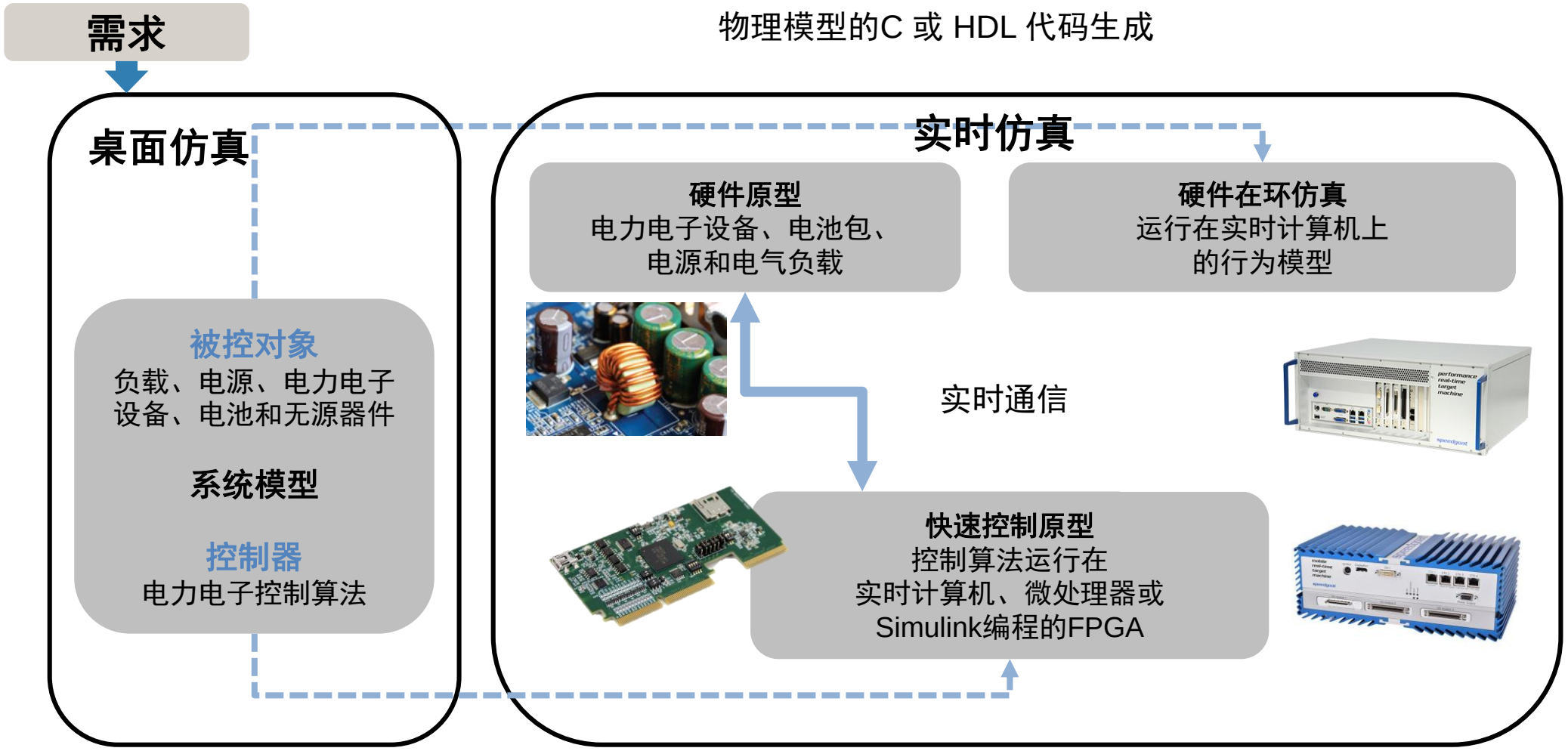
电压判据



频率判据

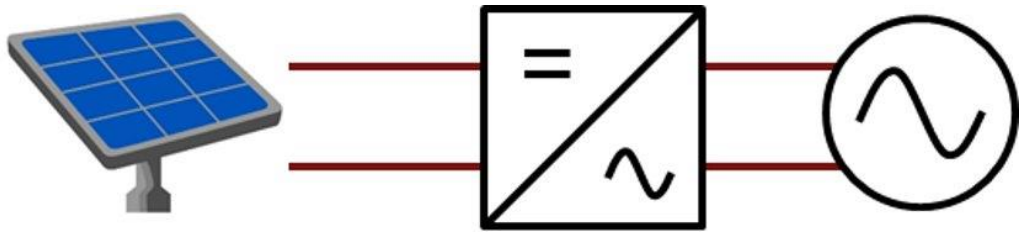


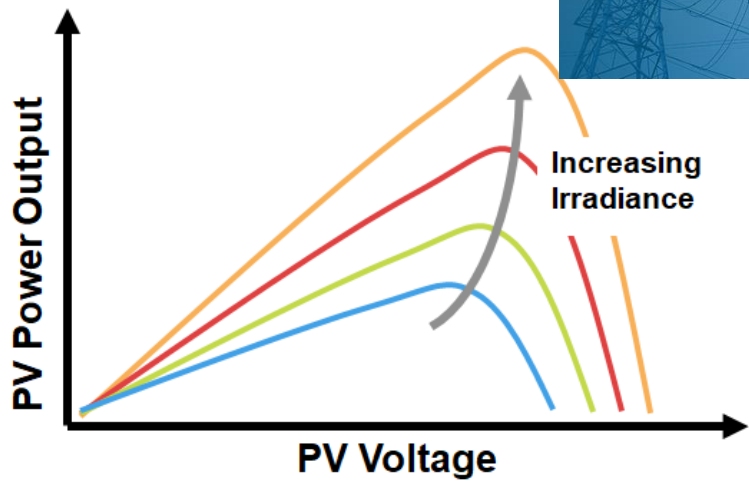
基于模型的设计方法在电力电子中的应用



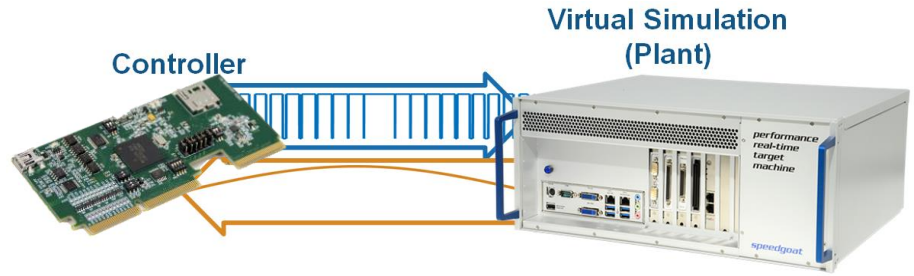
C or HDL Code generated from controller model

光伏逆变器开发



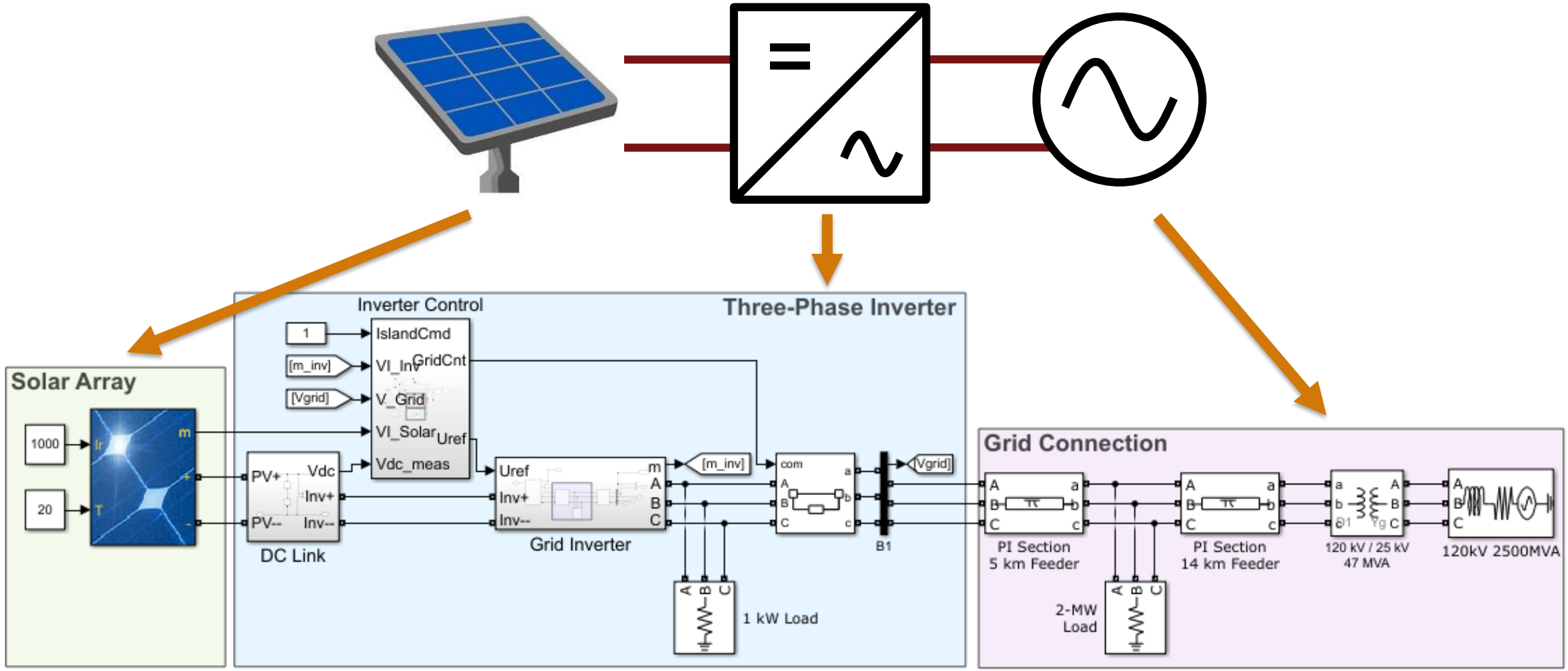


1. **被控对象模型**
   (光伏板, 逆变器, 电网)
2. **控制算法设计**
   (同期, 最大功率点跟踪MPPT)
3. **自动代码生成**
   (部署代码到 TI C2000 和 Speedgoat)
4. **硬件在环测试**
   (使用Speedgoat验证控制器)

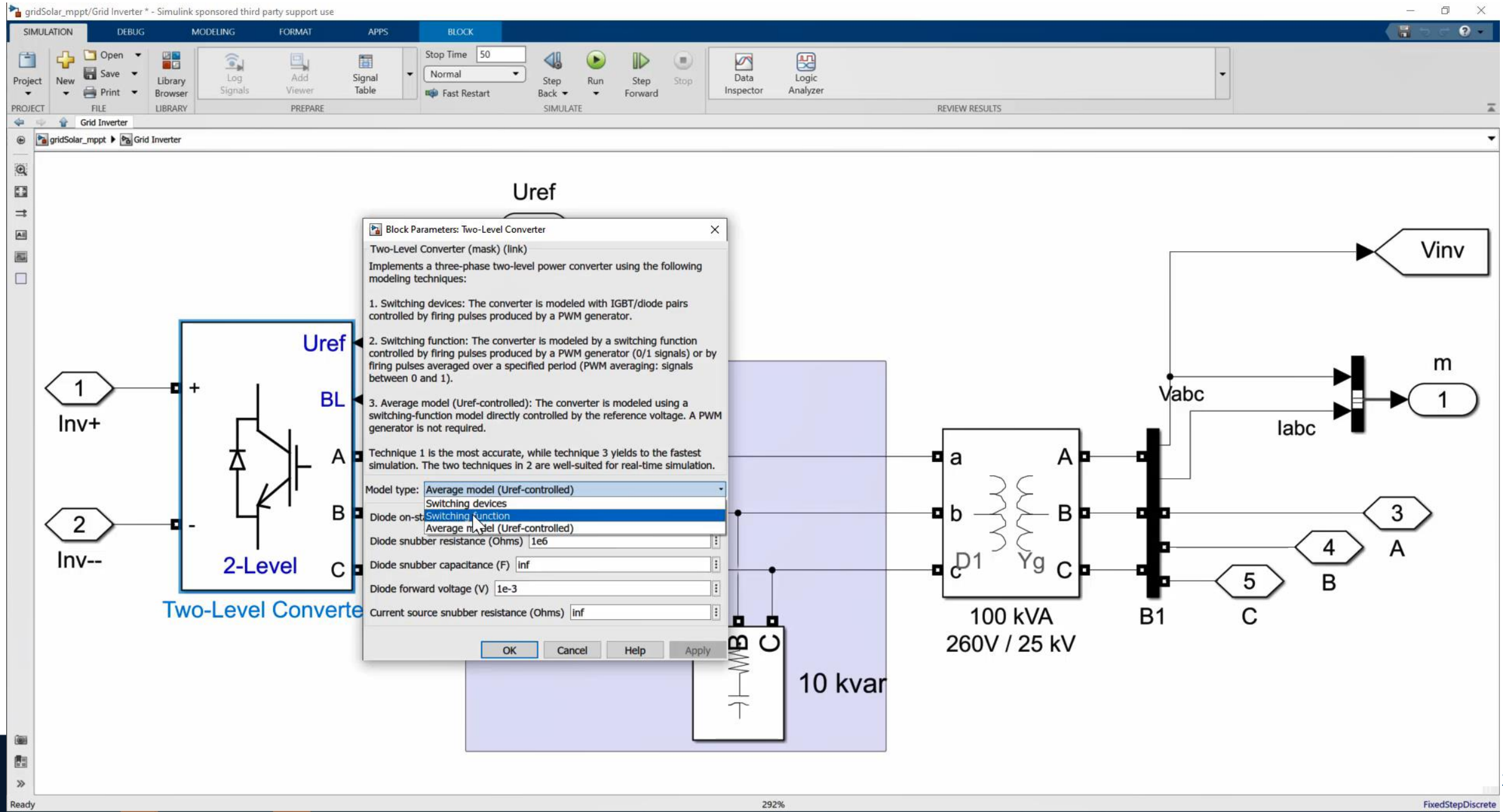


1 被控对象模型

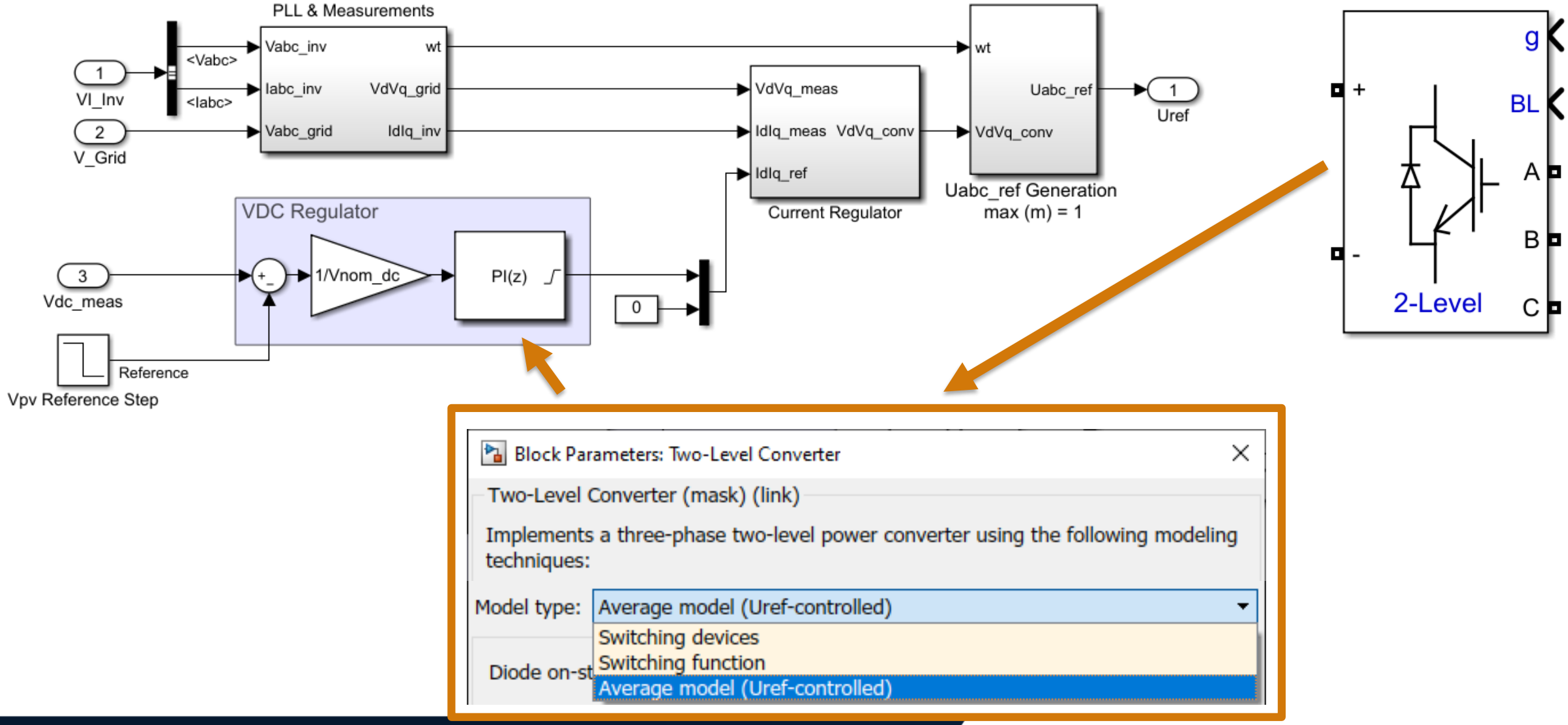
图形化建模电力电子拓扑



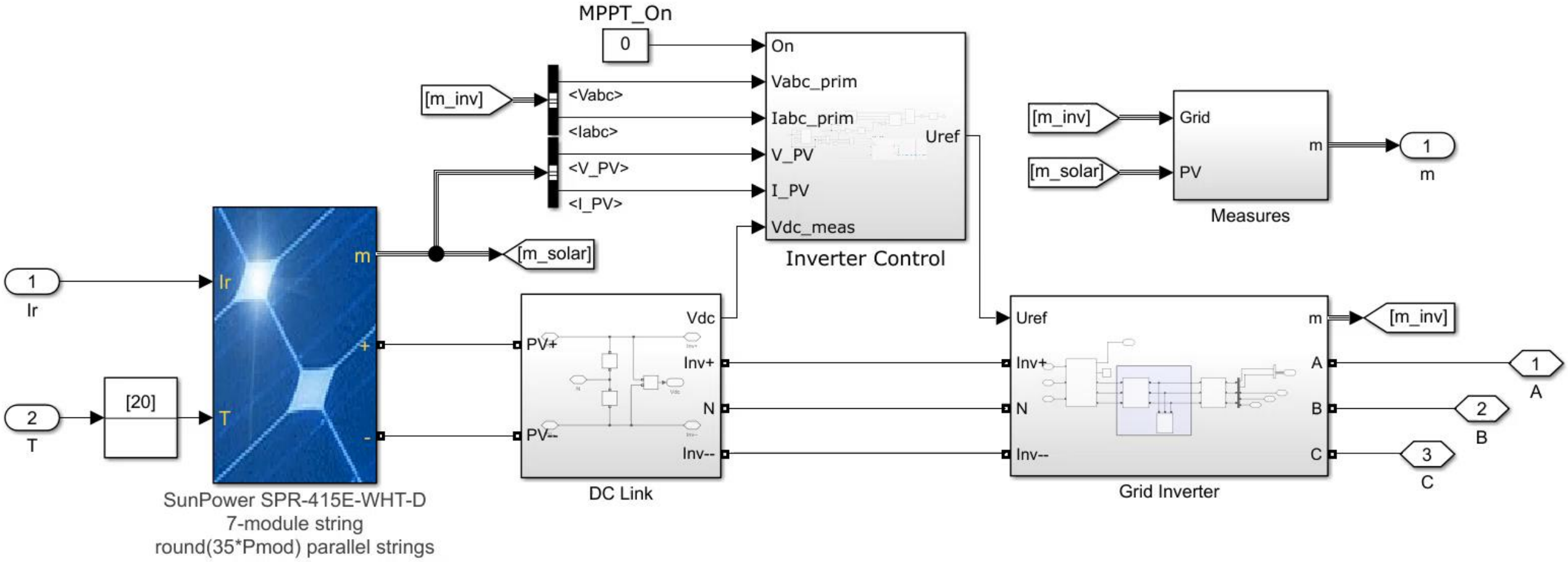
1 被控对象建模


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 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
Uref
BL
A
B
C
+
-
2-Level
Two-Level Converte
1
Inv+
2
Inv--
Vinv
Vabc
Iabc
m
1
a
b
c
A
B
C
D1
Yg
100 kVA
260V / 25 kV
B1
3
A
4
B
5
C
10 kvar
Ready
292%
FixedStepDiscrete

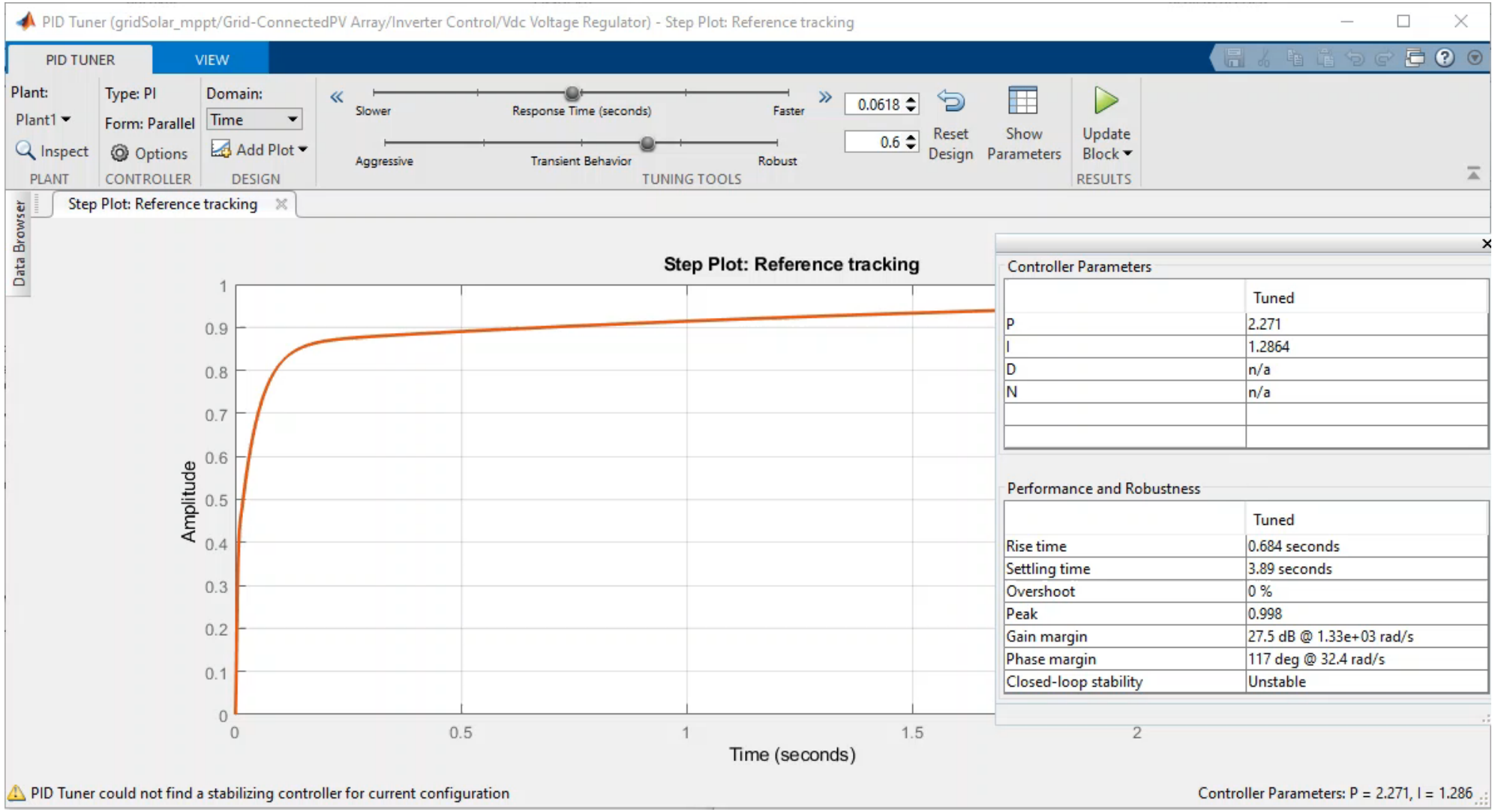
2 控制设计
电力电子控制 PID 调节 – Leverage 平均值模型



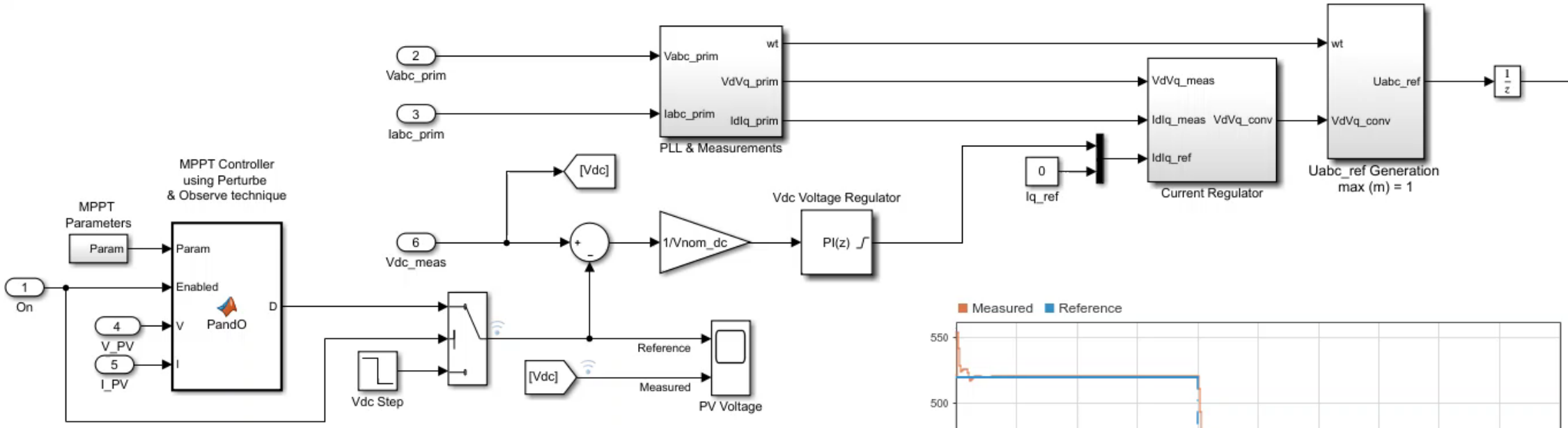
2 控制设计
光伏逆变器 PID 调节 – 平均值模型

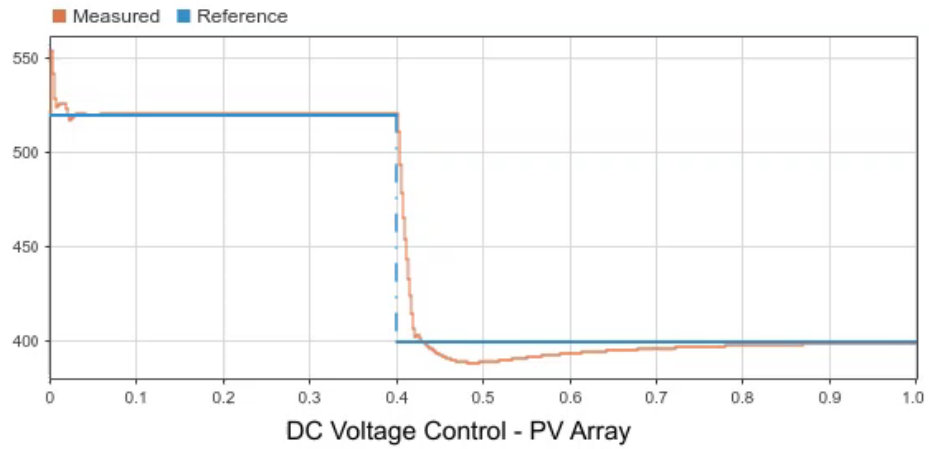


2 控制设计
光伏逆变器 PID 调节 – 平均值模型



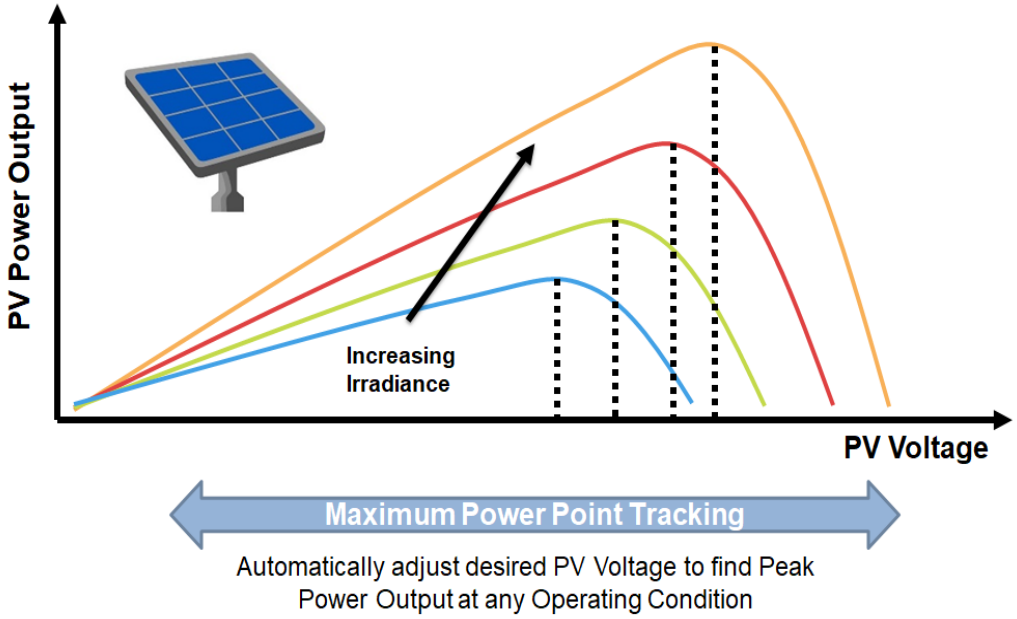
2 控制设计
光伏逆变器 PID 调节 – 平均值模型

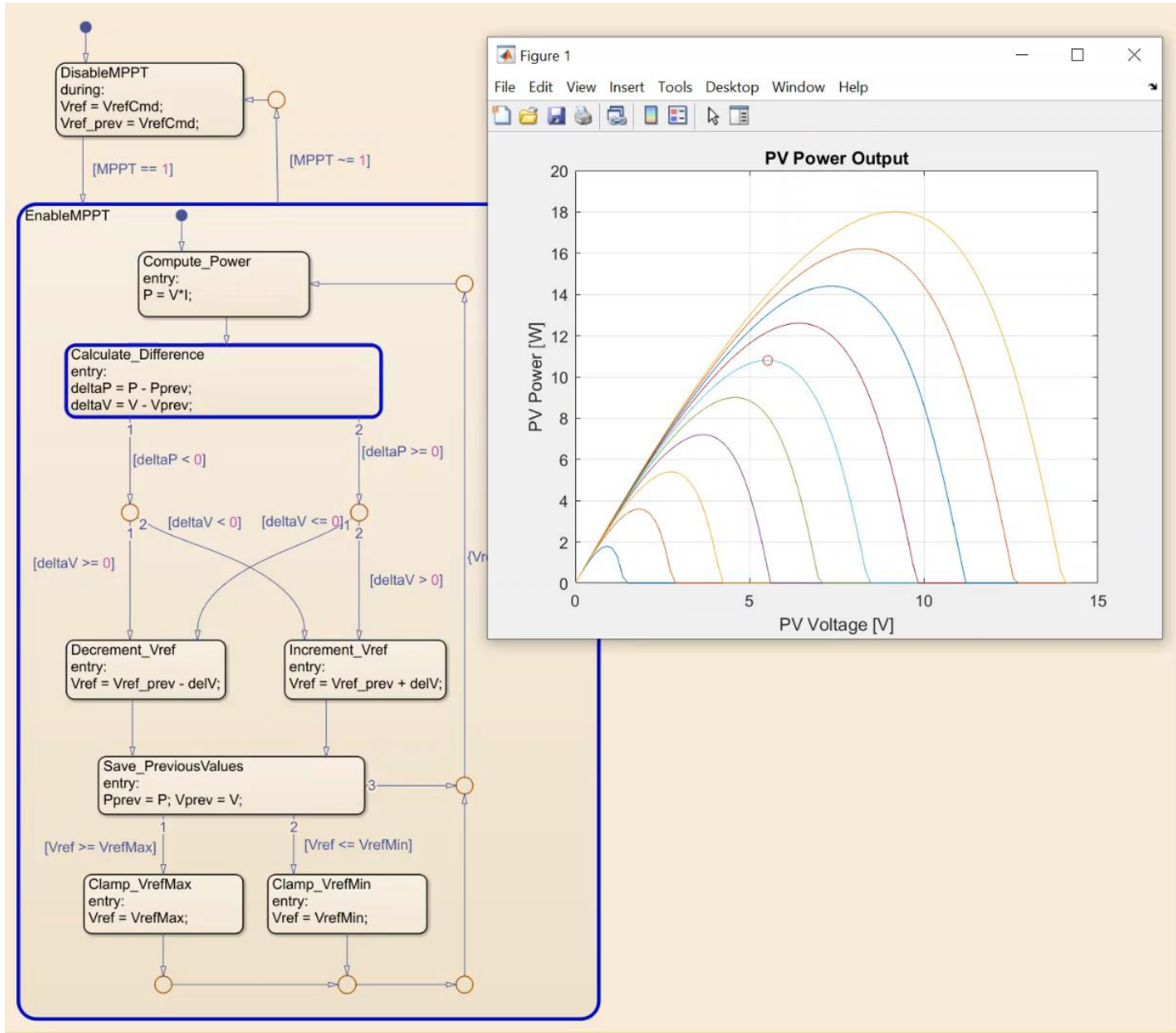




2 控制设计- MPPT

- 在逆变器控制中实现最大功率点跟踪



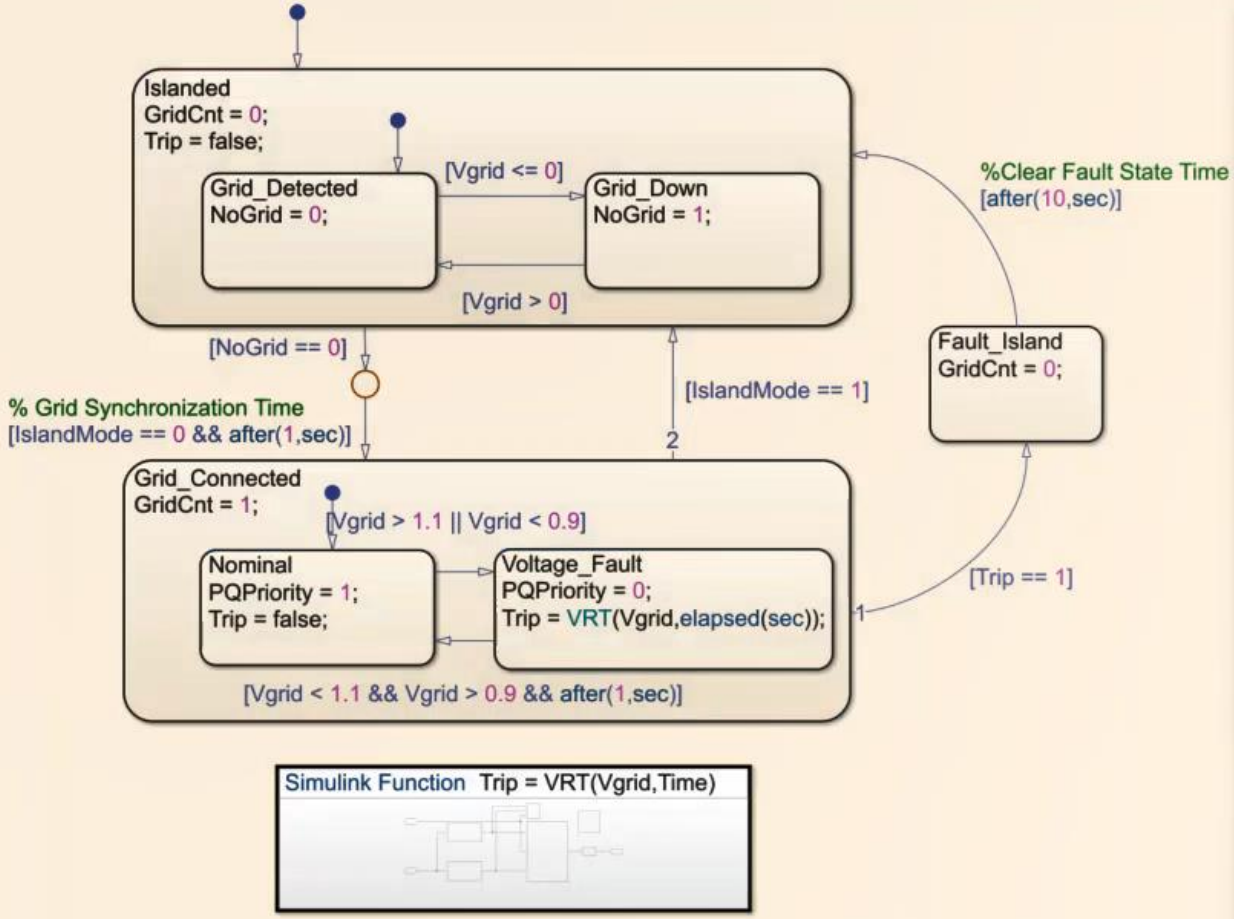


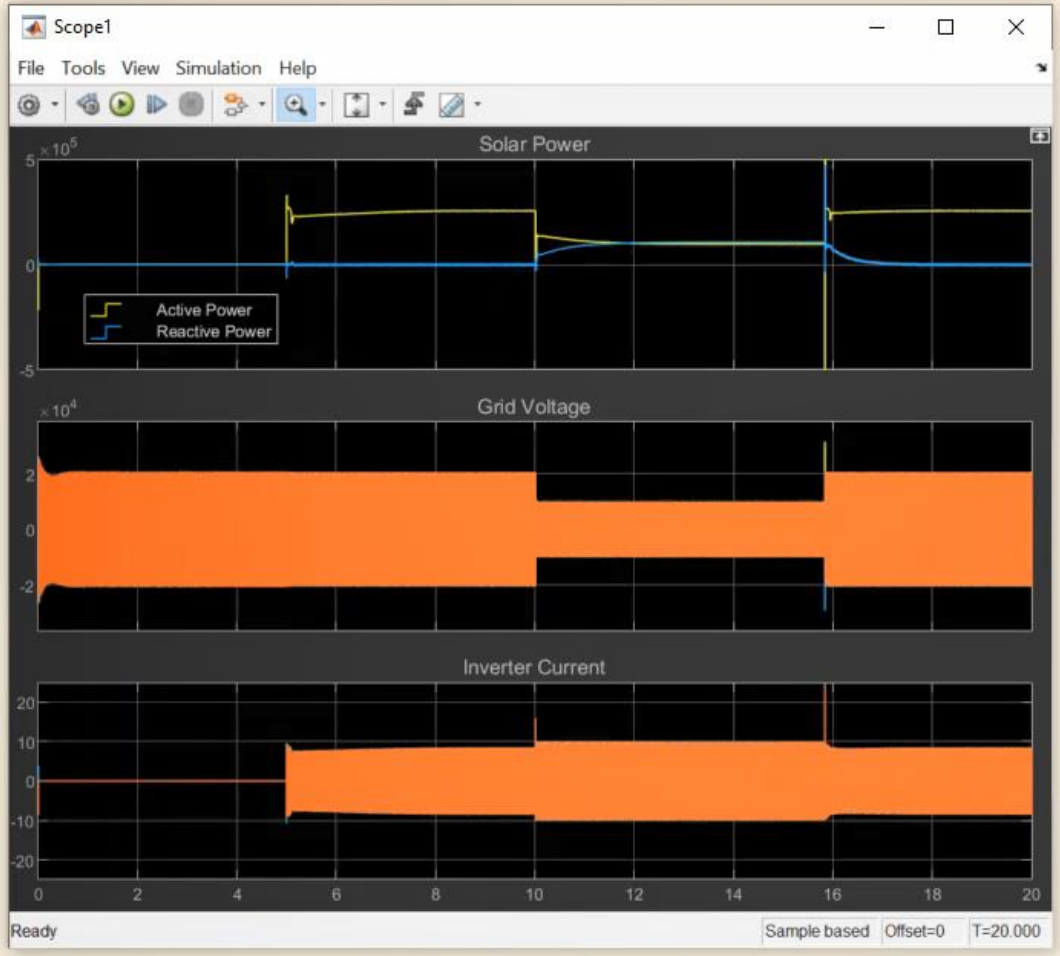
了解更多: [Webinar on Modeling, Simulating, and Generating Code for a Solar Inverter]

2 控制设计

故障穿越算法设计

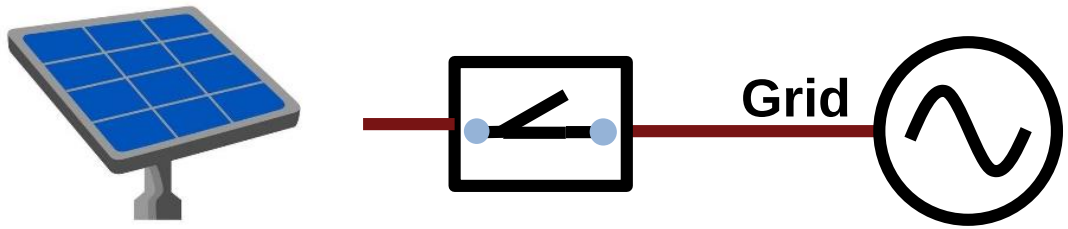
- 低电压穿越期间提供无功支持

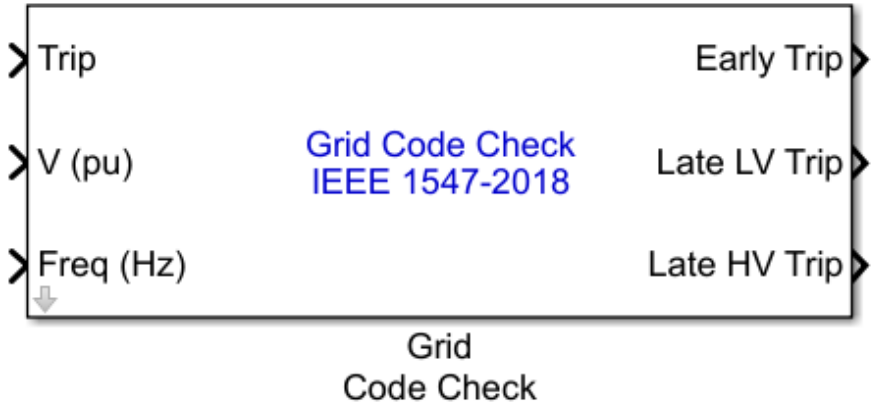


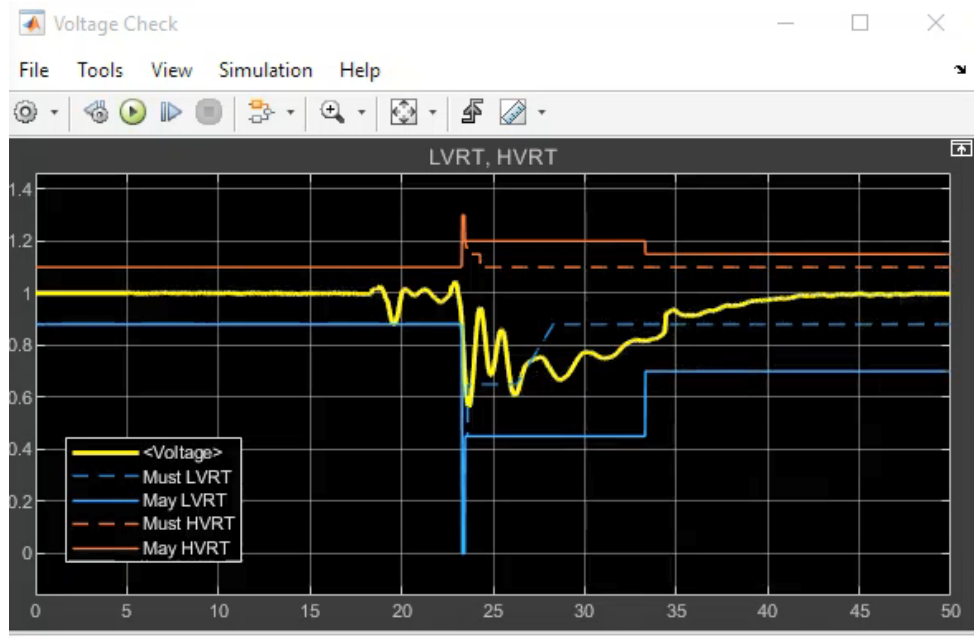


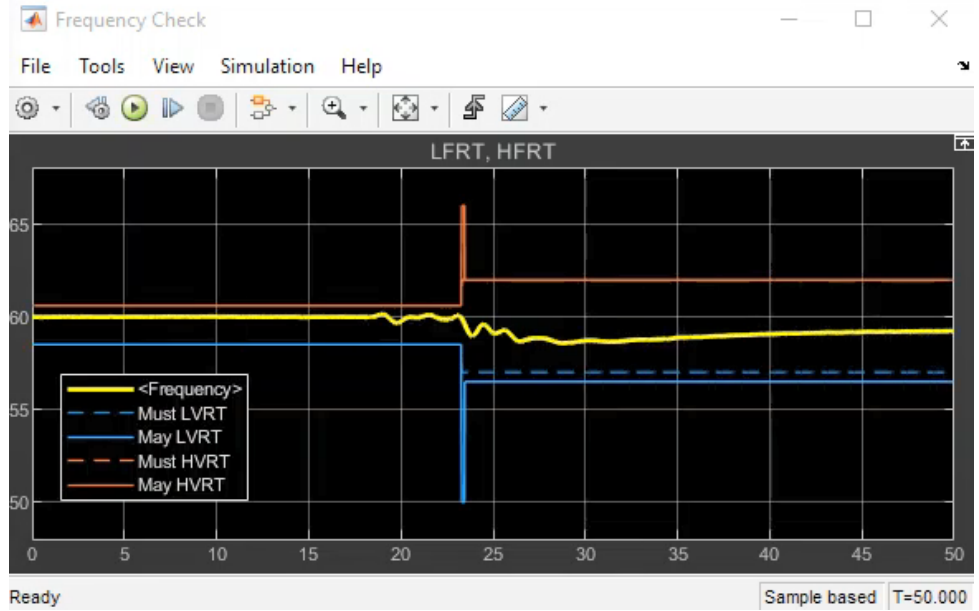
2 控制设计
故障穿越

- 故障穿越判据 - IEEE 1547-2018

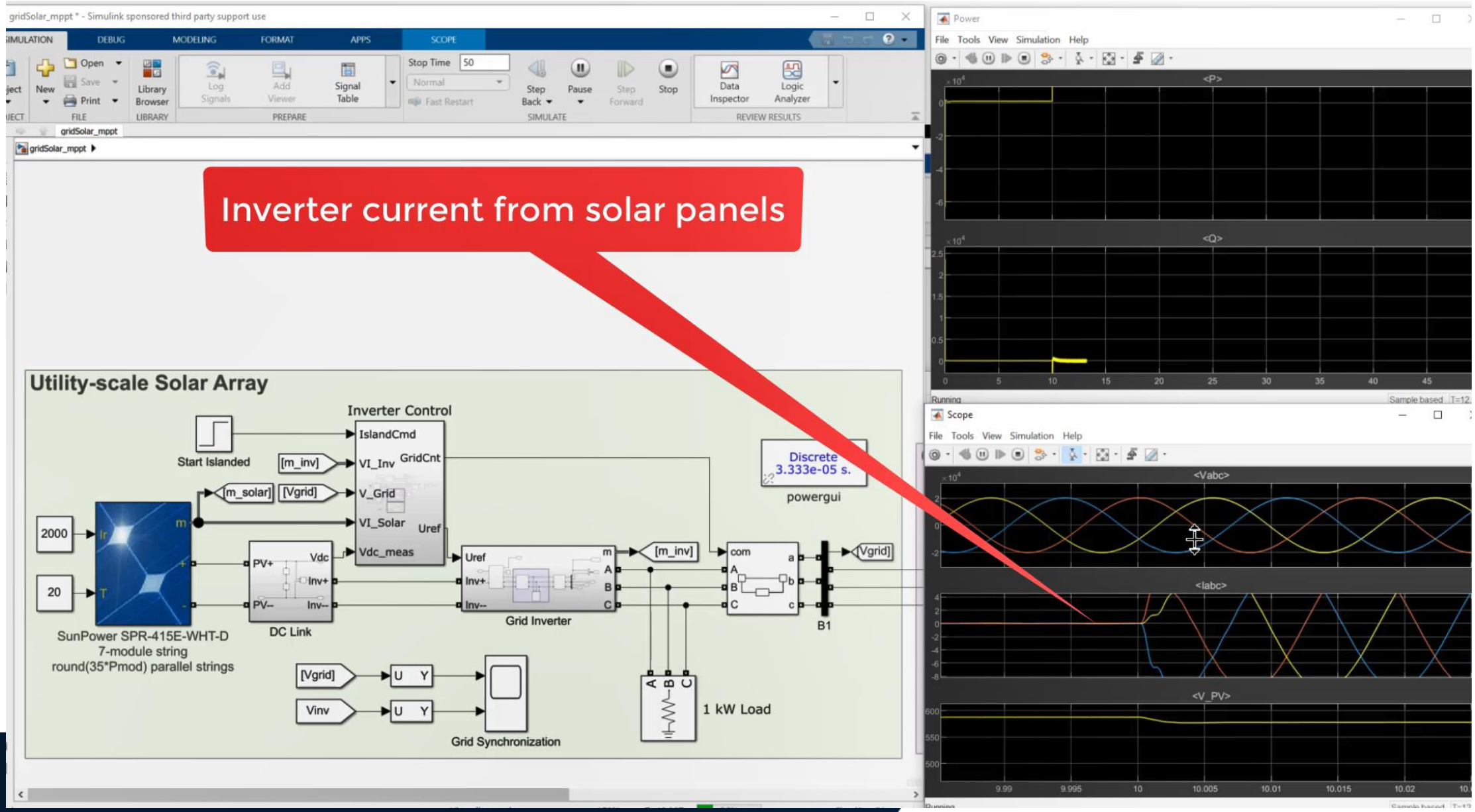








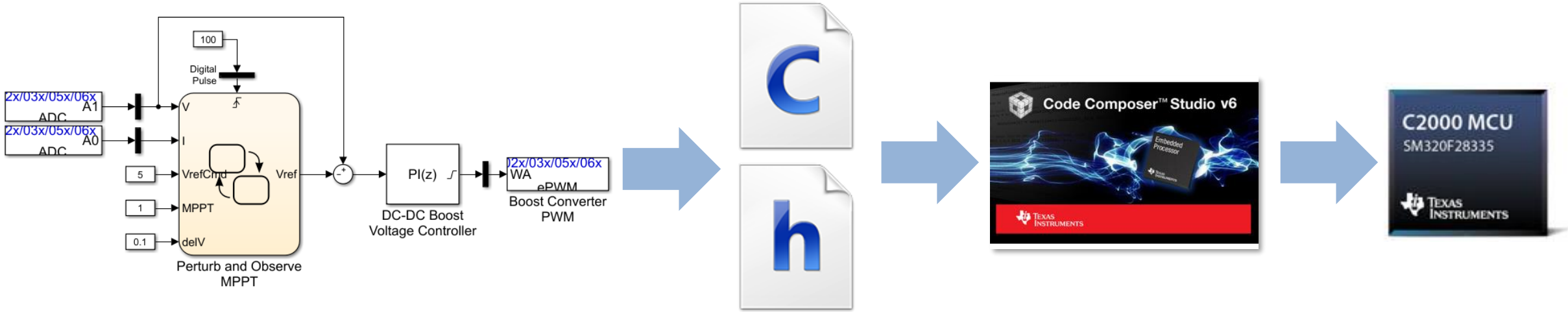
2 控制设计
并网仿真


gridSolar_mppt * - Simulink sponsored third party support use
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]
Discrete
3.333e-05 s.
powergui
2000
20
SunPower SPR-415E-WHT-D
7-module string
round(35*Pmod) parallel strings
PV+
PV-
Vdc
Inv+
Inv-
DC Link
Grid Inverter
com
B1
Vinv
Grid Synchronization
1 kW Load
Power
Scope
<P>
<Q>
<Vabc>
<Iabc>
<V_PV>
File Tools View Simulation Help

3 自动代码生成
控制器

- **Embedded Coder 和 C2000 硬件支持包**

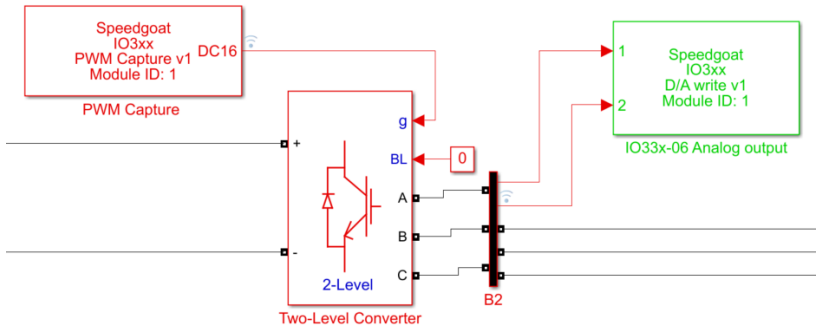
Simulink 算法与 C2000 IO 驱动结合	自动代码生成	使用CCS编译 并下载程序	在TI C2000 处理器中进行测试

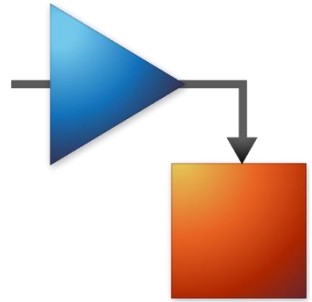


3 自动代码生成
Speedgoat 实时仿真器

- C 和 HDL 代码生成
- 部署到多核CPU或FPGA
- 丰富的 I/O、 通信协议

Simulink 模型与 Speedgoat 驱动结合	自动代码生成	使用 VS 编译并下载程序	在Speedgoat中进行测试

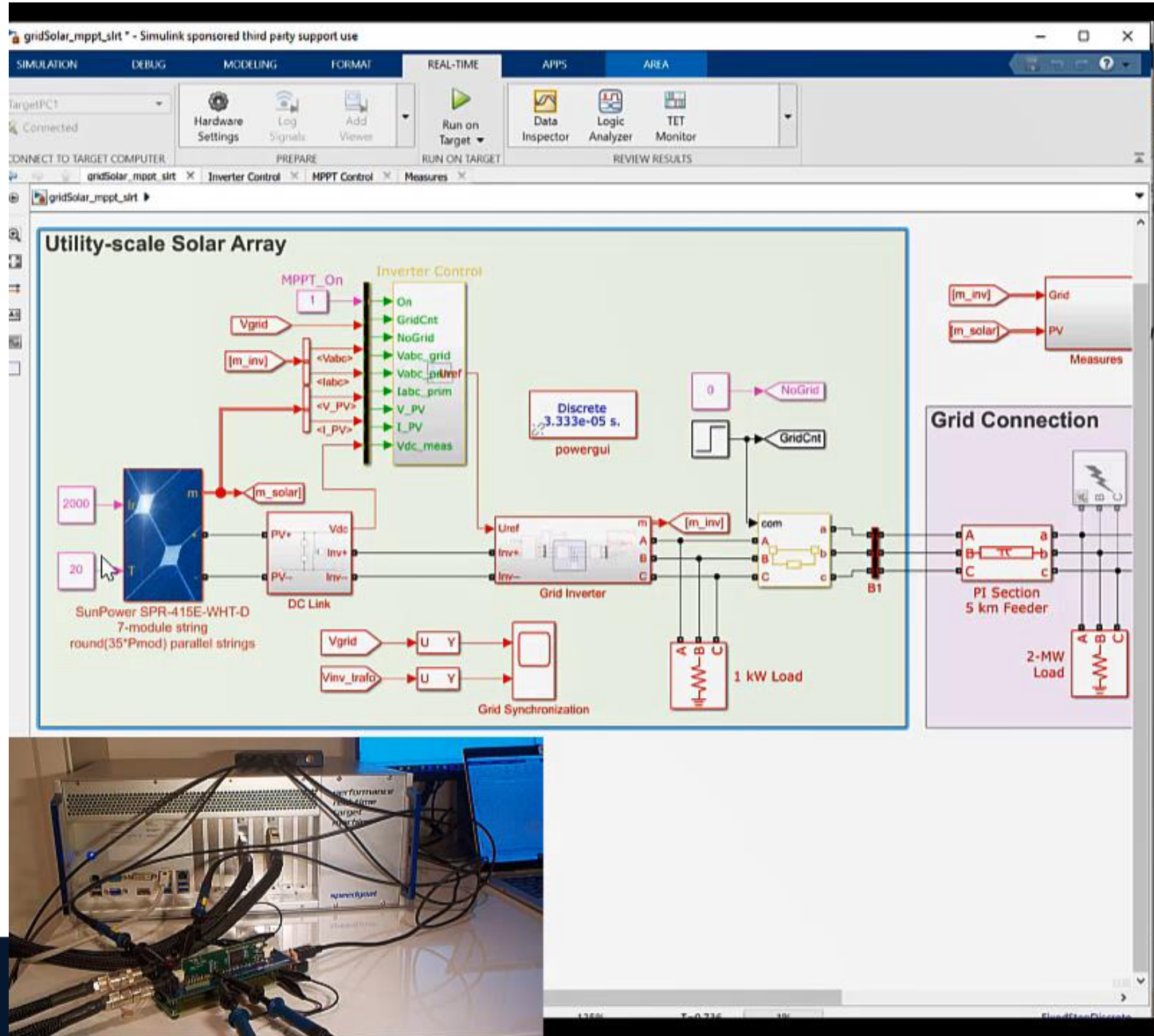


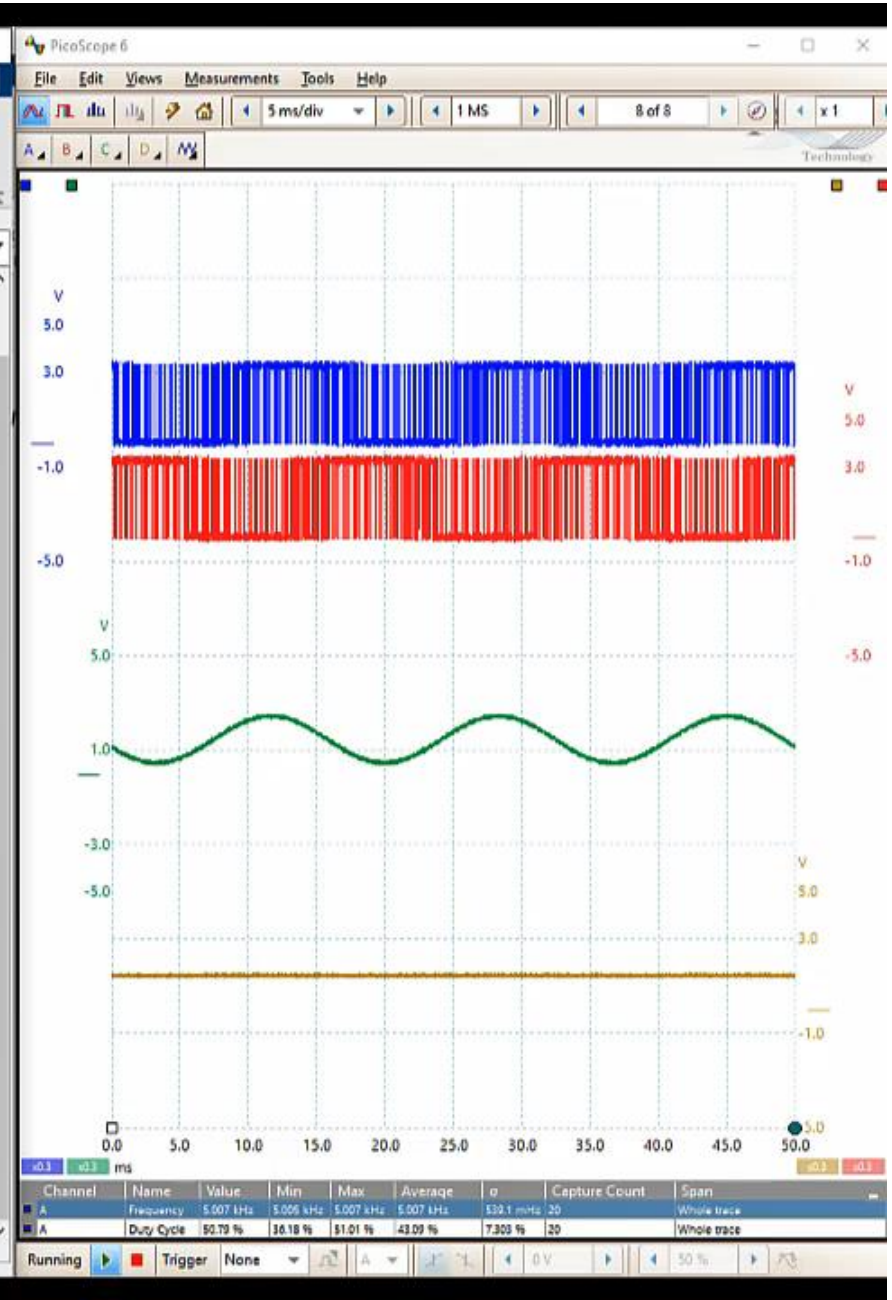


4 硬件在环测试

- 重用模型以实现 CPU 和 FPGA 中的不同精度仿真
- 自动代码生成
  - Simulink Real-Time 部署模型到多核 CPU
  - HDL Coder 部署 Simulink模型到 FPGA
- 多工具链兼容 Simulink, V&V 和 Speedgoat hardware
- 包含开关特性的硬件在环测试
  - CPU 方案 5 KHz 开关频率
  - FPGA 方案 100 kHz 开关频率

4 硬件在环测试


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
gridSolar_mppt_slrt
Inverter Control
MPPT Control
Measures
Utility-scale Solar Array
MPPT_On
Inverter Control
Vgrid
[m_inv]
[m_solar]
On
GridCnt
NoGrid
Vabc_grid
Vabc_prim
Iabc_prim
V_PV
I_PV
Vdc_meas
Discrete
3.333e-05 s.
powergui
NoGrid
GridCnt
Grid
PV
Measures
Grid Connection
2000
20
SunPower SPR-415E-WHT-D
7-module string
round(35*Pmod) parallel strings
DC Link
Grid Inverter
B1
PI Section
5 km Feeder
2-MW
Load
1 kW Load
Grid Synchronization
Vinv_trafo


PicoScope 6
File
Edit
Views
Measurements
Tools
Help
5 ms/div
1 MS
8 of 8
x 1
Channel
Name
Value
Min
Max
Average
Capture Count
Span
Running
Trigger
None

结论

- 利用Simscape Electrical 和 Simulink Real-Time 简化电力电子控制开发
- 自动生成 C 和 HDL 代码，用于控制器和实时仿真
- 使用硬件在环方法测试运行和故障工况，如低电压穿越

更多内容

- www.speedgoat.com – Speedgoat real-time solutions
- 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