

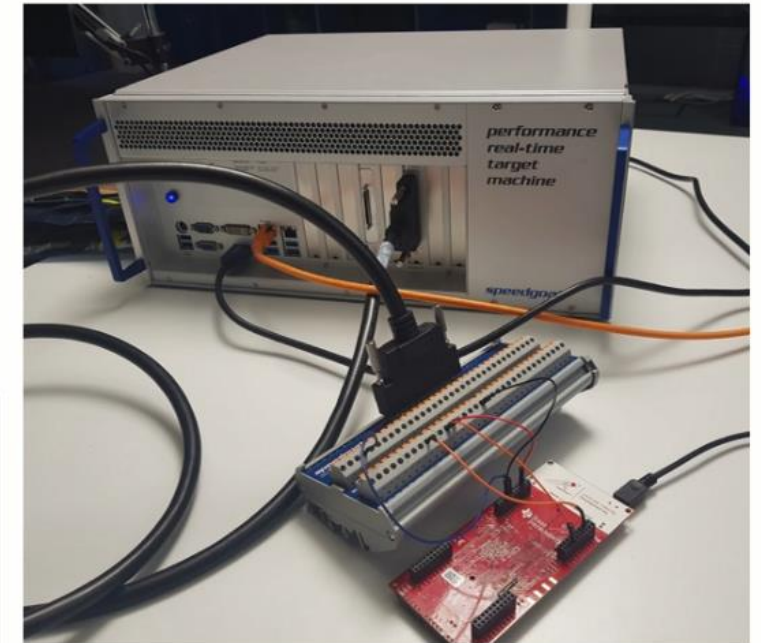
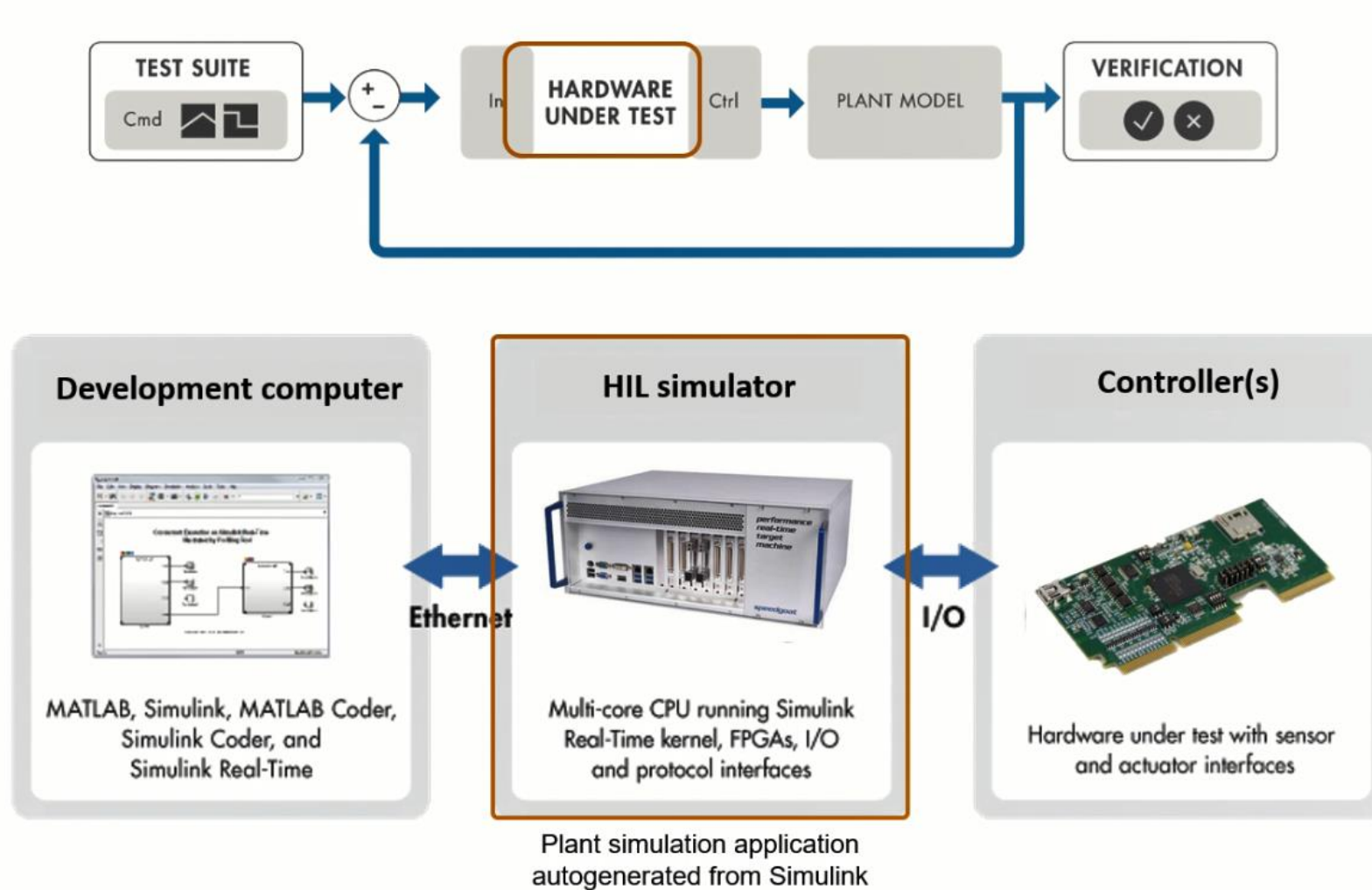
MATLAB EXPO 2021

模块化多电平变流器算法设计与硬件在环测试

周前程, MathWorks



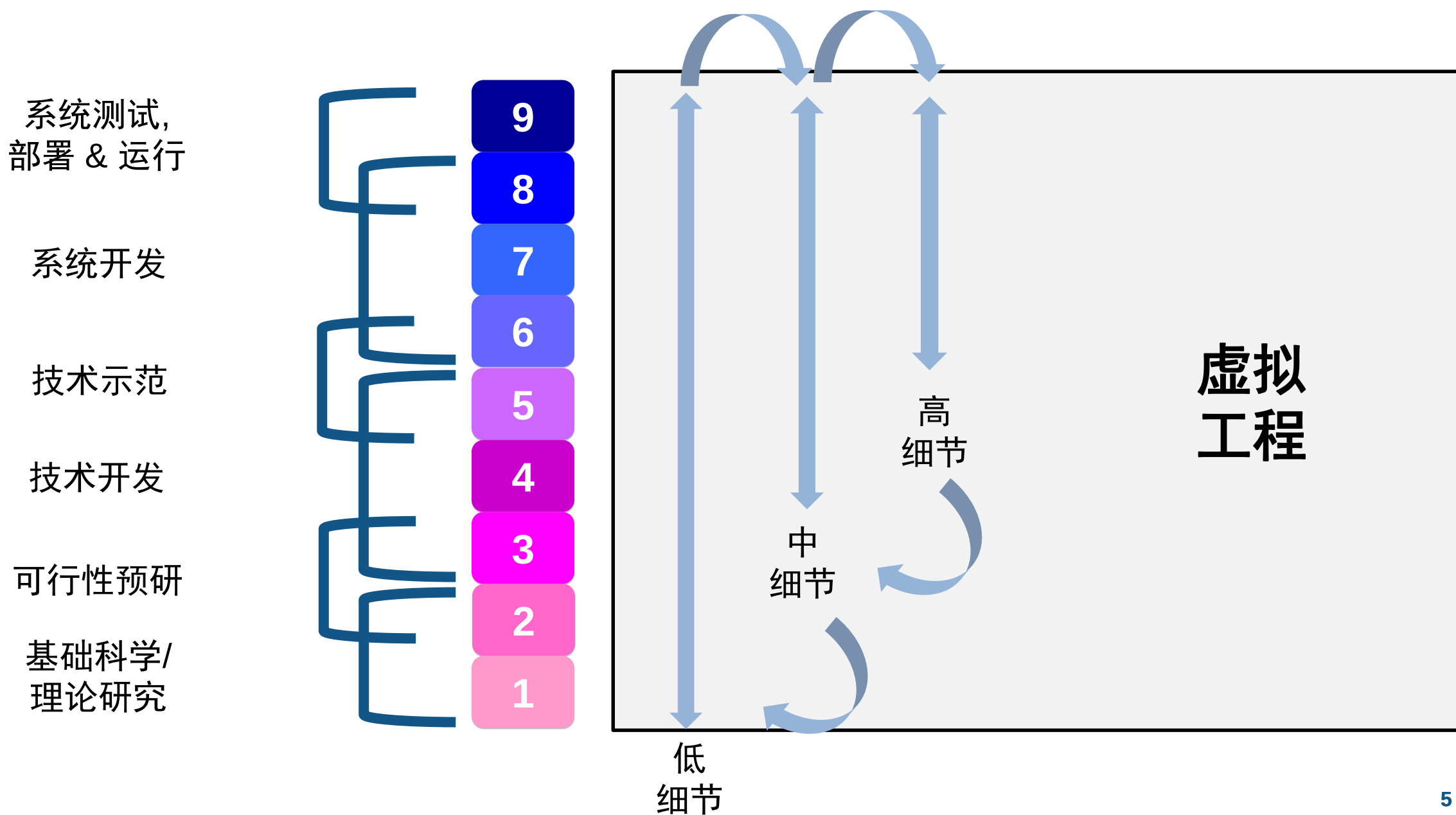
我们今天的主题



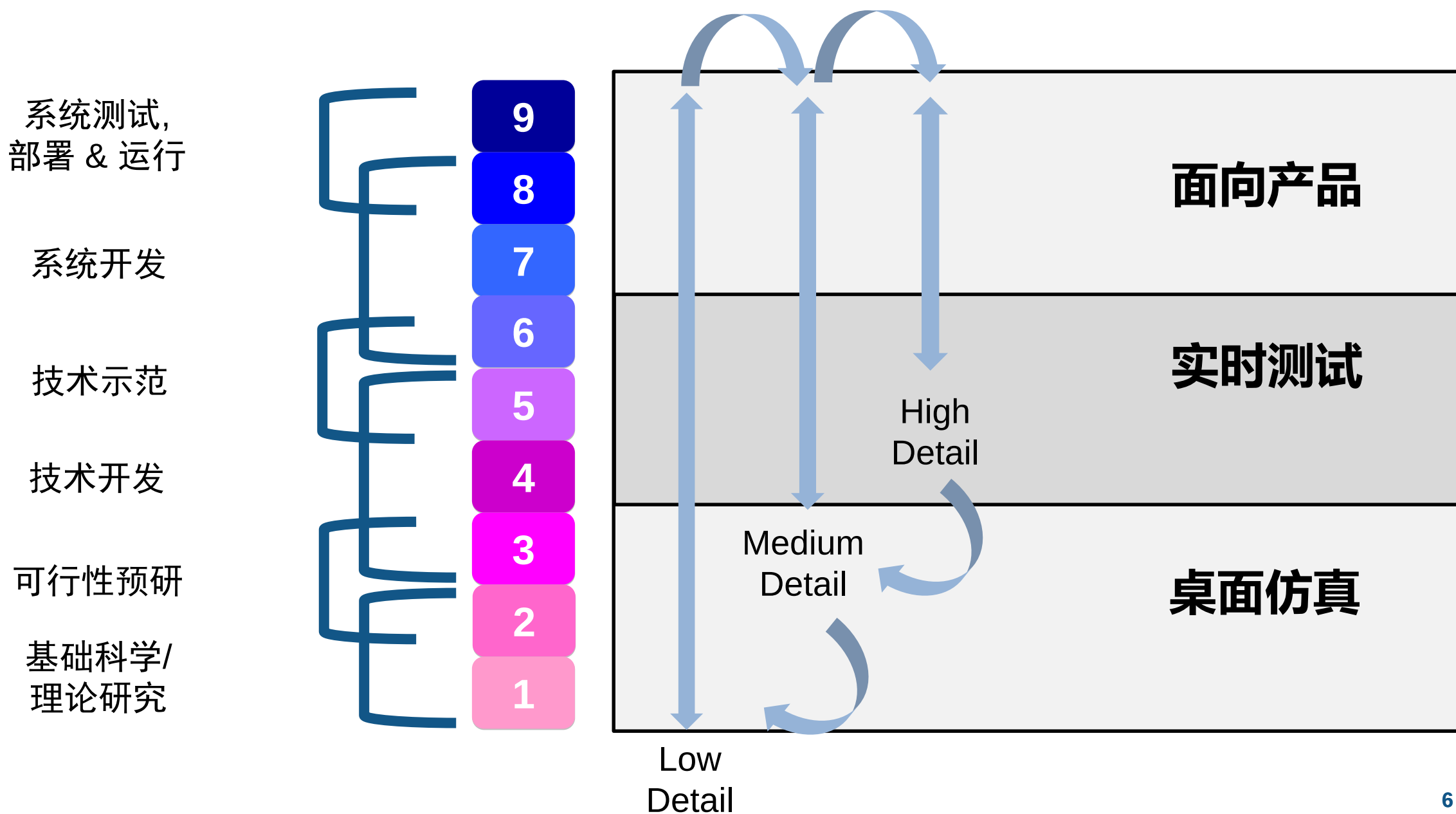
关键点

- Simulink 支持各个技术就绪程度的模型精度实现
- Simulink中复杂功率变换器建模
- 利用Simulink进行复杂变流器离线和实时仿真
- 变步长求解器实现PWM精确仿真
- 在模型中快速验证控制策略的功能正确性
- 利用自动代码生成和HIL测试将控制器实现的风险降到最低

基于模型的方法与技术就绪程度

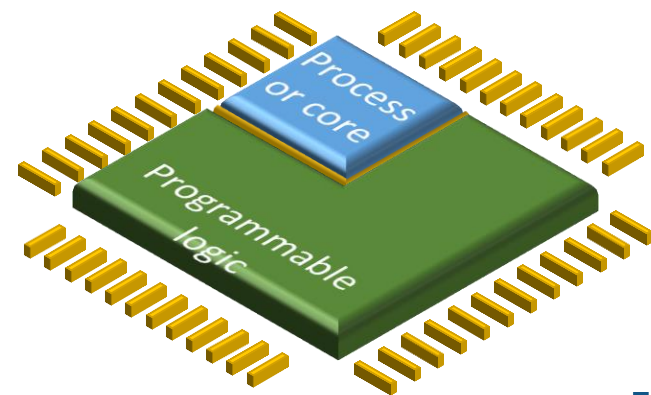
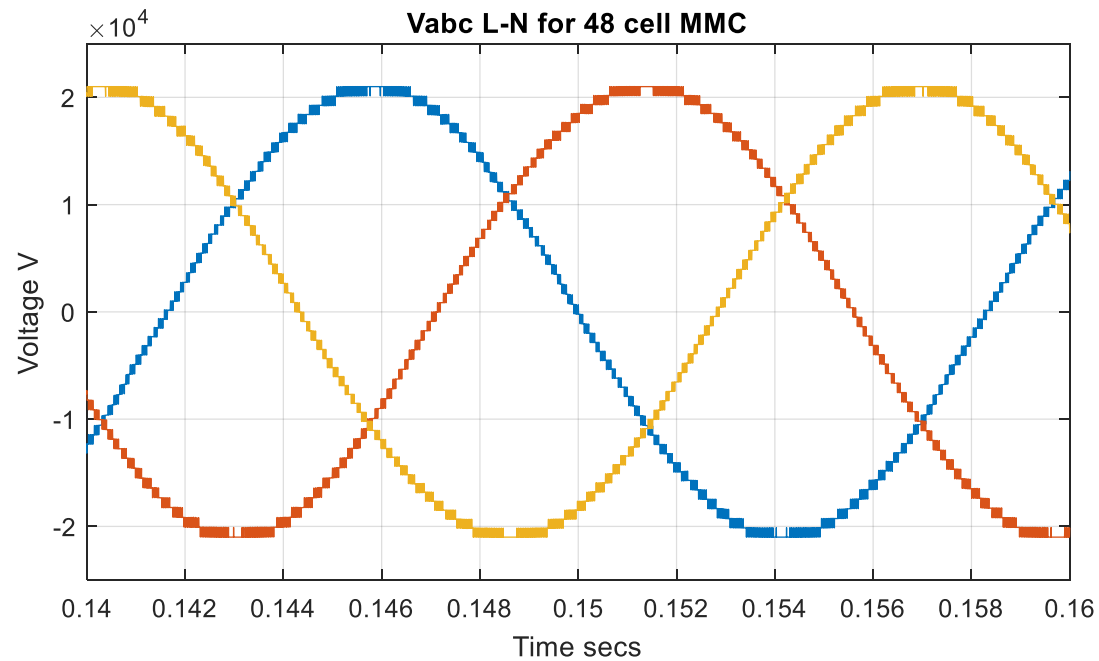
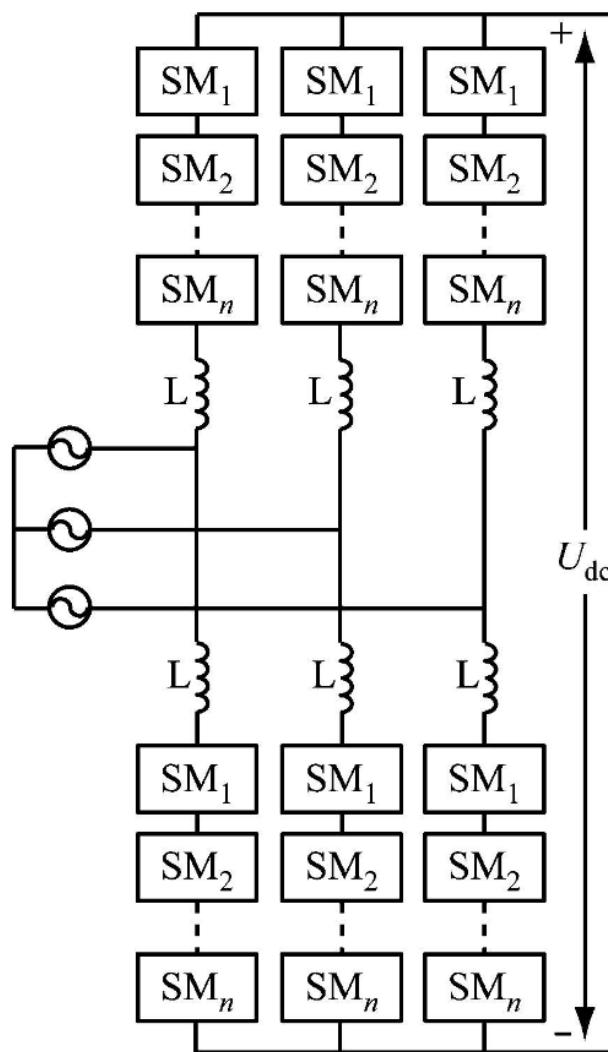


基于模型的方法与技术就绪程度



模块化多电平

柔性直流输电



Alstom Grid 使用基于模型设计开发HVDC控制系统

挑战

为了抓住风电场并网和智能电网市场机会，Alstom Grid要在24个月内容完成HVDC从概念到样机的开发。需要加快软件开发过程，同时尽量减少在过程后期发现的编码错误数量。

方法

采用基于模型的设计方法建模、仿真、验证、代码生成和文档自动化方法，完成整个控制保护系统开发。

结构

- 可量化的流程改进：将设计到代码（包含测试）的时间从1年减少到3个月，设计迭代从2个月减少到2周，文档更新从2周减少到几分钟。
- 与其他电力系统仿真软件快速集成：使用Embedded Coder快速将Simulink模型生成代码，在PSCAD/EMTDC中重用。
- 保护系统在一周内完成部署：使用Simulink和Stateflow进行建模，并生成代码，直接部署到嵌入式芯片



Alstom Grid's MMC结构HVDC 样机

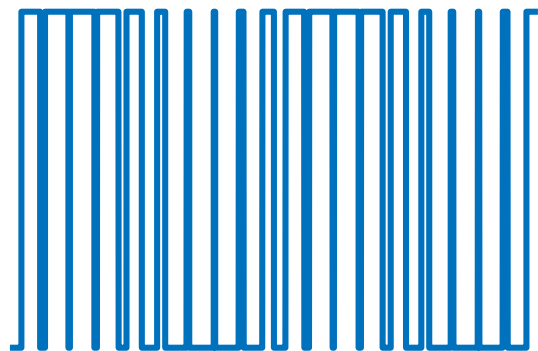
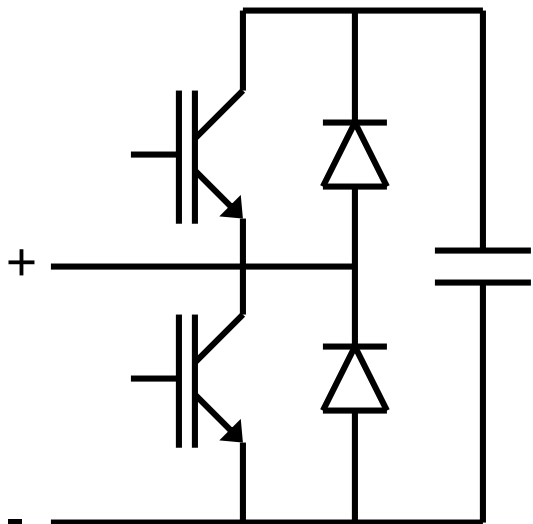
“使用基于模型的设计，我们开发了一个复杂的控制系统，其时间远远少于我们传统工艺所需的时间。我们通过从模型中生成代码来消除了数月的手动编码，我们使用仿真来实现早期的设计验证。”

- Anthony Totterdell, Alstom Grid

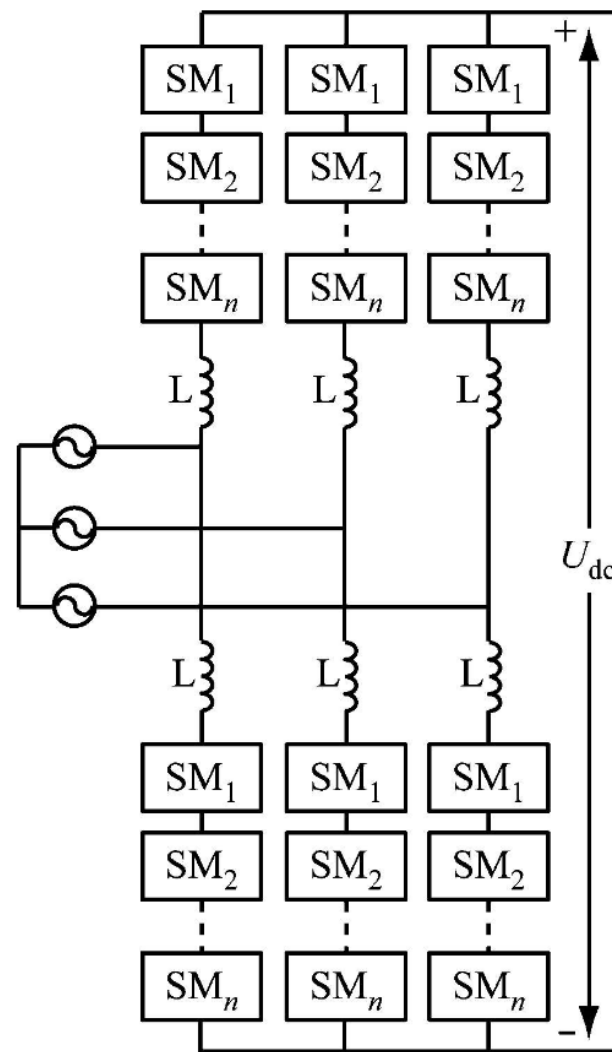
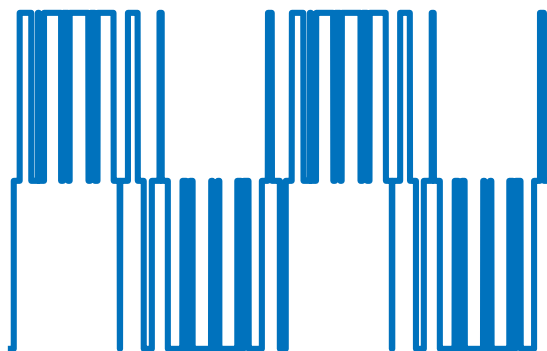
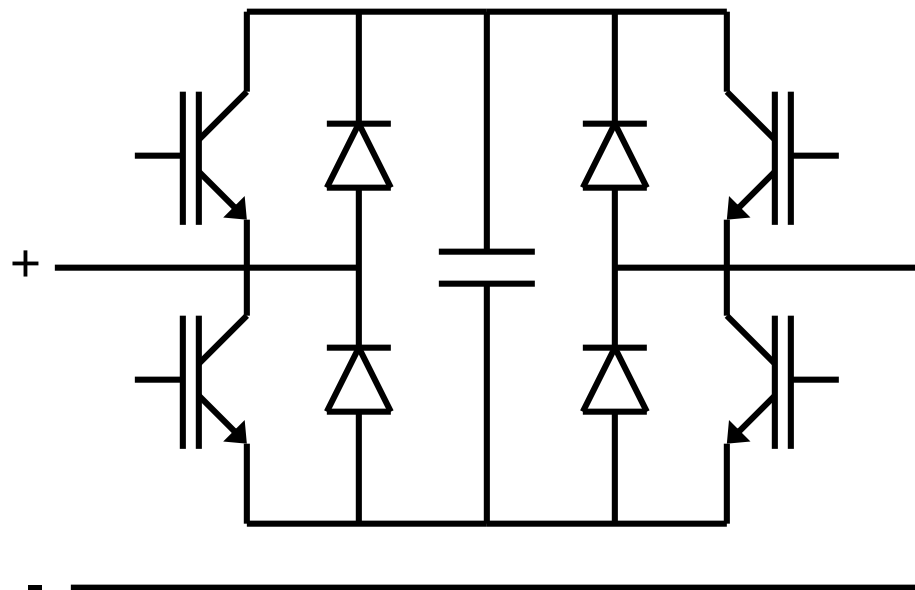
模块化多电平

基本原理

半桥

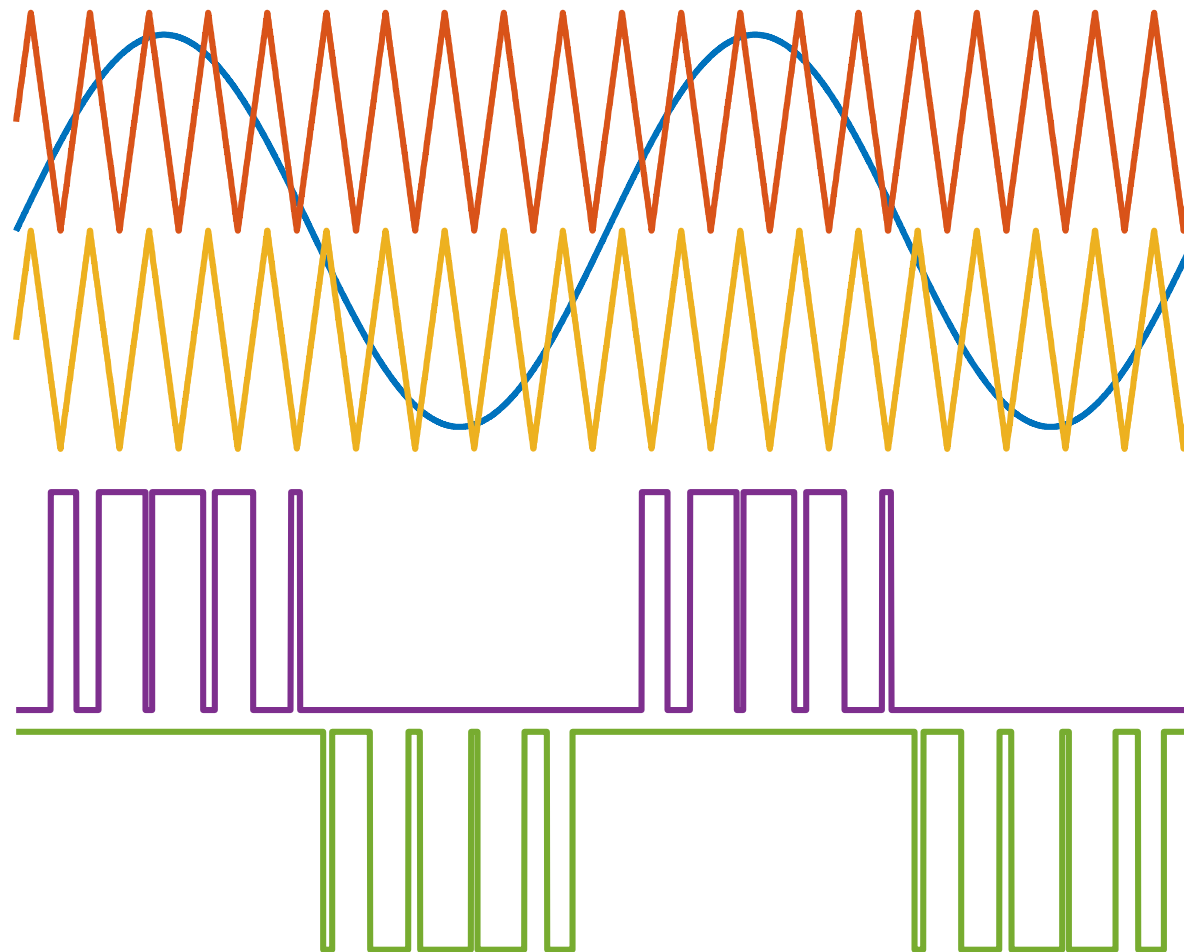
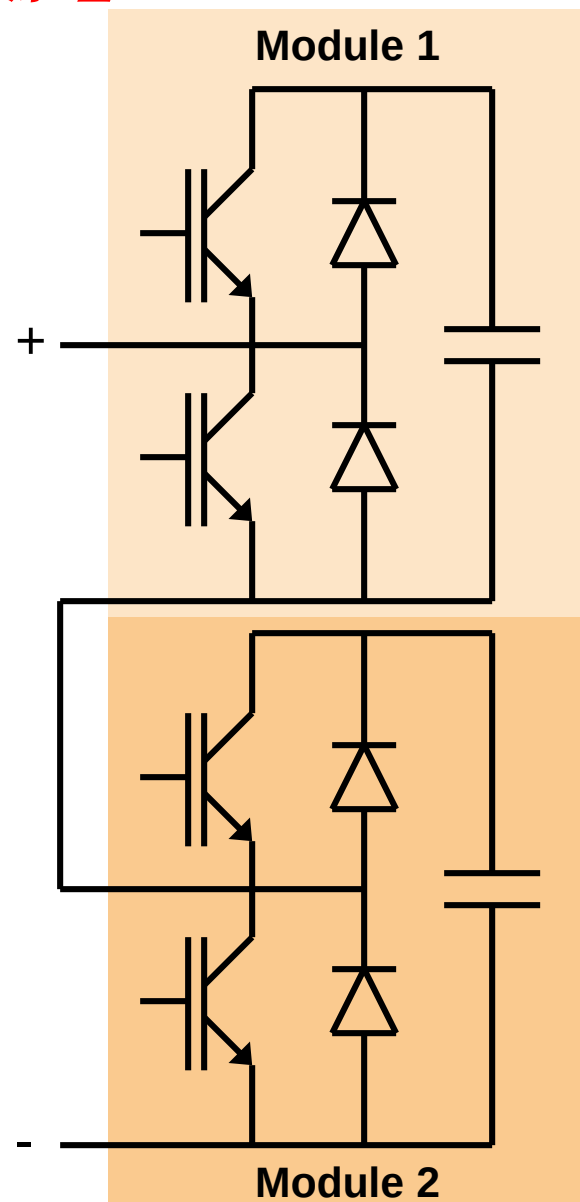


全桥



模块化多电平

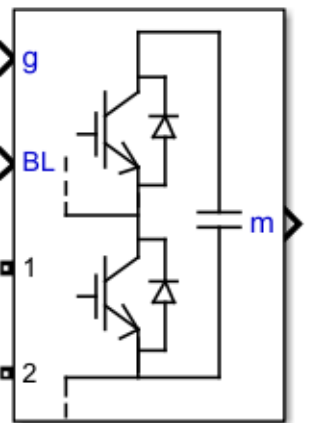
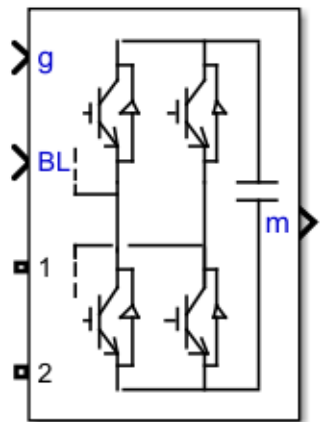
基本原理



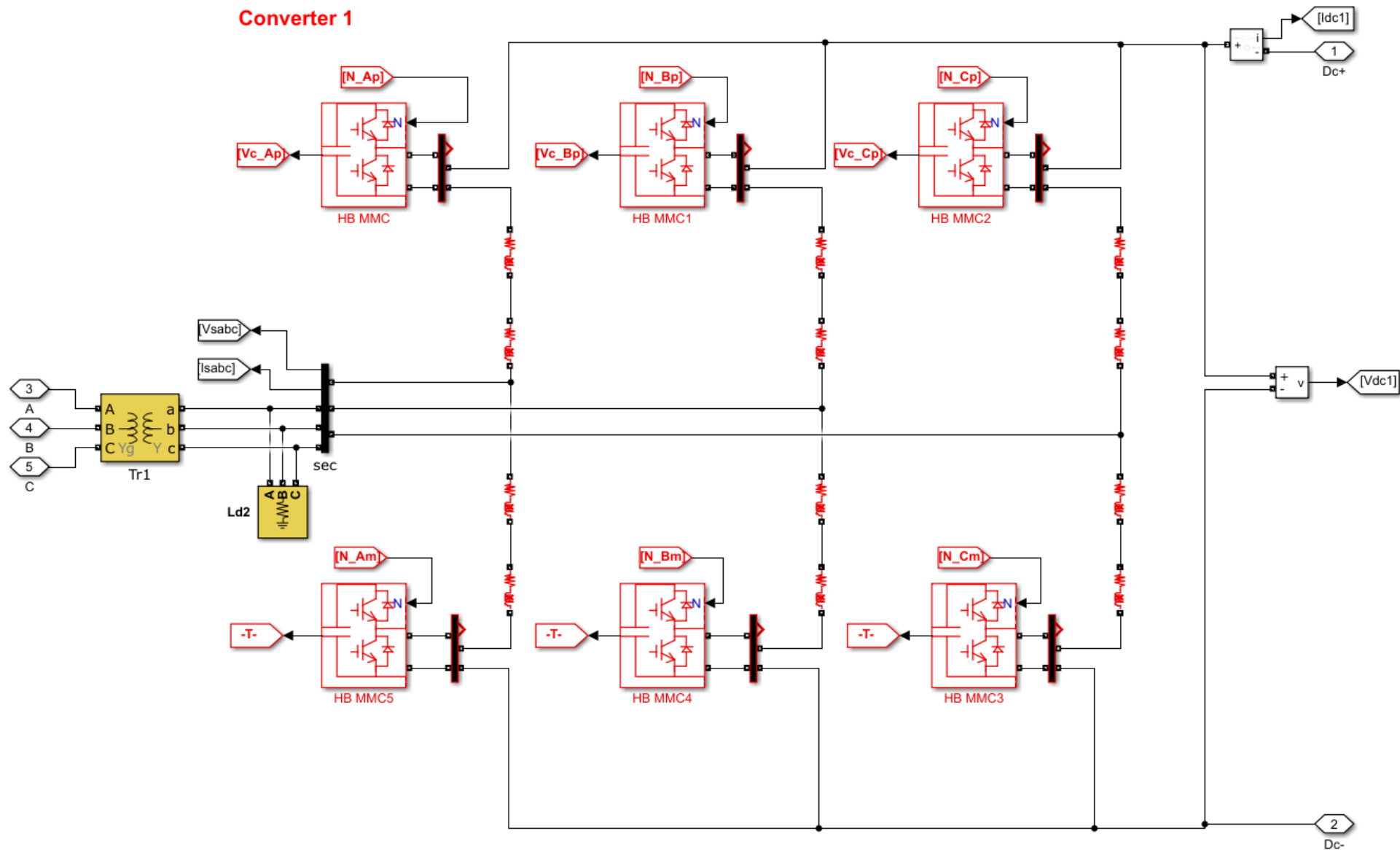
TRL 1

MMC建模

模型库自带MMC模块



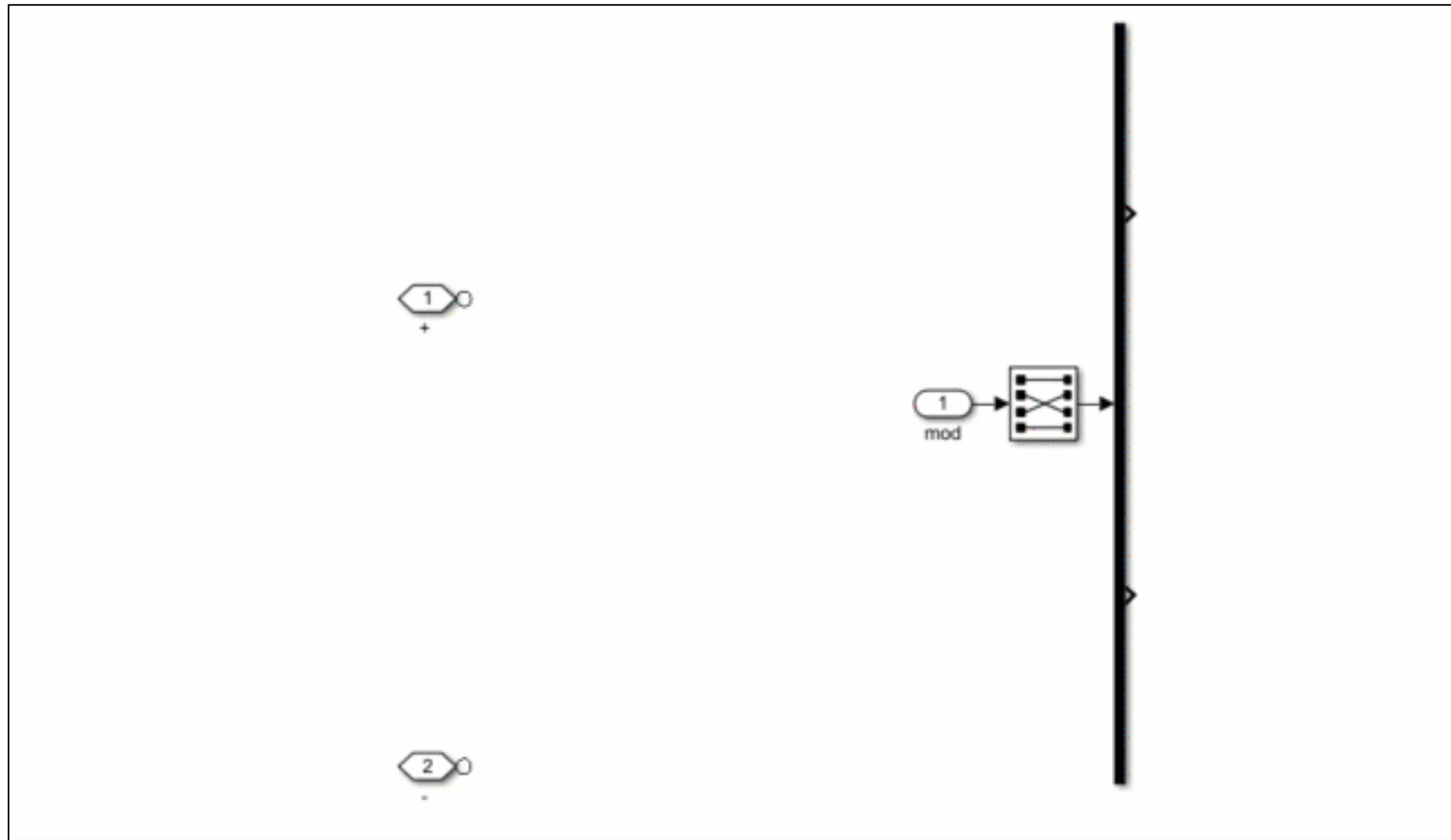
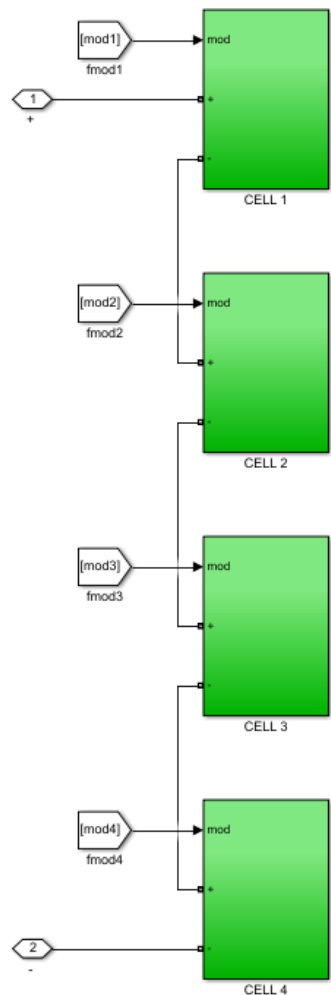
R2016b+



MMC建模

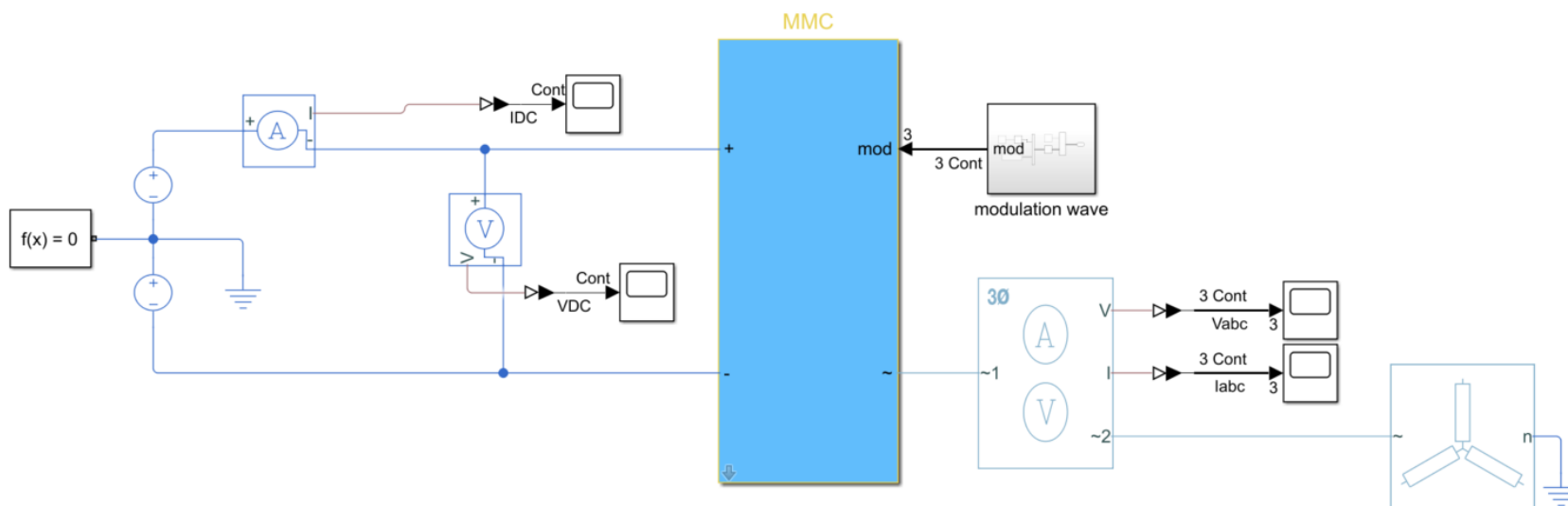
脚本自动化建模

- 通过MATLAB 调用Simulink API 可以实现复杂功率变换器的自动化建模



MMC仿真

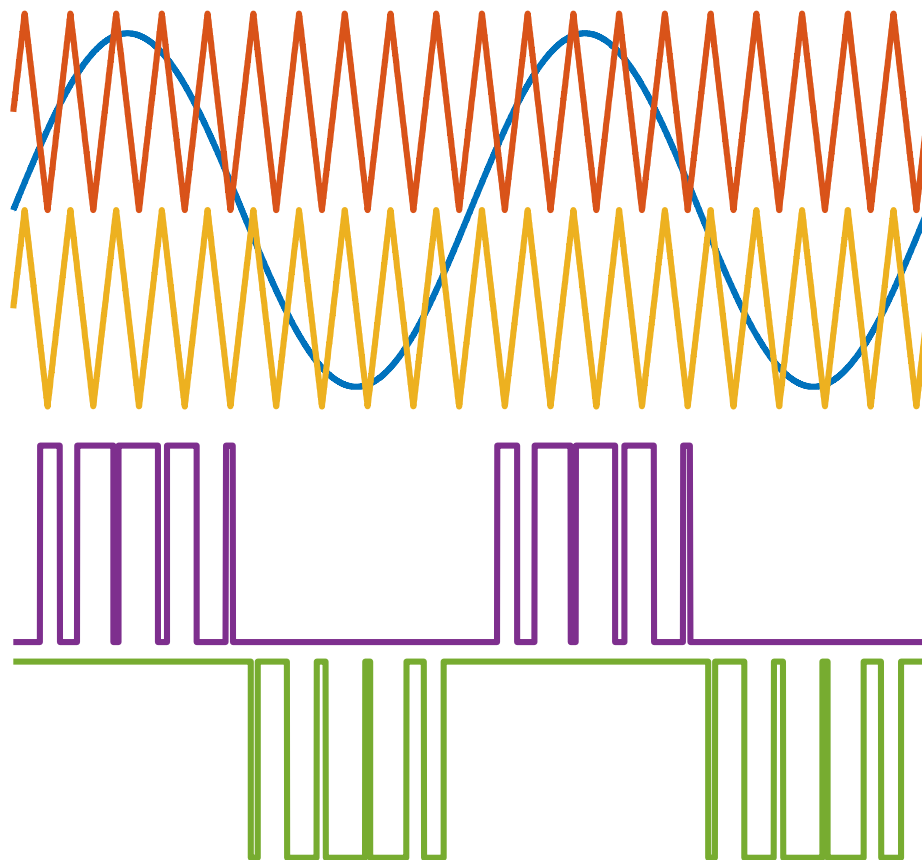
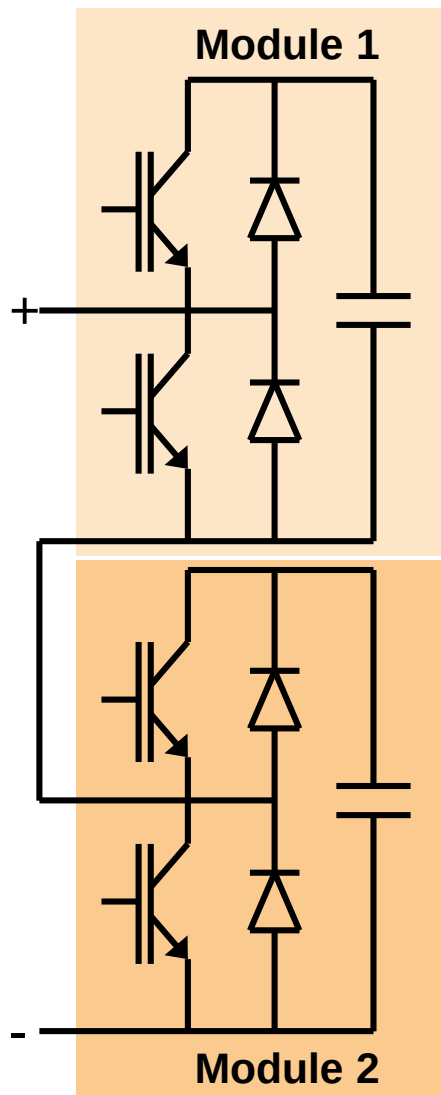
- 通过桌面仿真研究功率变换器结构和原理，例如
 - PWM与MMC输出一致性的校核
 - MMC单元均压算法的有效性
- 针对关注的问题建立单独的测试用例



TRL 2

MMC仿真

MMC 仿真对Solver的挑战

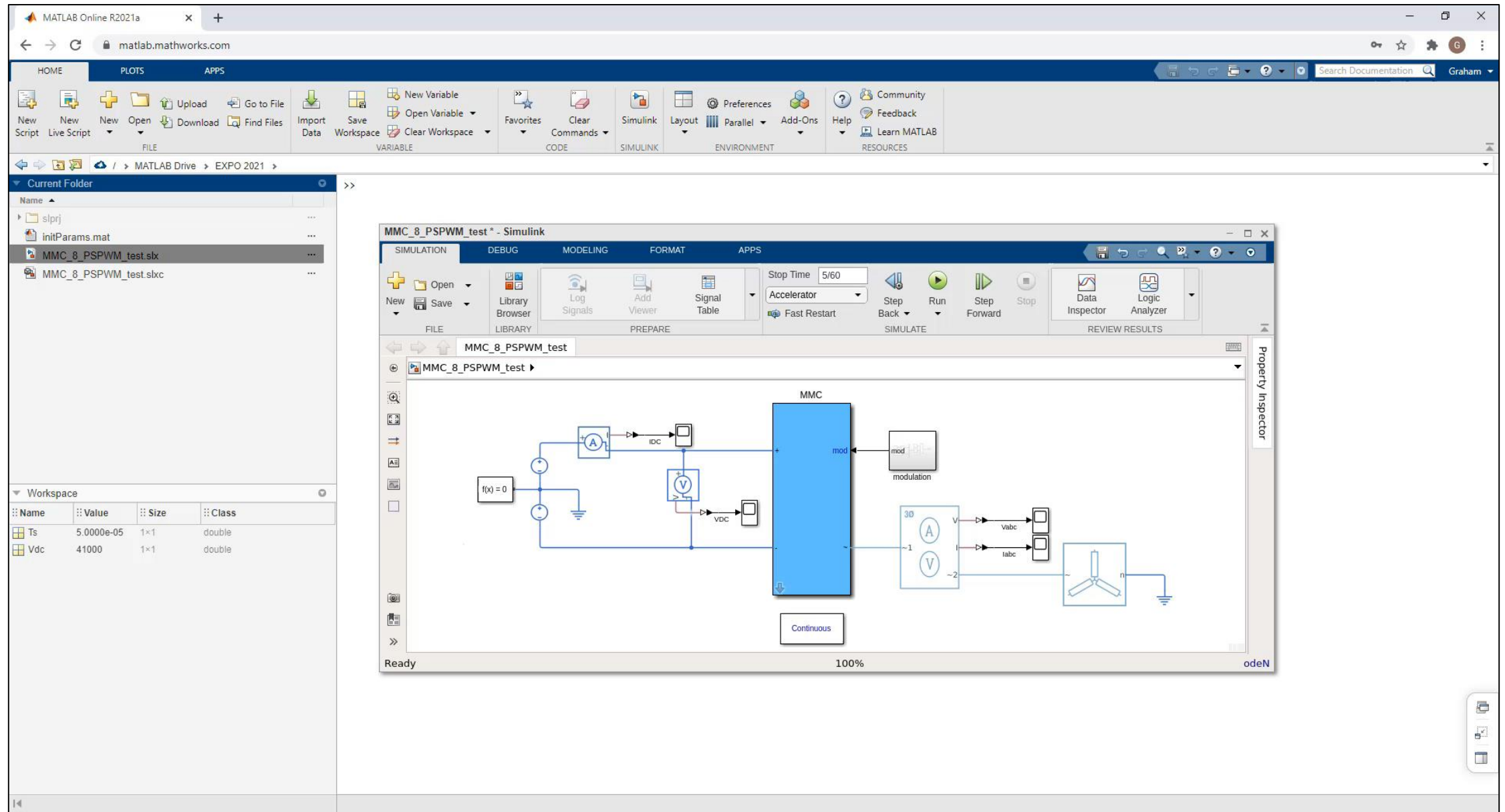


数量庞大的开关器件

仿真中捕获PWM变化瞬间
对仿真结果至关重要

变步长 Solver odeN

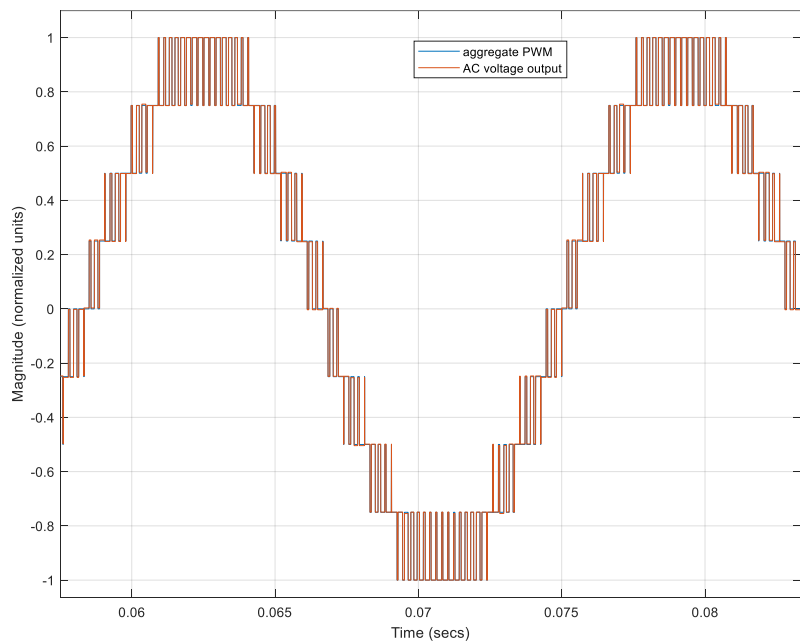
MMC仿真



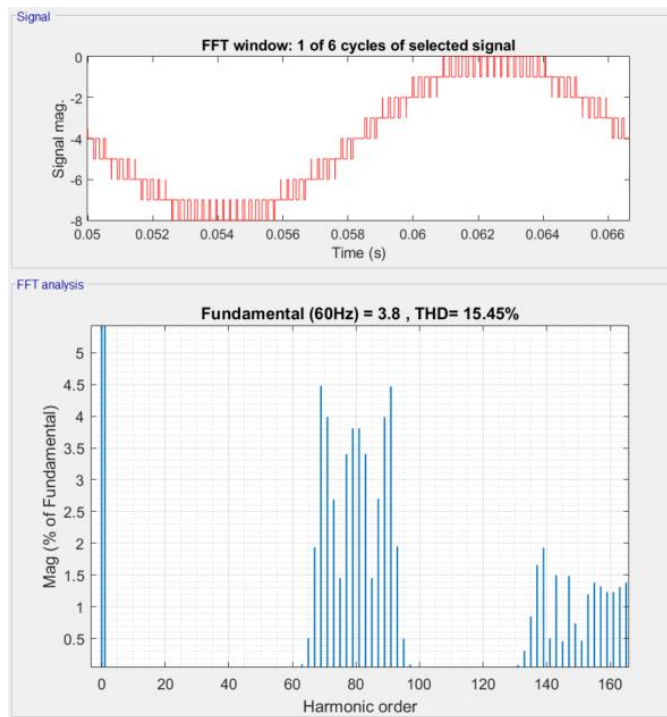
MMC仿真

■ 正常情况下

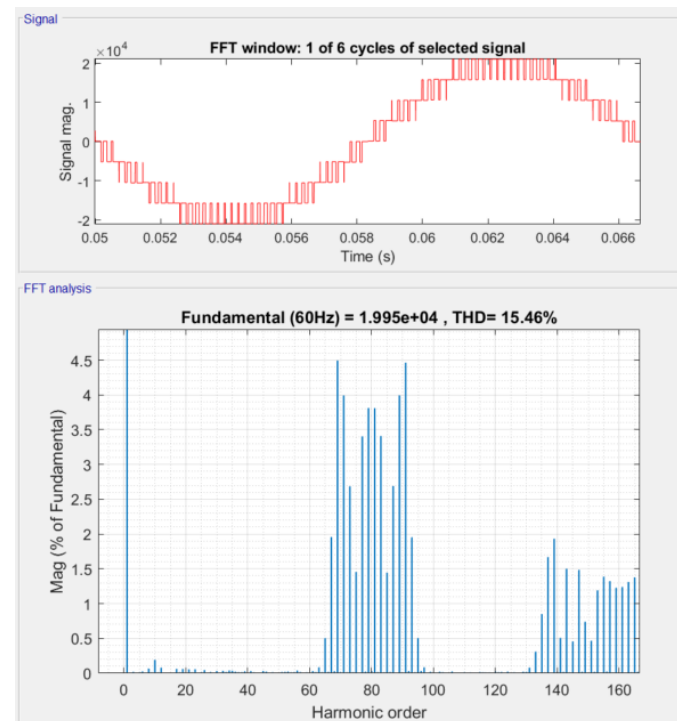
- 各模块PWM 信号之和应该与交流侧输出电压一致
- 两者谐波含量应该一致



(a) PWM之和 和交流侧输出电压



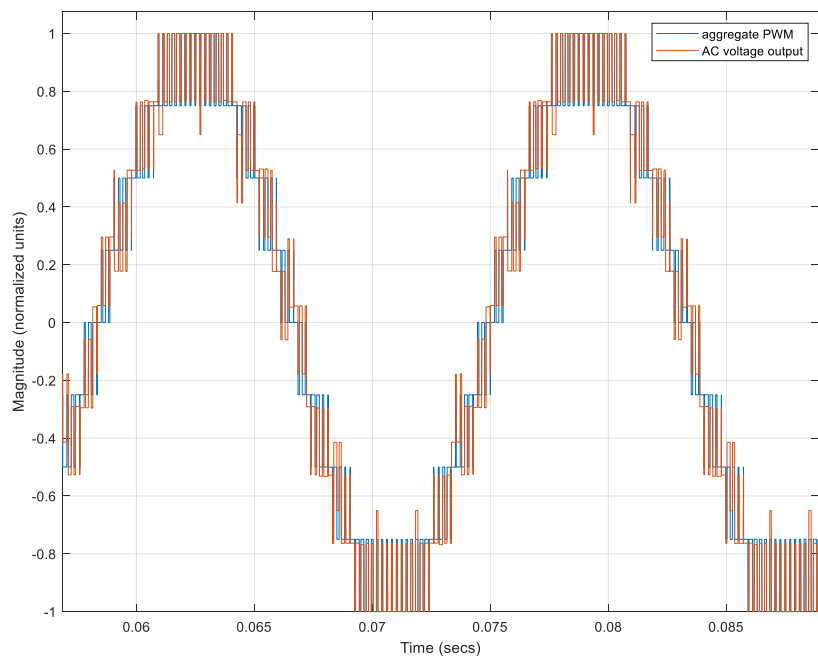
(b) PWM之和谐波



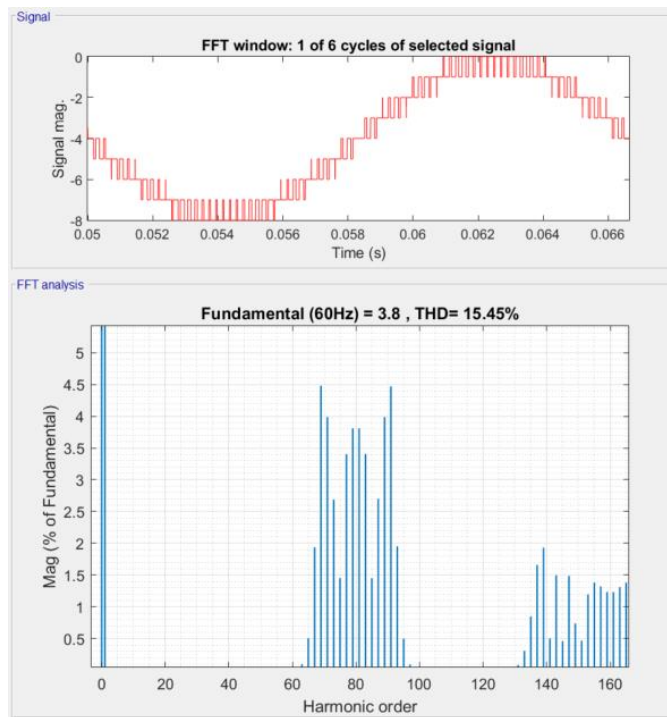
(c) 交流侧输出电压谐波

MMC仿真

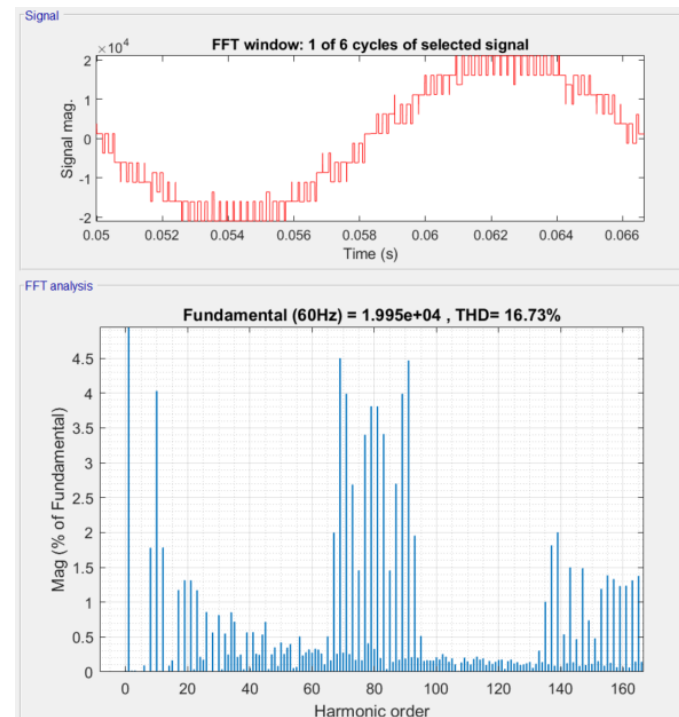
- 错误状态下，如模块模块PWM信号丢失
 - PWM信号之和与交流输出电压会出现明显的不一致
 - 谐波分布不一致



(a) PWM之和 和交流侧输出电压



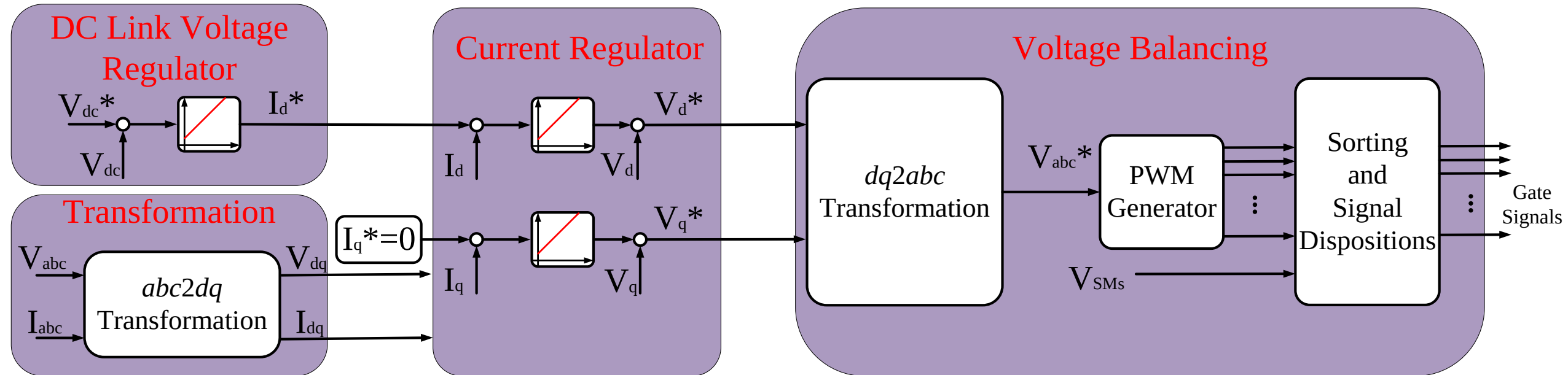
(b) PWM之和谐波



(c) 交流侧输出电压谐波

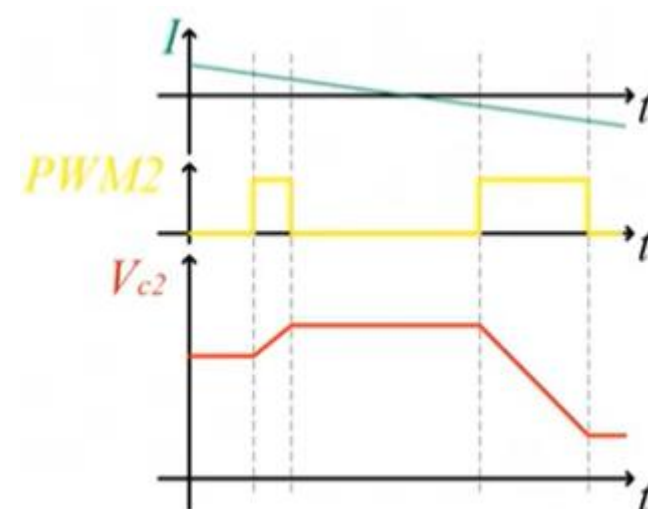
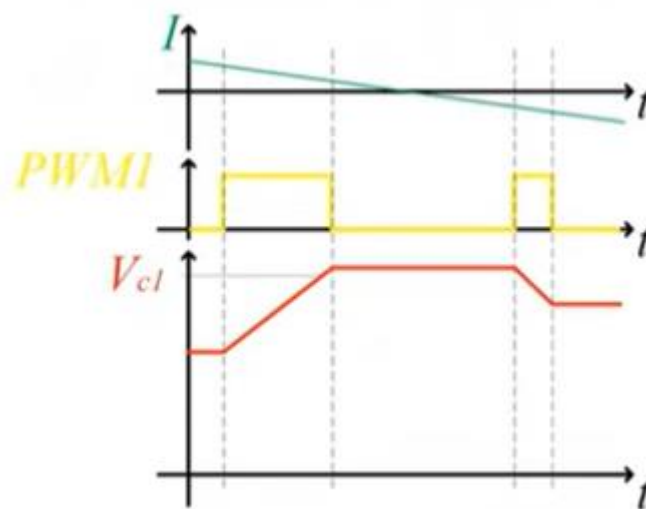
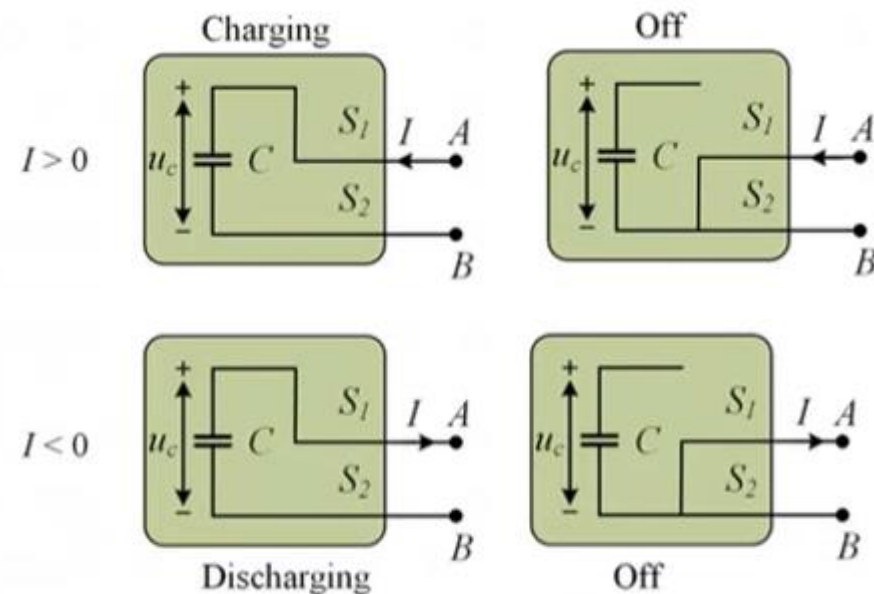
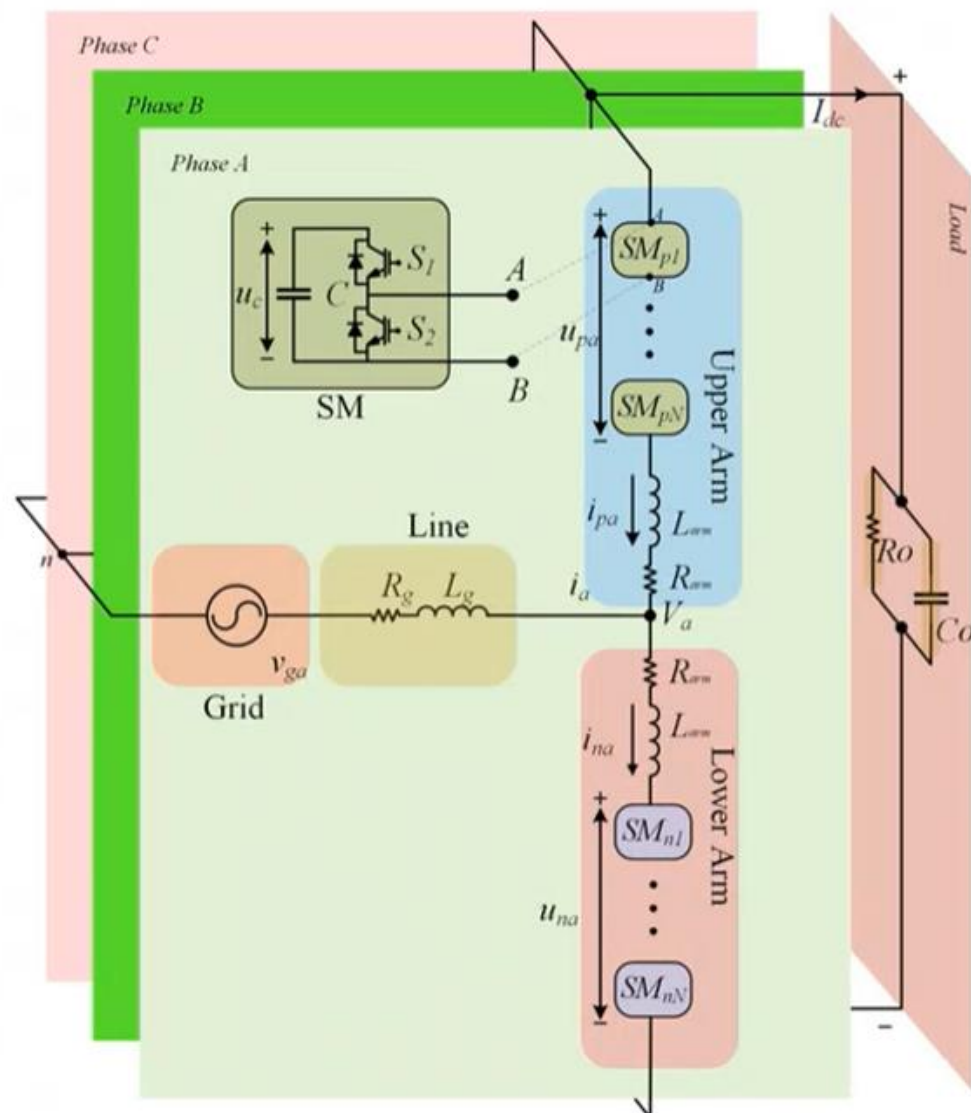
控制算法

矢量控制算法



控制算法

模块均压算法



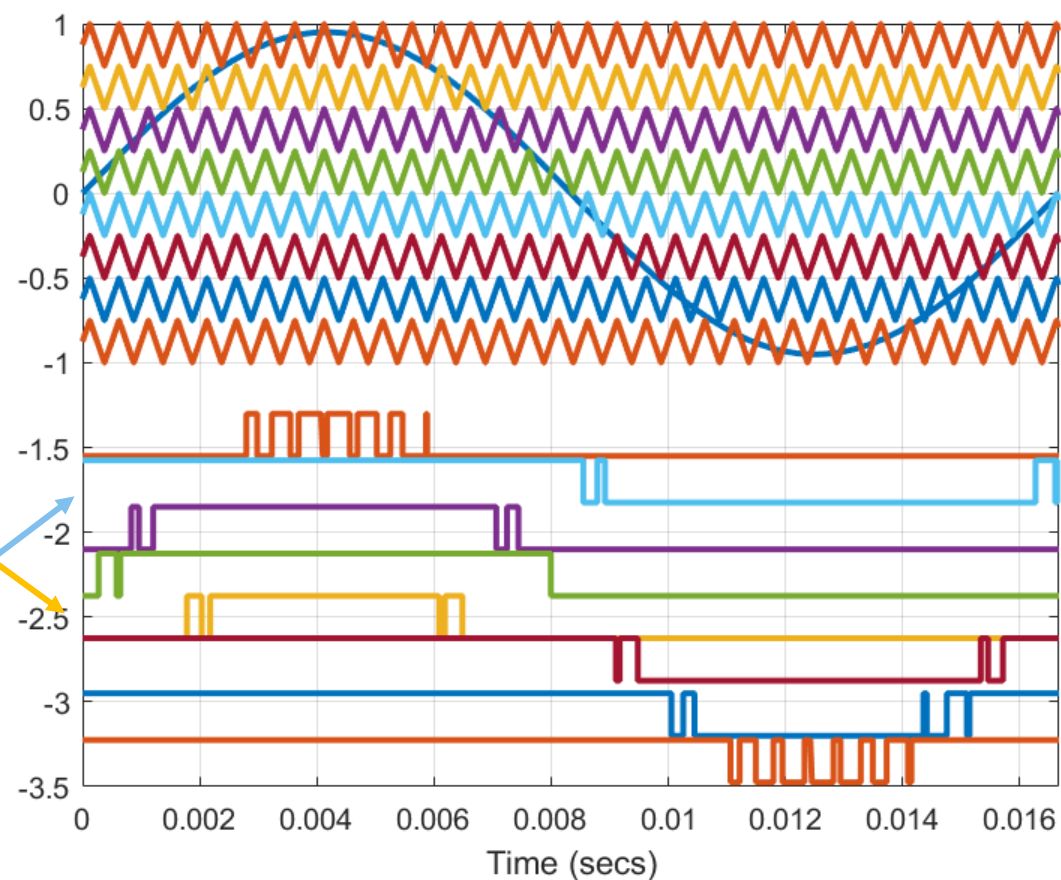
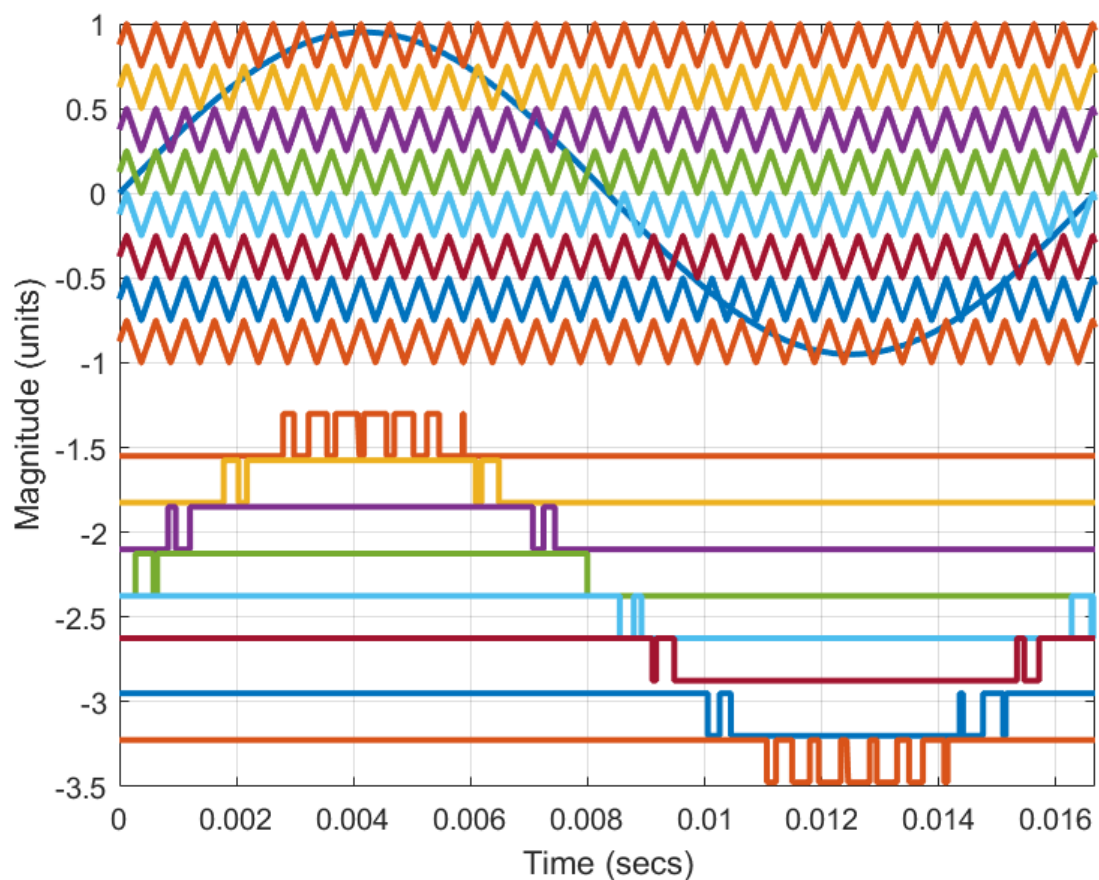
控制算法

模块均压算法

假设某相模块电压分别如下:

$$V_{c1} < V_{c5} < V_{c3} < V_{c4} < V_{c2} < V_{c6} < V_{c7} < V_{c8}$$

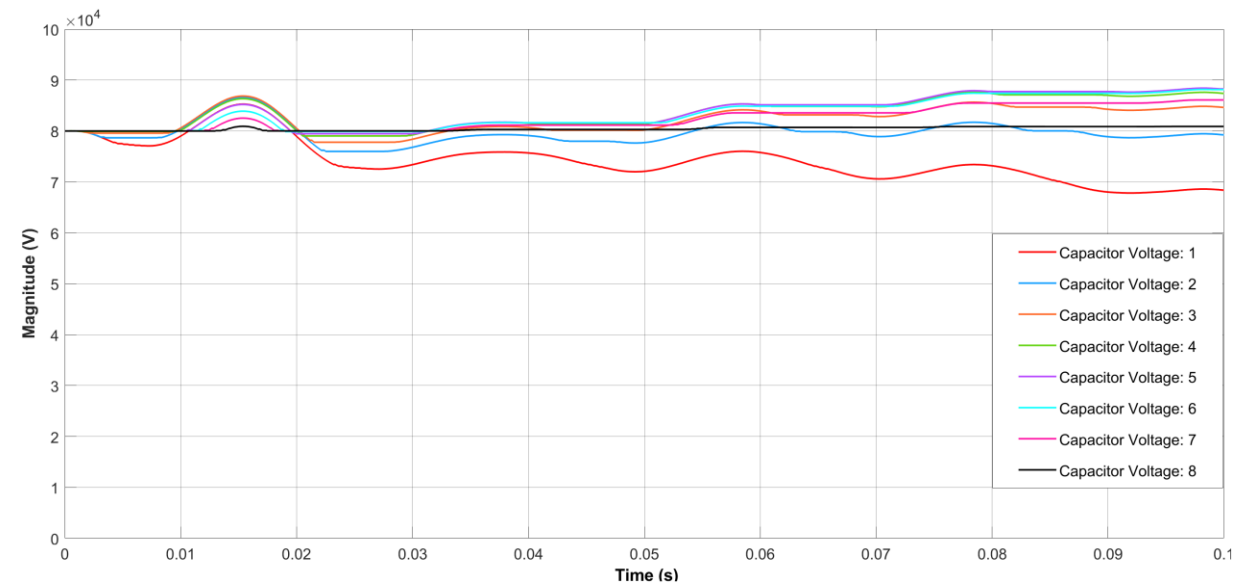
Level shifted PWM



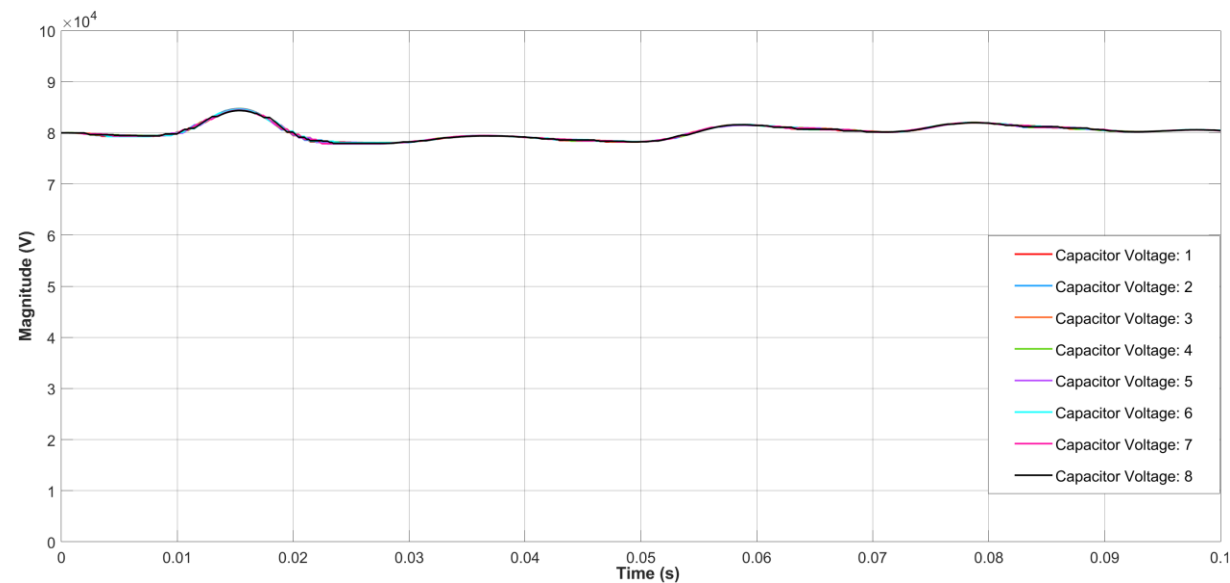
控制算法

模块均压算法

没有模块均匀算法情况下，电压分散



添加均匀算法后，电压保持一致

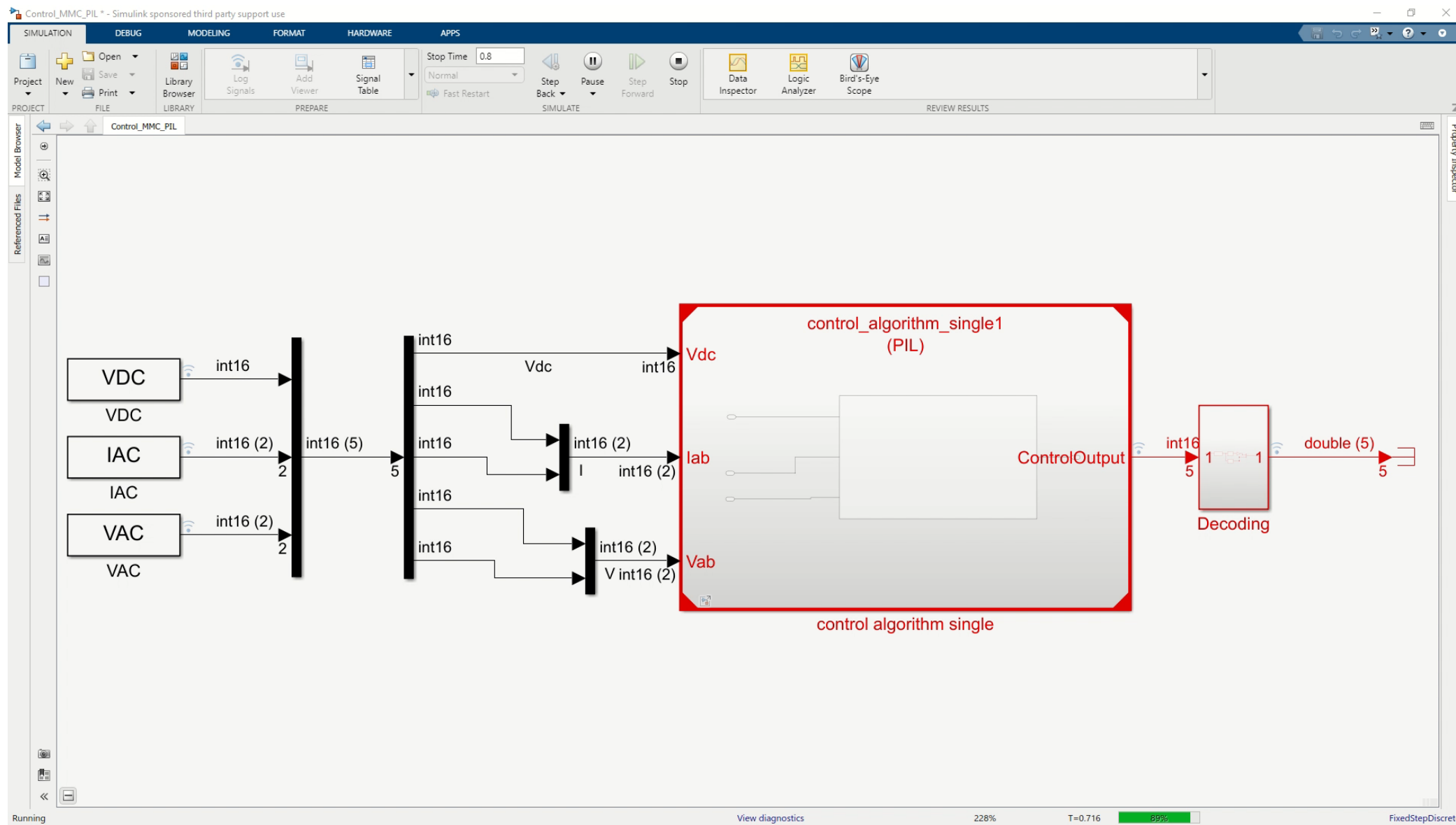


TRL 3



控制器实现

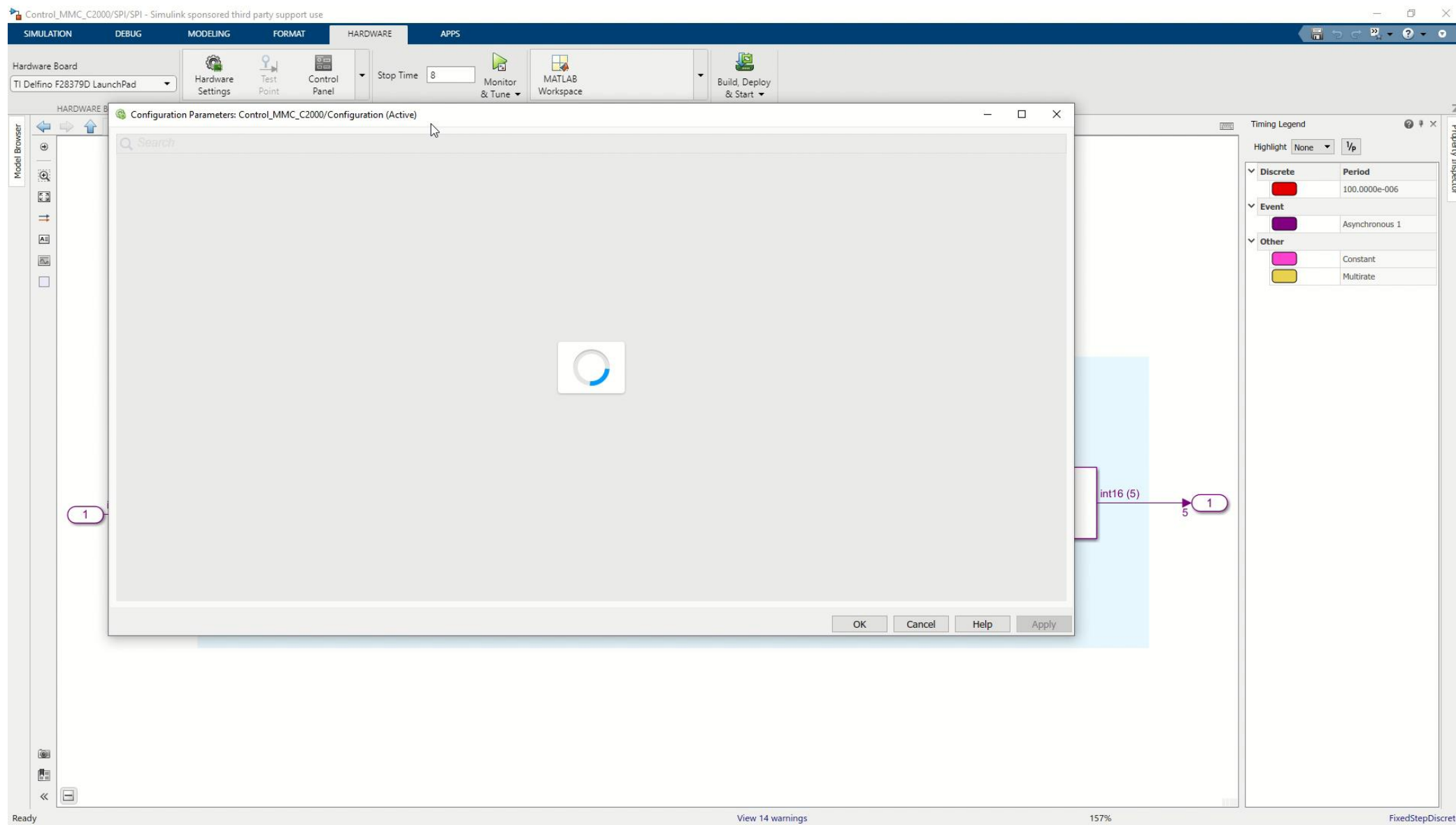
代码生成与处理器在环 (PIL) 测试





控制器实现

驱动参数设置



The screenshot shows the MATLAB/Simulink Hardware Configuration window for a TI Delfino F28379D LaunchPad. The window is titled "Configuration Parameters: Control_MMC_C2000/Configuration (Active)". The main area is a large gray rectangle with a loading spinner in the center. The bottom of the window has buttons for "OK", "Cancel", "Help", and "Apply".

The background Simulink model is partially visible, showing a block labeled "int16 (5)" connected to a block labeled "1".

The right sidebar contains the "Timing Legend" and "Property Inspector". The "Timing Legend" shows the following settings:

Highlight	None	1/p
Discrete	Period	100.0000e-006
Event	Asynchronous 1	
Other	Constant	
	Multirate	

The status bar at the bottom indicates "Ready", "View 14 warnings", "157%", and "FixedStepDiscrete".

控制器实现

软件下载

Control_MMC_C2000/SPI - Simulink sponsored third party support use

SIMULATION DEBUG MODELING FORMAT HARDWARE APPS

Hardware Board: TI Delfino F28379D LaunchPad

Hardware Settings Test Point

HARDWARE BOARD PREPARE

Model Browser

SPI Master Transfer

SPI Master transfer

1 int16 (5) 5

Byte Pack

uint16 (5) 5

Tx SPI Transmit Slave select: SPISTE

c28x Status uint16

SPI Receive Status Slave select: SPISTE

c28x Rx uint16 [5x1] [5x1]

Byte Unpack

int16 (5) 5

1

Diagnostic Viewer

Diagnostics

Control_MMC_C2000 SingleMMC_SLRTSPImaster

```
*** Terminating debug session...

*** LOAD & RUN DONE.
### Invoking custom build hook: CodeGenAfterMake
### Successful completion of build procedure for: Control_MMC_C2000
### Invoking custom build hook: CodeGenExit
### Simulink cache artifacts for 'Control_MMC_C2000' were created in
'C:\Work\Projects\MMC\V2\20200202_MMCProject\20200202_MMCProject\work\SimulationCache\Control_M
MC_C2000.slxc'.

Build process completed successfully

▼ Build Summary 1
Elapsed: 0.11 sec

Top model targets built:

Model      Action      Rebuild Reason
-----
Control_MMC_C2000  Code generated and compiled  Generated code was out of date.

1 of 1 models built (0 models already up to date)
Build duration: 0h 1m 27.515s
```

Timing Legend

Highlight	None	1/p
Discrete		Period
Event		Asynchronous 1
Other		Constant
		Multirate

Property Inspector

Ready

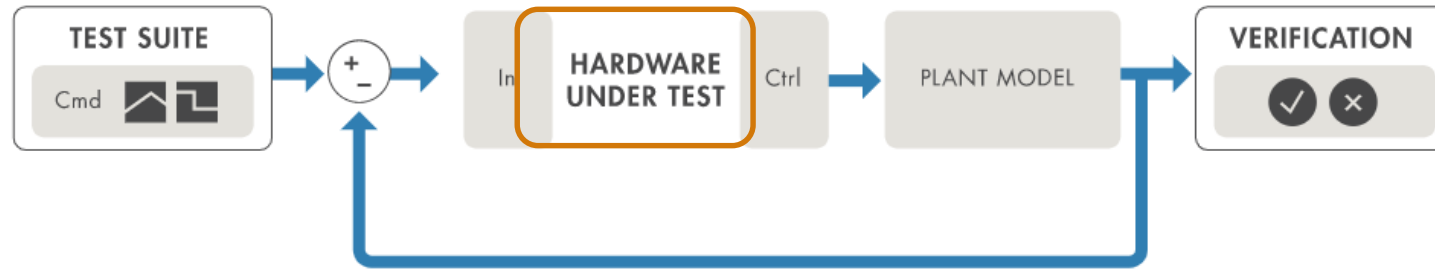
View diagnostics

157%

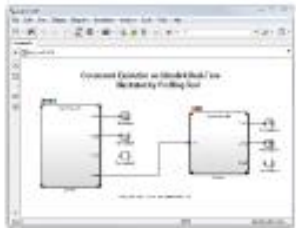
FixedStepDiscrete

控制器测试

硬件在环 (HIL)



Development computer



MATLAB, Simulink, MATLAB Coder,
Simulink Coder, and
Simulink Real-Time

Ethernet

HIL simulator



Multi-core CPU running Simulink
Real-Time kernel, FPGAs, I/O
and protocol interfaces

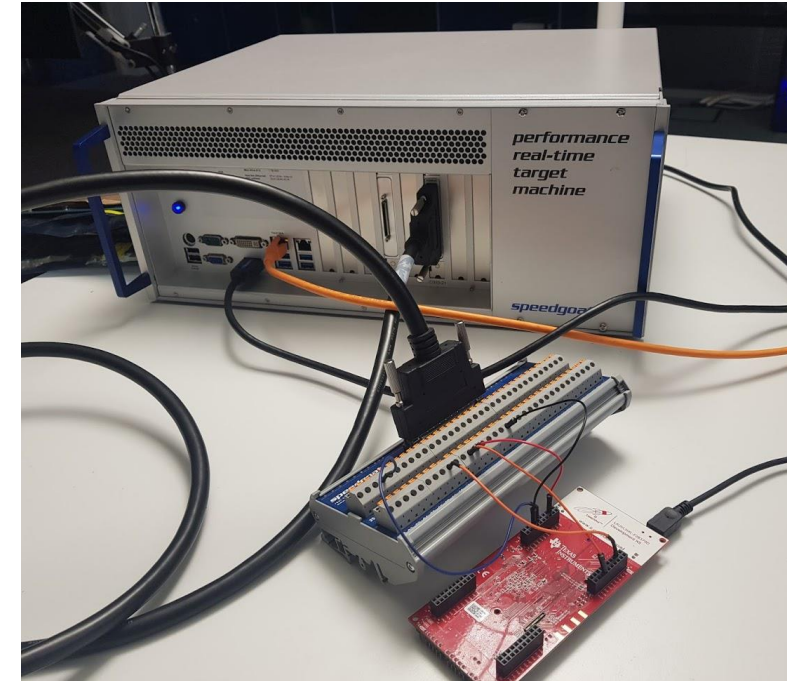
I/O

Controller(s)



Hardware under test with sensor
and actuator interfaces

Plant simulation application
autogenerated from Simulink



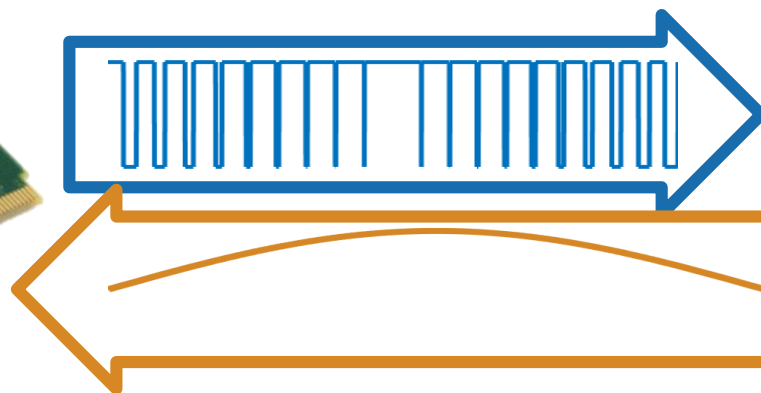
硬件在环测试

好处

- 代替实际硬件
- 尽早开展自动化测试
- 保证测试安全
- 在虚拟环境中探索更多可能的方案



控制器

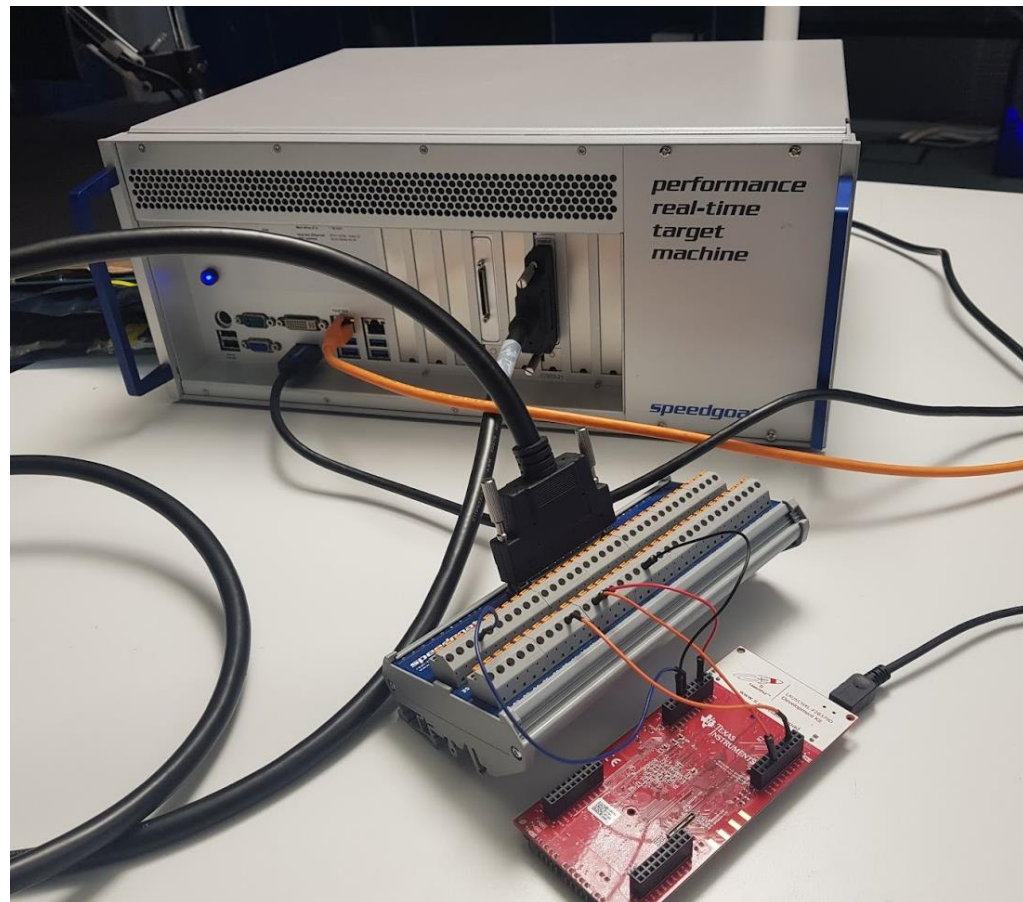


虚拟被控对象

硬件在环测试

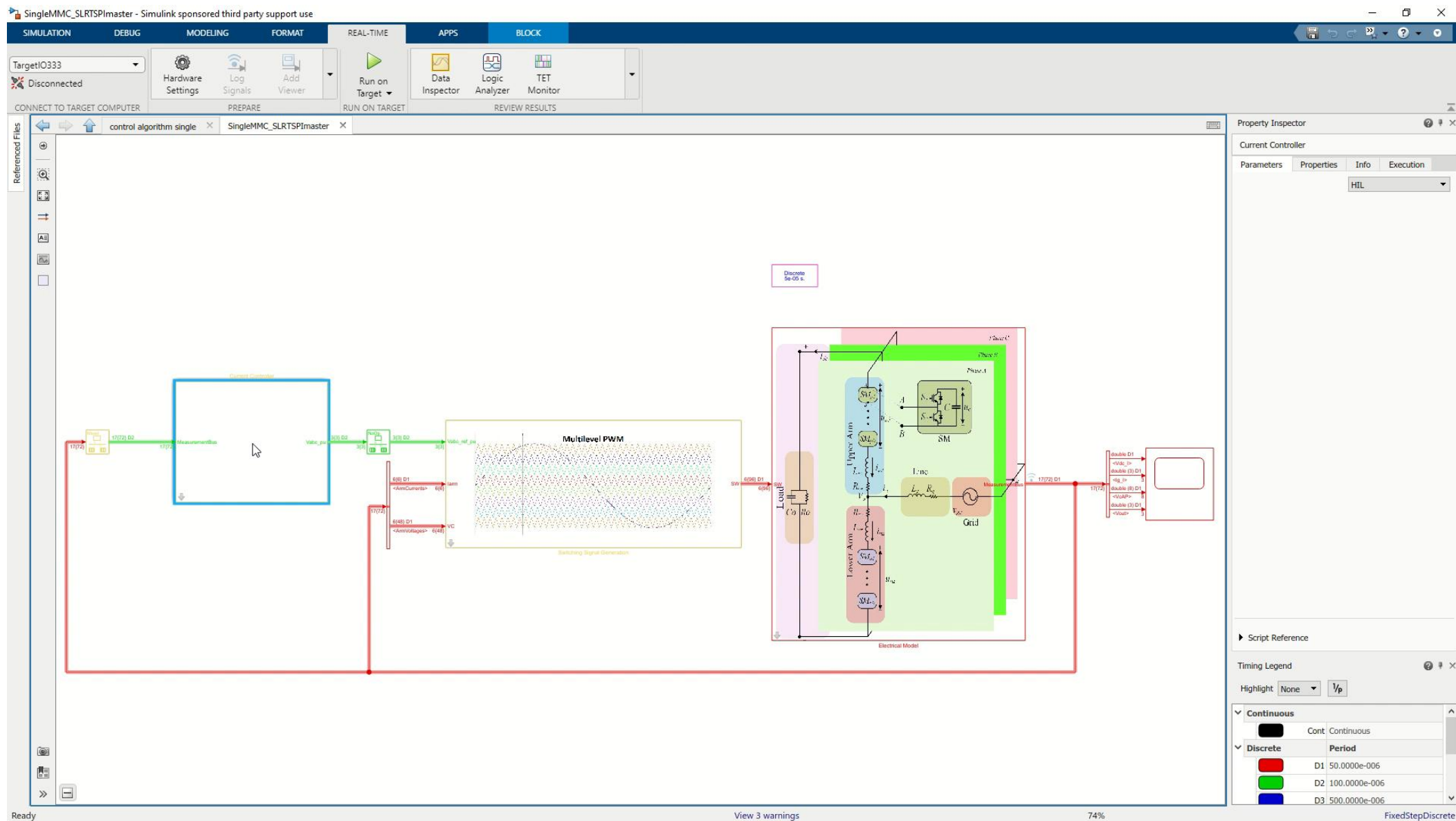
基本步骤

- 配置模型和硬件接口
- 将控制算法部署到控制
- 将被控对象和测试用例部署到Speedgoat
- 运行实时模型
- 检查结果是否正确



硬件在环测试

配置与控制的O接口



硬件在环测试

模型下载与仿真测试

MATLAB R2020b - sponsored third party support use

HOME PLOTS APPS PROJECT PROJECT SHORTCUTS

FILE TOOLS ENVIRONMENT SOURCE CONTROL

Current Folder: C:\Work\Projects\MMC\V2\20200202_MMCProject\20200202_MMCProject\SimulinkModels

Live Editor - initparams_MMCWC.mlx

Project - MMC_Christoph

Workspace

Name	Value
alpha_f	100
C	0.0200
C_sm	0.0200
C_sm_vector	[0.0200, 0.0200, 0.0200, ...]
Capacitor/Voltages...	1x1 Bus
carrier_max	[0.1250, 0.2500, 0.3750, ...]
carrier_min	[0.0, 0.1250, 0.2500, 0.375...
cf	300
Co	0.0100
data_type	'single'
f_g	50
f_sw	2000
I_f_max	10000
ind1	[1, 2, 3, 4, 5, 6, 7, 8]
ind2	[9, 10, 11, 12, 13, 14, 15, 16]
ind_reshape	1x16 double
inverter	1x1 struct
K_gc_id	65
K_gc_iq	65
K_gc_iW	25
K_gc_pd	0.6500
K_gc_pq	0.6500
K_gc_pW	1
L	1.0000e-04
L_arm	0.0030
L_f	0.0065
L_g	0.0050
LegCurrentsBus	1x1 Bus
logout	1x1 struct
mdl	'SingleMMC_SLRT'
num_sm	8
PI_params	1x1 struct
pmsm	1x1 struct
PWM_frequency	20000
R	5
R_arm	0.1000
R_f	0.1500
R_g	0.1000
R_gc_a	0.5000
R_res_a	1.0000e-03
Ro	2048
SI_System	1x1 struct
SwitchingSignalsB...	1x1 Bus
T_HIL	5.0000e-06
T_pwm	5.0000e-05
target	1x1 struct
tg	1x1 Target
Ts	5.0000e-05
Ts_CurrentControl	1.0000e-04

Command Window

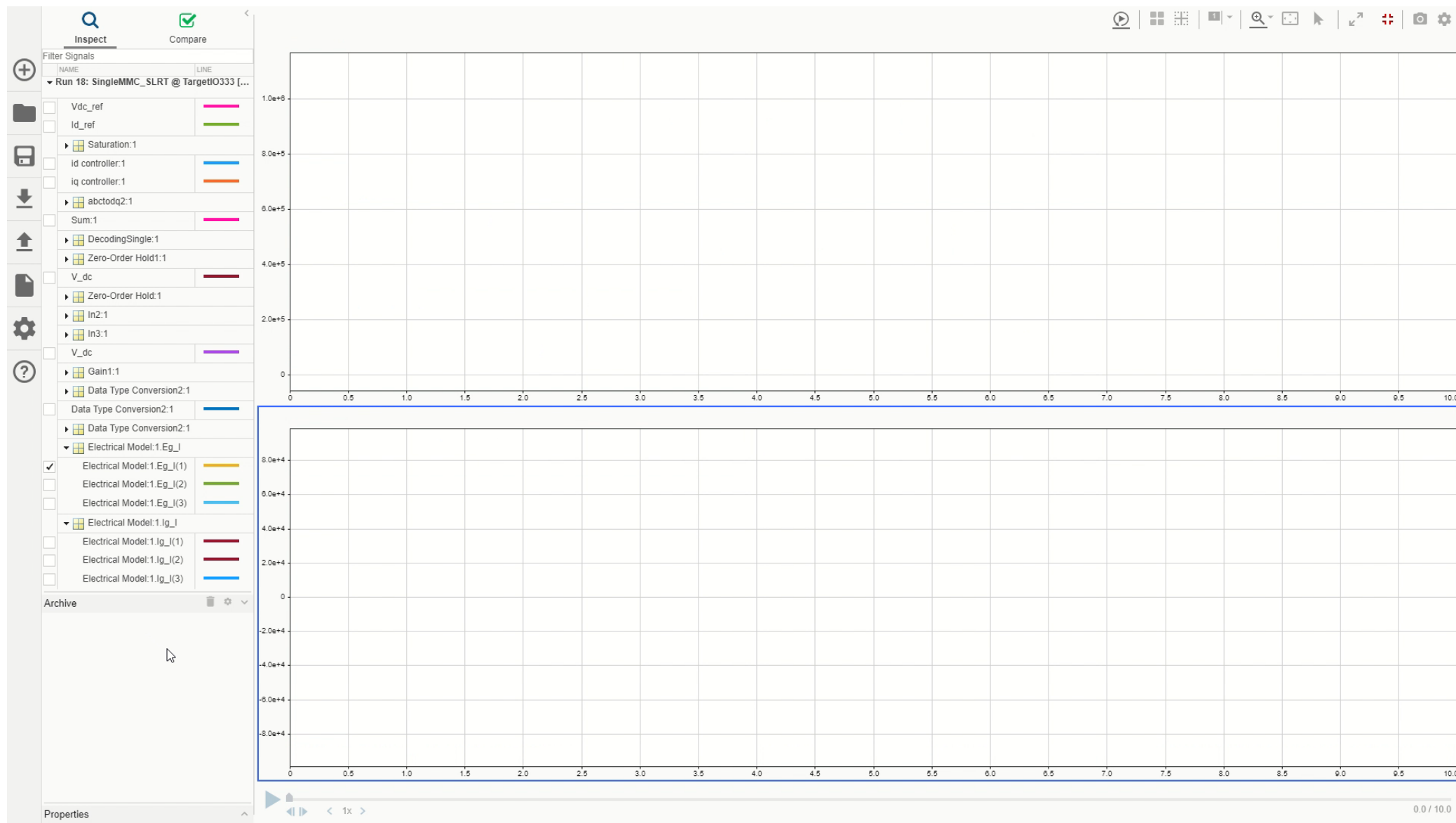
```
MC >>
```

SingleMMC_SLRT.slx (Simulink Model)

TRL 6~

硬件在环测试

结果查看



总结

- Simulink 支持各个技术就绪阶段的模型精度实现
- Simulink中复杂功率变换器建模
- 利用Simulink进行复杂功率变换器离线和实时仿真
- 变步长求解器实现PWM精确仿真
- 在模型中快速验证控制策略的功能正确性
- 利用自动代码生成和HIL测试将控制器实现的风险降到最低

MATLAB EXPO 2021

Thank you



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