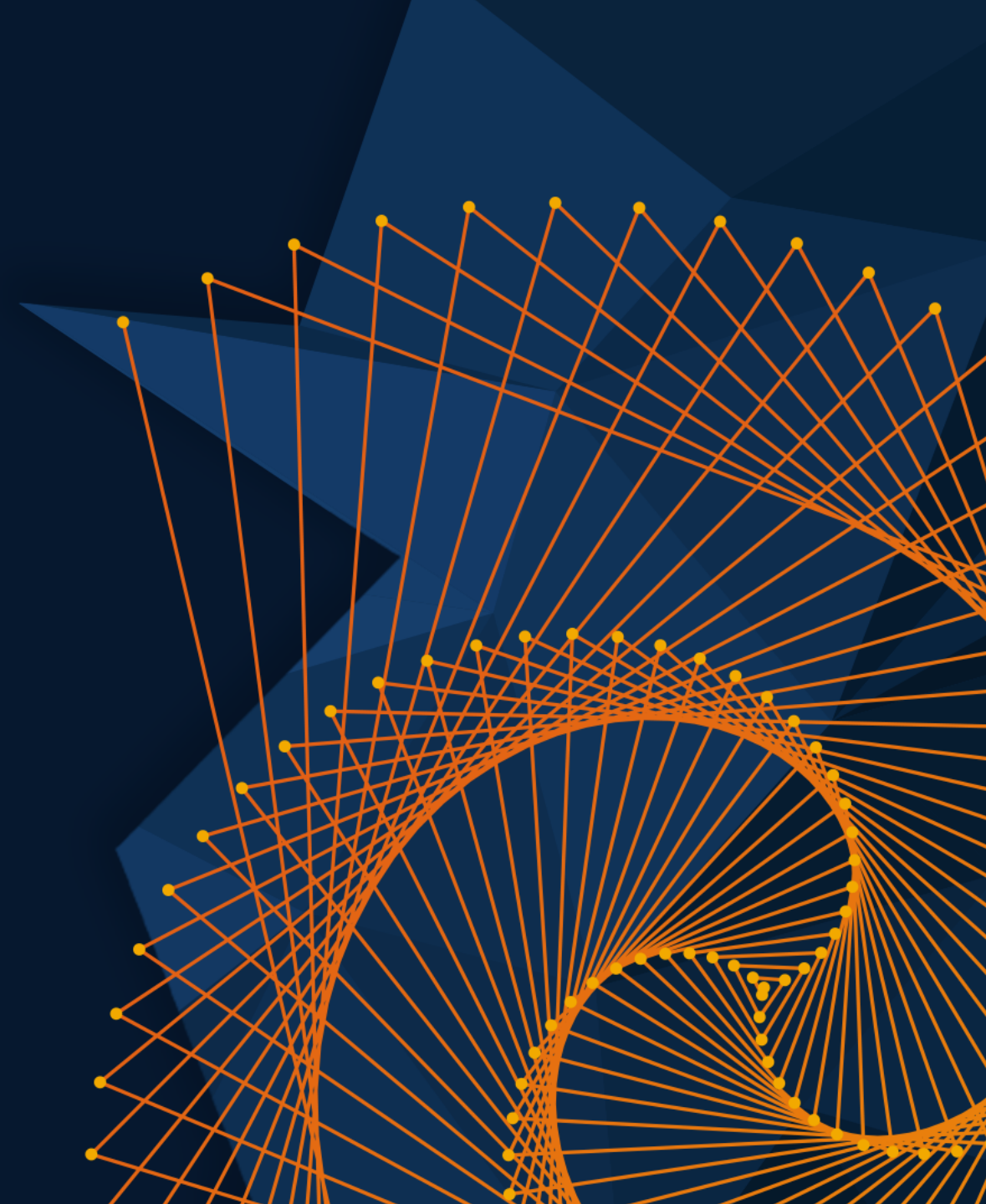


MATLAB EXPO

May 28, 2024 | Beijing

电力电子系统模型保真度选择

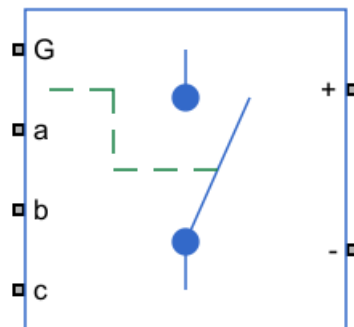
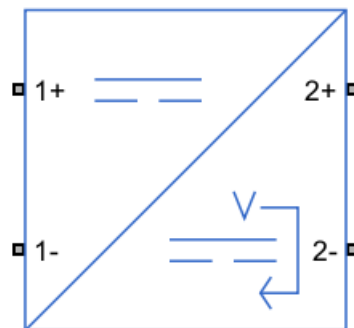
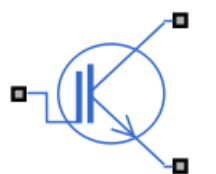
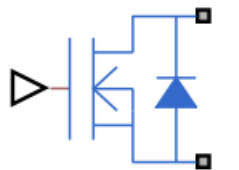
周前程, MathWorks



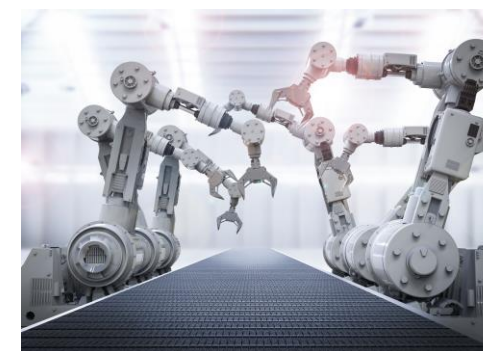
电力电子技术

■ 调节电能属性

- 直流：幅值
- 交流：幅值、频率、相角



电能生产



工业控制



生活电器

仿真是电力电子设计的重要手段



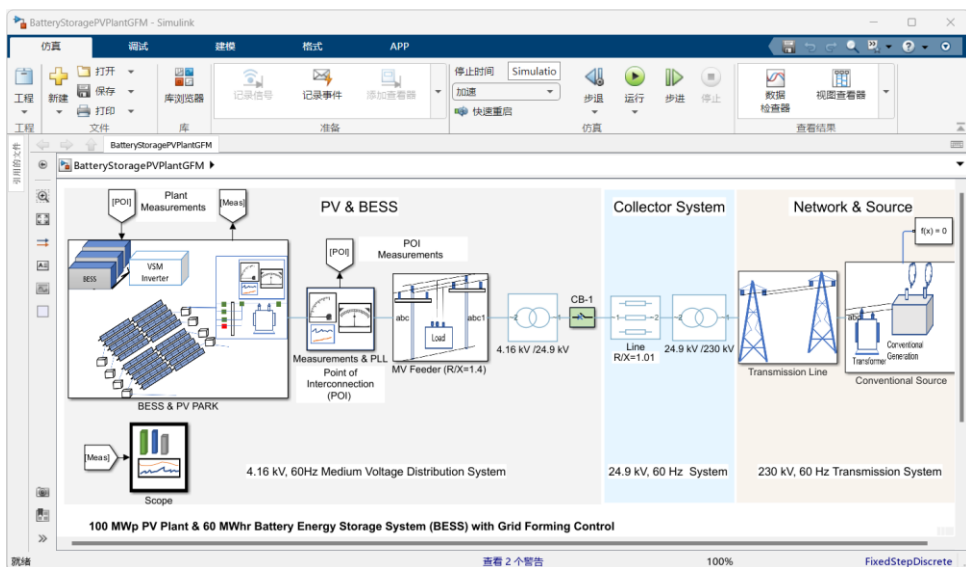
危及生命



测试环境难以控制



质量要求高



1. Edit simulation [Parameters](#)
2. Choose the BESS controller:
 - a) [BESS grid following with Voltage & frequency support](#)
 - b) [BESS grid forming virtual synchronous machine \(VSM\)](#)
 - c) [BESS grid forming droop controller](#)
3. Choose scenario to simulate & Plot results:
 1. Evaluate BESS response during sudden [Solar PV power variation](#)
 2. Evaluate BESS response during sudden [Load switching](#)
 3. Evaluate BESS response during sudden [Grid Outage](#)
 4. Evaluate LVRT & BESS response during [Temporary fault](#)
 5. Evaluate LVRT & BESS response during [Permanent fault](#)

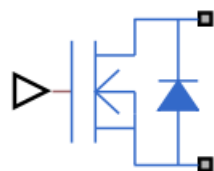
仿真面临的挑战



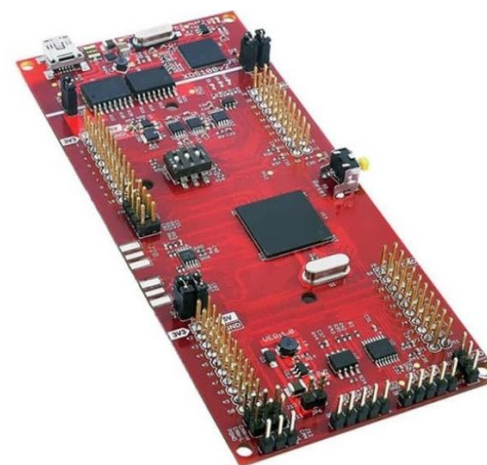
开关频率

控制验证

温升



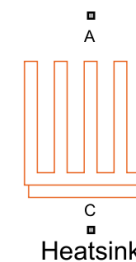
50kHz ~ 1MHz



损耗



500Hz ~ 10kHz



仿真时间尺度

微秒及以下

秒

秒~小时

仿真面临的挑战

- 如何准确模拟器件特性？
- 如何把握精度与仿真耗时之间的平衡？
- 如何简化建模过程？



概要

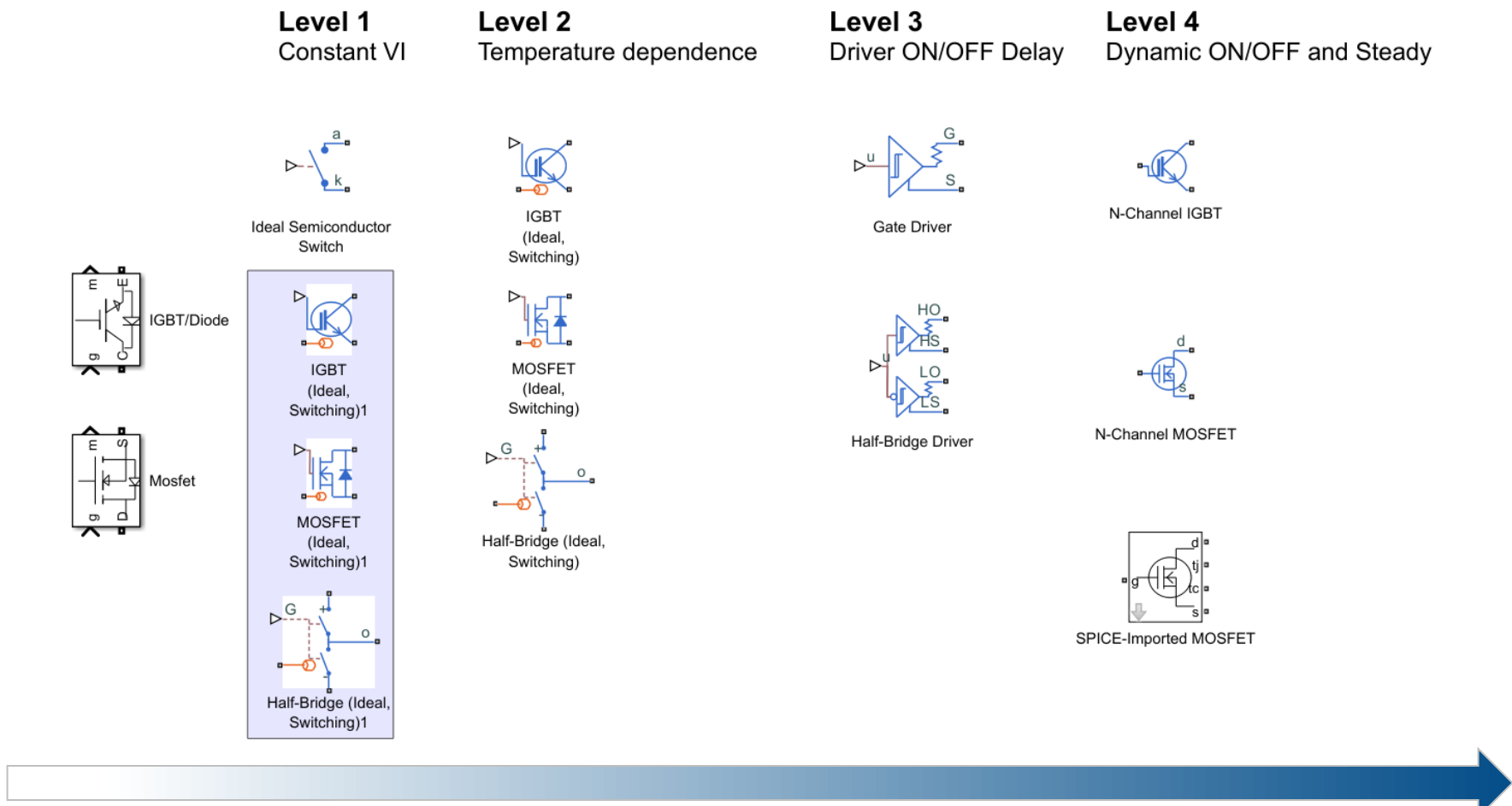
电力电子器件保真度

高保真模型建模方法

用于控制设计和温升仿真的模型

Simscape Electrical 提供的不同保真度器件模型

- 按研究目的选择保真度



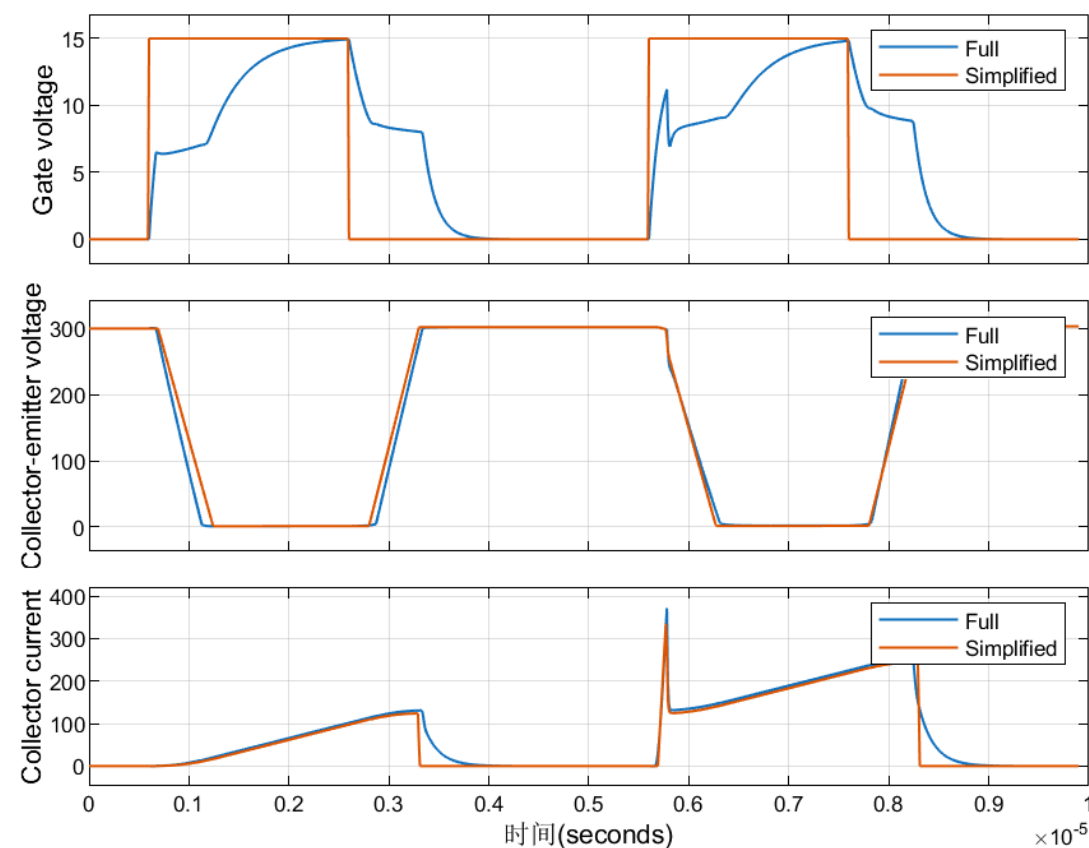
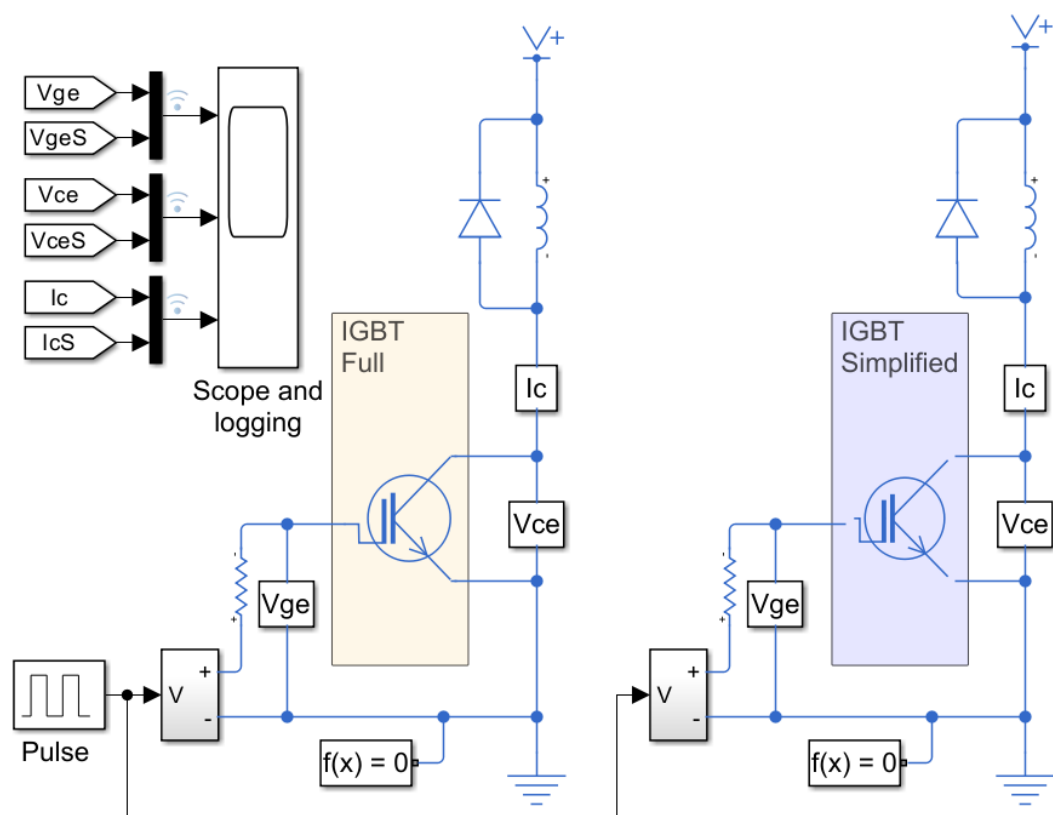
简化的开关模拟

保真度

准确的动态和稳态过程

高保真模型 vs. 简化模型

- 精细模型贴近实物，用于硬件研究
- 简化模型简化模拟实物行为，用于系统设计和软件设计



高保真模型建模方法

- 器件的重要特性模拟
 - 导通压降
 - 开关时间
 - 损耗大小
 - 温升变化

untitled * - Simulink

模块参数: N-Channel MOSFET

N-Channel MOSFET 自动应用

名称	值
Modeling option	Threshold-based
Main	
Number of terminals	Three
Parameterization	Lookup table (2-D, temperature independent)
Vector of gate-source voltages, Vgs	[-1, -5, 2, 3, 4, 5] <1x6 double> V
Vector of drain-source voltages, Vds	[0, 2, 4, 8, 12, 16, 20] V
Tabulated drain-source currents, Ids(Vg...	[0, 0, 0, 0, 0, 0, 0; 0, 0, 0, 0, 0, 0; ...] A
Ids-Vds parameterization	Provide negative and positive Vds data
Capacitance	
Parameterization	Specify tabulated input, reverse transfer, and output capacitance
Input capacitance, Ciss(Vds)	[720, 700, 590, 470, 390, 310] pF
Reverse transfer capacitance, Crss(Vds)	[450, 400, 300, 190, 95, 55] pF
Output capacitance, Coss(Vds)	[900, 810, 690, 420, 270, 170] pF
Corresponding drain-source voltages, V...	[1, .3, 1, 3, 10, 30] <1x6 double> V
Gate-source voltage, Vgs, for tabulated...	0 V
Body Diode	
Model body diode	Tabulated I-V curve
Table type	Table in If(Vf) form
Diode forward currents, If(Vf)	[.07, .12, .19, 1.75, 4.24, 7.32, 11.2] A
Diode forward voltages, Vf	[.5, .7, .9, 1.3, 1.7, 2.1, 2.5] <1x7 d...> V
Faults	
Enable faults	Off
Initial Targets	
Nominal Values	

就绪 250% VariableStepAuto

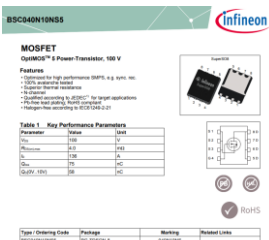
导通状态特性

开关断暂态特性

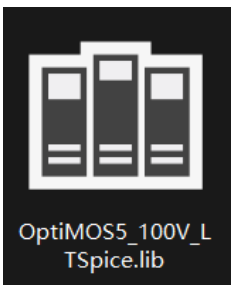
体二极管特性

高保真模型建模方法

- 从厂家提供的信息建模



数据手册



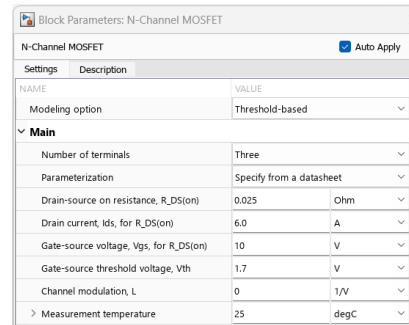
SPICE 模型



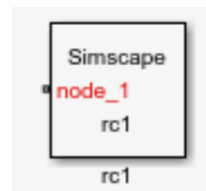
数据表

Parameter	Symbol	Conditions	Value			Unit
			min.	typ.	max.	
Static Characteristic						
Collector-emitter breakdown voltage	V_{BRICE}	$V_{GE} = 0V, I_C = 0.20mA$	650	-	-	V
Collector-emitter saturation voltage	V_{CEsat}	$V_{CE} = 15.0V, I_C = 50.0A$	-	1.66	2.10	V
		$T_{vj} = 25^{\circ}C$	-	1.90	-	
		$T_{vj} = 125^{\circ}C$	-	2.03	-	
Diode forward voltage	V_f	$V_{GE} = 0V, I_f = 25.0A$	-	1.54	1.80	V
		$T_{vj} = 25^{\circ}C$	-	1.52	-	
		$T_{vj} = 175^{\circ}C$	-	1.49	-	
Gate-emitter threshold voltage	$V_{GE(th)}$	$I_C = 0.30mA, V_{CE} = V_{GE}$	3.2	4.0	4.8	V
Zero gate voltage collector current	I_{C0}	$V_{CE} = 650V, V_{GE} = 0V$	-	-	40	μA
		$T_{vj} = 25^{\circ}C$	-	-	1200	
Gate-emitter leakage current	I_{GES}	$V_{CE} = 0V, V_{GE} = 20V$	-	-	100	nA
Transconductance	g_m	$V_{CE} = 20V, I_C = 50.0A$	-	62.0	-	S

参数

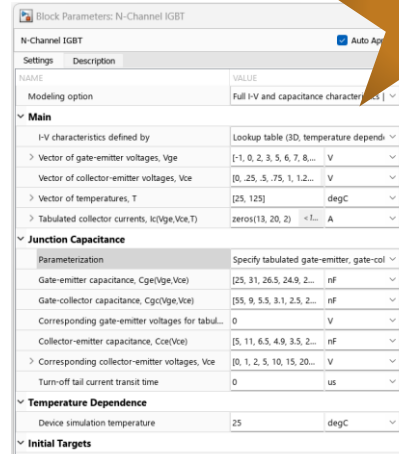


模块

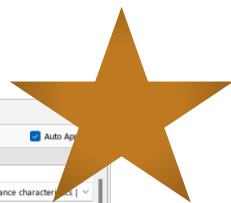


`ee.spice.semiconductorSubcircuit2lookup()`

数据表

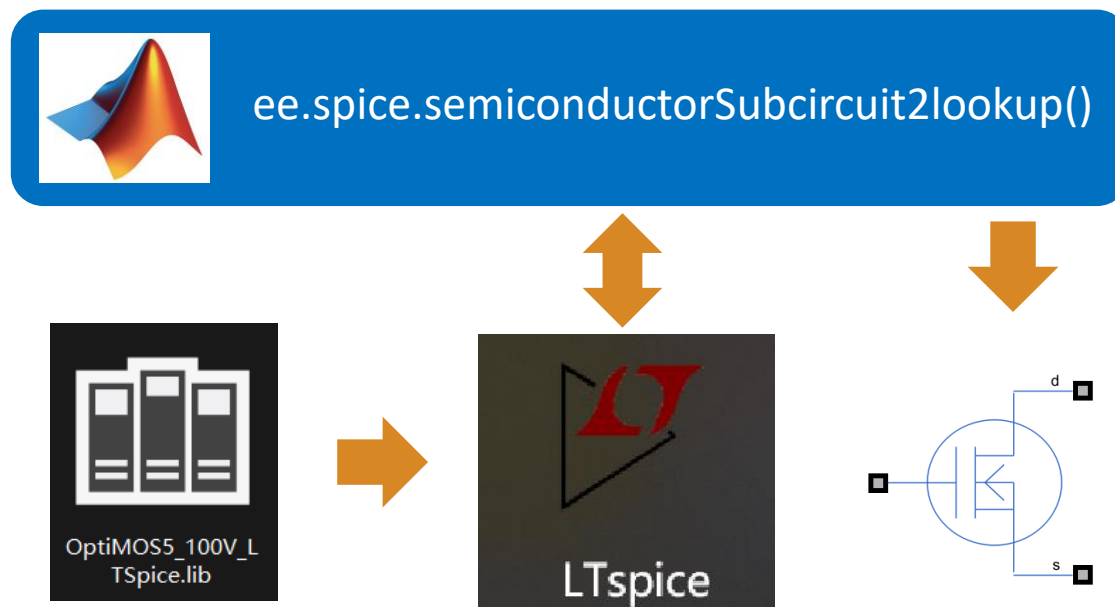


`ee_importDeviceParameters`



从 SPICE 生成数据表

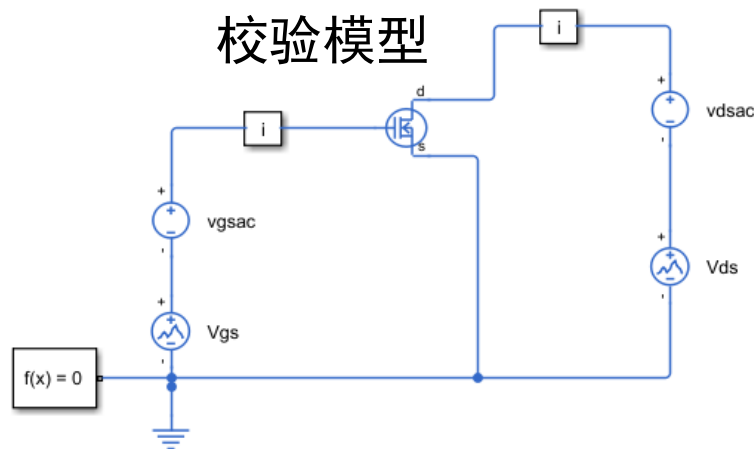
- 优势
 - 便捷模块参数化
 - 准确
- 支持的工具
 - SIMetrix
 - LTSpice



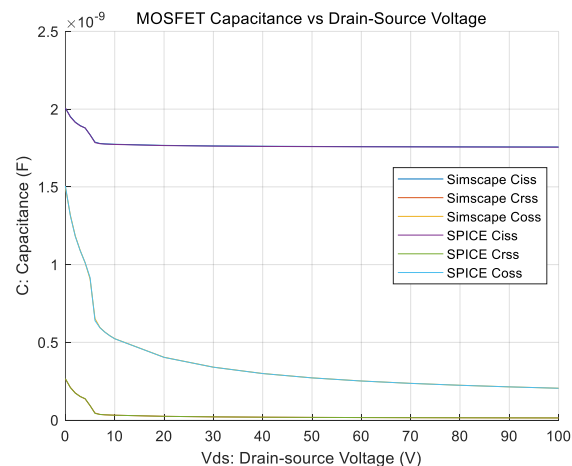
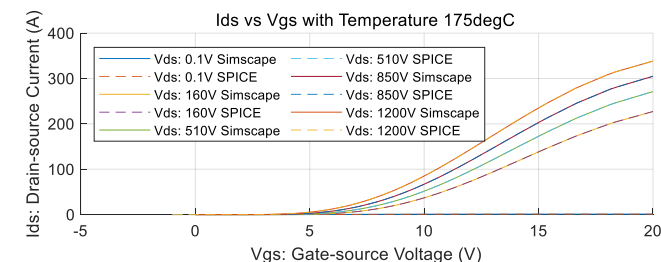
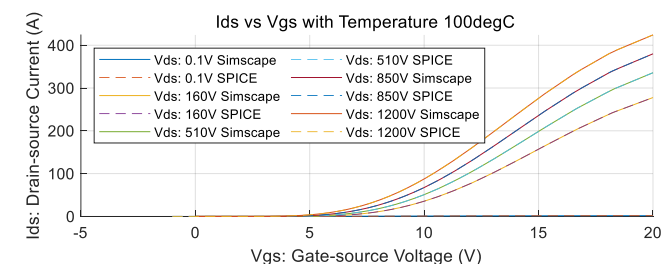
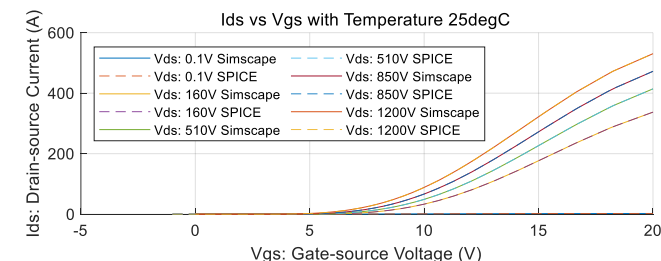
从 SPICE 生成数据表

参数化流程

- 获取SPICE文件
- 安装SPICE软件
- 定义表格所需元素
- 运行 `semiconductorSubcircuit2lookup`
- 校验模型精度



Simscape 对比 SPICE



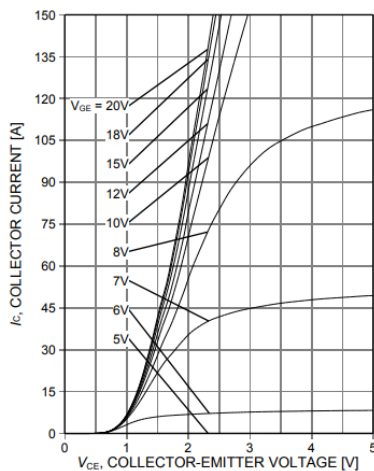
```

Editor - C:\OneDrive\OneDrive - MathWorks\Documents\MATLAB\Exam...
SICMOSFETFromSPICEResultsSetParameters.m
17 %% Set the SPICE simulation parameter to extract lookup tab:
18 subcircuitFile = fullfile("Infineon-IMBG120R045M1.lib");
19 subcircuitName = "IMBG120R045M1H_L3";
20 outputPath = "IMBG120R045M1";
21 SPICEPath = "C:\Program Files\SiMetrix850\bin64\Sim.exe"; %
22 terminals = [1,2,3,0,5]; % Terminal orders
23
24 % Define the gate-source voltage range, drain-source steps,
25 % steps for the transfer characteristics of the SiC MOSFET
26 flagIdsVgs = 1; % Flag for transfer
27 flagIdsVds = 0; % Flag for output cl
28 VgsRangeIdsVgs = [0 20]; % Vgs range
29 VdsStepsIdsVgs = [0.1:1:20.1,30:10:1200]; % Vds steps
30 T = [25 100 175]; % Temperature steps
31
32 % Define the gate-source voltage steps, drain-source steps,
33 % simulation parameters for capacitance characteristics
34 flagCapacitance = 1; % Flag for capacitance
35 VgsCapacitance = [-5:2:20]; % Vgs steps
36
    
```

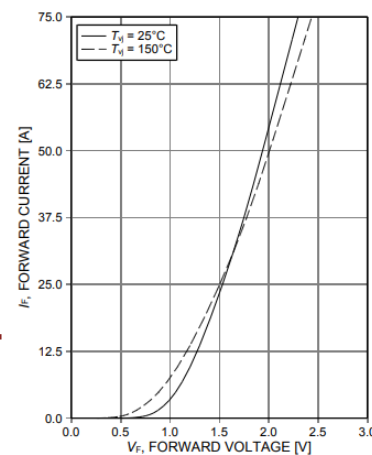
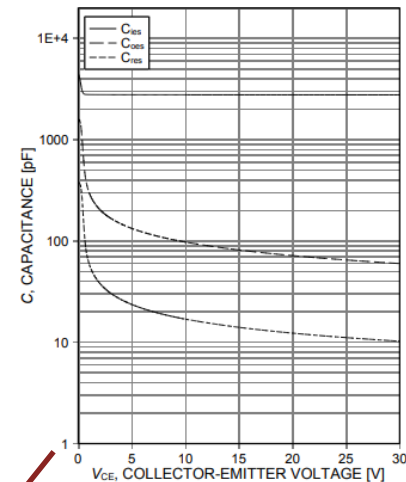
Infineon-IMBG120R030M1.lib

数据手册 vs. SPICE

- 部分厂家没有提供 **SPICE** 模型
- 每个厂家都会提供 **数据手册**



The screenshot shows the Simulink parameterization window for an N-Channel MOSFET. The window is titled "N-Channel MOSFET" and has tabs for "Settings" and "Description". The "Main" section includes parameters for modeling options, number of terminals, parameterization, gate-source voltages, drain-source voltages, and tabulated drain-source currents. The "Capacitance" section is highlighted with a red box and includes parameters for input, reverse transfer, and output capacitance, along with corresponding drain-source voltages and gate-source voltage. The "Body Diode" section is also highlighted with a red box and includes parameters for the model body diode, table type, diode forward currents, and diode forward voltages. The "Faults" section is also visible.



Datasheet 建模流程

从图像抓取数据

- 导入图像
- 坐标轴校准
- 选取数据
- 插值与数据处理
- 数据导出

graphImporter

The screenshot shows the graphImporter interface with the following components and annotations:

- 1**: File menu (新建, 打开, 保存, 会话).
- 2**: Axis calibration fields (x 轴第一个点, x 轴第二个点, y 轴第一个点, y 轴第二个点).
- 3**: Data selection controls (数据线条数, 选择数据线).
- 4**: Data table header (数据).
- 5**: Export button (导出数据).

The graph displays I_C COLLECTOR CURRENT [A] vs. V_{CE} , COLLECTOR-EMITTER VOLTAGE [V]. A red line with 'x' markers is selected. A red text box above the graph reads: 清除 "选取数据" 以拖动所选数据行上的数据点或编辑数据表条目.

x1	y1
0.4119	-0.0425
0.7551	-0.0171
0.9840	0.0593
1.1785	0.1103
1.3959	0.1612
1.6590	0.1697
2.2311	0.2036
3.2151	0.2206
4.7254	0.2546

清除 "选取数据" 以拖动所选数据行上的数据点或编辑数据表条目

高保真模型建模方法

■ 模块建模

— 将从数据手册抓取参数填入模块

- 静态V-I曲线
- 动态结电容参数
- 二极管参数

— 外部寄生电感建模

High speed fast IGBT in TRENCHSTOP™ 5 technology copacked with RAPID 1 fast and soft antiparallel diode

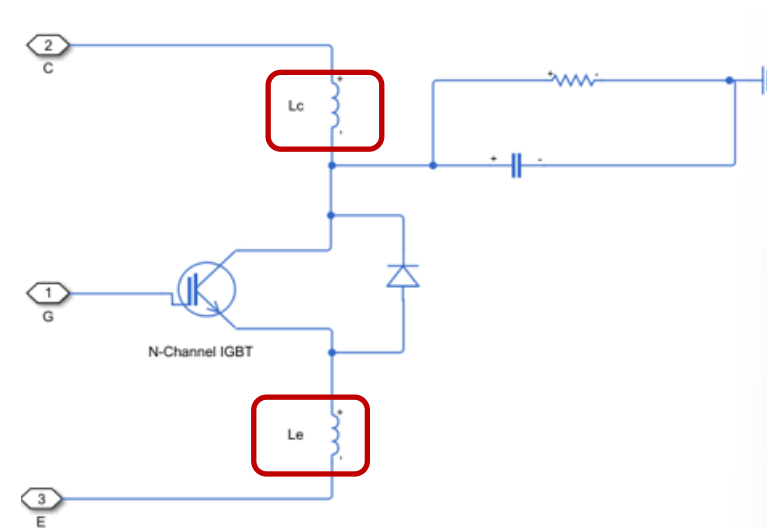
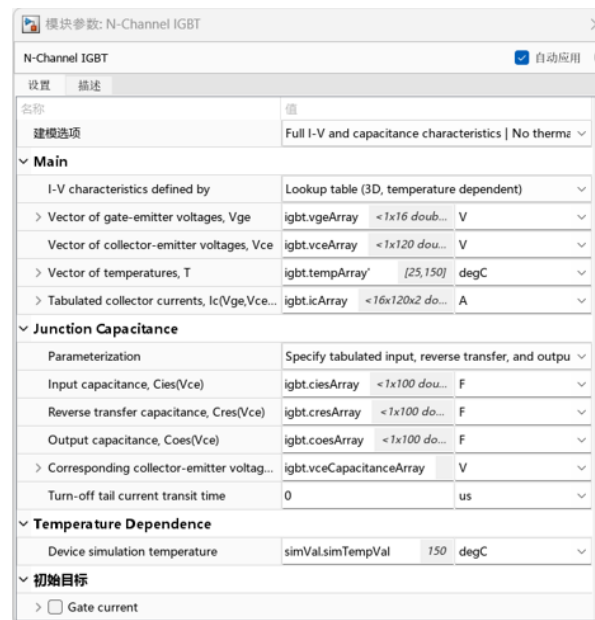
Features and Benefits:

- High speed F5 technology offering:
- Best-in-Class efficiency in hard switching and resonant topologies
- 650V breakdown voltage
- Low gate charge Q_g
- IGBT copacked with RAPID 1 fast and soft antiparallel diode
- Maximum junction temperature 175°C
- Dynamically stress tested
- Qualified according to AEC-Q101
- Green package (RoHS compliant)
- Complete product spectrum and PSpice Models: <http://www.infineon.com/igbt/>



Applications:

- Off-board charger
- On-board charger
- DC/DC converter
- Power-Factor correction



高保真模型测试

■ 静态特性测试

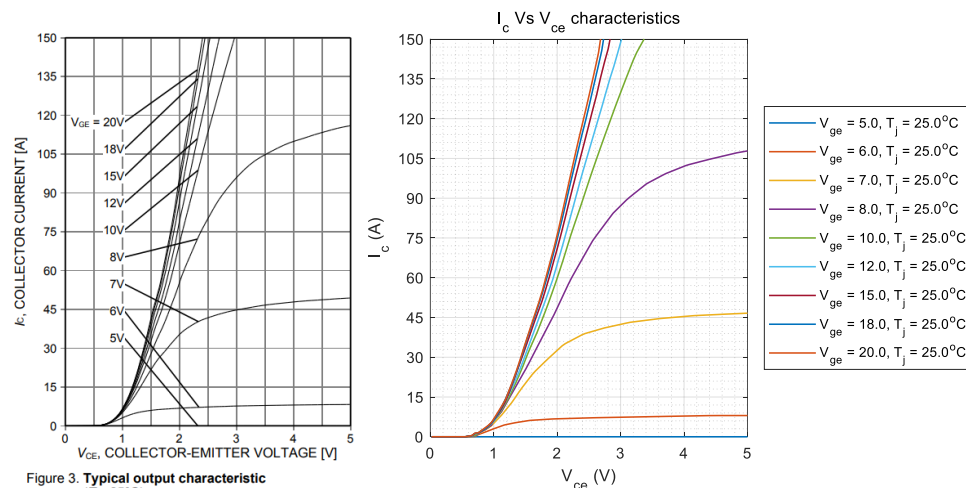
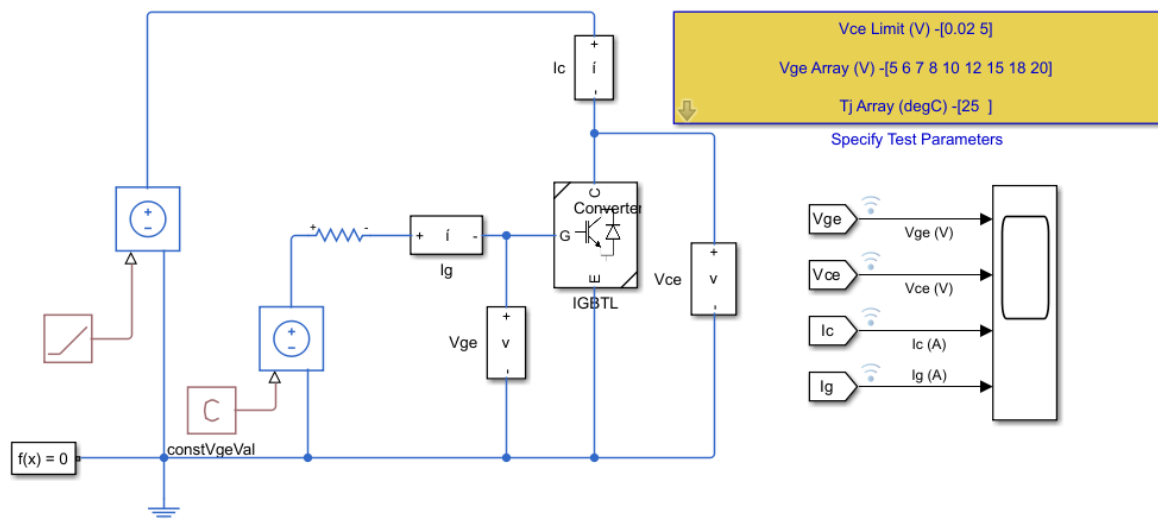
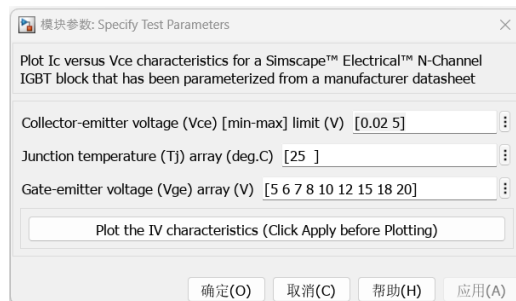


Figure 3. Typical output characteristic ($T_j=25^\circ\text{C}$)

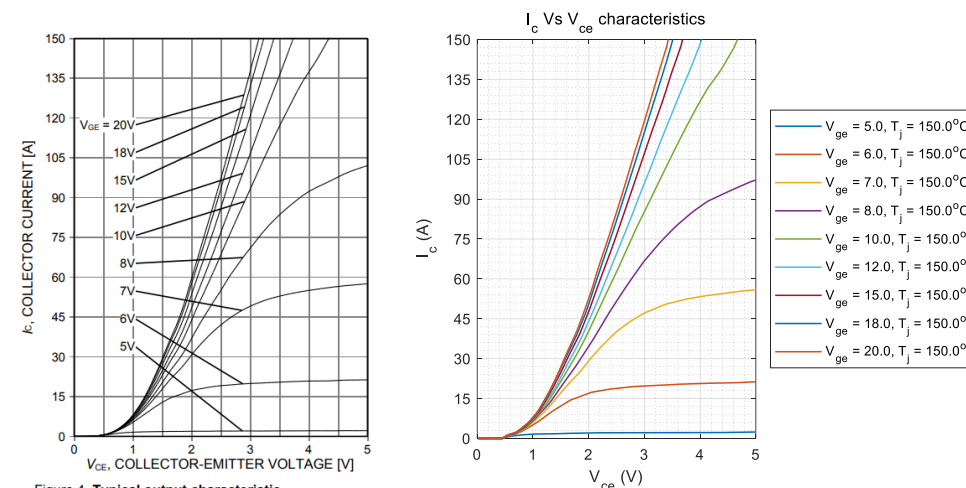


Figure 4. Typical output characteristic ($T_j=150^\circ\text{C}$)

驱动电路

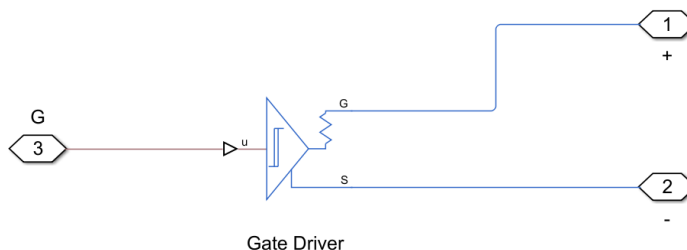
- 驱动电路对IGBT的影响

- 开关速度
- 开关损耗
- 电磁干扰

- 三种预置驱动电路

- 理想驱动
- 光耦驱动
- 隔离变压器驱动

理想驱动



Block Parameters: Gate Driver

Gate Driver Auto Apply

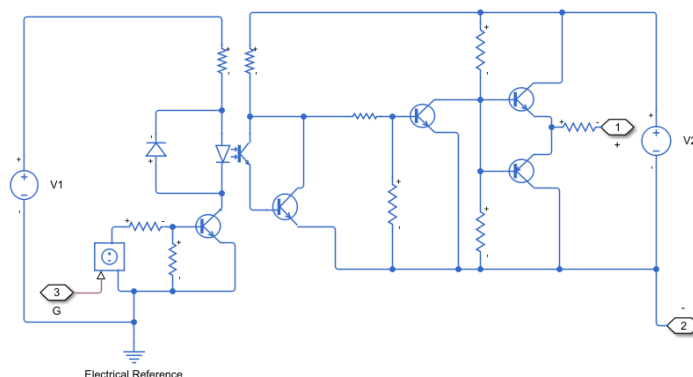
NAME	VALUE
Input Logic	
Input port	PS
> Logic 1 input value	0.7
> Logic 0 input value	0.3
Outputs	
> On-state gate-source voltage	simVal.simVgeOnVal V
> Off-state gate-source voltage	simVal.simVgeOffVal V
Timing	
> Propagation delay (logic 0->logic 1)	0 ns
> Propagation delay (logic 1->logic 0)	0 ns
Dynamics	
Parameterization	Output impedance
> On-state gate drive resistance	simVal.simRgOnVal Ohm
> Off-state gate drive resistance	simVal.simRgOffVal Ohm
Faults	
State fault	Add fault

输入信号

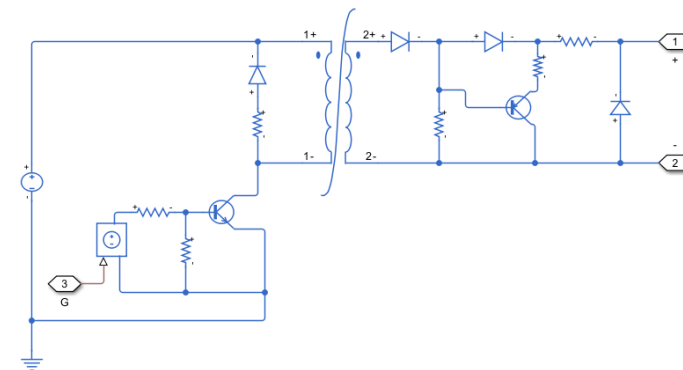
输出电平

延时

驱动电阻



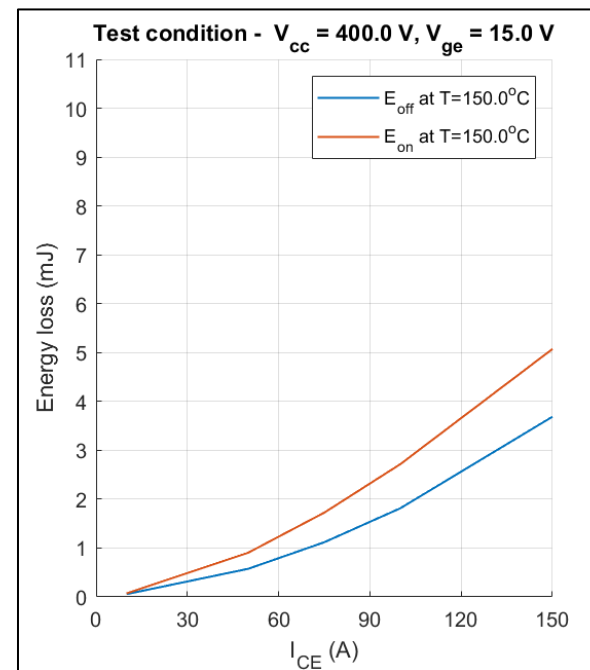
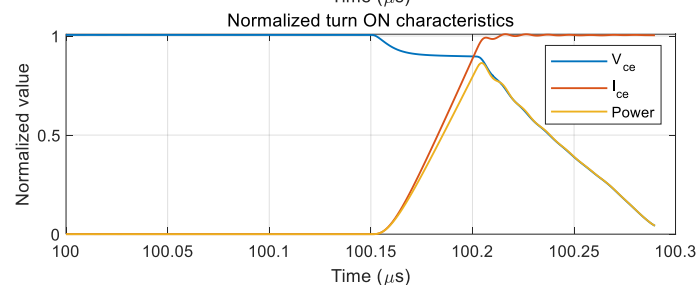
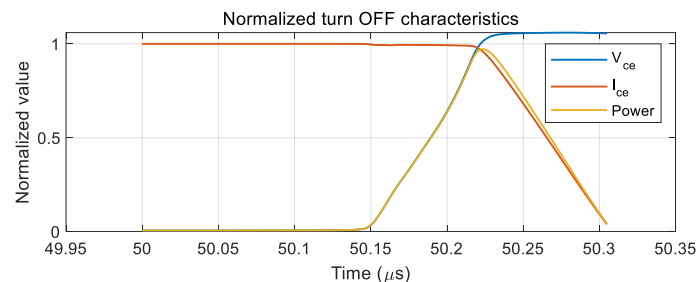
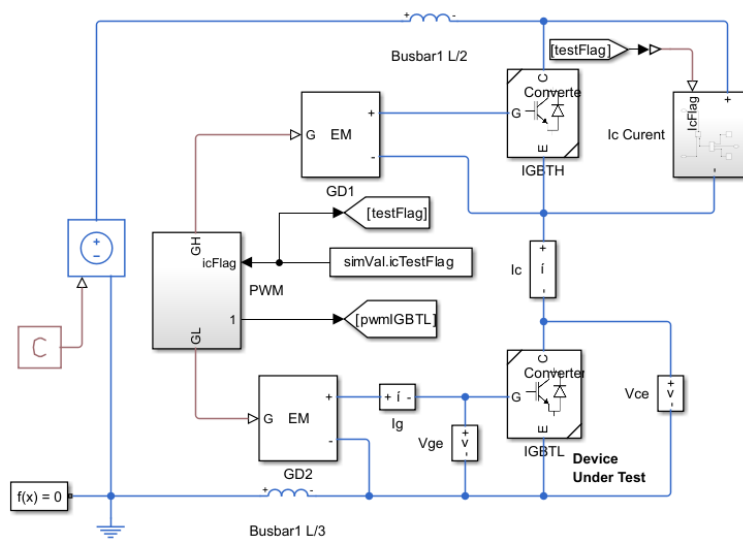
光耦驱动



隔离变压器驱动

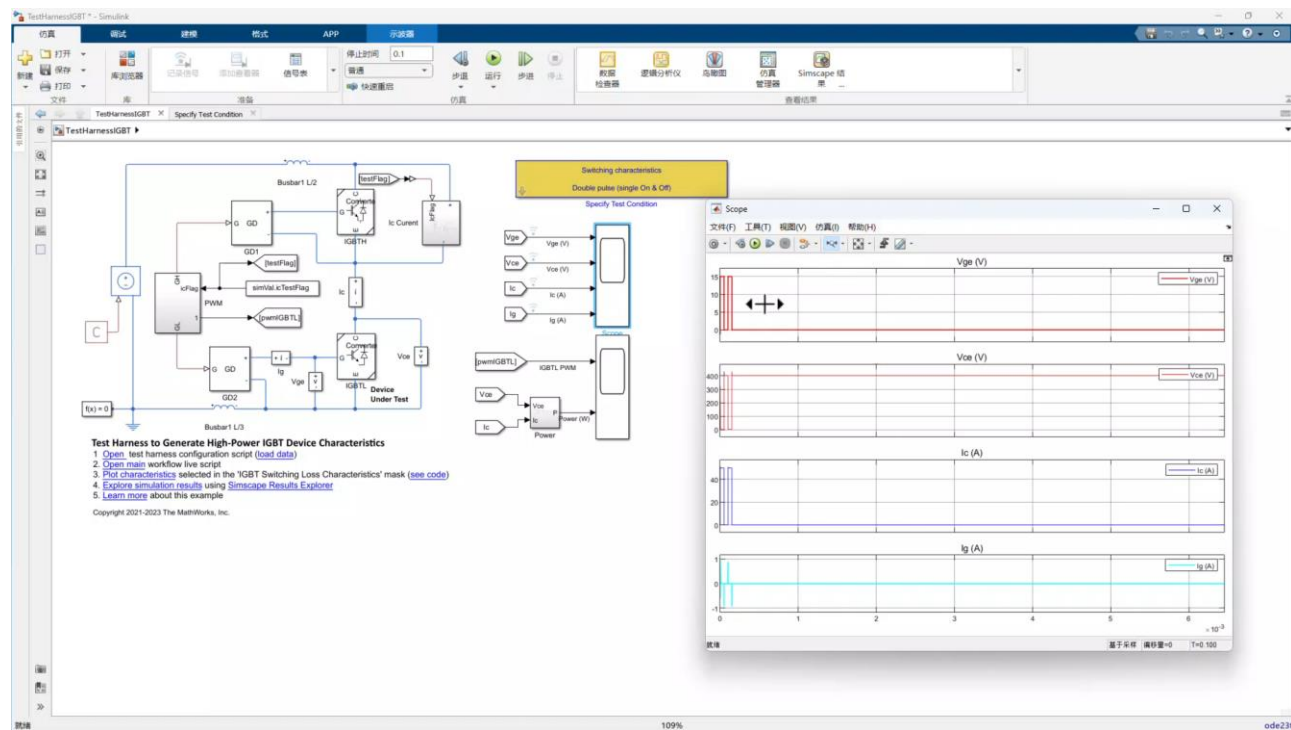
动态特性测试

- 双脉冲测试
 - 开关速度
 - 开关损耗
 - 电磁干扰



为什么要降低保真度？

- 高保真度模型能精确模拟器件
 - 静态和动态特性
 - 损耗和温升
- 仿真耗时长
 - 动态过程仿真较慢
 - 长时间尺度需求
 - 控制秒级
 - 秒到小时
 - 控制设计不需要高精度暂态过程



控制与温升模型

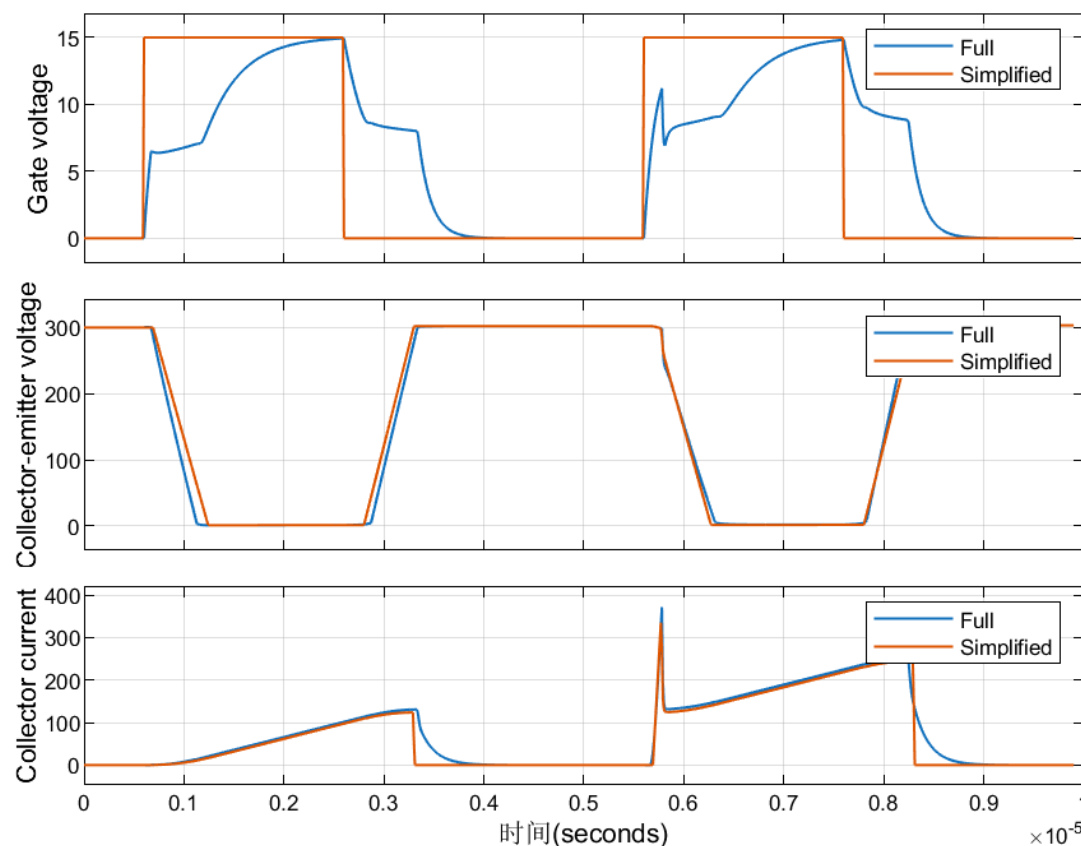
- 控制模型需求

- 电压面积准确

- 温升模型

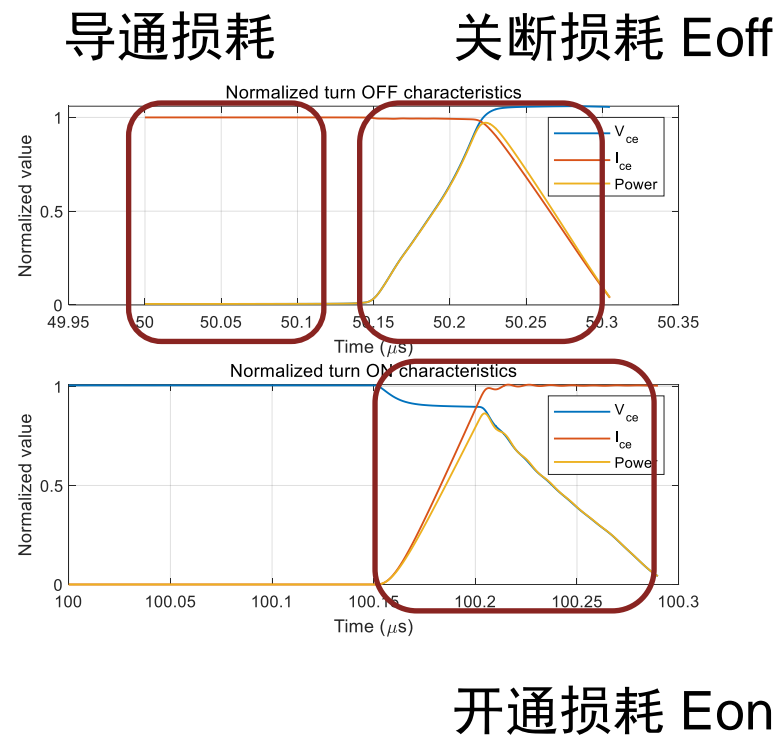
需求更高

- 导通损耗
 - 导通压降
- 开关损耗
 - 开关段器件功耗
- 散热模型



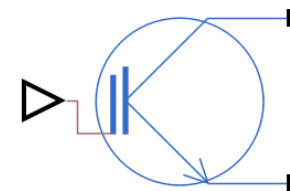
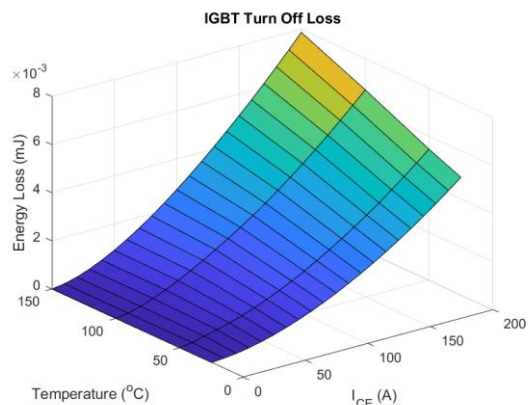
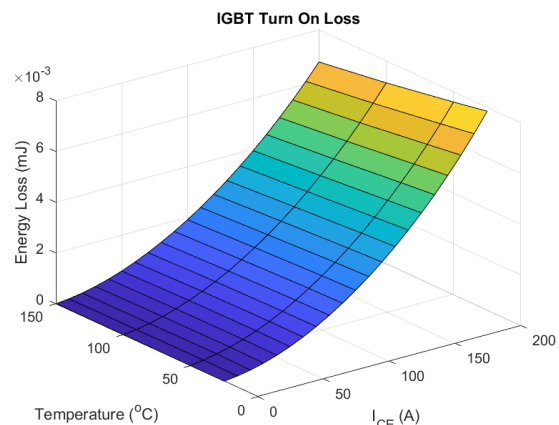
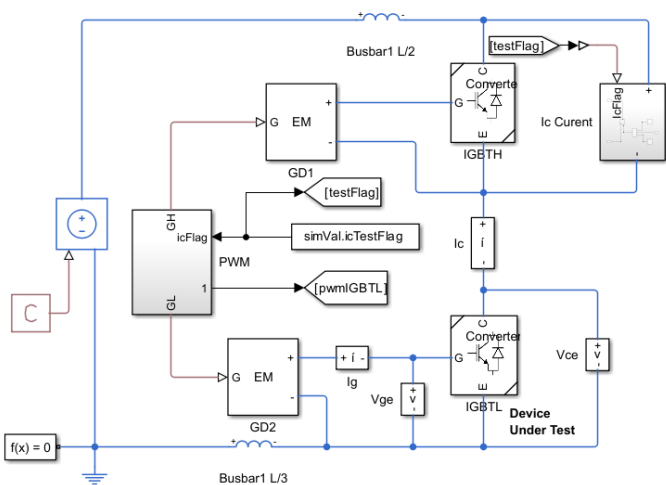
损耗模型

- 电力电子器件损耗
 - 导通损耗
 - 开通损耗 E_{on}
 - 关断损耗 E_{off}
- 降低保真度方法
 - 简化动态过程模型
 - 从高精度模型获取损耗数据



损耗模型

- 高精度模型仿真测试获取损耗数据



IGBT
(Ideal,
Switching)

Block Parameters: IGBT (Ideal, Switching)

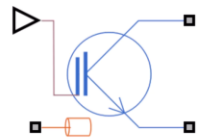
Settings Description

NAME	VALUE
Modeling option	Show thermal port
Selected part	<click to select>
Main	
Gate-control port	PS
Threshold voltage, V _{th}	ideallGBT.thresholdVoltage 4 V
On-state behavior and switching losses	Tabulate
On-state voltage, V _{ce} (T _j , I _{ce})	ideallGBT.vceArray <4x101 double> V
Configurability	Compile-time
Temperature vector, T _j	ideallGBT.idealTjArray [25.50,100,150] degC
Collector-emitter current vector, I _{ce}	ideallGBT.iyceArray <1x101 double> A
Off-state conductance	ideallGBT.offStateConductance 1e-06 1/Ohm
Switching Losses	
Switch-on loss, E _{on} (T _j , I _{ce})	ideallGBT.eOnLossArray <4x21 dou... J
Switch-off loss, E _{off} (T _j , I _{ce})	ideallGBT.eOffLossArray <4x21 dou... J
Temperature vector for switching losses, T _j	ideallGBT.switchingLossTjArray [25... degC
Collector-emitter current vector for switching losses, I _{ce}	ideallGBT.switchingLossIceArray <... A
<input type="checkbox"/> Include switching loss tabulation with off-state voltage	
Off-state voltage for switching loss data	ideallGBT.offStateVoltage 400 V

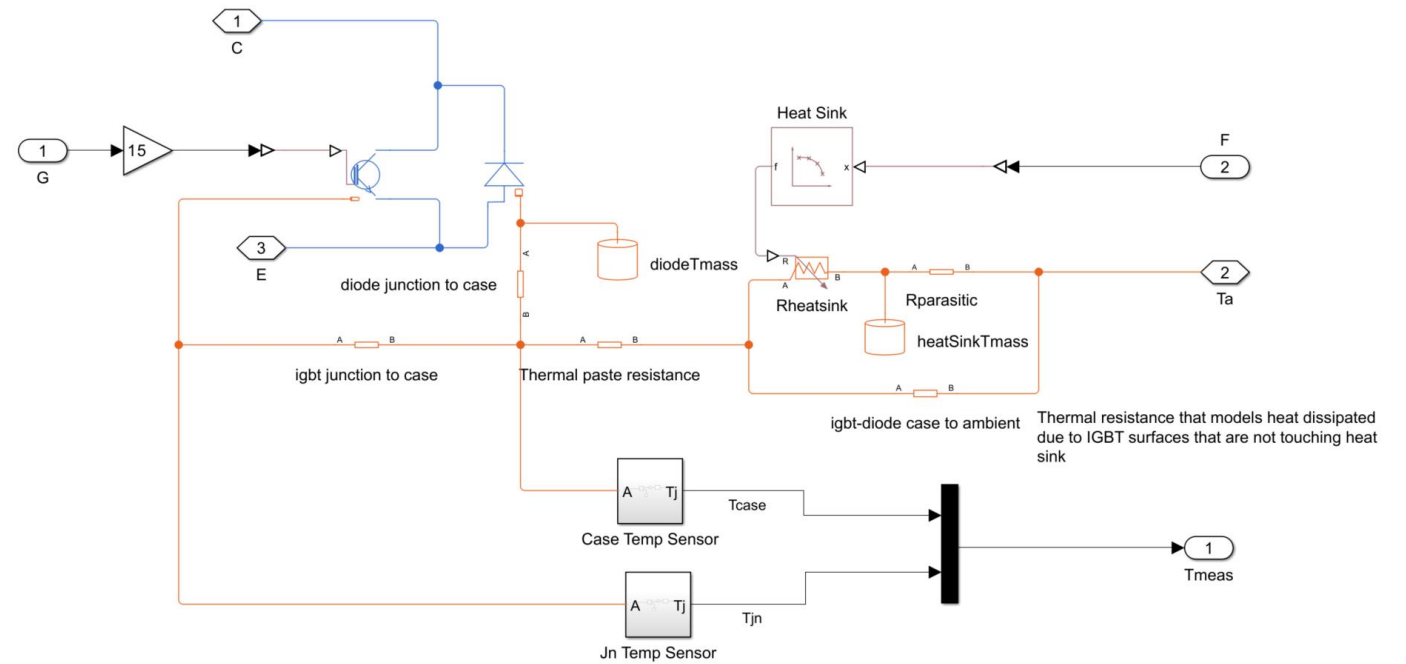


热模型

- 开放器件散热端口
- Simscape Thermal 建立散热模型



IGBT
(Ideal,
Switching)



三相两电平变流器温升测试

测试工况配置

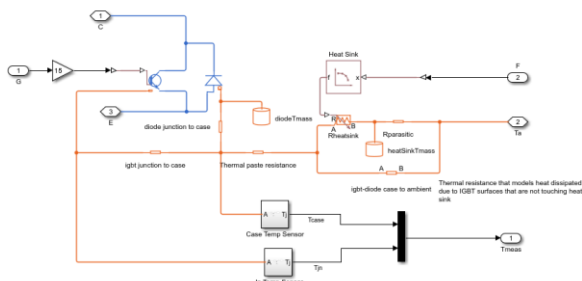
Block Parameters: Select parameters

Set converter and simulation parameters

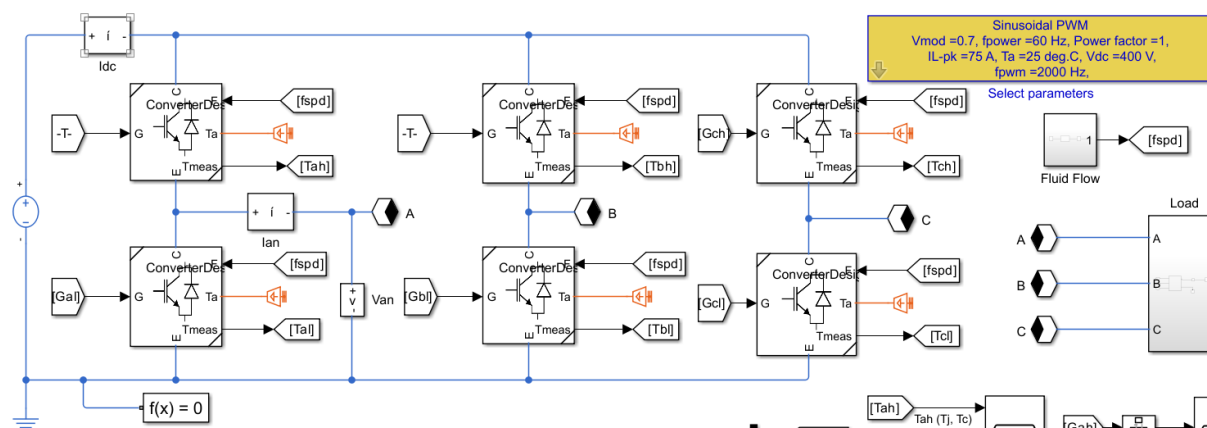
- PWM technique: State vector modulation (SPWM)
- Voltage modulation index (range [0,1]): 0.7
- Sinusoidal power frequency (Hz): 60
- Power factor (leading use positive, lagging use negative): 1
- Number of cycle simulated: 10
- PWM switching frequency (Hz): 4000
- Sinusoidal load phase current peak (Ic-peak) (A): 75
- DC bus voltage (Vdc) (V): 400
- Ambient temperature (Ta) (deg.C): 25
- Diode initial junction temperature (deg.C): 90
- IGBT initial junction temperature (deg.C): 90

Load parameters and simulate

OK Cancel Help Apply



IGBT电热耦合模型



PWM模型

Block Parameters: PWM

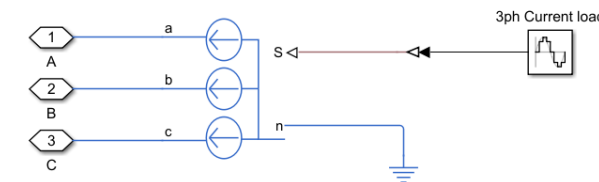
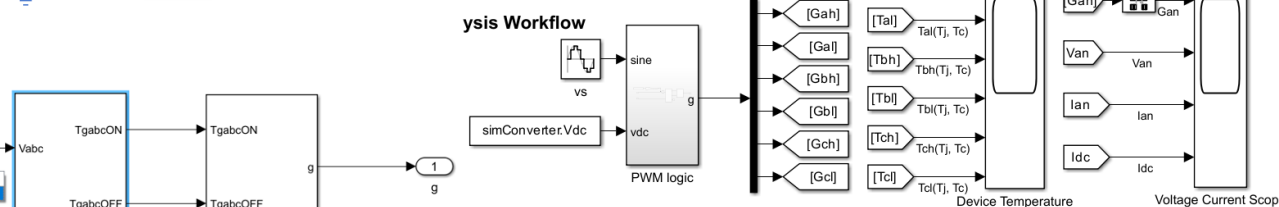
PWM Timing and Waveform Generator (Three-phase, Two-level)

This block implements a three-phase, two-level PWM timing generator.

Parameters

- PWM mode: **Discontinuous PWM (DPWM)**
- SPWM: sinusoidal PWM
- Sampling mode: Natural
- Switching frequency (Hz): simConverter.pwmFrequency

OK Cancel Help Apply

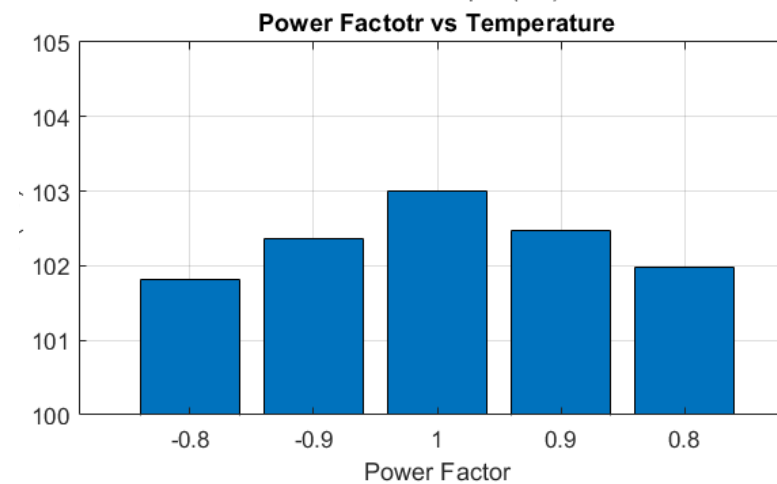
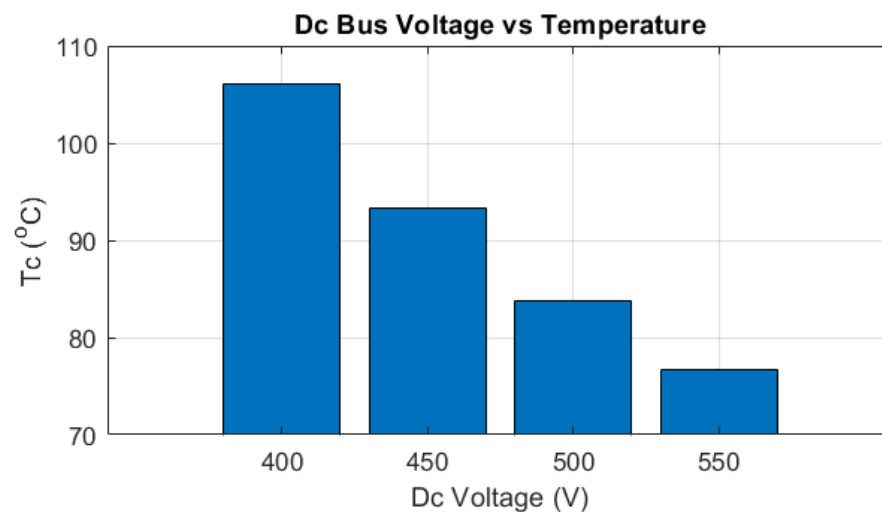
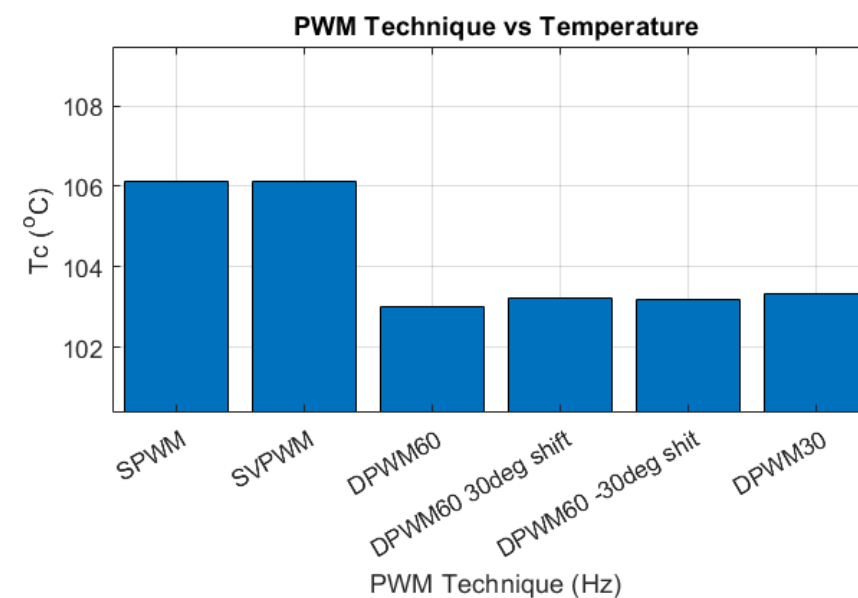
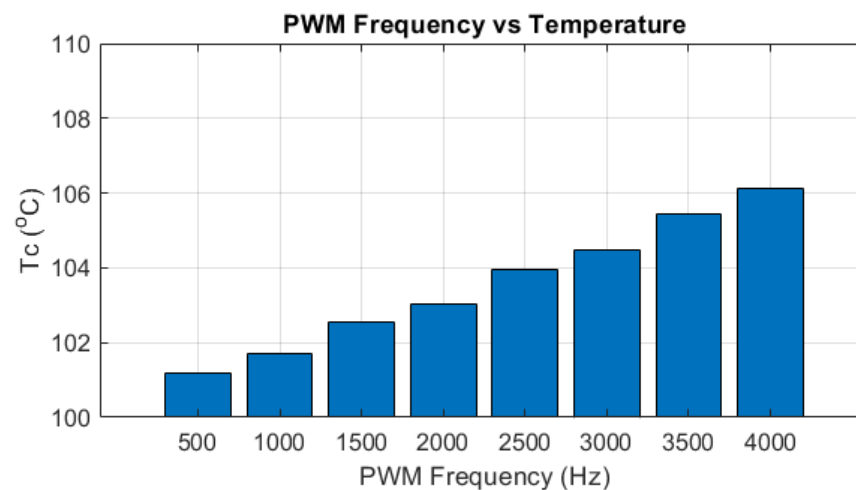


负载模型

构建热测试模型

■ 温升相关因素

- 开关频率
- PWM模式
- 直流电压
- 功率因素



总结

- Simscape Electrical 提供不同保真度模型
- 支持从SPICE、 数据手册等多种数据源建立器件模型
- 利用器件模型进行器件仿真和驱动电路设计
- 从高精度模型提取损耗信息实现热模型
- 建立变流器级热模型进行系统温升优化
- 实现仿真速度与保真度的平衡

MATLAB EXPO

Thank you



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