MATLAB EXPO

May 28, 2024 | Beijing

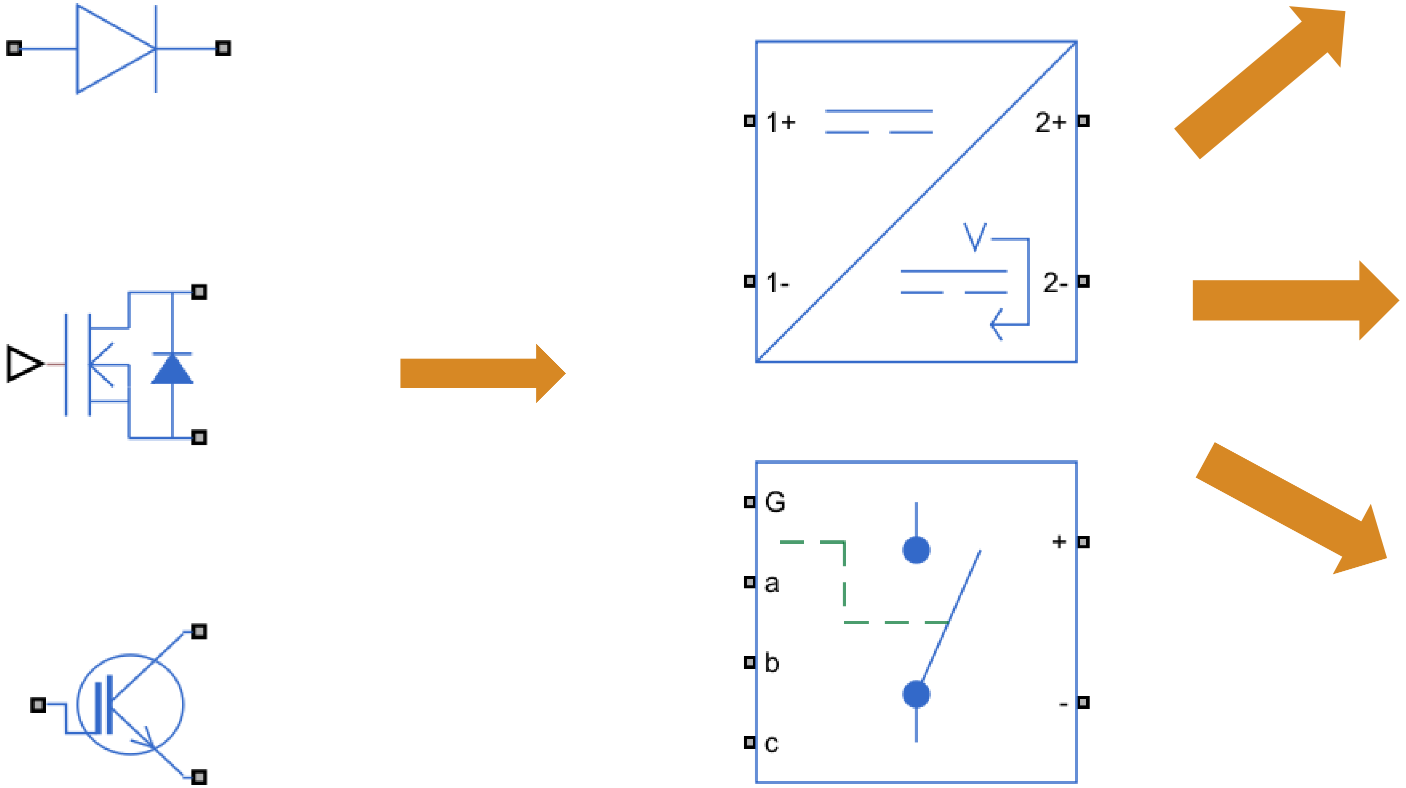
电力电子系统模型保真度选择

周前程, MathWorks

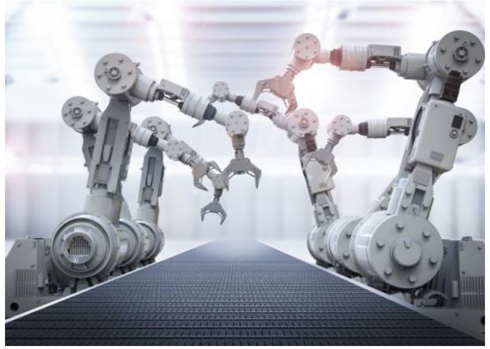
MathWorks

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

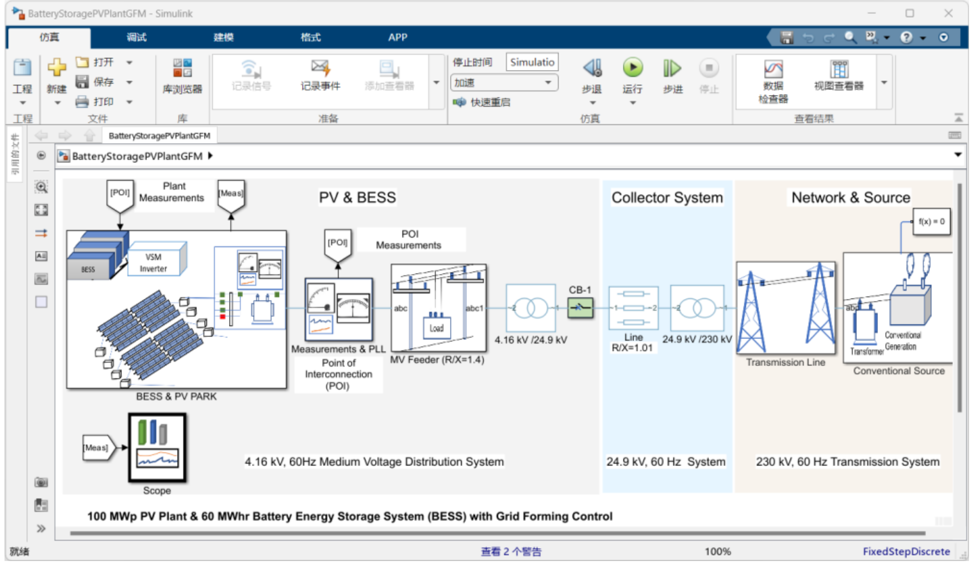
生活电器

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

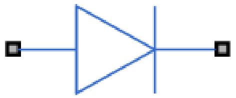
仿真面临的挑战

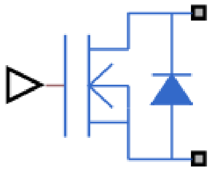
开关频率

控制验证

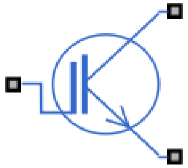
温升

损耗

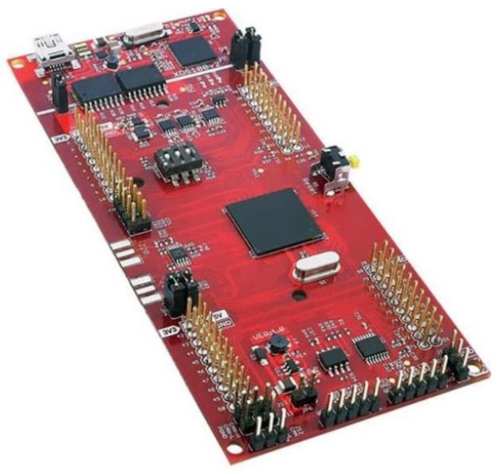


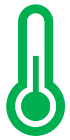


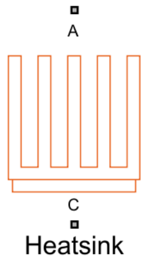
50kHz ~1MHz



500Hz ~ 10kHz







仿真时间尺度

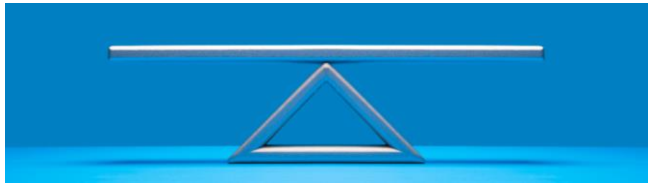
微秒及以下

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？



精度

时长

更小的仿真步长

更多的迭代步数

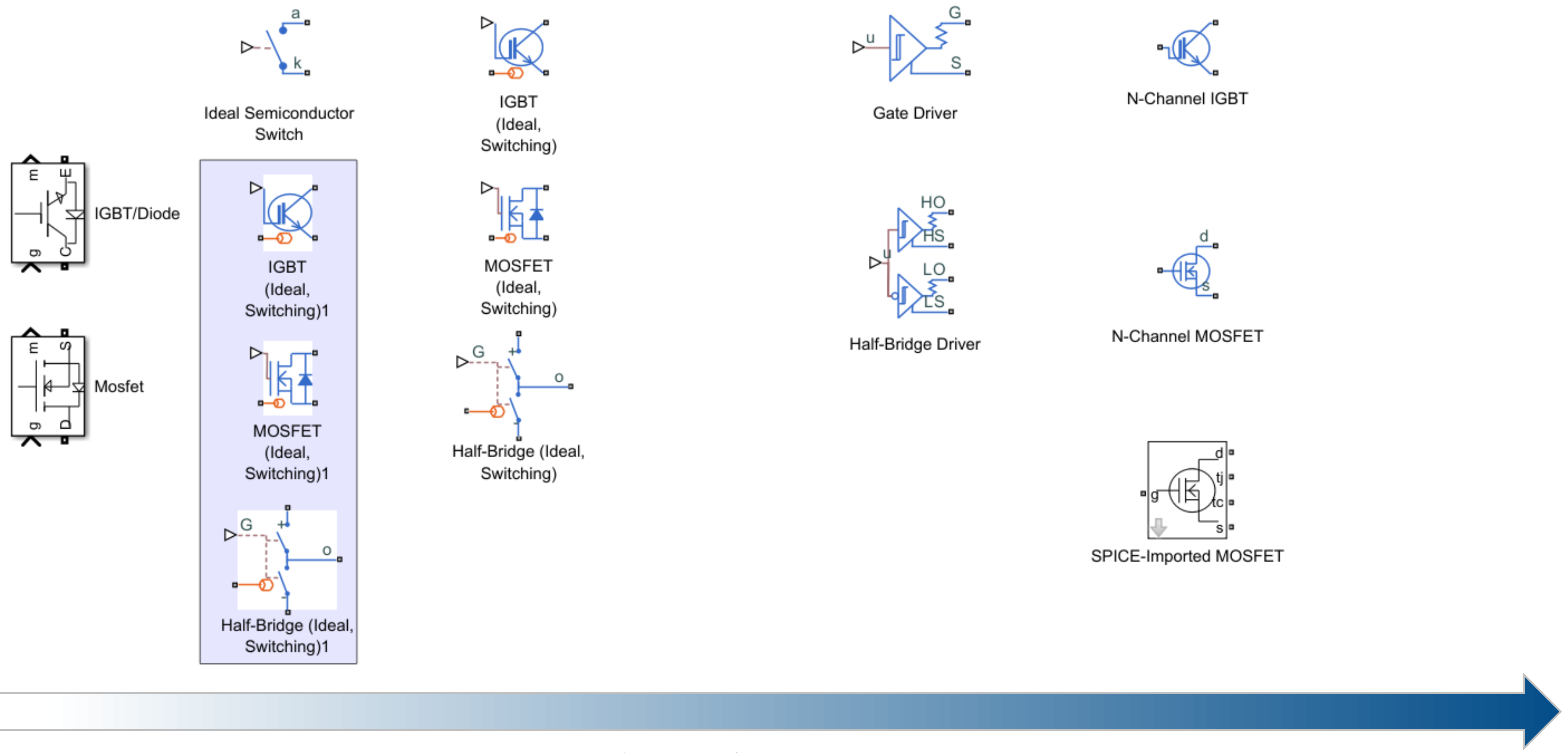
概要

- 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

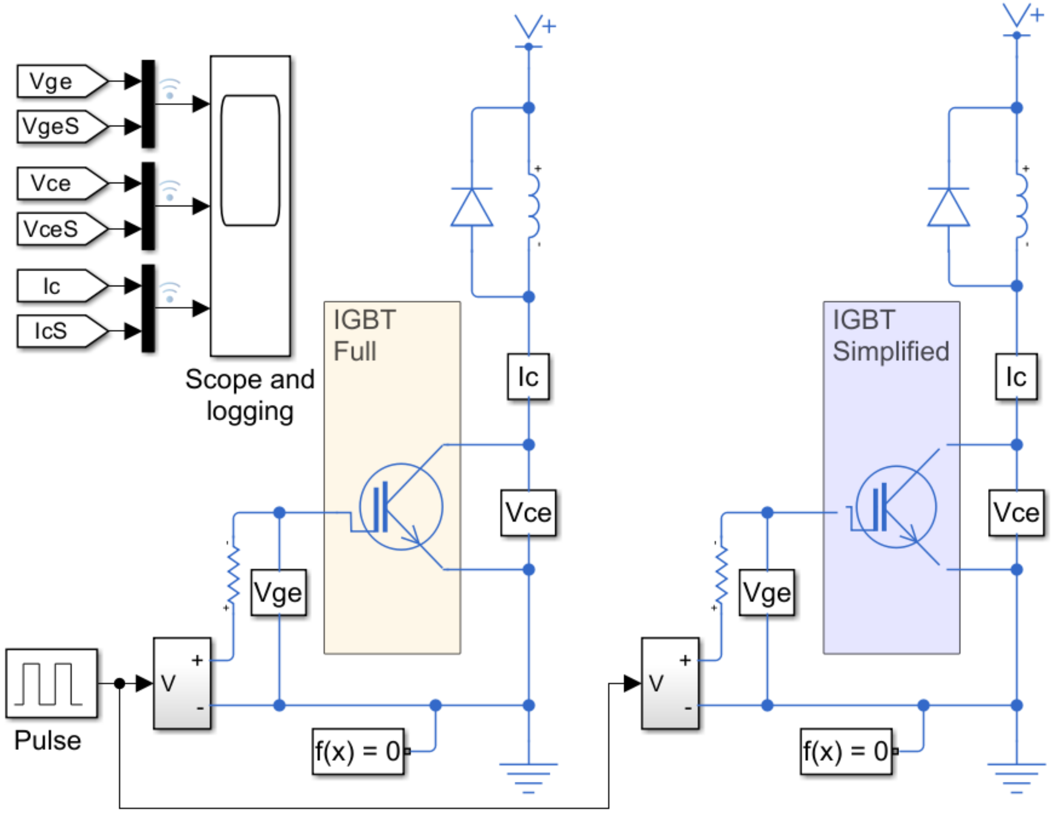
Level 1 Constant VI | **Level 2** Temperature dependence | **Level 3** Driver ON/OFF Delay | **Level 4** Dynamic ON/OFF and Steady

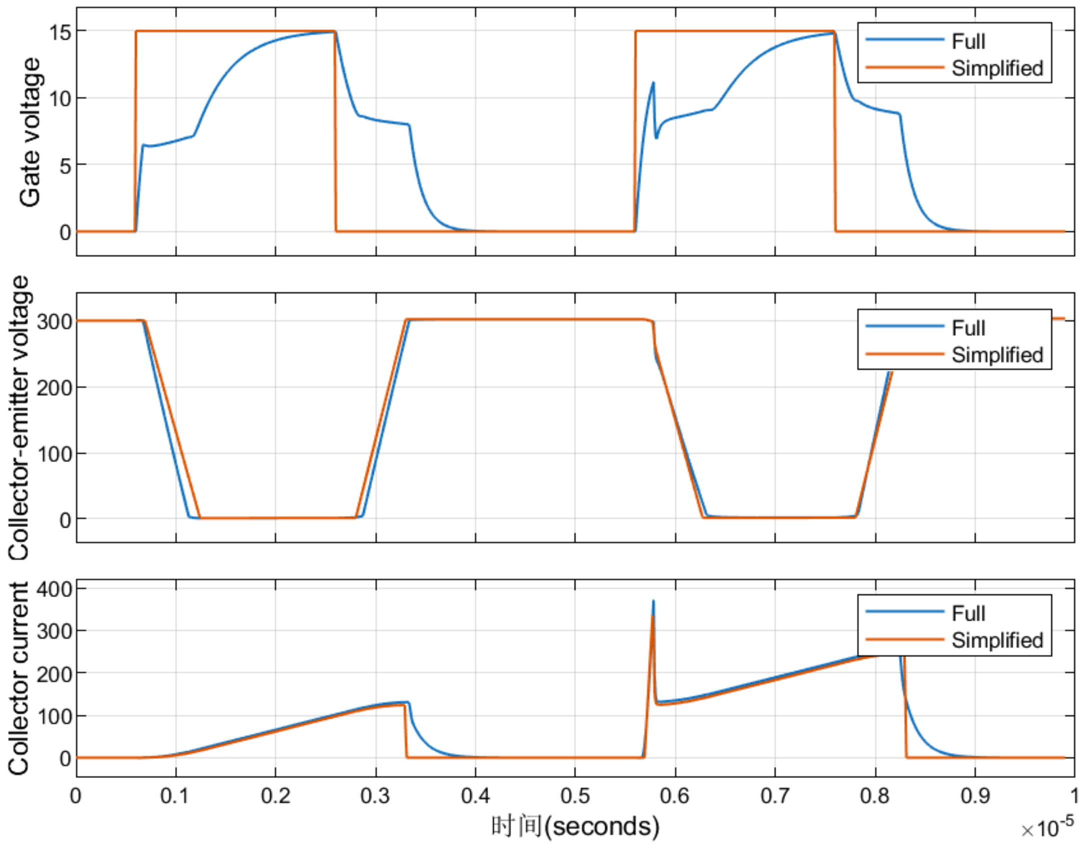


简化的开关模拟 保真度 准确的动态和稳态过程

高保真模型 vs. 简化模型

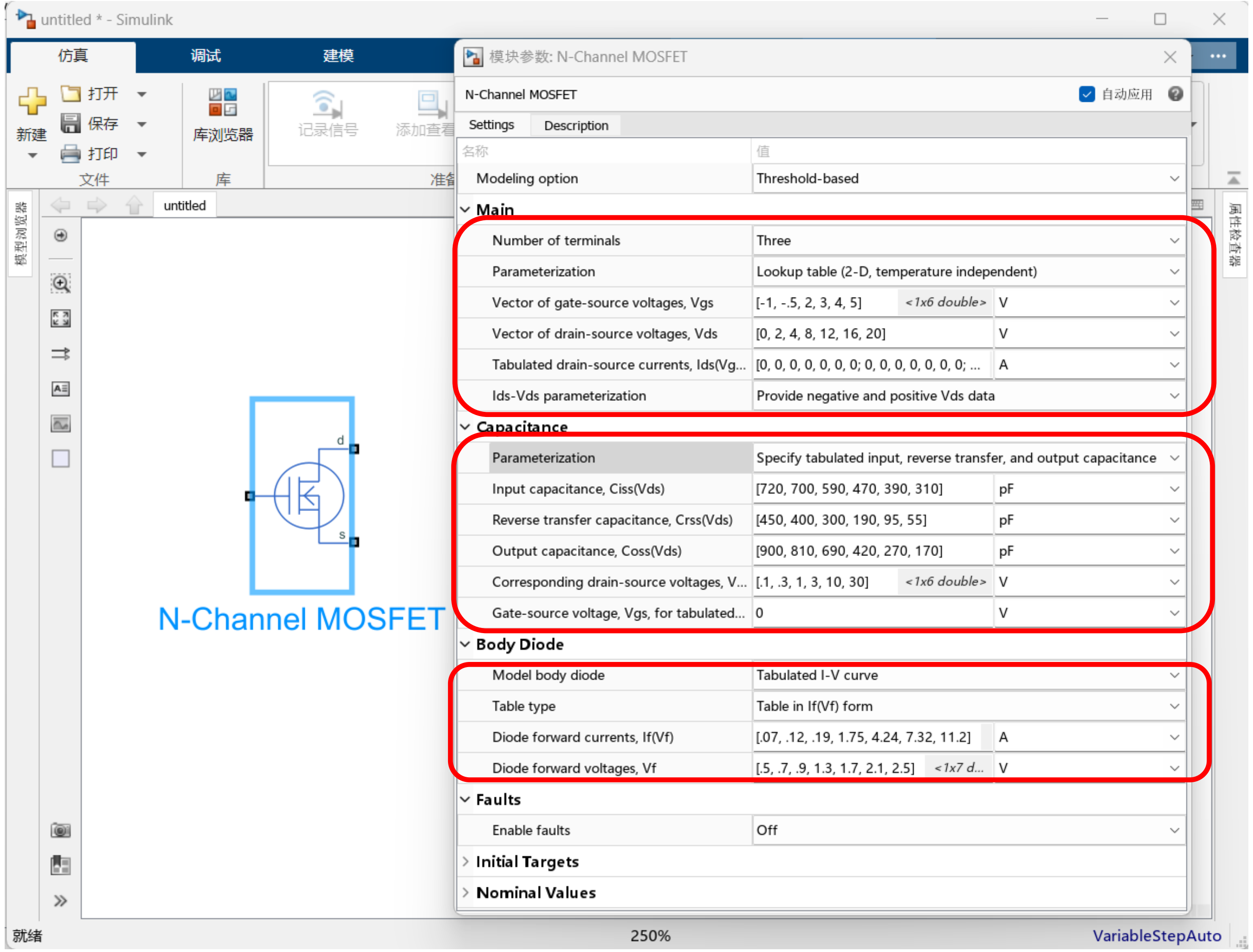
- 精细模型贴近实物，用于硬件研究
- 简化模型简化模拟实物行为，用于系统设计和软件设计





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



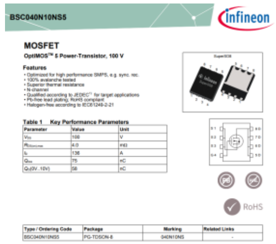
导通状态特性

开关断暂态特性

体二极管特性

高保真模型建模方法

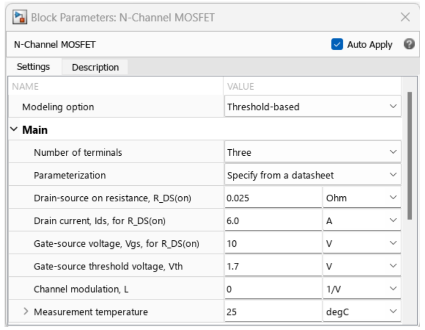
- 从厂家提供的信息建模



数据手册

Parameter	Symbol	Conditions	Value			Unit
			min.	typ.	max.	
Static Characteristic						
Collector-emitter breakdown voltage	$V_{(BR)CES}$	V_{GE} = 0V, I_C = 0.20mA	650	-	-	V
Collector-emitter saturation voltage	V_{CEsat}	V_{GE} = 15.0V, I_C = 50.0A T_{vj} = 25°C T_{vj} = 125°C T_{vj} = 175°C	- - -	1.66 1.90 2.03	2.10 - -	V
Diode forward voltage	V_F	V_{GE} = 0V, I_F = 25.0A T_{vj} = 25°C T_{vj} = 125°C T_{vj} = 175°C	- - -	1.54 1.52 1.49	1.80 - -	V
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_{CES}	V_{CE} = 650V, V_{GE} = 0V T_{vj} = 25°C T_{vj} = 175°C	- -	- 1200	40 -	µA
Gate-emitter leakage current	I_{GES}	V_{CE} = 0V, V_{GE} = 20V	-	-	100	nA
Transconductance	g_{fs}	V_{CE} = 20V, I_C = 50.0A	-	62.0	-	S

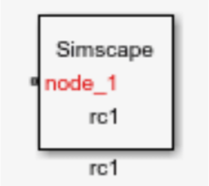
参数



SPICE 模型

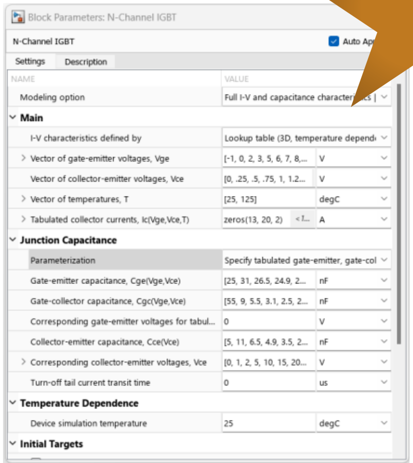
subcircuit2ssc

模块



ee.spice.semiconductorSubcircuit2lookup()

数据表



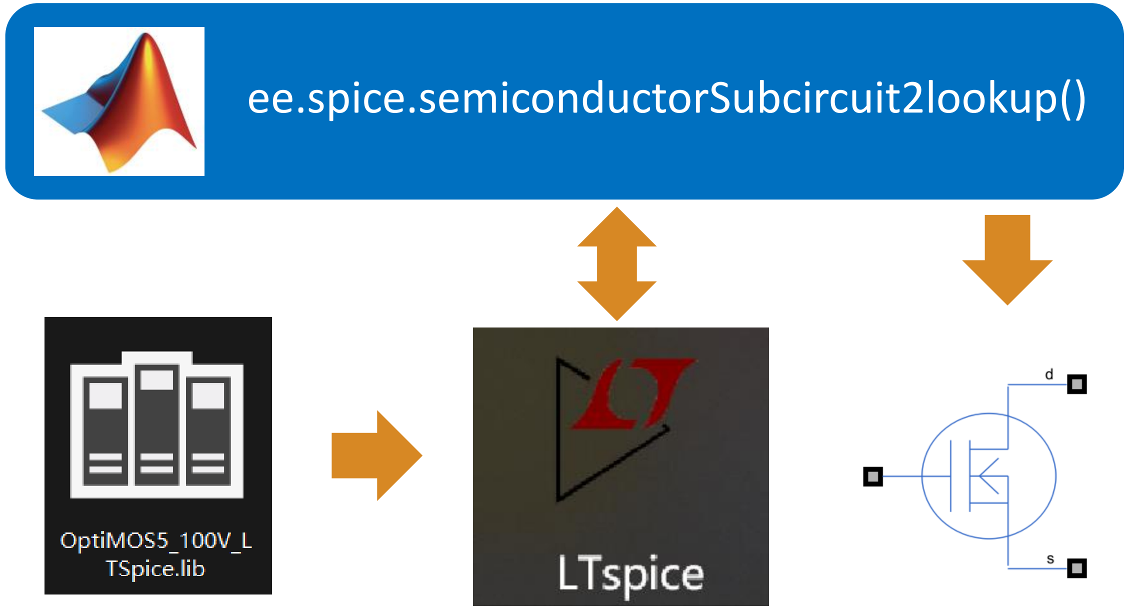
XML

数据表

ee_importDeviceParameters

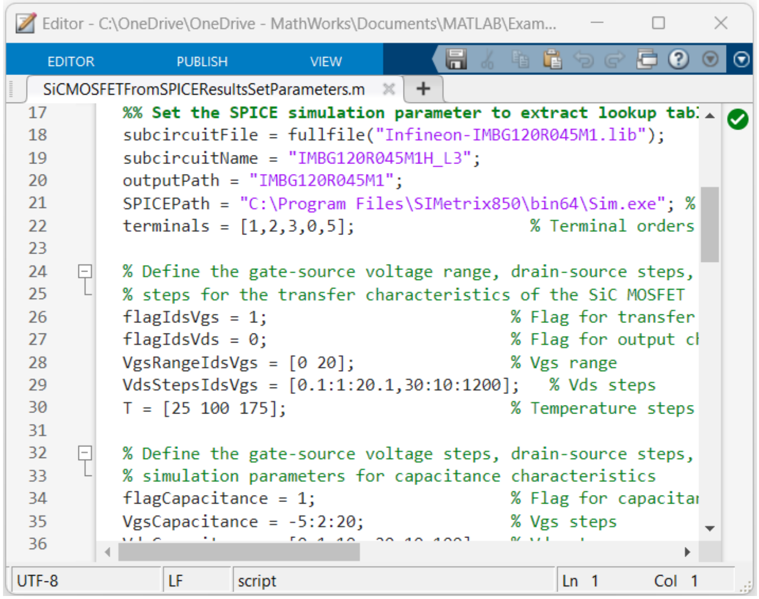
从 SPICE 生成数据表

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

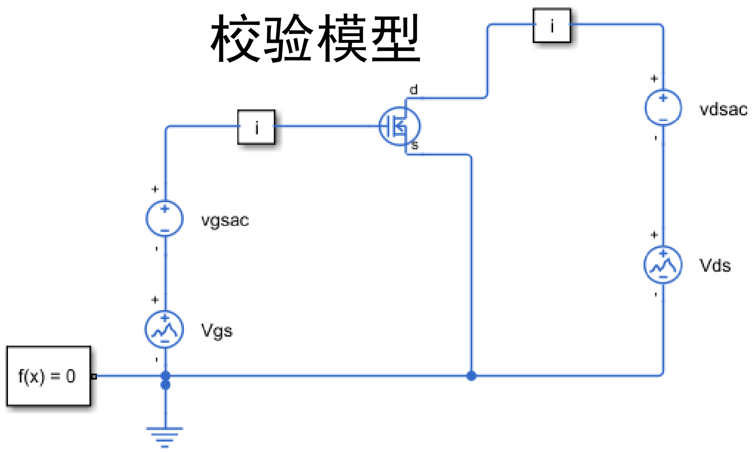


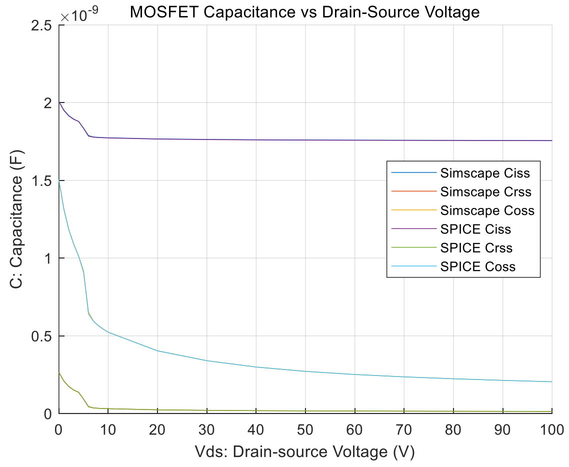
从 SPICE 生成数据表

- 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

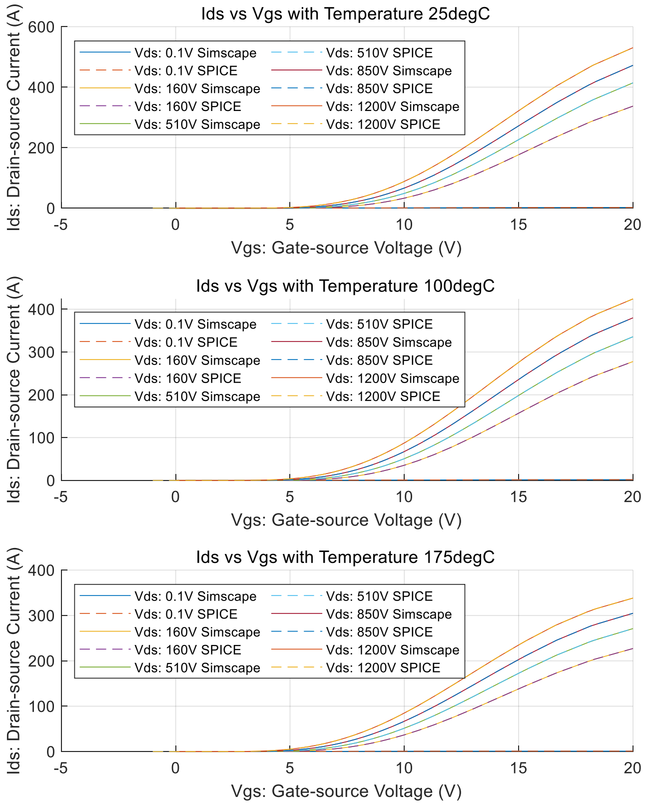


校验模型





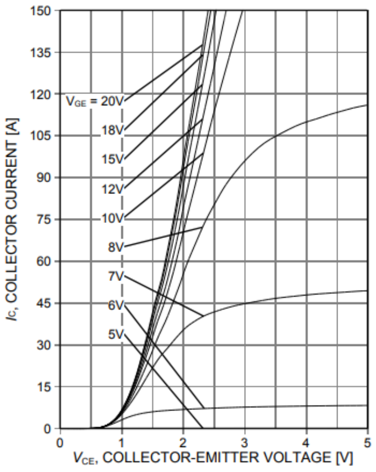
Simscape 对比 SPICE

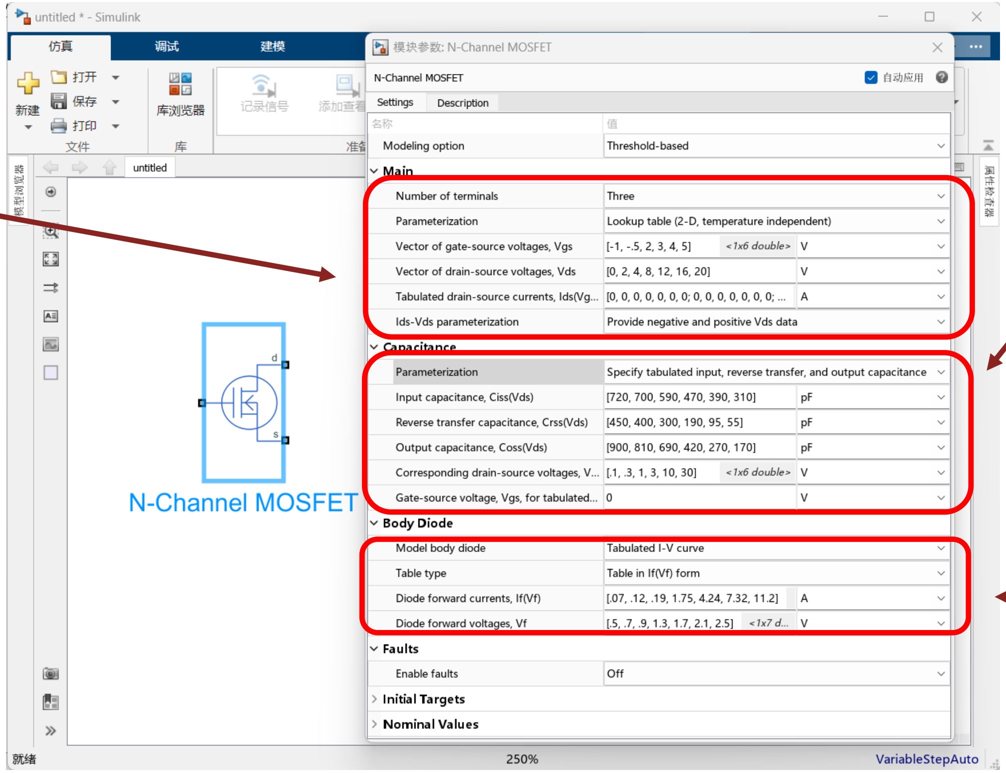


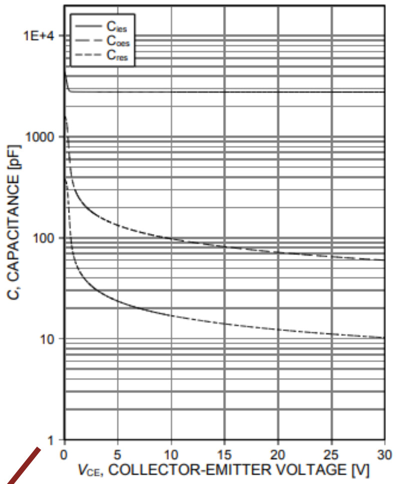
Infineon-IMBG120R030M1.lib

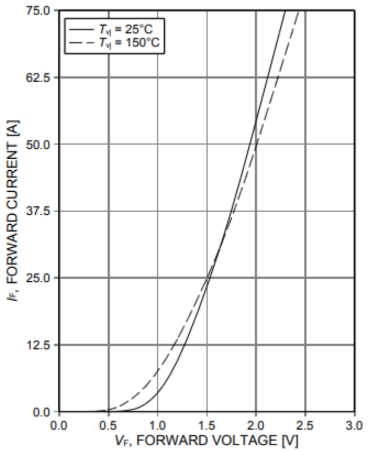
数据手册 vs. SPICE

- 部分厂家没有提供 SPICE 模型
- 每个厂家都会提供 数据手册





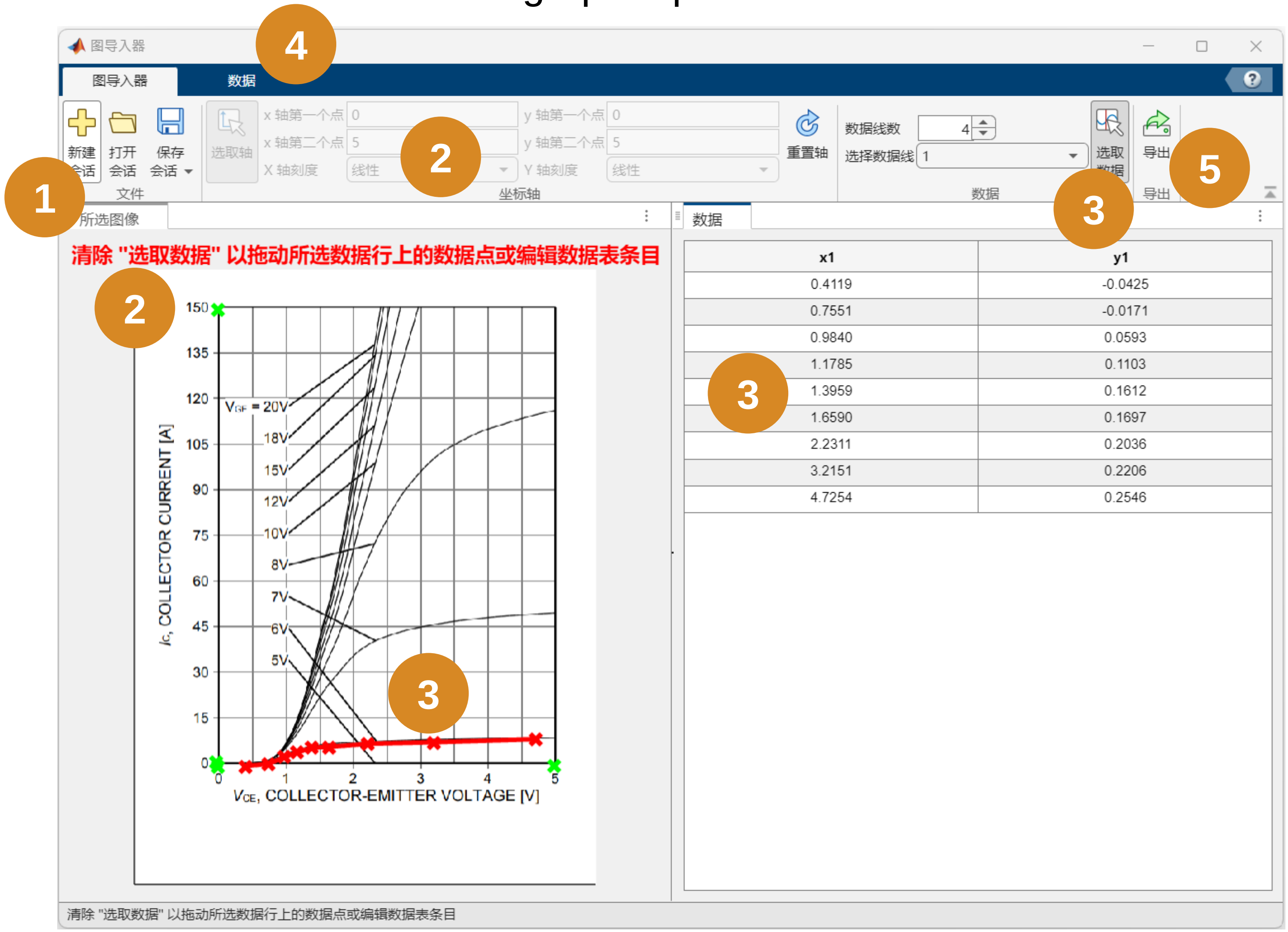




Datasheet 建模流程

- 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



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

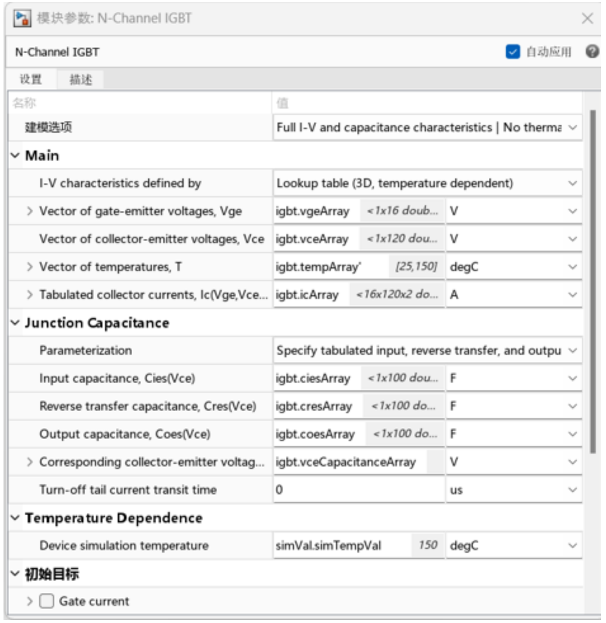
High speed fast IGBT in TRENCHSTOP™ 5 technology copacked with RAPID 1 fast and soft antiparallel diode

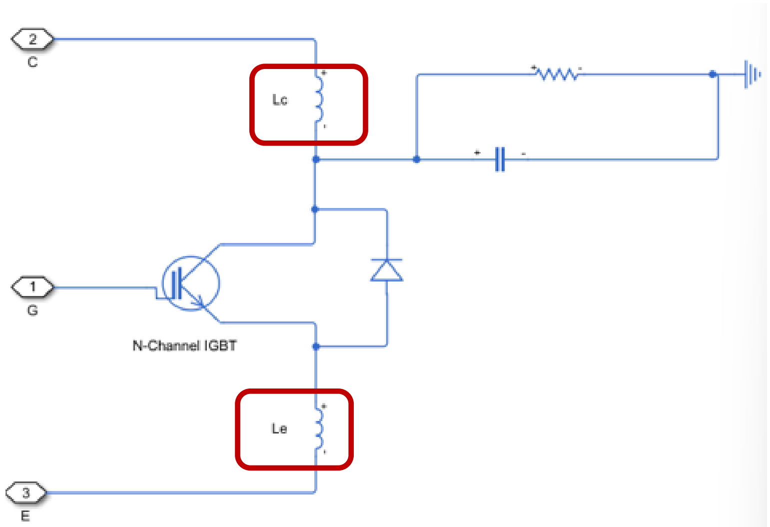
Features and Benefits:

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:

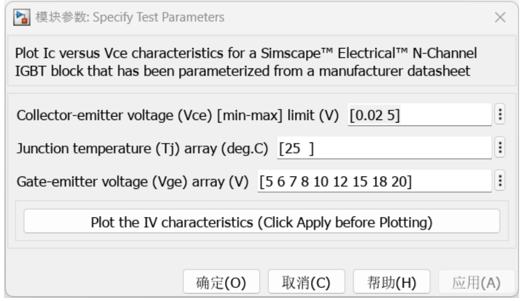
- Off-board charger
- On-board charger
- DC/DC converter
- Power-Factor correction

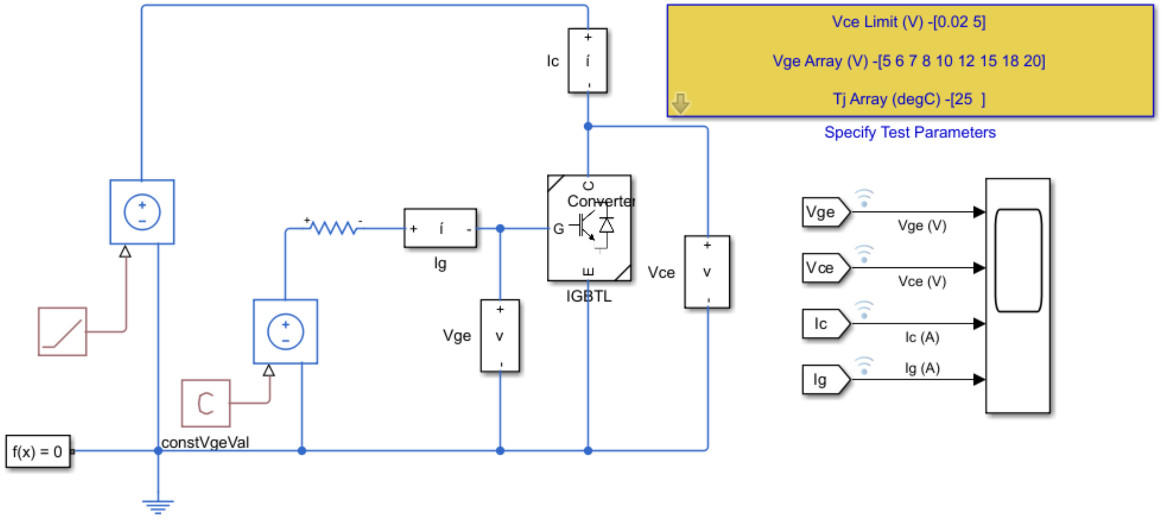




高保真模型测试

- 静态特性测试





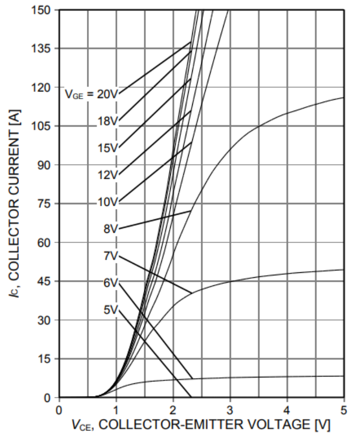
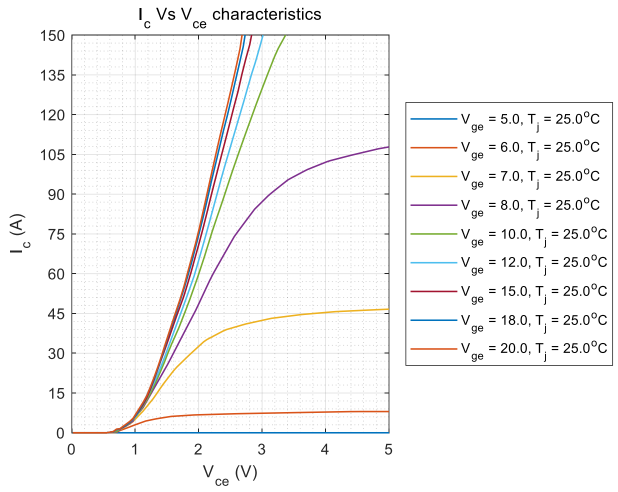


Figure 3. **Typical output characteristic**
(T_{vj}=25°C)



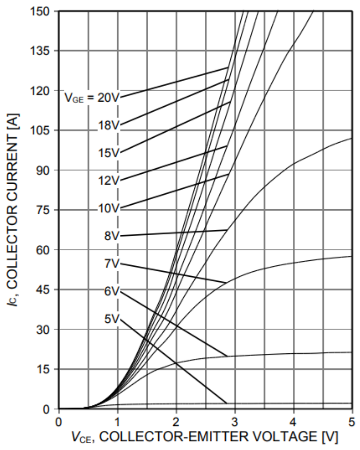
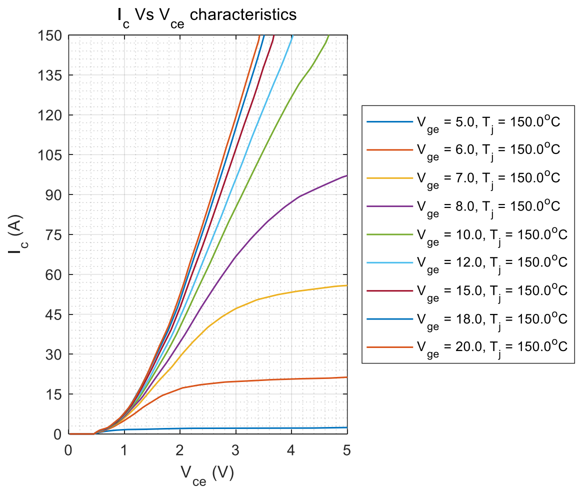


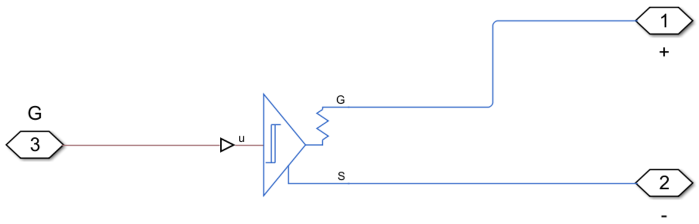
Figure 4. **Typical output characteristic**
(T_{vj}=150°C)



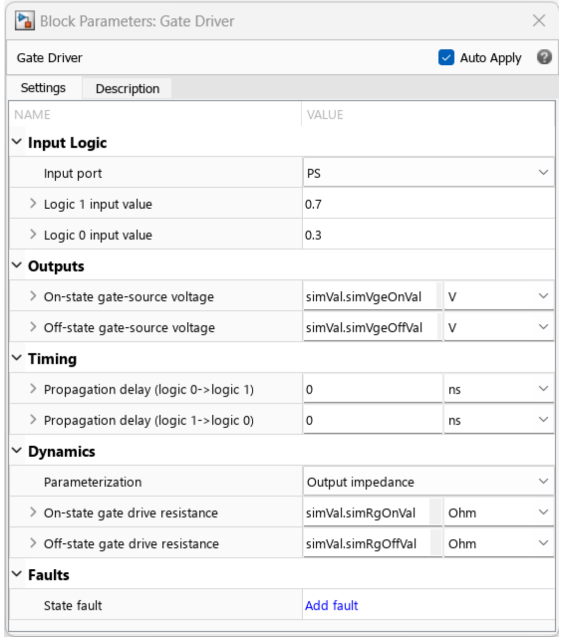
驱动电路

- 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



Gate Driver

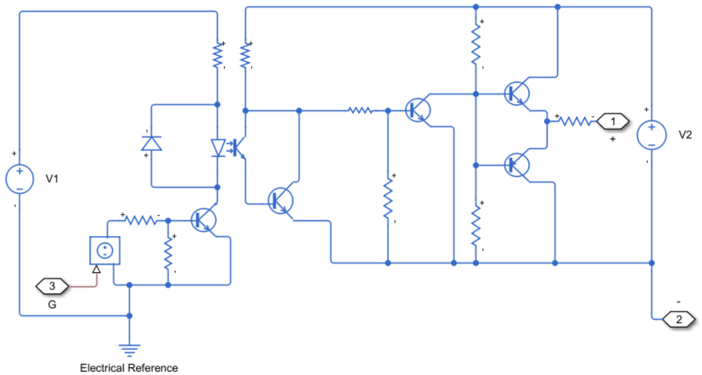


输入信号

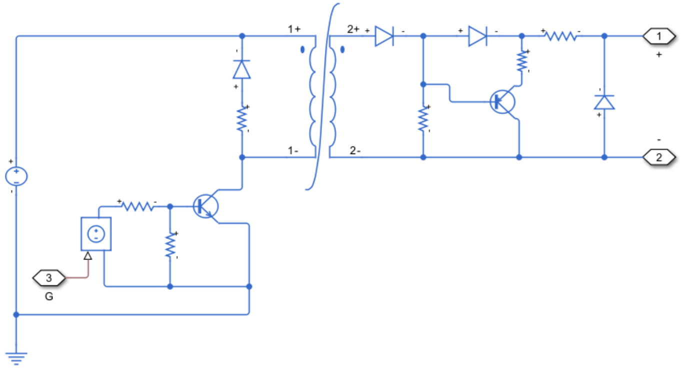
输出电平

延时

驱动电阻



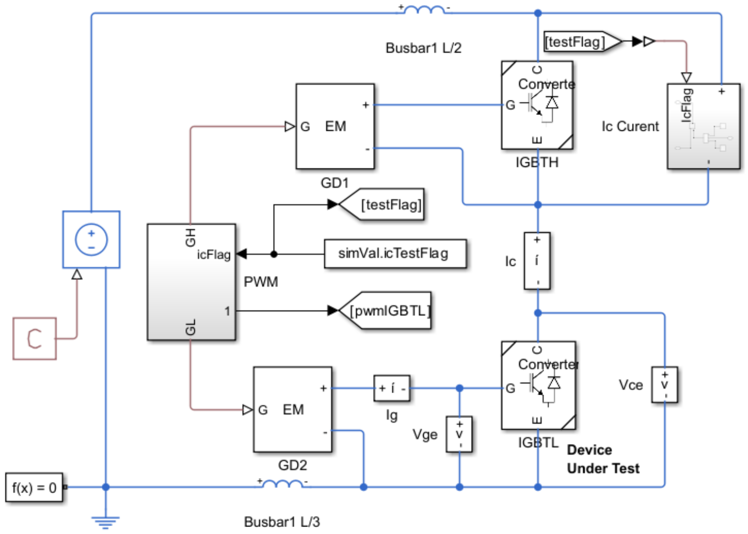
光耦驱动

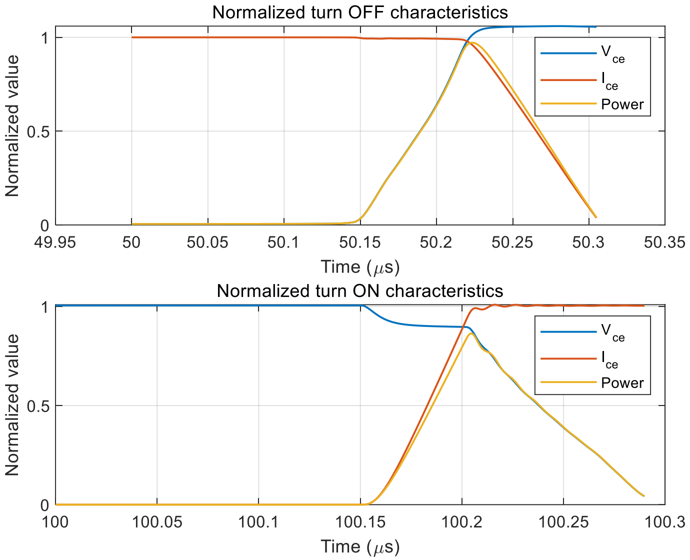


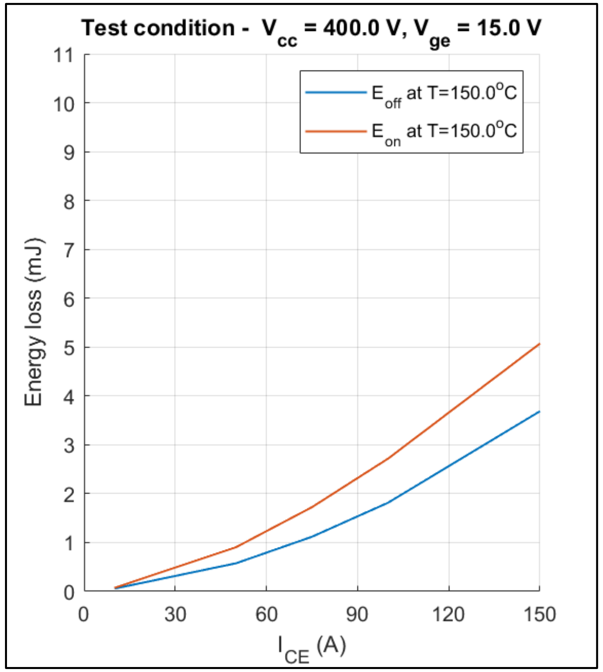
隔离变压器驱动

动态特性测试

- 双脉冲测试
  - 开关速度
  - 开关损耗
  - 电磁干扰

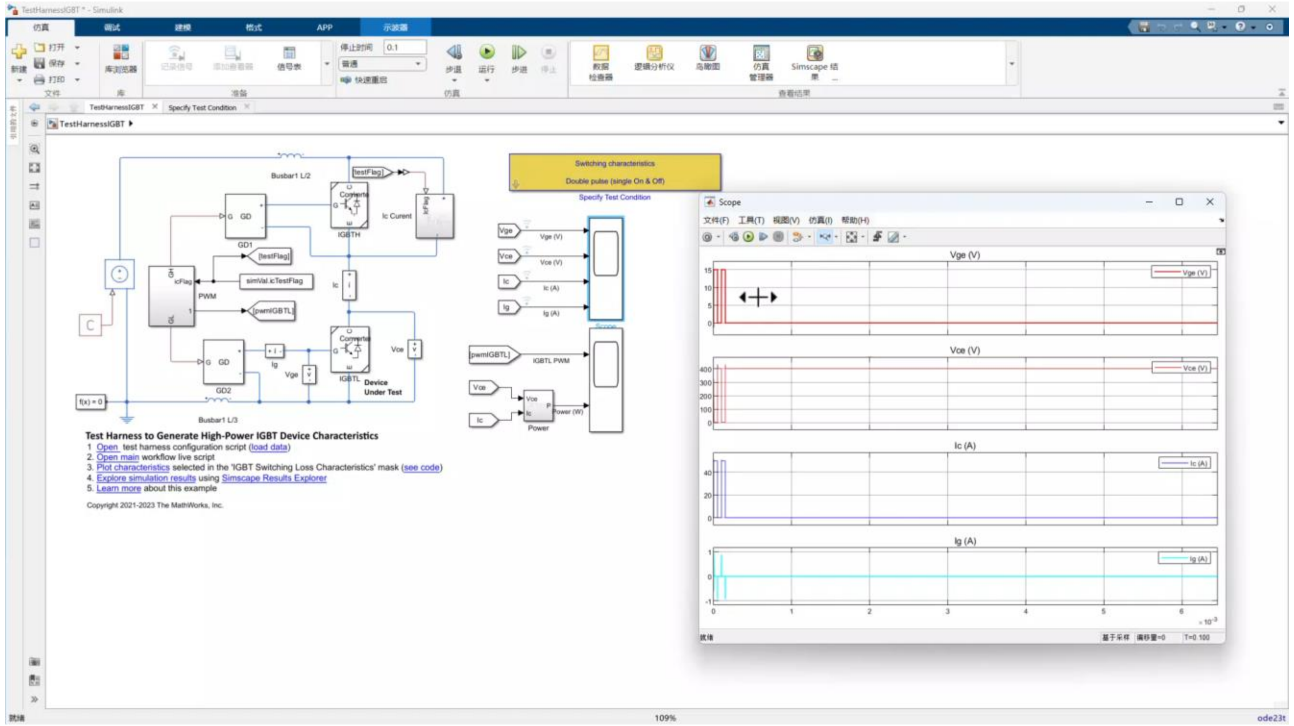






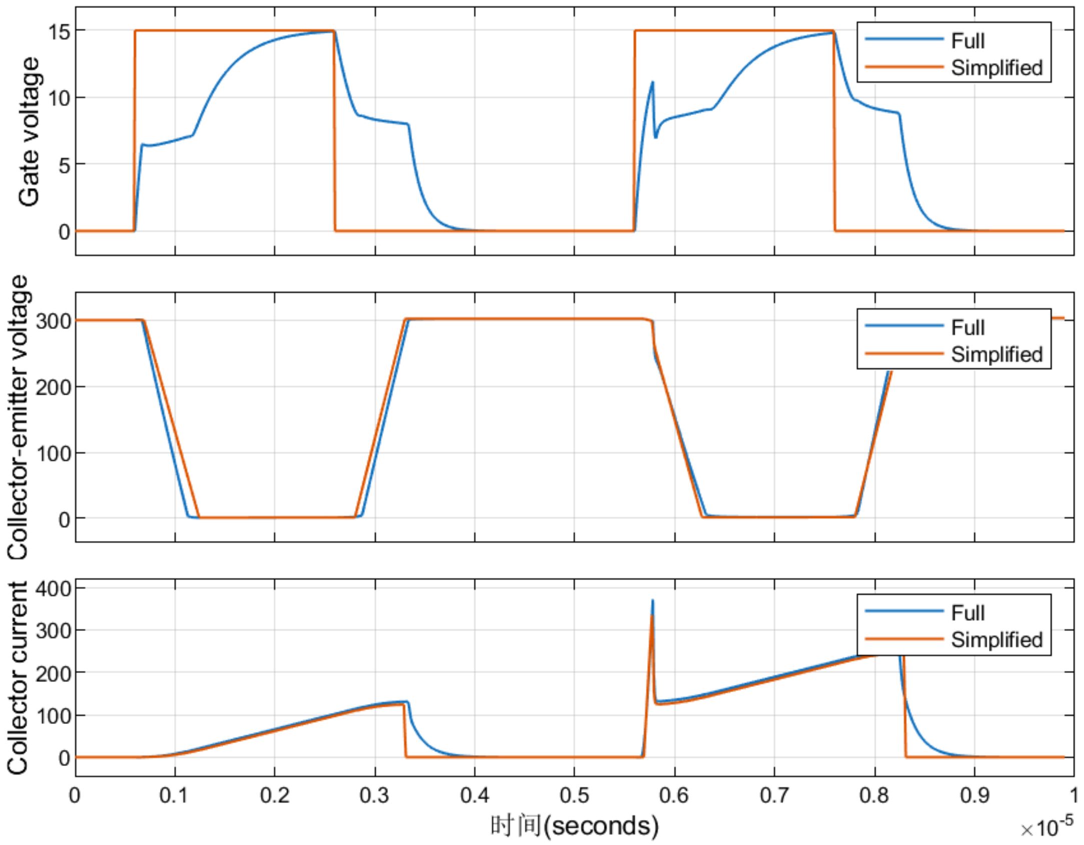
为什么要降低保真度？

- 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

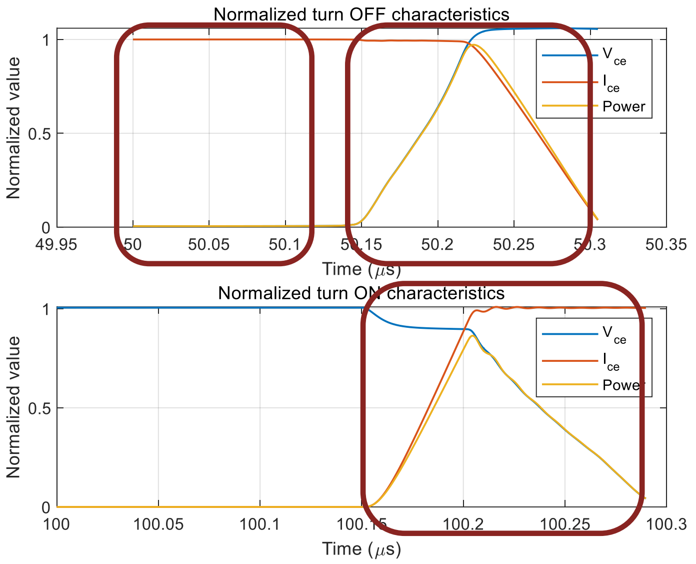
- 控制模型需求
  - 电压面积准确
- 温升模型 需求更高
  - 导通损耗
    - 导通压降
  - 开关损耗
    - 开关段器件功耗
  - 散热模型



损耗模型

- 电力电子器件损耗
  - 导通损耗
  - 开通损耗 Eon
  - 关断损耗 Eoff
- 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

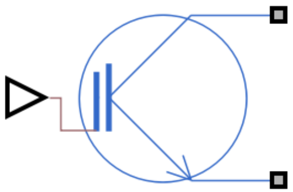
导通损耗 关断损耗 Eoff



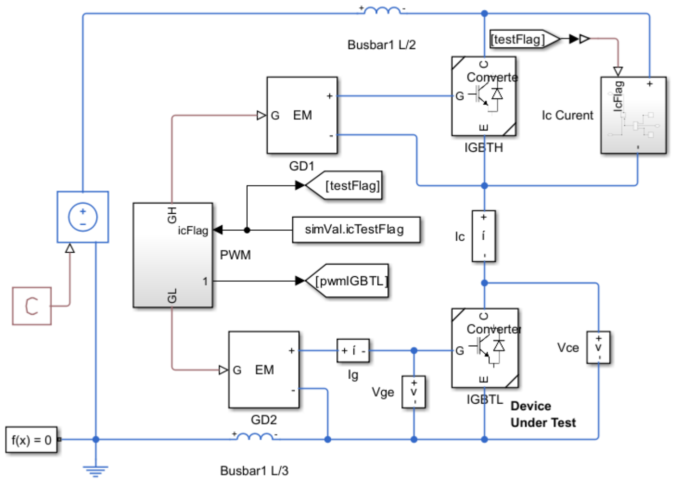
开通损耗 Eon

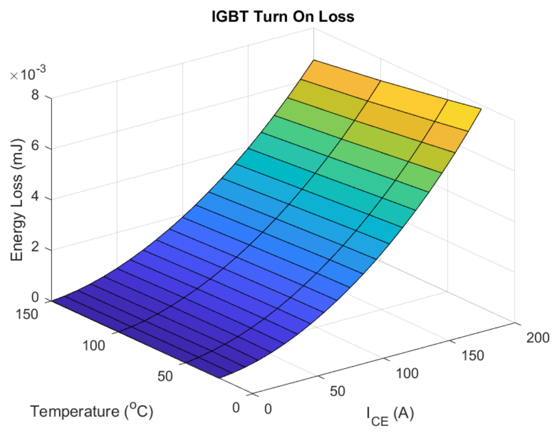
损耗模型

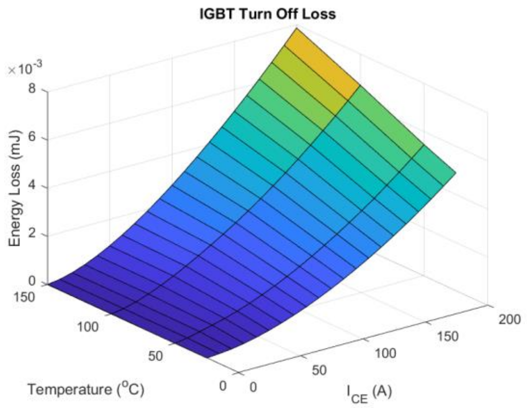
- 高精度模型仿真测试获取损耗数据

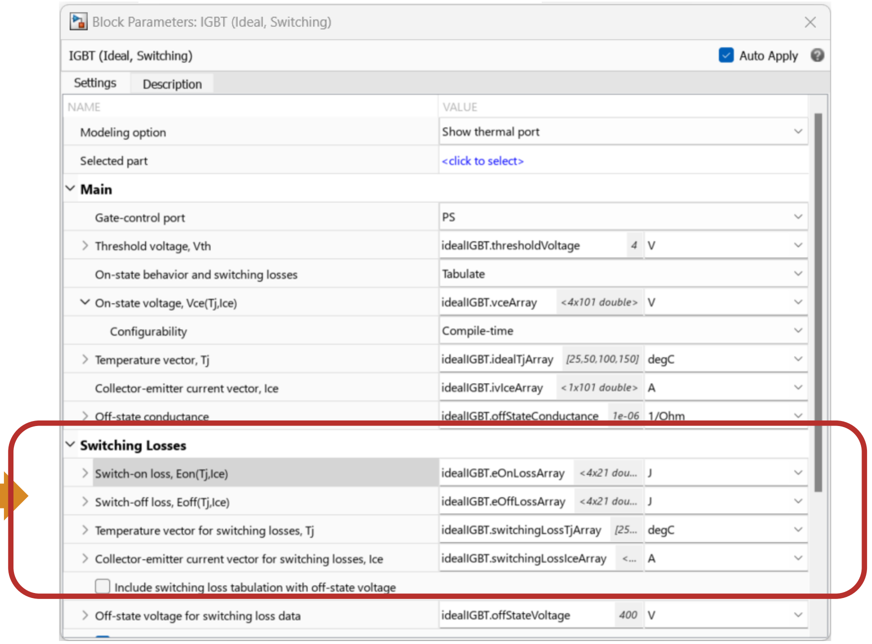


IGBT (Ideal, Switching)



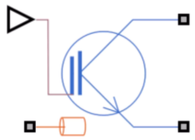




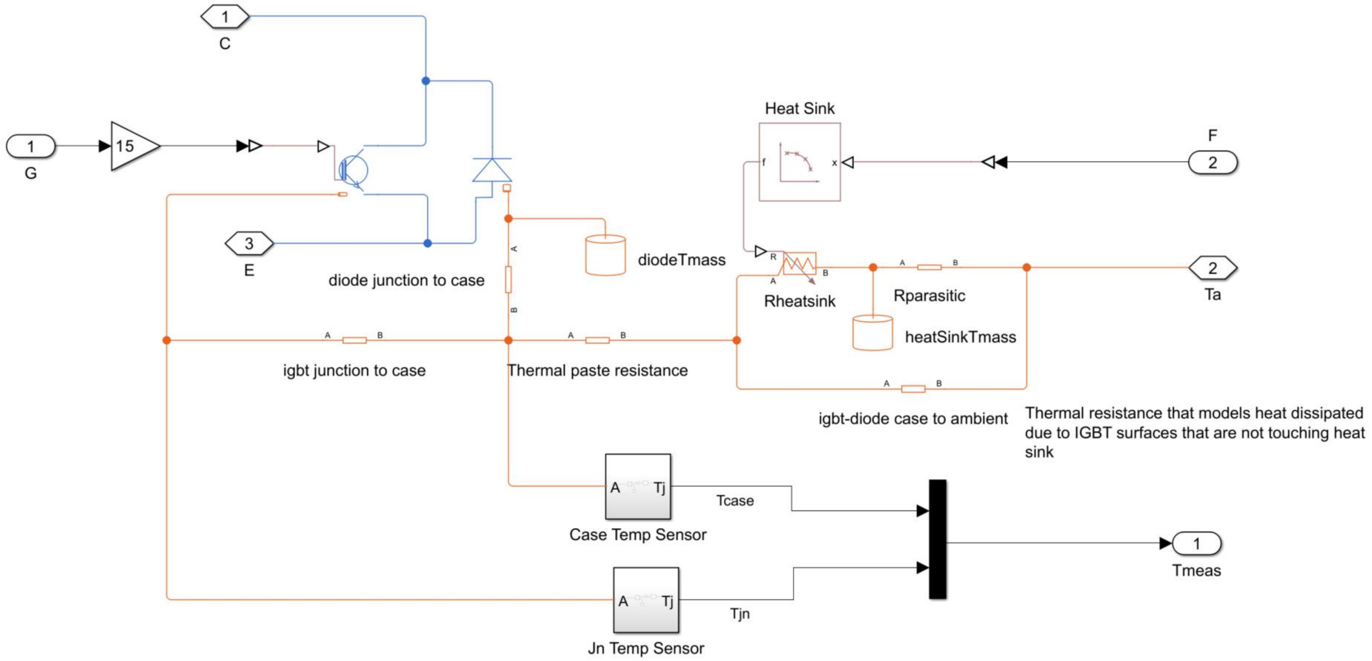


热模型

- 开放器件散热端口
- Simscape Thermal 建立散热模型

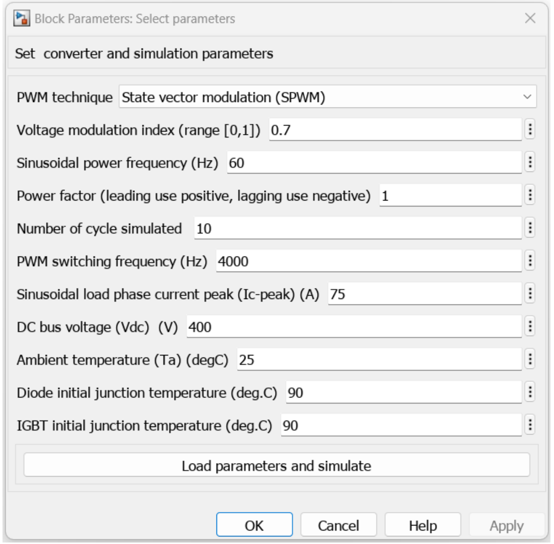


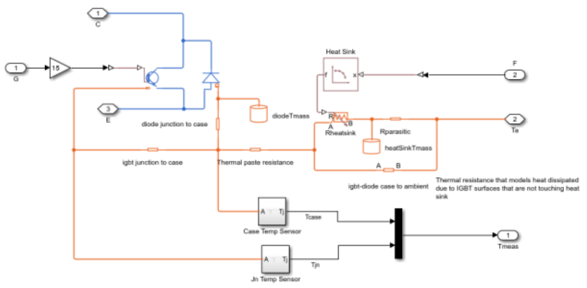
IGBT
(Ideal,
Switching)



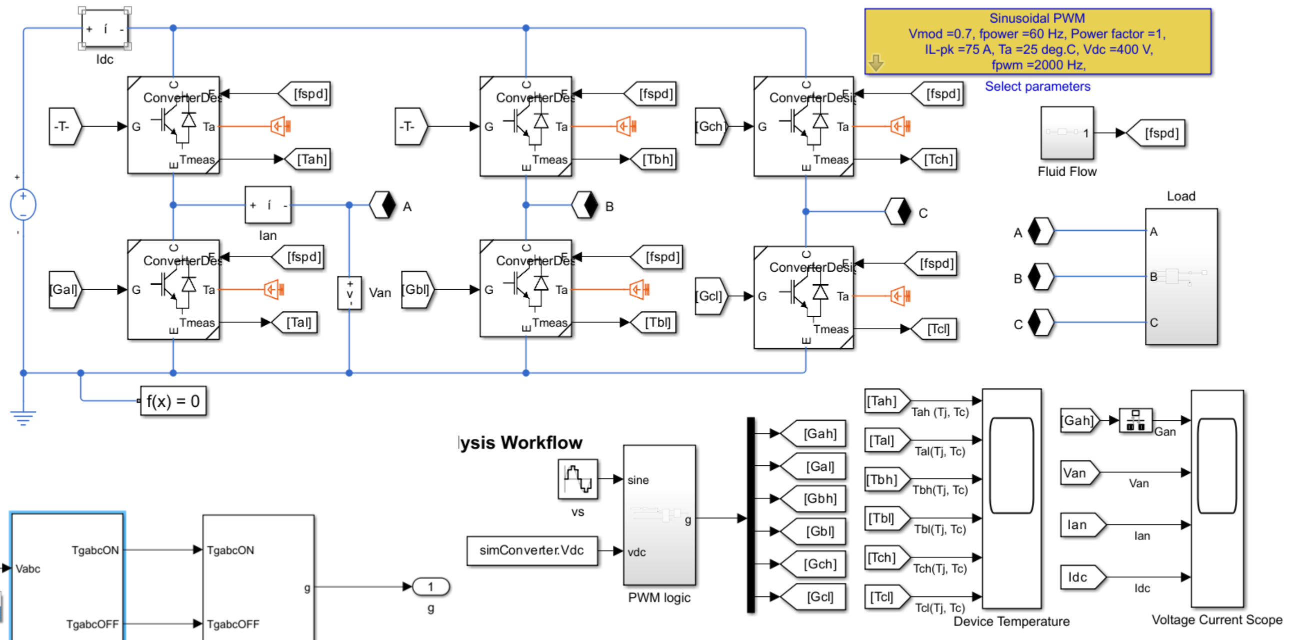
三相两电平变流器温升测试

测试工况配置

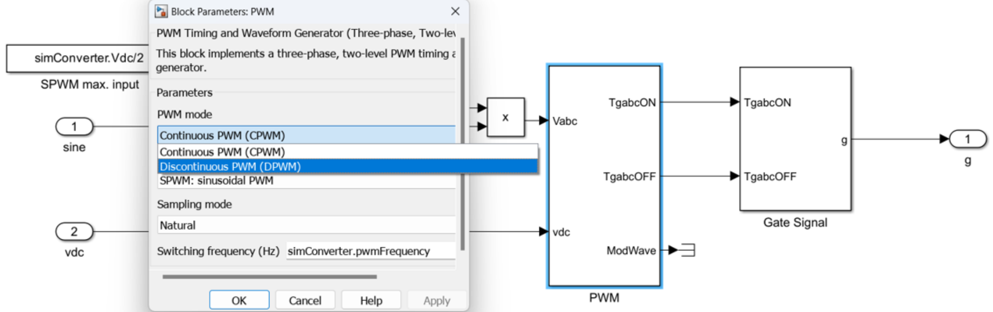


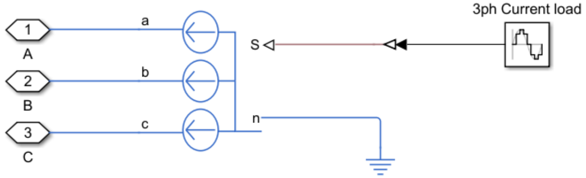


IGBT电热耦合模型



PWM模型

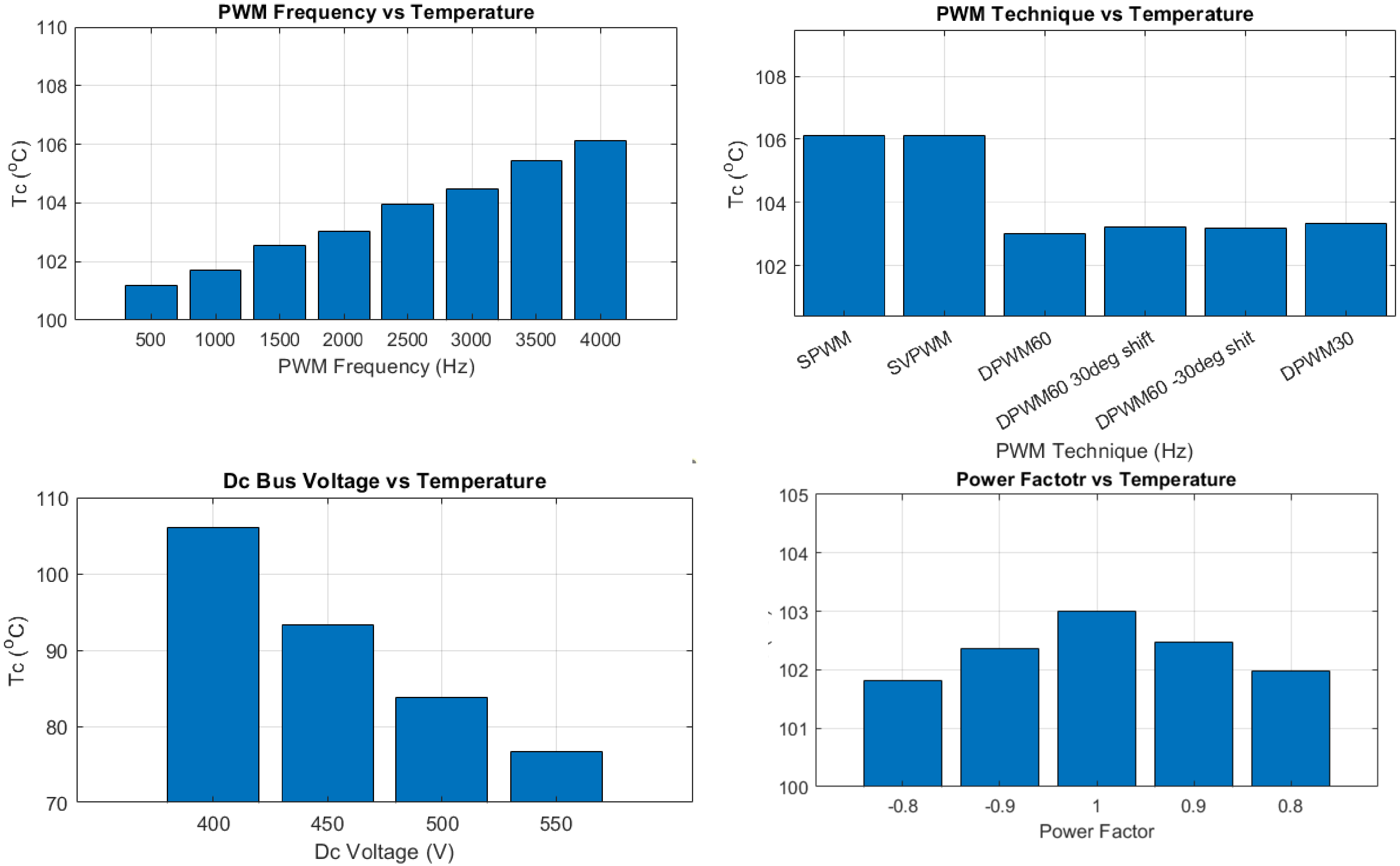




负载模型

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

MathWorks