

ANSYS



仿真
新时代

2017 ANSYS用户技术大会

中国·烟台

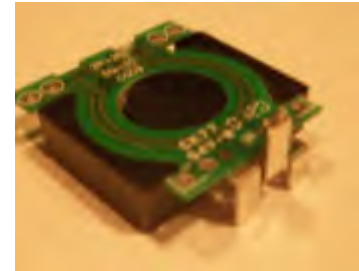
开关电源电磁兼容仿真方案

闵建军 / 博士

中车株洲电力机车研究所有限公司

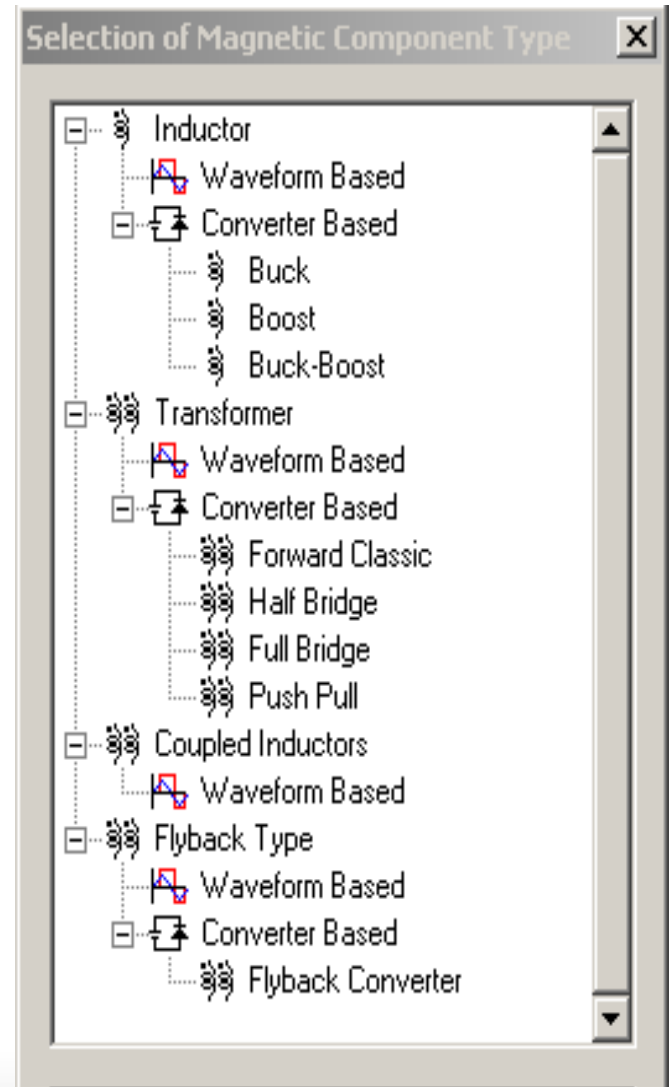
开关电源面临的技术问题

- ◆ 电感、变压器的精确设计问题
变压器的临近效应、趋肤效应、磁扩散与饱和
- ◆ 电源系统稳态、动态电气性能设计问题
主电路拓扑结构和控制电路，系统效率等
电力电子器件的非线性、开关动态过程等
- ◆ 共模、差模等滤波电感及电路设计问题
- ◆ 传导干扰及EMI/EMC问题

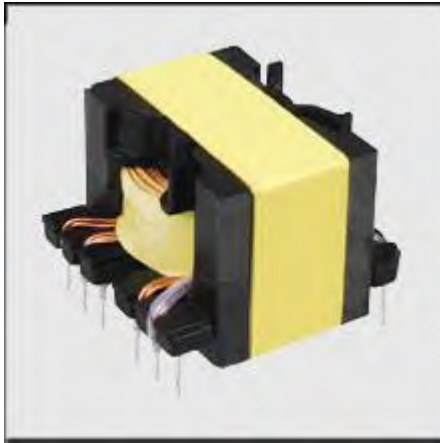


PExprt----电子变压器、电感设计专家

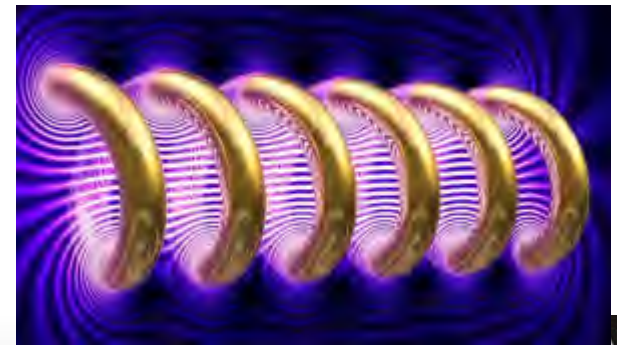
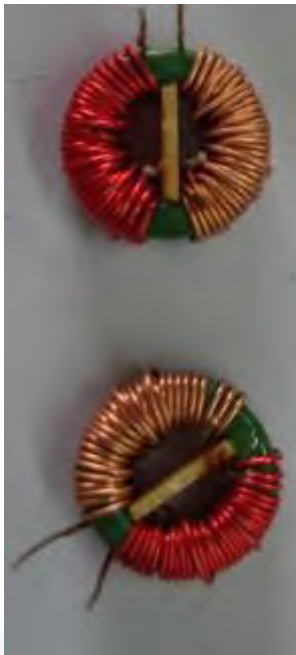
- ✓ 集成世界知名厂家库
- ✓ 磁路法快速设计和方案优选
- ✓ 有限元精确设计
-



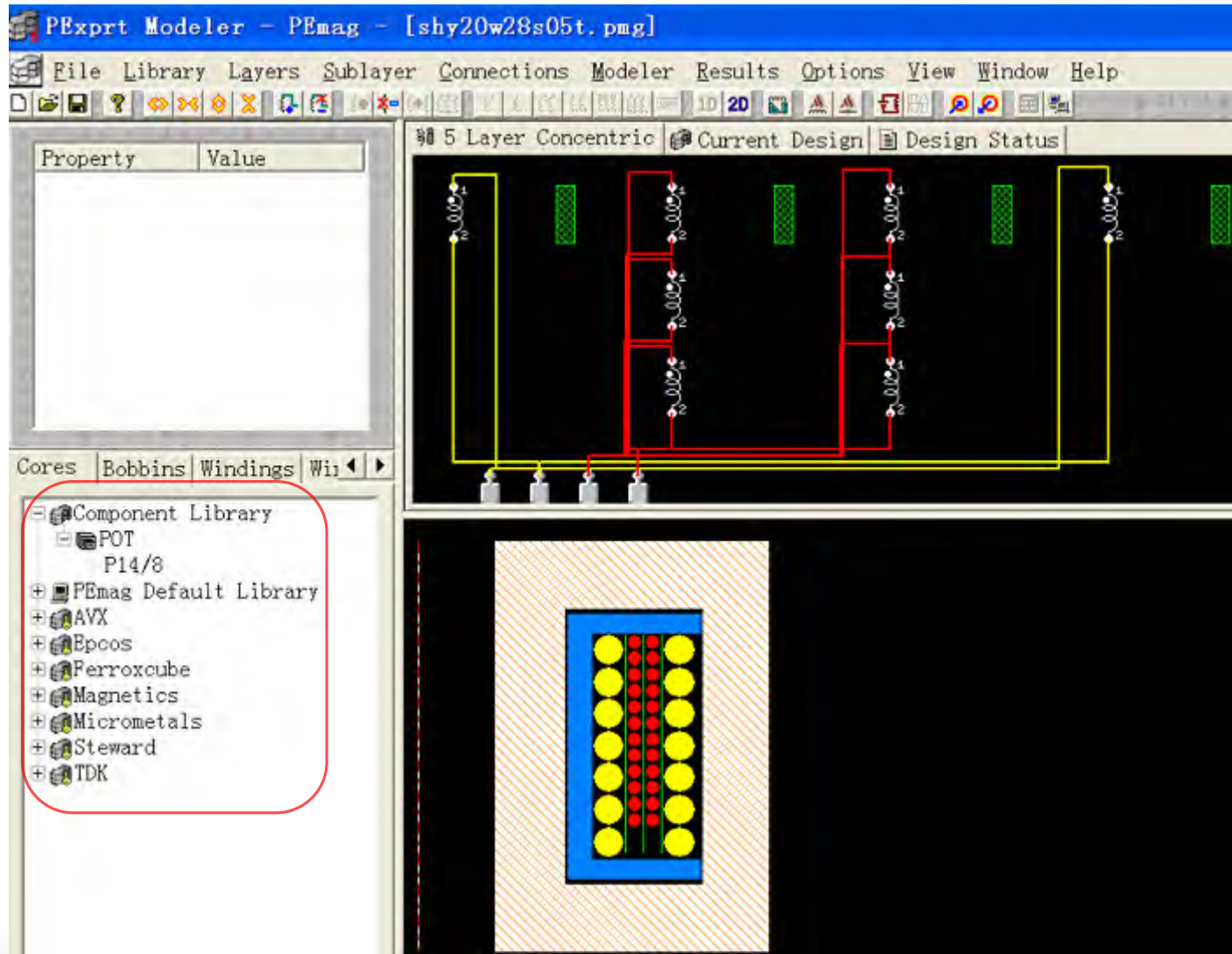
电感、变压器的精确设计问题



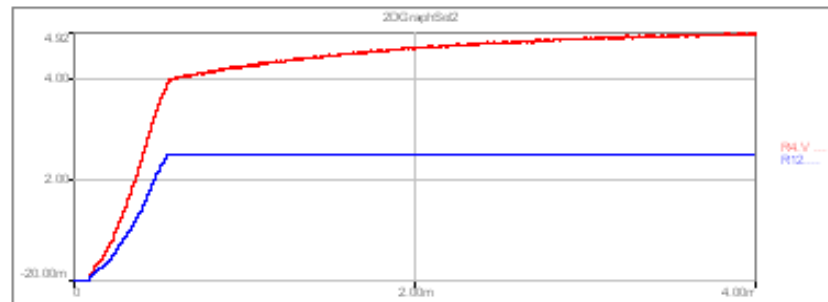
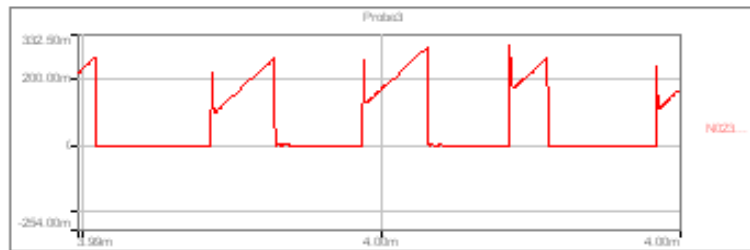
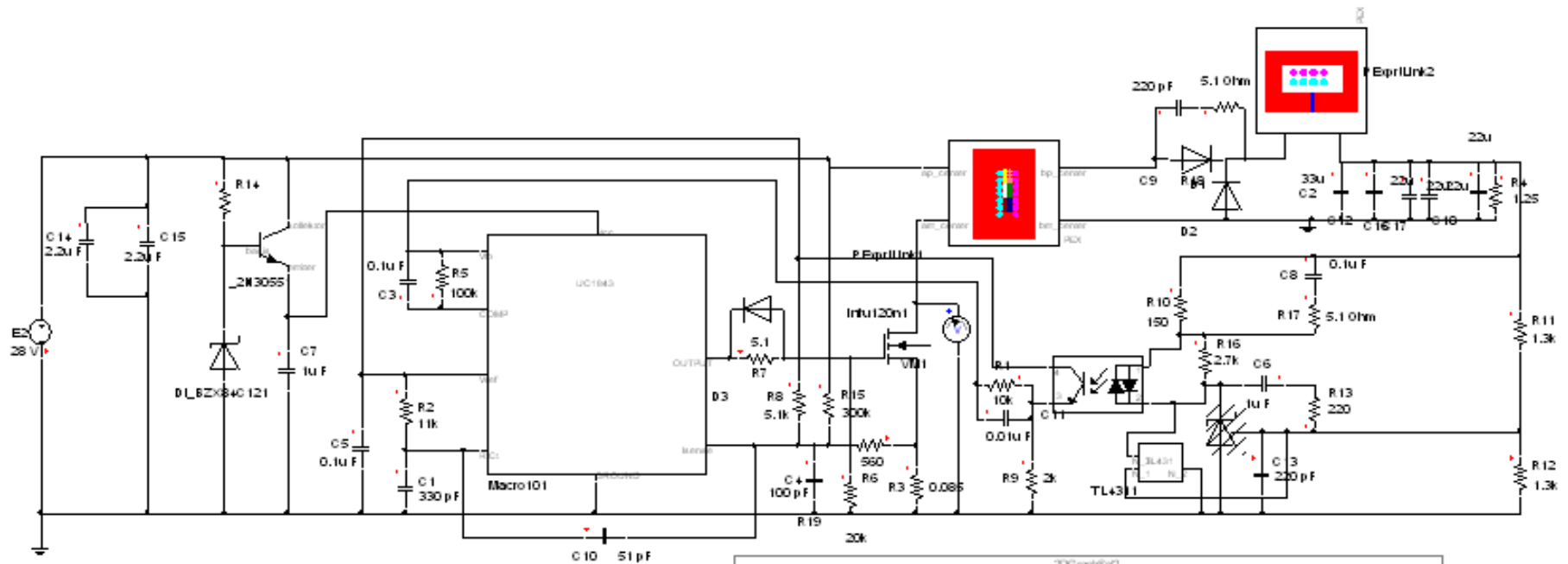
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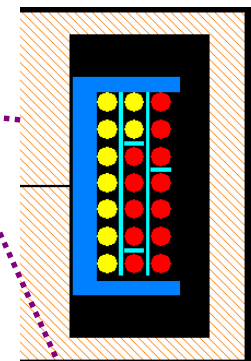
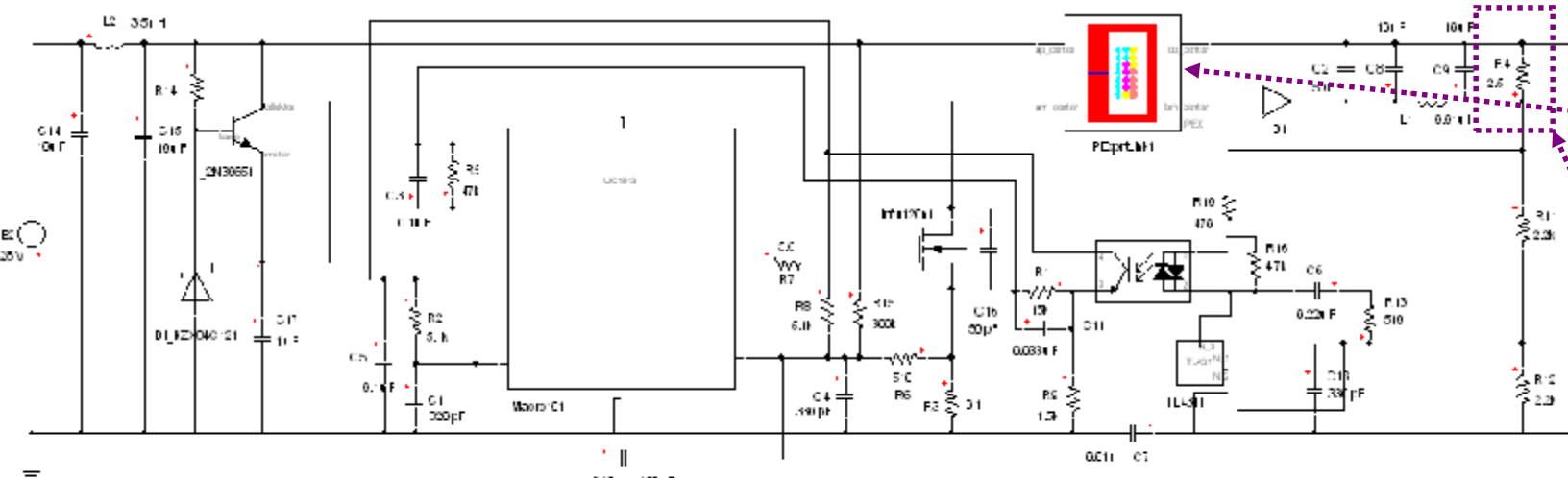
PExpert--集成世界知名厂家库



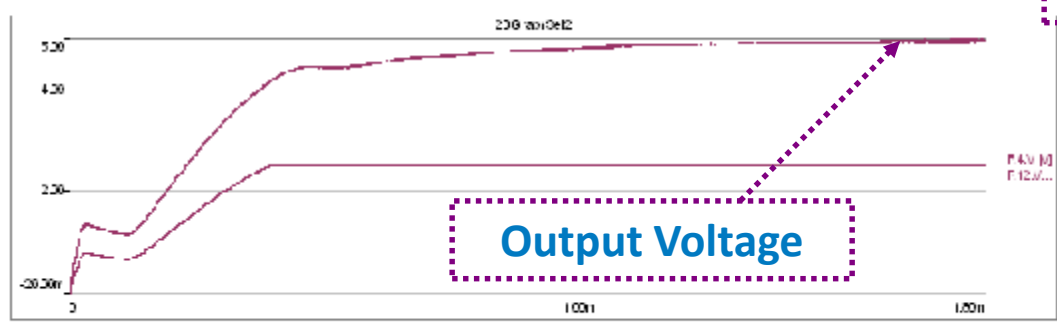
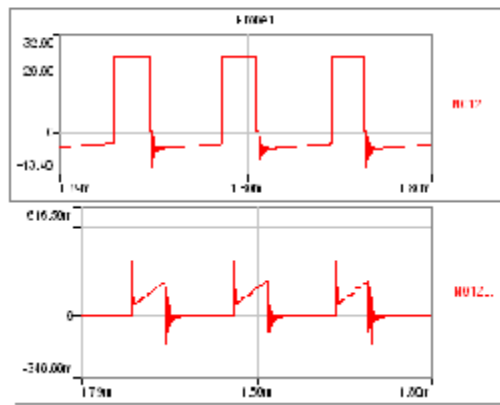
主电路拓扑结构和控制电路(Simplorer)



PExprt高保真阶模型直接集成到Simplorer



负载

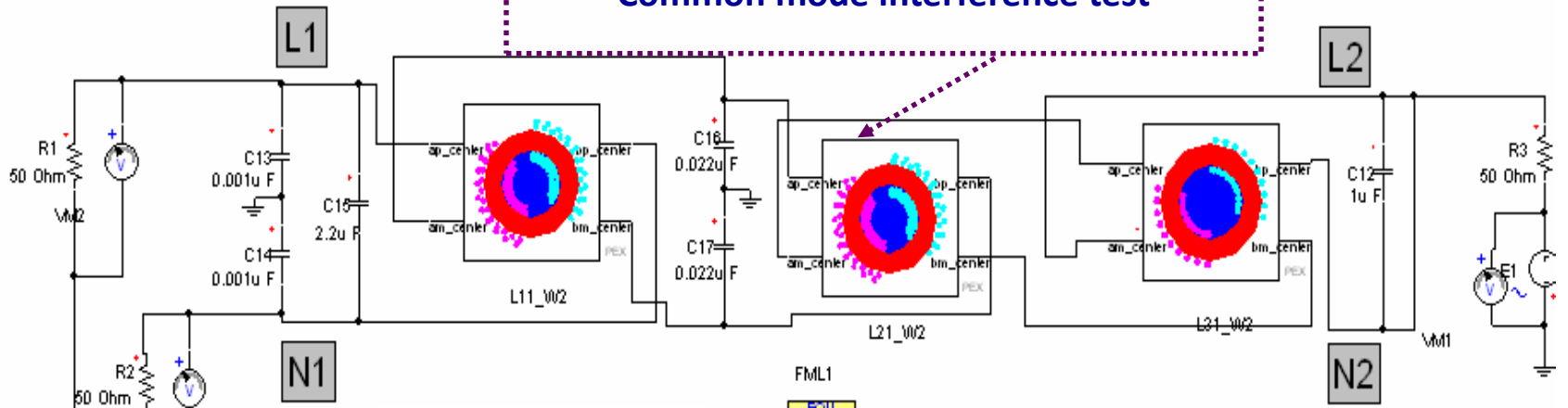


Customer's products: Flyback Simulation Circuit (10W)

共模、差模等滤波电感及电路设计 (Simplorer)



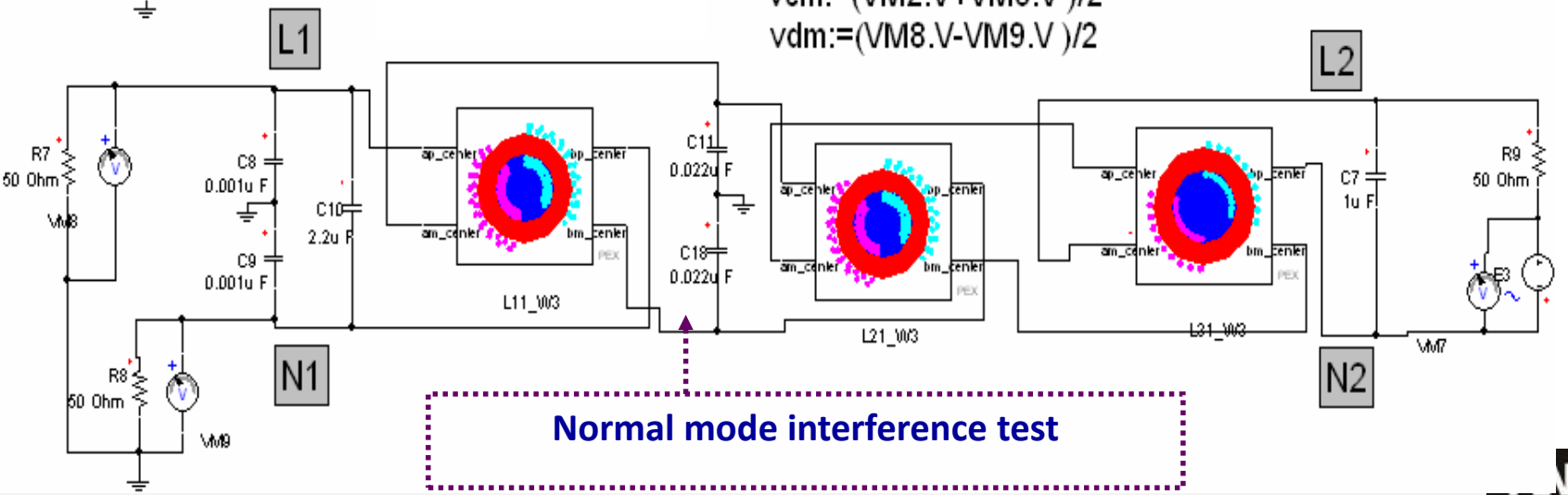
Common mode interference test



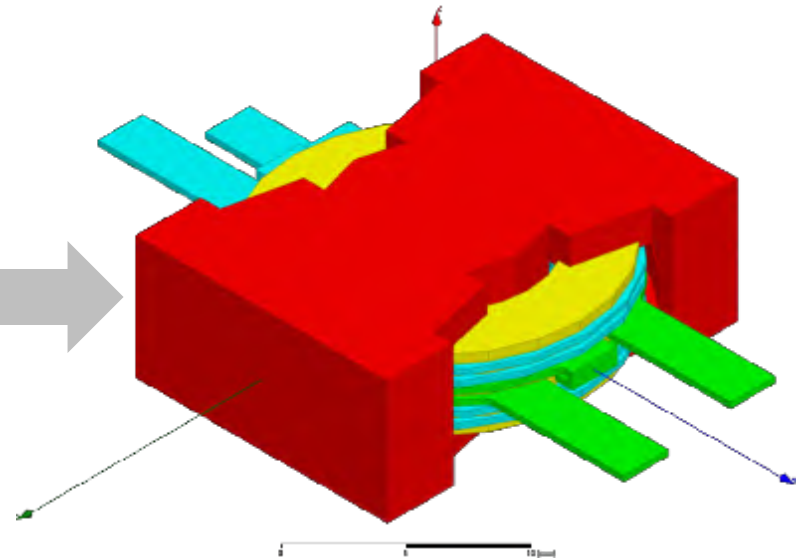
$$v_{cm} := (VM2.V + VM3.V) / 2$$

$$v_{dm} := (VM8.V - VM9.V) / 2$$

Normal mode interference test



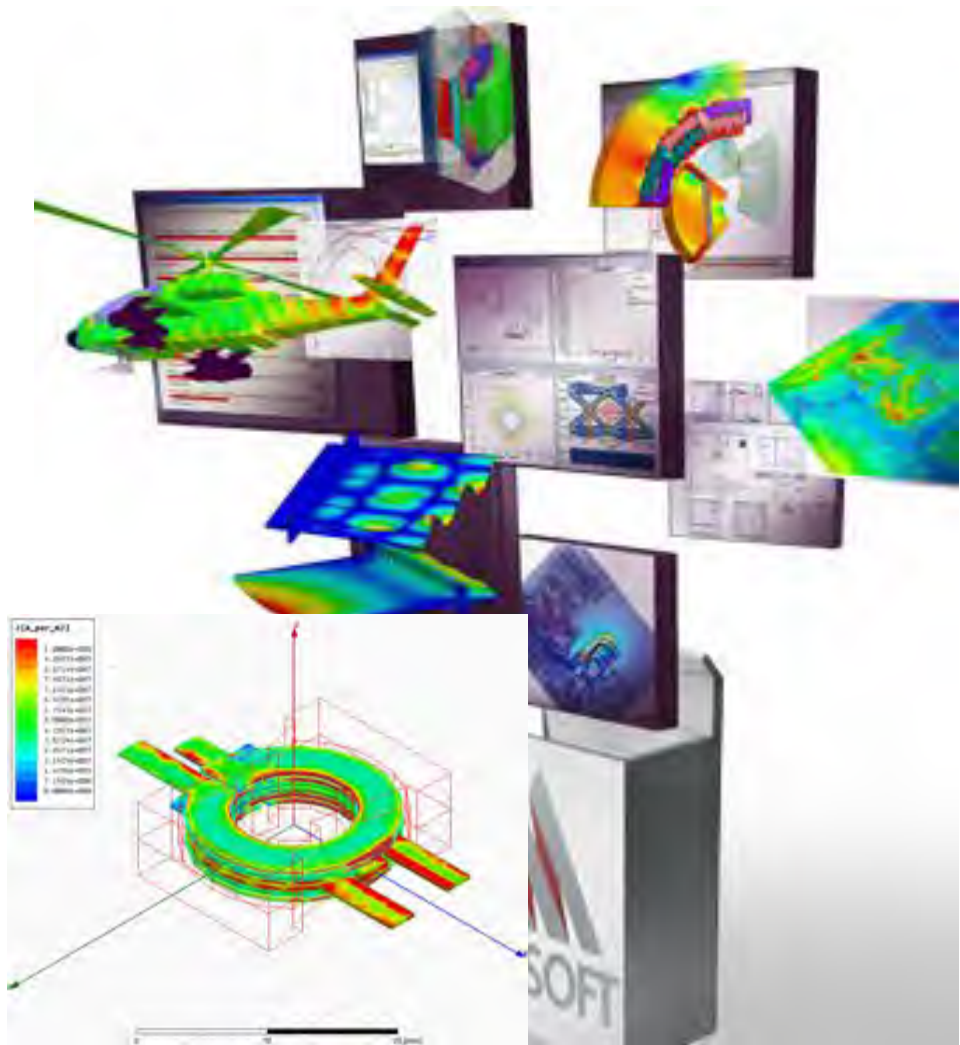
Maxwell : 非常规磁性器件



www.dianvuan.com

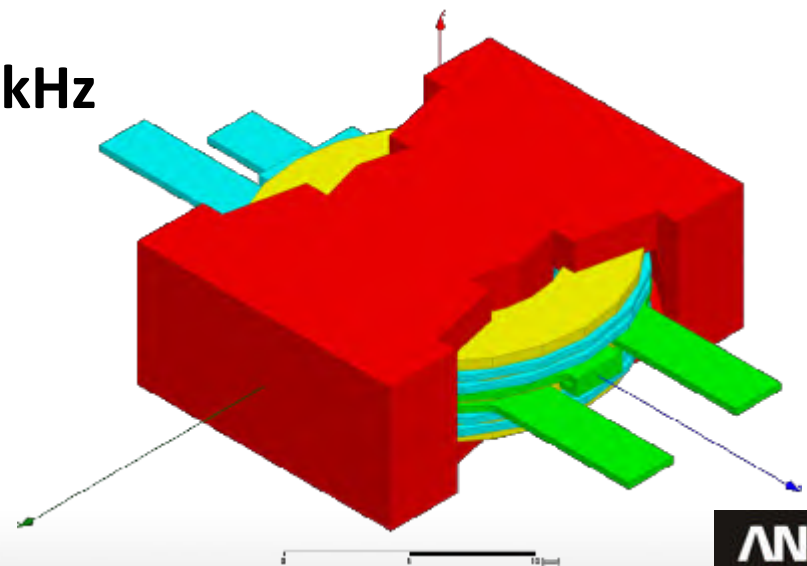
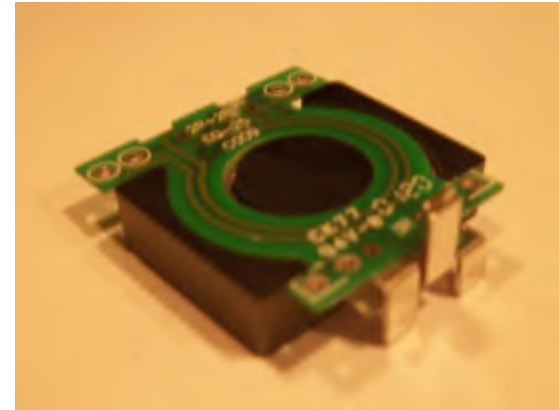
Maxwell 介绍

- 精确的2D/3D有限元分析
- 强大的瞬态功能
- 全面的电磁场仿真
- 自动自适应网格剖分技术



Electronic Planar Transformer

- Ferrite PQ Core
- Primary turns = 4
- Secondary turns = 2
- Insulation layers between conductors
- Fundamental Frequency = 100kHz



Core Material Properties - Inputs

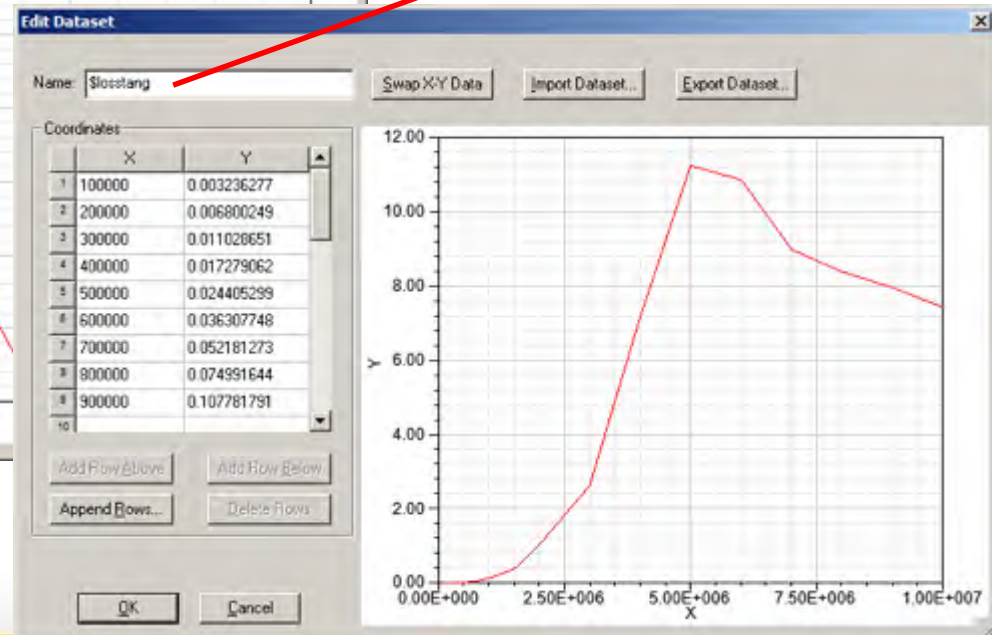
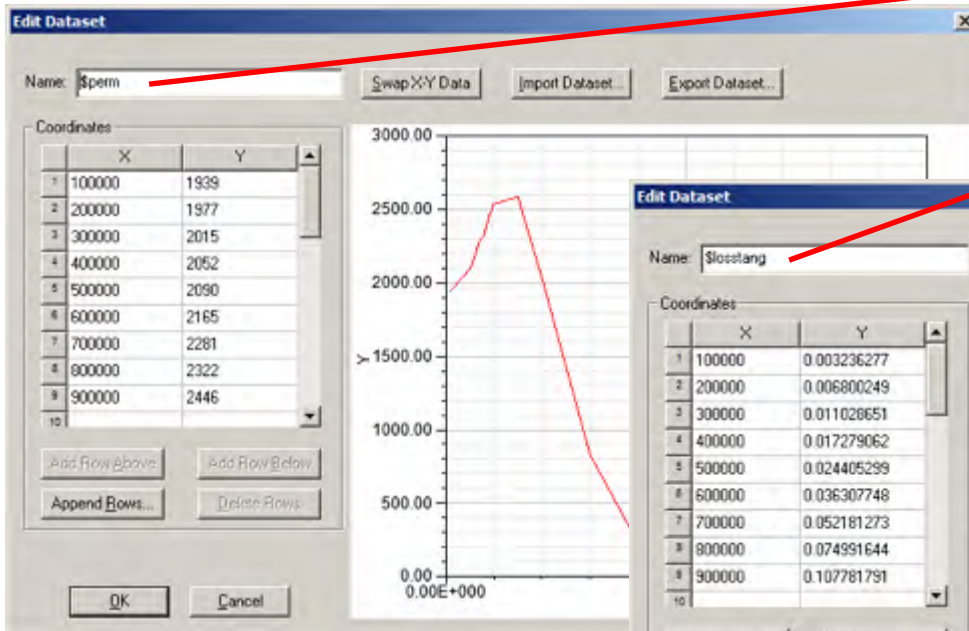
- **Datasets used to define properties vs. frequency:**
 - Relative Permeability = $pwl(\$perm, Freq)$
 - Magnetic Loss tangent = $pwl(\$losstan, Freq)$
- **Relative permittivity = 12**
- **Conductivity = 0.5 (S/m)**

View / Edit Material

Material Name: M_3c85_temp Material Coordinate System: Cartesian

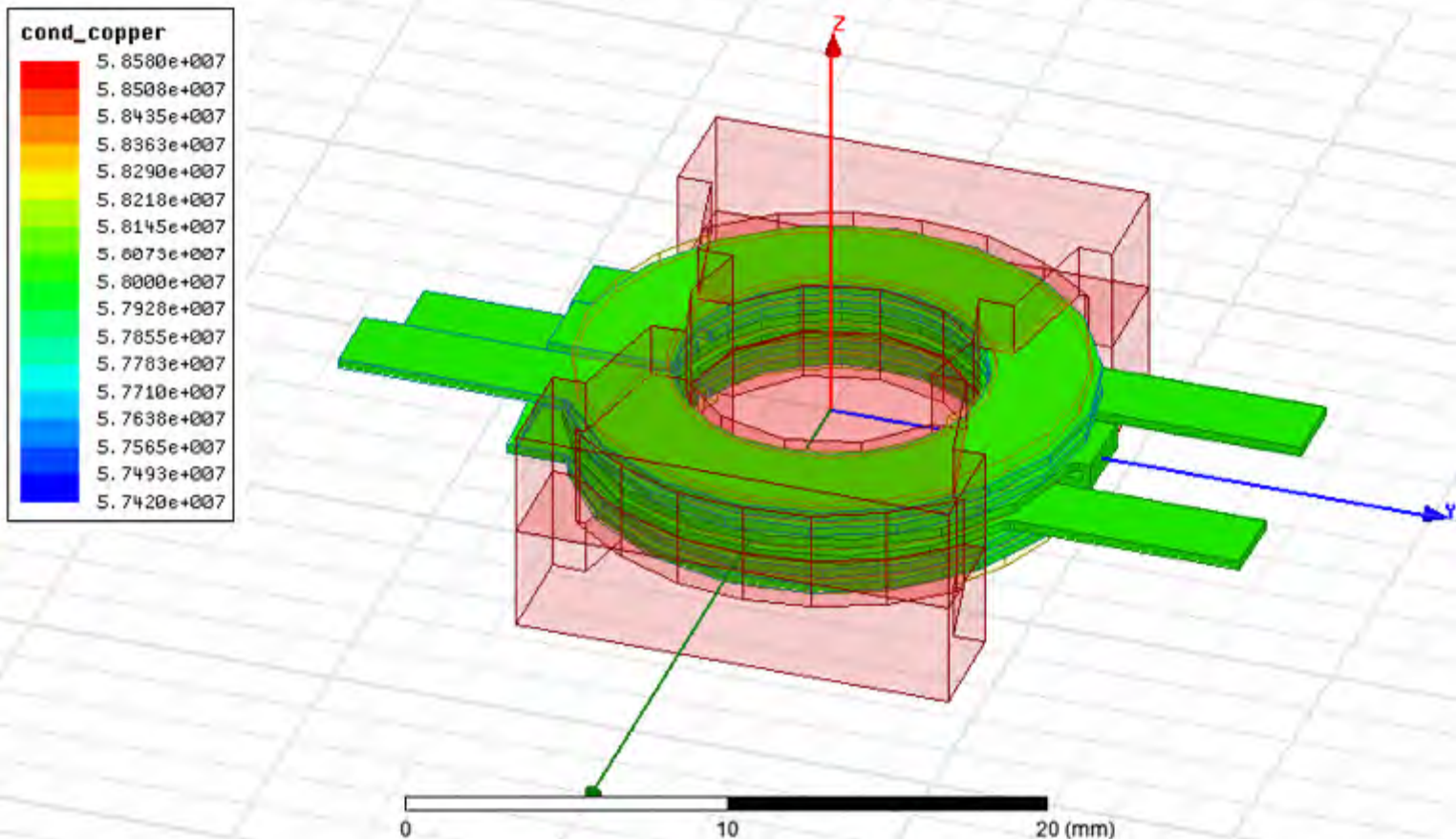
Properties of the Material

Name	Type	Value	Units
Relative Permittivity	Simple	12	
Relative Permeability	Simple	$pwl(\$perm, Freq)$	
Bulk Conductivity	Simple	0.5	siemens/m
Dielectric Loss Tangent	Simple	0	
Magnetic Loss Tangent	Simple	$pwl(\$losstan, Freq)$	
Core Loss Type	None		w/m ³
Mass Density	Simple	4600	kg/m ³

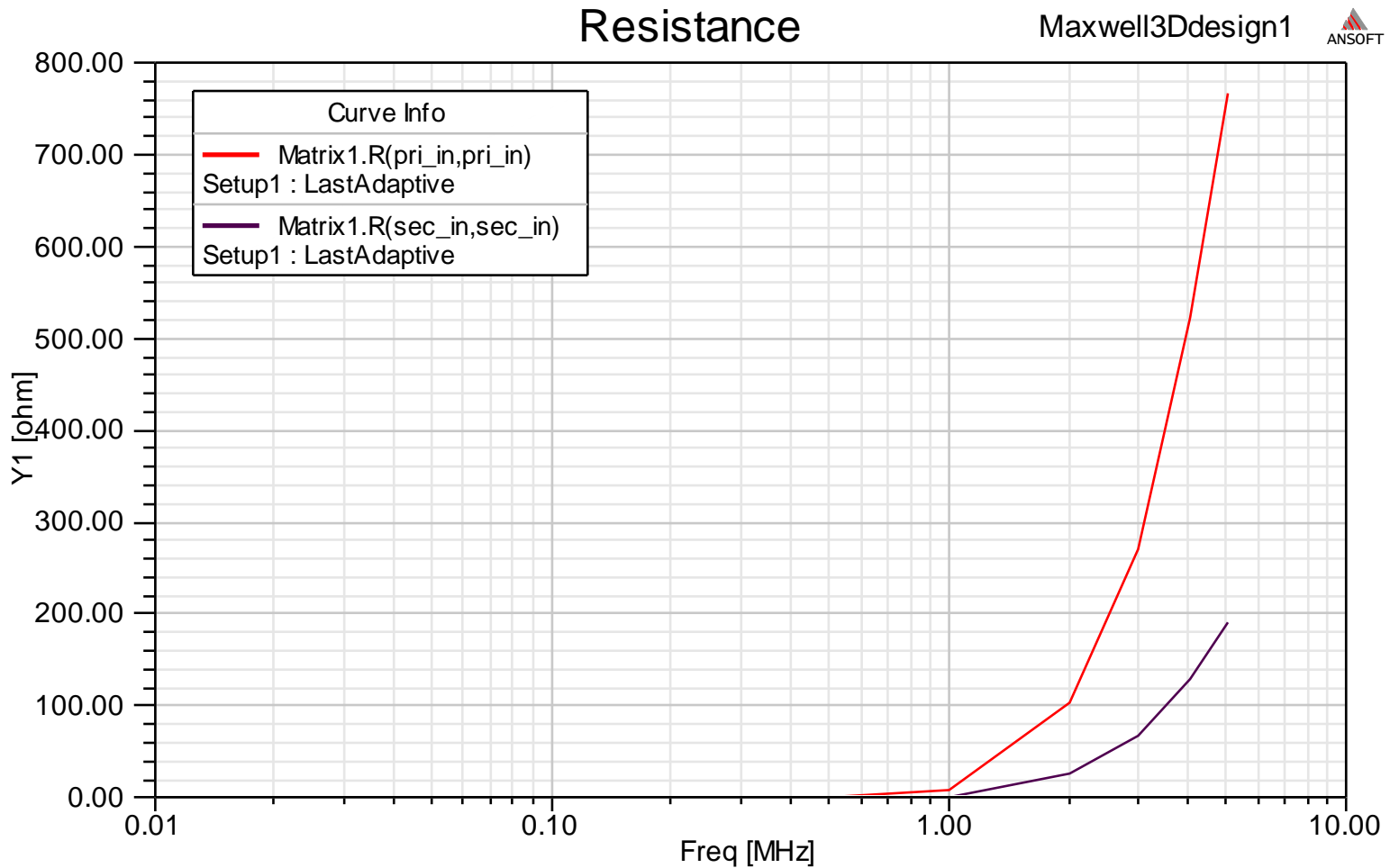


Initial Conductivity at 100kHz, 22 deg C

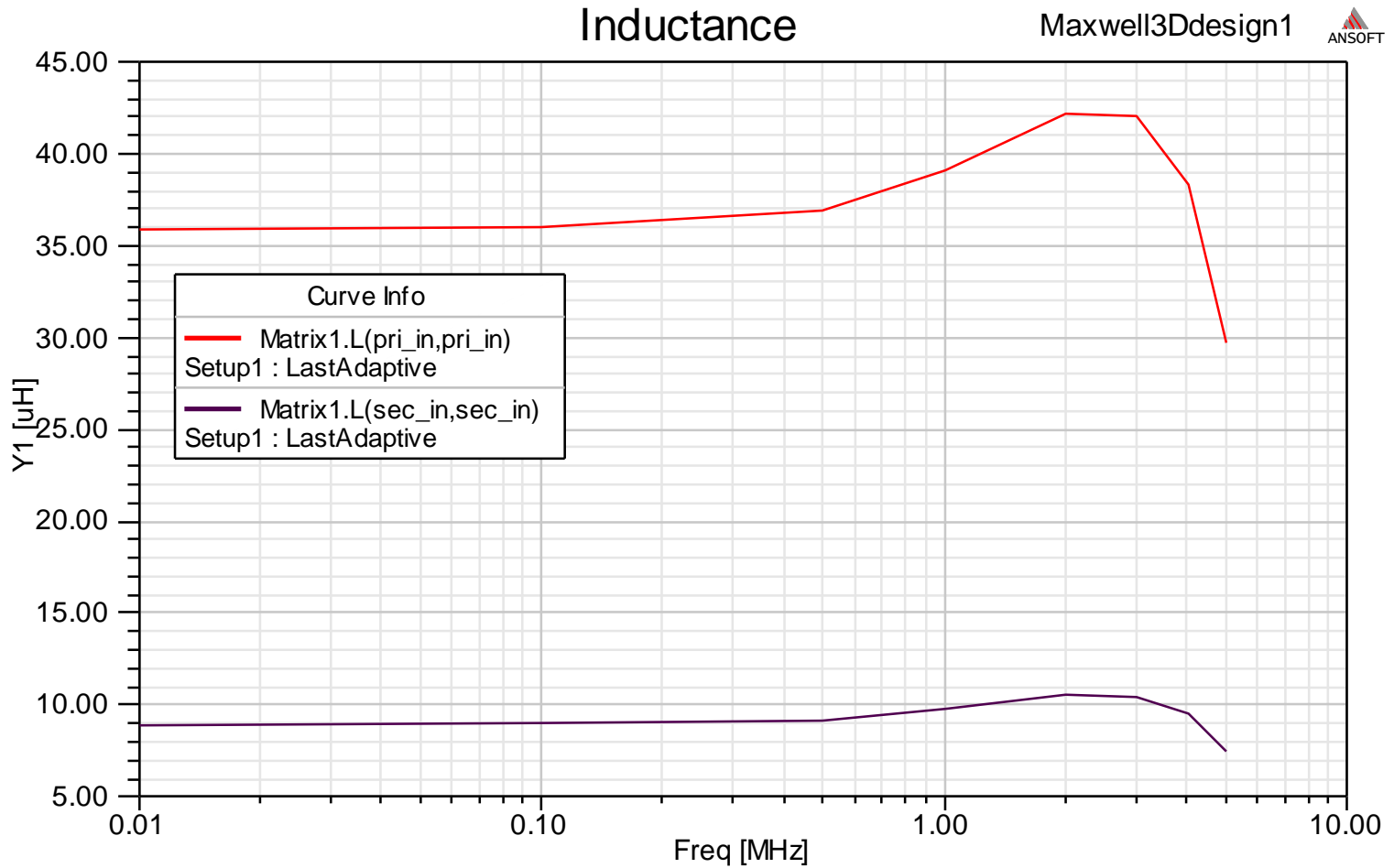
- Conductivity = $5.8e^7$ (S/m)
- Conductivity is constant throughout winding



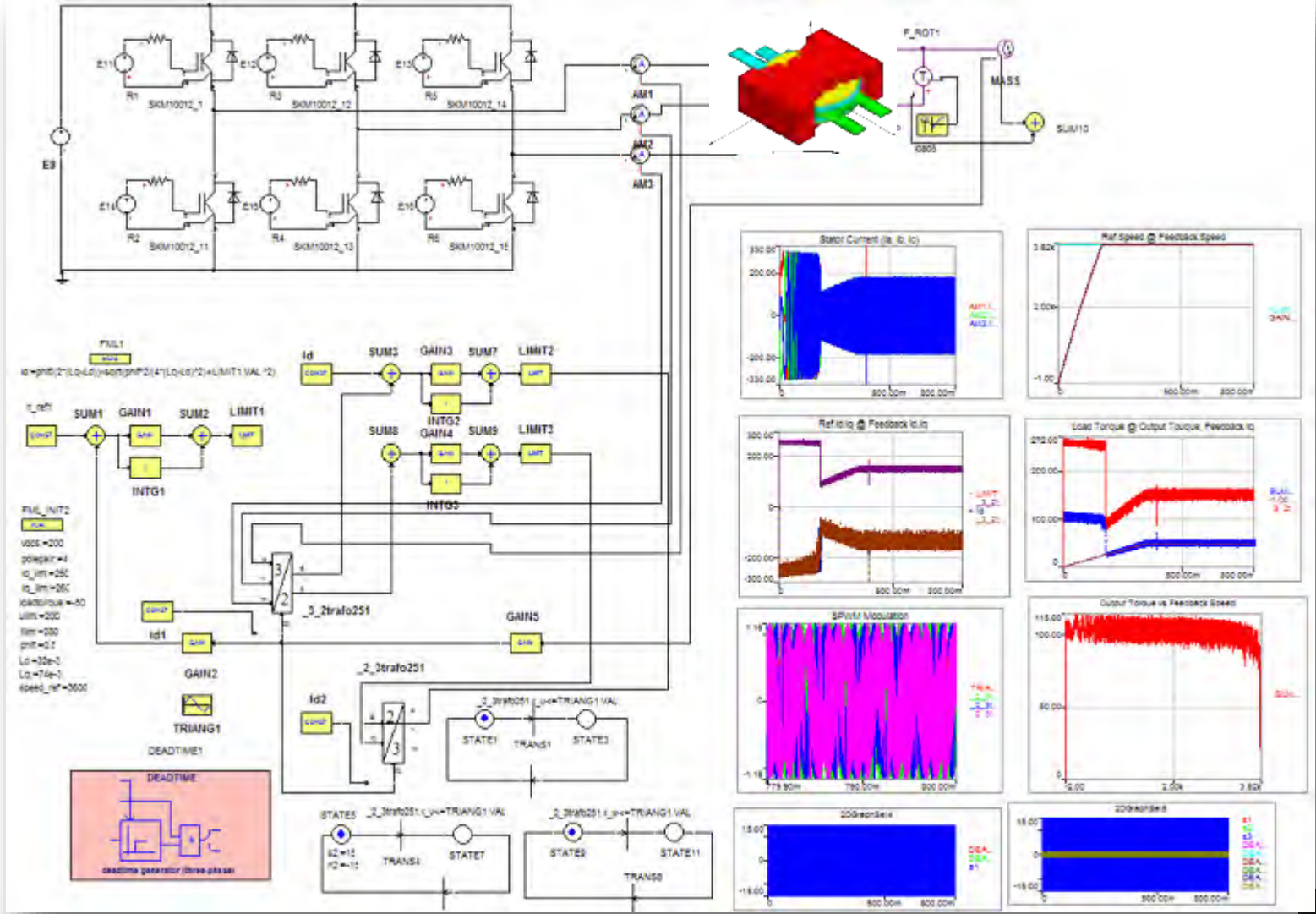
Simulated Resistance



Simulated Inductance



ANSYS System-level Simulation Example



开关器件物理原型建模

专业IGBT开关器件物理原型建模工具，可生成高精度的IGBT模型

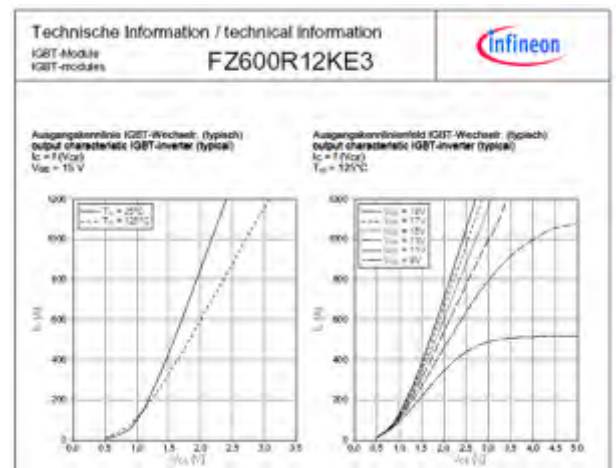
- 输入参数
- 高级动态模型：IGBT建模

数据	$V_{ce_{nom}}$, $I_{c_{nom}}$, $T_{j_{nom}}$, $V_{ce_{sat}}$, $V_{ge_{on-off}}$, C_{in} , C_r , $R_{g_{int}}$, $R_{cc_{ee}}$, L_{tot} , L_{ext} , $R_{g_{on-off}}$, $C_{ge_{ext}}$, C_{load} .
Sheetscan曲线	$I_c(V_{ge})$, $I_c(V_{ce})$, $I_f(V_f)$, Thermal impedance.
动态、能量参数	E_{on-off} , t_{on-off} , E_{rr} , Q_{rr} , Flux, C_{os} , V_{os} , T_{dG} , T_{rG} , T_{sG} , T_{fG} , T_{dI} , T_{rI} , T_{sI} , T_{fI} , T_{dV} , T_{rV} , T_{sV} , T_{fV} .

开关器件物理原型建模



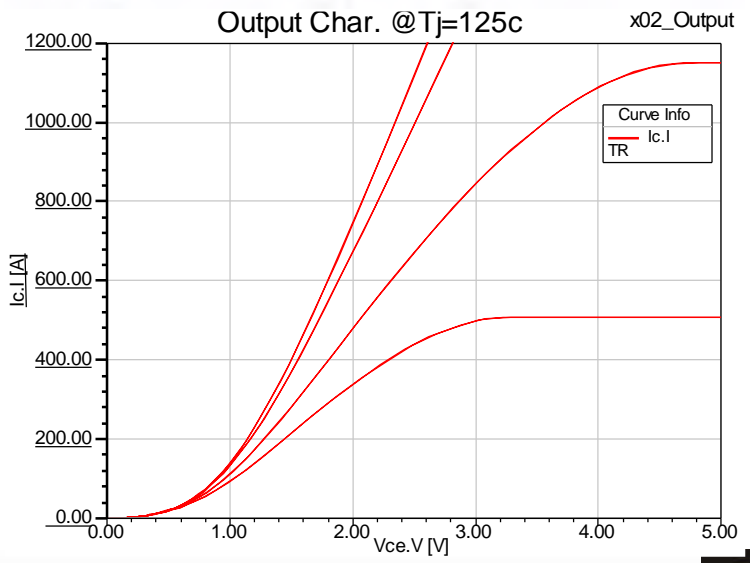
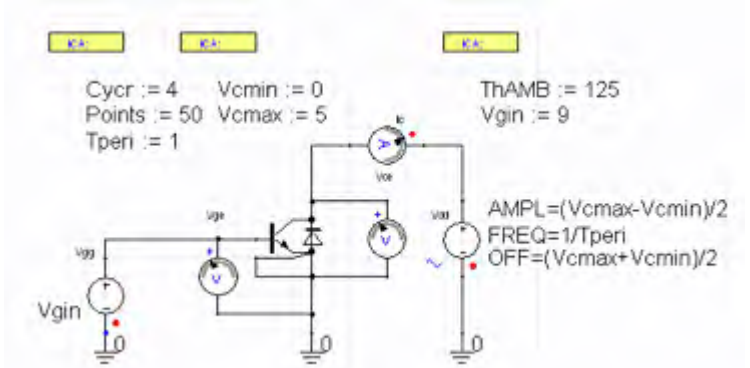
Infineon : FZ600R12KE3



数据手册



参数提取工具



输出特性曲线 Vce-Ic



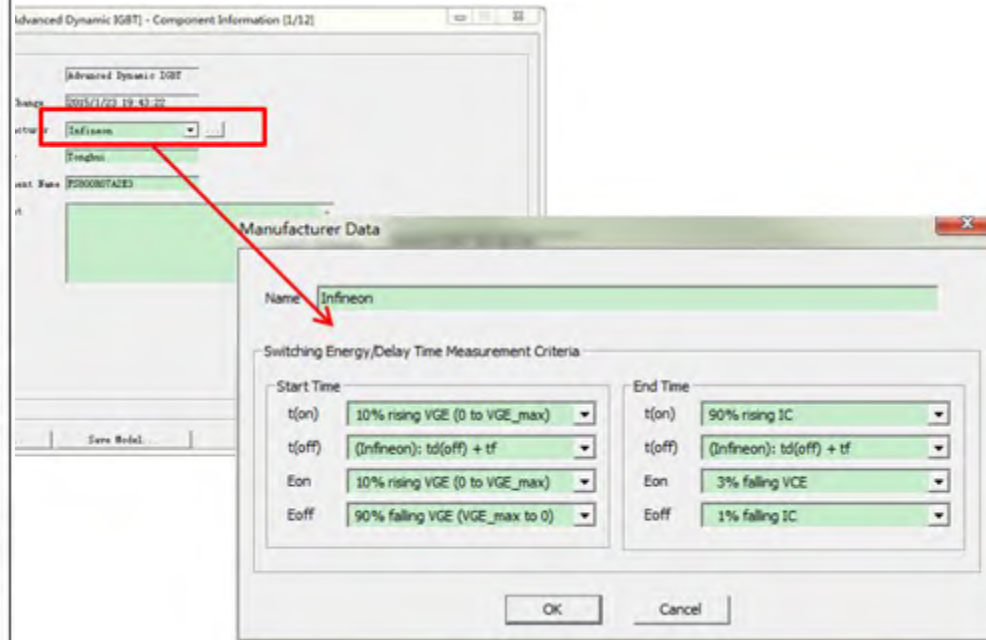
高级动态模型建模——判定标准

Höchstzulässige Werte / Maximum Rated Values

Kollektor-Emitter-Spannung Collector-emitter voltage	$T_{vj} = 25^{\circ}\text{C}$	V_{CE0}	850	V
Implementierter Kollektor-Strom Implemented collector current		I_{C0}	800	A
Kollektor-Dauergleichstrom Continuous DC collector current	$T_F = 75^{\circ}\text{C}, T_{vj} = 175^{\circ}\text{C}$ $T_F = 25^{\circ}\text{C}, T_{vj} = 175^{\circ}\text{C}$	$I_{C,cont}$ $I_{C,cont}$	550 700	A A
Periodischer Kollektor-Spitzenstrom Repetitive peak collector current	$t_p = 1 \text{ ms}$	$I_{C,peak}$	1000	A
Gesamt-Verlustleistung Total power dissipation	$T_F = 25^{\circ}\text{C}, T_{vj} = 175^{\circ}\text{C}$	P_{tot}	1500	W
Gate-Emitter-Spitzenspannung Gate-emitter peak voltage		V_{GE0}	+/-20	V

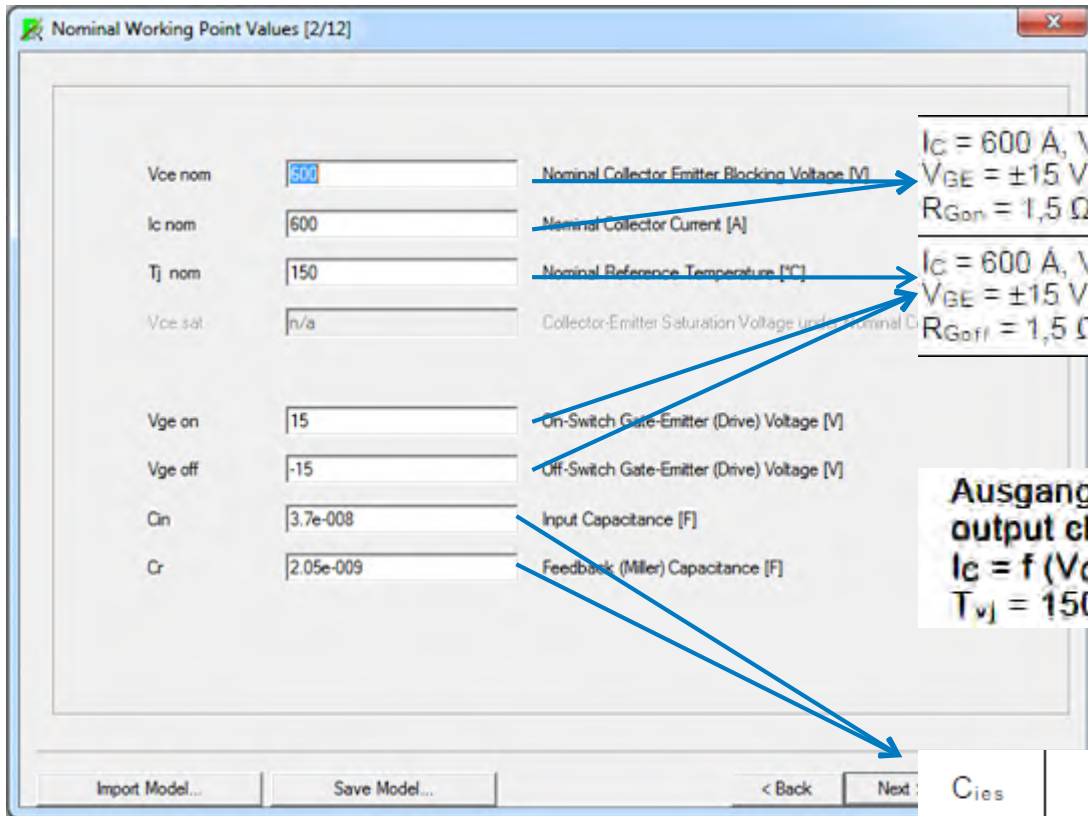
Charakteristische Werte / Characteristic Values

			min	typ	max
Kollektor-Emitter-Sättigungsspannung Collector-emitter saturation voltage	$I_C = 550 \text{ A}, V_{GE} = 15 \text{ V}$	$T_{vj} = 25^{\circ}\text{C}$		1,30	1,80
	$I_C = 550 \text{ A}, V_{GE} = 15 \text{ V}$	$T_{vj} = 125^{\circ}\text{C}$		1,35	
	$I_C = 550 \text{ A}, V_{GE} = 15 \text{ V}$	$T_{vj} = 150^{\circ}\text{C}$		1,40	
Gate-Schwellenspannung Gate threshold voltage	$I_C = 13,0 \text{ mA}, V_{CE} = V_{GE}, T_{vj} = 25^{\circ}\text{C}$		$V_{GE(th)}$	4,9	5,8
Gateladung Gate charge	$V_{GE} = -10 \text{ V} \dots +10 \text{ V}$		Q_{GE}	8,00	μC
Innere Gatewiderstand Internal gate resistor	$T_{vj} = 25^{\circ}\text{C}$		$R_{GE(int)}$	0,5	Ω
Eingangskapazität Input capacitance	$f = 1 \text{ MHz}, T_{vj} = 25^{\circ}\text{C}, V_{CE} = 25 \text{ V}, V_{GE} = 0 \text{ V}$		C_{in}	52,0	nF
Rückwirkungskapazität Reverse transfer capacitance	$f = 1 \text{ MHz}, T_{vj} = 25^{\circ}\text{C}, V_{CE} = 25 \text{ V}, V_{GE} = 0 \text{ V}$		C_{tr}	1,50	nF
Kollektor-Emitter-Reststrom Collector-emitter cut-off current	$V_{CE} = 850 \text{ V}, V_{GE} = 0 \text{ V}, T_{vj} = 25^{\circ}\text{C}$		$I_{CE(s)}$		5,0
Gate-Emitter-Reststrom Gate-emitter leakage current	$V_{CE} = 0 \text{ V}, V_{GE} = 20 \text{ V}, T_{vj} = 25^{\circ}\text{C}$		$I_{GE(s)}$		400
Einschaltverzögerungszeit, induktive Last Turn-on delay time, inductive load	$I_C = 550 \text{ A}, V_{CE} = 300 \text{ V}$ $V_{GE} = \pm 15 \text{ V}$ $R_{GE(int)} = 1,8 \Omega$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$ $T_{vj} = 150^{\circ}\text{C}$		$t_{d(on)}$	0,12 0,12 0,13
					μs μs μs
Anstiegszeit, induktive Last Rise time, inductive load	$I_C = 550 \text{ A}, V_{CE} = 300 \text{ V}$ $V_{GE} = \pm 15 \text{ V}$ $R_{GE(int)} = 1,8 \Omega$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$ $T_{vj} = 150^{\circ}\text{C}$		t_r	0,10 0,10 0,10
					μs μs μs
Abschaltverzögerungszeit, induktive Last Turn-off delay time, inductive load	$I_C = 550 \text{ A}, V_{CE} = 300 \text{ V}$ $V_{GE} = \pm 15 \text{ V}$ $R_{GE(int)} = 0,75 \Omega$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$ $T_{vj} = 150^{\circ}\text{C}$		$t_{d(off)}$	0,51 0,53 0,55
					μs μs μs
Fallzeit, induktive Last Fall time, inductive load	$I_C = 550 \text{ A}, V_{CE} = 300 \text{ V}$ $V_{GE} = \pm 15 \text{ V}$ $R_{GE(int)} = 0,75 \Omega$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$ $T_{vj} = 150^{\circ}\text{C}$		t_f	0,04 0,06 0,07
					μs μs μs
Einschaltverlustenergie pro Puls Turn-on energy loss per pulse	$I_C = 550 \text{ A}, V_{CE} = 300 \text{ V}, L_{ij} = 20 \text{ nH}$ $V_{GE} = \pm 15 \text{ V}, d_{i(on)} = 5500 \text{ A}/\mu\text{s} (T_{vj} = 150^{\circ}\text{C})$ $R_{GE(int)} = 1,8 \Omega$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$ $T_{vj} = 150^{\circ}\text{C}$		E_{on}	10,5 12,0 12,5
					mJ mJ mJ
Abschaltverlustenergie pro Puls Turn-off energy loss per pulse	$I_C = 550 \text{ A}, V_{CE} = 300 \text{ V}, L_{ij} = 20 \text{ nH}$ $V_{GE} = \pm 15 \text{ V}, d_{i(off)} = 2700 \text{ V}/\mu\text{s} (T_{vj} = 150^{\circ}\text{C})$ $R_{GE(int)} = 1,8 \Omega$	$T_{vj} = 25^{\circ}\text{C}$ $T_{vj} = 125^{\circ}\text{C}$ $T_{vj} = 150^{\circ}\text{C}$		E_{off}	21,0 25,0 26,0
					mJ mJ mJ



数据手册

高级动态模型建模——Nom工作点参数

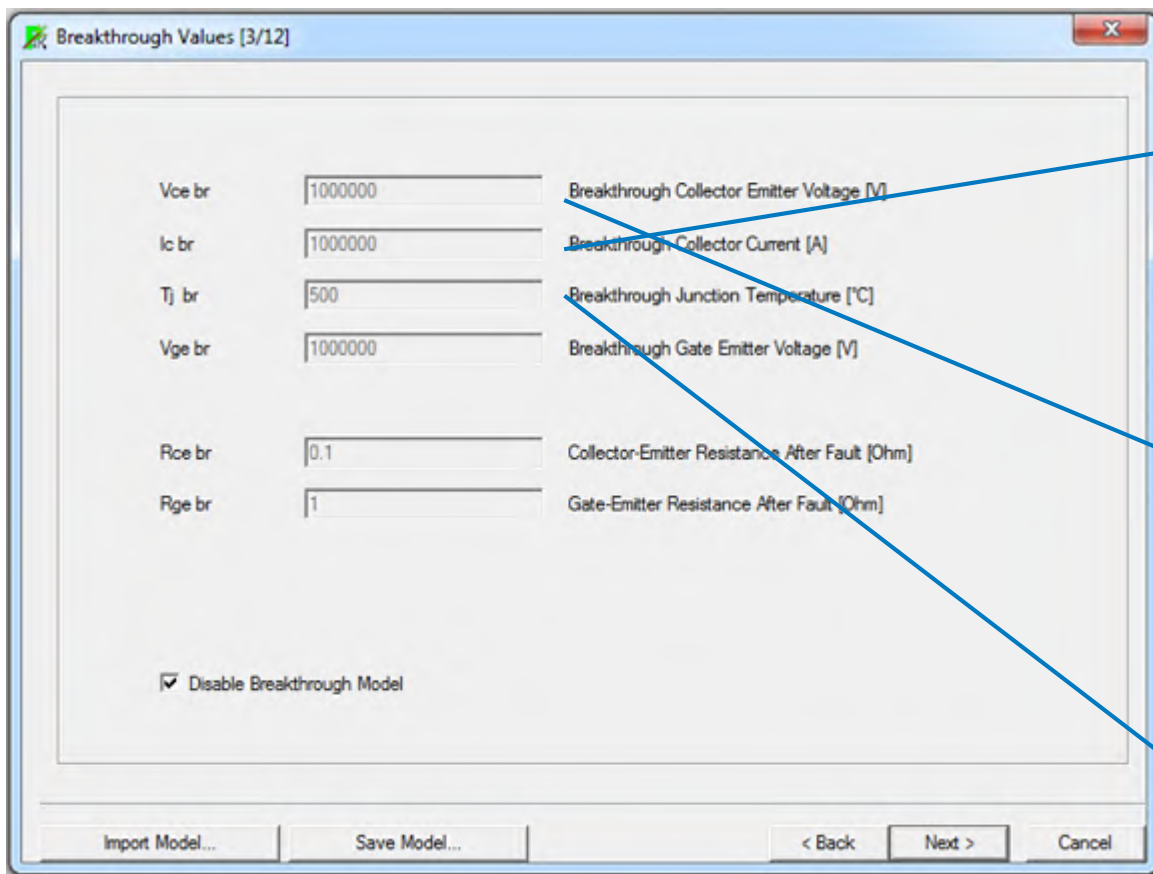


$I_C = 600 \text{ A}$, $V_{CE} = 600 \text{ V}$, $L_S = 35 \text{ nH}$ $V_{GE} = \pm 15 \text{ V}$, $di/dt = 5100 \text{ A}/\mu\text{s}$ ($T_{vj} = 150^\circ\text{C}$) $R_{Gon} = 1,5 \Omega$	$T_{vj} = 25^\circ\text{C}$ $T_{vj} = 125^\circ\text{C}$ $T_{vj} = 150^\circ\text{C}$	E_{on}
$I_C = 600 \text{ A}$, $V_{CE} = 600 \text{ V}$, $L_S = 35 \text{ nH}$ $V_{GE} = \pm 15 \text{ V}$, $du/dt = 3700 \text{ V}/\mu\text{s}$ ($T_{vj} = 150^\circ\text{C}$) $R_{Goff} = 1,5 \Omega$	$T_{vj} = 25^\circ\text{C}$ $T_{vj} = 125^\circ\text{C}$ $T_{vj} = 150^\circ\text{C}$	E_{off}

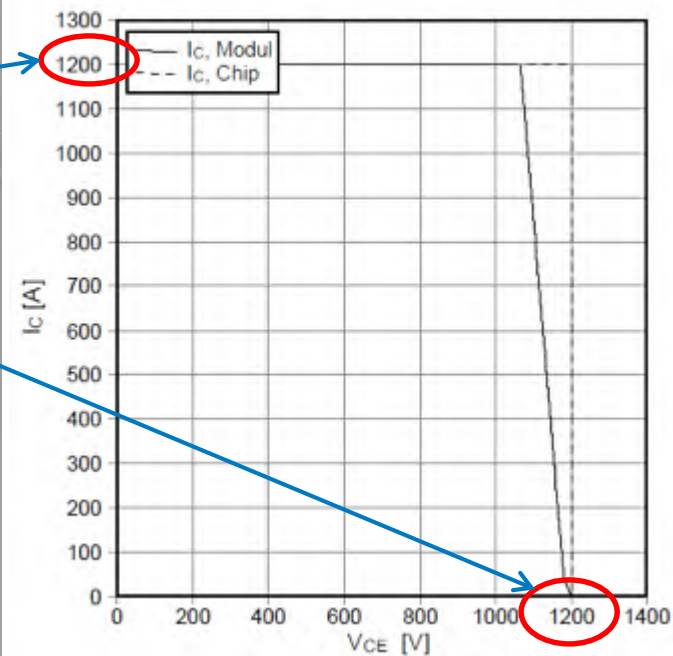
Ausgangskennlinienfeld IGBT-Wechselr. (typisch)
output characteristic IGBT-inverter (typical)
 $I_C = f(V_{CE})$
 $T_{vj} = 150^\circ\text{C}$

C_{ies}		37,0	nF
C_{res}		2,05	nF

高级动态模型建模——Breakdown参数

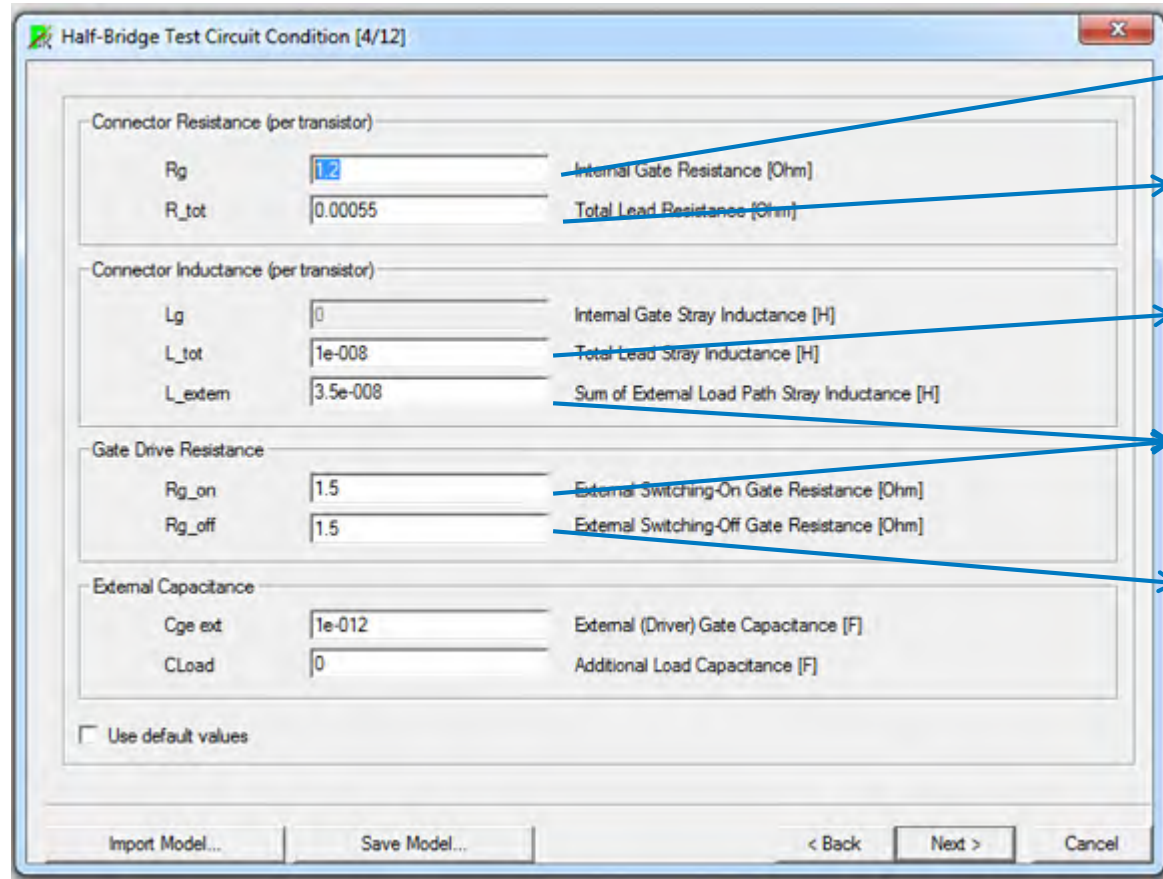


$V_{GE} = \pm 15\text{ V}$, $R_{Goff} = 1.5\ \Omega$, $T_{vj} = 150^\circ\text{C}$



$T_{vj\ max}$		175	$^\circ\text{C}$
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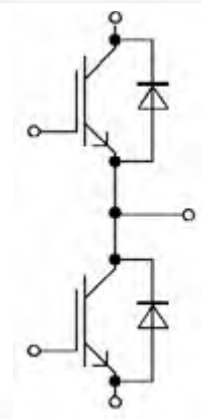
高级动态模型建模——测试电路参数



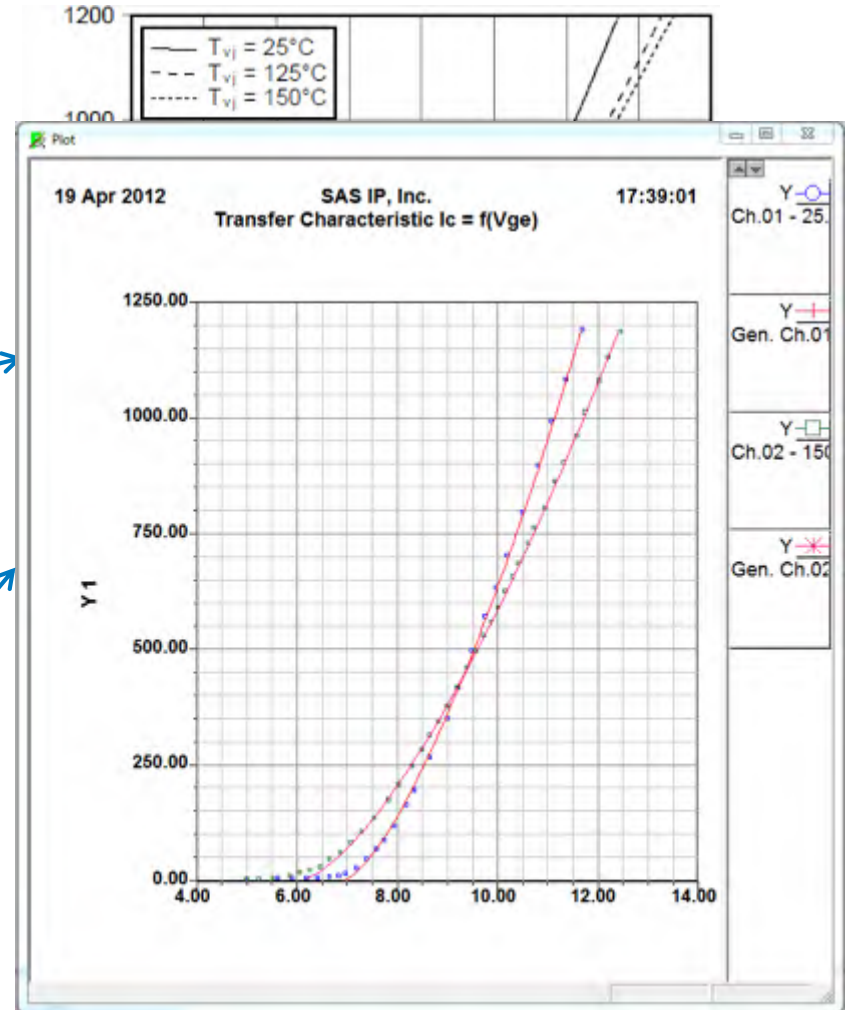
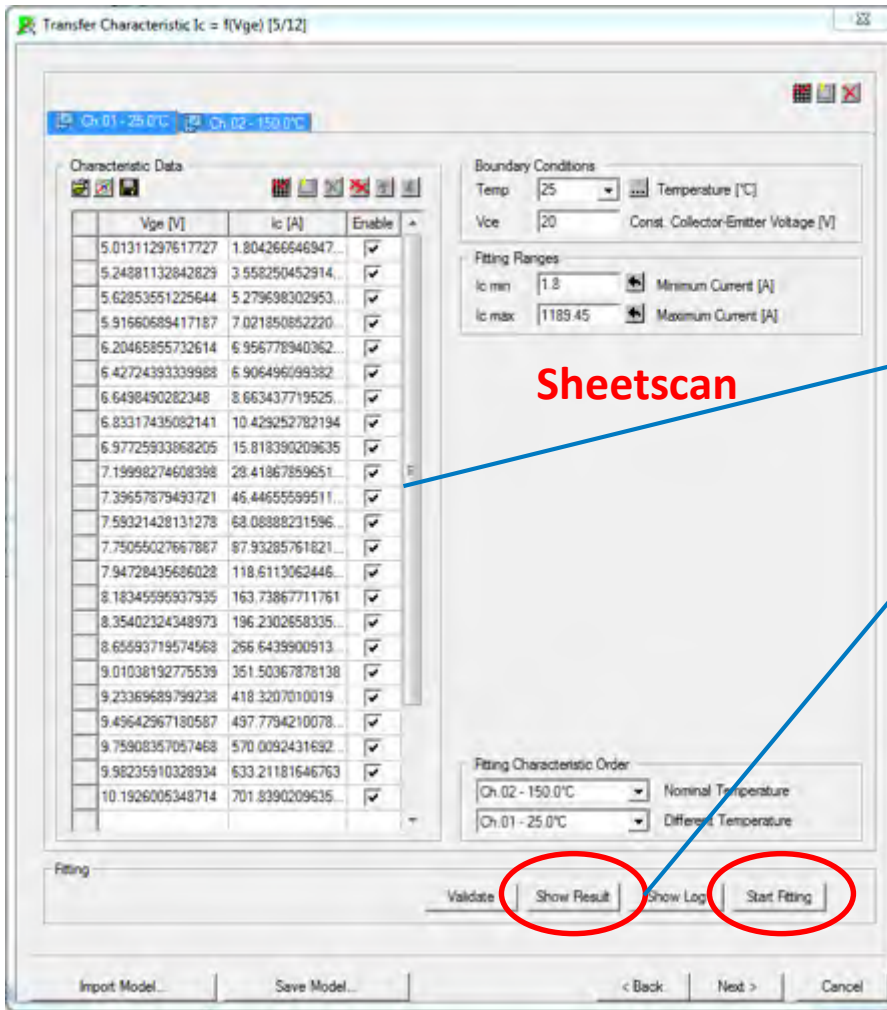
R_{Gint}	1,2	Ω
$R_{CC'-EE'}$	1,10	m Ω
L_{sCE}	20	nH

$I_C = 600 \text{ A}$, $V_{CE} = 600 \text{ V}$, $L_S = 35 \text{ nH}$
 $V_{GE} = \pm 15 \text{ V}$, $di/dt = 5100 \text{ A}/\mu\text{s}$ ($T_{vj} = 150^\circ\text{C}$)
 $R_{Goff} = 1,5 \Omega$

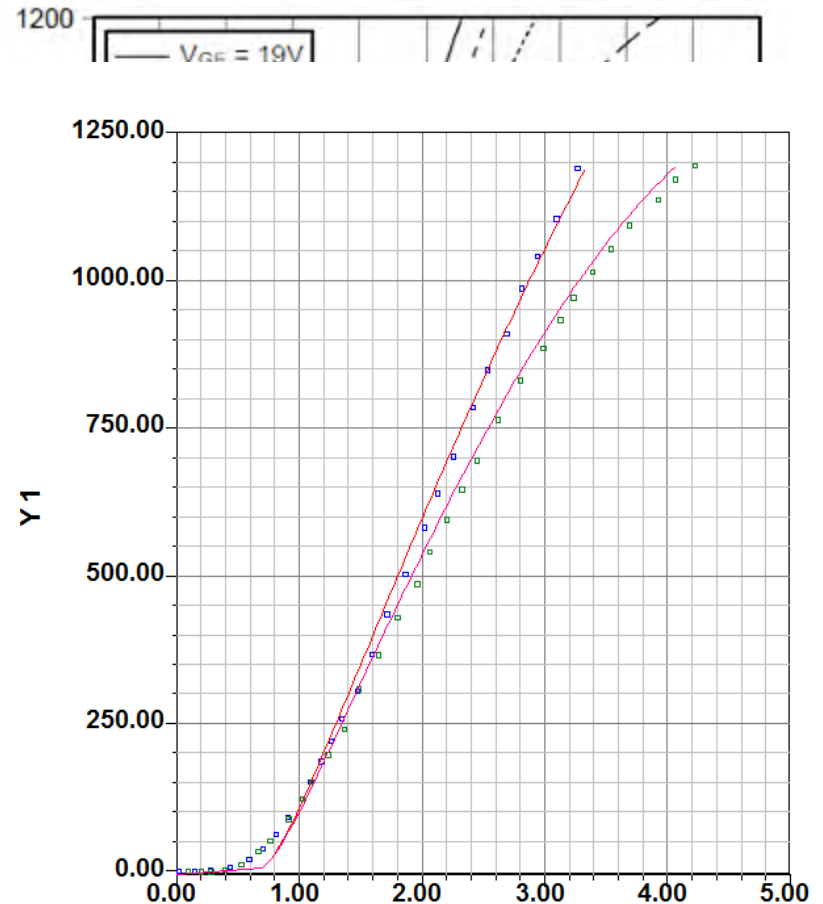
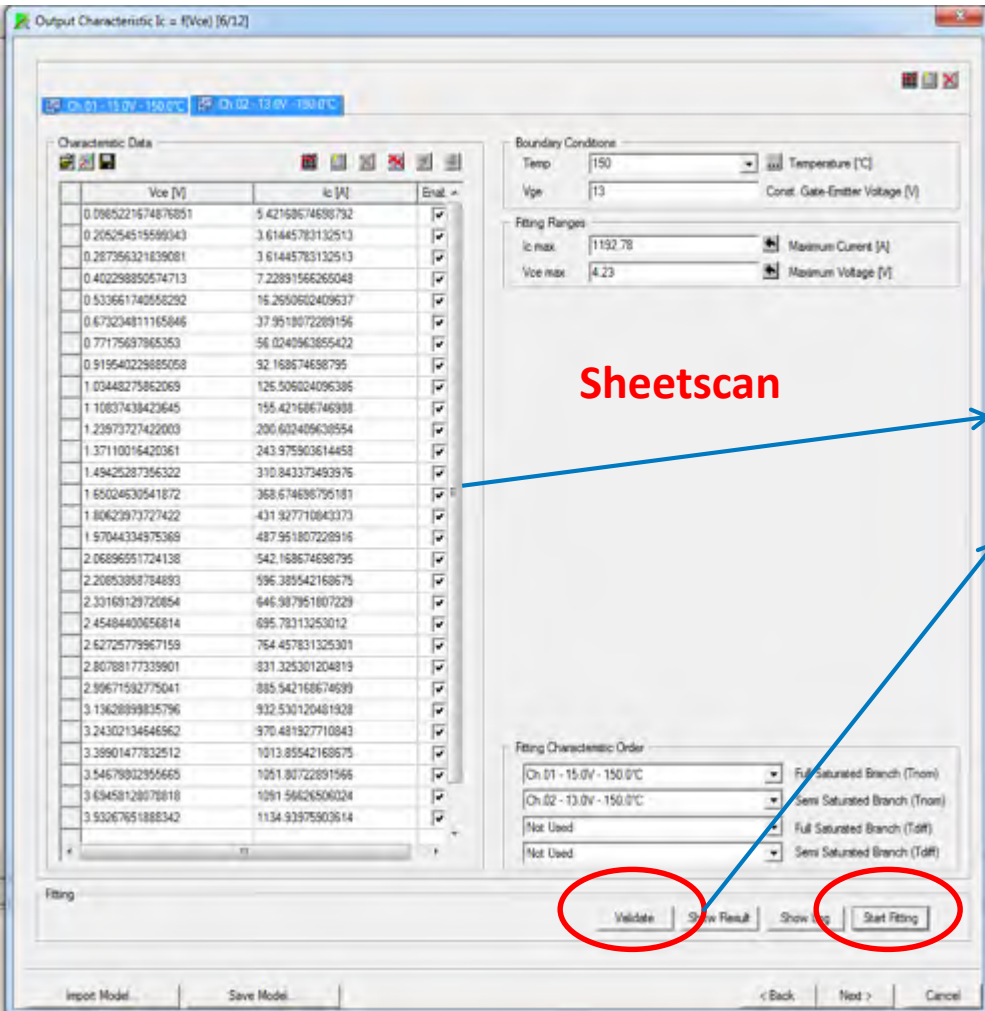
$I_C = 600 \text{ A}$, $V_{CE} = 600 \text{ V}$, $L_S = 35 \text{ nH}$
 $V_{GE} = \pm 15 \text{ V}$, $du/dt = 3700 \text{ V}/\mu\text{s}$ ($T_{vj} = 150^\circ\text{C}$)
 $R_{Gon} = 1,5 \Omega$



高级动态模型建模——Transfer参数



高级动态模型建模——Output曲线



高级动态模型建模——二极管Forward

Freewheeling Diode Characteristic If = f(V) [7/12]

Ch.01 - 150.0°C Ch.02 - 25.0°C

Characteristic Data

Vf [V]	If [A]	Enable
0.53902959481145	4.02641749231634	<input checked="" type="checkbox"/>
0.6098969163932	18.5594999369482	<input checked="" type="checkbox"/>
0.6650324284361	34.8906730229533	<input checked="" type="checkbox"/>
0.7319949855227	58.470584453637	<input checked="" type="checkbox"/>
0.7871542347358	82.0415944455021	<input checked="" type="checkbox"/>
0.8423075496564	103.802645210902	<input checked="" type="checkbox"/>
0.9092819753281	131.002475094516	<input checked="" type="checkbox"/>
0.9644412245412	154.573485086381	<input checked="" type="checkbox"/>
1.0235467782973	181.767380677449	<input checked="" type="checkbox"/>
1.10238385476808	227.075704264531	<input checked="" type="checkbox"/>
1.18907793456948	268.770043691229	<input checked="" type="checkbox"/>
1.26005800770963	317.692351438695	<input checked="" type="checkbox"/>
1.33496064822256	362.997707879504	<input checked="" type="checkbox"/>
1.40198848252722	406.487170801302	<input checked="" type="checkbox"/>
1.46508188087402	449.973666576828	<input checked="" type="checkbox"/>
1.51636603705471	491.64130168707	<input checked="" type="checkbox"/>
1.59521498211058	540.569543727082	<input checked="" type="checkbox"/>
1.6346958304177	582.228277398505	<input checked="" type="checkbox"/>
1.69384292422156	622.091887574828	<input checked="" type="checkbox"/>
1.74909712211538	674.622245190132	<input checked="" type="checkbox"/>
1.81221425763237	725.348577871518	<input checked="" type="checkbox"/>
1.85169510593949	767.007311542941	<input checked="" type="checkbox"/>
1.90296739353508	805.055028200253	<input checked="" type="checkbox"/>

Boundary Conditions
Temp: 150 Temperature [°C]

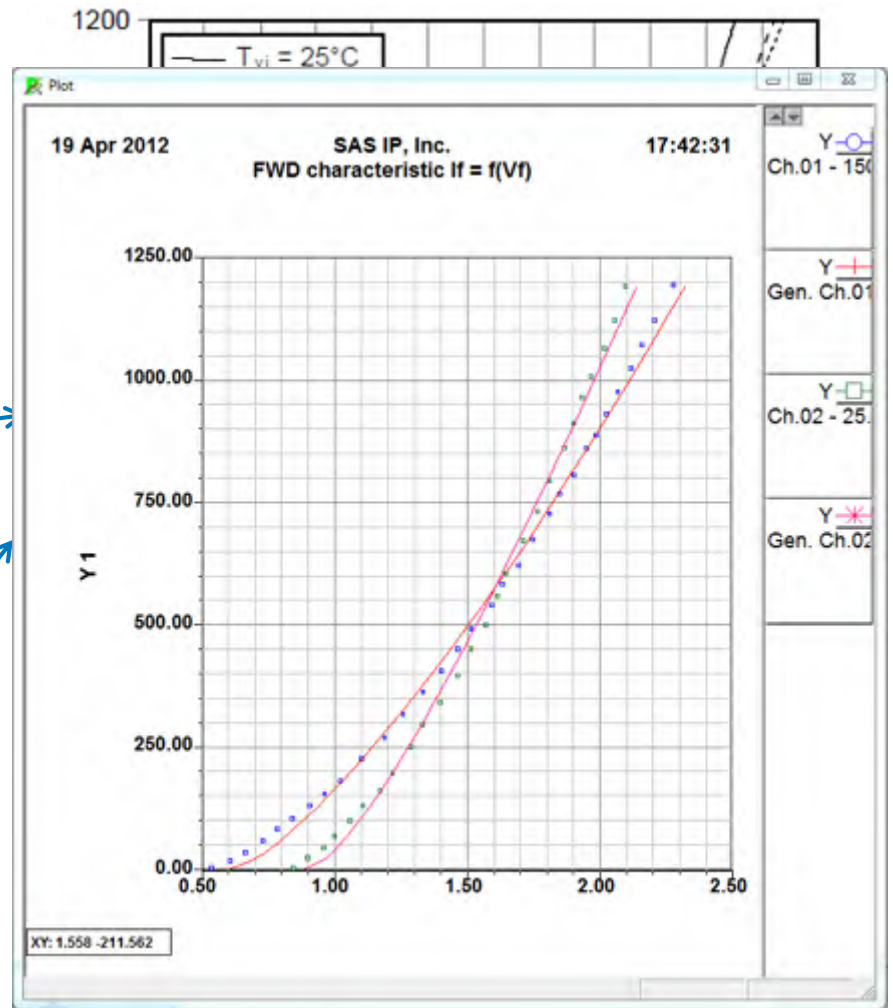
Fitting Ranges
If max: 1192.67 Maximum Current [A]
Vf max: 2.28 Maximum Voltage [V]

Fitting Characteristic Order
Ch.01 - 150.0°C Nominal Temperature
Ch.02 - 25.0°C Different Temperature

Fitting
 Disable Diode Validate **Show Result** **Show Log** **Start Fitting**

Import Model... Save Model... < Back Next > Cancel

Sheetscan



高级动态模型建模——IGBT Thermal

IGBT Thermal Model [8/12]

Use Transient Thermal Impedance

Use Fraction Coefficients

	r_i [K/W]	t_i [s]
1	0.0027	0.0006
2	0.0038	0.007
3	0.032	0.034
4	0.0025	0.51

Heatsink

Use external network

Thres: 1e-005 Thermal Resistance [K/W]

Chck: 1000 Thermal Capacitance [Ws/K]

Thermal Network Topology

Continued Fraction

Model Thermal Output: Celsius

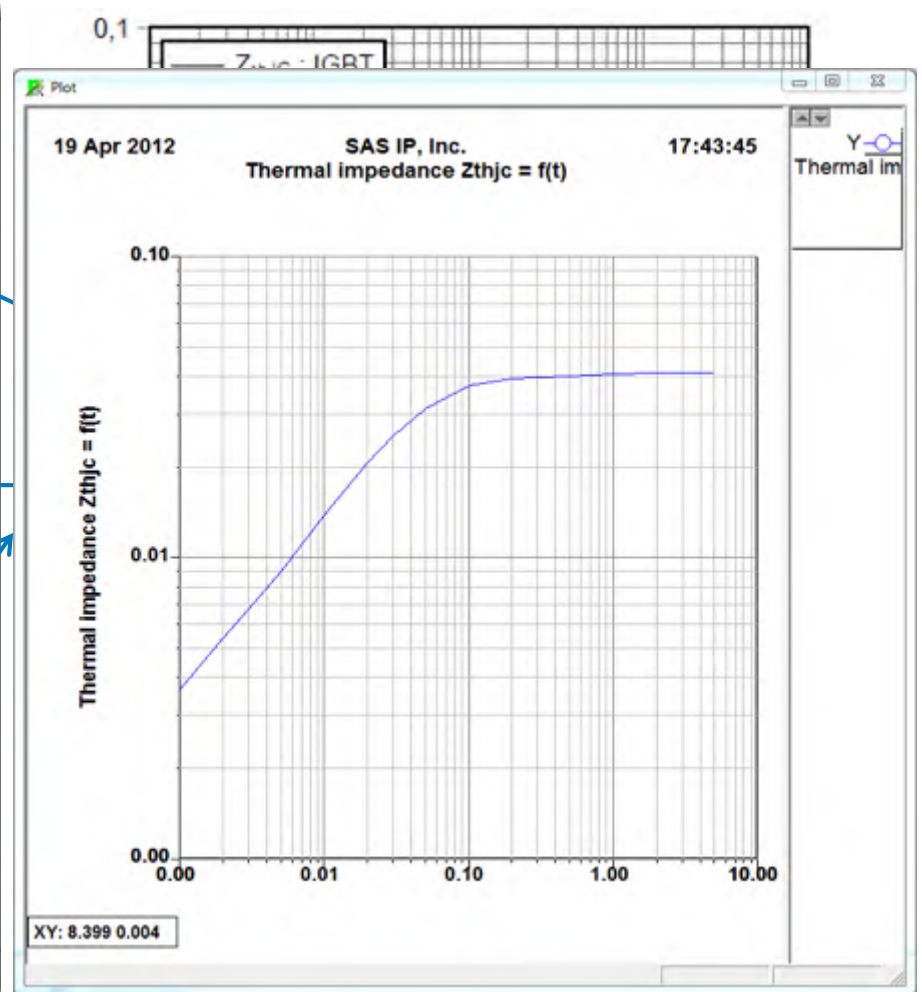
Fitting

Isothermal

Show Result Show Log Start Fitting

Import Model... Save Model... < Back Next > Cancel

Sheetscan



高级动态模型建模——Diode Thermal

Freewheeling Diode Thermal Model [9/12]

Use Transient Thermal Impedance

Use Fraction Coefficients

	n [K/W]	t_i [s]
1	0.006	0.0003
2	0.007	0.0056
3	0.049	0.032
4	0.005	0.71

Heatsink

Use external network

Thermal Resistance [K/W]

Thermal Capacitance [Ws/K]

Thermal Network Topology

Continued Fraction

Model Thermal Output: Celsius

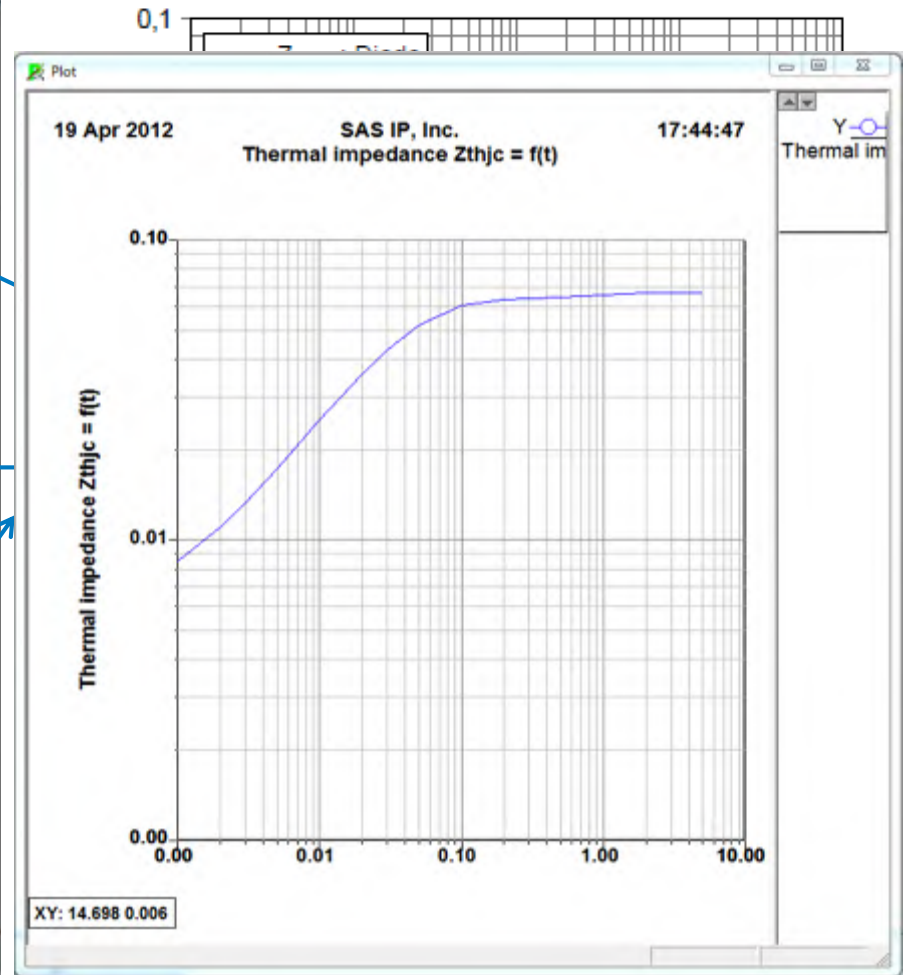
Fitting

Isothermal

Show Result Show Log Start Fitting

Import Model... Save Model... < Back Next > Cancel

Sheetscan



高级动态模型建模——定义抽取工况

Dynamic Model Input [10/12]

	Tj [°C]	Voe [V]	Ic [A]	Eon [mV]	Wei... Eon	Eoff [mV]	Wei... Eoff	Ton [ns]	Wei... Ton	Toff [ns]	Wei... Toff	Res [%]	Ena...	Info
Nom	150	600	600	90	1	79.5	1	310	1	770	1	5	<input checked="" type="checkbox"/>	Nominal Values
dT	25	600	600	62.5	1	47	1	250	1	550	1	5	<input checked="" type="checkbox"/>	Data at different Tj
nV	150	0	600	0	1	0	1	0	1	0	1	5	<input type="checkbox"/>	Data at Voe smaller than nominal Voe
pV	150	0	600	0	1	0	1	0	1	0	1	5	<input type="checkbox"/>	Data at Voe larger than nominal Voe
nI	150	600	0	0	1	0	1	0	1	0	1	5	<input type="checkbox"/>	Data at Ic smaller than nominal Ic
pI	150	600	0	0	1	0	1	0	1	0	1	5	<input type="checkbox"/>	Data at Ic larger than nominal Ic

Dynamic Parameter Extraction

Adv. Settings
 Measurement
 Show Log
 Extraction

Advanced Settings

Extraction Settings | Model & Goal Settings

Adv. Model Settings

Dynamic Behavior:

Miller Capacitances:

Feedback Capacitances:

Select Goals to Display

Goal	Display	Info
Eon	<input checked="" type="checkbox"/>	Info Eon
Eoff	<input checked="" type="checkbox"/>	Info Eoff
Ton	<input checked="" type="checkbox"/>	Info Ton
Toff	<input checked="" type="checkbox"/>	Info Toff

高级动态模型建模——抽取结果确认

Dynamic Parameter Validation [11/12]

Tj [°C]	Vce [V]	Ic [A]	Eon [mJ]	Eoff [mJ]	Ton [ns]	Toff [ns]	Enable	Eon [mJ]	Eoff [mJ]	Ton [ns]	Toff [ns]
150	600	600	90	79.5	310	770	<input checked="" type="checkbox"/>	91.67	78.84	308.7	735.1
25	600	600	62.5	47	250	550	<input checked="" type="checkbox"/>	59.67	47.15	255.3	551.9
150	0	600	0	0	0	0	<input type="checkbox"/>	0	0	0	0
150	0	600	0	0	0	0	<input type="checkbox"/>	0	0	0	0
150	600	0	0	0	0	0	<input type="checkbox"/>	0	0	0	0
150	600	0	0	0	0	0	<input type="checkbox"/>	0	0	0	0

Validation

Show Log Validate

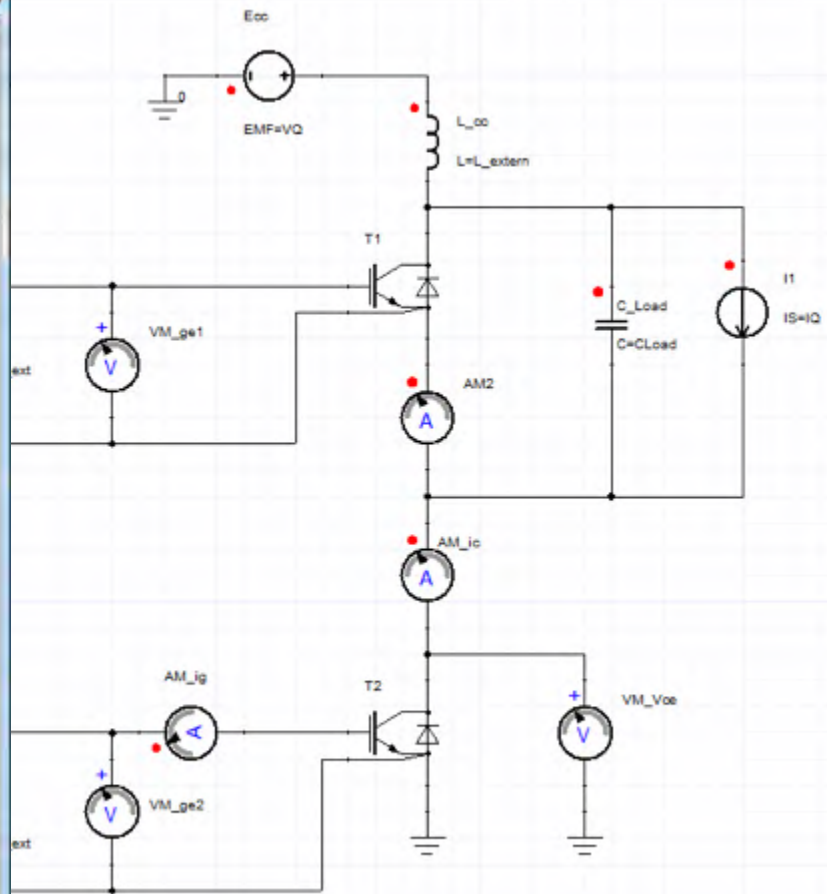
Import Model... Save Model... < Back Next > Cancel

高级动态模型建模——建模完成

Model Parameters (12/12)

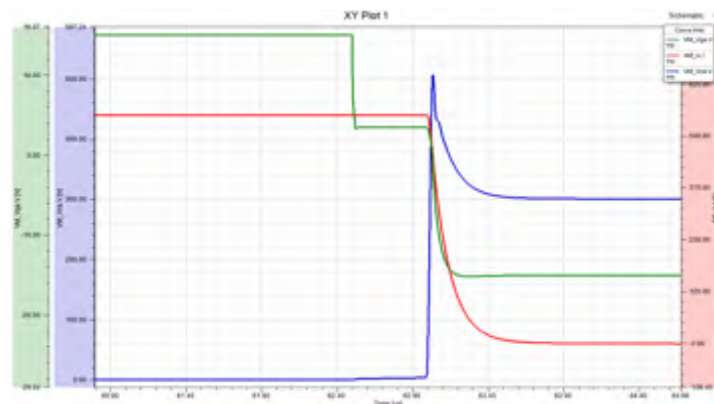
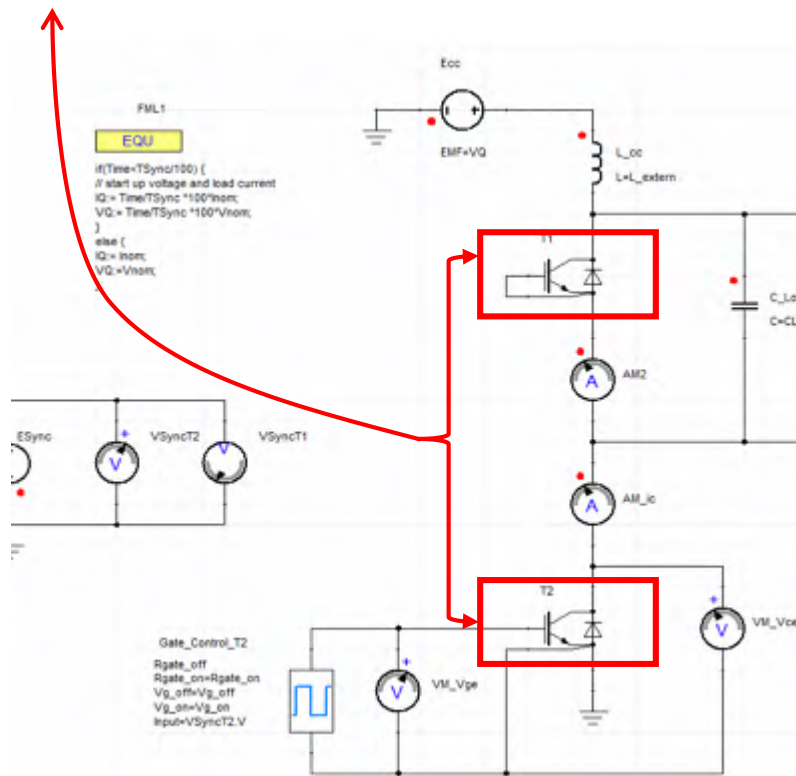
Parameter Name	Value	Failed	Parameter Info	Min value	Max value	Default
//*** Model Choice						
TYPE_IGBT	nIGBT	<input type="checkbox"/>	-2piGBT 2nIGBT	-2	2	2
TYPE_FWD	2	<input type="checkbox"/>	0:no 1:static 2:dynamic	0	2	1
TYPE_THERM	122	<input type="checkbox"/>	00k: 0:iso +1,2:dm: 0	0	212	2
TYPE_DYN	2011	<input type="checkbox"/>	0:stat 1:dm +10 me:s	0	2121	2011
TYPE_OUT	31393315	<input type="checkbox"/>	0:default 1..3i_on; +1..	0	3556323	646113
TYPE_BREAKTHROUGH	0	<input type="checkbox"/>	0:disable break thro...	0	1	0
//*** Temperature Related						
TEMPAMB	125	<input type="checkbox"/>	Ambient Temperature	-273.15	500	125
TEMPJCT0	125	<input type="checkbox"/>	Junction Temperature	-273.15	500	125
TNOM	150	<input type="checkbox"/>	Reference Temperature	-273.15	500	0
//*** Nominal Values						
VNOM	600	<input type="checkbox"/>	Nominal Collector Em...	0	1e+015	0
INOM	600	<input type="checkbox"/>	Nominal Collector Cur...	0	1e+015	0
SNOM_ON	33000000	<input type="checkbox"/>	Nominal On Switch G...	0	1000000000000	33000000
SNOM_OFF	33000000	<input type="checkbox"/>	Nominal Off Switch G...	0	1000000000000	33000000
VGAP	1.11	<input type="checkbox"/>	Band Gap Voltage	0.1	10	1.1
//*** Connectors						
LC	7e-009	<input type="checkbox"/>	Collector Connector L...	0	2	1e-008
RC	0.00055	<input type="checkbox"/>	Collector Connector R...	0	200	0
LE	7e-009	<input type="checkbox"/>	Emitter Connector In...	0	2	1e-008
RE	0	<input type="checkbox"/>	Emitter Connector R...	0	200	0
LG	0	<input type="checkbox"/>	Gate Connector Indu...	0	1	0
RIG	0.873142	<input type="checkbox"/>	Gate Connector Ref...	0	50	0.1
RAUX	0	<input type="checkbox"/>	Auxiliary Resistance	0	100	0
LAUX	0	<input type="checkbox"/>	Auxiliary Inductance	0	1	0
//*** Breakthrough Values						
VBREAK_CE	1000000	<input type="checkbox"/>	Output Voltage Break...	0	1000000000000	1000000
VBREAK_GE	1000000	<input type="checkbox"/>	Input Voltage Breakd...	0	1000000000000	1000000
IBREAK	1000000	<input type="checkbox"/>	Output Current Break...	0	1000000000000	1000000
TEMPBREAK	500	<input type="checkbox"/>	Temperature Breakdo...	0	1000	500

Select Component
 Select Component
 Motorcut - Halfbridge (2 IGBT)

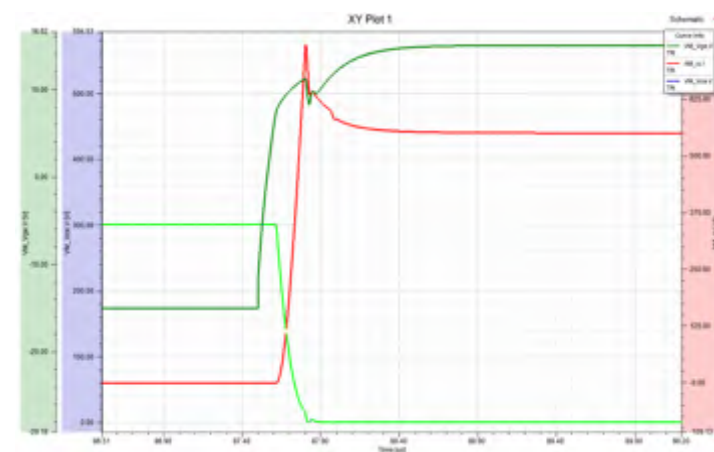


自动创建半桥测试电路

FS800R07A2E3特征化建模高级动态模型

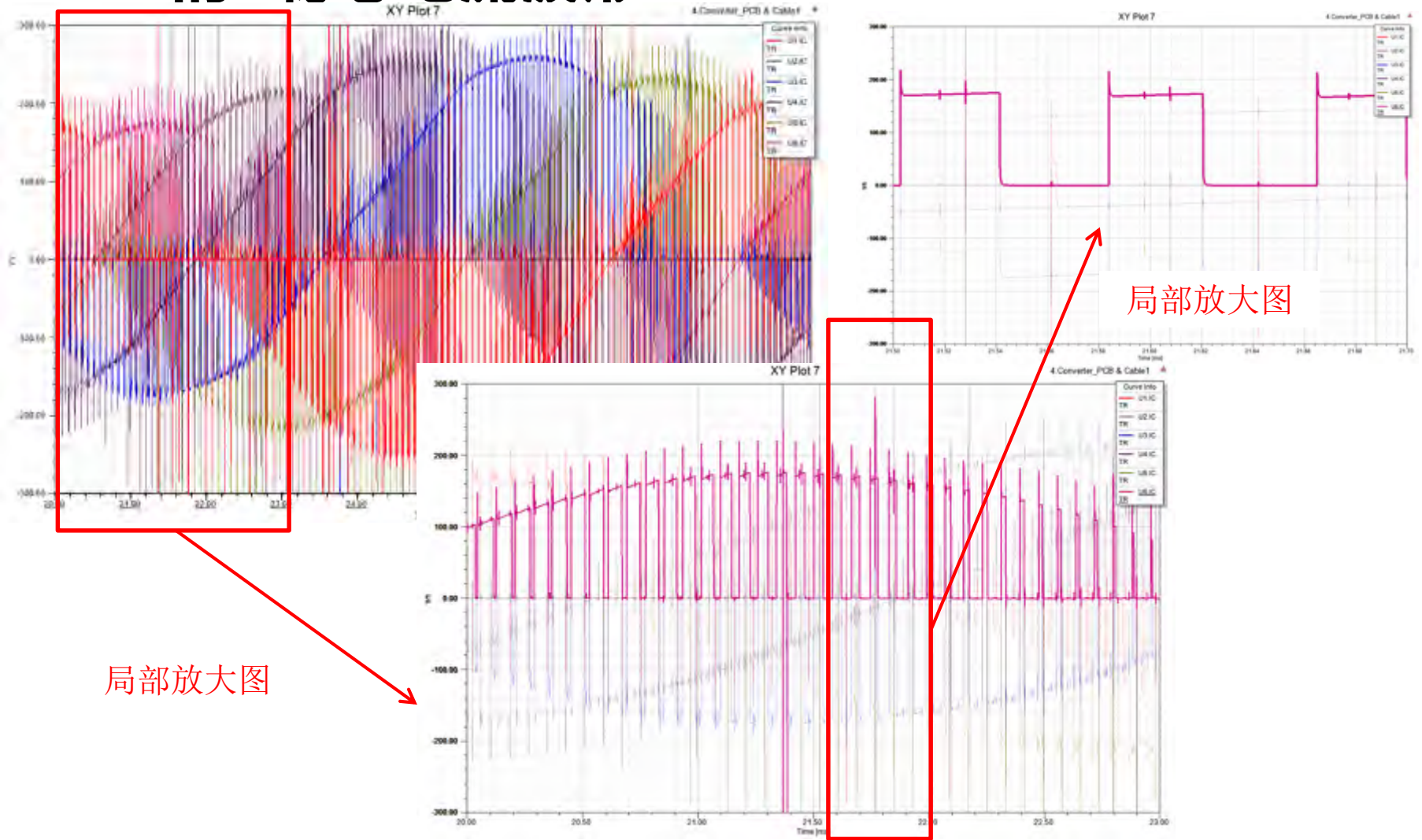


关断电压



开通电流

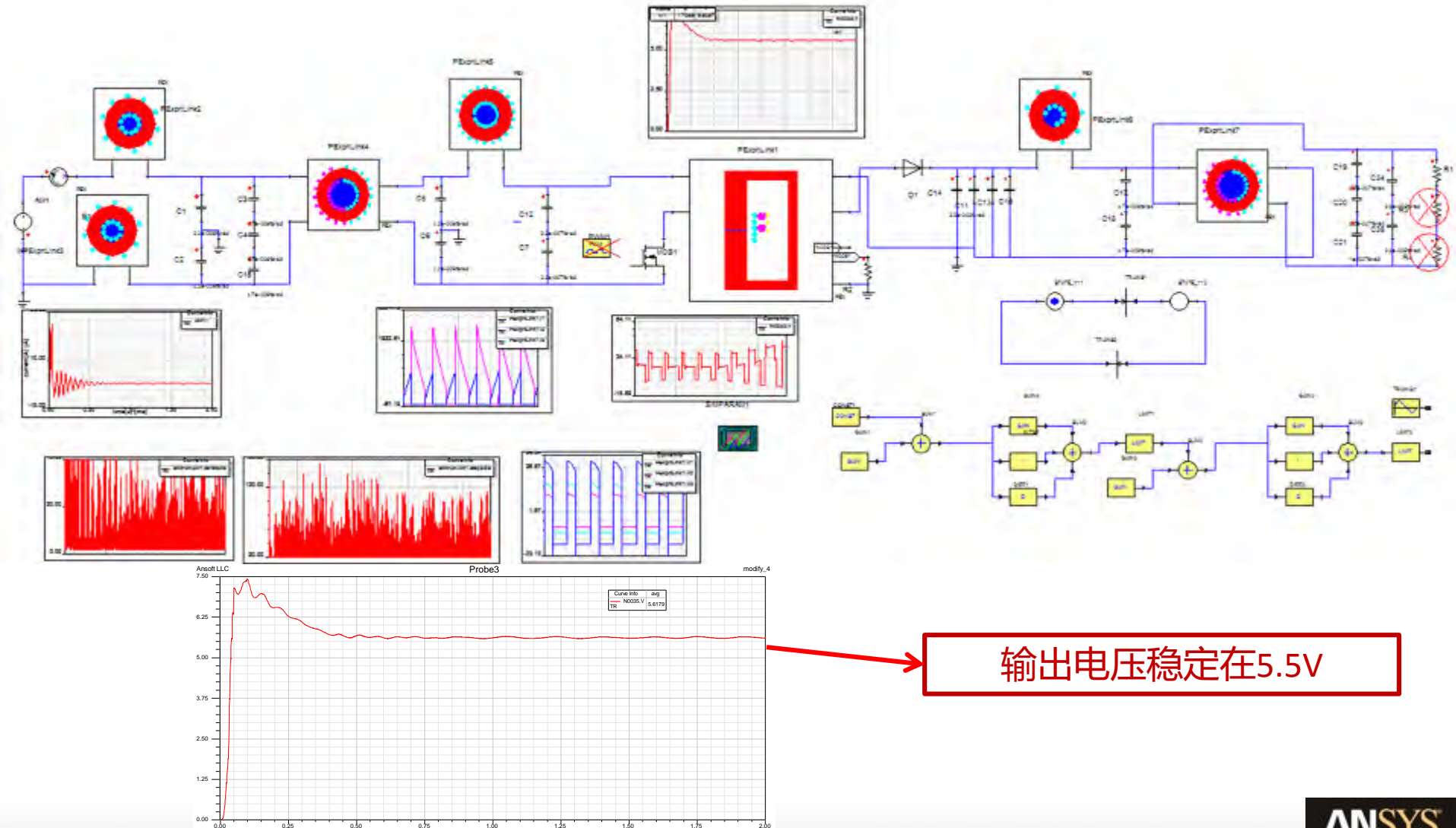
IGBT的 I_c 稳态电流波形



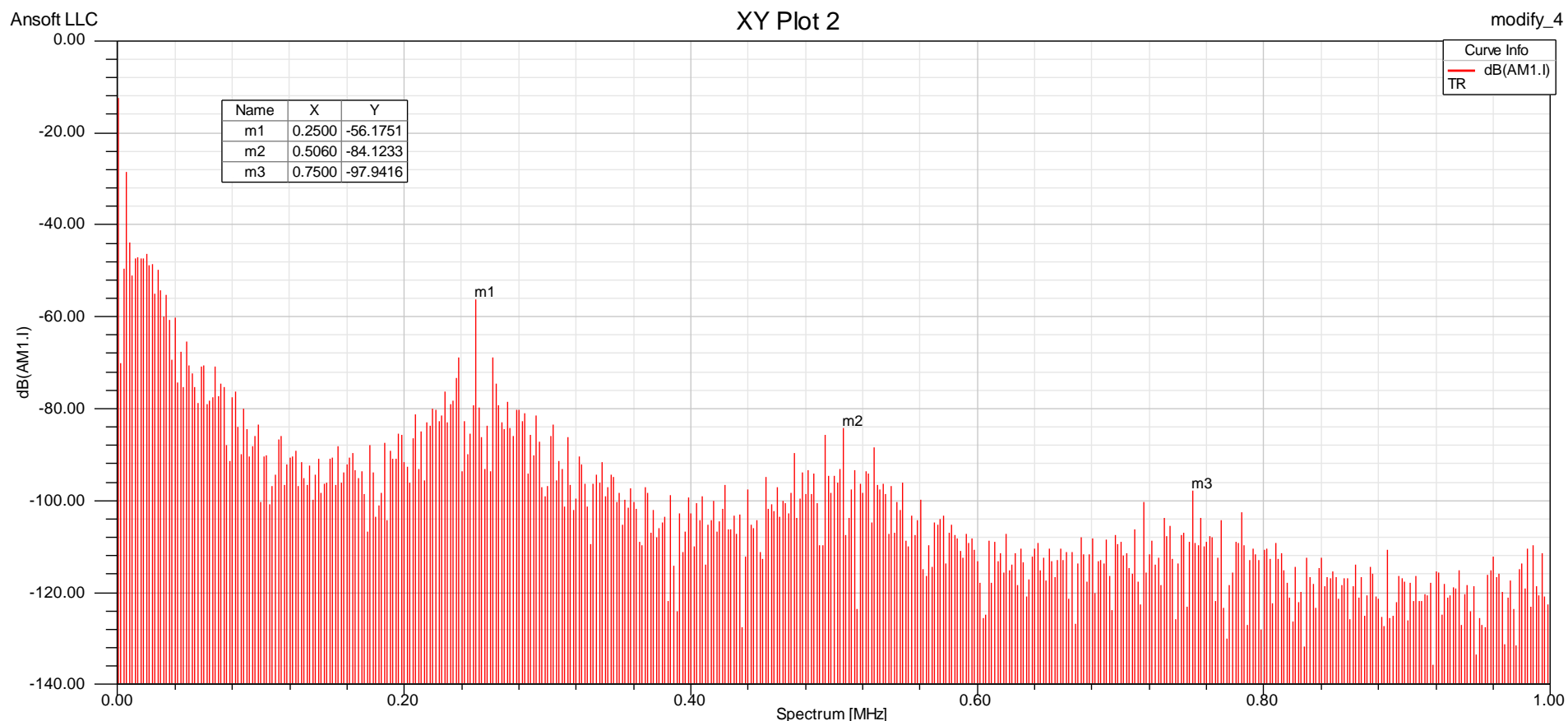
局部放大图

局部放大图

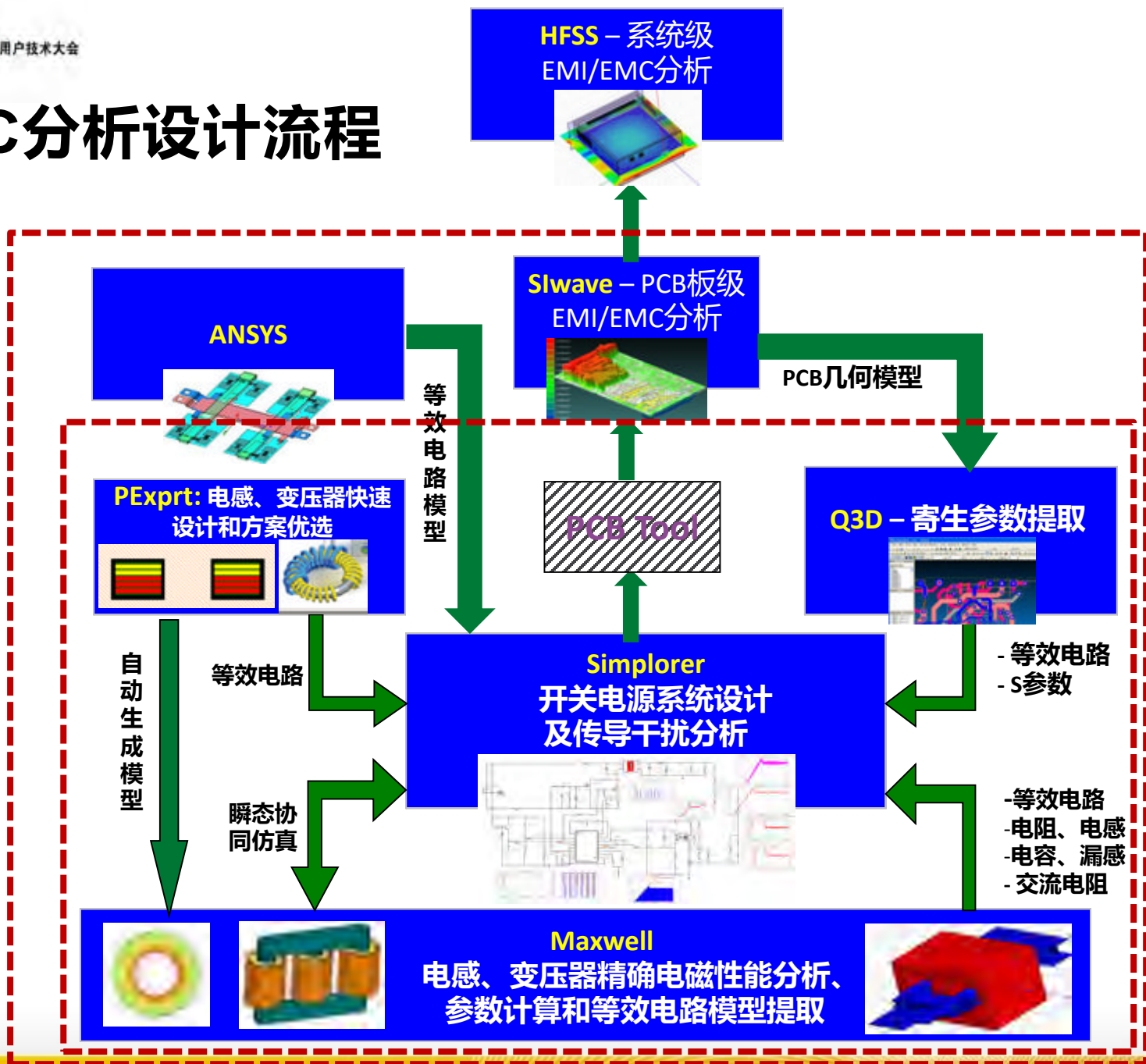
基于Simplorer集PExpert模型于一体的电路传导干扰



基于Simplorer的、集PExprt模型于一体的电路传导干扰



EMC分析设计流程



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