田村(中国)上海技术研发中心副所长
中国电源学会专家委员会委员
电源学会磁技术专委会委员
邵革良 主讲

开关电源的磁元件设计

技术培训

Quality Strengthens Chinese Local Core Competitiveness

21世纪电源网 21dianyuan.com

【开关电源的磁元件设计】

“开关电源设计干了4、5年了，不敢说大拿，也颇感小有成就！只是提及变压器电感的设计时，显然功底不足，用了不同的计算方法，结果却总能大相径庭，到底是哪个对的？！”

连不少资深的电源工程师，都常常如此苦恼！

其实，开关电源磁元件设计，也很简单！

---本培训继续演绎：**开关电源磁的元件设计**

21世纪电源网 21dianyuan.com

培训内容

- **开关电源磁元件的种类与技术要求**

  1）变压器（主变压器、互感器等）

  2）电感（PFC电感、Boost/Buck电感、谐振电感、AC滤波电感等）

  3）滤波电感（交流平滑滤波、EMI滤波器）

- **各种常用磁性材料的介绍**

  高频变压器用铁氧体、共模电感用高磁导率铁氧体、功率电感用铁氧体
非晶、纳米非晶、铁粉芯、铁硅、铁硅铝、硅钢、非晶粉芯等

- **磁元件设计技术基础**

  1）磁设计基本理论

  磁路、磁通密度、磁感应强度、变压器定义及基本模型

  2）磁元件的基本概念

  磁芯：BH特性、磁饱和、磁损耗、气隙、磁耦合和漏磁、

  线圈：直流损耗、趋附效应、临近效应、涡流损耗、阻抗特性、寄生电容、耦合系数

  元件：温升、热阻、励磁、绕组结构、绝缘、安规

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培训内容

- **常用磁元件设计与计算**
  1）功率变压器
  2）反激电源变压器
  3）驱动变压器
  4）谐振电感
  5）PFC电感（CRM、CCM 、交错并联）
  6）EMI共模电感

- **磁元件设计最新技术前沿介绍**
  1）磁元件仿真技术
  2）改变世界的磁元件设计创新
  磁集成技术、混合磁路技术、L-I trimming技术、SpikeBlocker技术等
  < UPS、服务器电源、光伏、充电桩、APF、变频空调应用最前沿 >

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培训介绍

培训对象

开关电源设计一线研发工程师

培训目的

从最基本的磁元件设计基础和理论出发，分析开关电源中各种磁元件的技术特征和要求；

详细介绍当前常用的磁芯材料的各个性能、特点；

通过对功率变压器、反激电源变压器、驱动变压器、谐振电感、PFC电感、共模滤波电感等设计方法的讲解，使学员能够快速、准确、清晰地把握开关电源磁元件设计的重要概念与设计计算方法；

同时，结合目前开关电源各个热门应用，本培训还将向大家揭示正在深刻影响电源行业革命性变化的最新磁元件技术，帮助和促进大家通过技术创新，迅速提高自身产品的核心竞争力的能力。

培训特点

紧密结合电源电路、注重基本概念、易学易懂、突出实用性和实战性

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第一讲 开关电源磁元件的种类与技术要求

1 变压器（主变压器、互感器、驱动变压器）

2 电感（PFC电感、Boost/Buck电感、谐振电感、AC滤波电感）

3 EMI电感（共模电感、差模电感、差共模磁集成电感）

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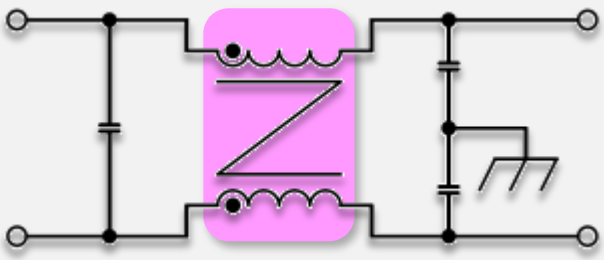
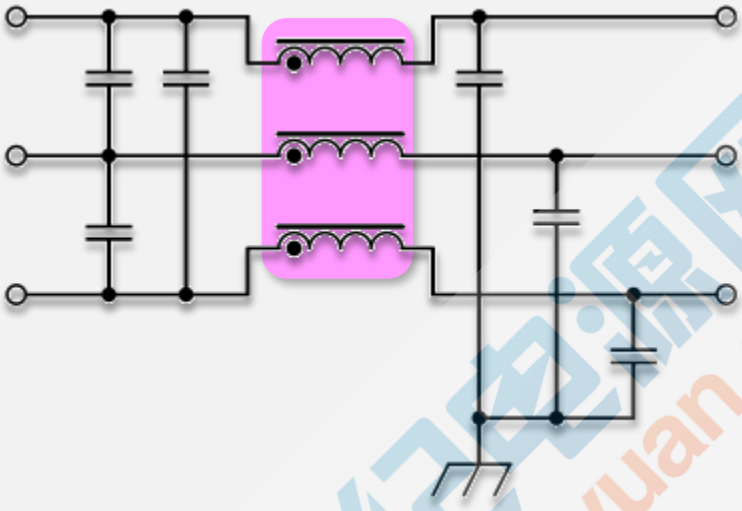
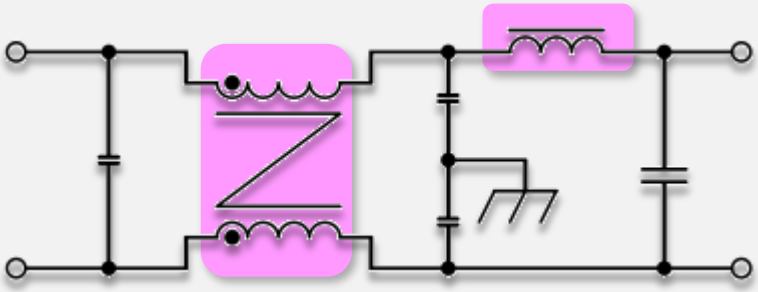
电源电路中的磁元件 （常见输入EMI滤波电路）



单相共模滤波



三相共模滤波



单相共模+差模滤波

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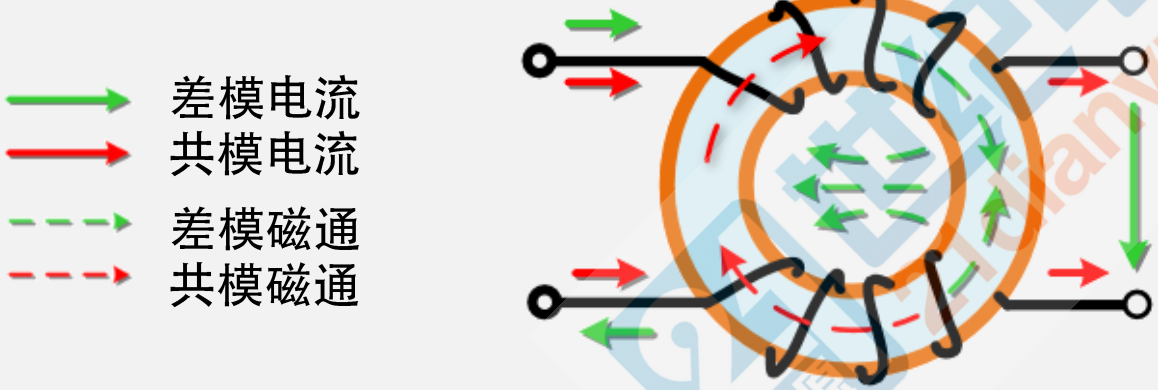
电源电路中的磁元件

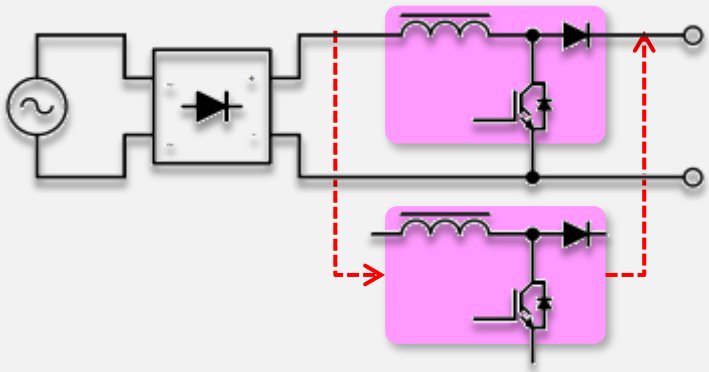
（EMI共模滤波电感的主要电气指标）

- 阻抗特性 Z-f　　*@150KHz~30MHz, ~100MHz*
- 电感特性 L-f　　*@1KHz, 100KHz~1MHz*
- 最低谐振频率 f_{SRF}　　≥1MHz or Higher
- 饱和共模电流I_{Sat}　　Higher is Best
- 差模电感L_{NOR}　　Higher is Best
- 总体损耗P_{Loss}　　$P_{coil(LF)}+P_{core(HF)}$

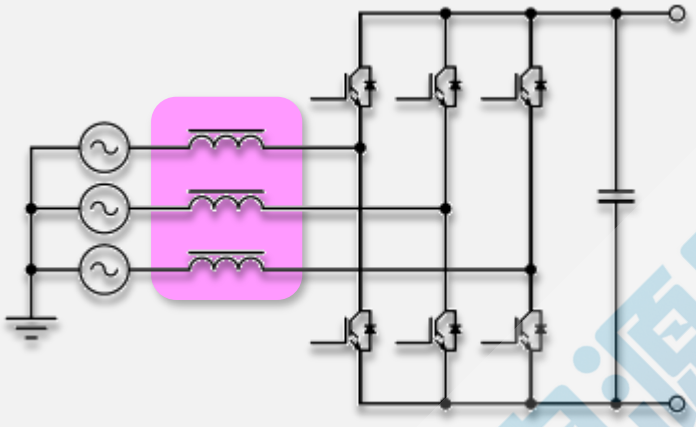


电源网 dianyuan.com

电源电路中的磁元件 （高次谐波抑制PFC电路）



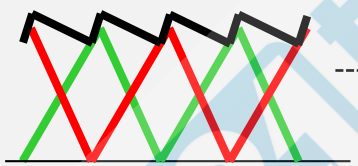
常见单相PFC、交错式PFC（CRM、CCM）

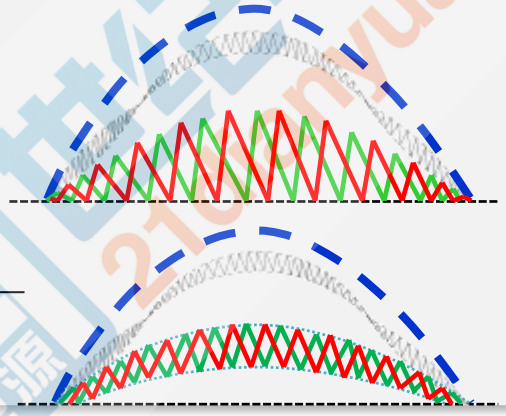


三相PFC（CCM）

电感量与电感损耗特点

- CRM vs CCM
- Single phase vs Multi-phase
- DC Boost vs Bridgeless
- Integrated Reactor





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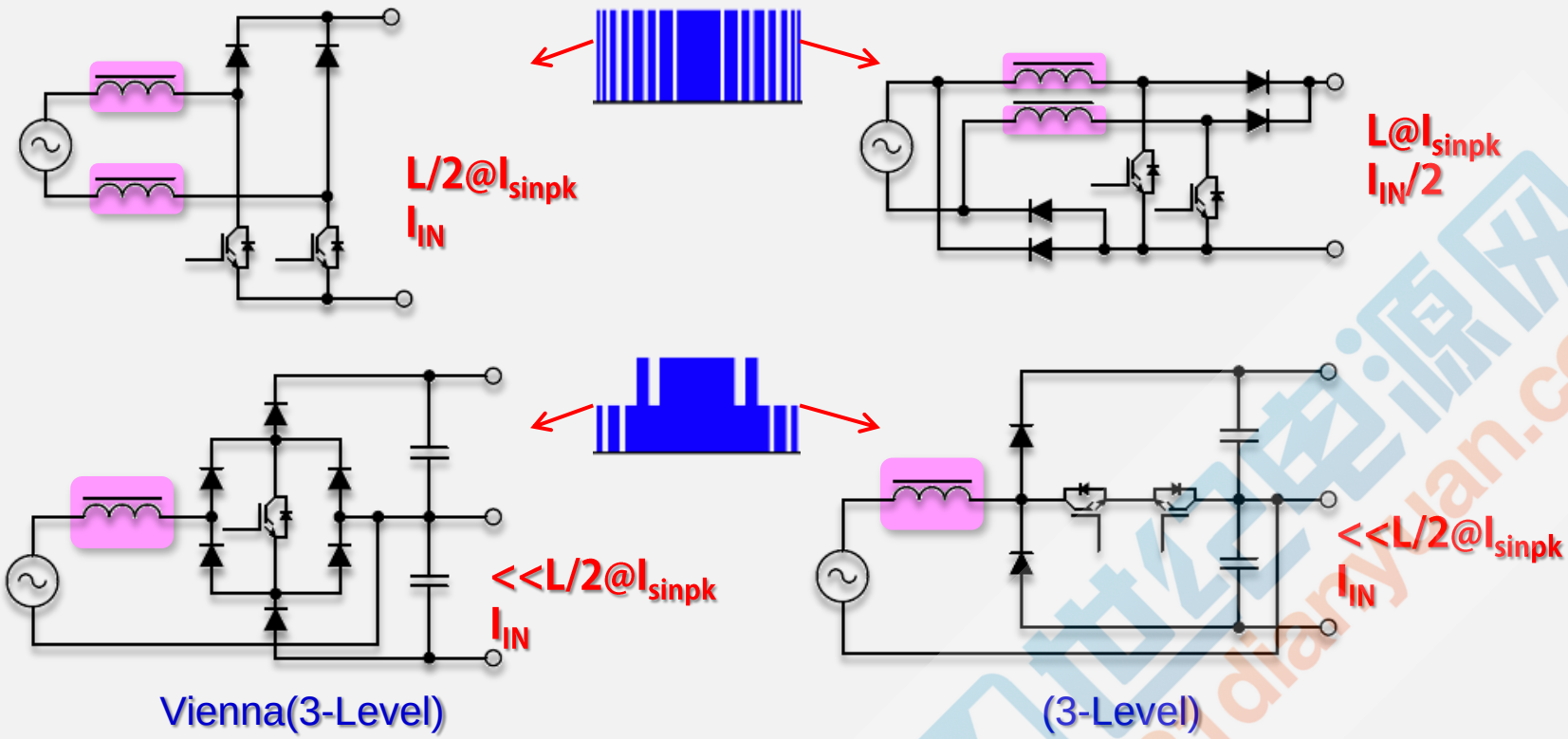
电源电路中的磁元件 （高次谐波抑制PFC电路）



各种单相无桥PFC (CCM)

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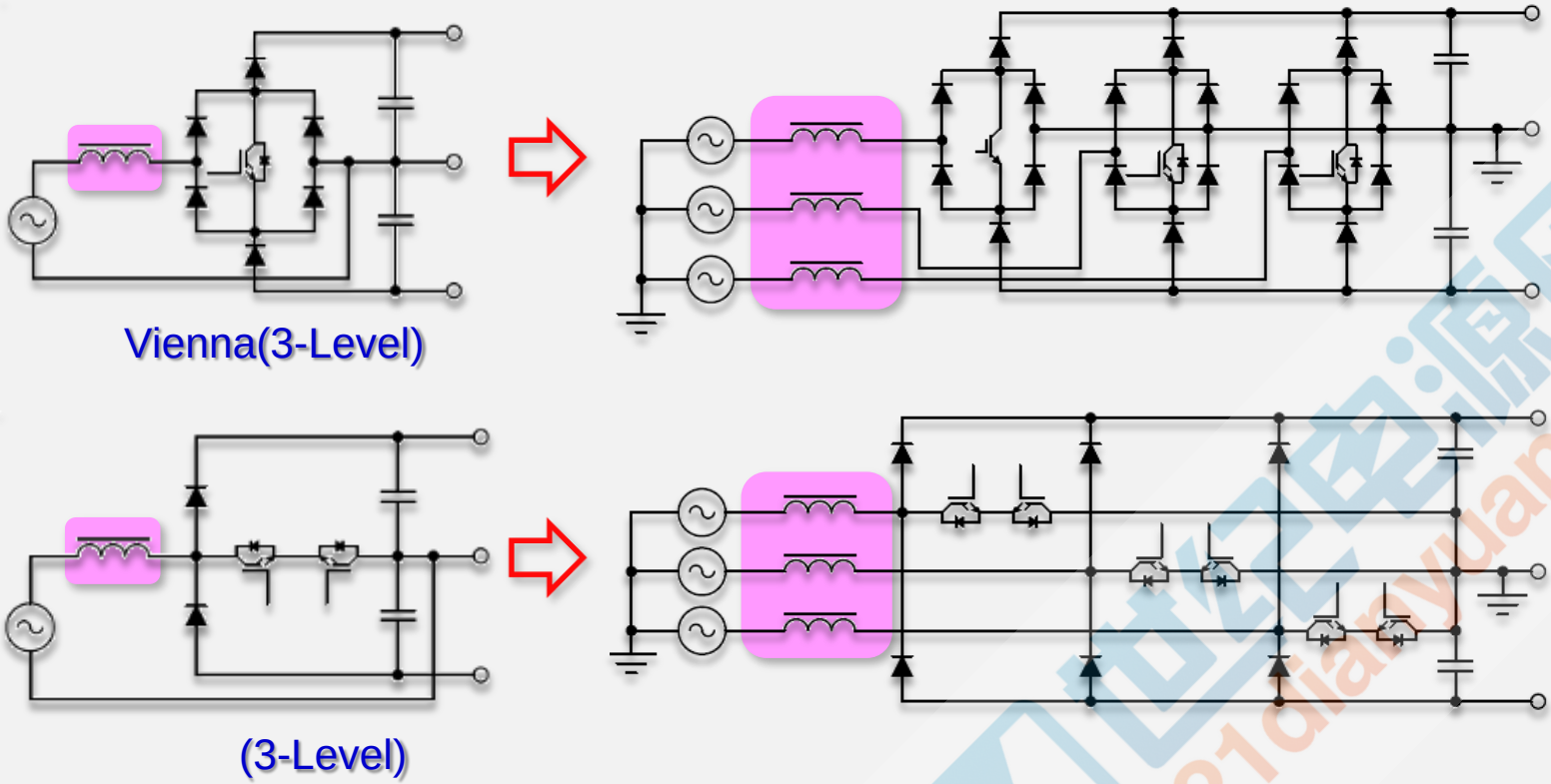
电源电路中的磁元件 （高次谐波抑制PFC电路）



三相三电平无桥PFC (CCM)

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电源电路中的磁元件

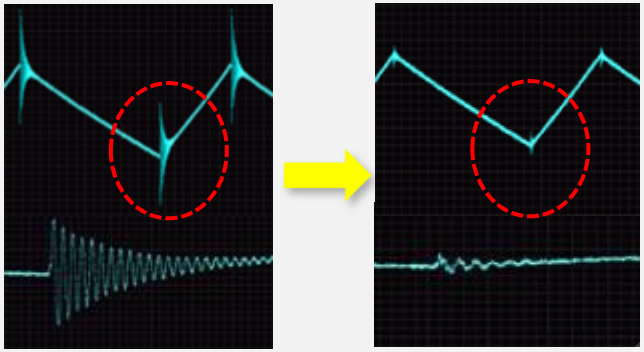
（交流电源高次谐波抑制PFC电感电气要求）

- 电感电流特性 L-I　　*L-I特性曲线（L @0A，I_{rating}，I_{sat}）*　　纹波控制
- 电感阻抗特性 Z-f　　*@100KHz~30MHz*
- 最低谐振频率 f_{SRF}　　≥1MHz or Higher

EMC控制

- DCR & Q
- 总体损耗P_{Loss}　　$P_{coil}+P_{core}$

损耗设计



EMC性能

Spike Blocker®

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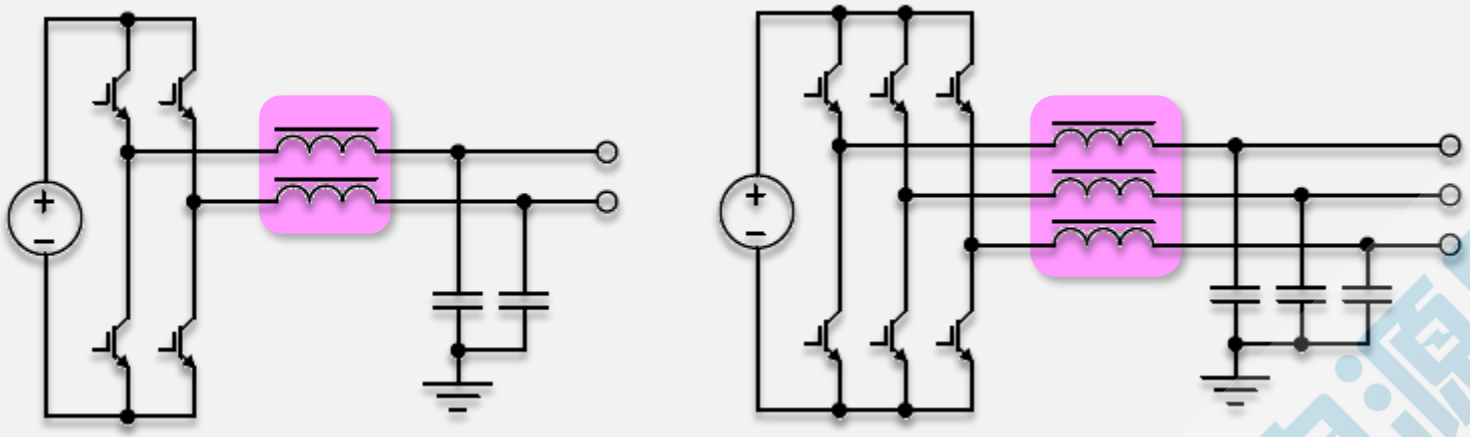
电源电路中的磁元件 （交流逆变器AC Filter电路）



常规单相、三相2-Level逆变拓扑

逆变器电感的特点

- 2 level vs 3 level
- Single vs Coupling reactor
- Hysteresis loss
- Harmonic current & noise

- 电感量要求（纹波、控制）
- 损耗要求（效率、温升）
- EMC要求（EMI、效率）
- 成本要求

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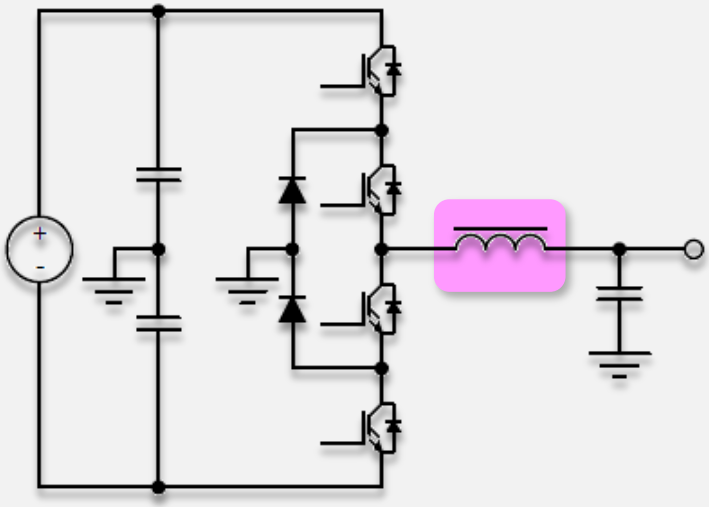
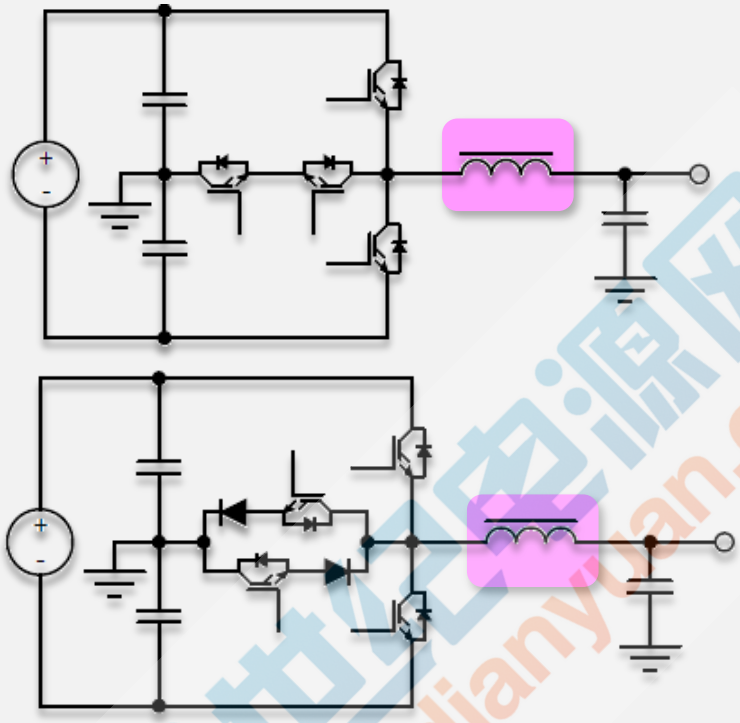
电源电路中的磁元件 （交流逆变器AC Filter电路）



NPC 3-Level



A-NPC 3-Level

常规单相、三相3-Level逆变拓扑

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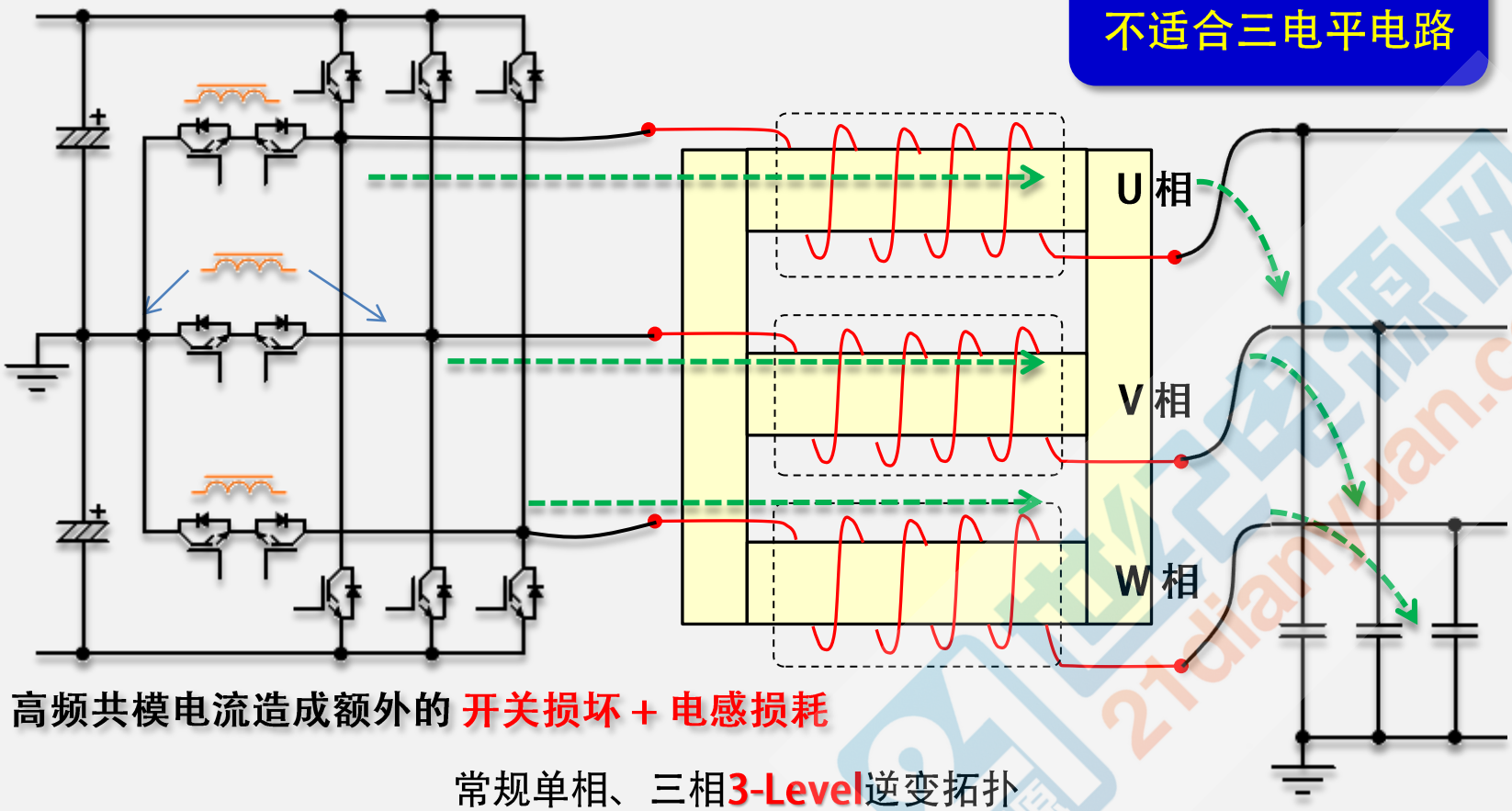
电源电路中的磁元件

（交流逆变器AC Filter电路）

常规三相耦合电感
不适合三电平电路



高频共模电流造成额外的 开关损坏 + 电感损耗

常规单相、三相3-Level逆变拓扑

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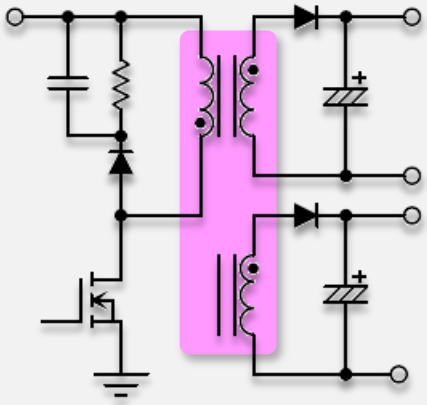
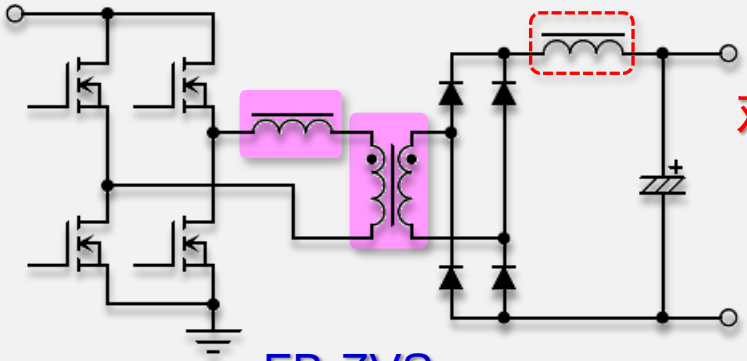
电源电路中的磁元件 （常用AC/DC电路）

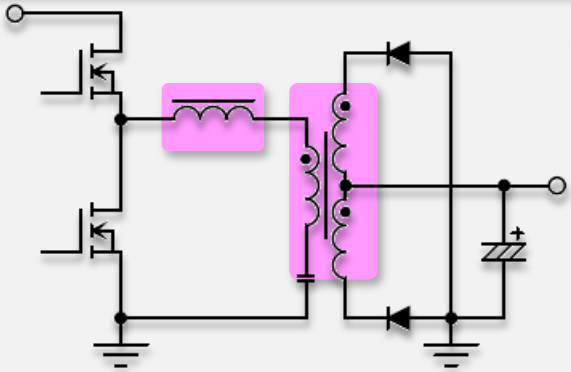


Flyback

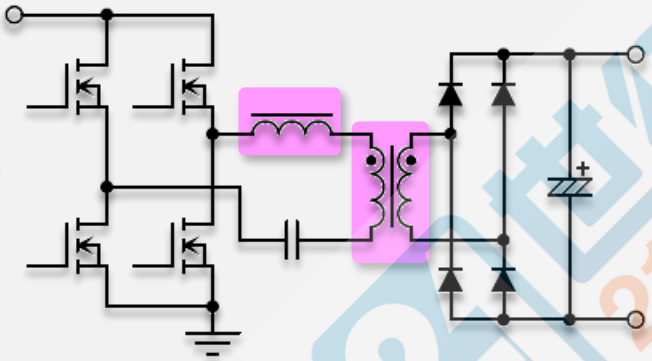


FB-ZVS

谐振电感
电流波形
对电感设计的影响



非对称LLC



FB-LLC

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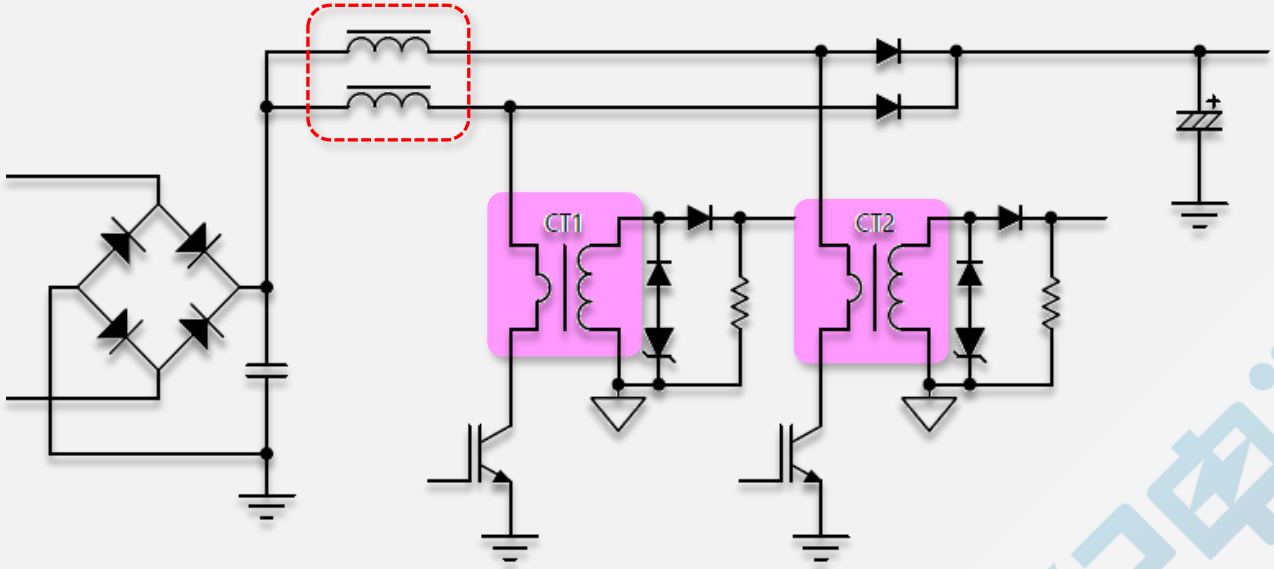
电源电路中的磁元件 （驱动变压器与CT）



- Improve Efficiency
- Isolation Current Sensing
- Easy to Control & Layout
- Reducing EMI Noise
- CT Output Never allowed to open
- Full flux reset avoids magnetic saturation

CCM Interleave PFC for Large Power Application

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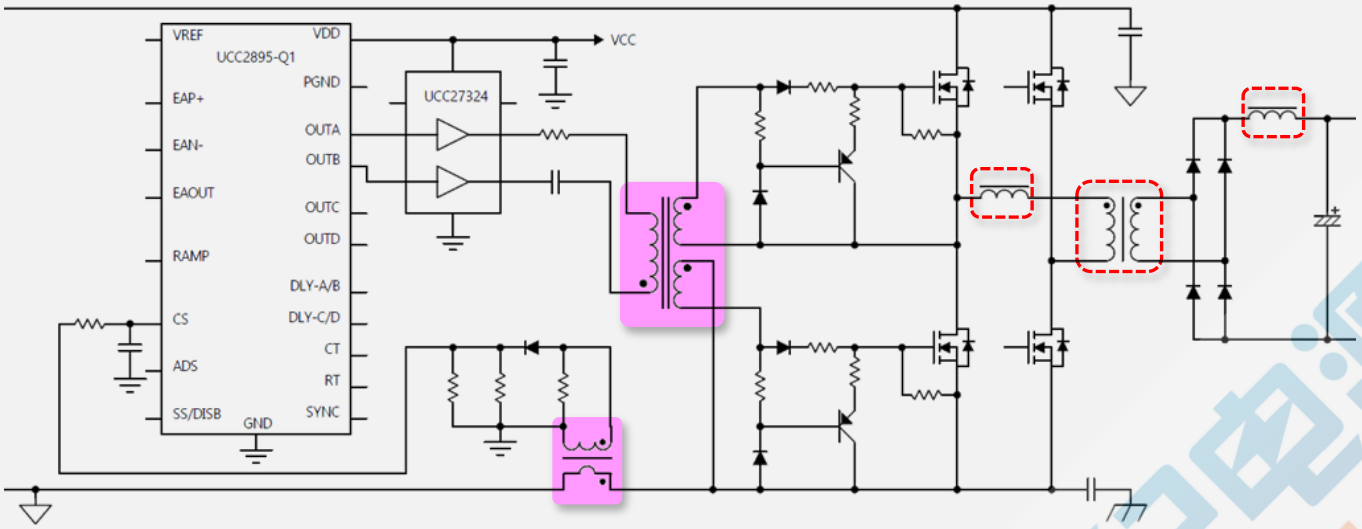
电源电路中的磁元件 （驱动变压器与CT）



- Isolated driving 绝缘
- Need magnetic reset 对称驱动
- Need low leakage inductance 高速低功耗

FB-ZVS Driver & Current Sensing

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第二讲 常用磁芯材料的介绍

1 变压器材料
锰锌铁氧体、铁基纳米非晶、铁基非晶、硅钢

2 电感材料
(低磁导) 铁镍钼、铁镍、铁硅、铁硅铝、非晶粉芯、铁粉芯
(高磁导) 锰锌铁氧体、硅钢、铁基非晶、铁基纳米非晶

3 共模电感材料
高导磁铁氧体、铁基纳米非晶

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变压器材料 （锰锌铁氧体-主要电气指标）

PC95的材质特点（例）

初始磁导率 μi	单位体积磁心损耗（磁心损耗）* Pcv (kW/m³) B=200mT 100kHz sine wave				饱和磁通密度 * Bs (mT) H=1194A/m				剩余磁通密度 * Br (mT) H=1194A/m				矫磁力 * Hc (A/m) H=1194A/m				居里温度 Tc (°C)	容积密度 * db (kg/m³) ×10³	体积电阻率 * ρv (Ω • m)
	25°C	60°C	100°C	120°C	25°C	60°C	100°C	120°C	25°C	60°C	100°C	120°C	25°C	60°C	100°C	120°C			
3300±25%	350		290	350	530	480	410	380	85	70	60	55	9.5	7.5	6.5	6	>215	4.9	6

开关电源变压器设计必要磁芯参数

- 磁导率μi
- 饱和磁密Bs
- 损耗特性Pcv(f, ΔB)
- 电感量AL
- 外形尺寸（Ae, Ve, le, Acp, Acw, Rθ）

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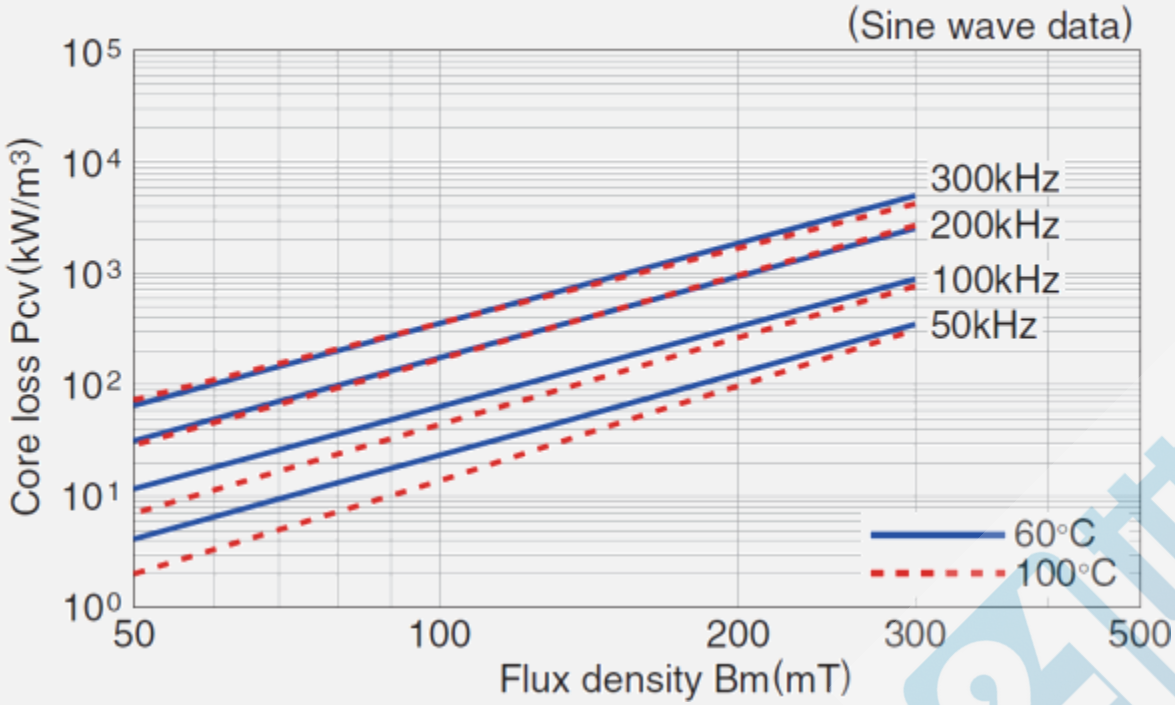
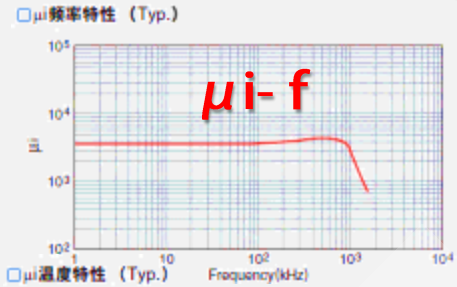
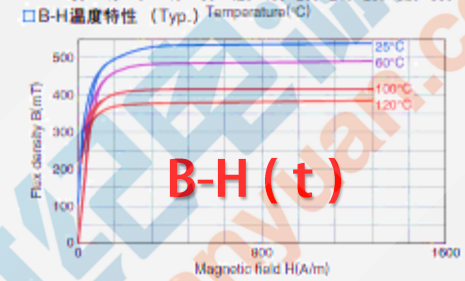
变压器材料 （锰锌铁氧体-主要电气指标）

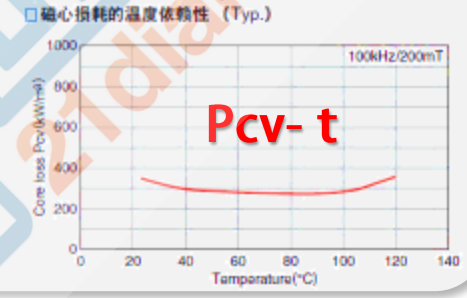
PC95的材质特点（例）

□磁心损耗 （Typ.）



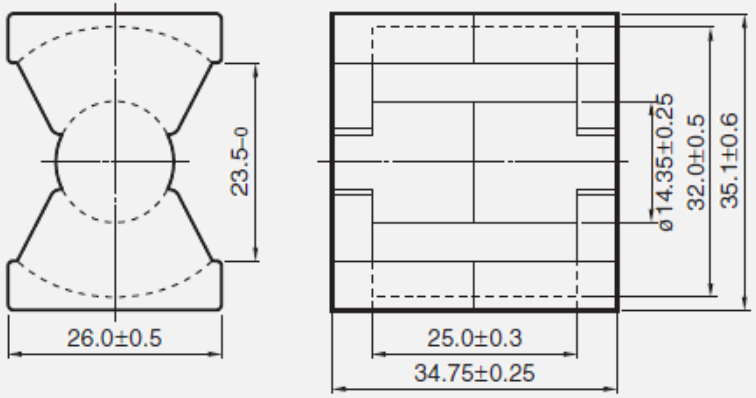




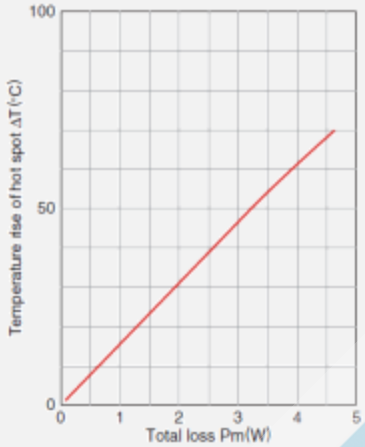


变压器材料 （锰锌铁氧体-主要电气指标）

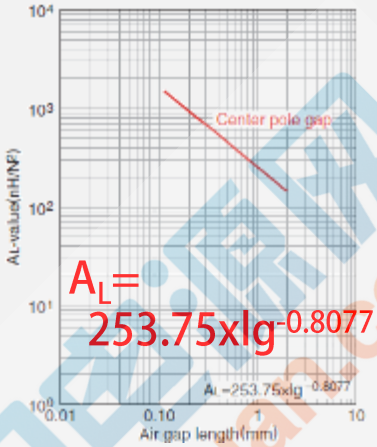
PC95的材质特点（例） 型号：PC95PQ35/35Z-12



温度上升 vs. 总损耗特性（Typ.）



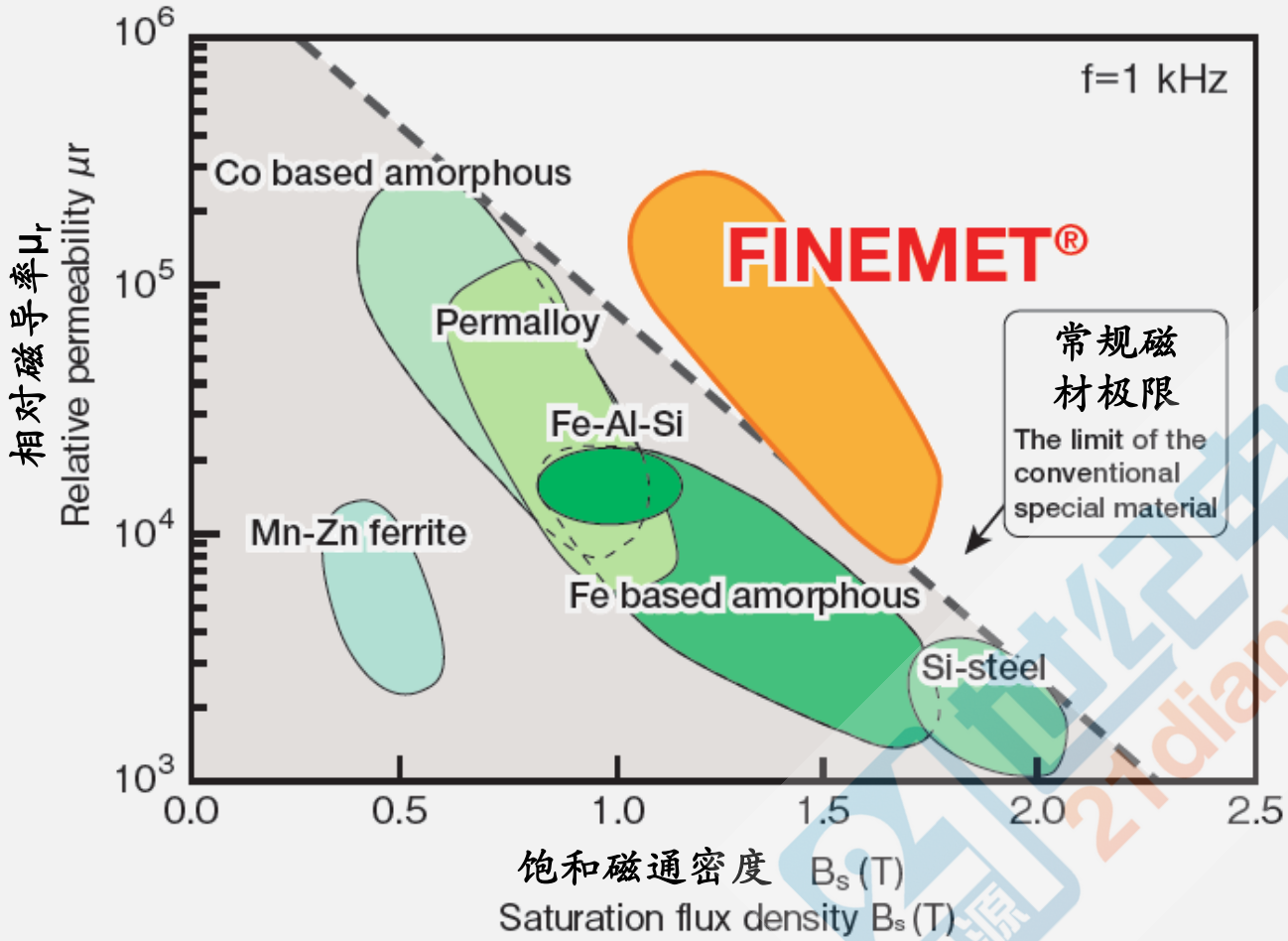
AL-value vs. 气隙长度（Typ.）



$A_L = 253.75 \times lg^{-0.8077}$

形状参数								电气特性			
磁心常数 C1 (mm⁻¹)	实效磁路长度 ℓe (mm)	实效截面面积 Ae (mm²)	实效体积 Ve (mm³)	中脚截面面积 Acp (mm²)	最小中脚截面面积 Acp min. (mm²)	卷线截面面积 Acw (mm²)	质量 (g/组)	AL-value * (nH/N²) 1kHz 0.5mA	磁心损耗 (W)max. 100kHz 200mT 25°C	80°C	120°C
0.448	87.9	196	17300	162	156	220.6	73	7320±25%	7.12	5.98	7.12

变压器材料 （纳米非晶-主要电气指标 日立FINEMET为例）



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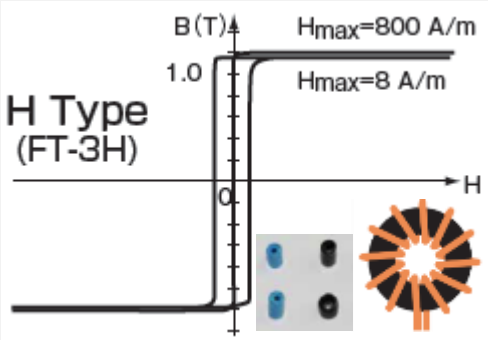
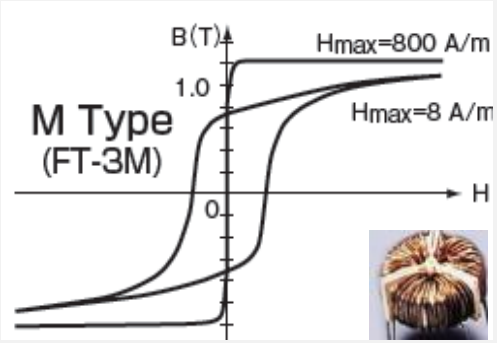
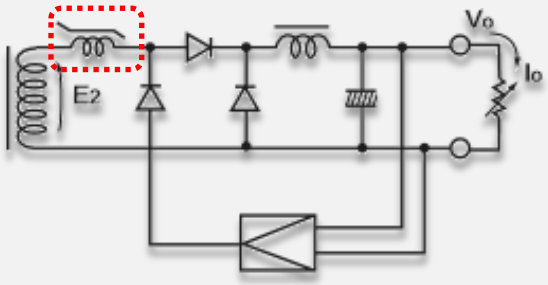
变压器材料 （纳米非晶-主要电气指标 日立FINEMET为例）



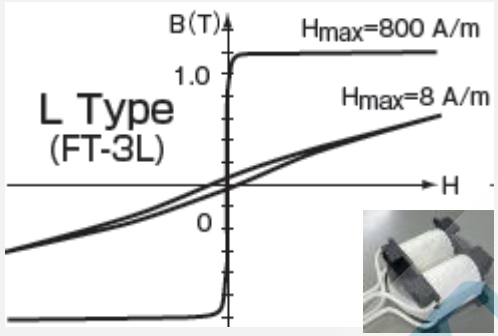
磁放大器、饱和磁珠
高压脉冲变压器



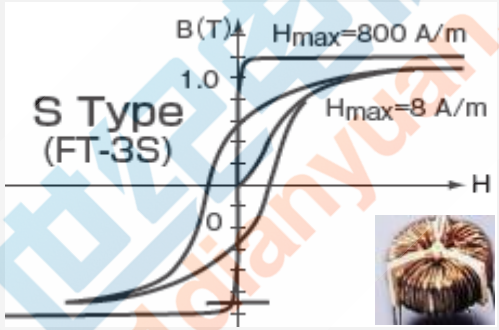
共模线圈、饱和磁珠



磁放大器电源原理



高频变压器



共模线圈

18μm带材不同热处理成的不同特性的材料

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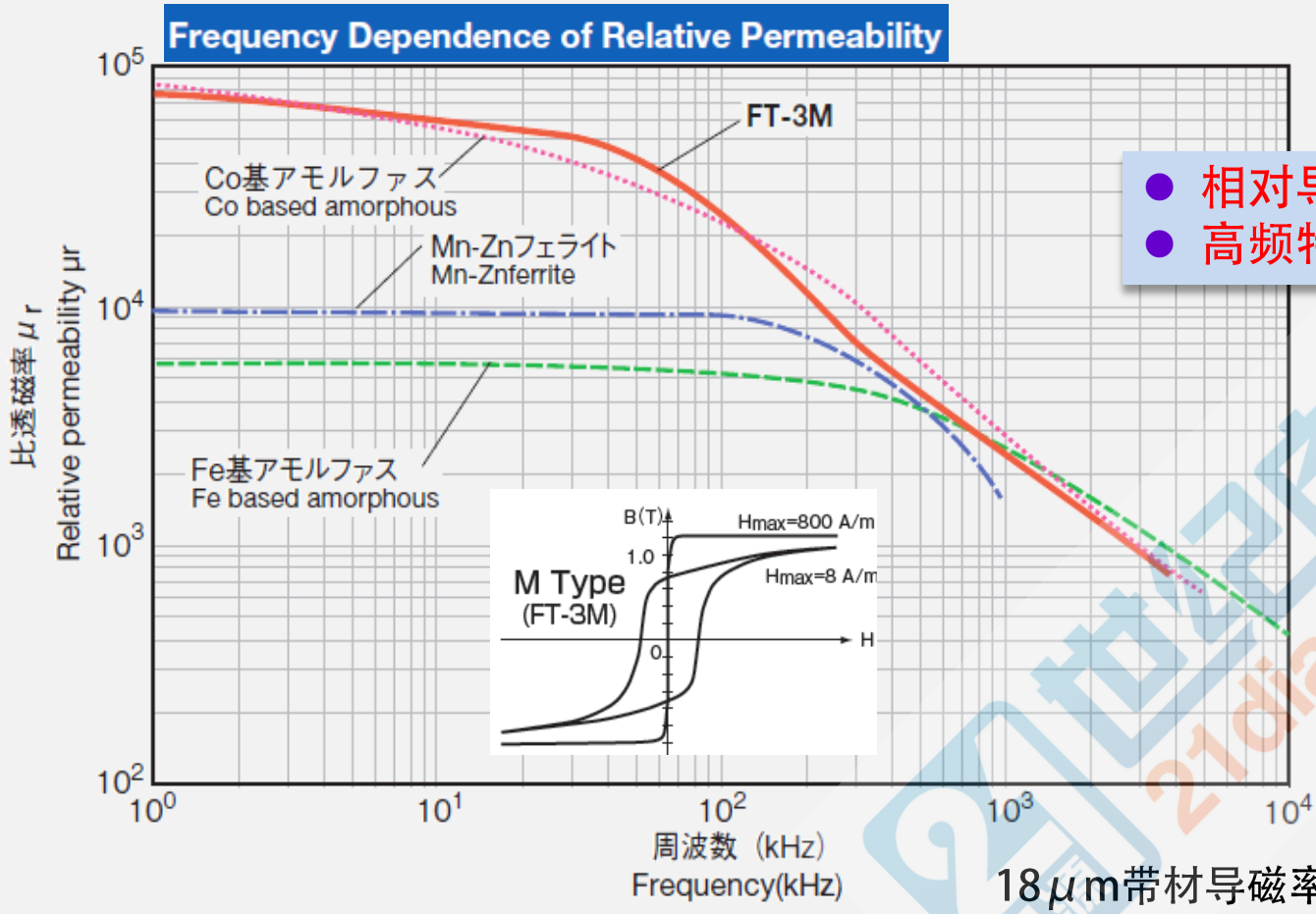
变压器材料 （纳米非晶-主要电气指标 日立FINEMET为例）



- 相对导磁率高
- 高频特性好

18μm带材导磁率-频率特性

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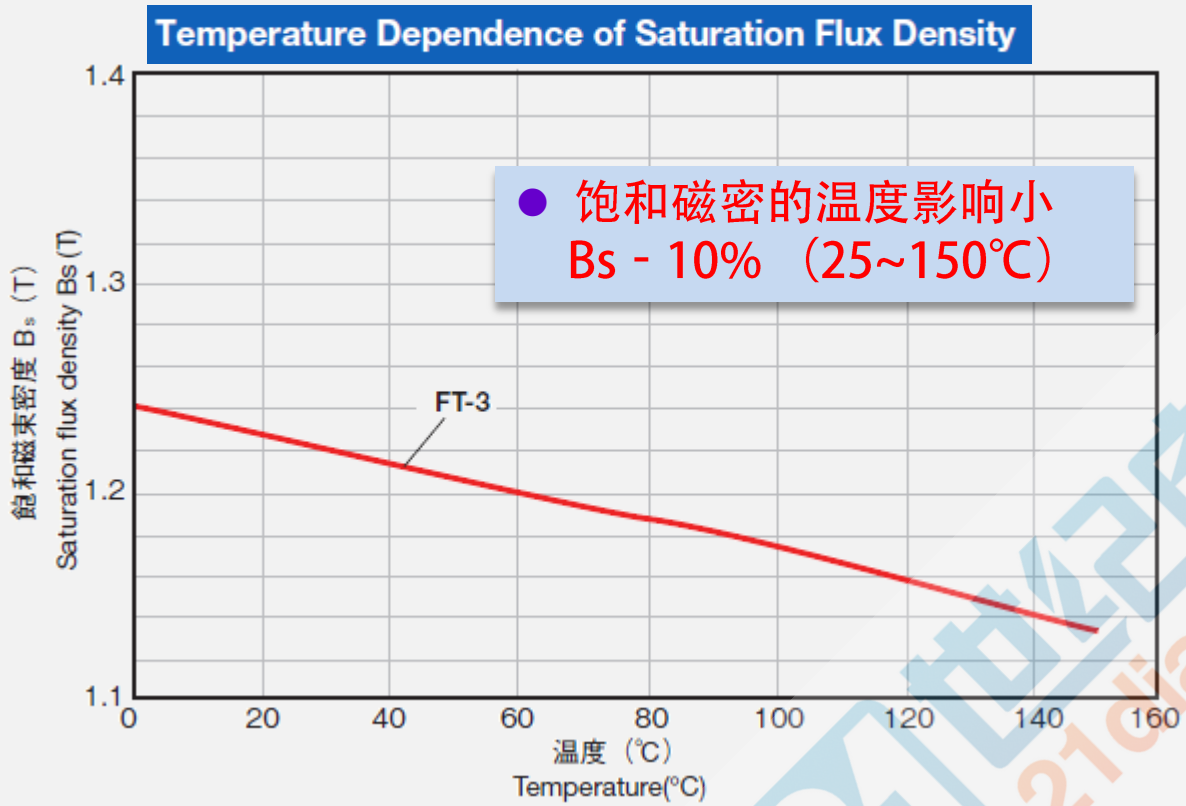
变压器材料 （纳米非晶-主要电气指标 日立FINEMET为例）



- 饱和磁密的温度影响小
  Bs - 10% （25~150℃）

18μm带材　饱和磁密-温度特性

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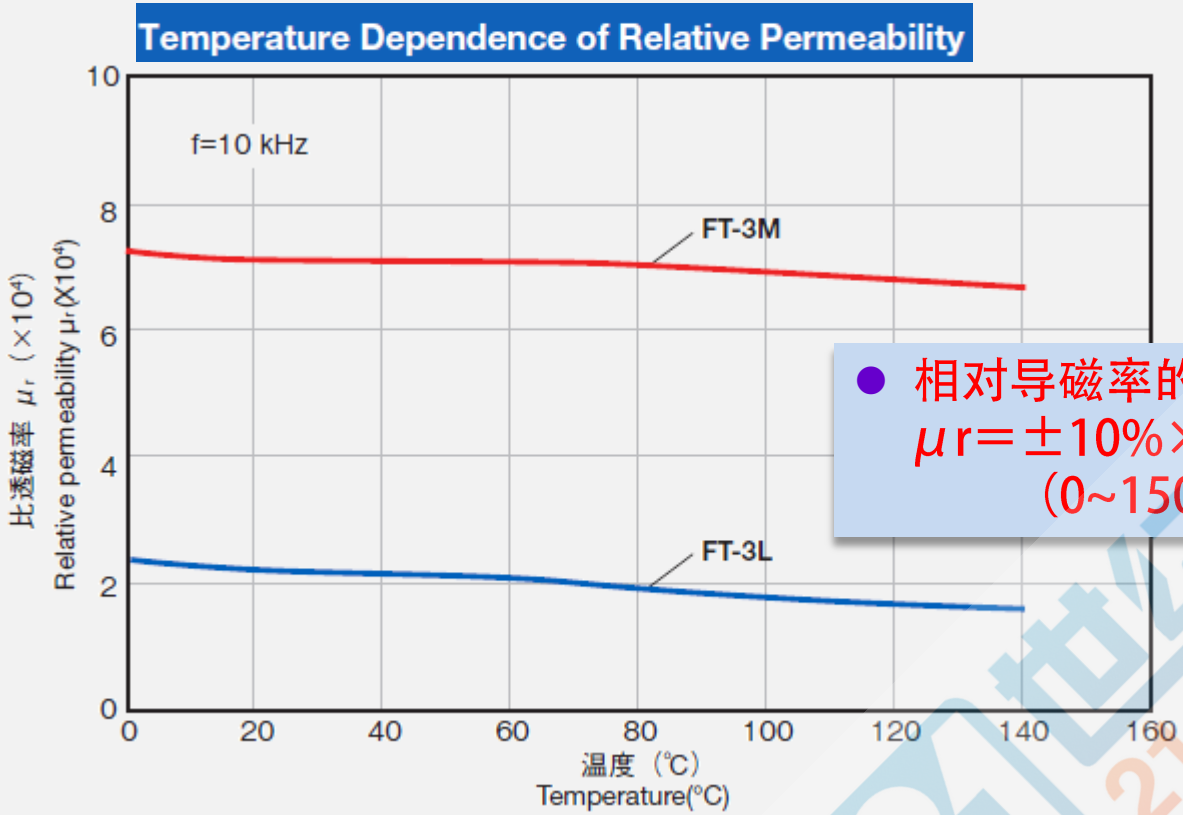
变压器材料 （纳米非晶-主要电气指标 日立FINEMET为例）



- 相对导磁率的温度影响小
  $\mu r = \pm 10\% \times \mu r_{25℃}$
  （0~150℃）

18μm带材 相对导磁率-温度特性

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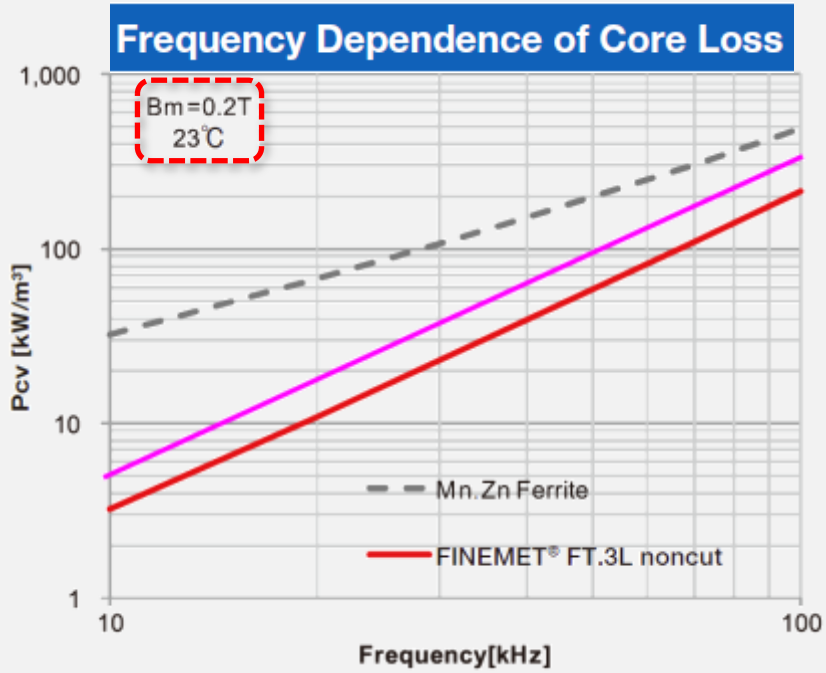
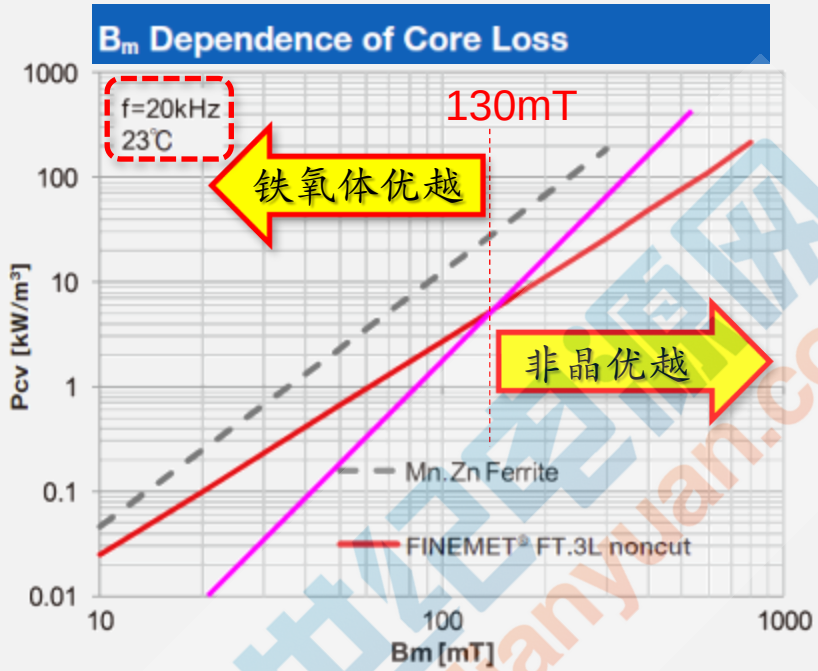
变压器材料 （纳米非晶-主要电气指标 日立FINEMET为例）





● 铁氧体PC95(100℃) ● 纳米非晶FT-3L(No cut)

功率变压器用纳米非晶 损耗特性 对比关系

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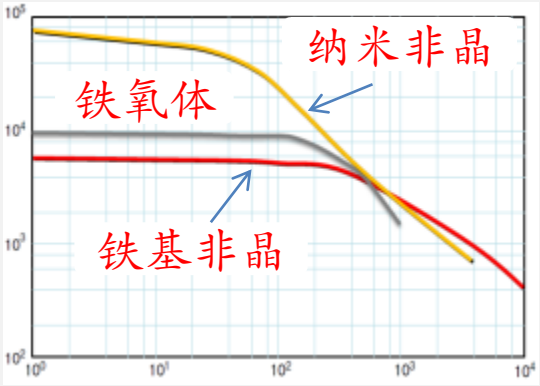
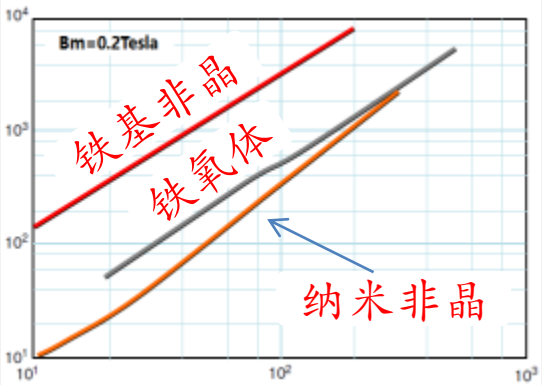
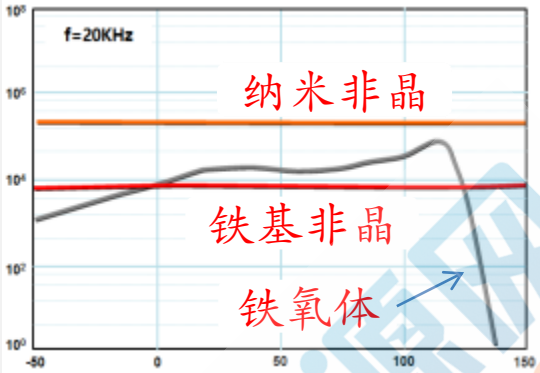
变压器材料 （纳米非晶-铁基非晶-铁氧体-硅钢片特性对比）



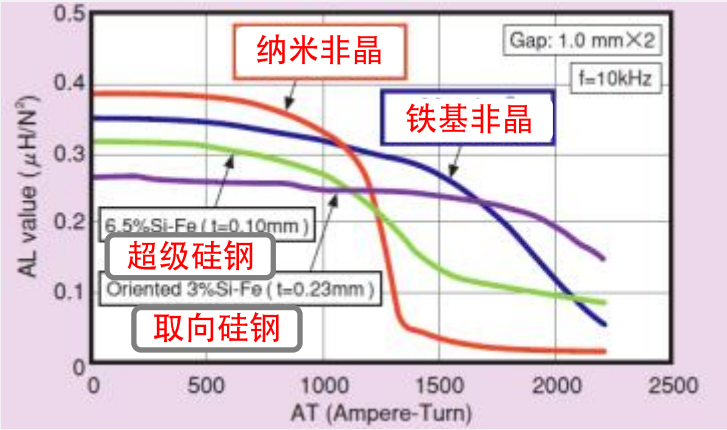
相对磁导率 μ_r--频率 f(KHz)

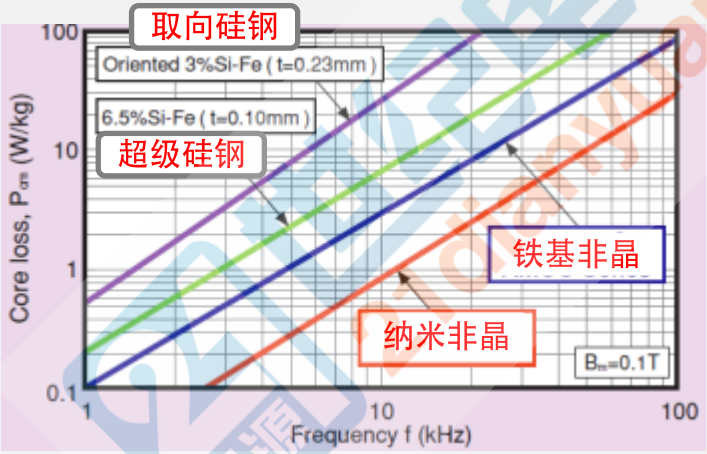


磁芯损耗 P_{CV}(KW/m³)--频率 f(KHz)



相对磁导率 μ_r --温度 T(℃)



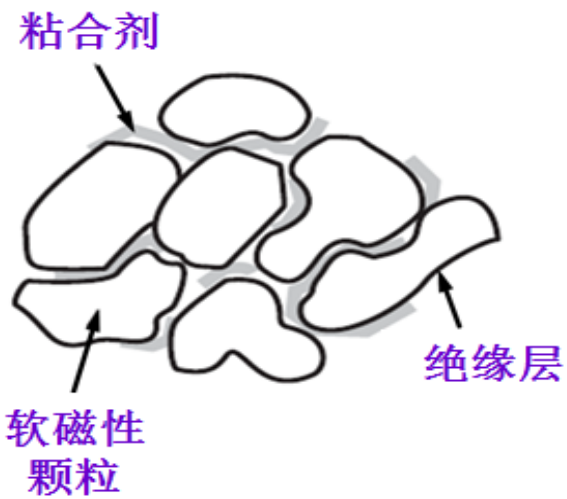


电感磁材料 （低导磁率金属软磁粉芯材料）

粉芯类材料适合电感设计

1）低磁导率
2）分布式均匀气隙
3）饱和磁密Bs高
4）磁粉颗粒小

金属软磁粉芯的本质



磁性粉末

微米级磁性粉末颗粒为特征

绝缘皮层

磁性颗粒间绝缘 → 降低铁损

粘合材料

通过粘合机将各个粉末颗粒进行固定

将金属软磁粉末颗粒压制成型→软磁粉芯磁芯

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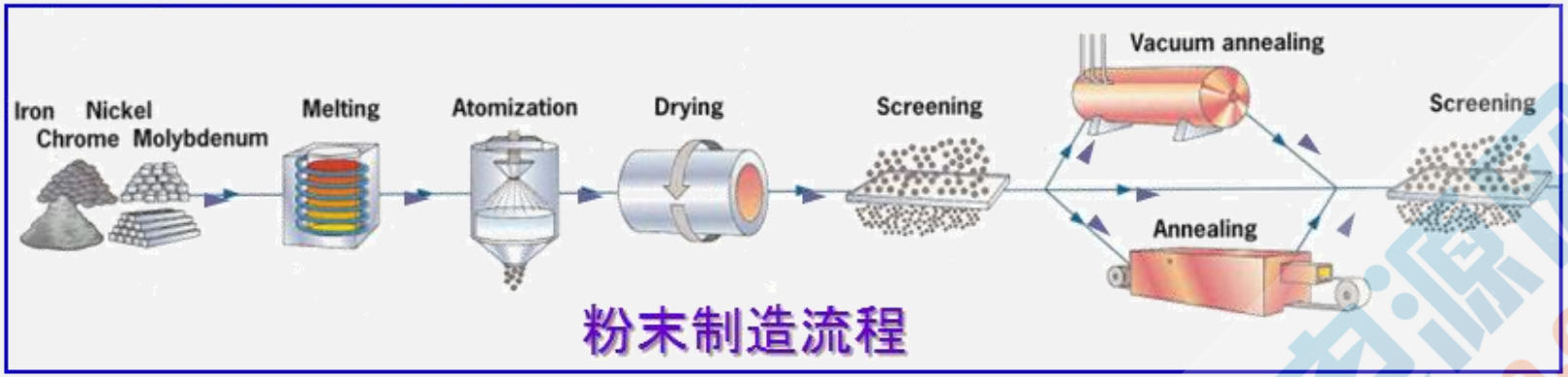
电感磁材料 （低导磁率金属软磁粉芯材料）

金属软磁粉芯的生产制造



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电感磁材料 （低导磁率金属软磁粉芯材料性能对比）

Materials	Perm. (μ_l)	Bs (kG)	Core Loss	DC Bias	Relative Cost	Temp. Stability	Curie Temp [℃]
铁镍钼	26-200	7	Lower	Better	High	Best	450
铁镍	26-160	15	Low	Best	Medium	Better	500
铁硅铝	26-125	10	Low	Good	Low	Good	500
铁硅	26-90	16	Medium	Best	Low	Better	700
铁粉芯	10-100	10	High	Poor	Lowest	Poor	770
Fe-Si Strip (Gap)		20	High	Better	Lowest	Good	740
Amorphous (Gap)		15	Low	Better	Medium	Good	399
Ferrite (Gap)		3-5	Lowest	Poor	Lowest	Poor	100~300

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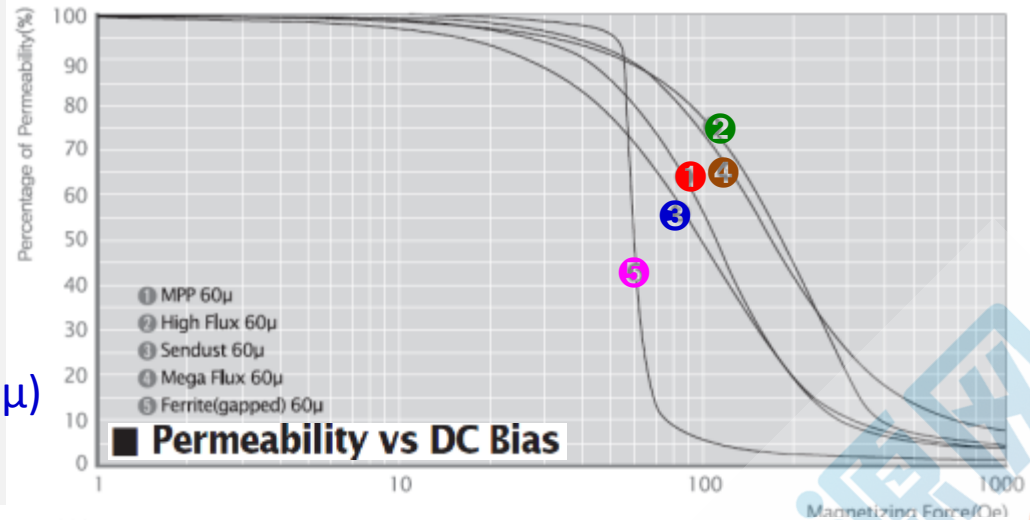
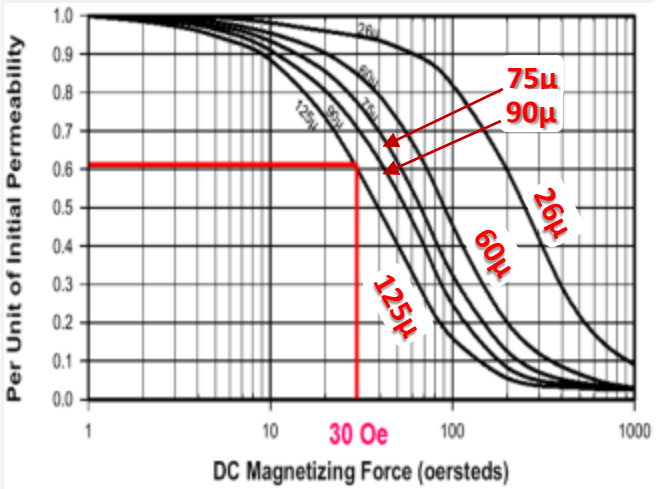
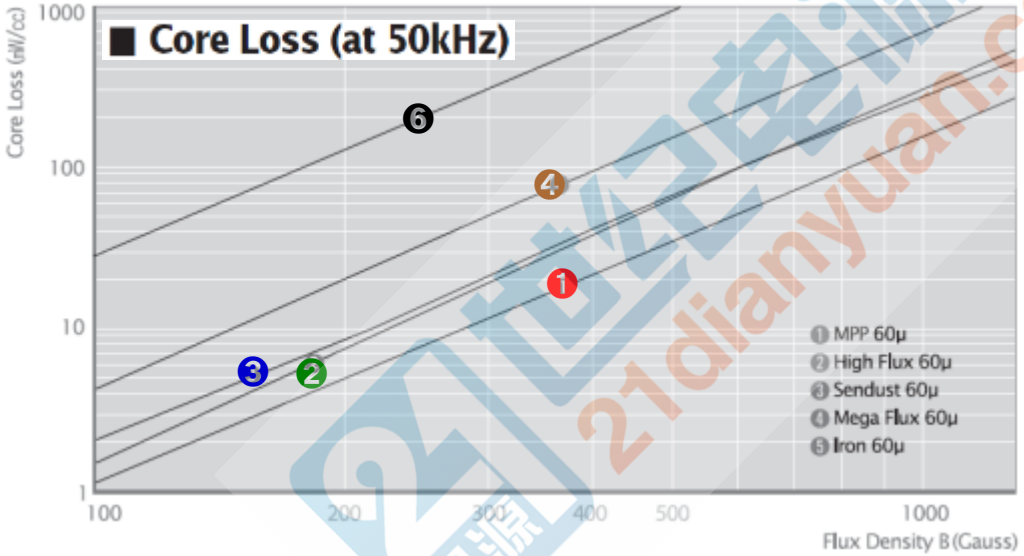
电感磁材料（性能对比）

❶铁镍钼 MPP
❷铁镍 High Flux
❸铁硅铝 Sendust
❹铁硅 FeSi
❺铁氧体 Ferrite(with Gap,60μ)
❻铁粉芯 Fe Powder







相同材质的μ-H曲线

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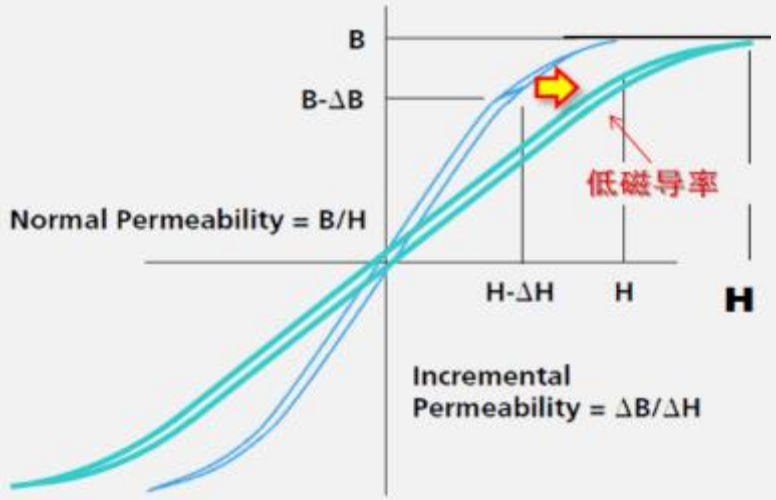
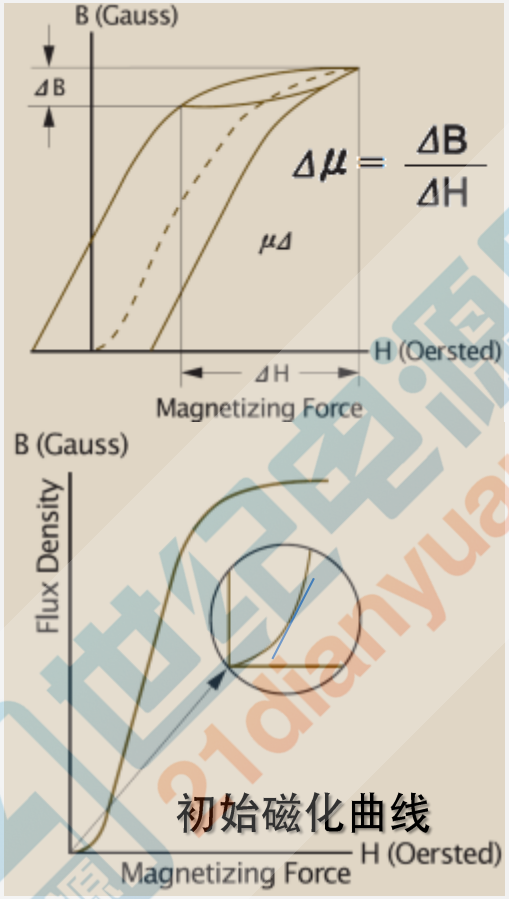
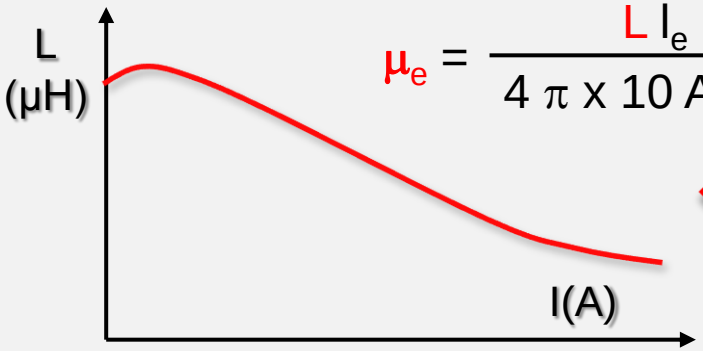
电感磁材料 （低导磁率金属软磁粉芯材料性能对比）







$$\mu_e = \frac{L\, l_e}{4\pi \times 10\, A_e\, N^2}$$

高磁导EMI共模材料（高μ铁氧体、纳米非晶）

FERRITE MATERIALS FOR EMI PREVENTION/EMC and PULSE TRANSFORMER

高透磁率材標準材質特性 铁氧体

High μi Material Characteristics

JFE

標準材質特性
Material Characteristics

材質名 Material			MA055	MA070	MA085	MA100	MA120	MA150
初透磁率 Initial permeability	μ_i		5500±20%	7000±25%	8500±25%	10000±25%	12000±30%	15000±30%
実効飽和磁束密度(1200A/m) Saturation flux density at 1200A/m	Bms	(mT)	434	440	422	415	410	400
実効飽和残留磁束密度 Remanence	Brms	(mT)	67	93	66	76	80	85
実効飽和保磁力 Coercivity	Hcms	(A/m)	5.2	3.4	3.3	3.0	3.0	2.0
相対損失係数(10kHz) Relative loss factor at 10kHz	$\tan\delta/\mu_i$	$\times10^{-6}$	0.75	1.4	1.3	1.9	6.4	6.8
初透磁率の相対温度係数 Relative temperature factor	$\alpha\mu r$	$\times10^{-6}$	−0.5~2.0	−0.5~2.0	−0.5~2.0	−0.5~2.0	−0.5~2.0	−0.5~2.0
キュリー温度 Curie temperature	Tc	(°C)	140min.	130min.	130min.	115min.	115min.	115min.
抵抗率 Resistivity	ρ	(-m)	0.8min.	0.3min.	0.2min.	0.1min.	0.02min.	0.02min.
密度 Density	d	(kg/m³)	4.9×10^3	4.95×10^3	4.95×10^3	5.0×10^3	5.0×10^3	5.0×10^3

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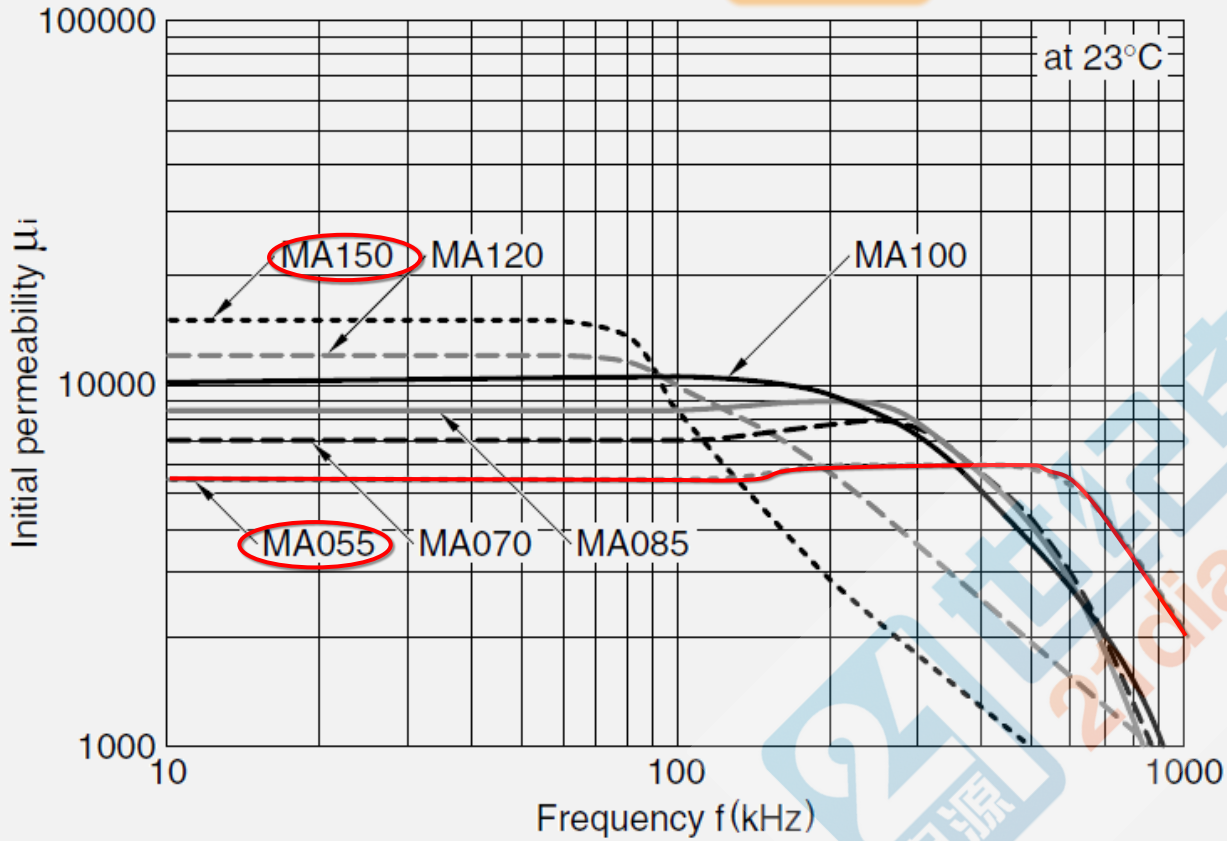
高磁导EMI共模材料（高μ铁氧体、纳米非晶）

μi-周波数特性
Permeability vs. Frequency(Typical) **铁氧体**



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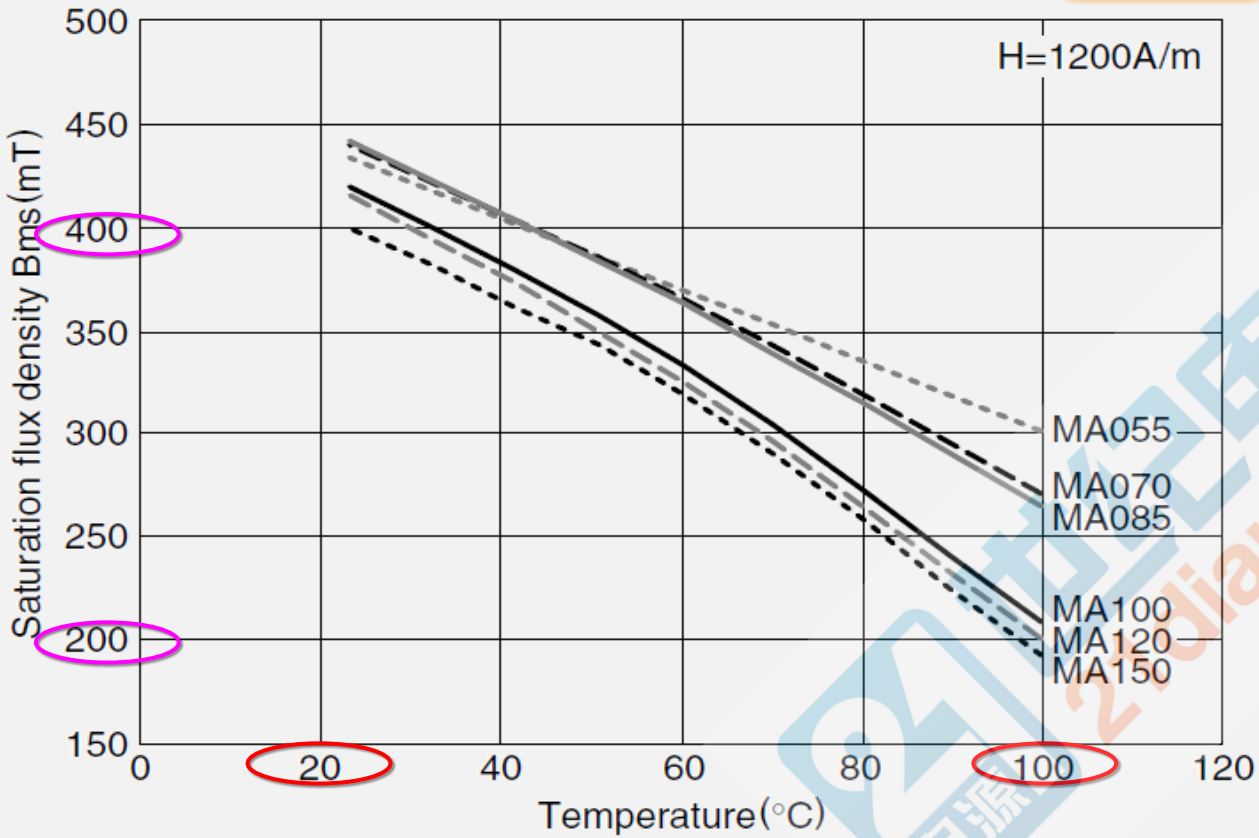
高磁导EMI共模材料（高μ铁氧体、纳米非晶）

Bms-温度特性
Saturation flux density vs. Temperature(Typical)

铁氧体



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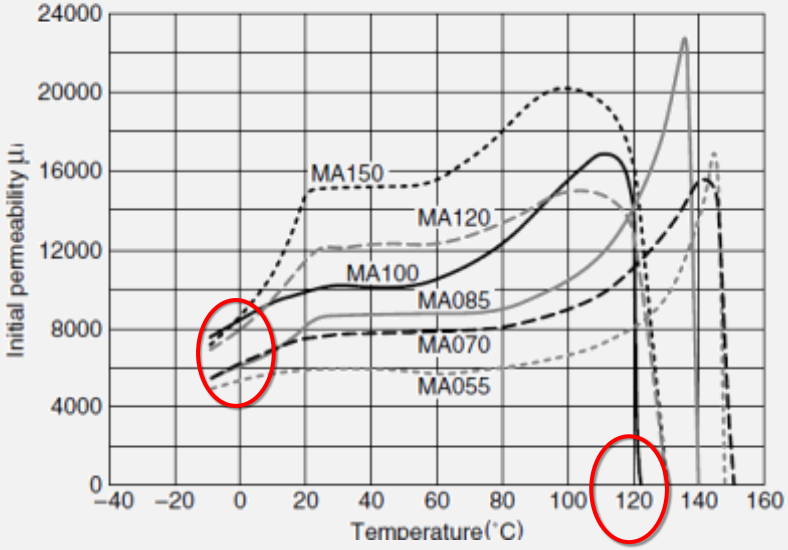
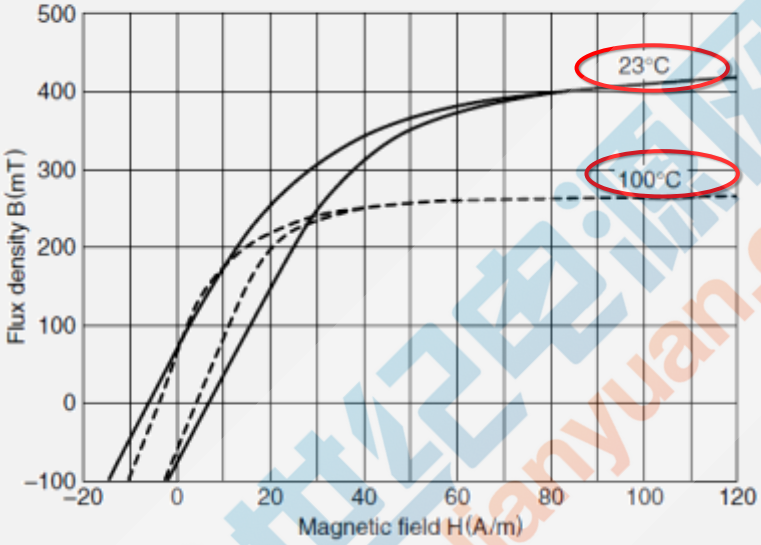
高磁导EMI共模材料（高μ铁氧体、纳米非晶）

铁氧体

μi-温度特性
Permeability vs. Temperature(Typical)



MA055 直流ヒステリシス特性
MA055 Static magnetization curves(Typical)



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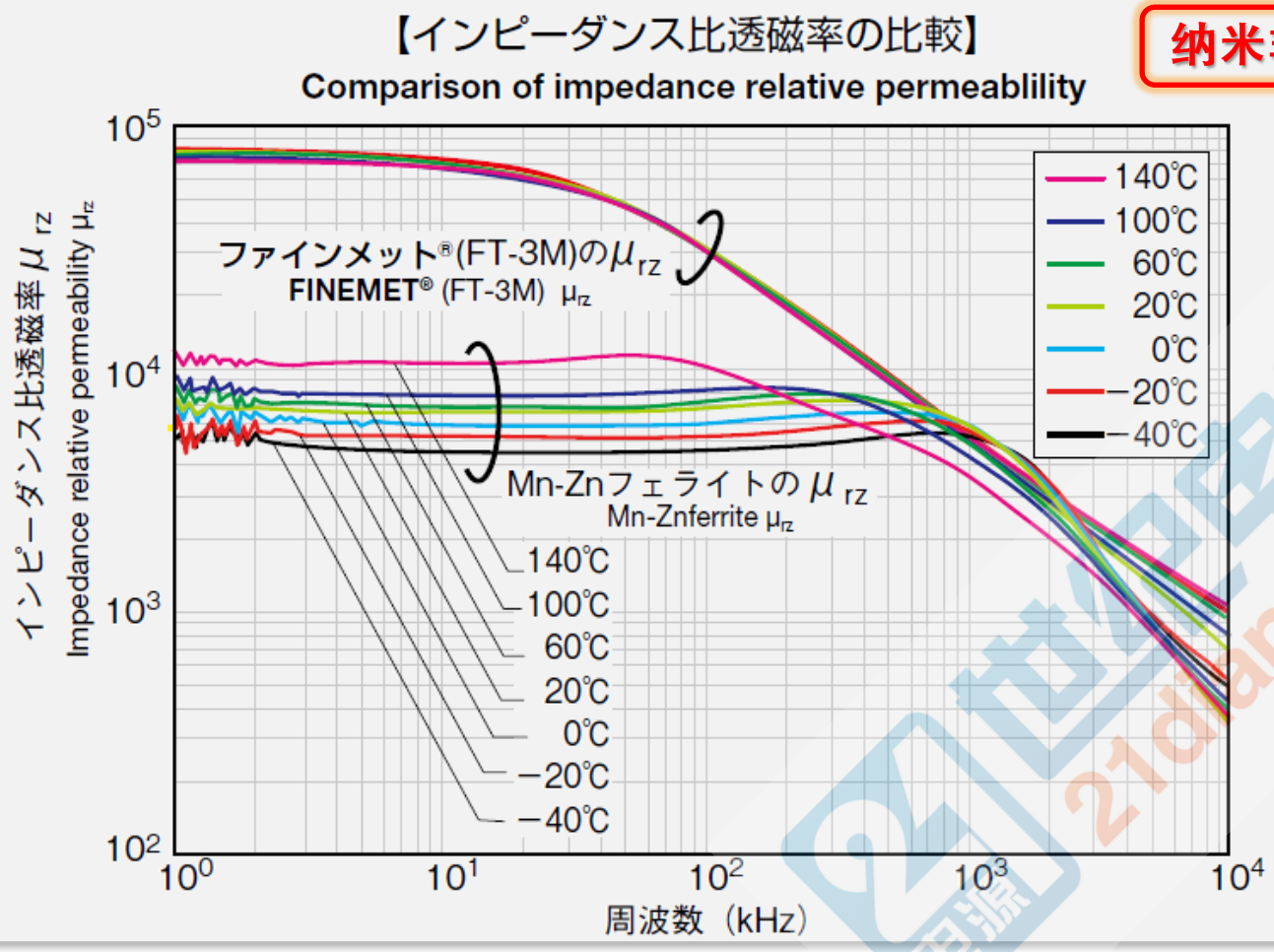
高磁导EMI共模材料（高μ铁氧体、纳米非晶）

纳米非晶



第三讲 磁元件设计技术基础

1 磁设计基本理论

磁路、磁通密度、磁感应强度、电感、变压器定义及基本模型

2 磁元件的基本概念

【磁芯】

BH特性、磁饱和、磁损耗、气隙、磁耦合和漏磁

【线圈】

直流损耗、趋附效应、临近效应、涡流损耗、阻抗特性、寄生电容、耦合系数

【元件】

温升、热阻、励磁、绕组结构、绝缘、安规

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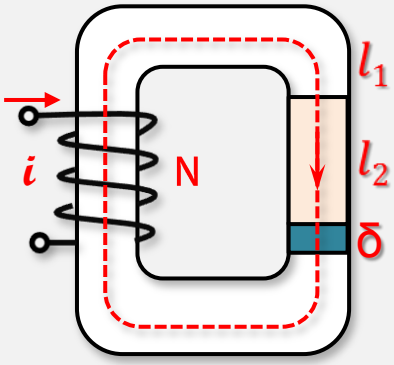
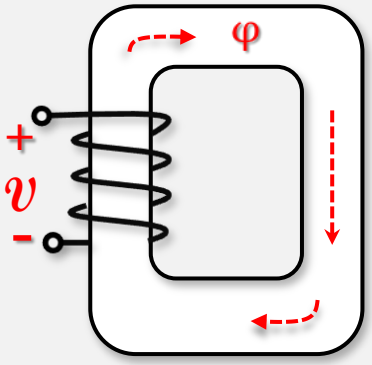
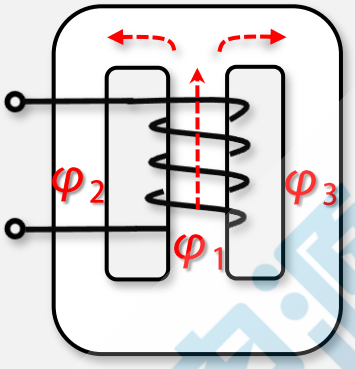
磁设计基本理论

◆ 磁路、磁通密度、磁感应强度、电感、变压器定义及基本模型







安倍环路定律

$$i \cdot N = H \cdot le = \mathcal{U}m$$

法拉第电磁感应定律

$$v = N \cdot \frac{d\varphi}{dt} = N \cdot A_e \cdot \frac{dB}{dt}$$

磁通连续性定律

$$\varphi_1 = \varphi_2 + \varphi_3$$

磁路欧姆定律

定义 $\varphi = B \cdot A_e$ $B = \mu \cdot H = \mu_0 \mu_r H$

$$\mathcal{U}m = H \cdot le = \frac{B}{\mu_0 \mu_r} \cdot le = \varphi \cdot \frac{l_e}{\mu_0 \mu_r A_e}$$ ← 磁阻$\mathcal{R}$

$$Ni = \sum_{k=1}^{3} H_k l_k = H_1 l_1 + H_2 l_2 + H_\delta \delta = \Phi_1 R_{m1} + \Phi_2 R_{m2} + \Phi_\delta R_{m\delta}$$

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磁设计基本理论

◆ 磁路、磁通密度、磁感应强度、电感、变压器定义及基本模型

安倍环路定律

$$\mathcal{U}m = i \cdot N$$

磁路欧姆定律

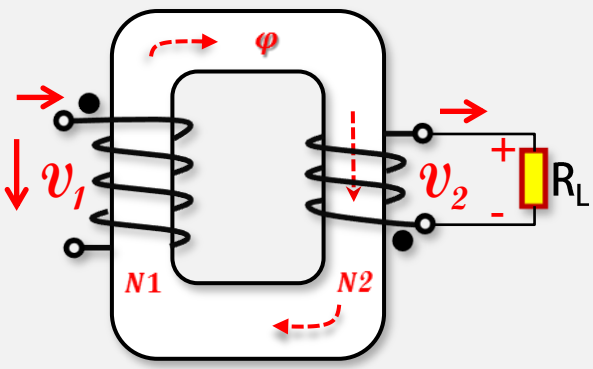
磁阻

$$\mathcal{U}m = \varphi \cdot \frac{l_e}{\mu_0 \mu_r A_e} = \varphi \cdot \mathcal{R} \Rightarrow \varphi = i \cdot N/\mathcal{R}$$

电感定义

$$L = \frac{N\varphi}{i} = N^2 \cdot 1/\mathcal{R} = N^2 \cdot \frac{\mu_0 \mu_r A_e}{l_e}$$

AL



理想变压器

$$v1 = N1 \cdot \frac{d\varphi}{dt} \quad v2 = N2 \cdot \frac{d\varphi}{dt} \Rightarrow \frac{v1}{v2} = \frac{N1}{N2}$$

$$N1 \cdot i1 + N2 \cdot i2 = \varphi \cdot \mathcal{R} = 0 \Rightarrow \frac{i1}{i2} = -\frac{N2}{N1}$$

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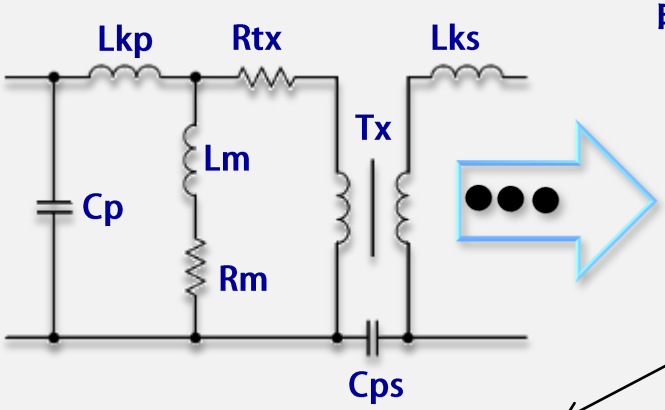
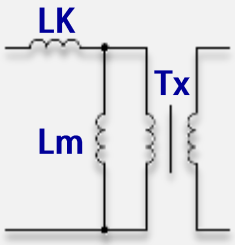
磁设计基本理论

◆ 磁路、磁通密度、磁感应强度、变压器定义及基本模型

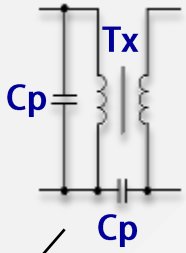
变压器模型例



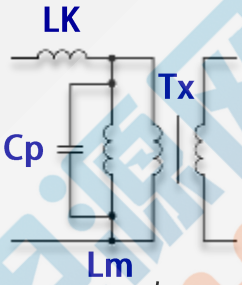
电气设计简化模型



EMI分析简化

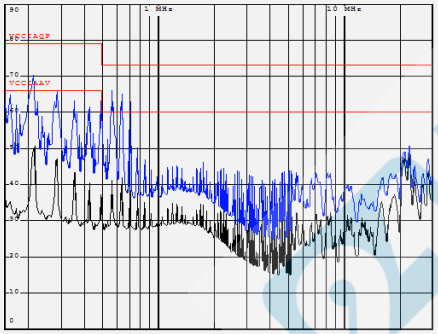


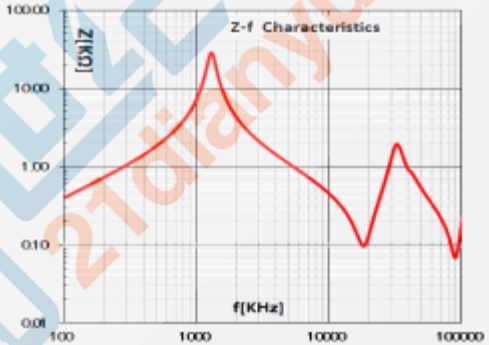
阻抗频谱分析



$$L = \frac{\mu_e \cdot \mu_0 \cdot N^2}{\sum \frac{l}{A}}$$

$$A_L = \frac{L}{N^2} = \frac{\mu_e \cdot \mu_0}{\sum \frac{l}{A}}$$





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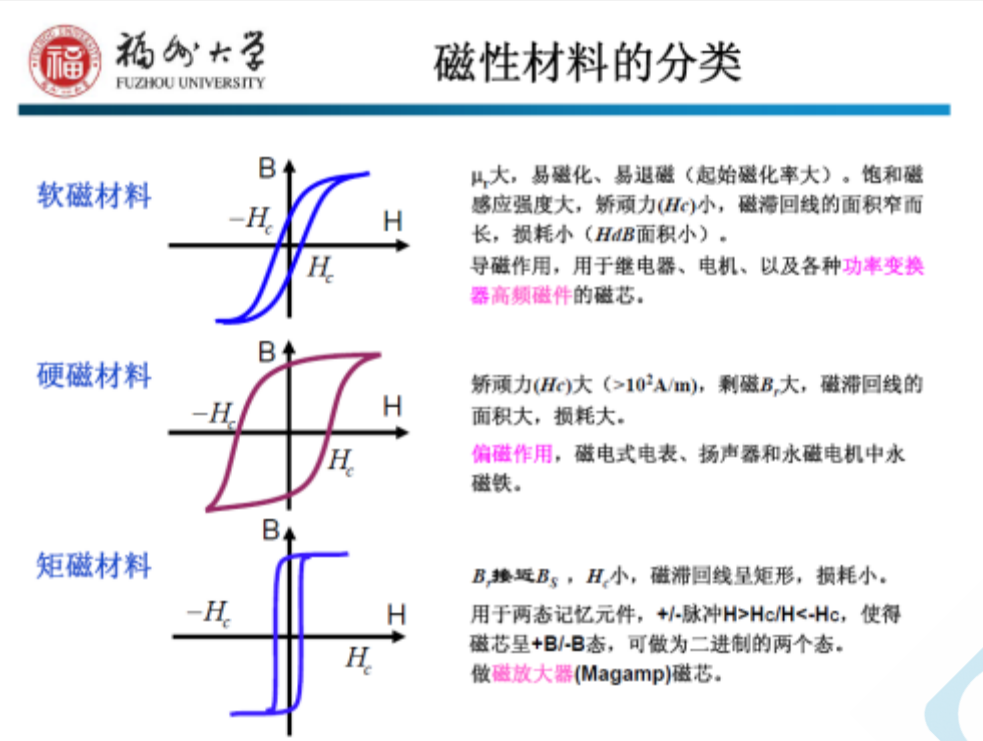
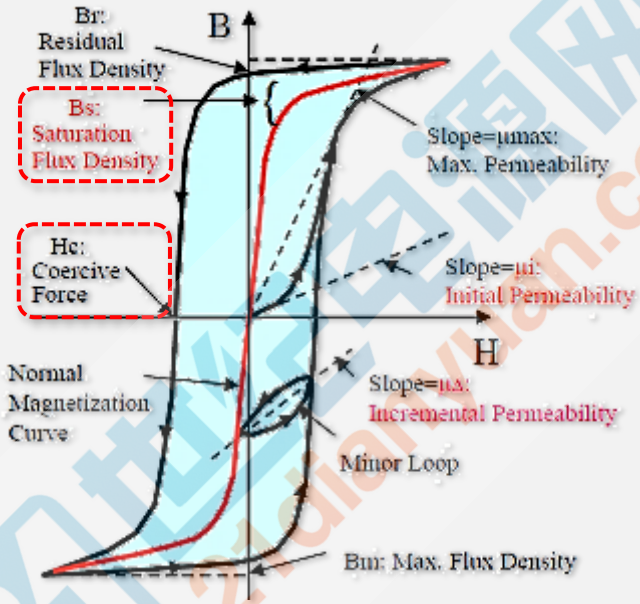
磁设计基本理论

◆ 磁元件的基本概念

【磁芯】BH特性、磁饱和、磁损耗、气隙、磁耦合和漏磁





μi, μa, μ_Δ , B_S, B_m , B_r , H_c

磁设计基本理论

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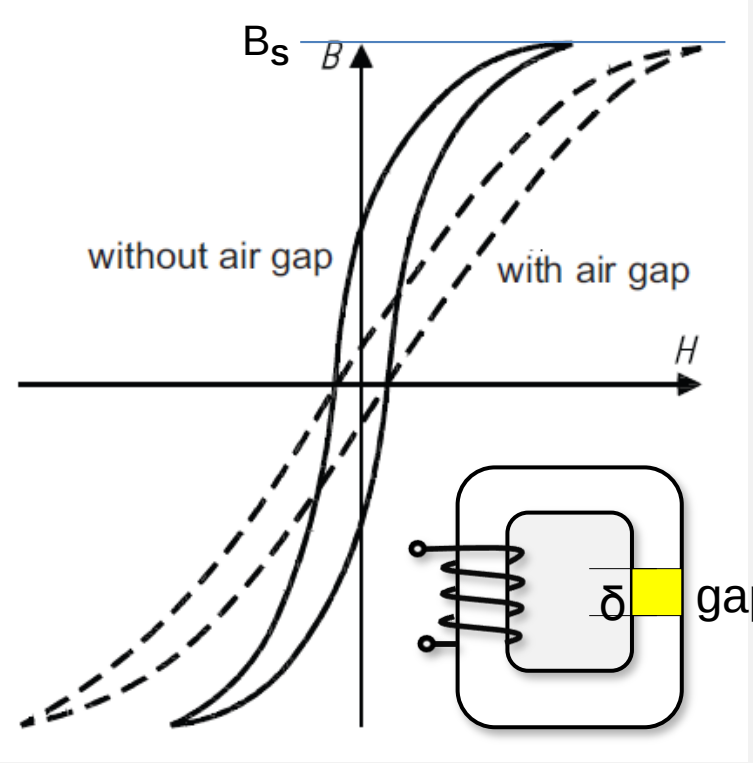

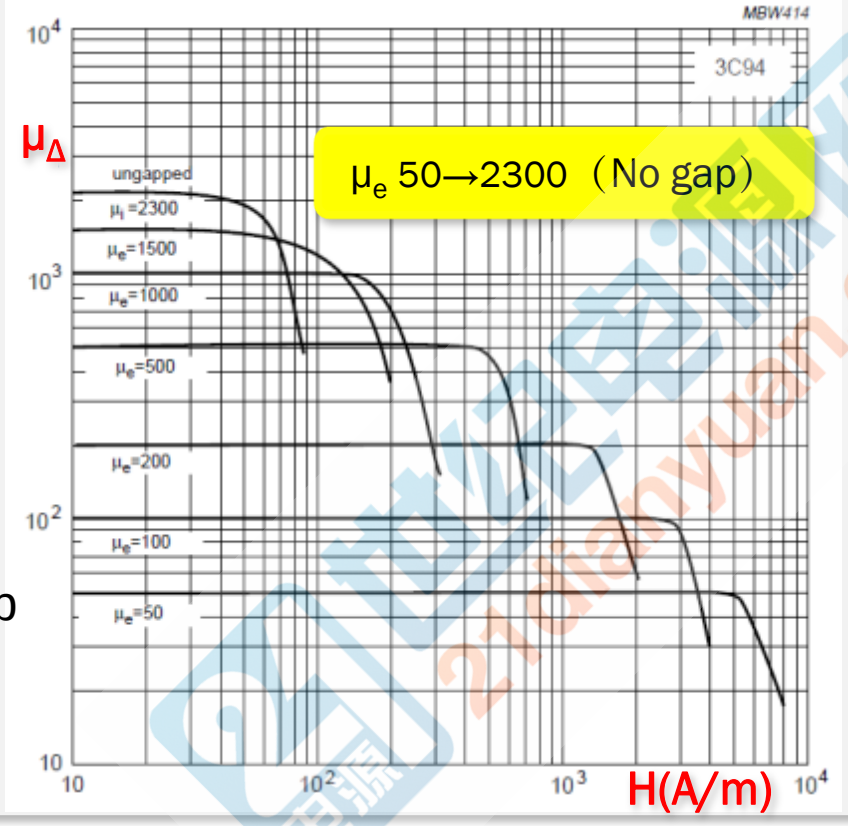

磁设计基本理论

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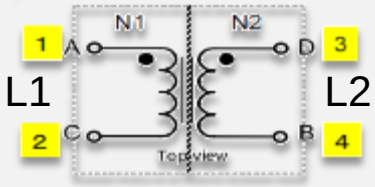
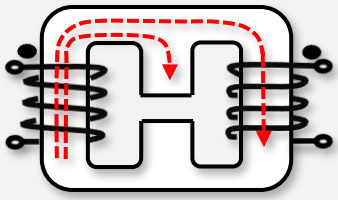
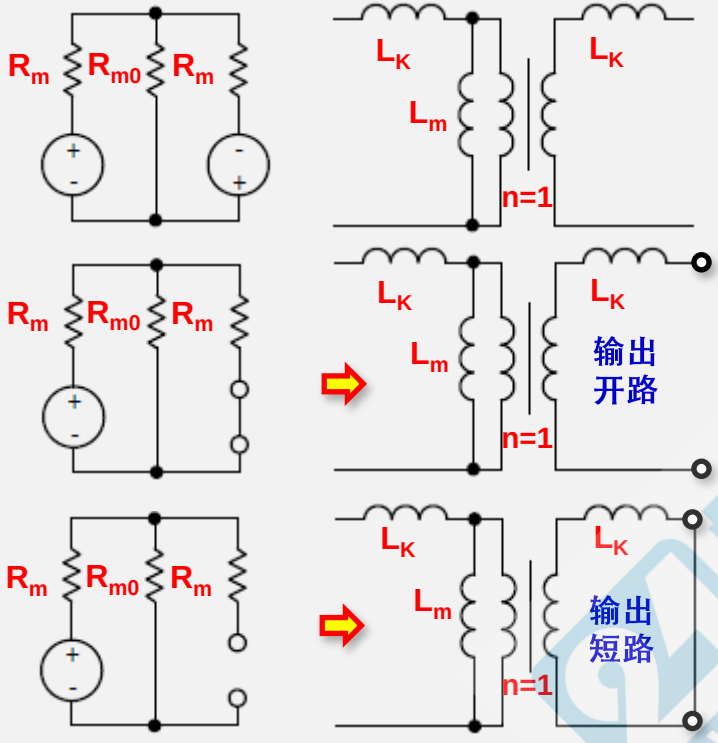




磁路对称模型
且N1=N2

等效磁路模型　　等效电路模型



耦合系数

$$k=\frac{L_m}{L_m+L_K}=\frac{R_{m0}}{R_m+R_{m0}}$$

$$\frac{N^2}{R_m+\frac{R_{m0}\cdot R_m}{R_{m0}+Rm}}=L_K+L_m=L1$$

$$\frac{N^2}{R_m+R_{m0}}=L_K+L_m//L_K$$

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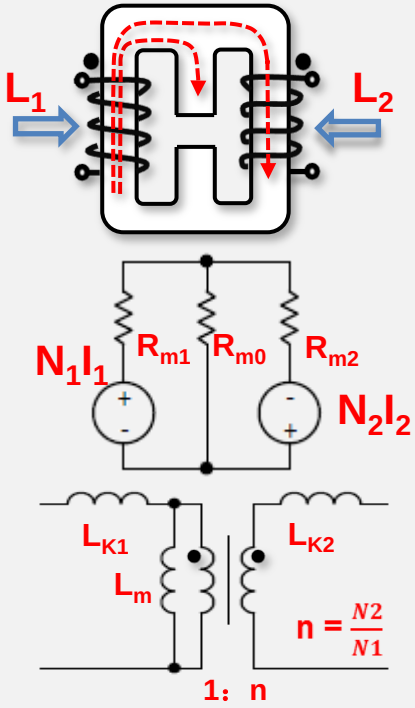
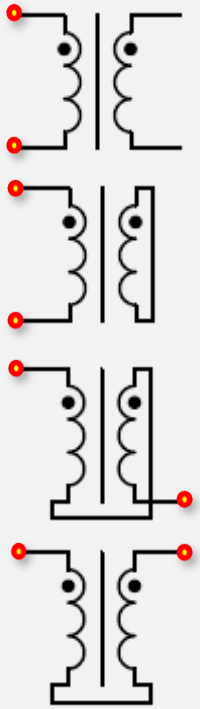
磁设计基本理论

◆ 磁元件的基本概念

【磁芯】BH特性、磁饱和、磁损耗、气隙、磁耦合和漏磁



任意磁路、N1≠N2



测量方法

$L_1 = L_{K1} + L_m$

$L_2 = L_{K2} + n^2 L_m$

$L_{s1} = L_{K1} + L_m // \left(\frac{L_{K2}}{n^2}\right)$

$L_{s2} = L_{K2} + (L_{K1} // L_m) \cdot n^2$

$L_F = L_1 + L_2 + (1 + n^2) L_m$

$L_R = L_1 + L_2 - (1 + n^2) L_m$

耦合系数

$$k1 = \frac{L_m}{L_1}$$

$$k2 = \frac{n^2 \cdot L_m}{L_2}$$

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磁设计基本理论

◆ 磁元件的基本概念

【线圈】

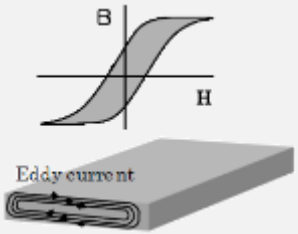
直流损耗、趋附效应、临近效应、涡流损耗、阻抗特性、寄生电容、耦合系数

①P_{core}

磁滞损耗

涡流损耗

残留损耗



$$P_V(f) \sim f^{(1+x)} \qquad 0 \le x \le 1$$

$$P_V(B) \sim B^{(2+y)} \qquad 0 \le y \le 1$$

②P_{coil}

LF：直流损耗、

HF：涡流损耗、趋肤效应、临近效应

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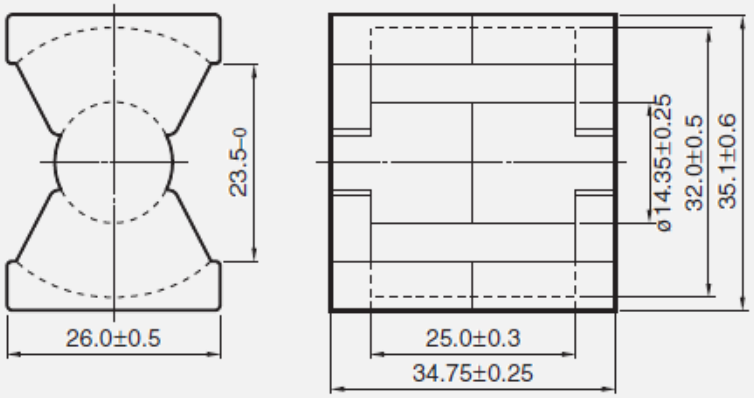
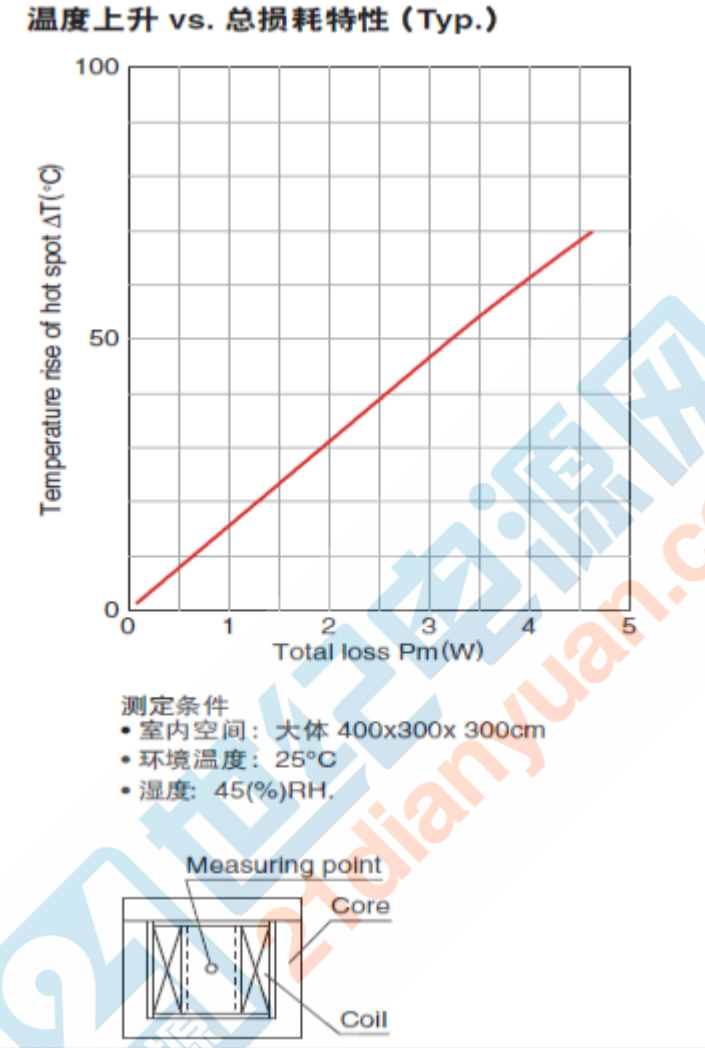
磁设计基本理论

◆ 磁元件的基本概念

【元件】 温升、热阻





第四讲 常用磁元件设计计算

1 高频功率变压器

2 反激电源变压器

3 驱动变压器

4 谐振电感

5 PFC电感（CRM、CCM、交错并联）

6 EMI共模电感

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磁元件设计计算（3KW AC/DC电源）

PFC电感、主变压器、谐振电感、输出DC电感　设计实例

Interleave PFC- 2 Boost L					
Vinac-min	Vinac-nom	Vinac-max	fsw1	ηPFC	PF
176 Vac	220 Vac	264 Vac	110KHz	98.0%	0.995
DC BUS			DC/DC		
Vbus-min	Vbus-nom	Vbus-max	fsw2	Dmax	ηDCDC
350 Vdc	418 Vdc	423 Vdc	110KHz	0.85	99.0%
DC/DC- Resonant L, T, Output L					
Vo-min	Vo-nom	Vo-max	Vd	Io-nom	Io-max
42.0 V	54.5 V	58.0 V	0.2 V	50.0 A	60.0 A

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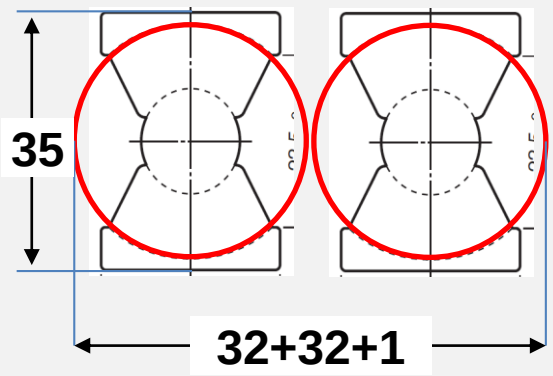
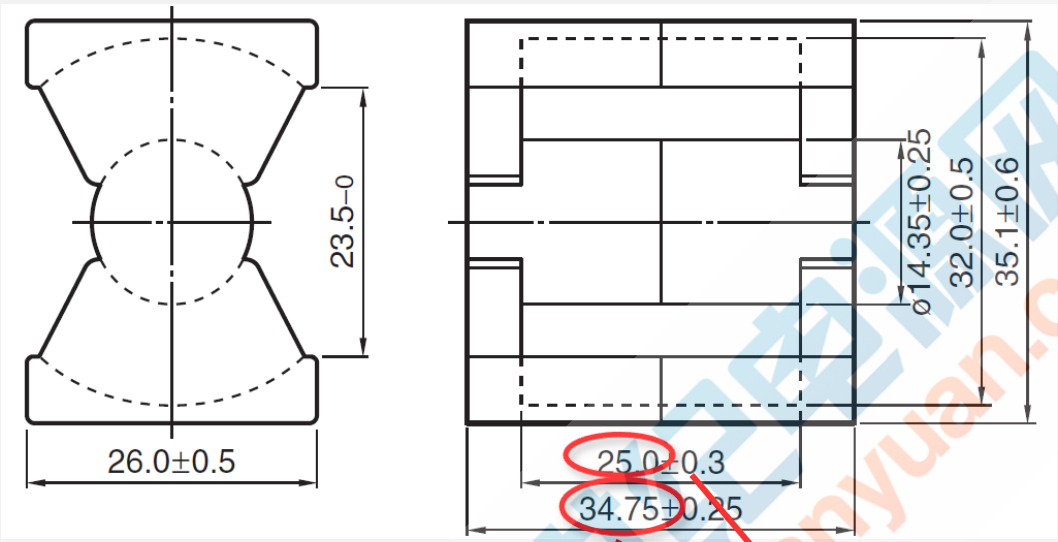
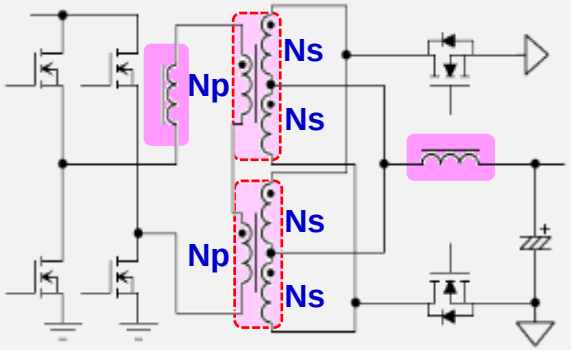
磁元件设计计算（3KW AC/DC电源）

主变压器设计

电源尺寸要求：1U，变压器空间要求：65mm*36m*33m







54.5V/50A

33-1=32　　25-3=22

原边串　N_P+N_P

副边并　$N_S//N_S$

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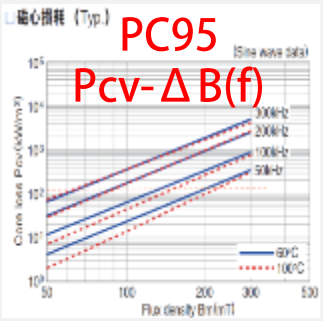
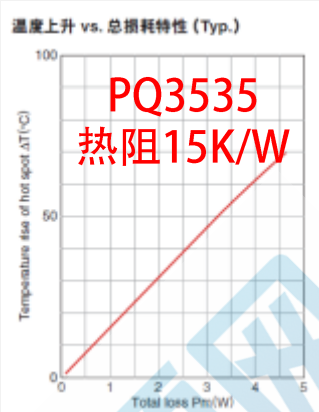
磁元件设计计算（3KW AC/DC电源）

主变压器设计

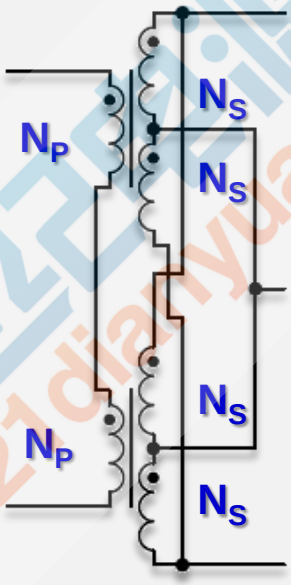
$$n = 2Np:Ns = \frac{Vbus_min \cdot Dmax}{Vo_max + Vd} = 5.11$$

$$Np = \frac{\frac{Vin_min}{2} \cdot Ton_max}{\Delta B \cdot Ae} = 13.91$$





PC95-PQ3532 (35)			Winding Window	
Ve	Ae	AL	Width	Height
17300	196	7320	10.4	22
Rt	Tmax	Ta-max	ΔT →	Pmax-PQ35
15K/W	110℃	55℃	55K	3.67W
→ Pcore		→ Pcv	→ ΔB	→ Np
50%	1.83W	106 KW/m3	0.248T	13.91
real Np	← Np ←	Ns ←		n ↓
15 T	15.3	6 T	← 5.4	5.1



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磁元件设计计算（3KW AC/DC电源）

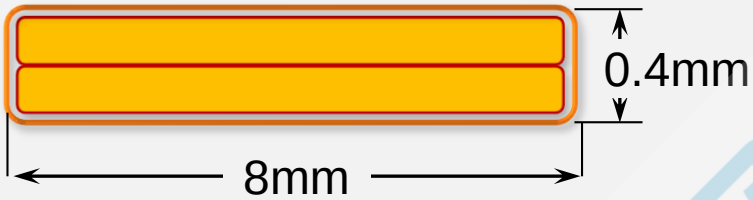
主变压器设计

Width	8	21	Height
real.Height		19.29	Cu-thick
10%	NP	0.67	0.4
8.83 A	NP	0.67	0.4
13.75 A	NS	0.77	0.5
	NP	0.67	0.4
Cu Area	NS	0.77	0.5
3.2 mm^2	NP	0.67	0.4
4.0 mm^2	NS	0.77	0.5
	NP	0.67	0.4
电密	NS	0.77	0.5
2.8 A/mm2	NP	0.67	0.4
3.4 A/mm2	NS	0.77	0.5
	NP	0.67	0.4
	NS	0.77	0.5
	NP	0.67	0.4
	NS	0.77	0.5
	NP	0.67	0.4
	NS	0.77	0.5
	NP	0.67	0.4
	NS	0.77	0.5
	NP	0.67	0.4
	NS	0.77	0.5
	NP	0.67	0.4
	NP	0.67	0.4

single-Cu	n（p）
0.2	2
0.25	2

Insulation film	
2δ	2θ
0.025	0.22

副边1	6T
原边	15T
副边2	6T



$$real.\Delta B = \frac{\frac{Vin_min}{2} \cdot Ton_max}{Np \cdot Ae} = 0.230T$$

$1.83W$

$Pcv = 99\ KW/m^3$ $real.Pcore = 1.71W$

$P_{coil} = P_{DCR} + P_{ACR}$

strap length
strap area
$\rho_{cu(100℃)}$ ⇨ Irms DCR ⇨ P_{DCR}

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磁元件设计计算（3KW AC/DC电源）

$real.Pcore = 1.71W$

strap length
strap area
$\rho_{cu(100℃)}$ ⇨ I_{rms} DCR ⇨ P_{DCR}

$$D_{pen} = \sqrt{\rho / (\pi \mu_0 \mu_r f_{sw2})} = 0.229\text{mm}$$

Q=Layer Thickness/D_{pen}

$Q_P = 0.20/0.229 = 0.87$

$Q_S = 0.25/0.229 = 1.09$

$R_{AC\text{-}P} = 1.24\ R_{DC\text{-}P}$

$R_{AC\text{-}S} = 1.60\ R_{DC\text{-}P}$

$P_{Coil\text{-}P} = 0.40 * (1+1.24) = 0.89$

$R_{Coil\text{-}S} = 0.61 * (1+1.60) = 1.60$

$P_{Total} = P_{CORE} + P_{COIL} = 1.71 + 2.49 = 4.2W$

主变压器设计

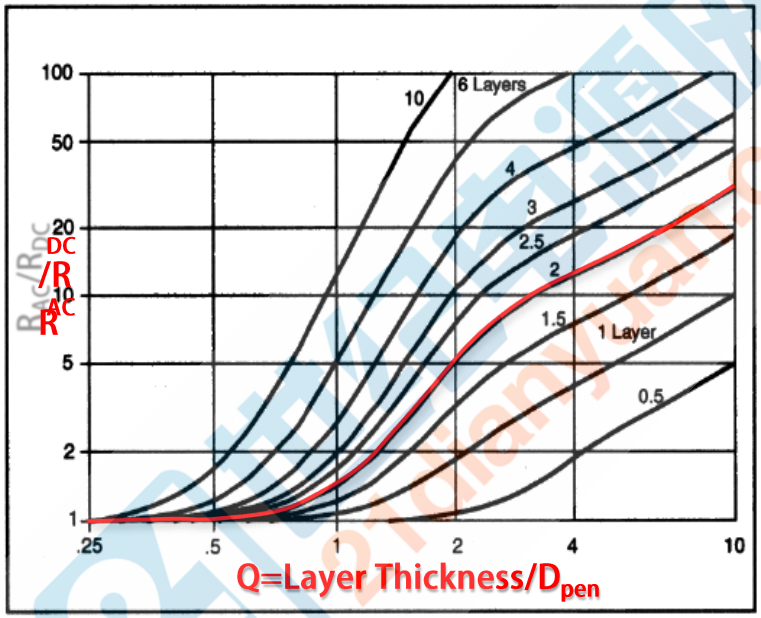

Figure. 3-5 Eddy Current Losses -- R_{AC}/R_{DC}

磁元件设计计算（3KW AC/DC电源）

主变压器设计

$P_{Total} = P_{CORE} + P_{COIL} = 1.71 + 2.49 = 4.2W$

$P_{CORE} = 41\% \ P_{total}$

$P_{COIL} = 59\% \ P_{total}$

$\Delta T = 4.2 \times 15 = 63K$ 自然冷却

同样可分别假定： $P_{CORE}/P_{Total} = 40\%, 60\%$

假定	Results							
P_{CORE}/P_{TOTAL}	N_P		N_S		P_{CORE}	P_{COIL}	P_{TOTAL}	ΔT
40%	18 T	0.15x8 2P	7 T	0.20x8 2P	2.30 W	2.03 W	4.33 W	65 K
50%	15 T	0.20x8 2P	6 T	0.25x8 2P	1.71 W	2.49 W	4.20 W	63 K
60%	12 T	0.20x8 3P	5 T	0.23x8 3P	1.02 W	2.82 W	3.84 W	58 K

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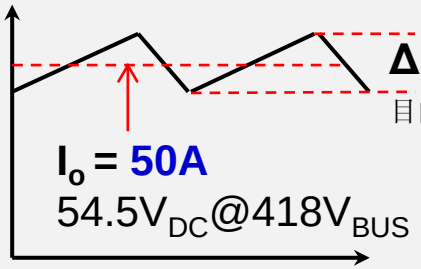
磁元件设计计算（3KW AC/DC电源）

输出滤波电感



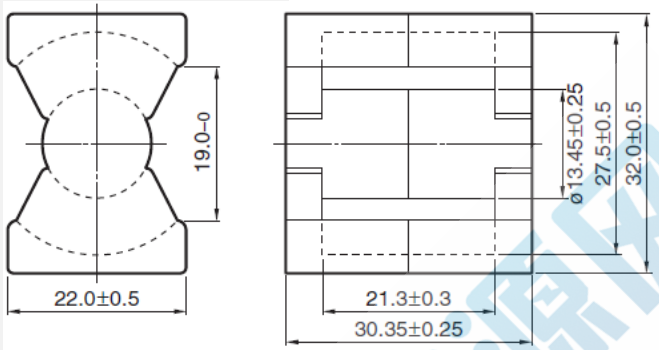
$A_L = 222.58 \times Ig^{-0.8109}$

Temp: 100°C

$NI_{20\%} = 56339 \times A_L^{-1.0191}$

$NI_{40\%} = 49671 \times A_L^{-0.9869}$

PC95PQ32/30Z-12



ΔI_{SP-P}	$D_{nom/max}$	$Ton_{nom-max}$	Lo	Io-rms	Io-max	Inductance Rating	
12.5 A	69.6%	3.16 uS	6.4 uH	50.1 A	66.3 A	6.5 uH	70 A

Ve	Ae	Acw	φavg	Rt	N	real-N	AL
12000	161	149.6	20.5	18.7	8.8 T	9 T	80 nH

B_{max}	ΔB	Pcv	Pcore	DCR_100℃	Pcoil	ΔT	Lg
0.314 T	56 mT	11 KW/m3	**0.13 W**	1.0 mΩ	**2.52 W**	**50 K**	3.5 mm

磁元件设计计算（3KW AC/DC电源）

输出滤波电感

$$L_o = (Vo_{max} - Vd) \cdot Toffn_{om_max} / \Delta I_{SP_P}$$

$$I_{o_rms} = \sqrt{I_{o_nom}^2 + \Delta I_{SP_P}^2/12}$$

$$N = \left(\frac{56339 \cdot Lo^{-1.0191}}{I_{L_{rating}}}\right)^{\frac{1}{1+2\cdot(-1.0191)}}$$

$$B_{max} = \frac{N \cdot I_{L\ rating} \cdot AL}{Ae} \qquad \Delta B = Bmax \cdot \frac{\Delta I_{SP-P}}{I_{L\ rating}}$$

PC95PQ32/30Z-12

Temp: 100°C

$NI_{20\%} = 56339 \times AL^{-1.0191}$

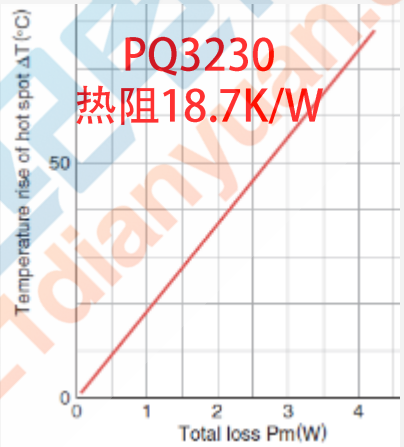
$NI_{40\%} = 49671 \times AL^{-0.9869}$

$AL = 222.58 \times lg^{-0.8109}$

ΔI_{SP-P}	$D_{nom/max}$	$Ton_{nom-max}$	Lo	Io-rms	Io-max	Inductance Rating	
12.5 A	69.6%	3.16 uS	6.4 uH	50.1 A	66.3 A	6.5 uH	70 A

Ve	Ae	Acw	ϕavg	Rt	N	real-N	AL
12000	161	149.6	20.5	18.7	8.8 T	9 T	80 nH

B_{max}	ΔB	Pcv	Pcore	DCR_100℃	Pcoil	ΔT	Lg
0.314 T	56 mT	11 KW/m3	0.13 W	1.0 mΩ	2.52 W	50 K	3.5 mm



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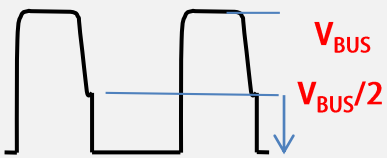
磁元件设计计算（3KW AC/DC电源）

谐振电感

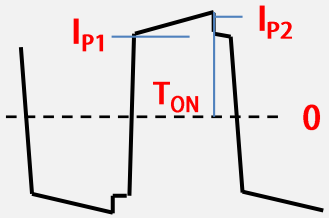
Pos.Vds



$$P_{on_sw} = \frac{C_{oss}}{2} \cdot U_c^2 \cdot f_{sw} = \frac{1}{4} \cdot \left(\frac{C_{oss}}{2} \cdot V_{BUS}^2 \cdot f_{sw}\right)$$

为了取得更高的效率，不必要实现Full-ZVS

Resonant. I_P



$$\Delta Im = \frac{V_{BUS\ nom}}{2 \cdot Lp} \cdot Ton_{_nom}$$

$$T_{on_nom} = \frac{V_{o\ nom} - VD}{V_{BUS\ nom}} \cdot n$$

$$L_P = N_P^2 \cdot AL$$

$$\Delta Im = 0.375A$$

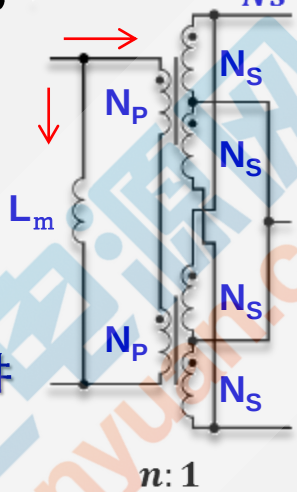
$$I_{P1} = 8.75\ A$$

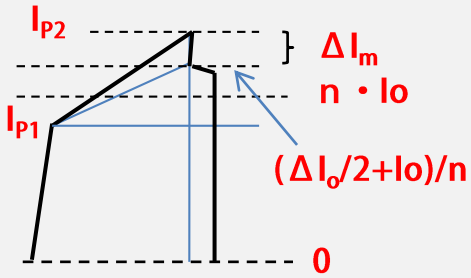
$$I_{P2} = 11.62A$$

$$I_{P_RMS} \approx 6.7A$$

谐振电感的电流条件

$$n = 2Np/Ns$$





谐振电感电感量确定

MOS Coss能量

续流能量损失

轻载条件(例20%负载)

谐振感量L

21世纪电源网 21dianyuan.com

磁元件设计计算（3KW AC/DC电源）

谐振电感

谐振电感电感量确定

MOS Coss能量
续流能量损失
轻载条件(例20%负载)

谐振感量L

infineon IPW60R099C7

600V CoolMOS™ C7 Power Transistor

Eoss@400V 4.95 μJ

续流时原边电流$I_{P_F.W}$

$I_{P_F.W}=I_{P2}-\Delta I_m=11.25A$

$$P_{mos}=E_{oss}\cdot f_{sw}\cdot\left(\frac{V_{bus\ nom}}{400}\right)^2\cdot 2=1.2\ W$$

20%负载时谐振电感能量

$$P_{L_resonant}=\frac{1}{2}\cdot L_{resonant}\cdot I_{P_F.W}^{\ 2}\cdot f_{sw}=0.84\ W \quad (@\ 3uH)$$

MOS Coss电容器残留能量$<\frac{1}{3}$，相当于Vds剩余20%的电压，由此断定：**3uH 足够**

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磁元件设计计算（3KW AC/DC电源）

谐振电感

谐振电感电感设计 3uH，7Arms，35Ap-p 150%过载

$$N = \left(\frac{23708 \cdot L_{resonant}^{-1.0232}}{I_{P2} \cdot 150\%}\right)^{\frac{1}{1-2\cdot 1.0232}}$$

$$= 9.6T \rightarrow 10T$$

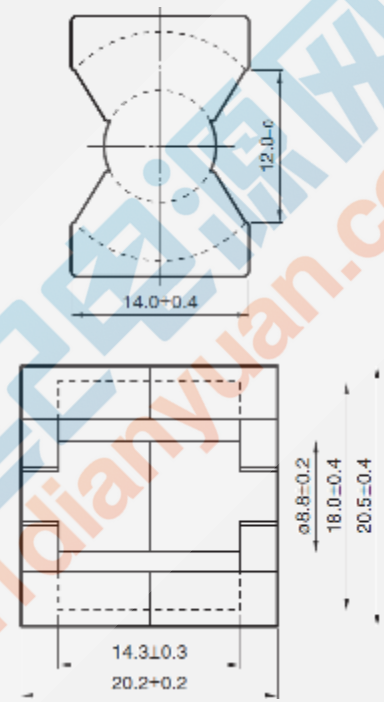
$$P_{loss} = P_{CORE} + P_{COIL} = 0.09 + 0.22 = 0.31W$$

$$\Delta T = 11\ K$$

PC95PQ20/20Z-12

$NI_{20\%} = 23708 \times A_L^{-1.0232}$

$A_L = 103.22 \times lg^{-0.7272}$



Ae	Ve	Acw	Rt	Ires.P-P	fsw	IP-rms
62	2790	65.8	35 K/W	23.2A	110 KHz	7 A
$L_{resonant}$	I_pp_max	N	real N	AL	gap	ΔB/2
3 uH	35 A	9.6 T	10 T	30 nH/N2	5.5 mm	0.056 T
real Acw/T	Cu-Ae	Length/T	DCR	Pcoil	Pcv	Pcore
4.61 mm2	2.30 mm2	45.6 mm	4.5 mΩ	0.22 W	33 KW/m3	0.09 W
					ΔT	11 K

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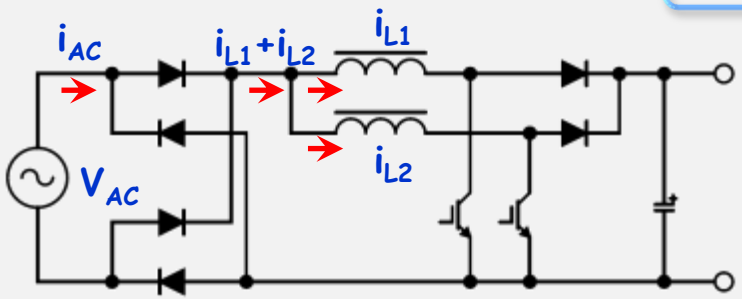
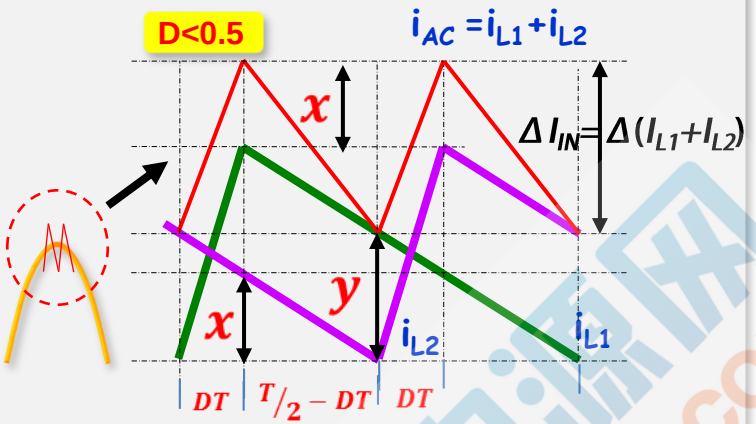
磁元件设计计算（3KW AC/DC）

CCM Interleave PFC电感





交错并联电感电流纹波叠加

D<0.5

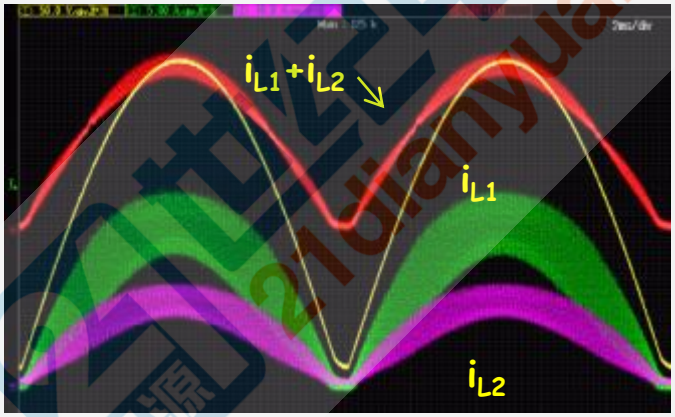
$$\Delta I_{L1+L2}=\frac{V_{in}}{L}\cdot DT+\frac{V_{in}}{L}\cdot DT-\frac{V_o-Vin}{L}\cdot\frac{1}{2}-\left(\frac{V_{in}}{L}\cdot DT-\frac{V_o-Vin}{L}\cdot\left(\frac{1}{2}-D\right)T\right)$$

$$=\frac{2V_{in}-Vo}{L}\cdot DT$$

同理

D>0.5

$$\Delta I_{L1+L2}=\frac{V_{in}}{L}\cdot(2D-1)T$$



其中 V_{in} 交流输入工频峰值电压、
Vo PFC直流输出电压
L 单个PFC电感感量

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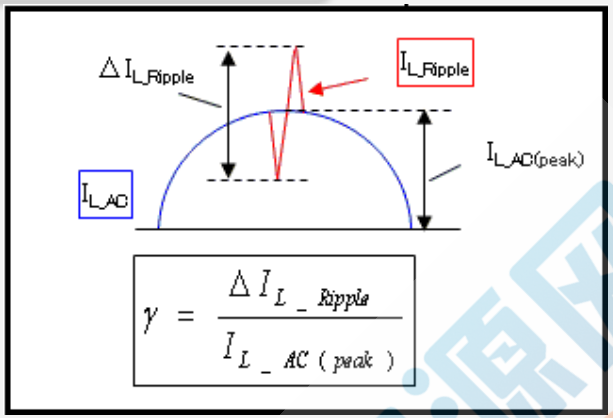
磁元件设计计算（3KW AC/DC）

CCM Interleave PFC电感

- 传导EMI低频段影响
- 滤波电容高频耐力
- 主电路开关应力损耗

例： $\gamma \leq 15\%$

Vinac-nom	Vbus-nom	fsw1
220 Vac	418 Vdc	110KHz
Vo-nom	**Io-nom**	**η**
54.5 V	50.0 A	97%



$$\gamma = \frac{\Delta I_{L_Ripple}}{I_{L_AC(peak)}}$$

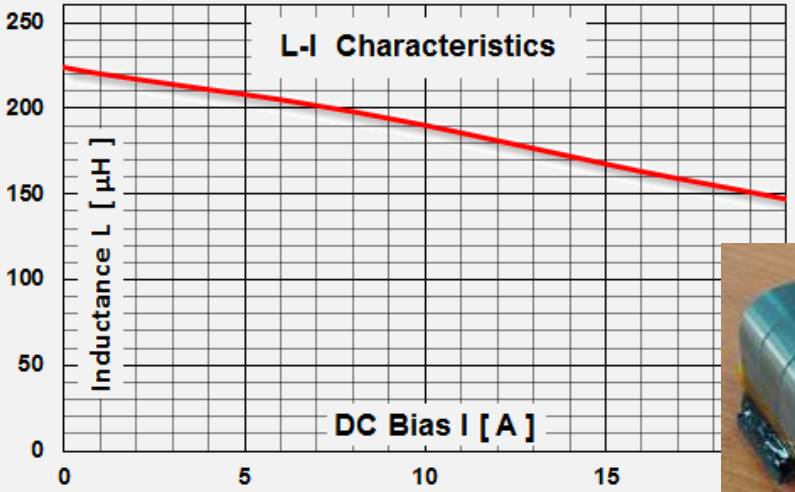
CCM Interleave PFC Tools

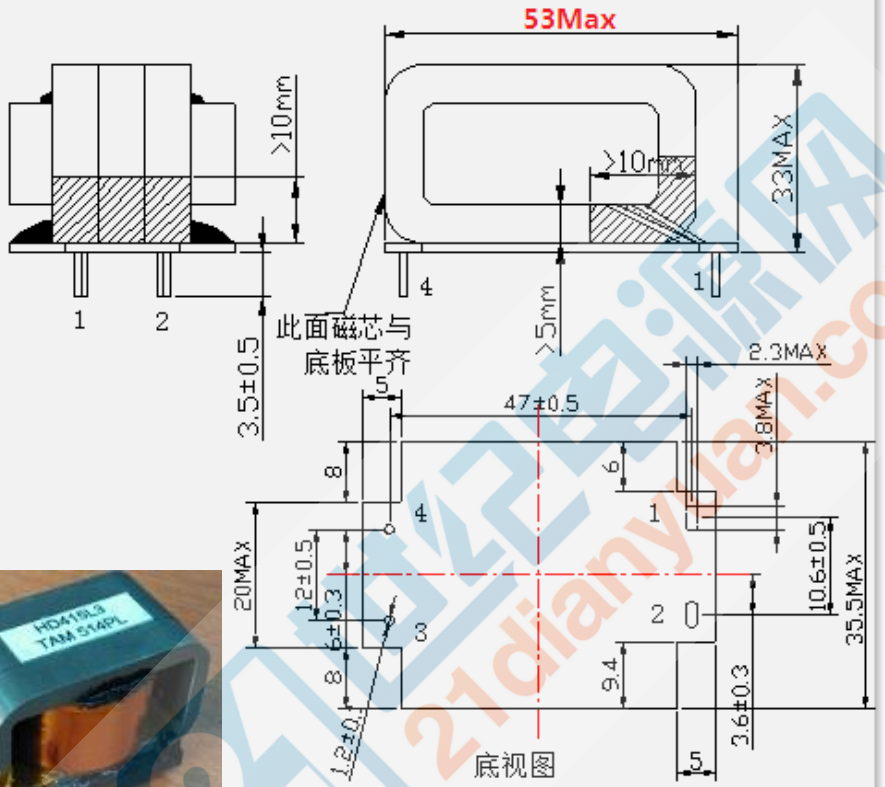
Discription	Variable Names	Vin min.		Vin nom		Vin max
Input rms Voltage	V_in_rms	176 V	200 V	220 V	240 V	264 V
Output Voltage	V_{OUT}	418 V	418 V	418 V	418 V	418 V
Output max Power	Pout(max)	2725 W	2725 W	2725 W	2725 W	2725 W
PFC Efficiency	η	95.4%	96.1%	97.0%	97.8%	98.8%
Reactor Induct	L1,L2(assume)	180 uH	180 uH	180 uH	180 uH	180 uH
Fixed Frequency	Frequency	110 KHz	110 KHz	110 KHz	110 KHz	110 KHz
Input Sine PK Current	I_in_ac_pk	23.0 A	20.0 A	18.1 A	16.4 A	14.8 A
Duty at Sine PK	Duty_sin_pk	40.5%	32.3%	25.6%	18.8%	10.7%
Max Current at sine PK of L1	Imax(L1,L2)_sin_pk	14.0 A	12.3 A	11.0 A	9.8 A	8.4 A
RMS current of each reactor	Irms(L1,L2)	8.2 A	7.2 A	6.5 A	5.9 A	5.3 A
Input current ripple (I_L1+I_L2)	ΔI(in)_pk	1.63	2.41	2.64	2.48	1.77
Boost Inductor Ripple/AC Current(pk-pk)	γ	7.1%	12.0%	14.6%	15.1%	12.0%

磁元件设计计算（3KW AC/DC） CCM Interleave PFC电感

$\gamma \leq 15\%$ ⇨ L1、L2 180uH @11A，6.5A.rms

L (Typ.)	**180 μH**	11 A
DCR (Typ.)	**22mΩ**	25℃
Appearance （mm^3 Max.)	**53 × 35.5 × 33**	





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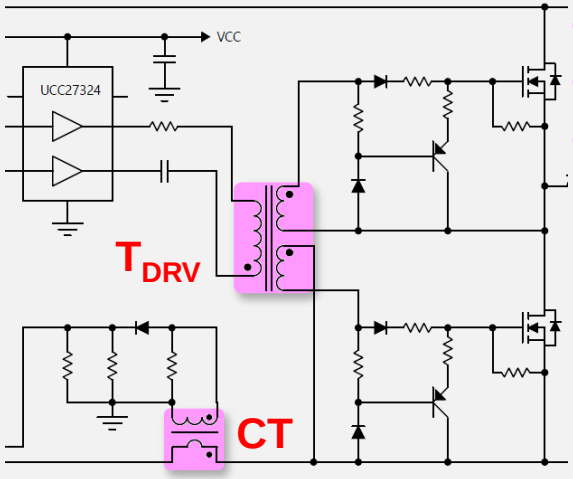
磁元件设计计算（3KW AC/DC）



- 辅助电源变压器T_{AUX}
- 驱动变压器T_{DRV}
- 电流互感器CT

驱动变压器设计 注意事项

- ✓ 绝缘处理
- ✓ 漏感解决方法
- ✓ 励磁电感确定原则
- ✓ 减小不必要的功率传输

CT电流互感器设计 注意事项

- ✓ 匝数多 → 减小损耗
- ✓ 避免输出开路
- ✓ 大占空比的单边直流脉冲检测
- ✓ 防止饱和的设计与判定

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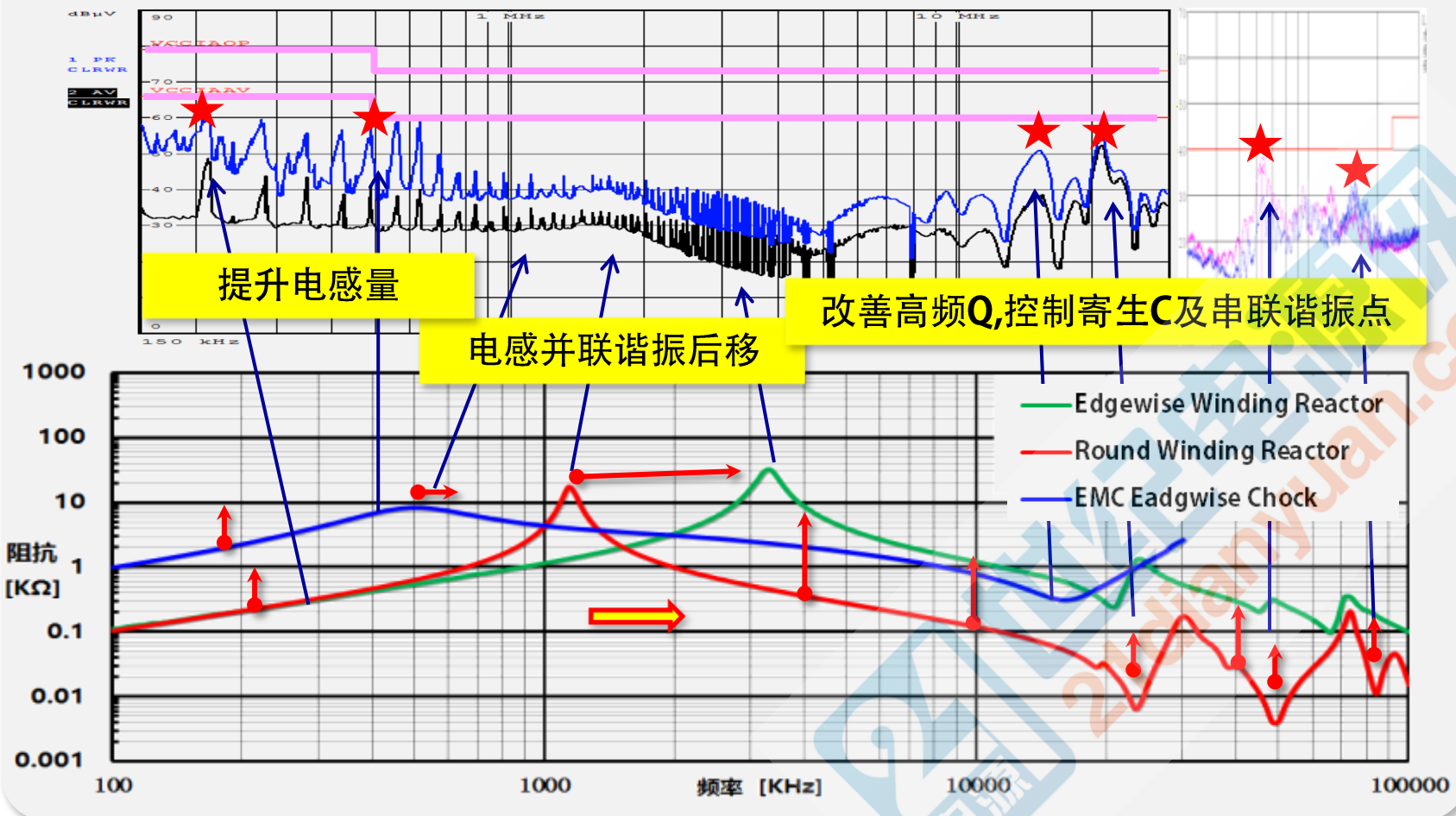
磁元件设计计算（3KW AC/DC） 共模电感设计要点



第五讲 磁元件设计最新技术前沿介绍

1 磁元件仿真技术

2 改变世界的磁元件设计创新
磁集成技术、混合磁路技术、L-I trimming技术、SpikeBlocker技术等

< UPS、服务器电源、光伏、充电桩、APF、变频空调应用最前沿 >

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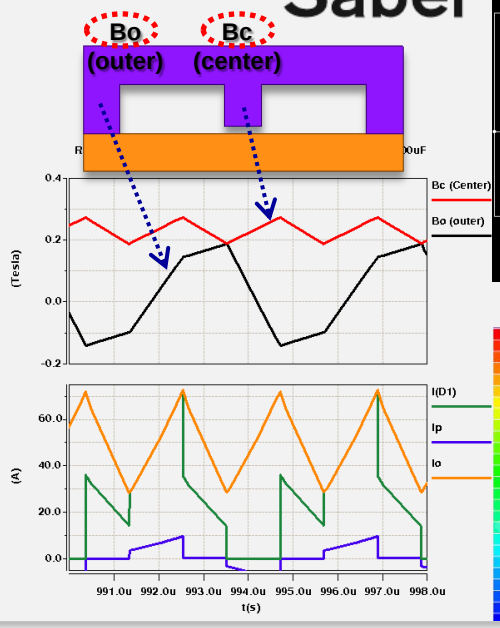
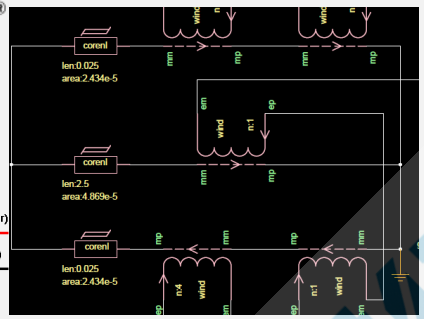
磁元件仿真技术介绍

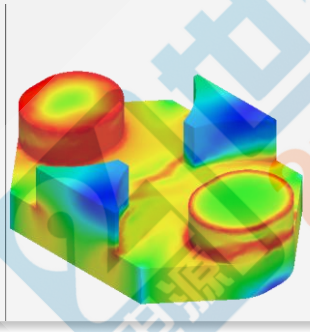
常用磁仿真软件

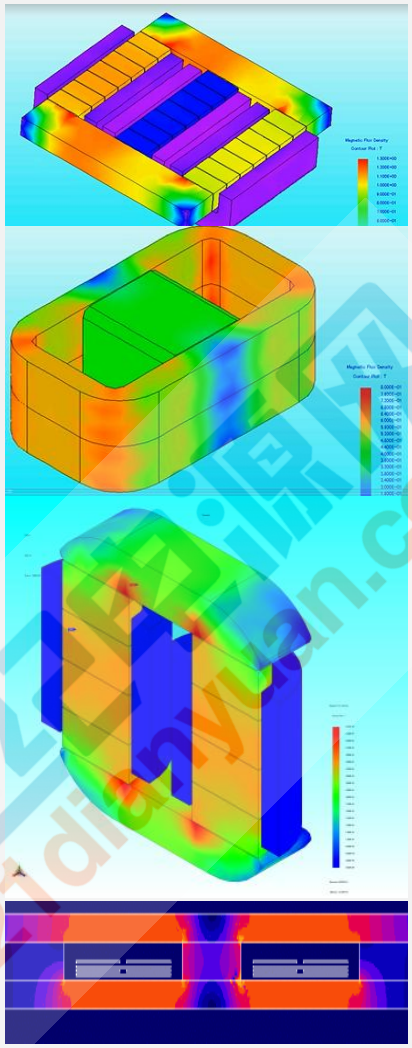
- Maxwell 2D 3D， PExprt
- JMAG
- FLUX
- Saber

- 资源要求
- 解析速度
- 建模效率
- 应用技巧
- 精度局限





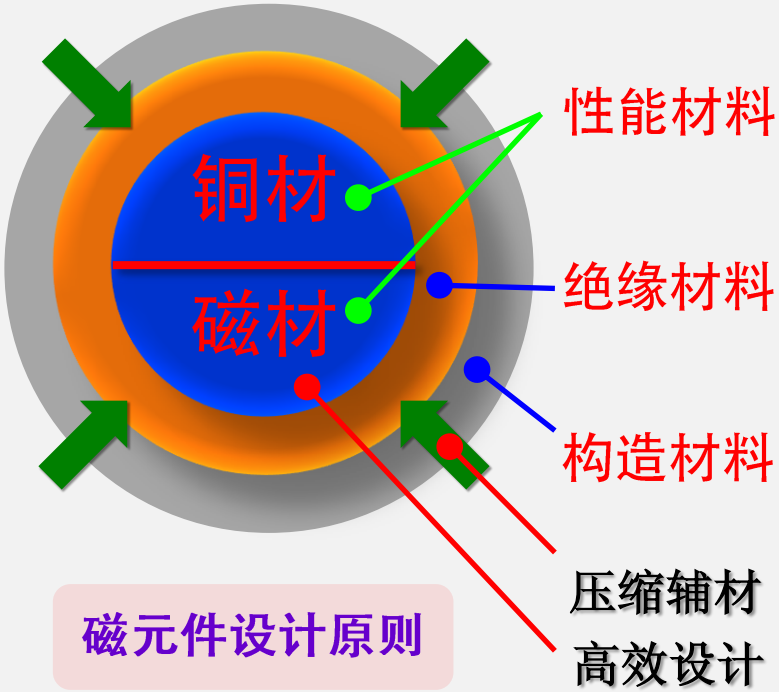




改变世界的磁元件设计创新

世界最先端パワー磁気技術

Innovation & Creation



磁元件设计原则

材料技术

+

应用技术

+

自动化技术

核心竞争力

- 材料改性
- 材料创新
- 工艺创新

根本

- 高性能低损耗
- 高附加价值
- 简单化低成本
- 自动化设计

途径

- 高品质生产
- 高效率生产
- 快速成本摊销

手段

突破

关键工艺瓶颈
关键质量瓶颈
关键成本瓶颈

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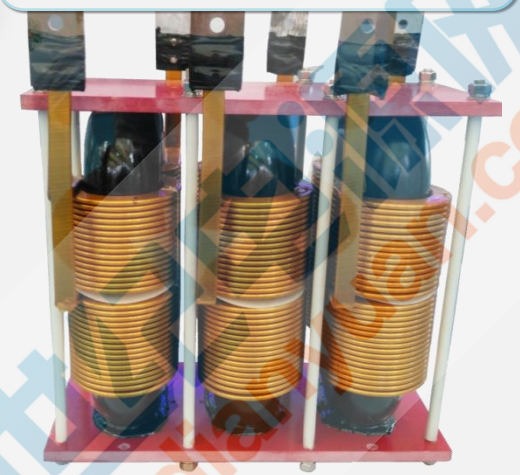
改变世界的磁元件设计创新

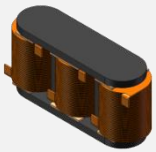
【磁元件技术】 优化、简约、易造、喜爱

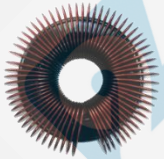
磁元件技术最前沿

Integrated Magnetics	磁気複合技術 磁集成技术
Hybrid Technique	ﾊｲﾌﾞﾘｯﾄﾞ磁気技術 混合磁路技术
Acoustic Technique	低騒音技術 静音技术
L-I Trimming Technique	L-Iトリミング技術 L-I Trimming技术
Big Powder Technique	大型リアクタ設計 超大型磁粉芯技术
Spike Blocker®	低EMCノイズ技術 Spike Blocker技术
Edgewise Technique	ｴｯｼﾞﾜｲｽﾞ設計 大功率立绕工艺

技术创新提升
磁元件核心竞争力







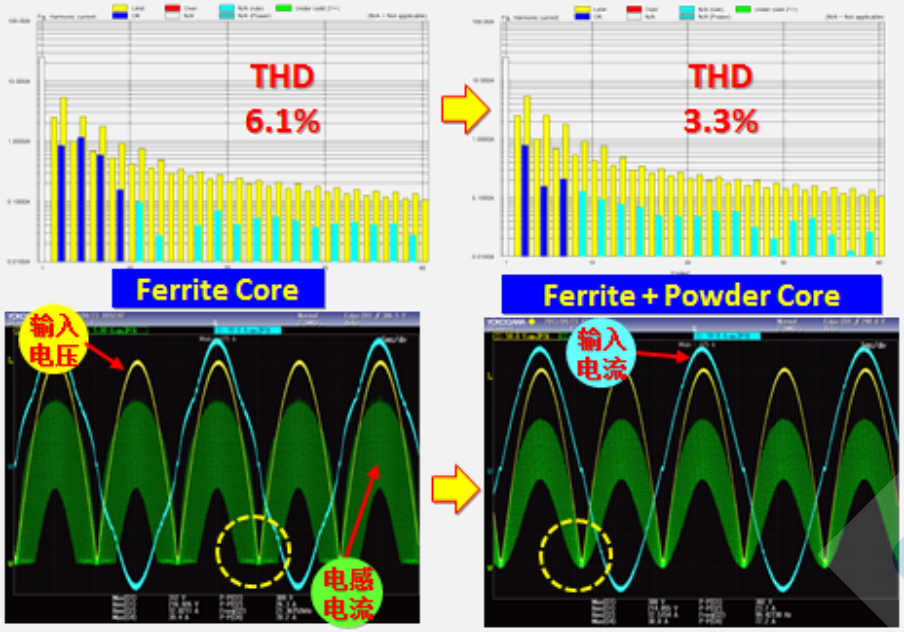
改变世界的磁元件设计创新

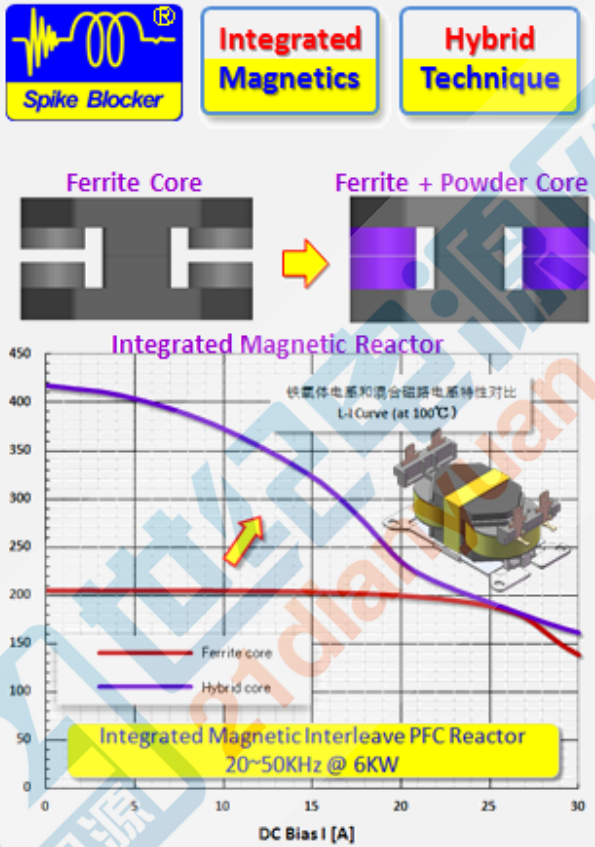
磁集成技术、混合磁路技术、L-I trimming技术、SpikeBlocker技术等

6KW混合磁路CCM PFC磁集成电感

高效率，大容量，低成本，高功率密度，EMC优异

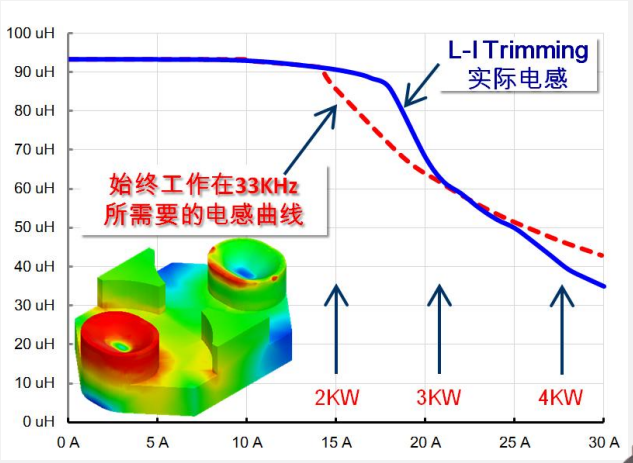
- 铁氧体与铁硅混合磁路
- 极少的漏磁提高功率密度
- L-I特性利于更低的THD
- 混合磁路提高电源效率

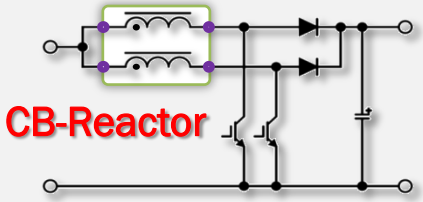


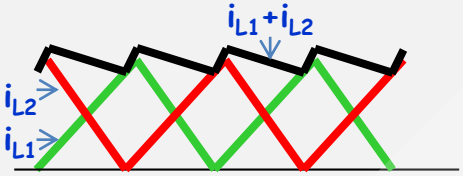


改变世界的磁元件设计创新

磁集成技术、混合磁路技术、L-I trimming技术、SpikeBlocker技术等



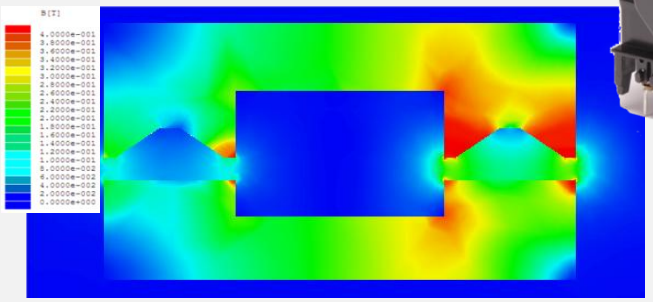


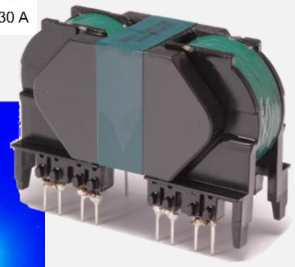


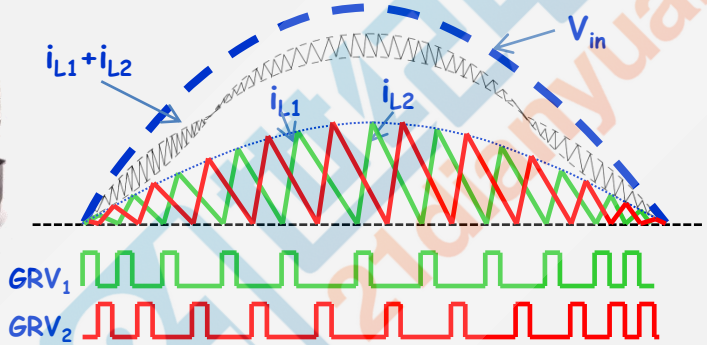
L-I Trimming Technique

Integrated Magnetics

Spike Blocker





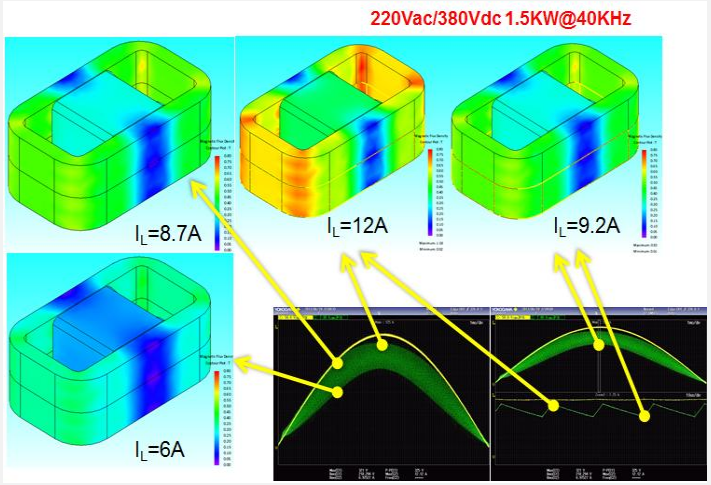


世界首创3KW IGBT CRM 交错式 PFC的实现

改变世界的磁元件设计创新

磁集成技术、混合磁路技术、L-I trimming技术、SpikeBlocker技术等

最佳磁芯尺寸确定

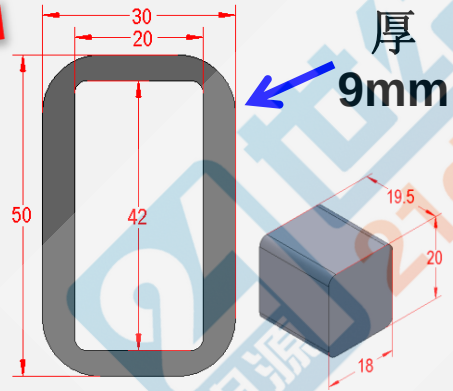


性能、可靠性、品质
量产性、成本竞争力
150s 一次性解决！

市场需求与技术融合

- 应用要求
- 材料技术
- 磁元件技术
- 电源技术
- 自动化技术

磁芯形状



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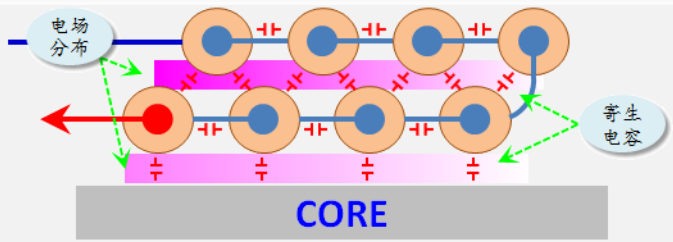
改变世界的磁元件设计创新

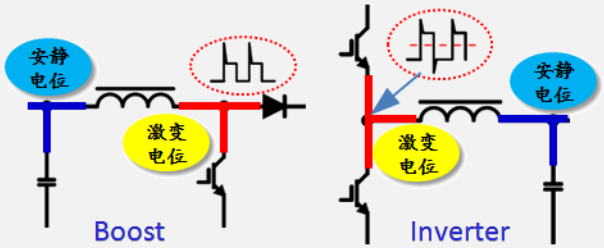
磁集成技术、混合磁路技术、L-I trimming技术、SpikeBlocker技术等

电感的EMC电磁兼容问题（机理）



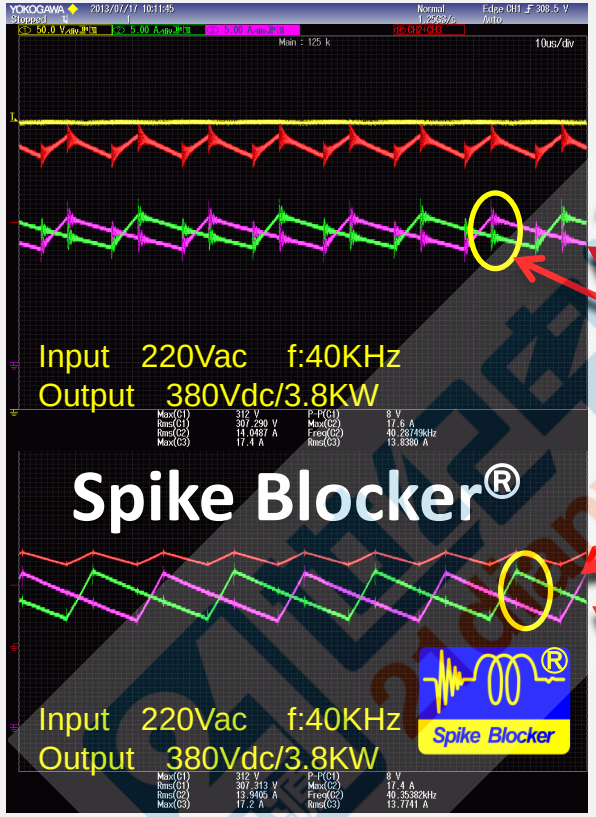
Parasitic capacitor construction

绕线间存在大量复杂的分布电容和漏感



电感两端始终存在高dV/dt对电容高频充放电

电感的复杂的LCR网络产生1MHz以上频谱丰富的高频振荡电流能量，电感成为大能量EMI干扰源！

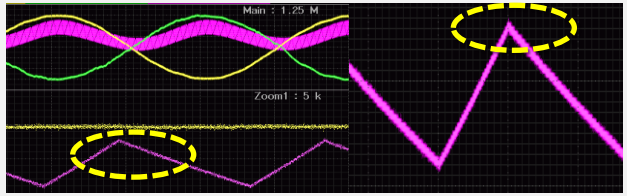


改变世界的磁元件设计创新

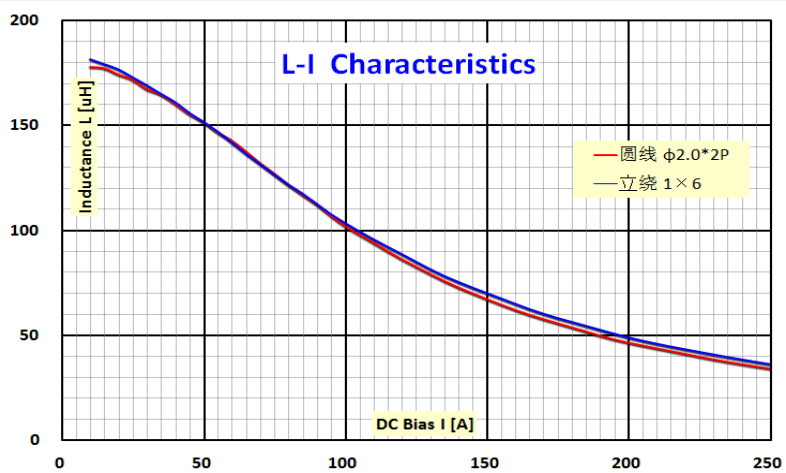
磁集成技术、混合磁路技术、L-I trimming技术、SpikeBlocker技术等

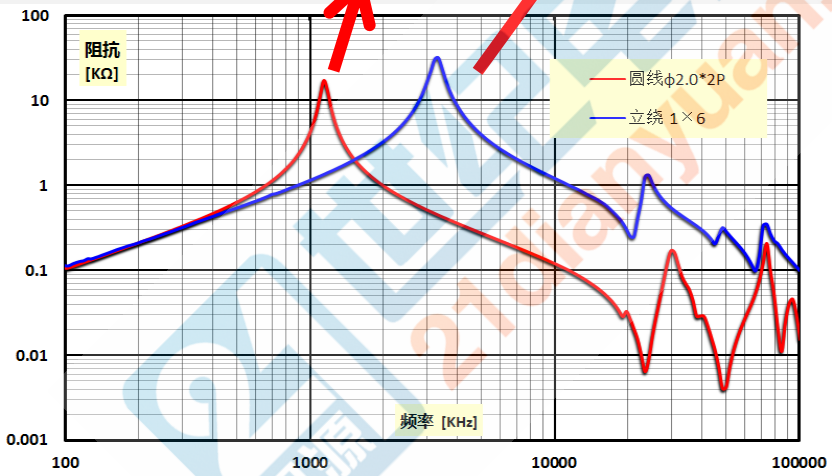
Spike Blocker

Edgewise Technique



Toroidal Edgewise Reactor





Change the World

We Supporting! (Q&A)

Innovation

Cooperation

Optimization

Thank you !

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