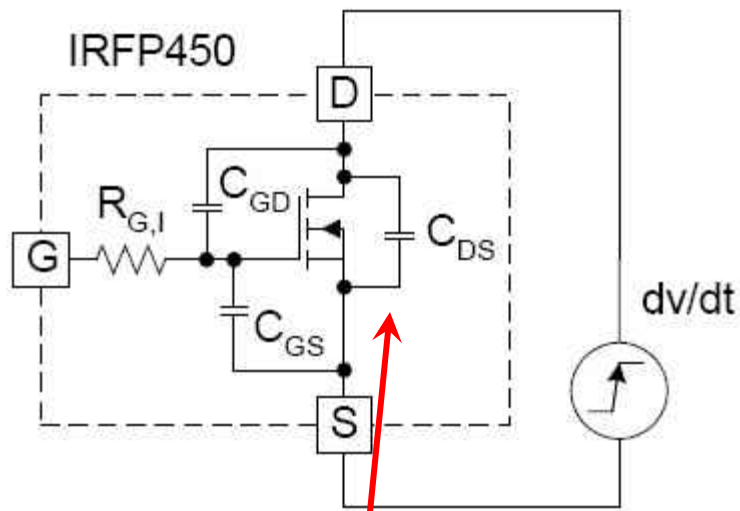


LLC设计步骤

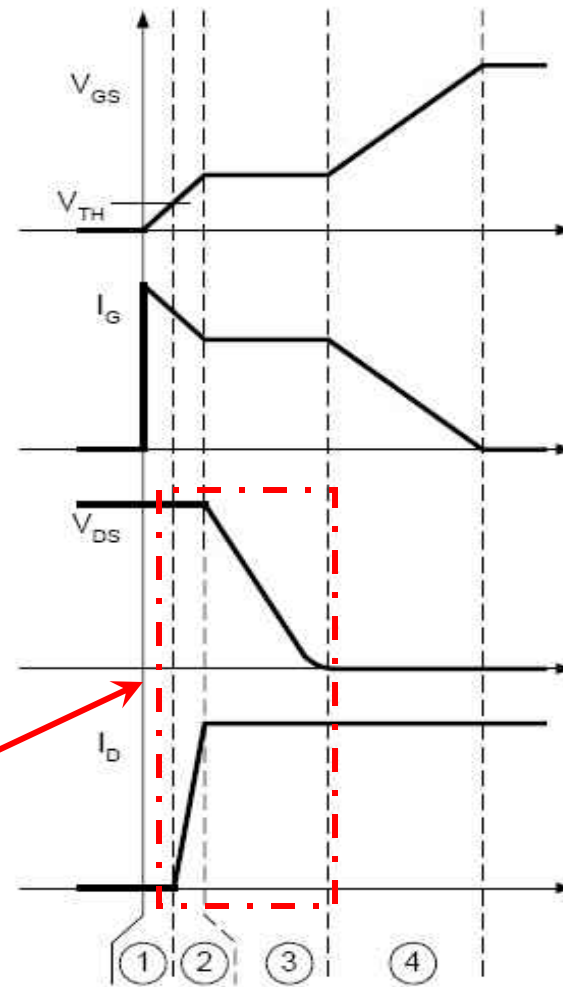
- LLC的基本原理
- LLC的设计方法
- LLC的几个问题

LLC的基本原理

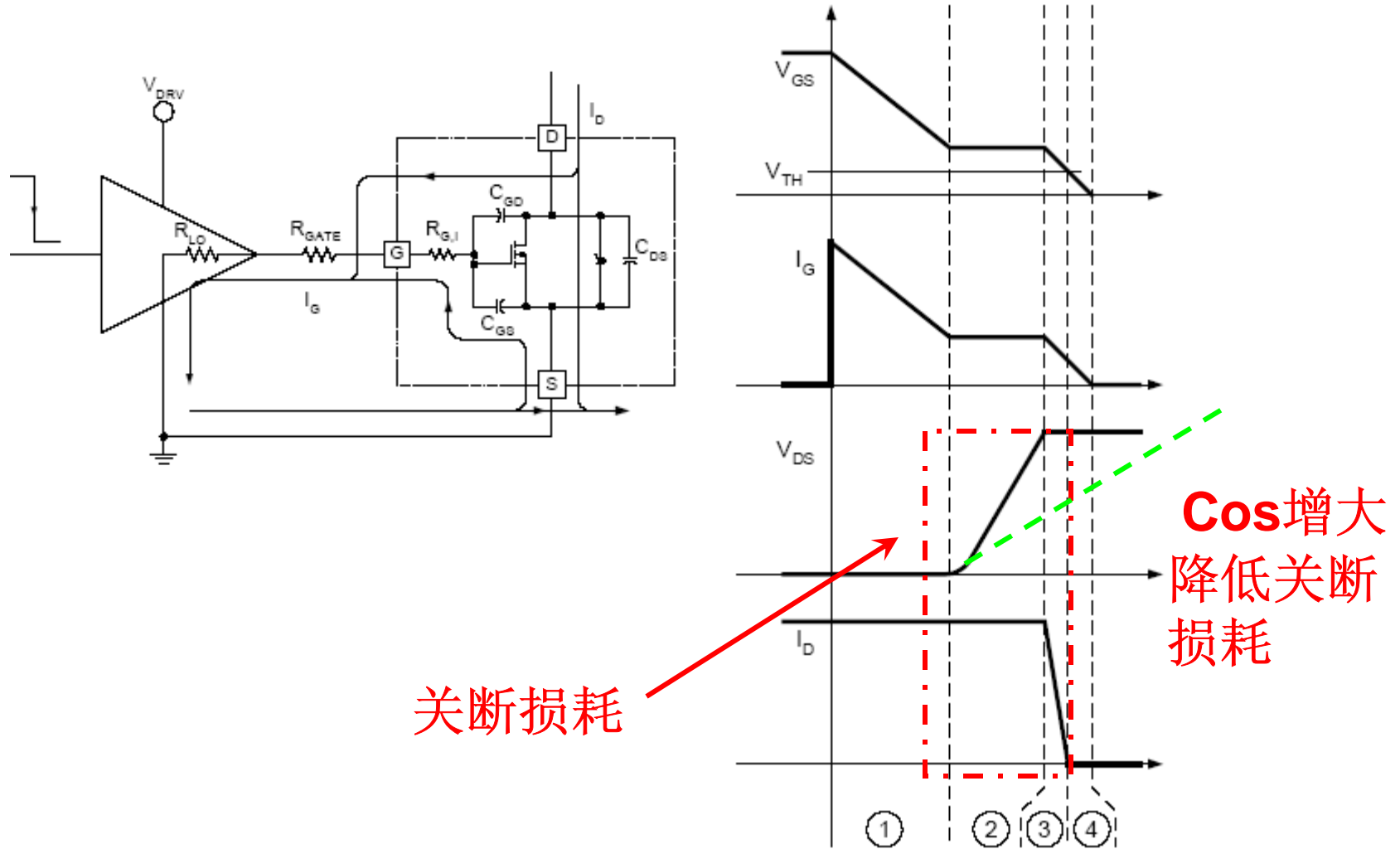
MOSFET适合零电压开关



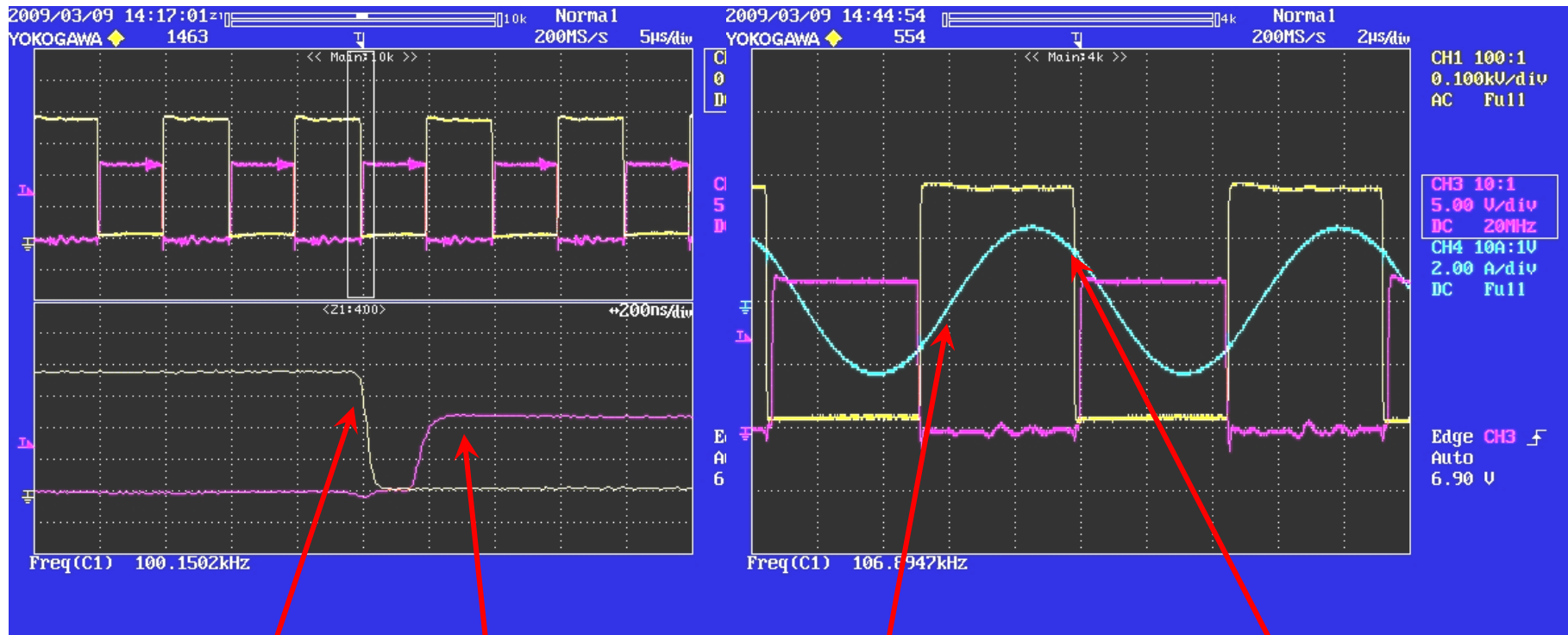
$$\frac{1}{2} C V_{DS}^2 + \text{开通损耗}$$



MOSFET适合零电压开关



MOSFET的零电压开关



V_{HB}

V_{GS}

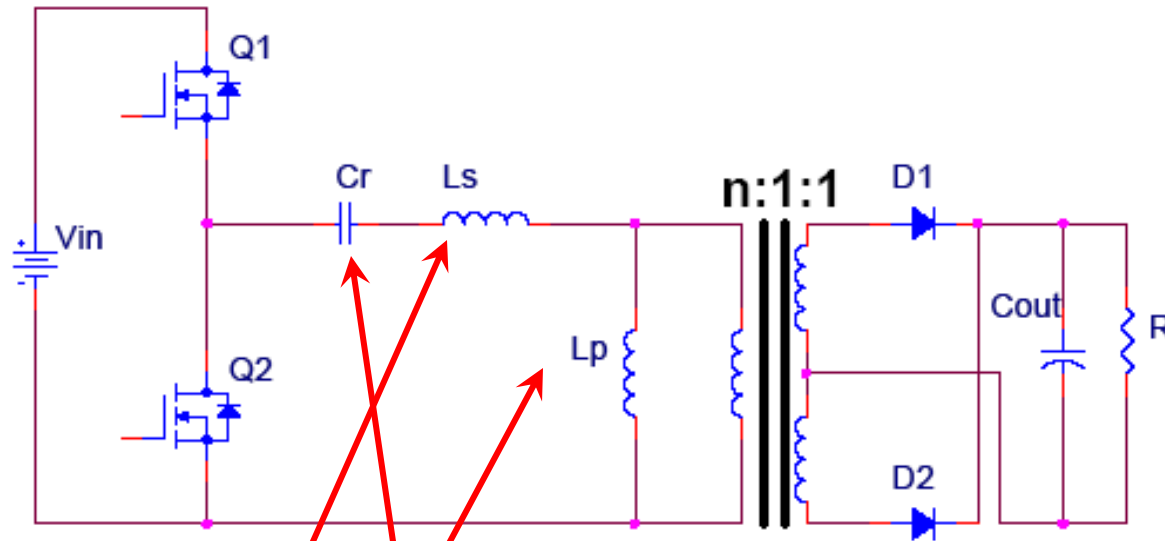
i_r

关断损耗避免不了

MOSFET开通前,其 V_{ds} 电压已经为零,则为零电压开通(ZVS)

ZVS的实现需要驱动信号来时有电流从S到D流通,LLC可以实现

LLC的架构



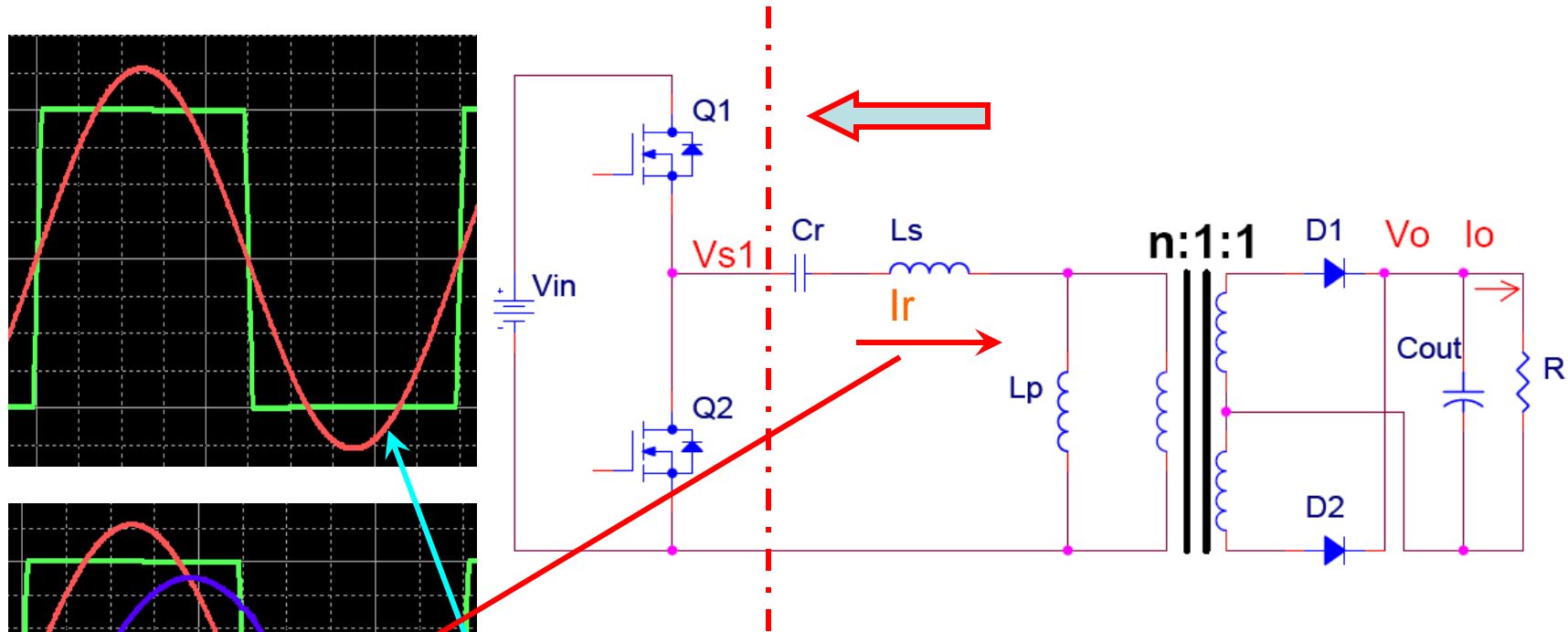
L L C
两个谐振频率

$$k = \frac{L_p}{L_s}$$

$$f_r = \frac{1}{2\pi\sqrt{L_s C_r}}$$

$$f_{r2} = \frac{1}{2\pi\sqrt{(L_s + L_p)C_r}}$$

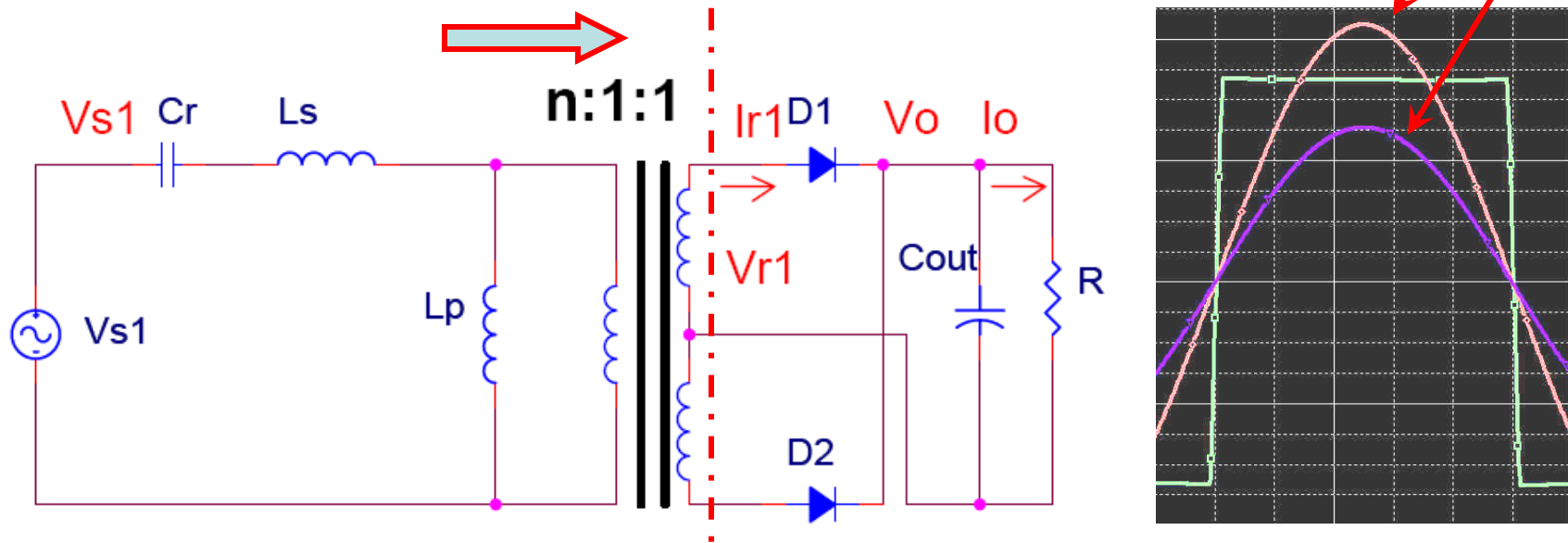
输入FHA等效电路



$$V_s = \frac{V_{in}}{2} + \frac{2}{\pi} V_{in} \sum_{n=1,3,5\dots} \frac{1}{n} \sin(2n\pi f_{sw} t)$$

$$V_{s1} = \frac{2}{\pi} V_{in} \sin(2\pi f_s t)$$

输出FHA等效电路



$$V_{r1} = \frac{4}{\pi} V_o \sin(2\pi f_s t - \varphi_R)$$

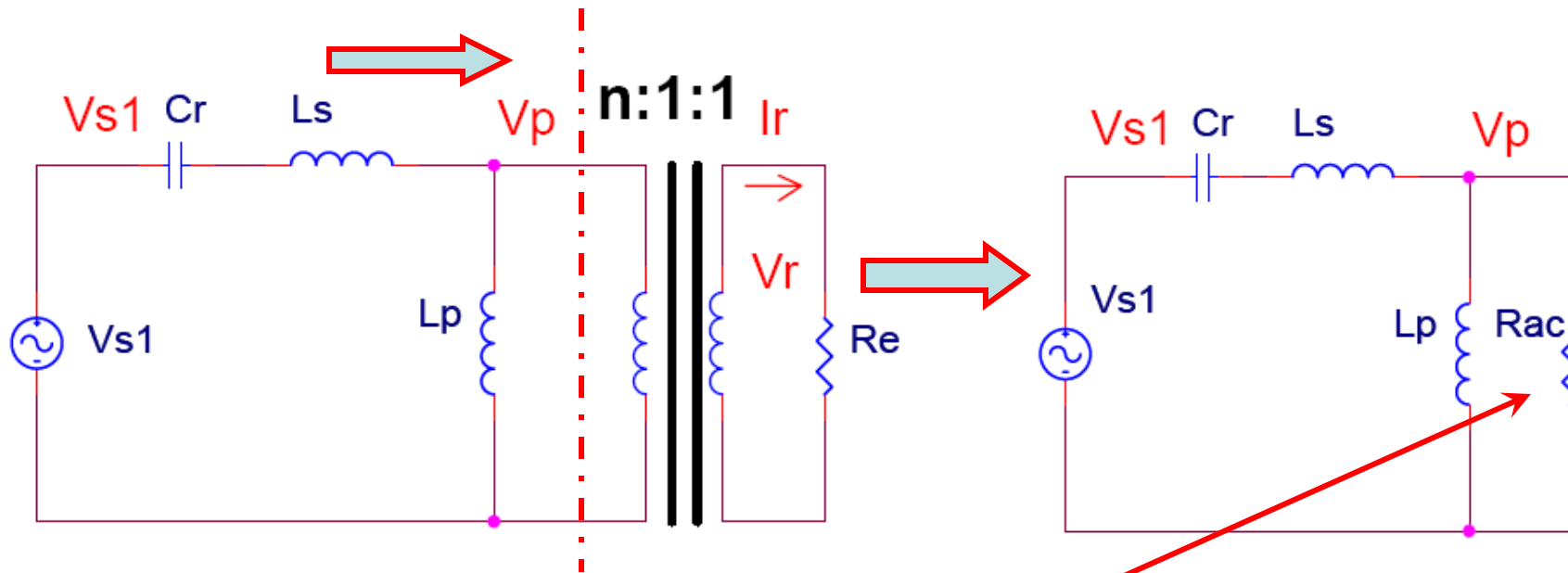
$$I_{r1} = I_{R1} \sin(2\pi f_s t - \varphi_R)$$

$$I_o = \frac{2}{T_S} \int_0^{T_S/2} I_{R1} |\sin(2\pi f_s t - \varphi_R)| dt = \frac{2}{\pi} I_{R1}$$

Vr1, Ir1同相,所以阻抗为电阻

$$Re = \frac{V_{r1}(t)}{i_{r1}(t)} = \frac{8}{\pi^2} * \frac{V_o}{I_o} = \frac{8R}{\pi^2}$$

输出FHA等效电路

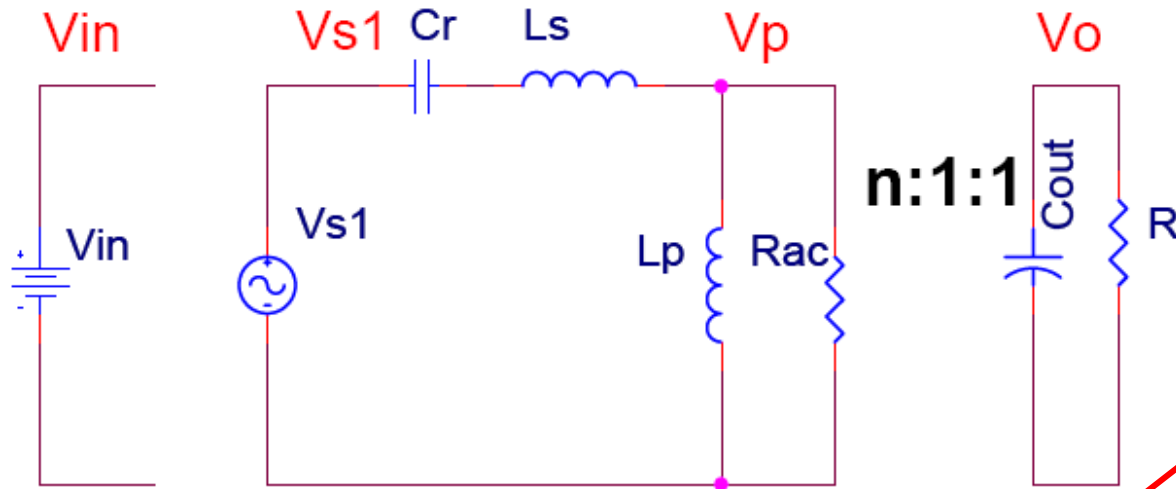


等效到初级侧

$$R_{AC} = n^2 R_e = n^2 \frac{8}{\pi^2} R$$

$$V_p = n V_{r1} = n \frac{4}{\pi} V_o$$

LLC的简化FHA等效电路



归一化增益

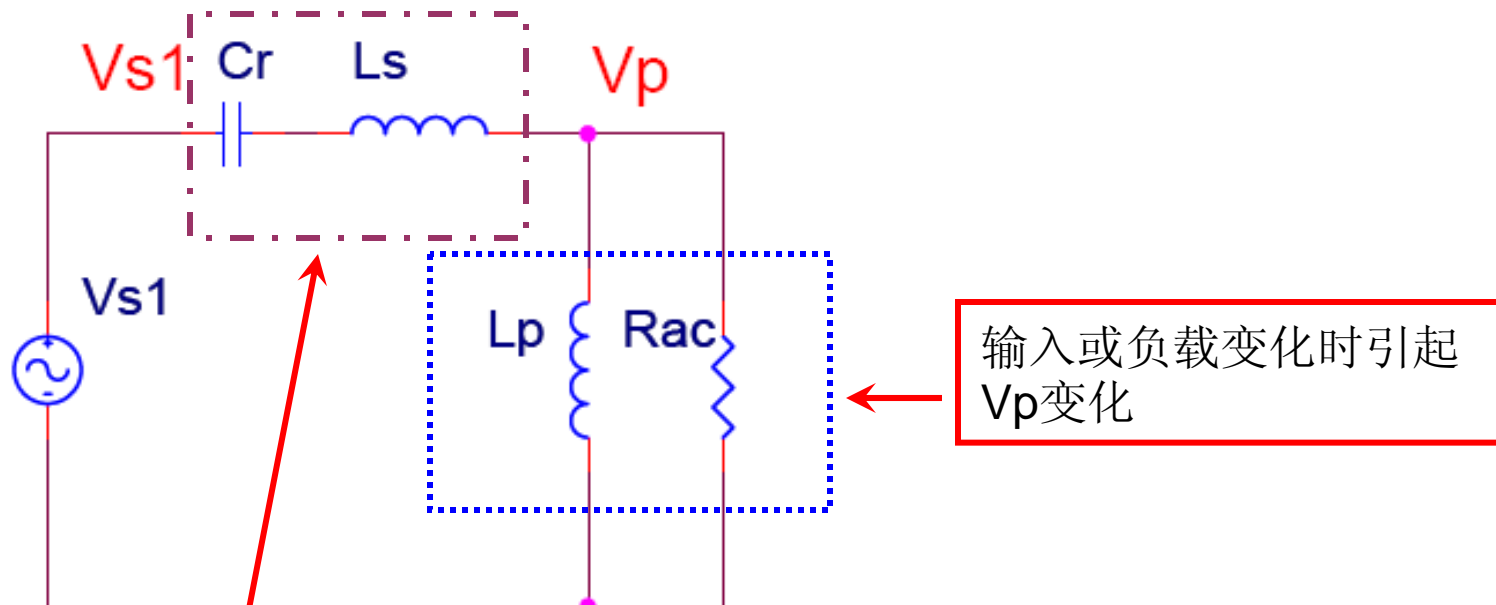
$$V_{s1} = \frac{2}{\pi} V_{in} \Rightarrow V_{in} = \frac{\pi}{2} V_{s1}$$

$$V_p = n V_{r1} = n \frac{4}{\pi} V_o \Rightarrow V_o = \frac{\pi}{4n} V_p$$

$$|G| = \frac{n V_o}{\frac{V_{in}}{2}} = \frac{n \frac{\pi}{4n} V_p}{\frac{\pi}{4} V_{s1}} = \frac{V_p}{V_{s1}}$$

$$= \frac{s L_p // R_{ac}}{1/s C_r + s L_r + (s L_p // R_{ac})}$$

LLC的稳压原理

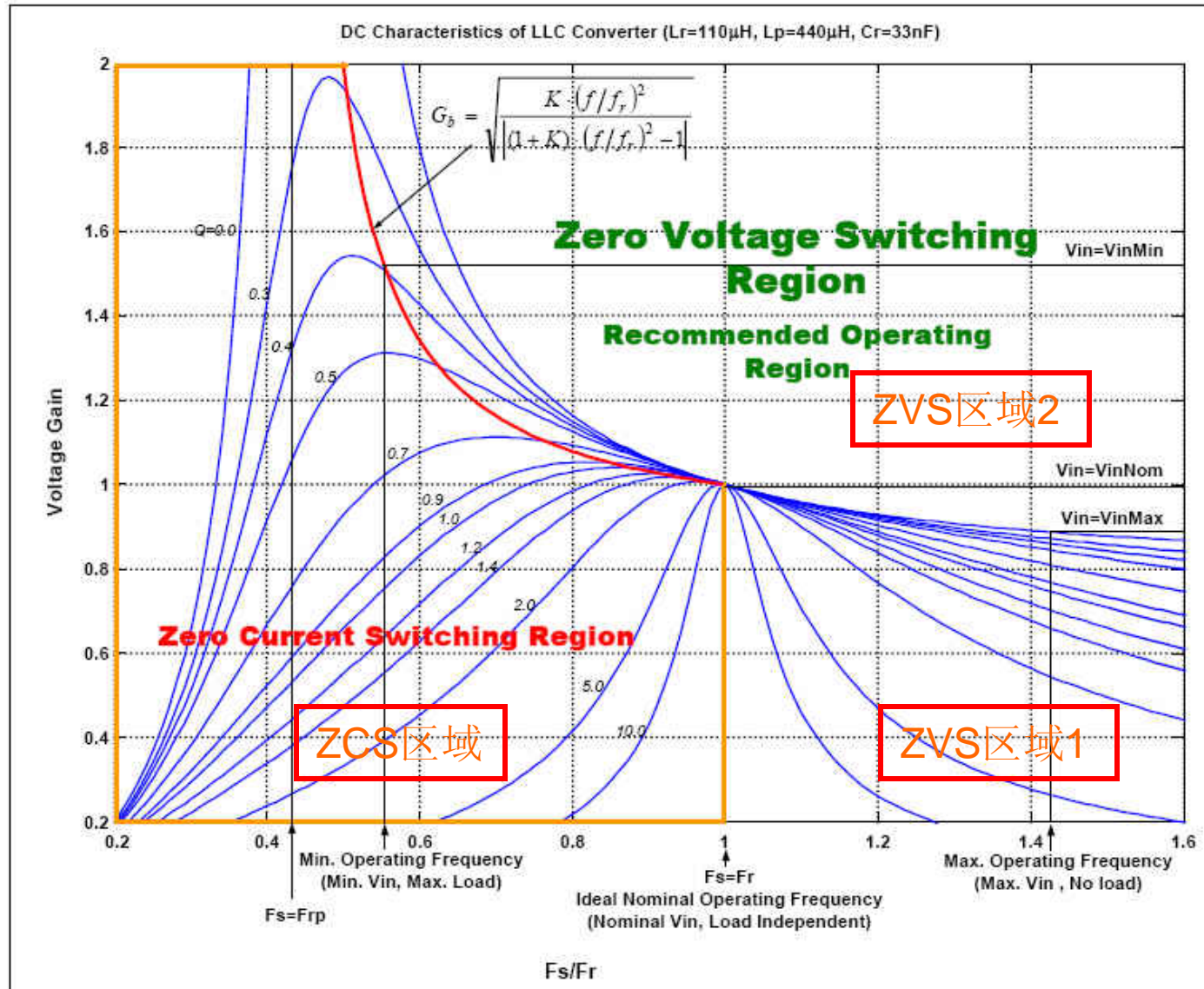


$$k = \frac{L_p}{L_s} \quad x = \frac{f}{f_r} \quad Q = \frac{2\pi f_r L_s}{R_{AC}}$$

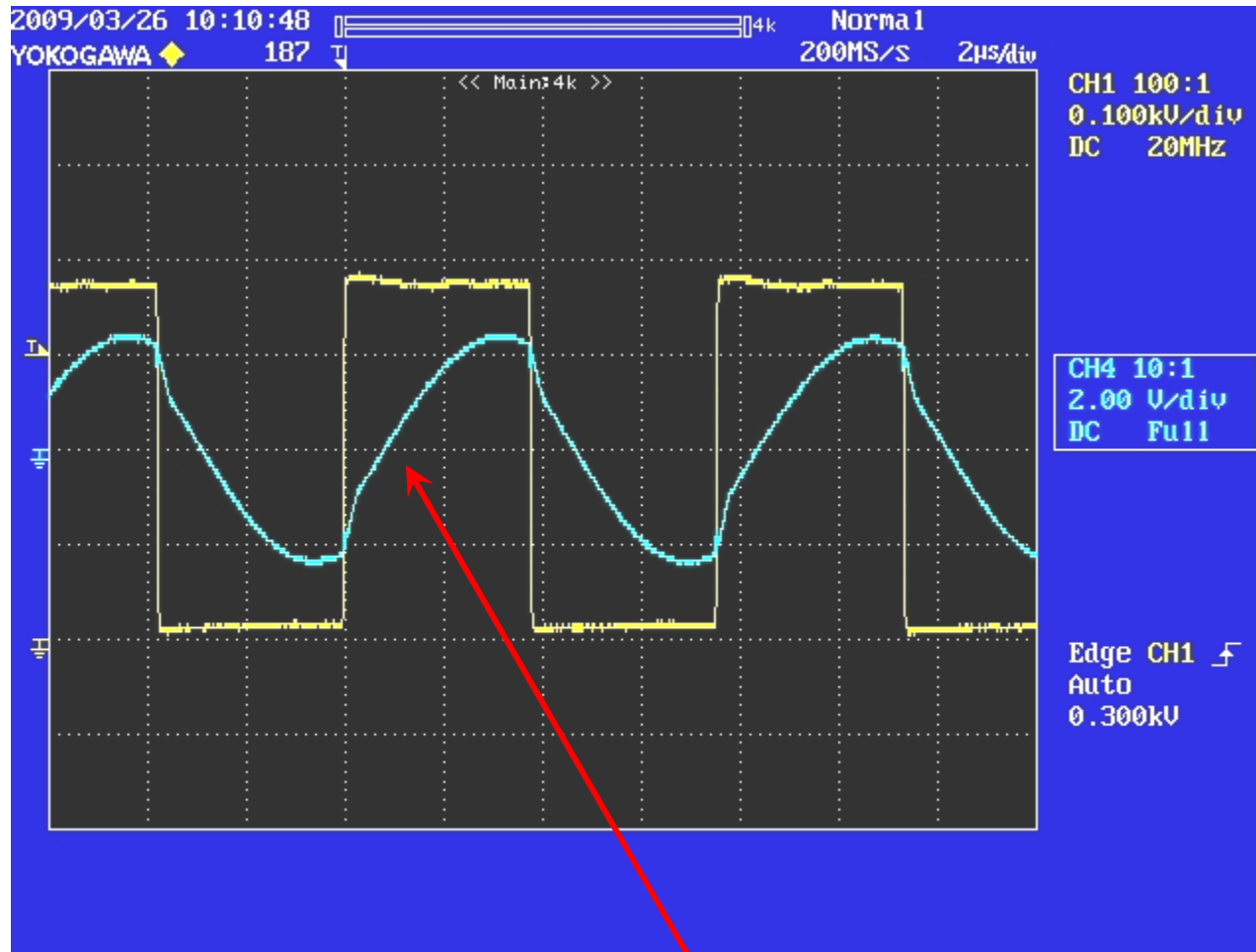
通过改变频率使 $1/sCr+sLr$ 的分压相应改变，最终维持负载电压不变，即 V_p 不变

$$|G(f)| = \frac{k * (x)^2}{\sqrt{\{(1+k) * (x)^2 - 1\}^2 + \{Qk(x) * [(x)^2 - 1]\}^2}}$$

LLC的DC特性

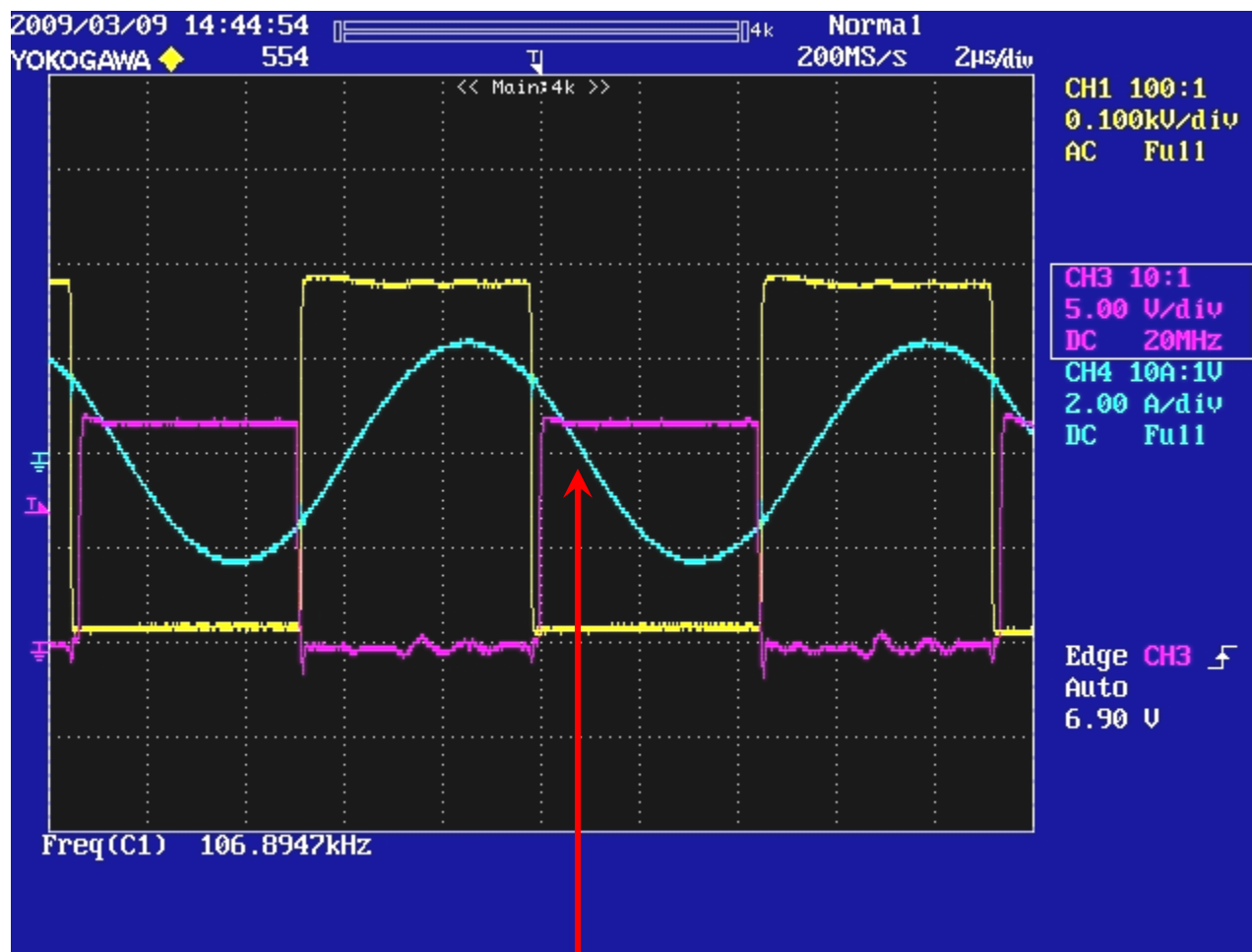


ZVS区域1的波形



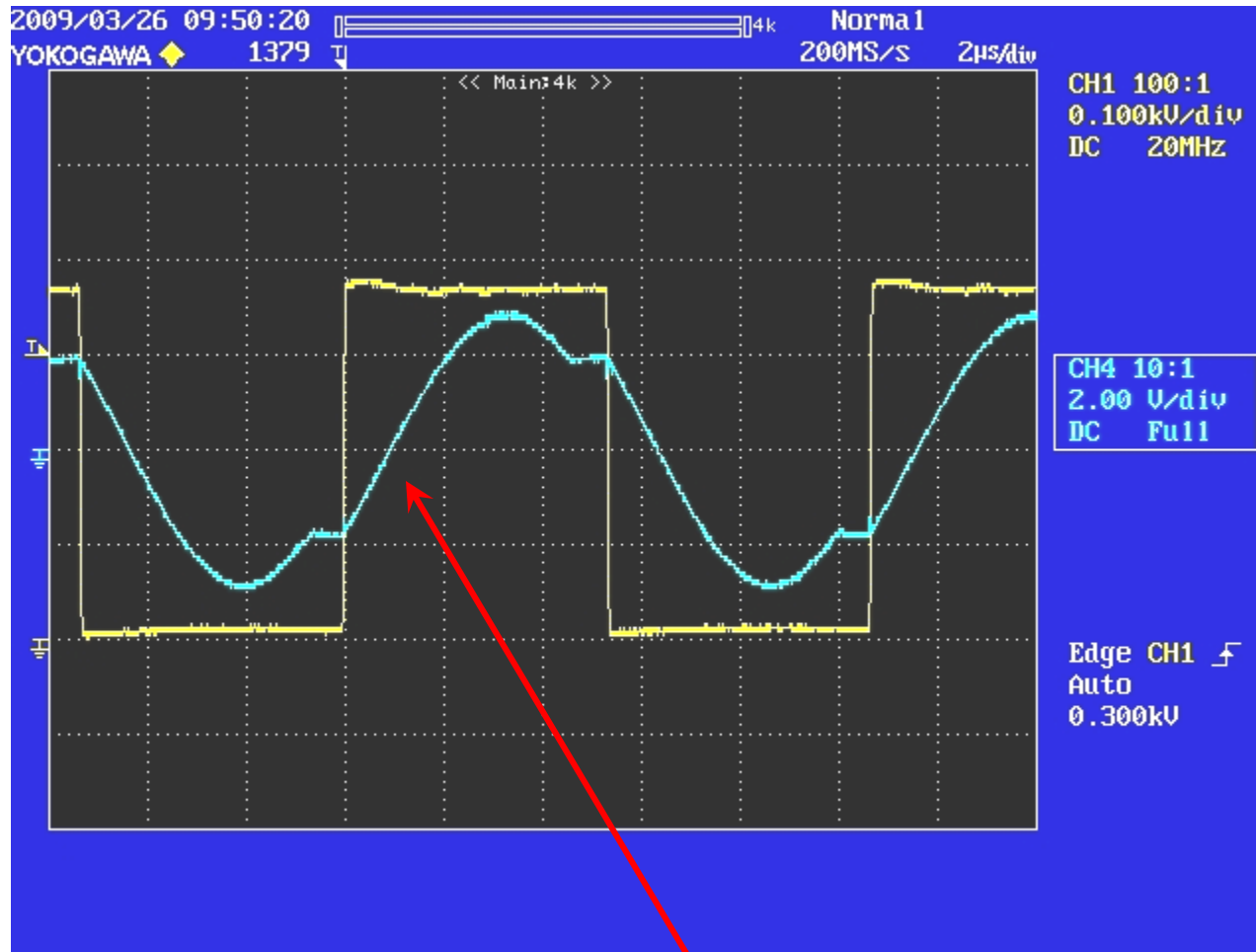
$f > f_r$ 开关频率大于谐振频率
上管开通前电流由S-D流通

谐振点的波形



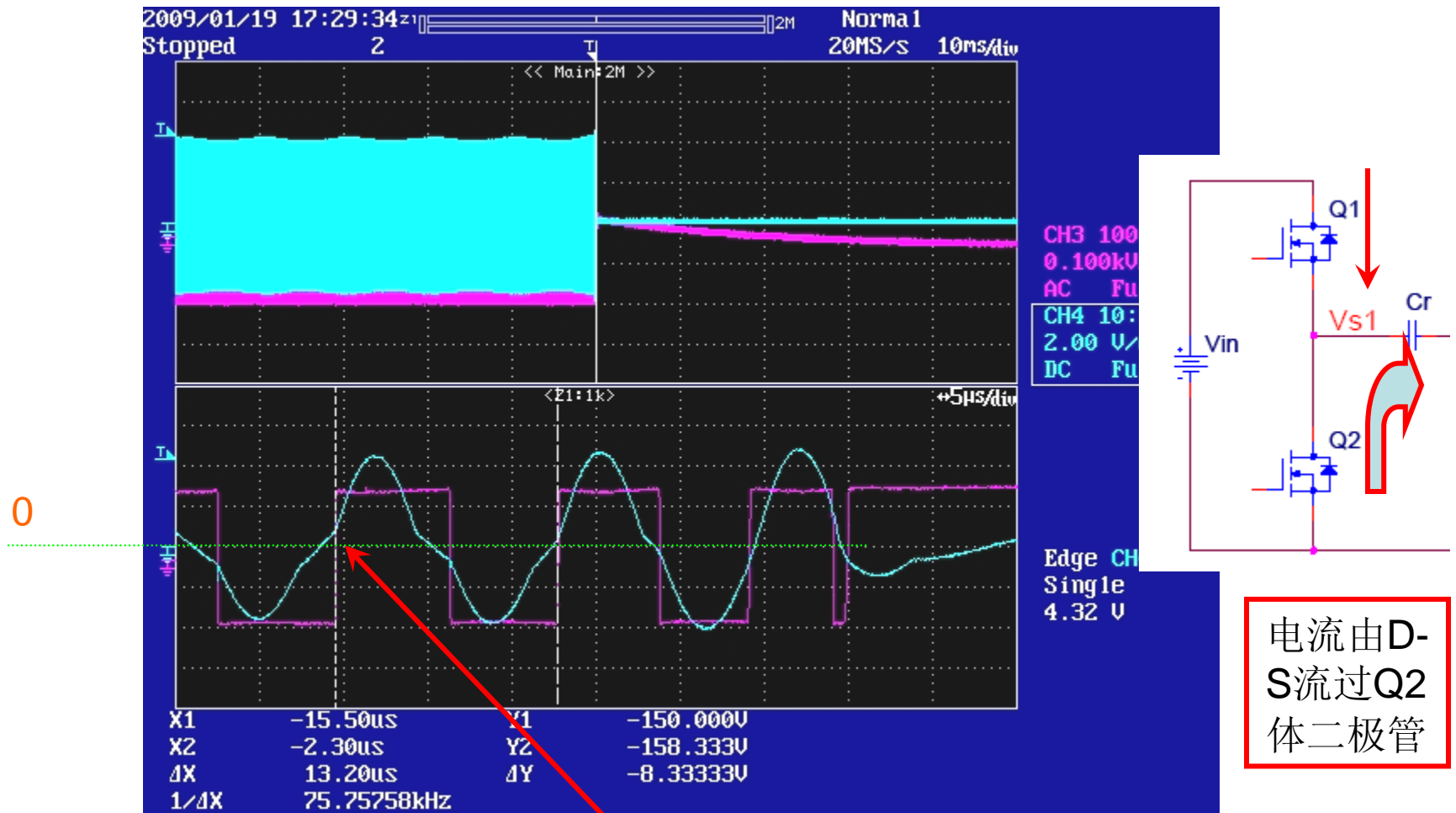
$f=f_r$ 开关频率等于谐振频率
下管开通前电流由S-D流通

ZVS区域2的波形



$f < f_r$ 开关频率小于谐振频率
上管开通前电流由S-D流通

ZCS区域的波形



$f < f_{r2}$ 开关频率小于谐振频率
上管开通前电流由D-S流通

LLC的设计方法

已知的条件

1. 输入电压范围
2. 输出电压、电流
3. 确定需要的谐振频率
4. 额定输入、输出满载时电源工作在 f_r 附近

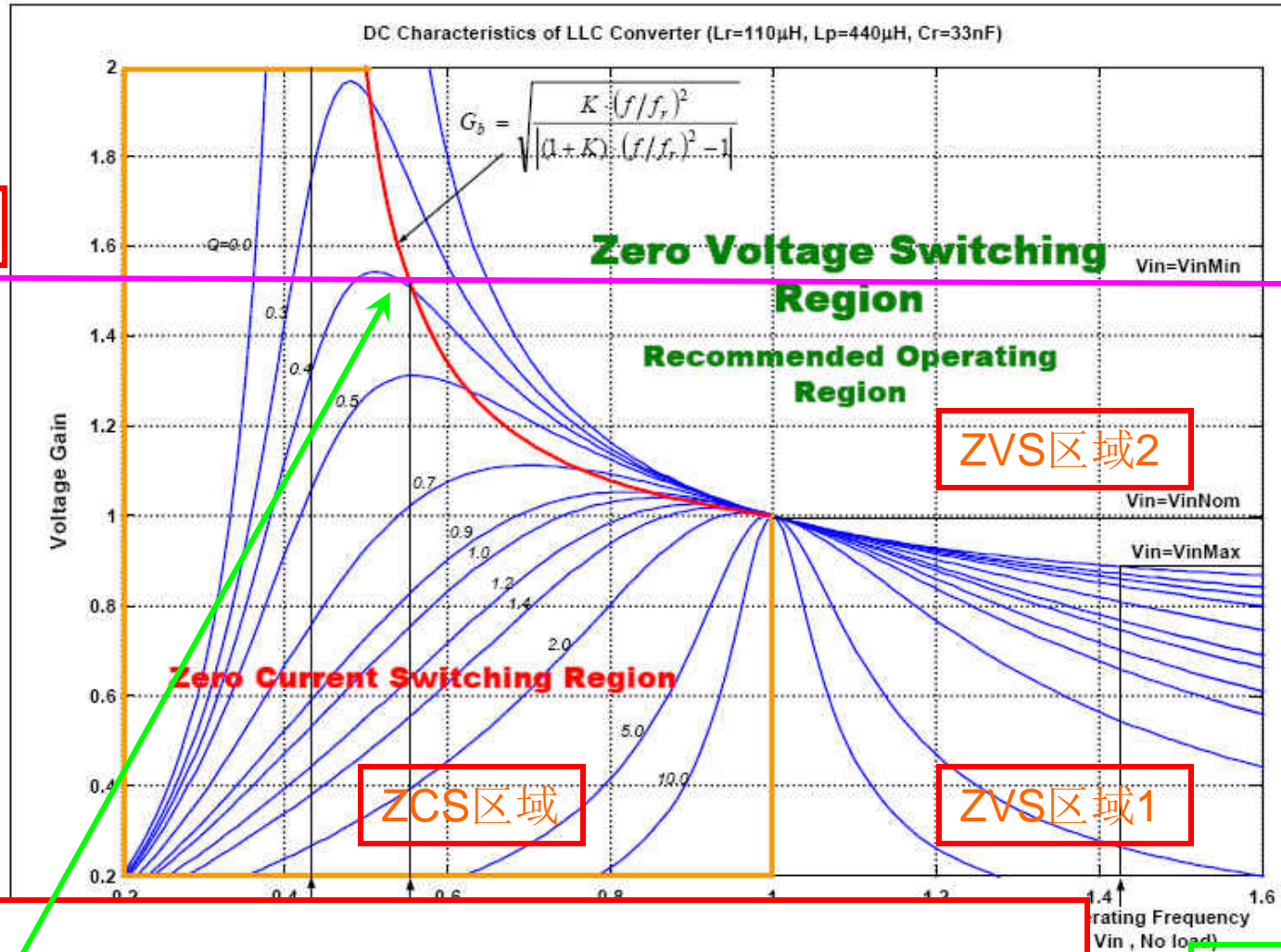
可简单得到的结果

1. 变压器变比 n
2. 需要的电压增益 G_{max}, G_{min}
3. $R_{ac}; k$

需要求解的量

1. Q值，由此得到 C_r, L_s, L_p
2. 最小、最大开关频率

LLC的DC特性



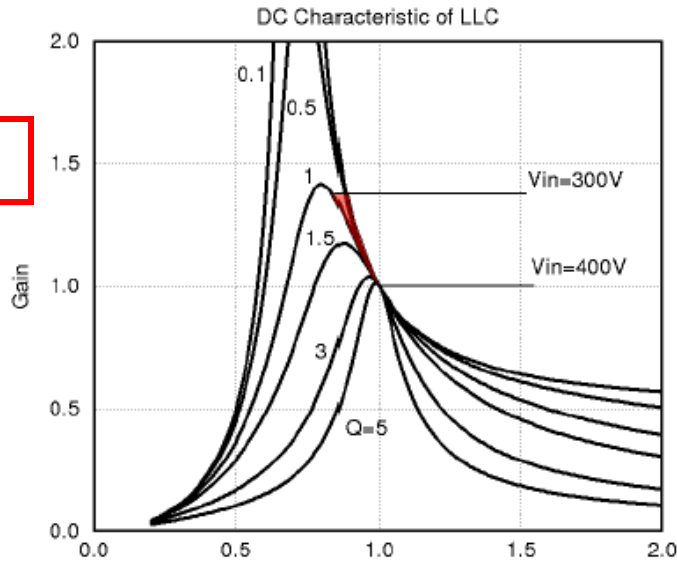
Gmax

$$|G(f)| = \frac{k \cdot (x)^2}{\sqrt{\{(1+k) \cdot (x)^2 - 1\}^2 + \{Qk(x) \cdot [(x)^2 - 1]\}^2}}$$

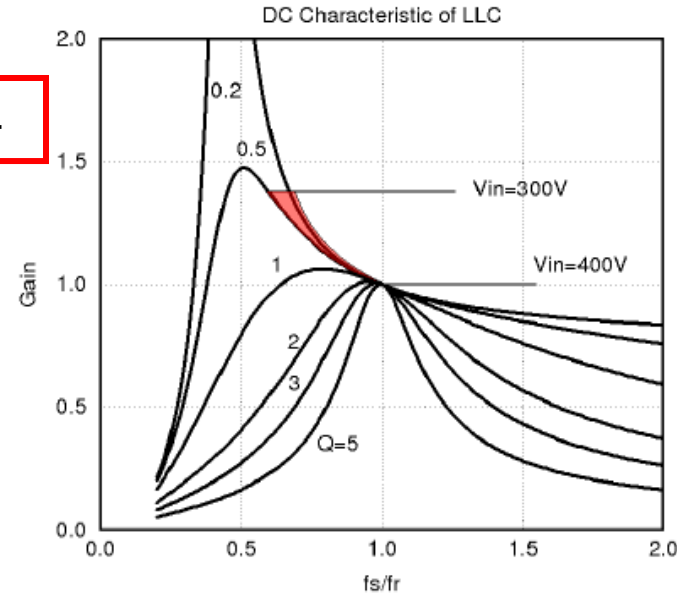
Gmax已知，3个变量，无法求出Q值

K值的确定

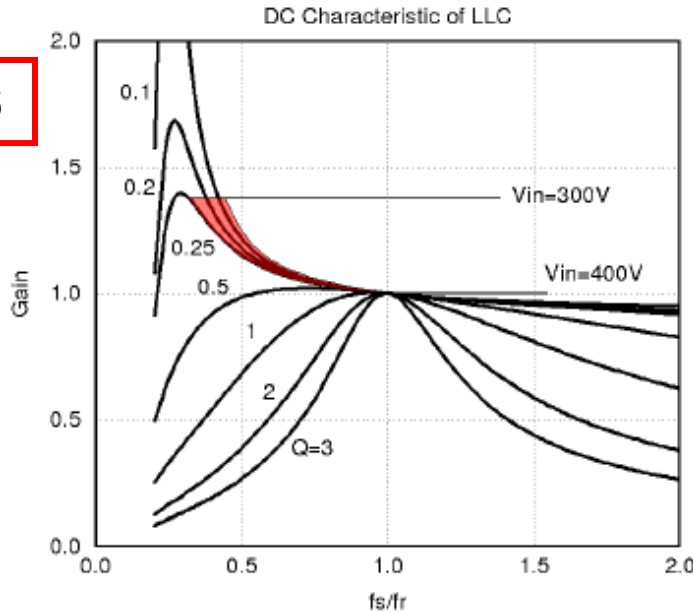
k=1



k=4

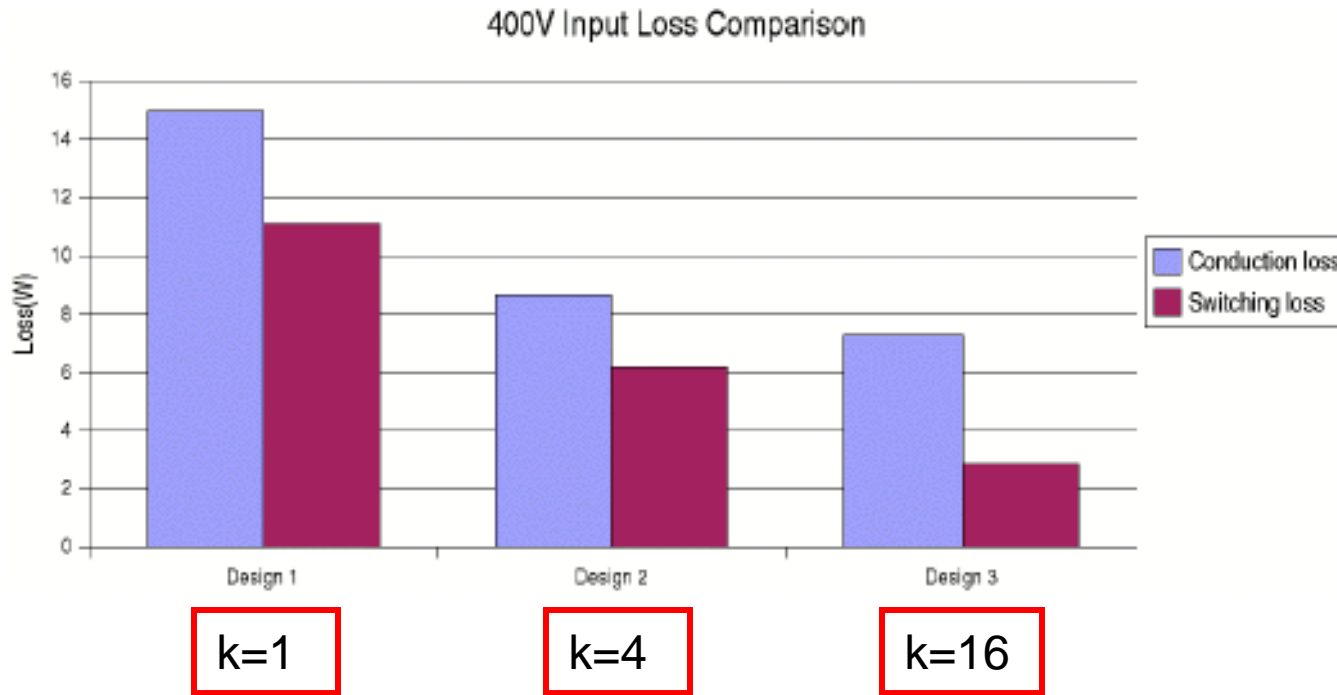


k=16



K值越小，获得相同增益的频率变化范围越窄
K值越大，获得相同增益的频率变化范围越宽

K值的确定

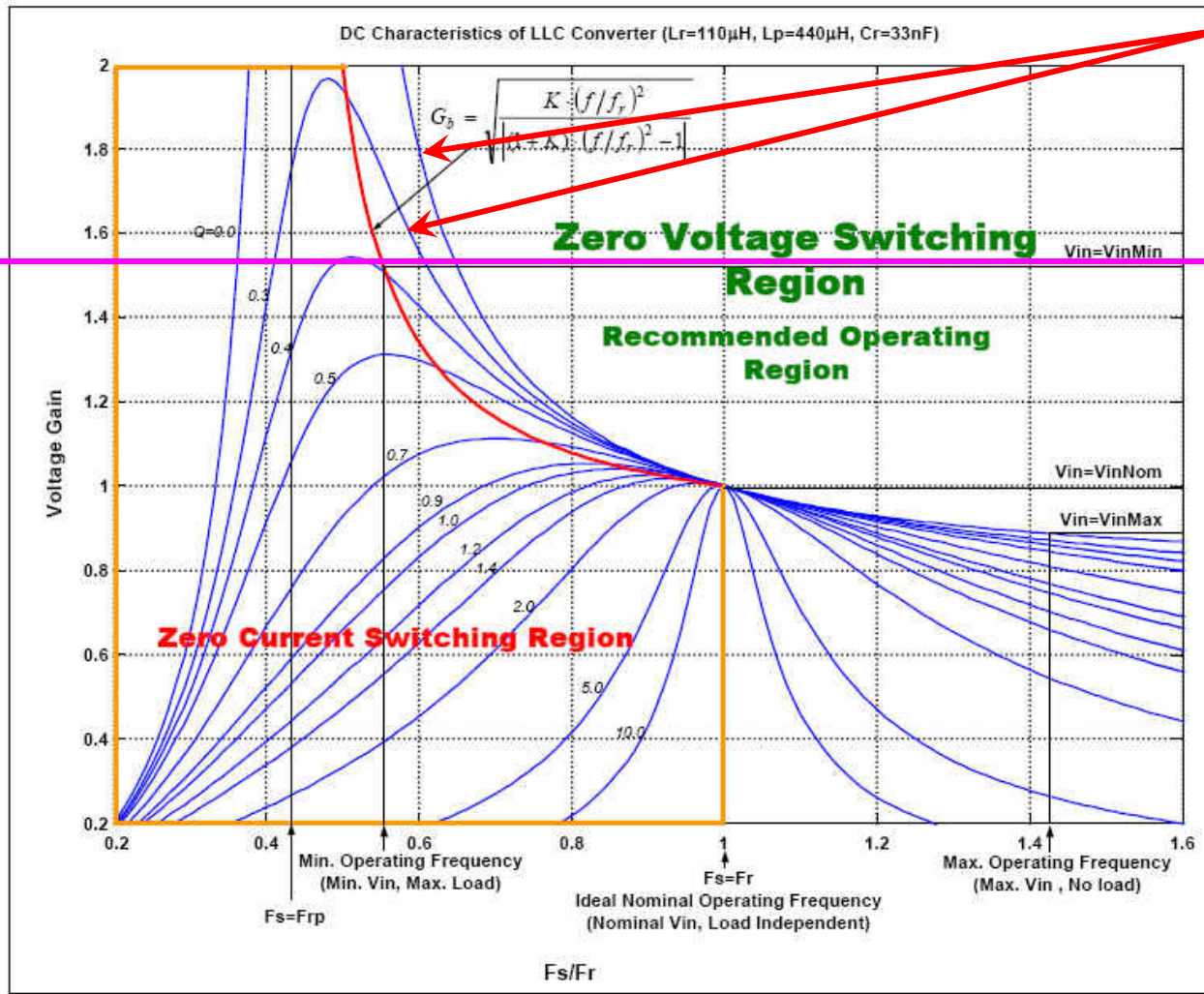


k值越大，MOSFET在 f_r 附近的导通损耗和开关损耗越低

综合以上考虑k一般取2.5-6的范围

Q值的讨论

Gmax

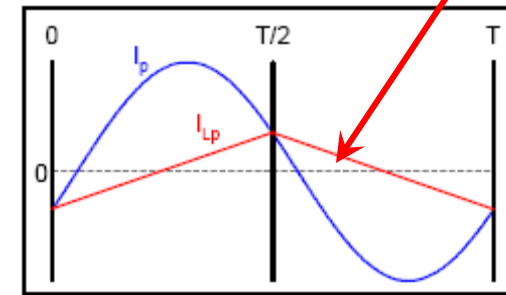


满足Gmax的
Q值有很多

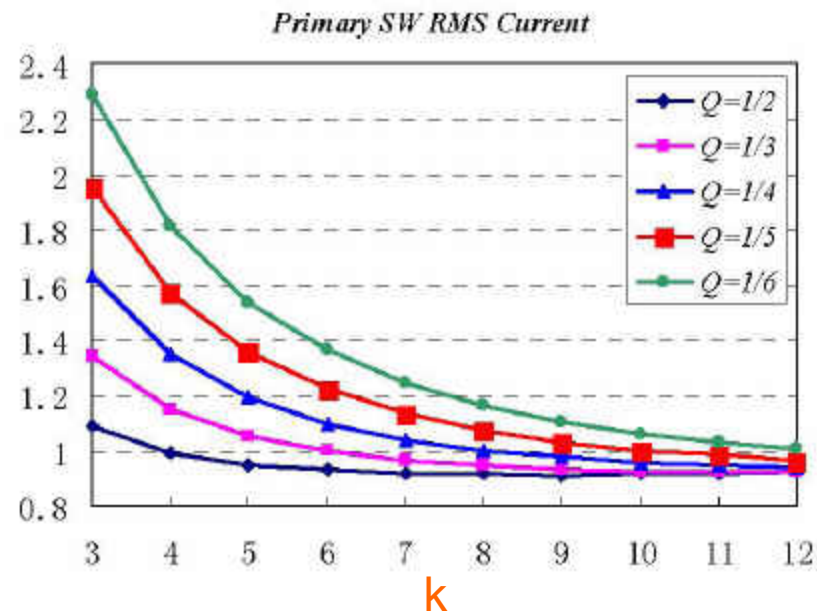
Q对初级电流的影响

$$Q = \frac{2\pi f_r L_s}{R_{AC}} \Rightarrow Q \downarrow \Rightarrow L_s \downarrow \Rightarrow L_p = k * L_s \downarrow \Rightarrow L_m = (L_s + L_p) \downarrow \Rightarrow I_{LP} \uparrow$$

$$I_{rms} = \frac{V_o}{8nR_L} \sqrt{\frac{2n^4 R_L^2}{L_m^2 f_r^2} + 8\pi^2} \uparrow \Rightarrow \eta \downarrow$$



K值固定后，在保证ZVS的条件下尽量选用大的Q值



再看变量

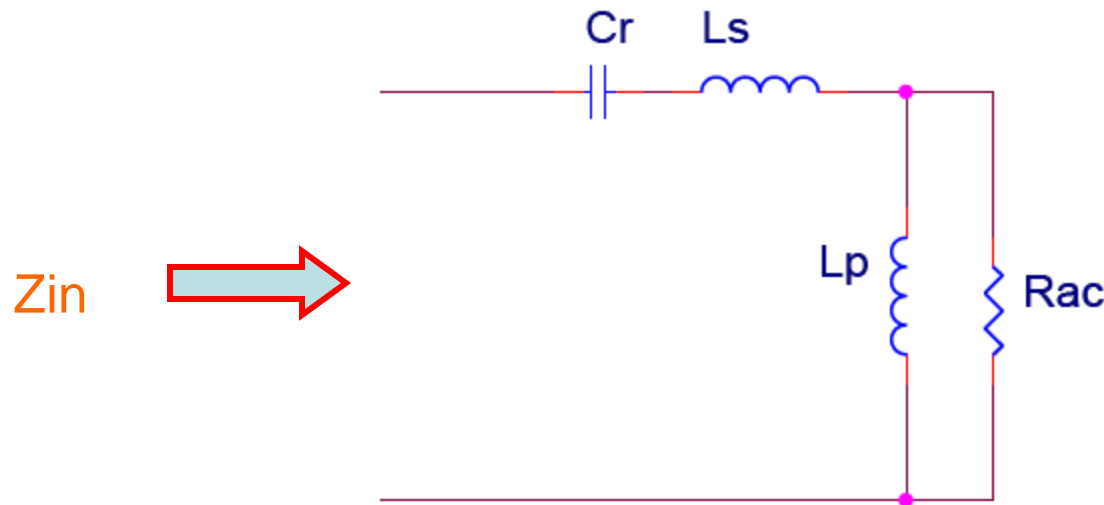
$$|G_{\max}| = \frac{k * (x)^2}{\sqrt{\{(1+k) * (x)^2 - 1\}^2 + \{Qk(x) * [(x)^2 - 1]\}^2}}$$

已知量

仍有Q, x 为未知量，需要新的条件才能解出Q值，从而确定Cr, Lr, Lm

从阻抗想办法

LLC的阻抗特性



$$x = \frac{f}{f_r}$$

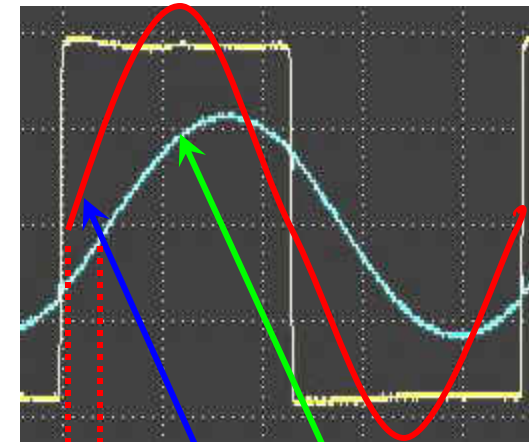
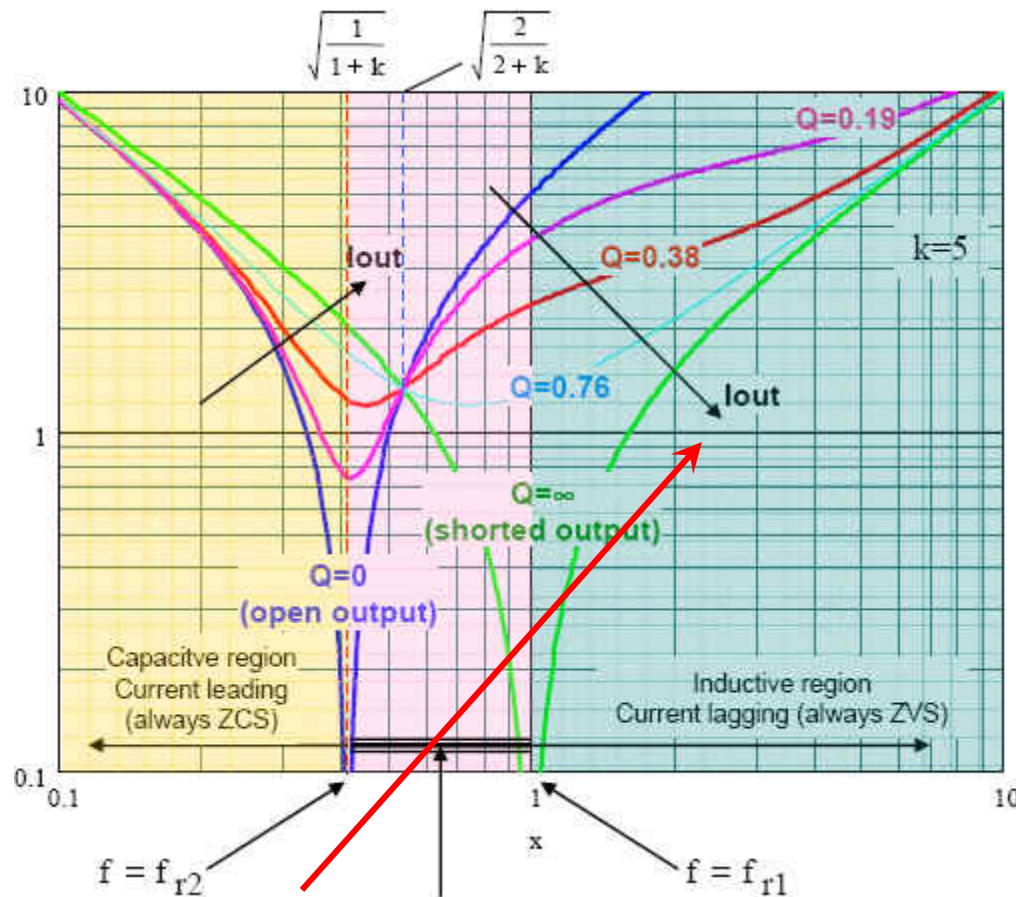
$$k = \frac{L_p}{L_s}$$

$$Q = \frac{2\pi f_r L_r}{R_{AC}}$$

$$Z_{in} = \frac{1}{sC_r} + sL_r + (sL_p // R_{ac})$$

$$= Z_o * \left\{ Q * \frac{x^2 k^2}{1 + x^2 k^2 Q^2} + j \left[x - \frac{1}{x} + \frac{xk}{1 + x^2 k^2 Q^2} \right] \right\}$$

LLC的输入阻抗



电压
波形

电流
波形

相位差 \emptyset 为0是感性
容性的分界线

ZVS的条件:电流落后于电压,
即Zin为感性——频率增加,阻
抗增加

LLC的阻抗特性

虚部为零，是感性容性的分界线，由此条件得到

$$Z_{in} = Z_o * \left(Q * \frac{x^2 k^2}{1 + x^2 k^2 Q^2} + j \left[x - \frac{1}{x} + \frac{xk}{1 + x^2 k^2 Q^2} \right] \right)$$

$$x - \frac{1}{x} + \frac{xk}{1 + x^2 k^2 Q^2} = 0 \quad \Rightarrow \quad Q_{\max}(x) = \sqrt{\frac{1}{k(1-x^2)} - \frac{1}{(kx)^2}}$$

再看增益公式，把 $Q_{\max}(x)$ 带入公式，可求出 x ，再得到 Q_{\max} ，从而得到 C_r, L_r, L_m ；令 $Q=0$ 得空载工作频率

$$|G_{\max}| = \frac{k * (x)^2}{\sqrt{\{(1+k) * (x)^2 - 1\}^2 + \{Q * k * (x) * [(x)^2 - 1]\}^2}}$$

已知量

代换为 x

只有 x 是未知量

解求各参数

由最高输入电压时的增益(G_{\min})和空载条件($Q=0$)求解最高工作频率

$$|G_{\min}| = \frac{k^*(x)^2}{\sqrt{\{(1+k)^*(x)^2 - 1\}^2 + \{Qk(x)^*[(x)^2 - 1]\}^2}}$$

已知量

令 $Q=0$

$$|G_{\min}| = \frac{k^*(x)^2}{(1+k)^*(x)^2 - 1}$$

只有 x 是未知量

结果

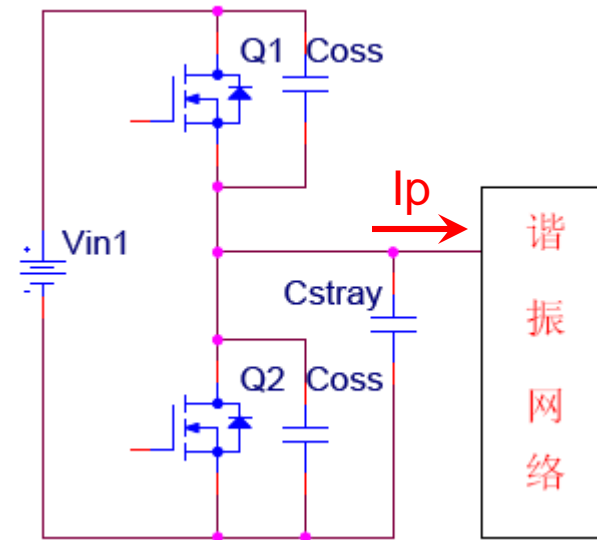
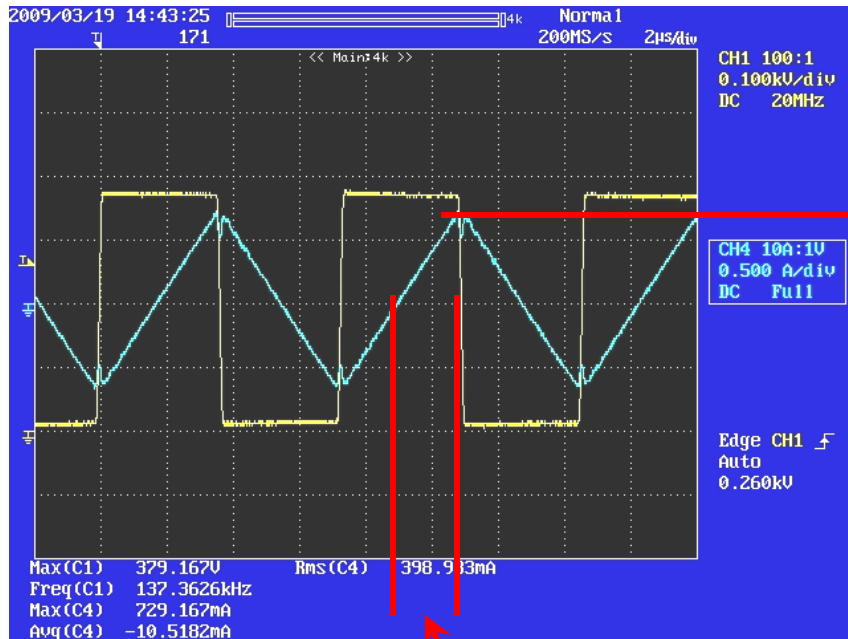
$$f_{\min} = \frac{f_r}{\sqrt{1 + k(1 - \frac{1}{G_{\max}^2})}} \quad f_{\max} = \frac{f_r}{\sqrt{1 + k(1 - \frac{1}{G_{\min}^2})}}$$

$$Q = 0.95Q_{\max} = \frac{0.95}{k * G_{\max}} * \sqrt{k + \frac{G_{\max}^2}{G_{\max}^2 - 1}}$$

$$L_s = \frac{Q * R_{AC}}{2\pi f_r} \quad C_r = \frac{1}{2\pi * f_r * R_{AC} * Q}$$

$$L_p = k * L_s$$

ZVS的另一个限制



$$I_p > (2C_{oss} + C_{stray}) \frac{V_{in}}{T_d}$$

$$I_m = \frac{V_{inMax}}{L_s + L_p} * \frac{T_{min}}{4}$$

$$= \frac{V_{inMax}}{4 f_{max} * (L_s + L_p)}$$

输入电压最高时的Im

保证ZVS的Ip

核算Im>Ip, 不满足重选Q

归一化的计算步骤

1. 确定输入输出指标
2. 选择谐振频率和选择操作区域
3. 计算变压器变比和谐振元件值
4. 计算功率器件电压电流应力
5. 选择器件和变压器设计

实际计算步骤

1. 输入输出指标

输入电压范围： $V_{inMin}=250V$, $V_{inMax}=420V$

额定输入电压： $V_{inNom}=400VDC$

输出电压电流（最大值）： $24V/10A$, $12V/4A$

输出功率： $P_o=24 \times 10 + 12 \times 4 = 288W$

2. 选择谐振频率和工作区域

谐振频率 $f_r=100KHz$

额定输入输出时电源工作在 f_r

3. 计算变压器变比和谐振元件值

3.1 理论变比

$$n = \frac{\frac{V_{inNom}}{2}}{V_o + V_D} = \frac{\frac{400}{2}}{24 + 0.7} = 8.1$$

实际计算步骤

3.2 最高、最低输入电压的增益

$$G_{\min} = 2n * \frac{(V_o + V_d)}{V_{inMax}} = 2 * 8.1 * \frac{(24 + 0.7)}{420} = 0.952$$

$$G_{\max} = 2n * \frac{(V_o + V_d)}{V_{inMin}} = 2 * 8.1 * \frac{(24 + 0.7)}{250} = 1.6$$

3.3 计算等效为24V输出的负载电阻和反射电阻

$$R_L = \frac{V_o^2}{P_o} = \frac{24^2}{288} = 2\Omega$$

$$R_{AC} = n^2 \frac{8}{\pi^2} R_L = 8.1^2 * \frac{8}{\pi^2} * 2 = 106.5$$

实际计算步骤

3.4 取 $k=3$

3.5 计算 $Q, f_{\min}, f_{\max}, L_s, L_p, C_r$

$$Q = \frac{0.95}{k * G_{\max}} * \sqrt{k + \frac{G_{\max}^2}{G_{\max}^2 - 1}} = \frac{0.95}{3 * 1.6} * \sqrt{3 + \frac{1.6^2}{1.6^2 - 1}} = 0.426$$

$$f_{\min} = \frac{f_r}{\sqrt{1 + k(1 - \frac{1}{G_{\max}^2})}} = \frac{100}{\sqrt{1 + 3(1 - \frac{1}{1.6^2})}} = 59.5 \text{ KHz}$$

$$f_{\max} = \frac{f_r}{\sqrt{1 + k(1 - \frac{1}{G_{\min}^2})}} = \frac{100}{\sqrt{1 + 3(1 - \frac{1}{0.952^2})}} = 108.5 \text{ KHz}$$

实际计算步骤

$$C_r = \frac{1}{2\pi * f_r * R_{AC} * Q} = \frac{1}{2\pi * 100 * 106.5 * 0.426} = 35nF$$

$$L_s = \frac{Q * R_{AC}}{2\pi f_r} = \frac{0.426 * 106.5}{2\pi * 100} = 72\mu H$$

$$L_p = k * L_r = 3 * 72 = 216\mu H$$

3.6 核算 $I_m > I_p$

$$I_m = \frac{V_{inMax}}{4f_{max} * (L_r + L_p)} = \frac{420}{4 * 108.5 * (72 + 216)} = 3.36A$$

$$I_p = (2C_{oss} + C_{stray}) \frac{V_{in}}{T_d} = 500 * 10^{-12} * \frac{420}{200 * 10^{-9}} = 1.05A$$

$$I_m > I_p$$

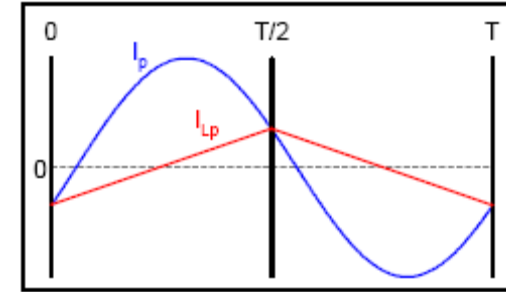
如不满足需降低Q或增大 $L_r + L_p$

实际计算步骤

4. 计算功率器件电压电流应力

4.1 初级电流有效值

$$I_{rms} = \frac{V_o}{8nR_L} \sqrt{\frac{2n^4 R_L^2}{L_m^2 f_r^2} + 8\pi^2} = 1.6A$$



4.2 MOSFET电压,电流最大值,电流有效值

$$V_{Mos} = V_{inMax} = 420V$$

$$I_{Max_Mos} = I_{OCP}$$

$$I_{rms_Mos} = \frac{I_{rms}}{\sqrt{2}} = \frac{1.6}{\sqrt{2}} = 1.13A$$

$$P_{Conduct_loss} = I_{rms_Mos}^2 R_{ds} = 1.28R_{ds}$$

实际计算步骤

4.3 次级整流管电压,电流,损耗(24V输出)

$$V_{D_Max} = 2 * V_O = 2 * 24 = 48$$

$$I_{D_Avg} = \frac{I_o}{2} = \frac{10}{2} = 5A(24V)$$

$$P_{D_Conduct_loss} = V_{D_Conduct_Avg} * I_{D_Avg} = 0.7 * 5 = 3.5W$$

4.4 谐振电容电流有效值、最大电压

$$I_{Cr_rms} = I_{rms} = \frac{V_o}{8nR_L} \sqrt{\frac{2n^4 R_L^2}{L_m^2 f_r^2} + 8\pi^2} = 1.6A$$

$$V_{Cr_Max} \cong \frac{V_{in_Max}}{2} + \sqrt{2} * I_{rms_Max} * \frac{1}{2\pi f_r C_r} = \frac{420}{2} + \frac{I_{OCP}}{2\pi f_r C_r}$$

实际计算步骤

4.5 输出电容的电流有效值(f=fr,24V输出)

$$I_{Co_Rms} = \sqrt{\left(\frac{\pi I_o}{2\sqrt{2}}\right)^2 - I_o^2} = \sqrt{\frac{\pi^2 - 8}{8}} I_o = 2.32A$$

实际计算步骤

5. 选择器件和变压器设计

MOSFET: 满足20%裕量,电压500V, 电流从发热和Coss考虑(保证高压时ZVS)

Cr: 满足RMS电流的要求, 电压为计算值1.5倍左右

Co:满足RMS电流要求

D: 电压满足20%裕量;电流考虑到不平衡,取40%裕量, 其余从发热考虑

变压器实际变比

$$n_{real} = n * \sqrt{\frac{Lr + Lp}{Lp}} = n * \sqrt{\frac{k + 1}{k}} = 8.1 * \sqrt{\frac{3 + 1}{3}} = 9.35$$

实际计算步骤

初级最小匝数(EER40)

$$N_{P_Min} = \frac{n_{real}(V_o + V_d)}{2f_{min} * \Delta B * A_e} = \frac{9.35(24 + 0.7)}{2 * 59.5 * 0.4 * 149} * 10^3 = 32.5$$

选择次级匝数，计算初级匝数使其大于32.5T

$$N_{12}=2T; N_{24}=4T$$

$$N_p=9.35*4=37.4>33$$

最终结果:

$$N_p=37T$$

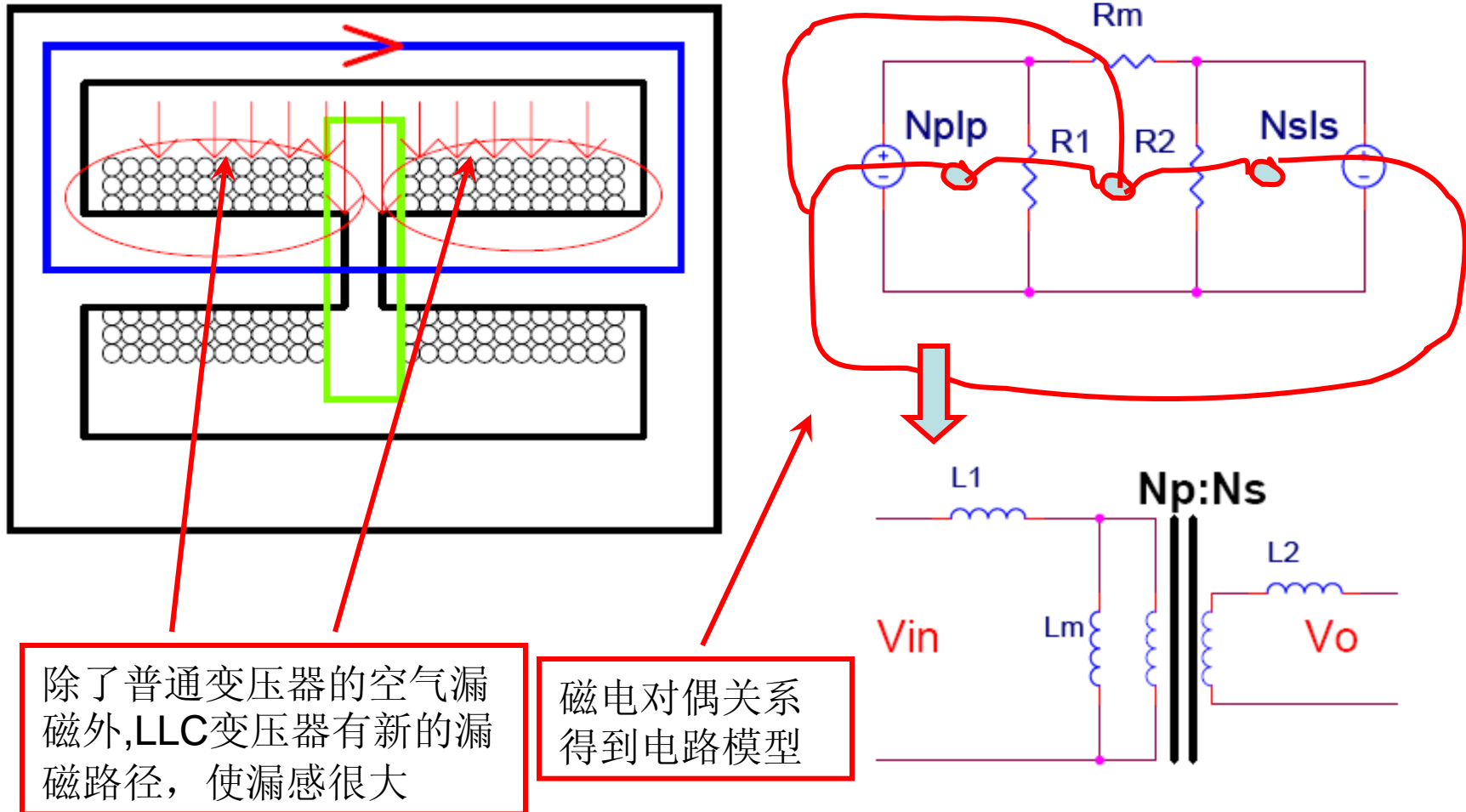
$$N_{12}=2T$$

$$N_{24}=4T$$

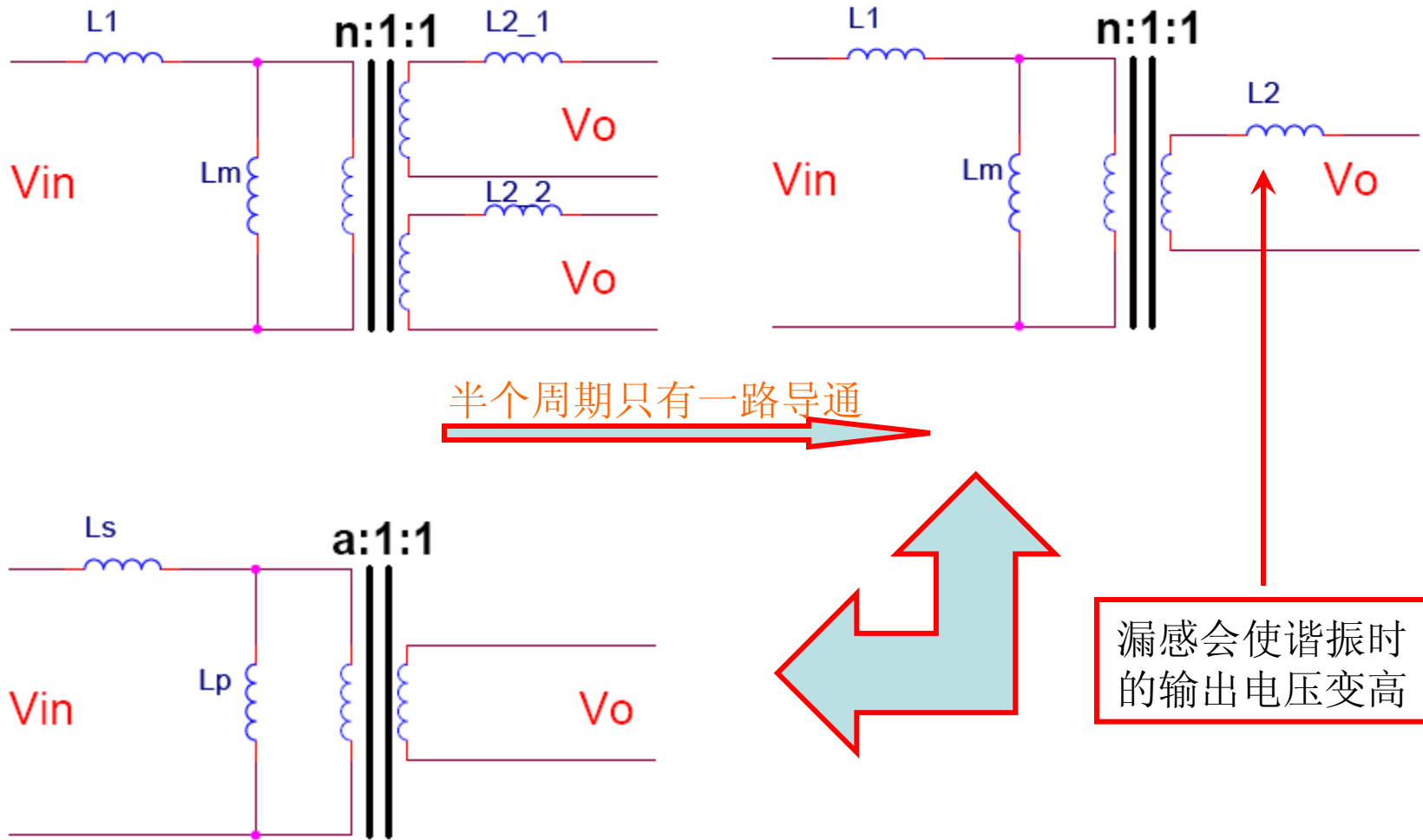
LLC的几个问题讨论

1. 变压器变比和结构
2. 电流不对称

LLC变压器磁阻模型



LLC变压器电路模型



LLC变压器电路模型

① $\times L_m$ 得

$$\begin{cases} L_m \cdot V_{in} = L_1 \cdot L_m \frac{di}{dt} + n L_m V_o + \frac{L_1 \cdot L_m}{n} \cdot \frac{di_o}{dt} \\ L_1 V_{in} = L_1 (L_1 + L_m) \frac{di}{dt} - \frac{L_1 \cdot L_m}{n} \cdot \frac{di_o}{dt} \end{cases}$$

⑧ + ⑨ 得

$$(L_1 + L_m) V_{in} = L_1 (L_1 + 2L_m) \frac{di}{dt} + n L_m V_o$$

⑩ $V_{in} = \frac{L_1 (L_1 + 2L_m)}{L_1 + L_m} \cdot \frac{di}{dt} + \frac{n L_m}{L_1 + L_m} \cdot V_o$

⑪ $\begin{cases} L_s = L_1 + L_m // n L_2 = L_1 + L_m // L_2 = L_1 + \frac{L_1 \cdot L_2}{L_1 + L_m} = \frac{L_1 (L_1 + 2L_m)}{L_1 + L_m} \\ L_s + L_p = L_1 + L_m = L \end{cases}$

由⑪得 $L_m = L - L_s$ ⑫

把⑫代入⑩得

$$L_s = L_1 + \frac{L_1 \cdot L_m}{L_1 + L_m} = L - L_m + \frac{(L - L_m) \cdot L_m}{L - L_m + L_m} = L - L_m + \frac{(L - L_m) \cdot L_m}{L}$$

两边同乘以L得

$$\begin{cases} L \cdot L_s = L^2 - L \cdot L_m + L_1 \cdot L_m - L_m^2 \Rightarrow L_m^2 = L^2 - L \cdot L_s \Rightarrow L_m = \sqrt{L^2 - L \cdot L_s} \\ L_1 = L - L_m = L - \sqrt{L^2 - L \cdot L_s} \end{cases}$$

把⑬代入⑩得

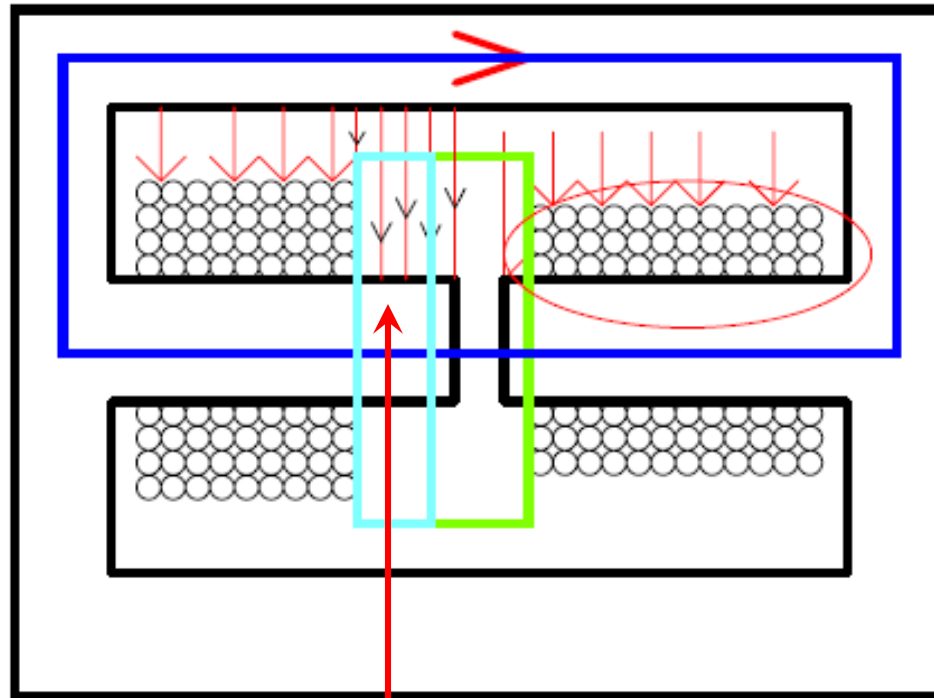
$$V_{in} = \left[L_1 + \frac{L_1 \cdot L_m}{L_1 + L_m} \right] \frac{di}{dt} + \frac{n \sqrt{L^2 - L \cdot L_s}}{L} V_o = L_s \frac{di}{dt} + n \sqrt{\frac{L \cdot L_p}{L_1}} \cdot V_o$$

$$= L_s \frac{di}{dt} + n \sqrt{\frac{L \cdot L_p}{L_1}} \cdot V_o \quad \text{由图②得 } a = n \sqrt{\frac{L_p}{L_1}} \Rightarrow n = a \sqrt{\frac{L_1 \cdot L_p}{L_p}}$$

a为理论变比, n为实际变比

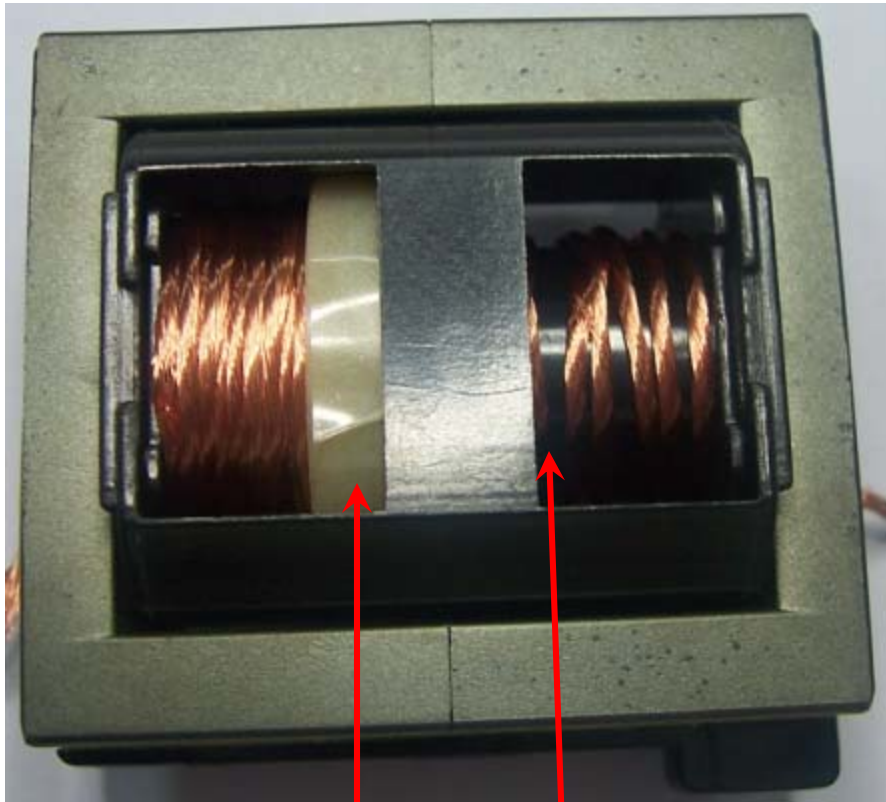
由于fr时的增益>1,实际变比比理论变比大才能得到理论电压

LLC变压器漏感的调整



增加初次级的距离增加了漏感

一个变压器实测结果



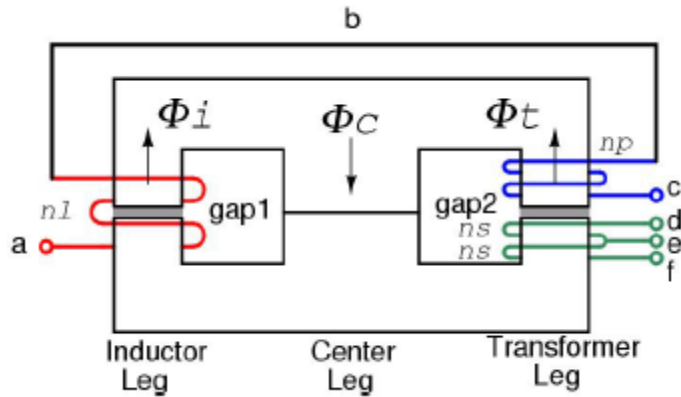
初次级都不加3.6mm档墙
 $L_m=680\mu\text{H}$, $L_s=123\mu\text{H}$
在次级加3.6mm档墙
 $L_m=680\mu\text{H}$, $L_s=140\mu\text{H}$

初级加3.6mm,次级不加3.6mm档墙
 $L_m=700\mu\text{H}$, $L_s=146\mu\text{H}$
初级、次级都加3.6mm档墙
 $L_m=700\mu\text{H}$, $L_s=160\mu\text{H}$

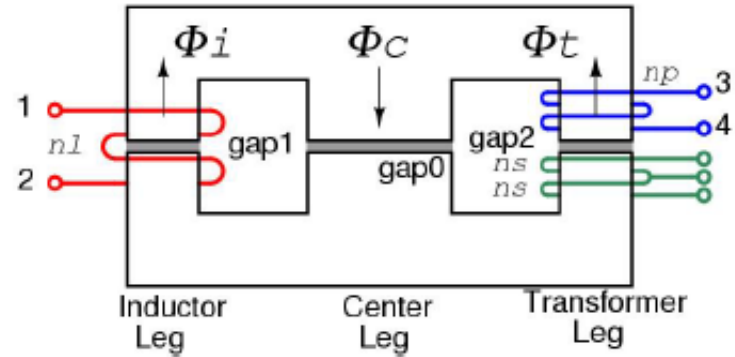
档墙

次级加的位置

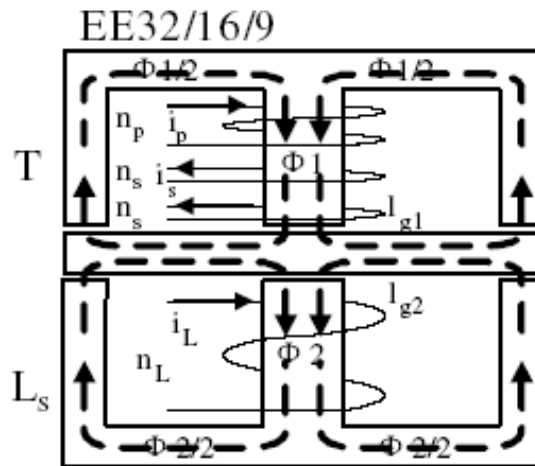
可能的变压器集成方式



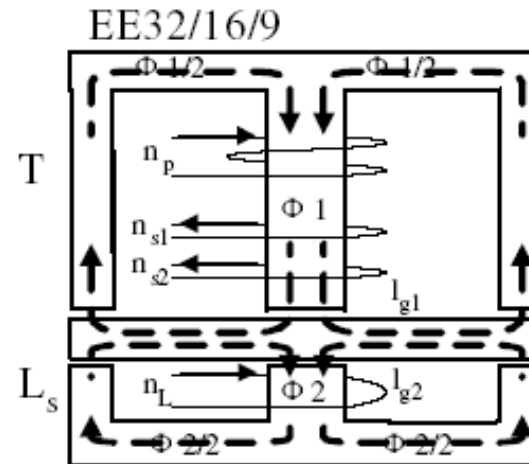
A



B

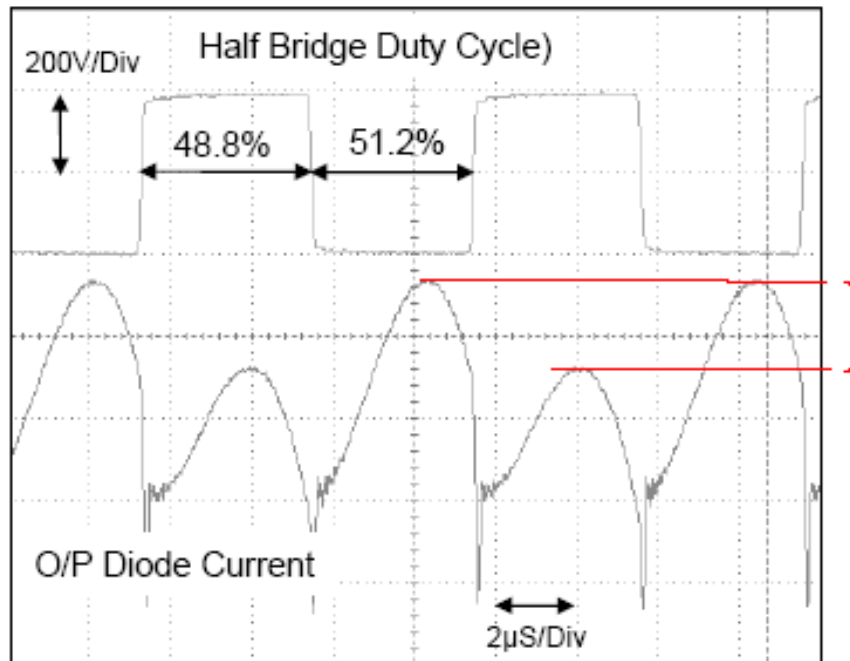


C



D

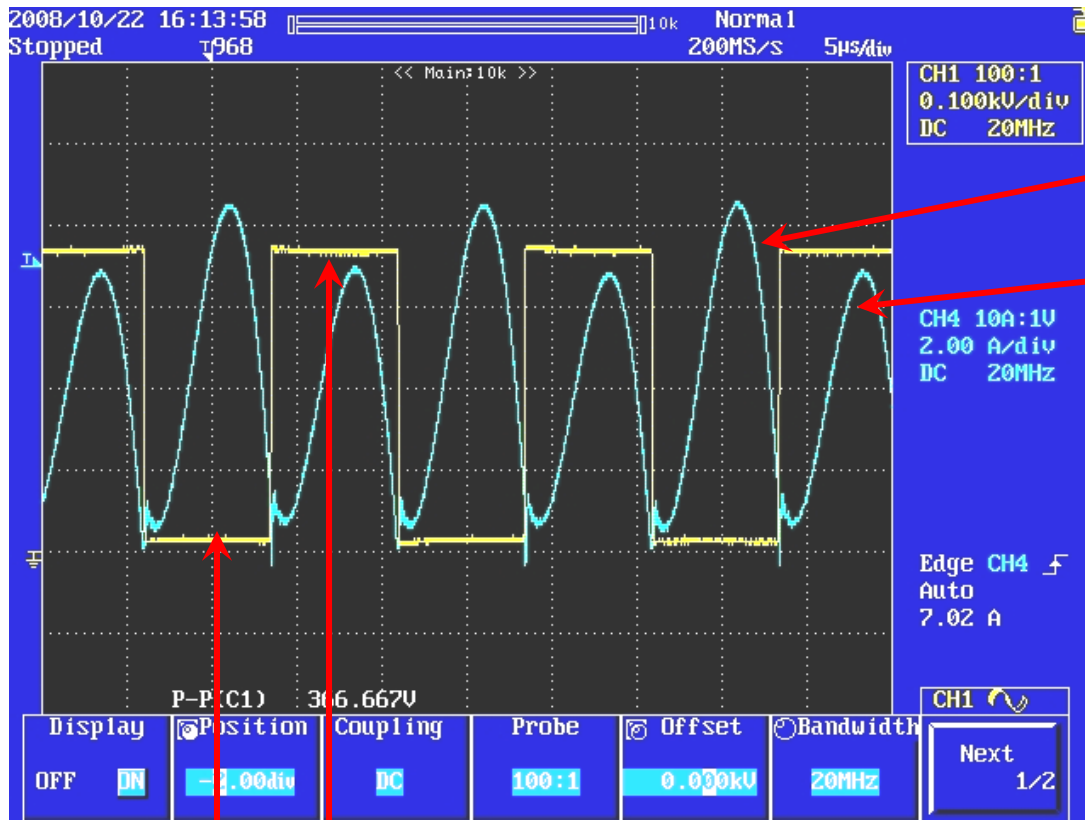
驱动不对称造成电流不对称



实际测量结果:

- 二极管经受2.4%的占空比失衡时, 就会存在±20%的RMS电流失配
- 导致二极管过度设计

驱动对称就好了吗？



电流不平衡由正负半周的漏感不同引起

驱动几乎完全对称

双线并绕可以减少这种情况

一款新颖的控制芯片



POWER[®]
INTEGRATIONS

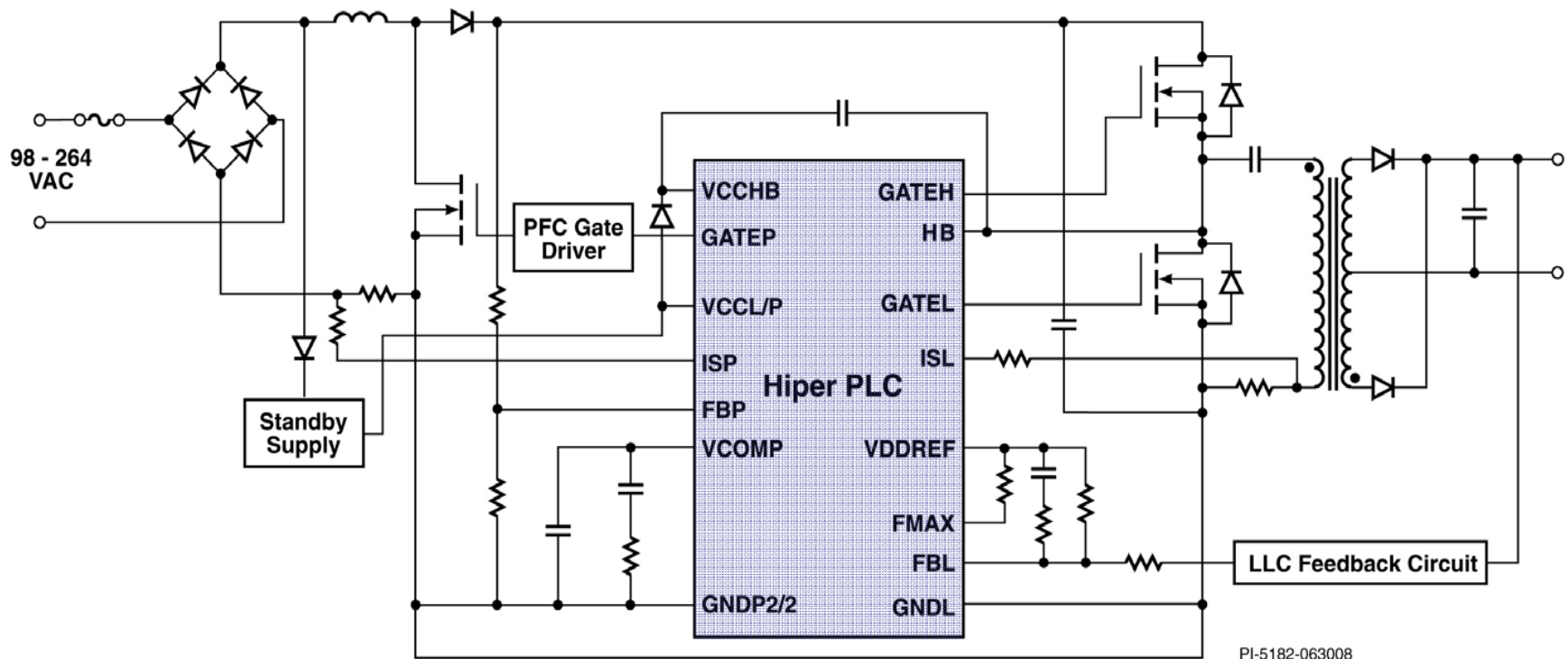


HiperPLC

用于LCD TV的全新高集成解决方案

HiperPLC: LCD TV主电源解决方案

- 集成度最高的LCD TV, LED路灯主电源解决方案
 - 集成了PFC、LLC控制器以及LLC半桥驱动器
- 非常适合150 W至600 W的功率应用



主要特点及优点

1. 连续模式PFC，Doff 控制无需检测输入波形

CCM模式降低了差模干扰和磁损，Doff控制减少了外部元件

2. PFC与LLC级之间的频率相位锁定

避免差频干扰，纹波电流抵消降低了高压电解成本

3. PFC/LLC避免边缘冲突

避免了互相干扰

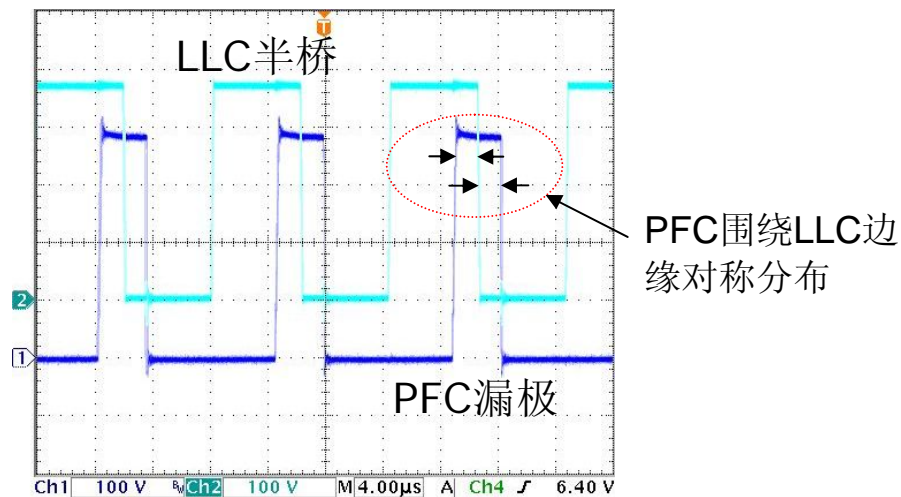
4. 占空比匹配与严格限制的死区时间优化了LLC效率

两相不平衡度小于1%

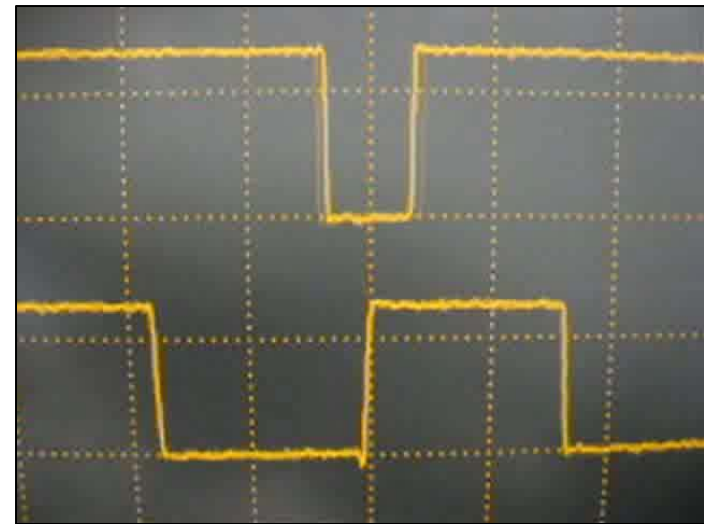
5. 集成了供电控制和各种保护功能

HiperPLC LLC/PFC同步可节省成本

- LLC与PFC之间无差频
- 纹波抵消
- 无内部边缘冲突
 - 边缘从不相交，这样可以降低噪声及互相干扰
- 简化单层电路板的布局



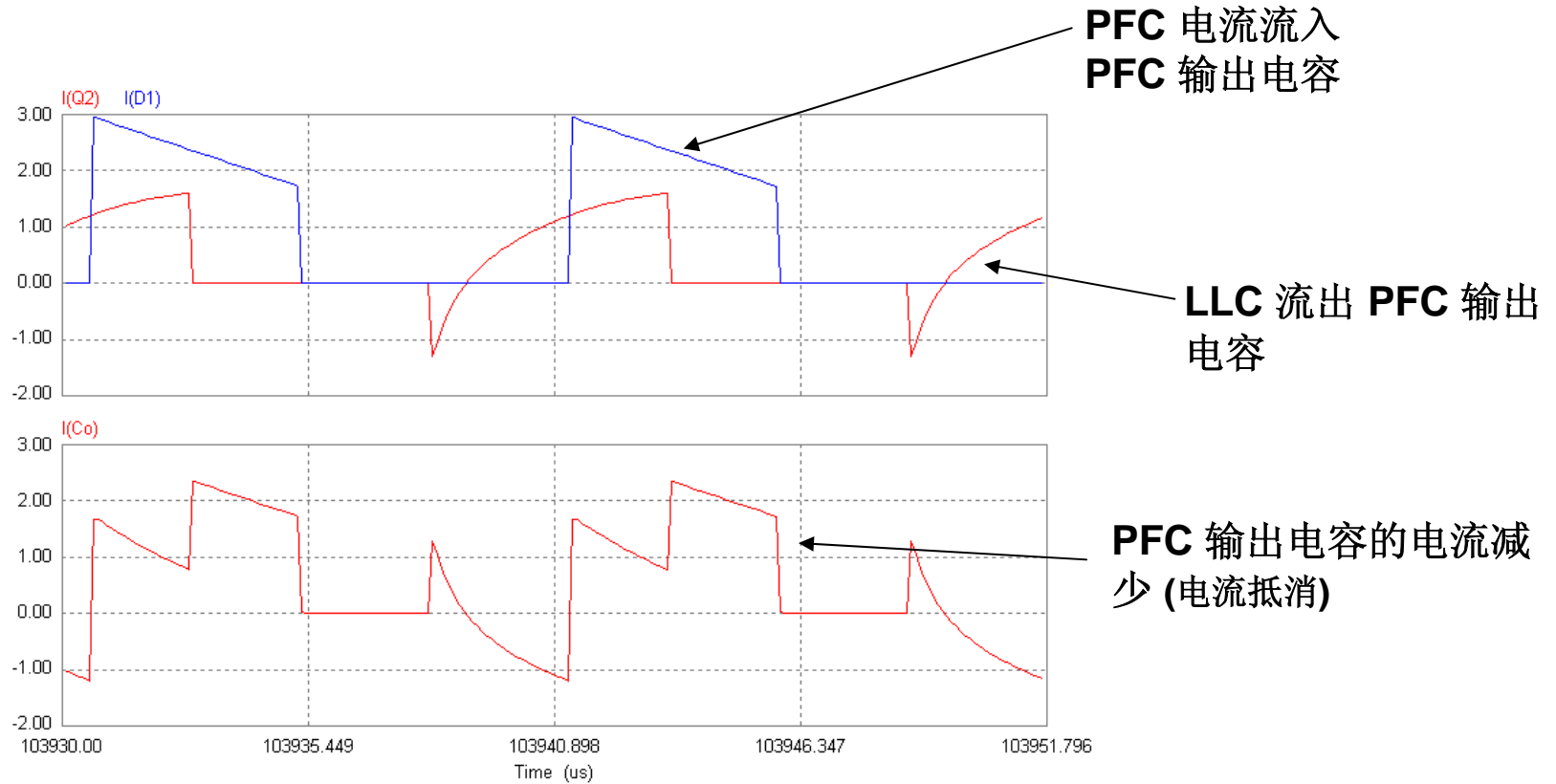
HiperPLC – 显示LLC与PFC相位锁定



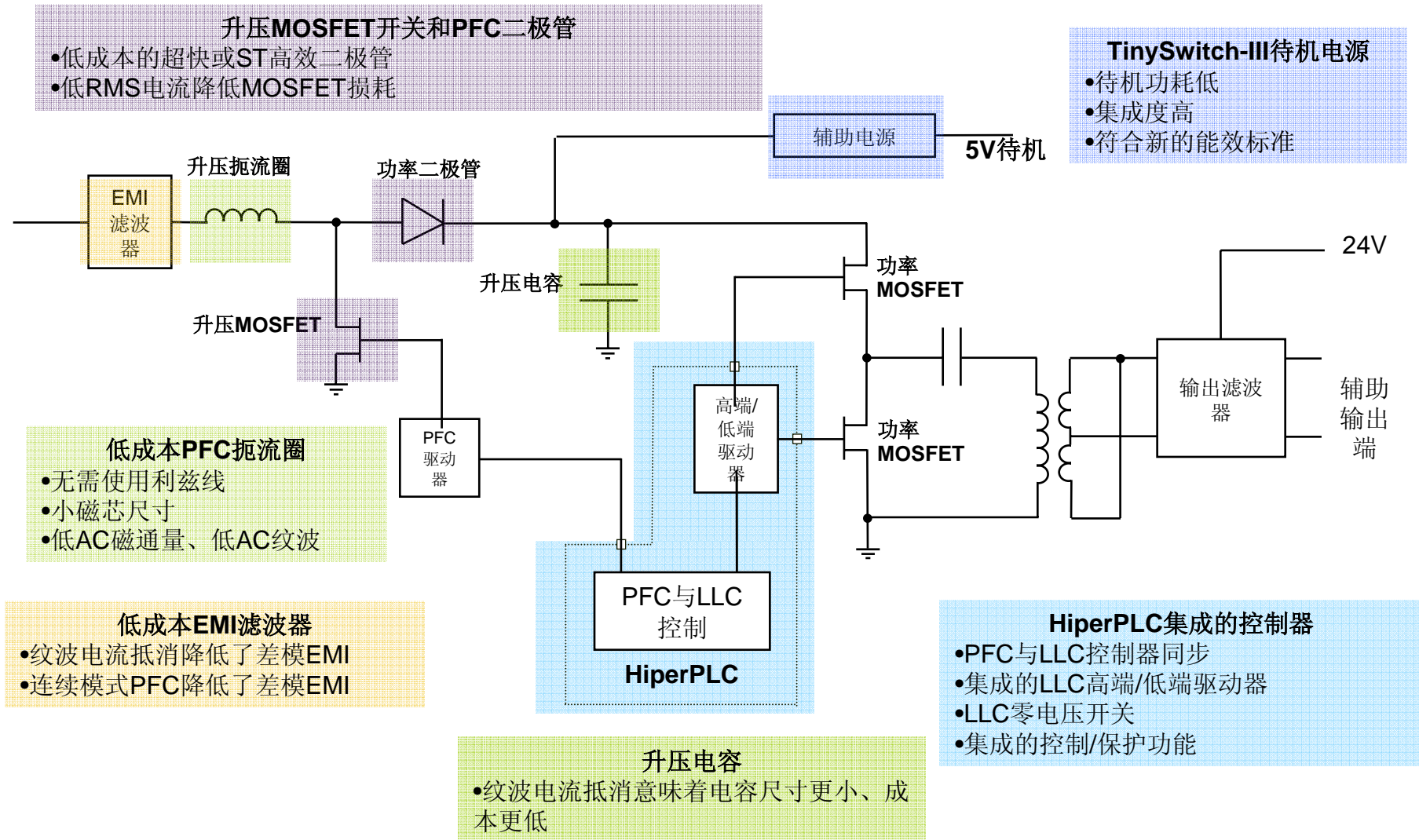
实测波形

PFC & LLC 仿真

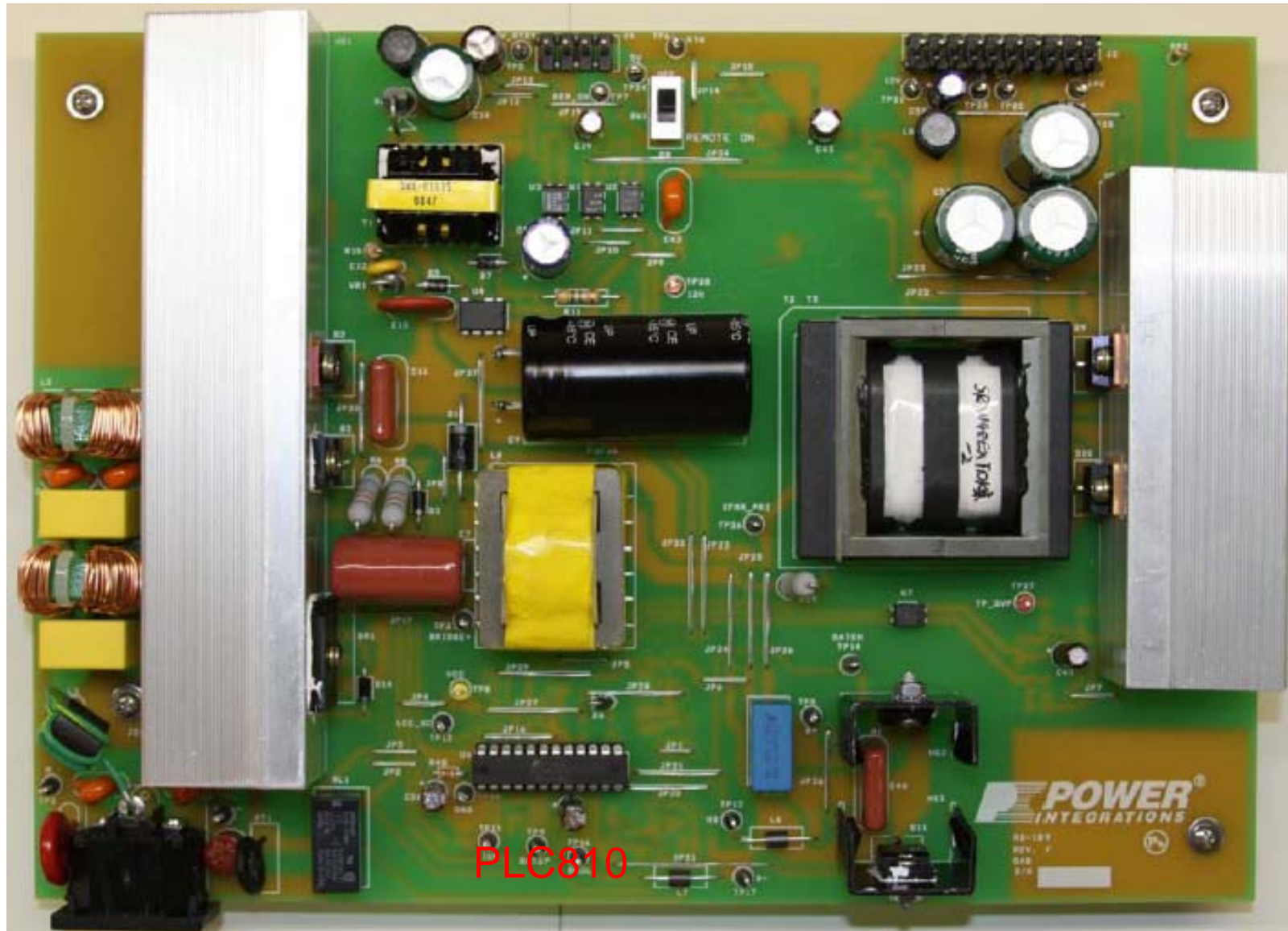
纹波减少 (Vac(max), 接近正弦)



参考设计结构框图



参考样板



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