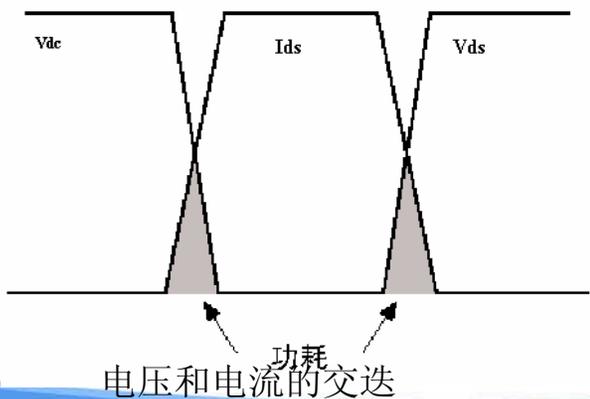
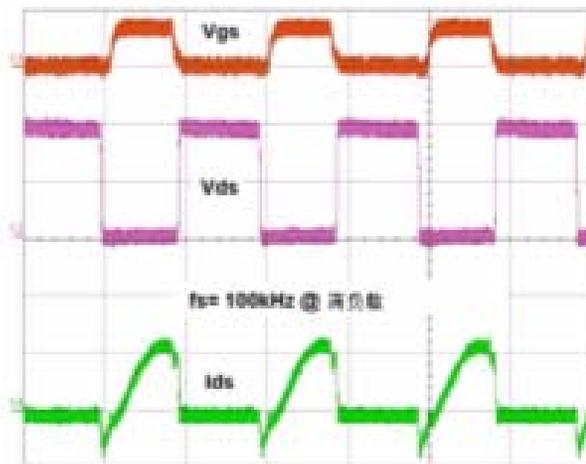


LLC 谐振转换器的设计要素

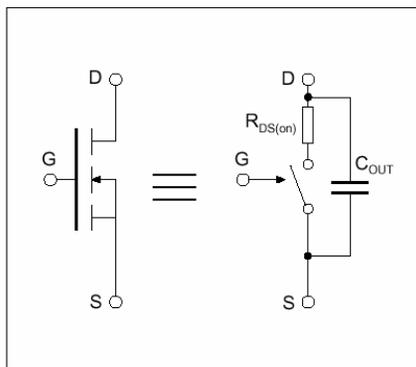
- 功率变换器设计中，对大功率密度和小尺寸的要求越来越高，迫切需要设计师提高效率提高开关频率
- 但是，硬开关的开关损耗影响了频率的升高。于是人们寻求软开关技术来克服这个问题。
- LLC谐振能实现ZVS所需元件少是近年来百瓦功率级比较流行的方案
 - 通过 ZVS 降低开关功耗：提高效率
 - 宽负载范围下频率变化范围小
 - 零电压开关，即使在无负载的情况下硬开关



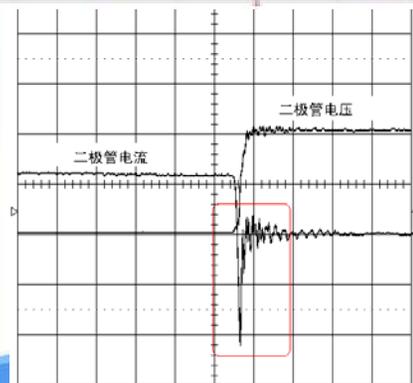
高频工作 →



简单 MOSFET 模型



容性功耗



反向恢复功耗

增益特性

- ✓ 存在两个谐振频率 (f_o 和 f_p)
- ✓ 不管负载怎么变化, 在谐振频率 (f_o) 处增益都是固定的。

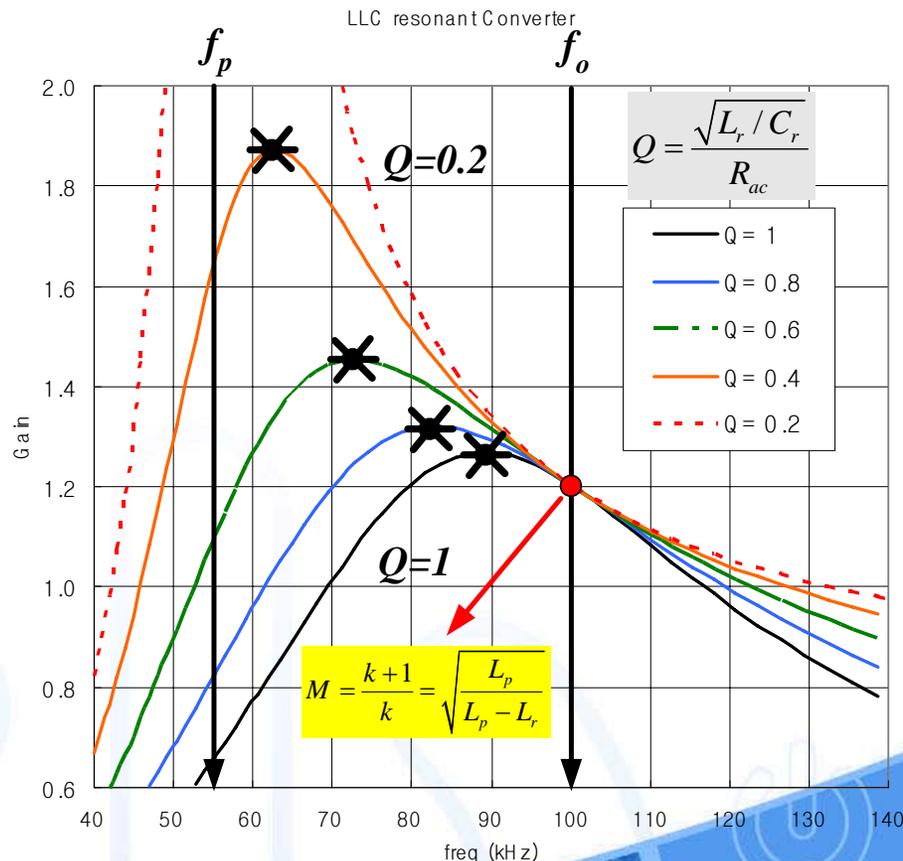
$$M = M_V = \sqrt{\frac{L_p}{L_p - L_r}} = \sqrt{\frac{m}{m-1}} \quad \text{at } \omega = \omega_o$$

- ✓ 峰值增益频率在 f_o 和 f_p 之间
- ✓ 随着 Q 降低 (如负载降低), 峰值增益频率向 f_p 移动, 得到较高的峰值增益。
- ✓ 随着 Q 上升 (如负载增加), 峰值增益频率向 f_o 移动, 峰值增益下降。

$$L_p = L_m + L_r, \quad R_{ac} = \frac{8n^2}{\pi^2} R_o, \quad m = \frac{L_p}{L_r}$$

$$Q = \sqrt{\frac{L_r}{C_r}} \frac{1}{R_{ac}}, \quad \omega_o = \frac{1}{\sqrt{L_r C_r}}, \quad \omega_p = \frac{1}{\sqrt{L_p C_r}}$$

频率 LLC 谐振变换器



50%占空比半桥谐振(LLC)—ZVS, 效率高

内置MOS寄生二极管反向恢复快, 达120ns

死区时间固定350ns

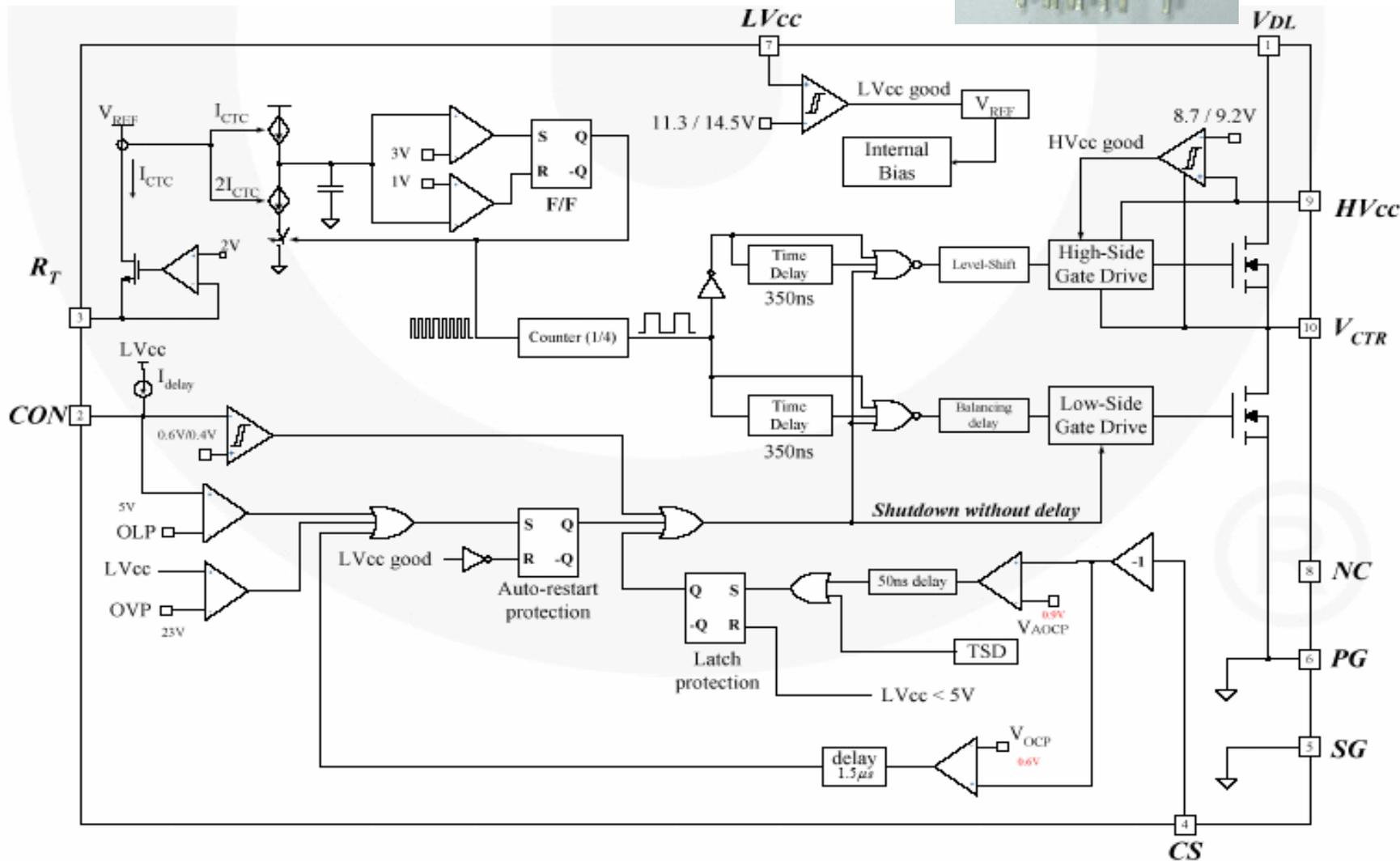
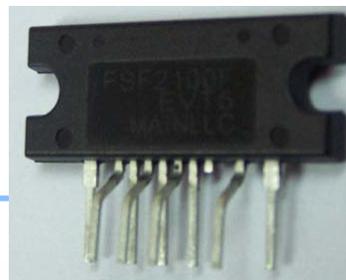
可调间歇工作模式—可在轻载时限制频率降低功耗

在控制脚可简单实现ON/OFF控制

保护齐全OVP,OLP,OCP,AOCP,TSD

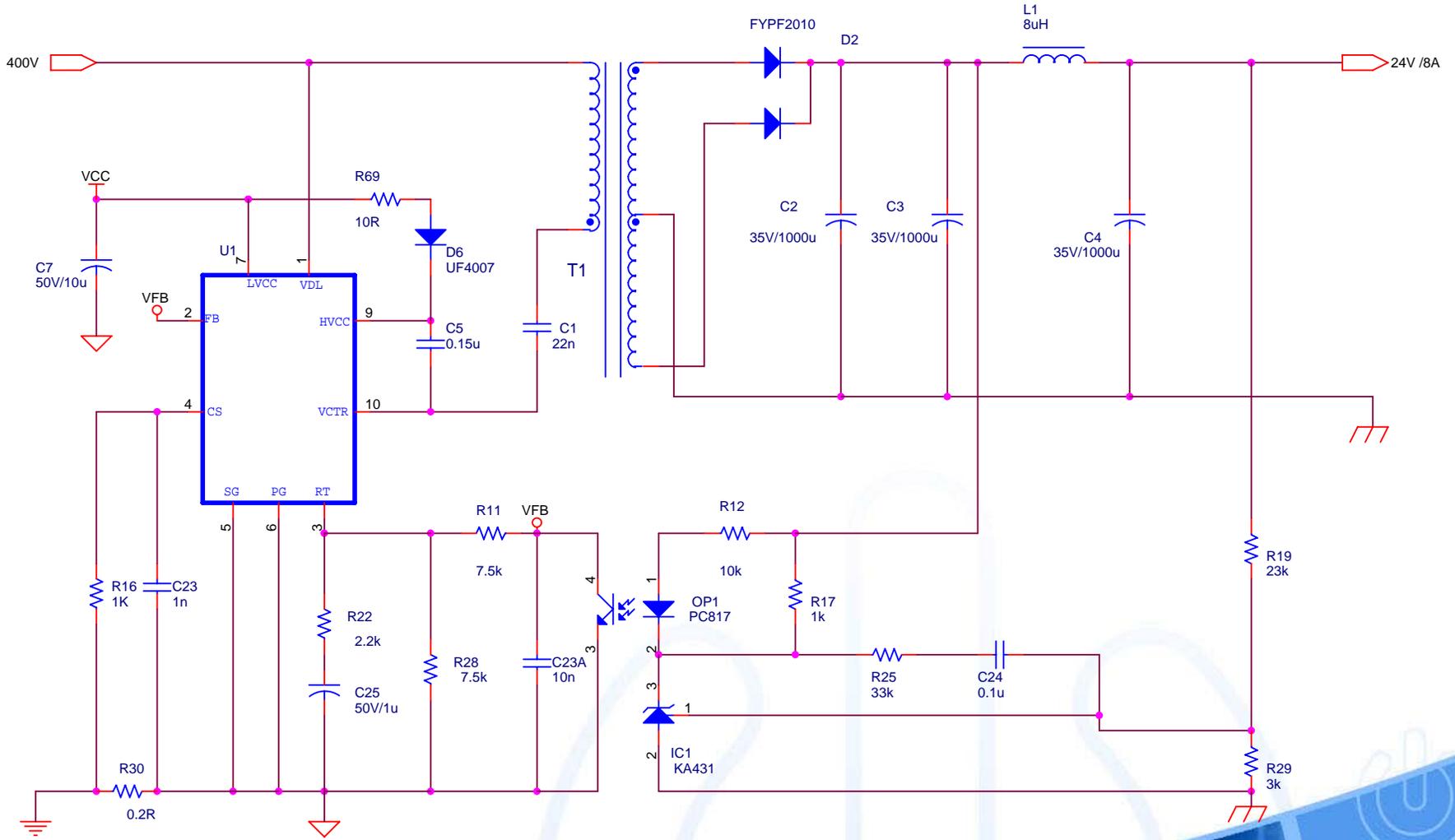
Part Number	Package	Operating Temperature	$R_{DS(ON_MAX)}$	Maximum Output Power without Heatsink ($V_{IN}=350\sim400V$) ^(1,2)	Maximum Output Power with Heatsink ($V_{IN}=350\sim400V$) ^(1,2)
FSFR2100	9-SIP	-40 to +85°C	0.38Ω	200W	450W
FSFR2000 ⁽³⁾	9-SIP	-40 to +85°C	0.67Ω	160W	350W
FSFR1900 ⁽³⁾	9-SIP	-40 to +85°C	0.85Ω	140W	300W
FSFR1800 ⁽³⁾	9-SIP	-40 to +85 °C	0.95Ω	120W	260W

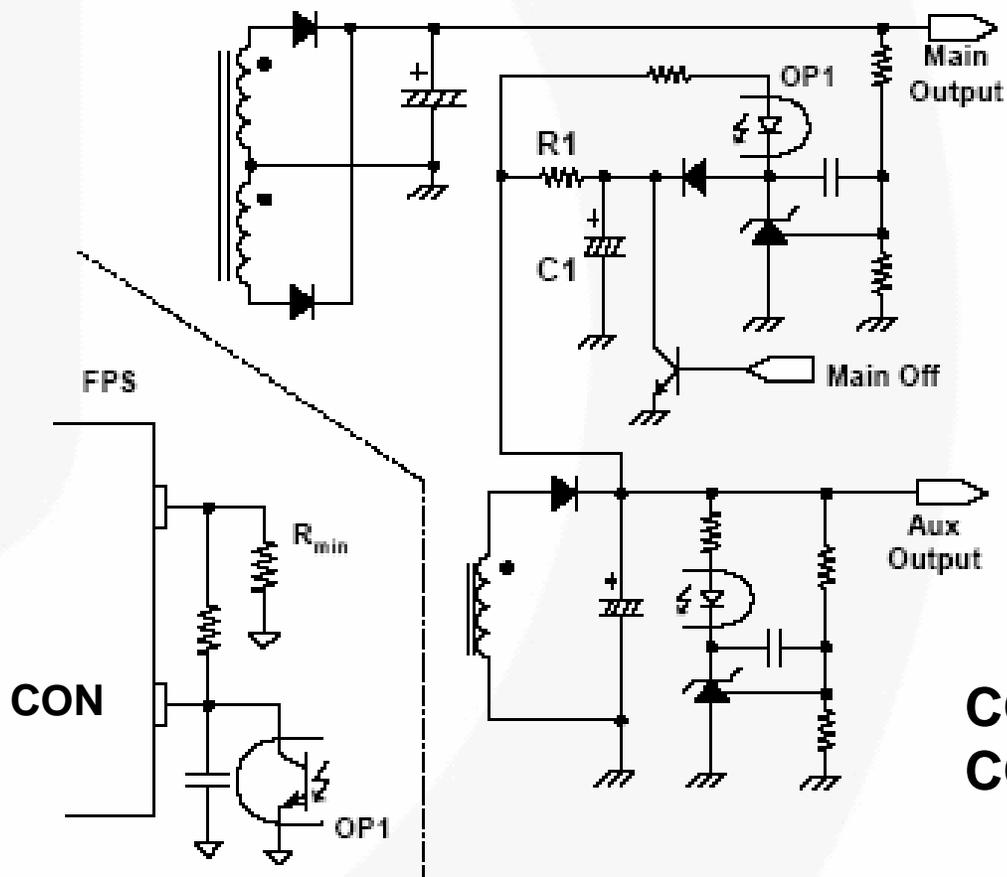
FSFR系列内框图



Internal Block Diagram

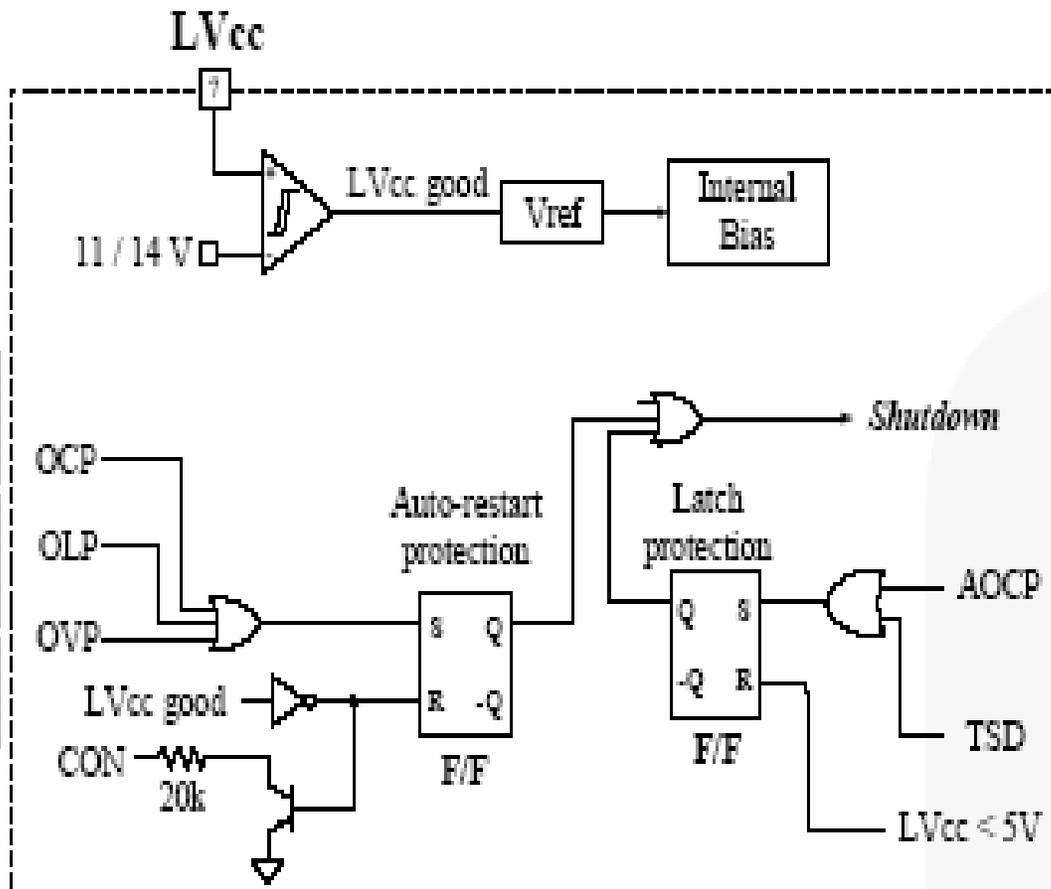
FSFR系列工作线路





CON 脚电压 < 0.4V IC 不工作
CON 脚电压 > 0.6V IC 恢复工作

Figure 23. Remote On / Off Circuit



- 检测谐振电流
VCS < -0.6V OCP
- 检测CON电压
VCON > 5V OLP
- 检测LVCC电压
LVCC > 23V OVP

- 检测谐振电流
VCS < -0.9V AOCIP

- 检测MOS温度
TMOS > 130C TSD

Protection Blocks

当检流脚电压低于 $-0.6V$ 时，OCP 启动

1.5us 延迟防止启机时的误触发

通常输出短路时触发 OCP

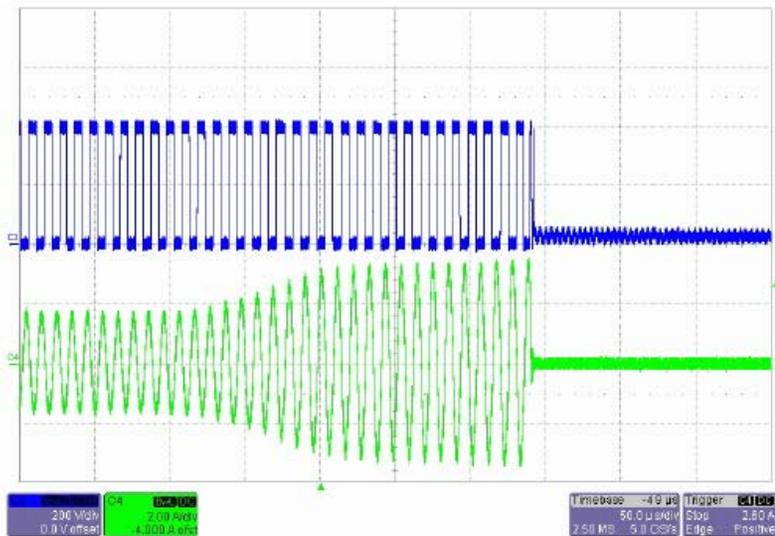
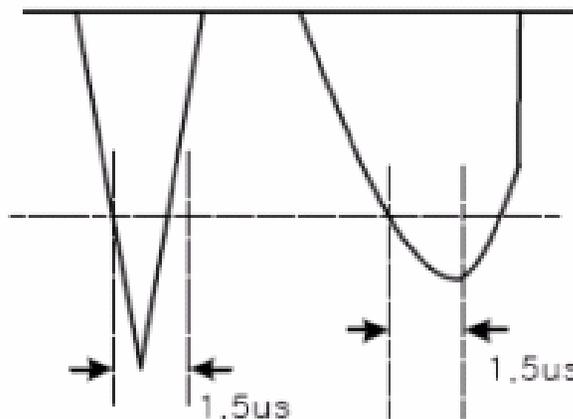


Figure 21. Protection waveform at over load condition [Vin=390Vdc, (Io=8A→16A)]
C3: Low side drain voltage (200V/div), C4: Transformer Primary side current (2A/div), time: 50us/div

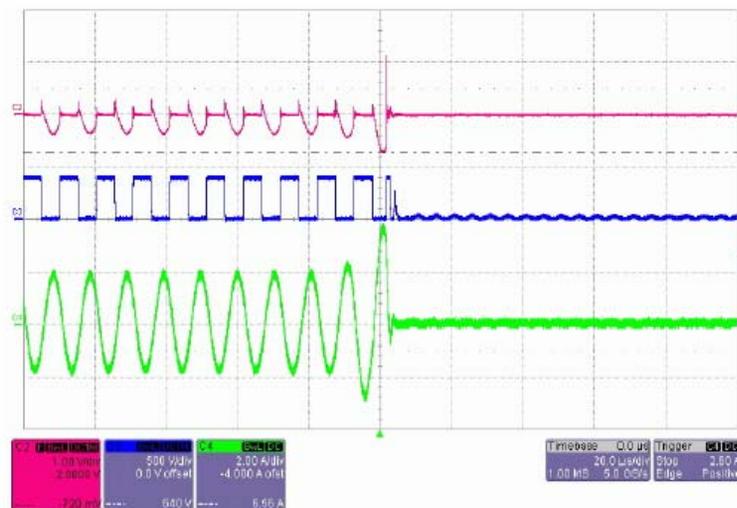
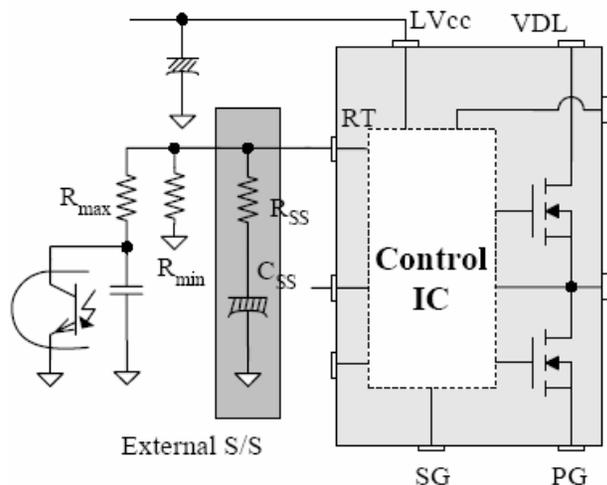


Figure 22. Protection waveform at output short condition [Vin=390Vdc, (Io=8A→short)]
C2: Current sensing pin (CS) voltage (1V/div), C3: Low side MOSFET Vds (500V/div)
C4: Transformer Primary side current (2A/div), time: 20us/div

输出过载 OCP 触发

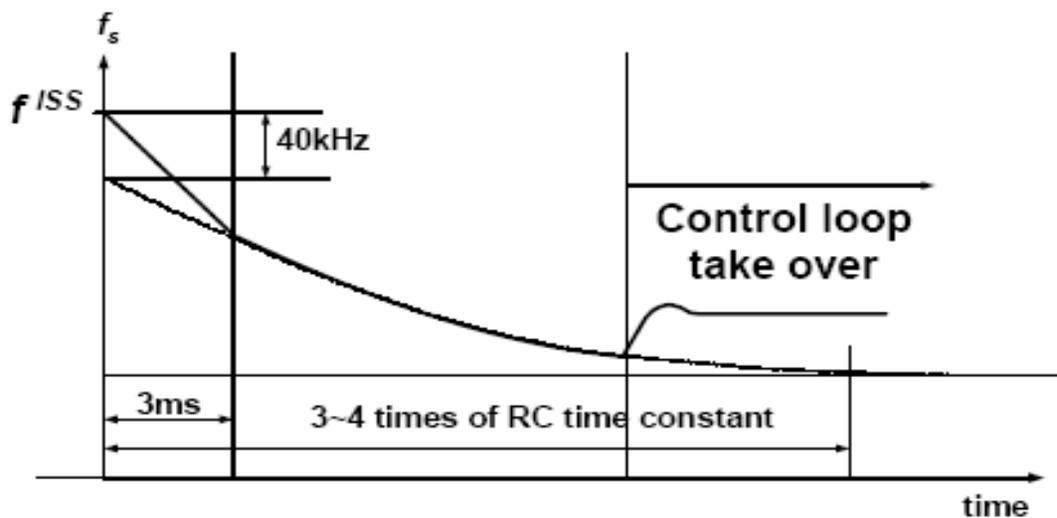
输出短路 OCP 触发



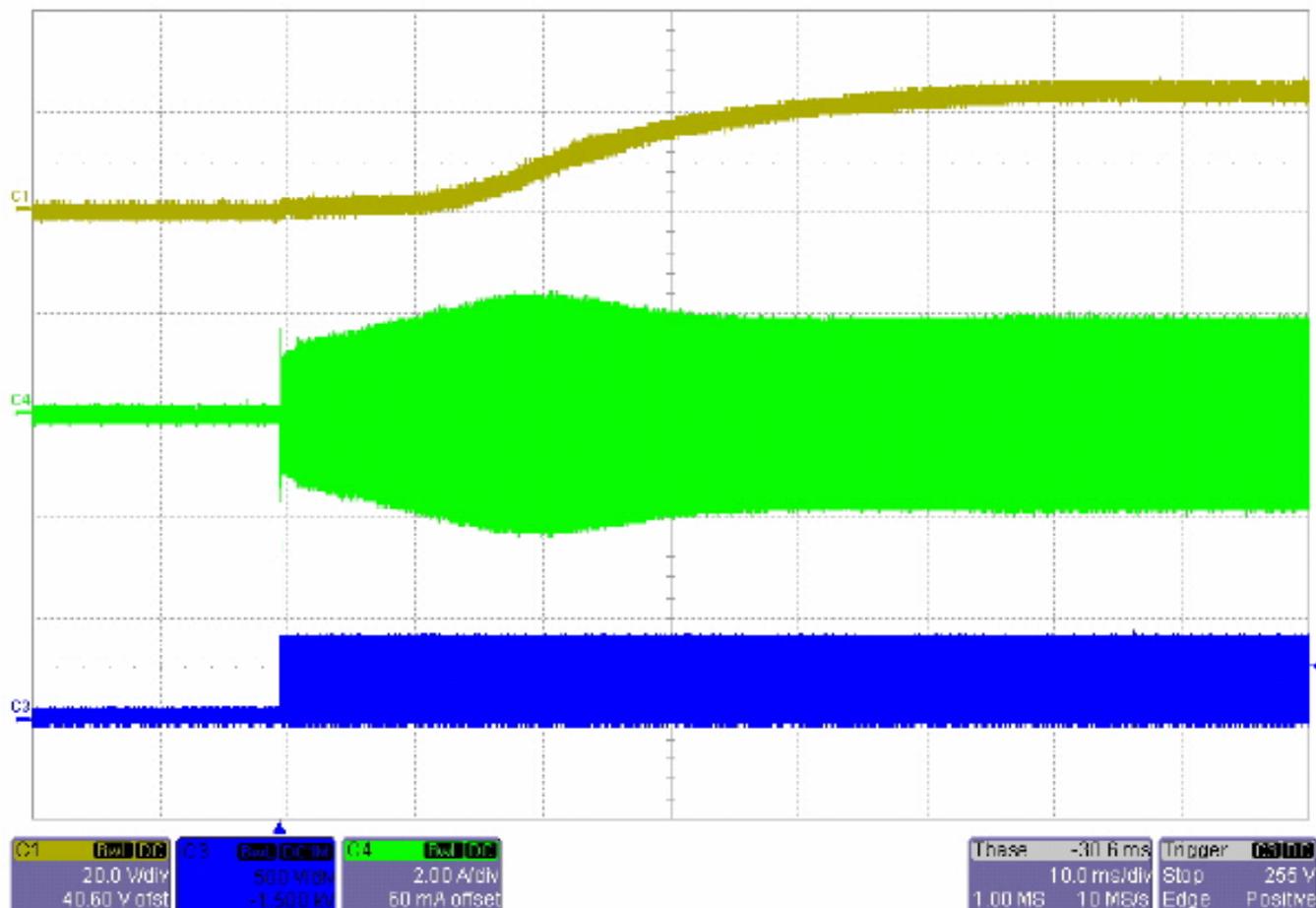
$$f^{ISS} = \left(\frac{5.2k\Omega}{R_{min}} + \frac{5.2k\Omega}{R_{SS}} \right) \times 100 + 40 \text{ (kHz)}$$

通常软启动频率是正常工作频率的2-3倍

$$T_{SS} = 3 \sim 4 \text{ times of } R_{SS} \cdot C_{SS}$$

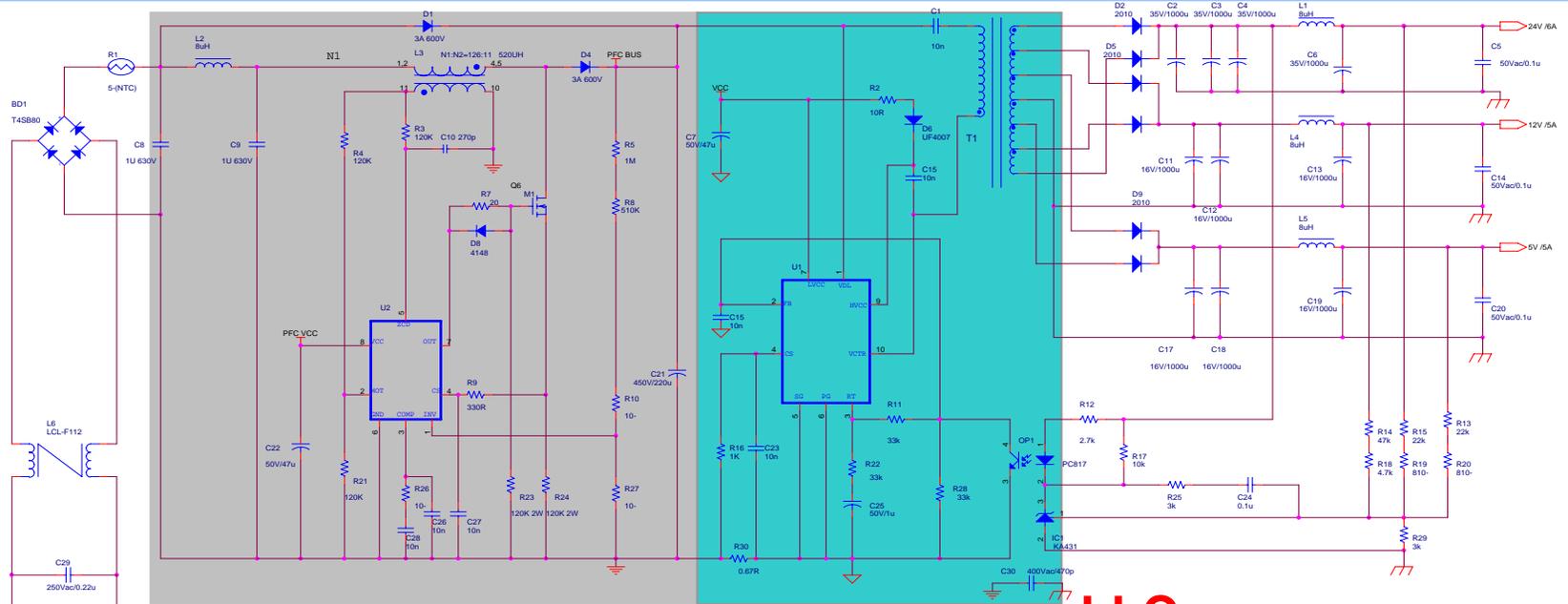


Frequency Sweep of the Soft-start

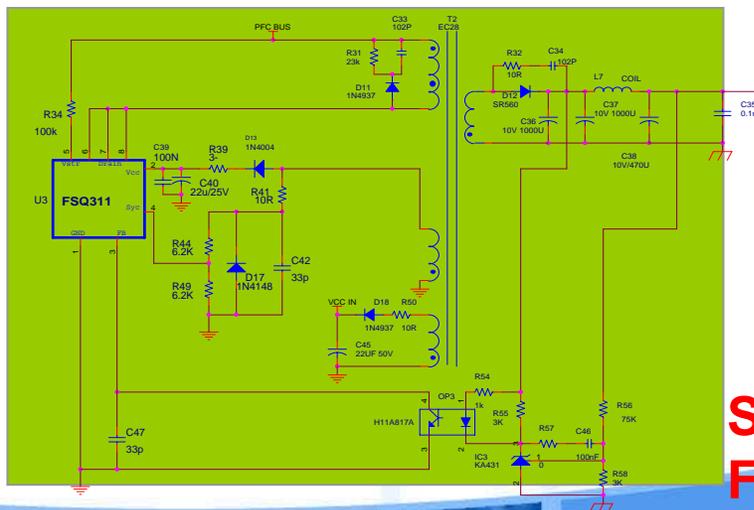


正常开机软启动波形 [Vin=390Vdc, Po=192W (24V/8A)]

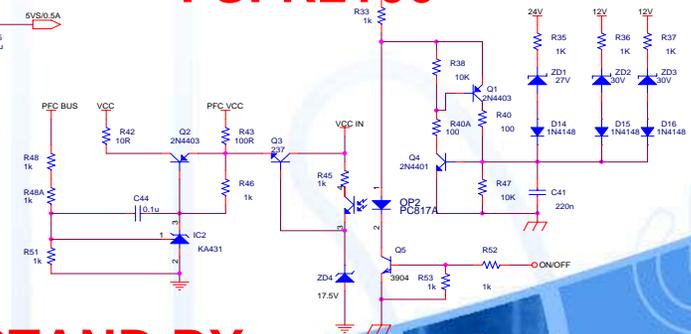
- C1: 输出电压 (20V/div), C4: 变压器初级电流 (2A/div)
C3: Low side MOSFET Vds (500V/div), time: 10ms/div



**LLC
FSFR2100**



**STAND BY
FSQ311**



■ 使用FSFR2100设计的实例

- 输入电压: 400Vdc (PFC 输出)
- 输出: 24V/8A (192W)
- 保持时间要求: 20ms
- PFC 输出电容: 220uF



定义系统参数

- ✓ 预估效率 (E_{ff})
- ✓ 输入电压范围：最小输入电压必须考虑保持时间

$$V_{in}^{\min} = \sqrt{V_{O.PFC}^2 - \frac{2P_{in}T_{HU}}{C_{DL}}}$$

(Design Example) Assuming the efficiency is 92%,

$$P_{in} = \frac{P_o}{E_{ff}} = \frac{192}{0.92} = 209W$$

$$V_{in}^{\max} = V_{O.PFC} = 400V$$

$$\begin{aligned} V_{in}^{\min} &= \sqrt{V_{O.PFC}^2 - \frac{2P_{in}T_{HU}}{C_{DL}}} \\ &= \sqrt{400^2 - \frac{2 \cdot 209 \cdot 20 \times 10^{-3}}{220 \times 10^{-6}}} = 349V \end{aligned}$$

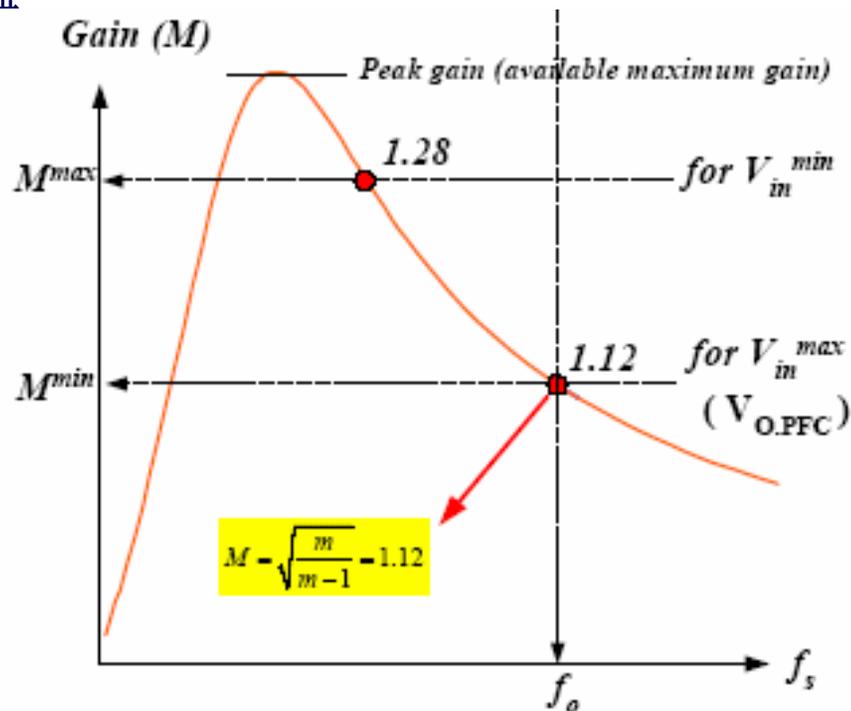
选择 m ，确定谐振网络的最大和最小压增益

一般， m 取 3~7，此时谐振频率 (f_o) 下的增益为 1.1~1.2

(Design Example) The ratio (m) between L_p and L_r is chosen as 5. The minimum and maximum gains are obtained as:

$$M^{\min} = \frac{V_{RO}}{V_{in}^{\max}/2} = \sqrt{\frac{m}{m-1}} = \sqrt{\frac{5}{5-1}} = 1.12$$

$$M^{\max} = \frac{V_{in}^{\max}}{V_{in}^{\min}} M^{\min} = \frac{400}{349} \cdot 1.12 = 1.28$$



确定变压器圈数比 ($n=N_p/N_s$)

$$n = \frac{N_p}{N_s} = \frac{V_{in}^{\max}}{2(V_o + V_F)} \cdot M^{\min}$$

(Design Example) assuming V_F is 0.9V,

$$n = \frac{N_p}{N_s} = \frac{V_{in}^{\max}}{2(V_o + V_F)} \cdot M_{\min} = \frac{400}{2(24 + 0.9)} \cdot 1.12 = 9.00$$

计算等效负载阻抗 (R_{ac})

$$R_{ac} = \frac{8n^2 V_o^2}{\pi^2 P_o}$$

(设计实例)

$$R_{ac} = \frac{8n^2 V_o^2}{\pi^2 P_o} = \frac{8 \cdot 9.0^2 \cdot 24^2}{\pi^2 \cdot 192} = 197\Omega$$

设计谐振网络

- 利用第二步选择的 m 值，从增益曲线中读取合适的 Q 值

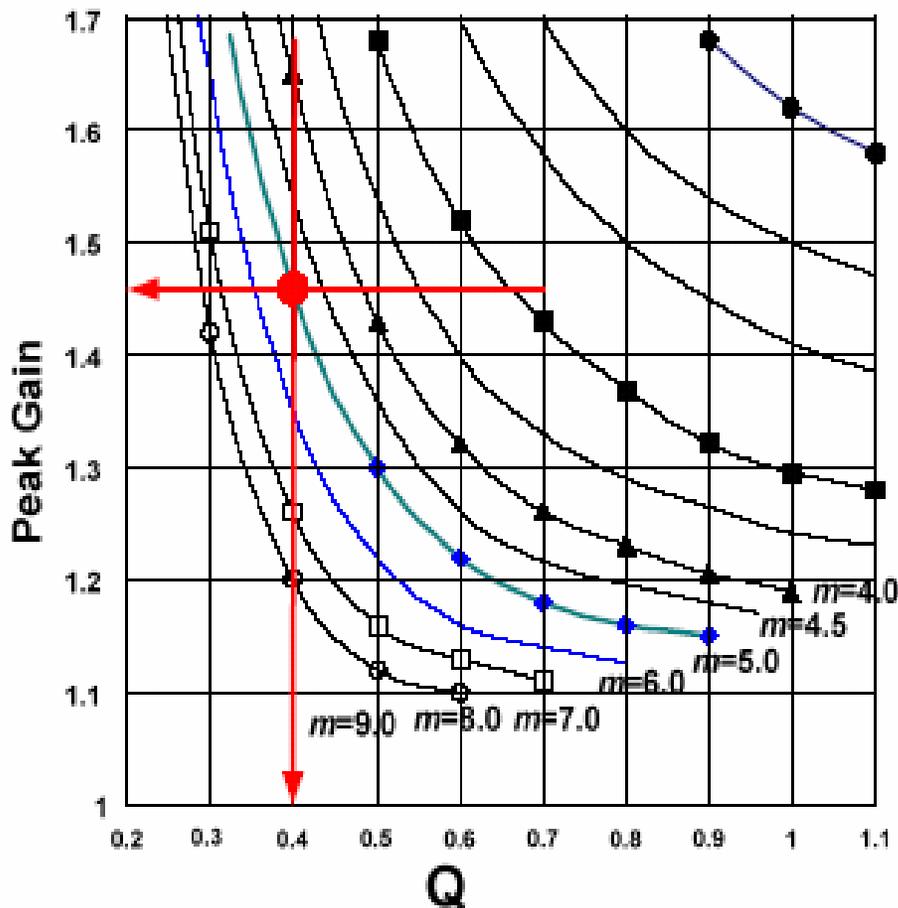
$m=5$, $M^{\text{required}} = 1.28$ 考虑15%的余量，取 $M^{\text{required}} = 1.47$

读取 $Q=0.4$

$$C_r = \frac{1}{2\pi Q \cdot f_o \cdot R_{\infty}} = \frac{1}{2\pi \cdot 0.4 \cdot 100 \times 10^3 \cdot 197} = 20.2 \text{ nF}$$

$$L_r = \frac{1}{(2\pi f_o)^2 C_r} = \frac{1}{(2\pi \cdot 100 \times 10^3)^2 \cdot 20.2 \times 10^{-9}} = 126 \mu\text{H}$$

$$L_p = m \cdot L_r = 630 \mu\text{H}$$



设计变压器

- 利用增益曲线，读取最小切换频率。然后，利用下面的等式计算变压器的初级最小线圈数

$$N_p^{\min} = \frac{n(V_o + V_F)}{2f_s^{\min} \cdot \Delta B \cdot A_e}$$

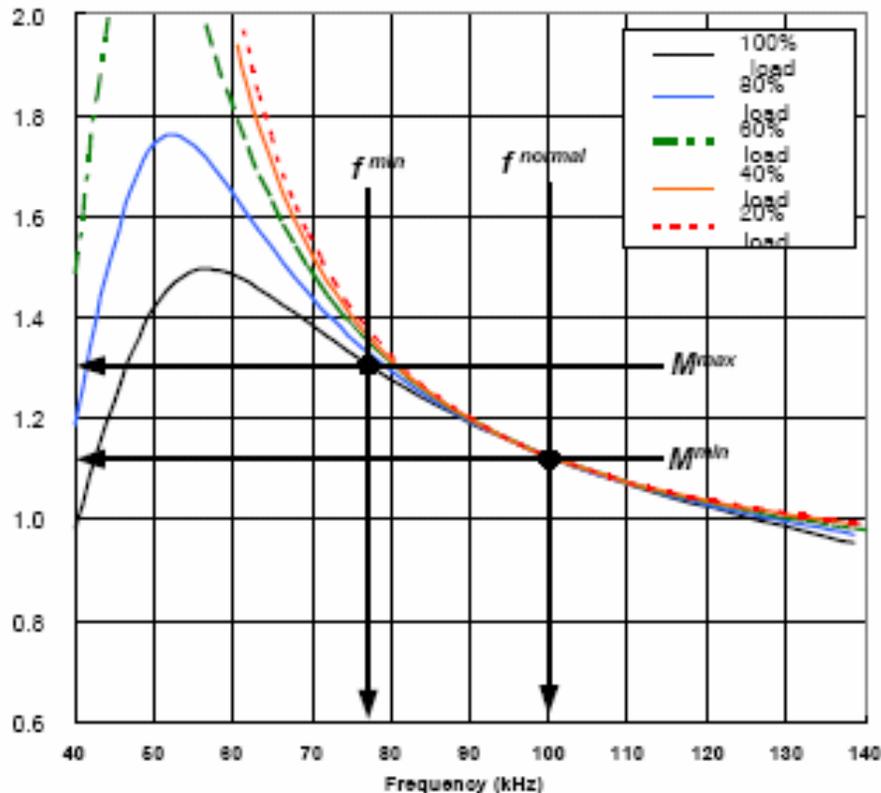
(Design Example) EER3542 core ($A_e=107\text{mm}^2$) is selected for the transformer. From the gain curve of Figure 21, the minimum switching frequency is obtained as 78kHz. The minimum primary-side turns of the transformer is given as:

$$\begin{aligned} N_p^{\min} &= \frac{n(V_o + V_F)}{2f_s^{\min} \Delta B \cdot 1.11 \cdot A_e} \\ &= \frac{9.0 \times 24.9}{2 \cdot 77 \times 10^3 \cdot 0.4 \cdot 1.11 \cdot 107 \times 10^{-6}} = 30.5 \text{ turns} \end{aligned}$$

利用匝比计算变压器的初级最小线圈数

次级取4匝时

$$N_p = n \cdot N_s = 4 \times 9.0 = 36 > N_p^{\min}$$



变压器构造

- 由于 LLC 变换器设计需要一个相对大的 L_p ，一般采用一种可组合线轴
- 线圈数和绕线结构是决定 L_r 大小的主要因素
- 变压器芯的气隙长度不会影响 L_r 太多
- 通过调整气隙长度却可以轻松控制 L_p

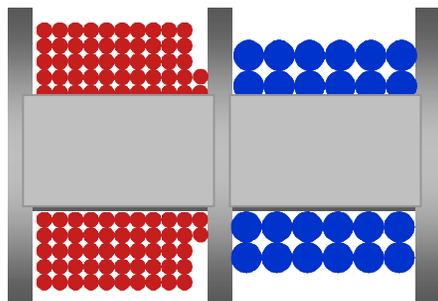
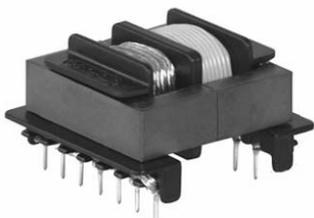


Table 2. Measured L_p and L_r with Different Gap Lengths

Gap length	L_p	L_r
0.0mm	2,295 μ H	123 μ H
0.05mm	943 μ H	122 μ H
0.10mm	630 μ H	118 μ H
0.15mm	488 μ H	117 μ H
0.20mm	419 μ H	115 μ H
0.25mm	366 μ H	114 μ H

设计值: $L_r=126\mu\text{H}$, $L_p=630\mu\text{H}$

选择谐振电容

$$I_{C_r}^{RMS} \cong \sqrt{\left[\frac{\pi I_o}{2\sqrt{2}n}\right]^2 + \left[\frac{n(V_o + 2 \cdot V_F)}{4\sqrt{2}f_o L_m}\right]^2} \quad V_{C_r}^{\max} \cong \frac{V_{in}^{\max}}{2} + \frac{\sqrt{2} \cdot I_{C_r}^{RMS}}{2 \cdot \pi \cdot f_o \cdot C_r}$$

(设计实例)

$$\begin{aligned} I_{C_r}^{RMS} &\cong \frac{1}{E_{ff}} \sqrt{\left[\frac{\pi I_o}{2\sqrt{2}n}\right]^2 + \left[\frac{n(V_o + V_F)}{4\sqrt{2}f_o M_V (L_p - L_r)}\right]^2} \\ &= \frac{1}{0.92} \sqrt{\left[\frac{\pi \cdot 8}{2\sqrt{2} \cdot 9.0}\right]^2 + \left[\frac{9.0 \cdot (24 + 0.9)}{4\sqrt{2} \cdot 99 \times 10^3 \cdot 1.11 \cdot 512 \times 10^{-6}}\right]^2} \\ &= 1.32A \end{aligned}$$

$$\begin{aligned} V_{C_r}^{\max} &\cong \frac{V_{in}^{\max}}{2} + \frac{I_{OCP}}{2 \cdot \pi \cdot f_o \cdot C_r} \\ &= \frac{400}{2} + \frac{3}{2 \cdot \pi \cdot 99 \times 10^3 \cdot 22 \times 10^{-9}} = 419V \end{aligned}$$

选630V耐压的电容

选择输出线路

采用中间抽头方式整流时

输出二极管的最低耐压

$$V_D = 2(V_o + V_F)$$

流过输出二极管的电流的有效值

$$I_D^{RMS} = \frac{\pi}{4} I_o$$

(设计实例)

$$V_D = 2(V_o + V_F) = 2(24 + 0.9) = 49.8$$

$$I_D^{RMS} = \frac{\pi}{4} I_o = 6.28 A$$

可选择**100V20A**的肖特基

设计控制线路

R_{\min} 是由最低工作频率决定的

$$f_{\min} = \frac{5.2k\Omega}{R_{\min}} \times 100 (kHz)$$

R_{\max} 是由最高工作频率决定的

$$f_{\max} = \left(\frac{5.2k\Omega}{R_{\min}} + \frac{4.68k\Omega}{R_{\max}} \right) \times 100 (kHz)$$

R_{SS} 是由软启动频率决定的

$$f_{ISS} = \left(\frac{5.2k\Omega}{R_{\min}} + \frac{5.2k\Omega}{R_{SS}} \right) \times 100 + 40 (kHz)$$

(设计实例)

由第六步最低工作频率为**72K**

$$R_{\min} = \frac{100kHz}{f_{\min}} \times 5.2k\Omega = 7.2k$$

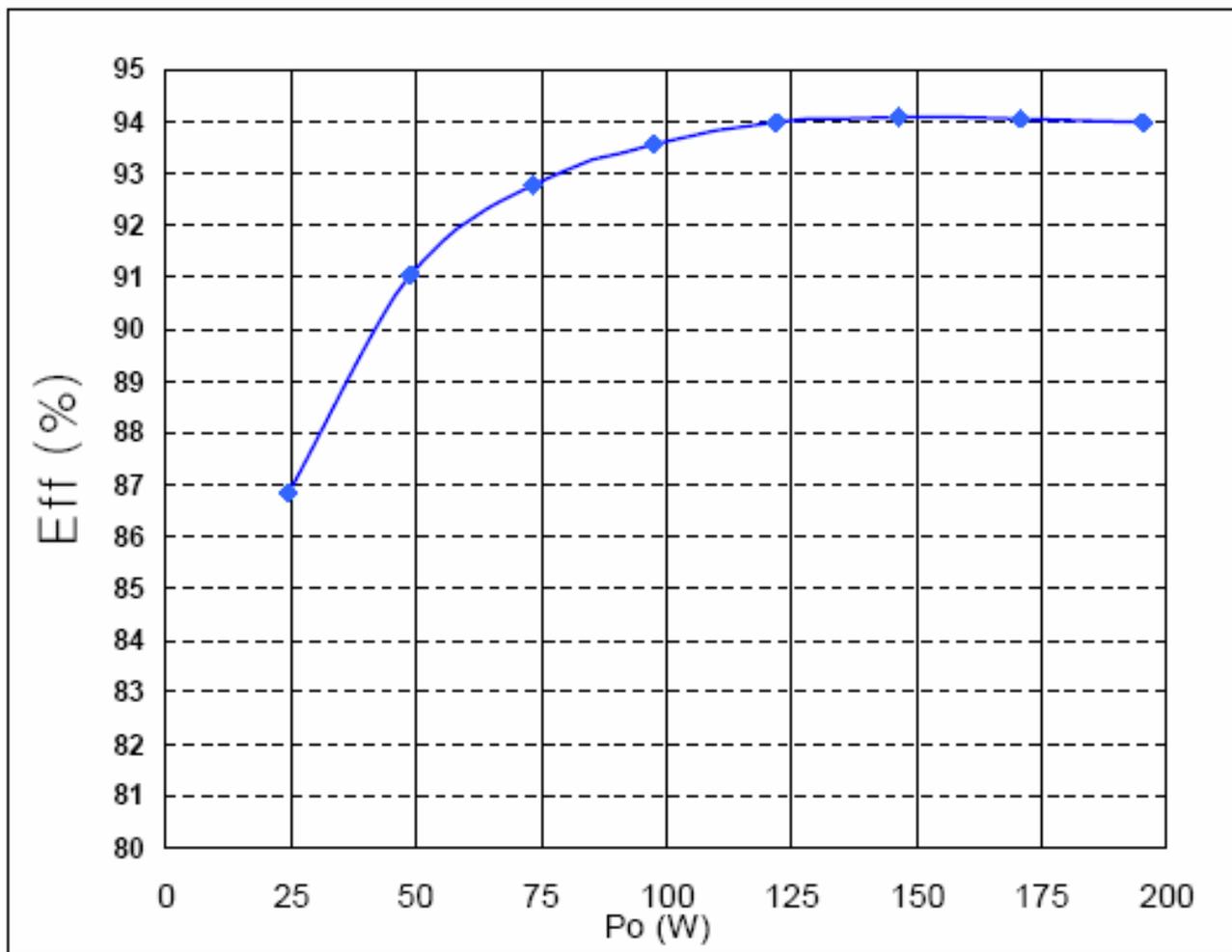
设最高工作频率为**140K**

$$\begin{aligned} R_{\max} &= \frac{4.68k\Omega}{\left(\frac{f_o \times 1.40}{100kHz} - \frac{5.2k\Omega}{R_{\min}} \right)} \\ &= \frac{4.68k\Omega}{\left(\frac{99kHz \times 1.4}{100kHz} - \frac{5.2k\Omega}{7.2k\Omega} \right)} = 7.1k\Omega \end{aligned}$$

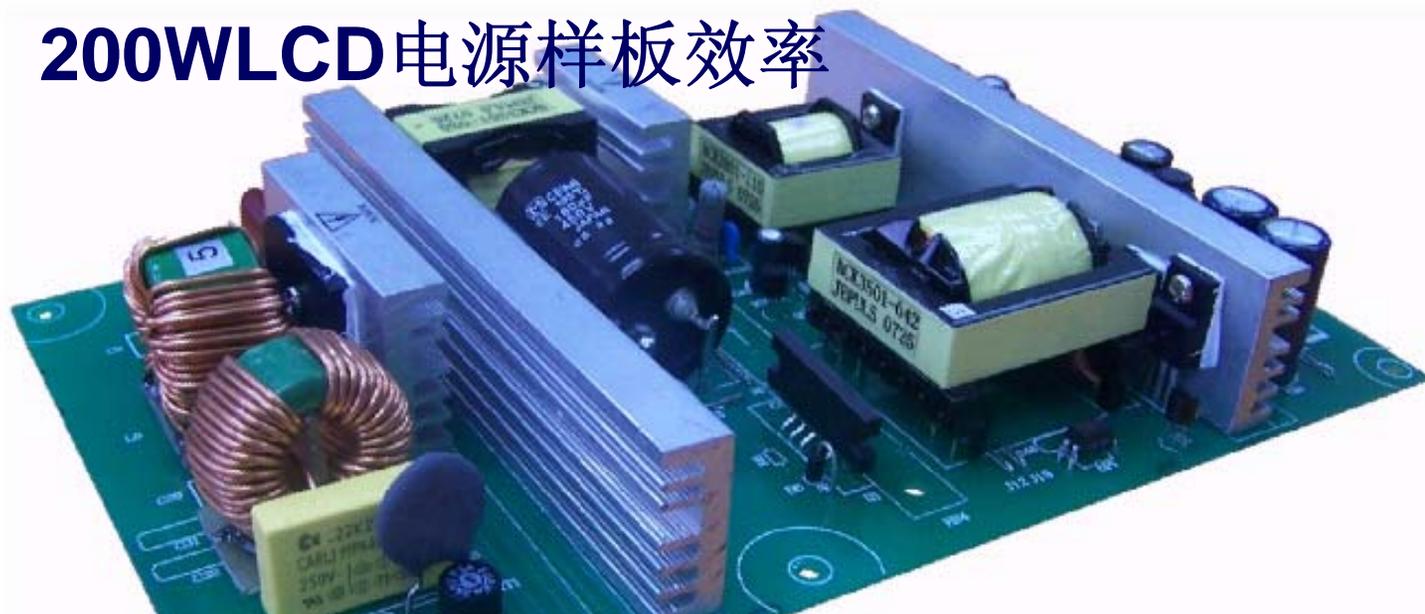
设起始软启动频率为**250K**

$$\begin{aligned} R_{SS} &= \frac{5.2k\Omega}{\left(\frac{f_{ISS} - 40kHz}{100kHz} - \frac{5.2k\Omega}{R_{\min}} \right)} \\ &= \frac{5.2k\Omega}{\left(\frac{250kHz - 40kHz}{100kHz} - \frac{5.2k\Omega}{7.2k\Omega} \right)} = 3.8k\Omega \end{aligned}$$

24V/8A样板效率



200WLCD电源样板效率



Input Voltage [⊕]	Load condition [⊕]	Output Power(w) [⊕]	Input Power(w) [⊕]	Efficiency (%) [⊕]	Power Factor [⊕]
90Vac [⊕]	5V/1A [⊕]	197.07 [⊕]	225.22 [⊕]	87.47 [⊕]	0.9992 [⊕]
	12V/4A [⊕]				
	24V/6A [⊕]				
110Vac [⊕]	5V/1A [⊕]	197.11 [⊕]	220.56 [⊕]	89.36 [⊕]	0.9984 [⊕]
	12V/1A [⊕]				
	24V/6A [⊕]				
220Vac [⊕]	5V/1A [⊕]	197.07 [⊕]	214.80 [⊕]	91.70 [⊕]	0.9953 [⊕]
	12V/4A [⊕]				
	24V/6A [⊕]				
264Vac [⊕]	5V/1A [⊕]	197.07 [⊕]	214.31 [⊕]	91.96 [⊕]	0.9918 [⊕]
	12V/4A [⊕]				
	24V/6A [⊕]				

高压INVERTER方案

