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AN-6208

FAN6208在LLC谐振变换器的次级同步整流(SR)中的应用

引言

近来, LLC谐振变换器引起了更多的关注, 这是因为这种变换器具有超越传统串联谐振变换器和并联谐振变换器的优势: 宽负载范围内频率变化范围窄、输入电压可变、整个负载范围内零电压切换 (ZVS)。

在LLC谐振变换器中, 整流二极管被典型地采用从变压器次级绕组获得直流输出电压。在LLC谐振变换器中, 二极管整流器的导通损耗占整个功耗的比重相当大, 尤其当输出电压低时更是如此。整流器的导通损耗与它的正向压降和导通电流的乘积成正比。对于同步整流(SR), 由于采用具有较低导通电阻($R_{DS(on)}$)的MOSFET取代二极管, 同步整流的正向压降远低于二极管整流器的正向压降, 因此整流器的导通损耗大大降低。

FAN6208是一款专用于隔离型LLC或LC谐振变换器的同步整流控制器, 它可以同时驱动两只独立的SR MOSFET来仿效整流二极管的性能。通过监测每只SR漏极-源极之间的电压, FAN6208能够测量每个开关周期中SR的导通时间, 并能够确定SR门极驱动的最优时机。FAN6208还能根据光耦中二极管电流的变化, 在负载瞬变时自适应地收缩SR门极驱动信号的持续时间, 防止直通发生。为了提高轻载下的效率, 绿色模式禁用SR驱动信号, 最大限度地降低轻载条件下门极驱动功耗。

本使用说明书描述了采用FAN6208实现SR电路的设计过程, 也提供有印刷电路板 (PCB) 布局指南和带有实验结果的设计范例。图1中给出了FAN6208的典型应用电路。

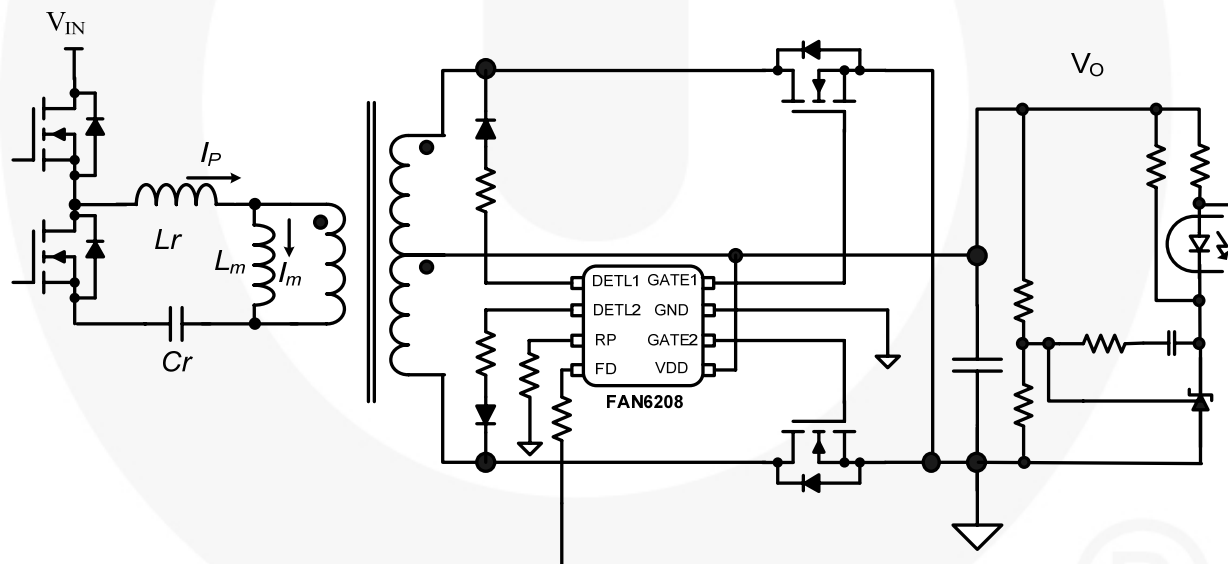


Figure 1. 典型应用

采用SR的LLC谐振变换器

图2 给出了简化后半桥谐振变换器的原理图，图中 L_m 指有分流作用的励磁电感， L_r 指串联谐振电感， C_r 指谐振电容。由于励磁电感相对较小，会产生高幅值的励磁电流(I_m)，该电流在初级进行续流与功率传输无关。初级电流 (I_p) 为励磁电流与次级电流反射到初级的电流之和。

图3 中给出了半桥LLC谐振变换器的典型增益曲线。为了实现初级开关的零电压切换 (ZVS)，必须采用具有感性阻抗特性的增益曲线，在该区间中随着频率上升，增益下降。谐振网络的谐振频率决定于 L_r 与 C_r 之间的谐振。当开关频率低于谐振频率时（即欠谐振），在初级开关关断之前，次级电流（二极管电流）反射的半个谐振完成，如图4所示。当开关频率高于谐振频率时（即过谐振），在次级电流（二极管电流）反射的半个谐振完成之前，初级开关关断，如图5所示。

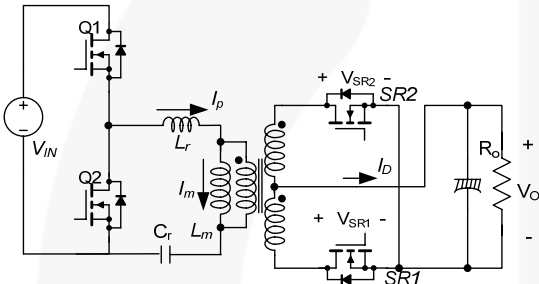


Figure 2. 采用SR的LLC谐振变换器的原理图

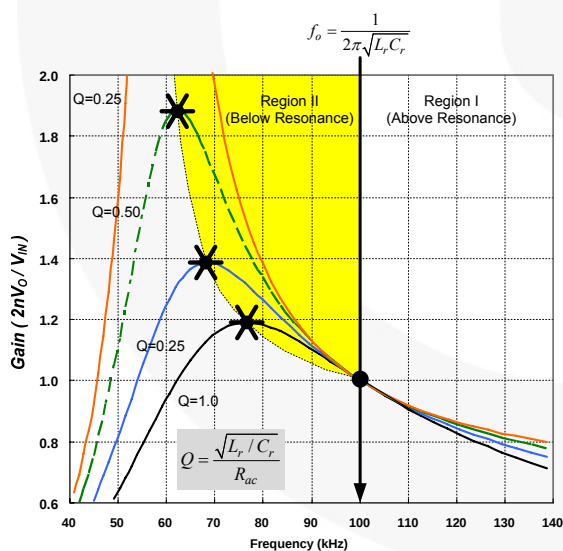


Figure 3. LLC谐振变换器的典型增益曲线

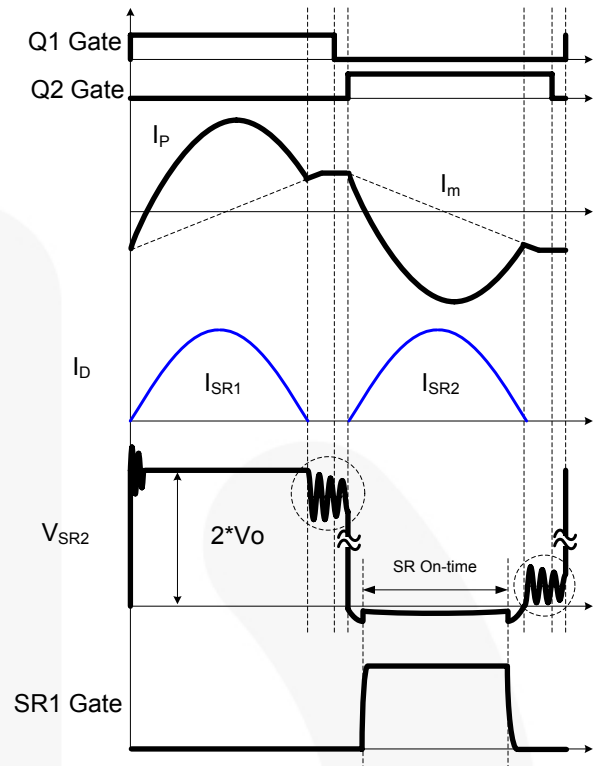


Figure 4. 欠谐振工作时的基本波形

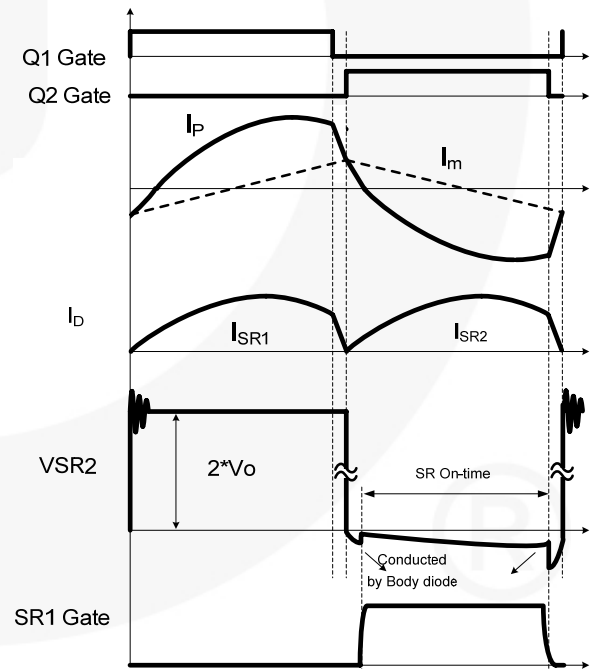


Figure 5. 过谐振工作时的基本波形

应用电路

图6中给出了FAN6208的典型应用电路，图7中给出了SR门极驱动信号的典型时序图。FAN6208检测每个SR的漏极-源极电压，用于确定门极驱动时序。一旦SR的体二极管开始导通，漏极-源极电压下降至零。当DETL上的电压跌至2V时再过 $t_{ON-ON-DETL}$ （大约350ns）后，FAN6208开通MOSFET。如图8所示，开通延时($t_{SR-ON-DETL}$)为反跳时间(150ns)与传播延时(200ns)之和。

FAN6208测量SR导通时间(t_{DETL})，在此期间，DETL电压保持低于2V，采用该信息确定下一开关周期中SR门极的关断时刻，如图7所示。通过将前一开关周期中被测SR导通时间减去死区时间(t_{DEAD})，可以得到关断时刻。

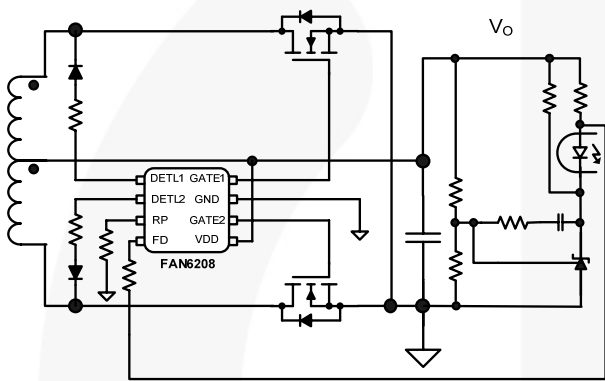


Figure 6. FAN6208的应用电路

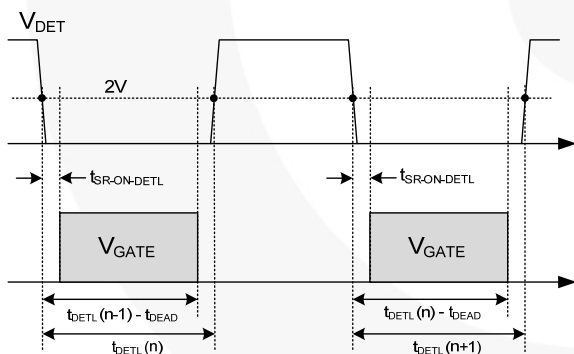


Figure 7. SR导通时间的确定

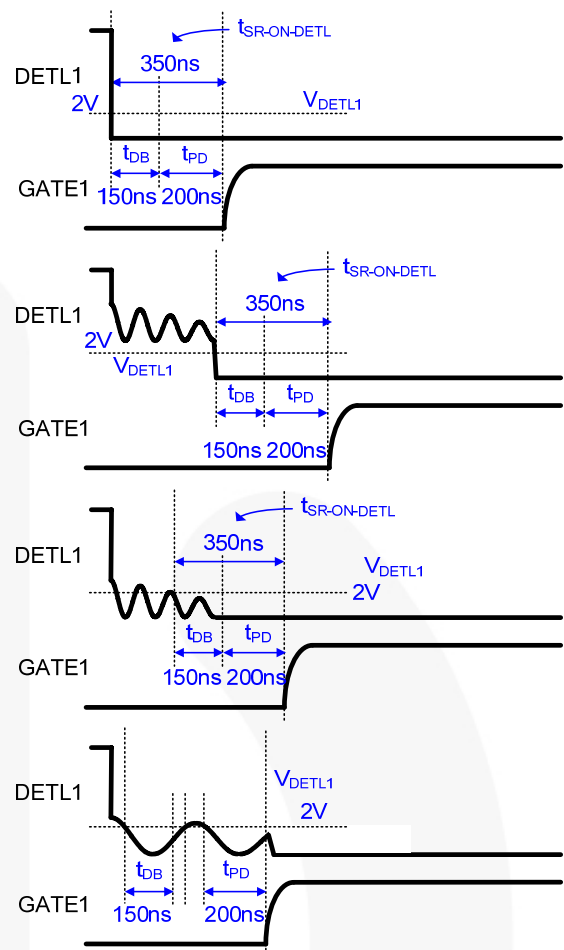


Figure 8. SR导通的时序图

DETL 管脚配置

DETL管脚的允许电压为-0.3V~7V。鉴于SR漏极-源极电压的最高值为输出电压的2倍，为了防止高压，DETL管脚需要一只二极管(D_{DETL})。 D_{DETL} 一般选择二极管1N4148。由于DETL管脚的内部电流源为50 μ A，确定 R_{DETL} 时，应留足裕量，确保当SR导通时DETL电压低于低检测阈值(2V)。如果SR电流很小，鉴于SR的正向压降可以低至零，则DETL电阻应满足：

$$R_{DETL} < \frac{(2 - V_{FD})}{50\mu A} \quad (1)$$

式中， V_{FD} 指DETL二极管的正向压降。

为了能够实现DETL管脚上正确的低压检测，一般不建议 R_{DETL} 大于20k Ω 。

当SR两端出现最大压降时，确定 R_{DETL} 时应使DETL电压高于-0.3V，例如：

$$R_{DETL} > \frac{I_{SR}^{max} R_{DS,ON} - V_{FD} - 0.3}{50\mu A} \quad (2)$$

式中, I_{SR}^{max} 指SR的最大电流, $R_{DS,ON}$ 指高温时SR MOSFET的最大导通电阻。

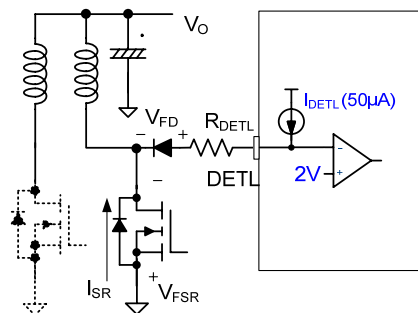


Figure 9. DETL管脚的应用电路

RP管脚配置

借助RP管脚上的电阻, 可以编程死区时间。RP管脚上电阻取值不同时, 死区时间与SR导通时间(t_{DETL})之间的关系如图10和图11所示。当 t_{DEAD} 小于125ns时, 在保护功能(门极收缩功能)作用下, SR导通时间收缩, R_p 应正确选择, 以使在最高开关频率时门极收缩功能不起作用。

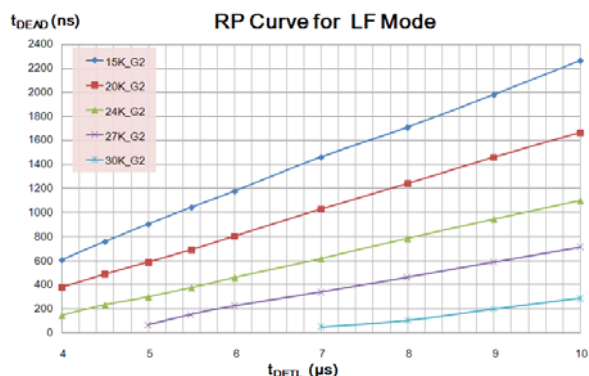


Figure 10. 不同 R_p 时 t_{DEAD} 相对 t_{DETL} 的关系(低开关频率)

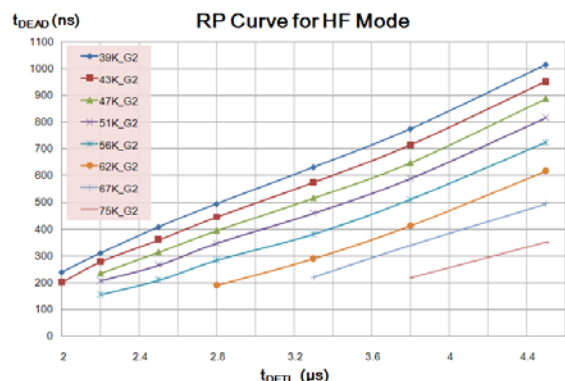


Figure 11. 不同 R_p 时 t_{DEAD} 相对 t_{DETL} 的关系(高开关频率)

RP 管脚具有一个内部恒流源(41.5μA), 因此该管脚电压取决于 R_p 电阻。根据 R_p 管脚电压不同, t_{DETL}

的绿色模式阈值可按照图 12 确定。当 R_{RP} 小于 36kΩ 时, FAN6208 工作在低频模式, 如果 t_{DETL} 小于 3.75μs, 则绿色模式被启用。当 R_{RP} 大于 36kΩ 时, 器件工作在高频模式, 如果 t_{DETL} 小于 1.90μs, 则绿色模式被启用。

RP管脚还具有两个内部阈值, 用于管脚开路与短路保护。采用RP管脚短路保护, 可以实现远程通/断控制, 如图13所示。

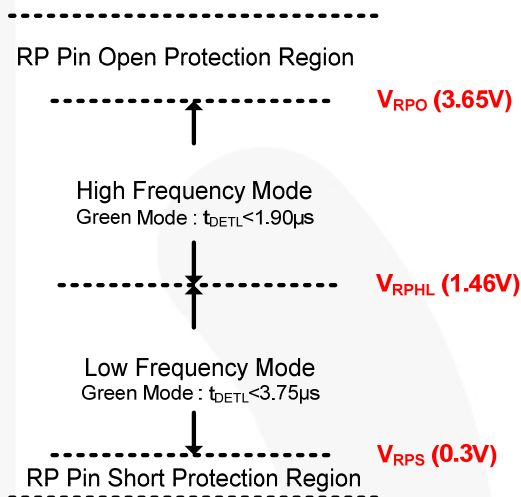


Figure 12. RP管脚的工作原理

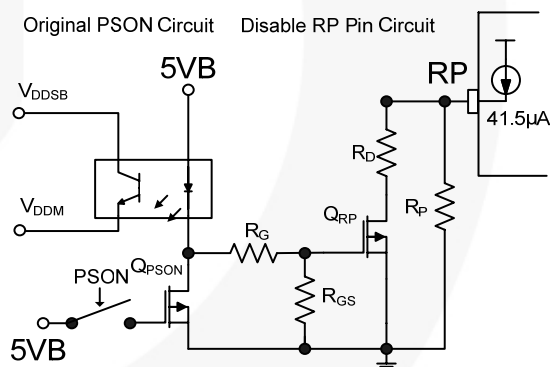


Figure 13. 用于远程通/断的RP管脚应用电路

门极收缩功能

在正常操作中, 关断时刻决定于上一开关周期中被测SR导通时间与死区时间(t_{DEAD})的差值, 如图7所示。当变换器处于稳态和开关频率变化也不大时, 这样做可以保证SR MOSFET 具有正确的驱动时序。但是, 当开关频率快速增加以及当初级MOSFET的开关转换发生在SR发出关断命令之前时, 这种控制方法会引起SR MOSFET的直通。为了防止直通问题, FAN6208设计了门极收缩功能。门极收缩发生具有以下三种条件:

1. 当检测到前一个开关周期中的死区时间不足时。在SR门极关断后, 在检测窗口的125ns内, 如果

DETL转变为高，则下一个开关周期中的门极驱动信号将缩短 $t_{SHRINK-DT}$ ，大约 $1.25\mu s$ ，目的是增加死区时间，如图14所示。

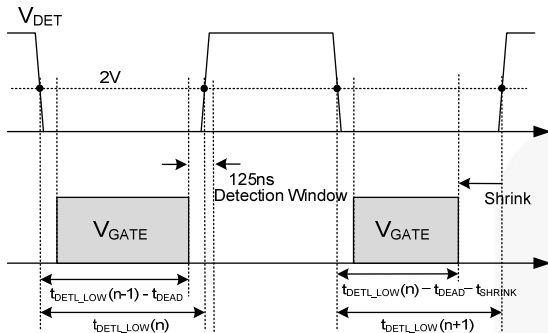


Figure 14. 死区时间不足引起的门极收缩

- 当反馈信息变化很快时，通过测量与光耦二极管串联电阻的压降，FAN6208可以监控流过光耦二极管的电流，如图15所示。如果流过光耦二极管的反馈电流增加并超出前一开关周期中反馈电流的20%，则SR门极信号收缩 $t_{SHRINK-FD}$ ，大约为 $1.4\mu s$ ，此时 $t_{D-SHRINK-FD}$ 大约为 $90\mu s$ ，如图16所示。

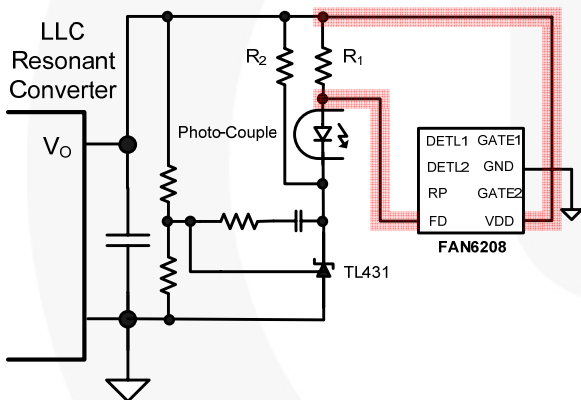


Figure 15. FD管脚的应用电路

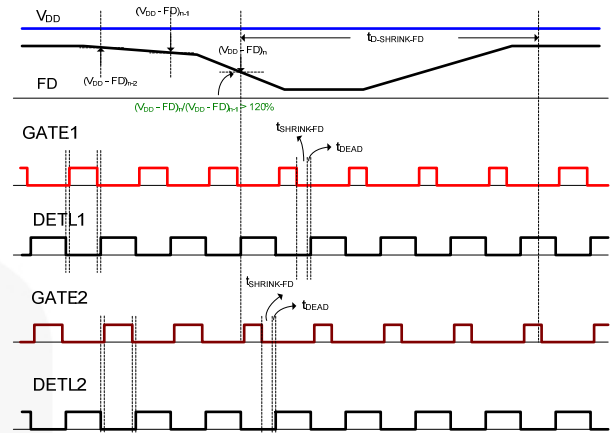


Figure 16. 反馈检测引起的门极收缩

- 当DETL电压在零附近振荡时。如图17所示，在轻载条件下，在初级开关状态切换后，SR的漏极电压在零附近振荡。在DETL电压跌落至零之后的 $350ns$ 之内，DETL电压上升高于 $2V$ ，并且保持时间高于 $150ns$ ，则门极收缩 $1.2\mu s$ ($t_{SHRINK-RNG}$)，如图17所示。

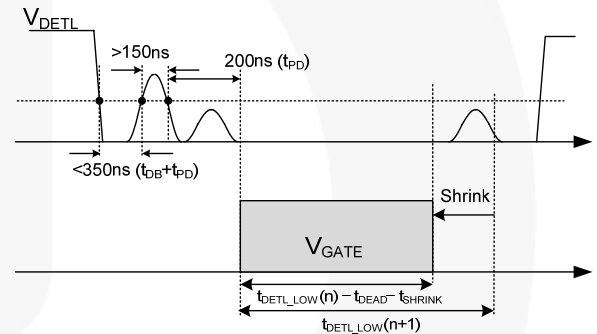


Figure 17. DETL电压振荡引起的门极收缩

印刷电路板布局

在图18中，功率敷线标记为粗线。良好的PCB布局可以改善功率系统的效率和可靠性，并最大限度地抑制EMI。

指南

- 对于反馈检测，FD管脚应该连接到光电二极管的阳极。通过一只电阻与FD管脚相连可以改善系统的浪涌抗扰度。确保敷线1远离任何具有脉冲电流的功率敷线。
- 为了最大限度地抑制干扰，控制地（敷线2）和功率地（敷线7）应该单点相连。连接敷线也应该尽可能缩短。

- 如敷线4所示，反馈环路的地应该连接到输出电容 C_o 的负极端子。
- 敷线5应该放长且远离 V_o 端子。
- 敷线6的长度尽可能缩短。
- 如敷线7所示， Q_1 与 Q_2 的源极端子应该连接到 C_o 的负极端子。保持敷线7尽可能缩短，直接连接和采用宽线。
- 如敷线8所示， C_o 的负极端子应该直接连接到机壳。

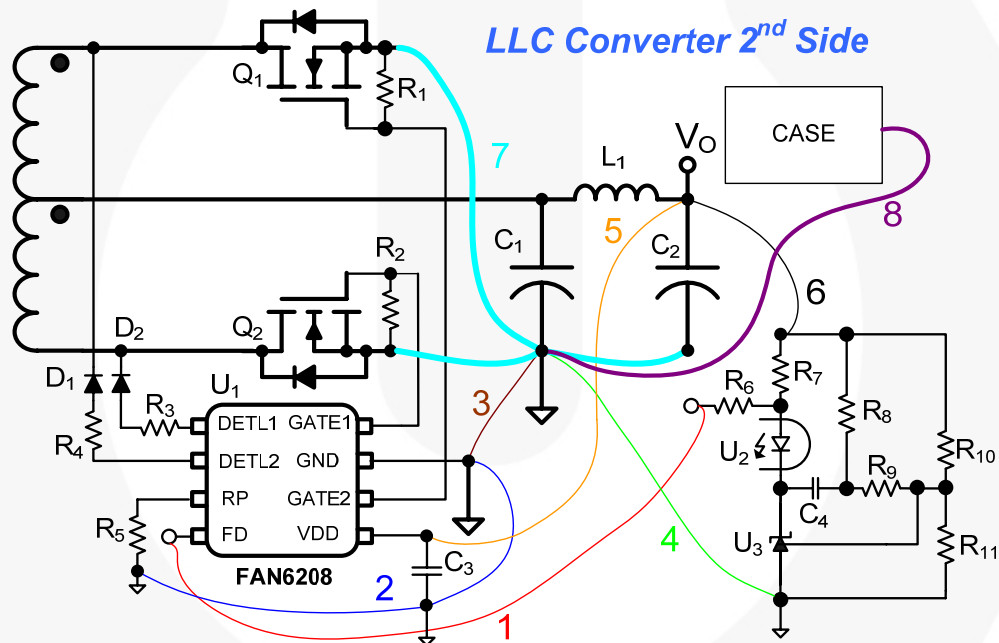


Figure 18. 布局考虑

设计范例

以下范例为一种12V/300W单路输出的电源，采用了LLC谐振变换器拓扑。如图19所示，FAN7621控制器用于设计LLC谐振变换器。集成的CCM PFC控制器FAN6982用于设计PFC电路。

主要系统参数清单如表1所示，材料单（BOM）总结如表2所示。

采用了FAN6982的两级PFC输出电压功能，其中典型的PFC输出电压为390V。低电源电压和轻载条件下，PFC输出电压减少到360V，可以提升PFC电路的效率。对于PFC电路，典型的开关频率(f_s)为65kHz。

表 1. 系统指标

输入电压范围	90~264V _{AC}
PFC输出	360~390V _{DC}
PFC控制器	FAN6982
主电源控制器	FAN7621
输出电压 (Vo)	12V
输出功率 (Vo)	300W
PFC开关频率	65kHz
LLC谐振变换器开关频率	60~140kHz

TX_1 的匝比 n 为13.5， L_m 为1.2mH， L_r 为150 μ H， C_r 为47nH。D201与D202选用1N4148，其额定电压为100V。R204 (R_{RP})选择27k Ω ，用于低频模式设置。

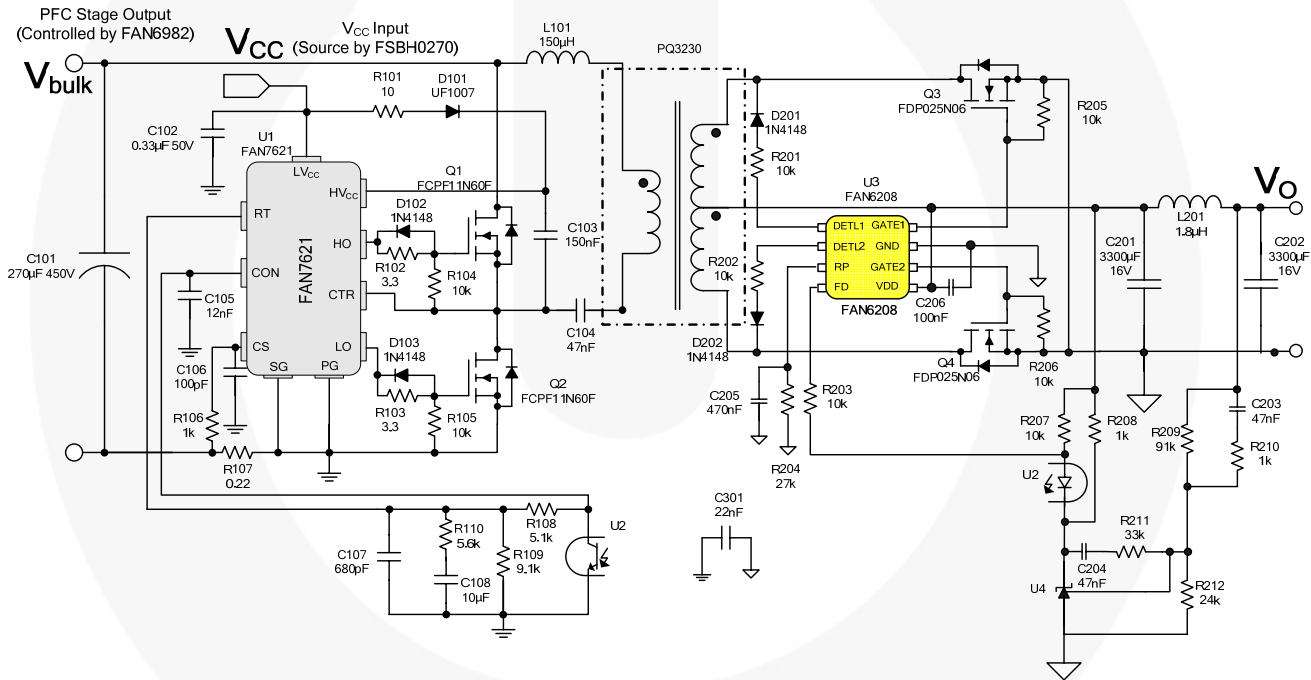


Figure 19. 完整电路图

表 2. 材料单

器件	值	备注	器件	值	备注
电阻			电容		
R ₁₀₁	10Ω	1/4W	C ₁₀₈	10μF	25V
R ₁₀₂	3.3Ω	1/4W	C ₂₀₁	3300μF	16V
R ₁₀₃	3.3Ω	1/8W	C ₂₀₂	3300μF	16V
R ₁₀₄	10kΩ	1/8W	C ₂₀₃	47nF	50V
R ₁₀₅	10kΩ	1/8W	C ₂₀₄	47nF	50V
R ₁₀₆	1kΩ	1/8W	C ₂₀₅	470nF	25V
R ₁₀₇	0.2Ω	2W	C ₂₀₆	100nF	50V
R ₁₀₈	5.1kΩ	1/8W	C ₃₀₁	22nF/250V	Y-电容
R ₁₀₉	9.1kΩ	1/8W	变压器		
R ₁₁₀	5.6kΩ	1/8W	TX ₁	L _r = 10μH/ L _m = 1200μH	PQ3230
R ₂₀₁	10kΩ	1/8W	二极管		
R ₂₀₂	10kΩ	1/8W	D ₁₀₁	UF1007	1A/1000V
R ₂₀₃	10kΩ	1/8W	D ₁₀₂	1N4148	
R ₂₀₄	27kΩ	1/8W	D ₁₀₃	1N4148	
R ₂₀₅	10kΩ	1/8W	D ₂₀₁	1N4148	
R ₂₀₆	10kΩ	1/8W	D ₂₀₂	1N4148	
R ₂₀₇	10kΩ	1/8W	电感		
R ₂₀₈	1kΩ	1/8W	L101	L = 150μH	QP2914
R ₂₀₉	91kΩ	1/8W	L201	L = 1.8μH	
R ₂₁₀	1kΩ	1/8W	MOSFET		
R ₂₁₁	33kΩ	1/8W	Q ₁	FCPF11N60F	
R ₂₁₂	24kΩ	1/8W	Q ₂	FCPF11N60F	
电容			Q ₃	FDP025N06	
C ₁₀₁	270μF	450V	Q ₄	FDP025N06	
C ₁₀₂	0.33μF	50V	IC 集成电路		
C ₁₀₃	150nF	1kV	U ₁	FAN7621	LLC控制器
C ₁₀₄	47nF	1kV	U ₂	PC817	
C ₁₀₅	12nF	50V	U ₃	FAN6208	SR控制器
C ₁₀₆	100pF	50V	U ₄	TL431	
C ₁₀₇	680pF	50V			

图20和图21中给出了不同 R_P 时SR门极驱动波形。可以发现，SR驱动的死区时间可以编程。

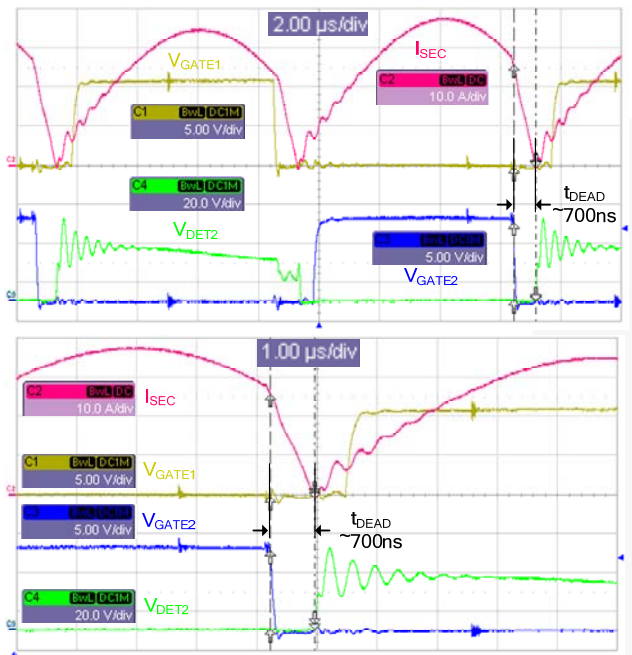


Figure 20. $R_P=24k\Omega$ 时次级电流和SR门极信号

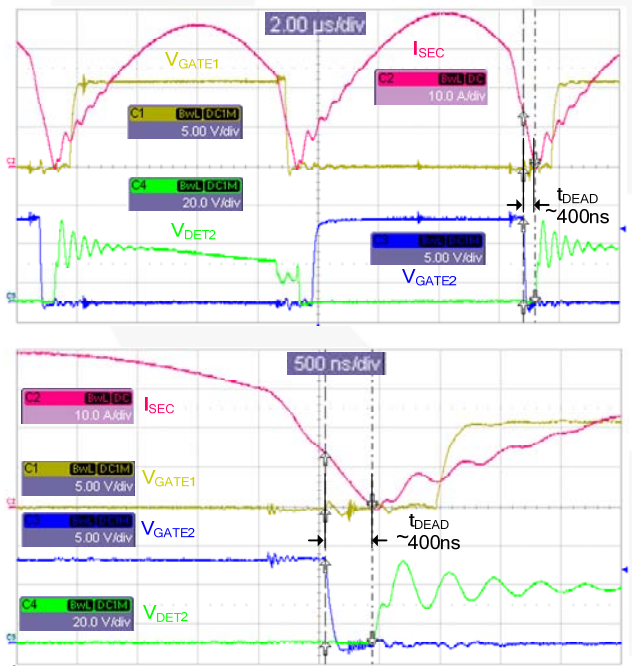


Figure 21. $R_P=27k\Omega$ 时次级电流和SR门极信号

肖特基二极管与同步整流器的效率测试结果如表13和表14所示。图22中比较了肖特基二极管与同步整流器的效率。可以发现，采用同步整流技术，效率提高了1~2%。图22中还给出了死区时间对效率的影响。通过精调死区时间，效率可以进一步提升。

表 3. $V_{AC}=115V$ 时采用肖特基二极管(MBRP3045) 300W PC电源的测量效率

负载	输入功率(W)	输出功率(W)	效率
100%	358.070	307.658	85.920%
50%	176.38	154.91	87.82%
20%	73.30	62.19	84.80%

表 4. $V_{AC}=115V$ 时采用同步整流器(FDP025N06 和 $R_{RP}=30k\Omega$) 300W PC电源的测量效率

负载	输入功率(W)	输出功率(W)	效率	相比肖特基二极管
100%	347.70	307.62	88.47%	+2.55%
50%	172.81	154.77	89.56%	+1.74%
20%	72.41	62.21	85.91%	+1.11%

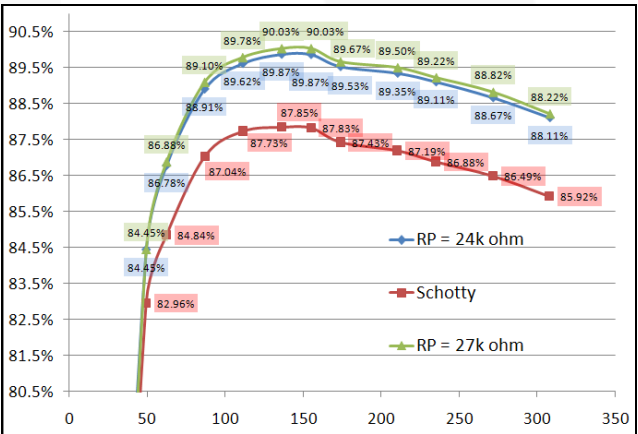


Figure 22. 效率分析

相关资料

[FAN6208 — 适用LLC拓扑的次级同步整流控制器](#)

[FAN7621 — 适用半桥谐振变换器的PFM 控制器](#)

[FAN6982 — CCM 功率因数控制器](#)

[FDP025N06 — FDP025N06 N-沟道 PowerTrench® MOSFET 60V, 265A, 2.5mΩ](#)

[1N/FDLL 914/A/B / 916/A/B / 4148 / 4448 — 小信号二极管](#)

[FSFR2100 — 适用半桥谐振变换器的飞兆半导体功率开关](#)

[AN4137 — 采用飞兆半导体 \(FPS\) 的离线反激变换器的设计指南](#)

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