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AN-9737

采用FL6961的LED照明用单级反激AC-DC变换器的设计指南

概要

本应用指南介绍了一种基于FL6961的单级功率因数校正器（PFC），重点讨论了一个全电压输入条件下的16.8W（24V/0.7A）LED照明应用如何选择和设计反激变压器。采用FL6961的反激变换器工作于临界导通模式（CRM），具有恒流/恒压（CC/CV）反馈电路、软启动以及逐周期电流限制等功能，适用于LED照明应用。

引言

目前，鉴于LED具有寿命长，功效高，价格便宜，环保以及终端用户需求旺盛等优点，工程师们已经将各种类型的LED应用于普通照明系统。同时，高功率因数（PF）、安全隔离与保持LED颜色恒定的恒流控制（CC）日益成为LED应用的必要条件。

通常的规定是：输入功率高于25W以上时，要求功率因数校正。但是在更多情况下，希望降低该功率定额，并

且适用固态照明的新能源之星指令要求商业应用的功率因数必须大于0.9。预计关于功率因数的规定将变得更加严格。

基本原理：高功率因数反激变换器

实现高功率因数(PF)反激变换器的基本思路是采用临界导通模式(CRM) PFC控制器。传统的PFC IC(比如FL6961)采用恒定导通时间和可变关断时间的控制方式，意味着输入平均电流始终跟随输入电压波形。

图1给出了单级PFC拓扑的典型应用原理图。单级PFC与常规CRM升压型变换器的主要区别是二极管整流桥后级没有使用大电容。通常，单级PFC方案采用一个小电容(图1中的C1)作为噪声滤波器来衰减高频成分，并且不使用INV管脚调节输出电压。

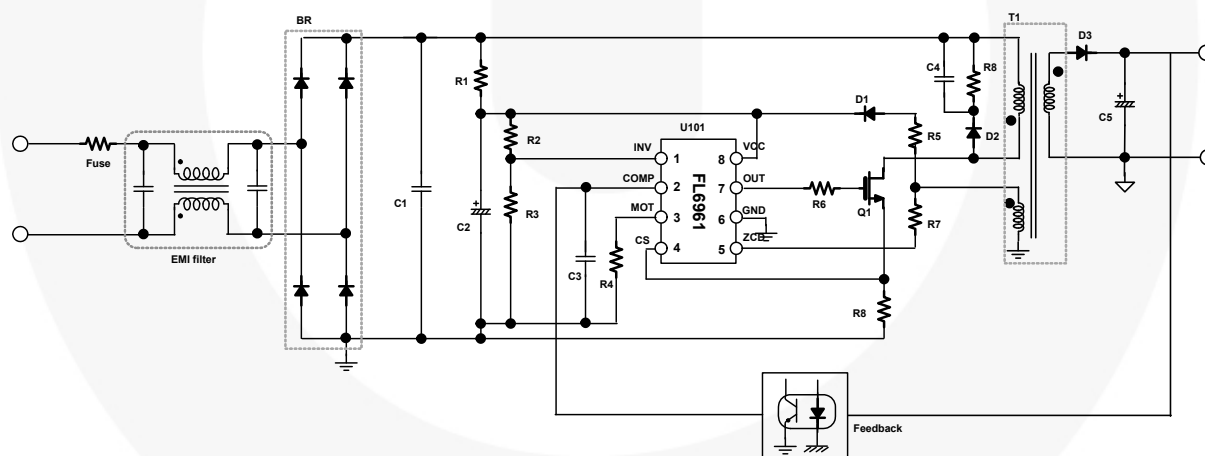


Figure 1. 采用FLS6961的高功率因数反激变换器的原理简图

图2为CRM工作模式下反激变换器简化电路的典型波形。当MOSFET (Q1)导通时, 变压器的原边电流线性增大, 并被钳位于某一内部电平, 这是因为FL6961和传统电流模式控制IC(如FAN7527B)一样没有逐周期电流限制。其峰值决定于原边励磁电感大小和固定导通时间。取代逐周期原边电流限制, FL6961具有一个过电流保护(OCP)功能。如果电流传感信号大于内部检测电平, FL6961不再提供驱动MOSFET(Q1)的输出信号。

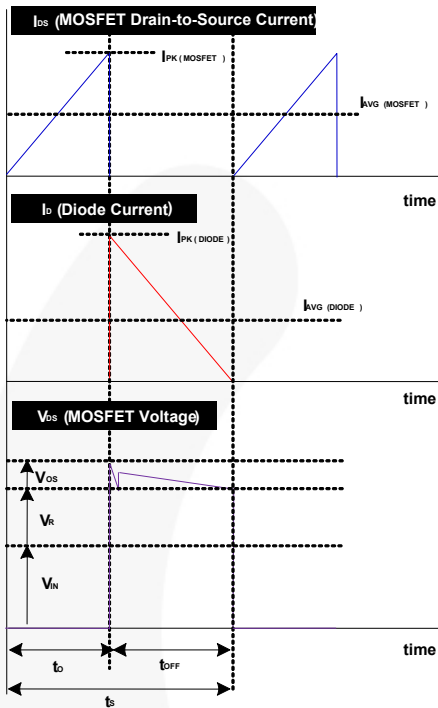


Figure 2. CRM模式下反激变换器的关键波形

FL6961在整个运行过程中具有恒定的导通时间。输入平均电流始终跟踪输入电流峰值, 如下式所示:

$$I_{AVG(MOSFET)} = \frac{1}{2} I_{PK} t_{ON} \quad (1)$$

它也与输入瞬时电压成正比。这意味着输入电流波形始终与输入电压波形保持一致。二极管反向电压线性增大并且等于:

$$V_{PK(DIODE)} = V_O + V_{IN} \frac{N_S}{N_P} \quad (2)$$

在MOSFET关断期间, 也就是二极管导通期间, 输入电流迅速下降为零, 副边二极管导通, 且其电流线性下降。副边峰值电流等于原边峰值电流与原边(N_P)、副边(N_S)之间匝数比的乘积保持一致, 并自然降低至零。副边平均电流为:

$$I_{AVG(DIODE)} = \frac{1}{2} \frac{N_P}{N_S} I_{PK} t_{off} \quad (3)$$

二极管正向压降随着电流的降低而降低, 输出电压反射到了原边绕组, 并且原边绕组还会增加一个因漏感和

MOSFET (Q1)寄生电容共振引起的过冲电压。结果是, MOSFET关断期间出现了一个叠加电压:

$$V_{MOSFET(off)} = V_{IN} + V_R + V_{OS} \quad (4)$$

其中, V_R 表示反射电压, V_{OS} 表示电压过冲部分。

反射电压 V_R 受变压器原、副边匝数比影响, 输出电压可由下式计算:

$$V_R = \frac{N_P}{N_S} V_O \quad (5)$$

图3给出了MOSFET (Q1)上的原边电流和二极管上的副边电流的理想波形。原边的输入峰值电流和平均电流时跟随输入电压波形。通常, 由于匝数比问题, 二极管上的副边电流大于原边电流。

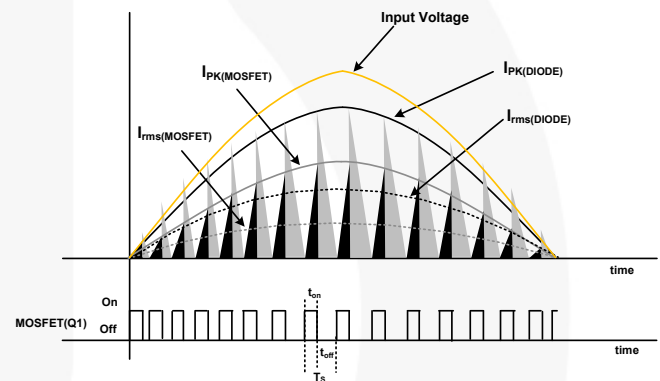


Figure 3. 理想波形

因此, 为构建稳定系统, 设计人员在选择元件之前应考虑给原边MOSFET (Q1)和副边二极管 (D3)的电压、电流参数留出足够的余量两个条件。

图给出了反激变换拓扑在边界条件下两个器件的选取方法。

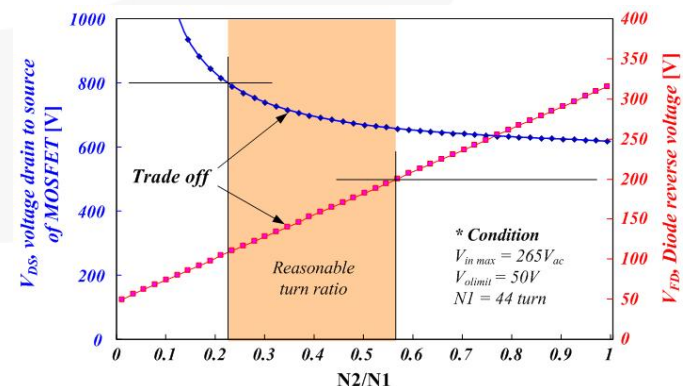


Figure 4. 反激变换器拓扑的边界条件(参考AN-8025)

设计实例

A. 变压器设计

提供了一个采用FL6961的16.8W单级反激AC-DC变换器的设计指南。应用系统参数如表1所示。

Table 1. 系统参数

参数	值
主要输入电压范围, $V_{AC(main)}$	90V~265V
输出电压, V_{OUT}	24V
输入电流 I_{OUT}	0.7A
$V_{AC(min)}$ 时最小开关频率	50kHz
二极管压降, V_d	1V
MOSFET导通电阻, R_{MOS}	1 Ω
窗口利用率	0.4
目标系统效率	0.82
$V_{ac(min)}$ 时最大占空比	0.35
工作最大磁通密度	0.35
调整率, α	0.5%

说明:

1. 调整率与铜损的相关性很强, 调整率为0.5%意味着变压器有0.084W的损耗。

确定磁芯和线圈的尺寸以及匝数有多种方法, 比如采用AL值并遵循常见做法。本指南中, 使用与磁芯几何参数相关的 K_g 值来获取最佳的磁芯和线圈信息。

步骤1. 计算总周期, T :

$$T = \frac{1}{f} = 20 \text{ } [\mu s]$$

步骤2. 计算原边MOSFET的最大导通时间。

$$t_{on} = TD_{max} = (20 \times 10^{-6})(0.35) = 7 \text{ } [\mu s]$$

步骤3. 计算输出功率

$$P = I_o(V_o + V_d) = 0.7(24 + 1) = 17.5 \text{ } [W]$$

步骤4. 计算最大输入电流, I_{max} :

$$I_{in(max)} = \frac{P_o}{V_{min}\eta} = \frac{17.5}{(\sqrt{2} \times 90)(0.82)} = 0.168 \text{ } [A]$$

步骤5. 计算MOSFET压降, V_{vd} :

$$V_{vd} = I_{in(max)}R_{MOS} = 0.168 \text{ } [V]$$

步骤6. 计算变压器原边电压, V_p :

$$V_p = V_{min} - V_{vd} = 127 - 0.168 \approx 127 \text{ } [V]$$

$$V_p = 126.83 \text{ use } 127 \text{ 实际采用 } 127$$

步骤7. 计算变压器原边峰值电流, I_{ppk} :

$$I_{ppk} = \frac{2TP}{\eta V_p t_{on(max)}} = \frac{2(20 \times 10^{-6})(17.5)}{0.82(127)(7 \times 10^{-6})} = 0.96 \text{ } [A]$$

步骤8. 计算变压器原边有效电流, I_{prms} :

$$I_{prms} = I_{ppk} \sqrt{\frac{t_{on}}{3T}} = 0.96 \sqrt{\frac{(7 \times 10^{-6})}{3(20 \times 10^{-6})}} = 0.32 \text{ } [A]$$

步骤9. 计算所需的最小电感, L :

$$L = \frac{V_p t_{on(max)}}{I_{ppk}} = \frac{127(7 \times 10^{-6})}{0.96} = 0.926 \text{ } [mH]$$

$L = 0.926[mH]$, 实际采用1[mH]

步骤10. 计算能量处理能力, 单位为瓦秒, $w\cdot s$:

$$ENG = \frac{LI_{ppk}^2}{2} = \frac{(1 \times 10^{-3})(0.96^2)}{2} = 0.0004608 \text{ } [w\cdot s]$$

步骤11. 计算电气条件, K_e :

$$K_e = 0.145PB_m^2 \times 10^{-4} = 0.145(17.5)(0.35^2) \times 10^{-4} = 0.00003108$$

步骤12. 计算磁芯几何系数, K_g :

$$K_g = \frac{(ENG)^2}{K_e \alpha} = \frac{(0.0004608)^2}{0.00003108(0.5)} = 0.0136 \text{ } [cm^5]$$

步骤13. 磁芯尺寸见表2。

为了防止磁芯饱和, 通过对比两个 K_g 值, 选择一个稍大的磁芯: 步骤12的计算值与表2中的现有值。

表2中, 在2500磁导率下PQ-42016具有较大的 K_g 值(0.01327)。

步骤14. 计算电流密度, J :

$$J = \frac{2(ENG) \times 10^{-4}}{B_m A_p K_u} = \frac{2(0.0004608) \times 10^{-4}}{0.35(0.2484)(0.4)} = 265 \text{ } [A/cm^2]$$

步骤15. 计算所需的导线面积, $A_{w(B)}$:

$$A_{w(B)} = \frac{I_{rms}}{J} = \frac{0.32}{265} = 0.001207 \text{ } [cm^2]$$

步骤16. 计算匝数, N :

$$N = \frac{W_a K_u}{A_{w(B)}} = \frac{0.4283 \times 0.4}{0.001207} = 141.93 \text{ } [T]$$

$N = 141.93$; use 142 turns. 实际使用142匝。

步骤17. 计算所需的间隙, l_g :

$$l_g = \frac{0.4\pi(N)(\Delta I) \times 10^{-4}}{\Delta B_m} = \frac{0.4\pi(142)(0.96) \times 10^{-4}}{0.35} = 0.0489 \text{ } [cm]$$

步骤18. 按照步骤15, 考虑间隙, 重新计算匝数, 。

$$N = \sqrt{\frac{L(l_g + \frac{MPL}{\mu_i})}{0.4\pi(A_c)}} = \sqrt{\frac{1 \times 10^{-3}(0.0489 + \frac{3.74}{2500})(10^8)}{0.4\pi(0.58)}} = 83.153 \text{ [T]}$$

N=83.153; use 83[T]. 实际使用83[T]。

其中, μ_i 为所选磁芯材料的磁导率, MPL是所选磁芯的磁路长度。

步骤19. 计算边缘磁通, F:

$$F = (1 + \frac{l_g}{\sqrt{A_c}} \ln \frac{2G}{l_g}) = (1 + \frac{0.0489}{\sqrt{0.58}} \ln \frac{2(1.001)}{0.0489}) = 1.238$$

其中, G为所选磁芯的窗口高度。

步骤20. 重新计算匝数, N_{new} :

$$N = \sqrt{\frac{l_g L}{(0.4\pi)(A_c)F(10^{-8})}} = \sqrt{\frac{0.0489 \times 1 \times 10^5}{(0.4\pi)(0.58)(1.238)}} = 73.6 \text{ [T]}$$

$N_{new}=73.6$; use 74. 实际采用74。

步骤21. 计算交流磁通密度, B_{AC} , 单位为特斯拉;

$$B_{ac} = \frac{(0.4\pi)N(\frac{I_{PK}}{2})F(10^{-4})}{l_g} = \frac{(0.4\pi)(74)(\frac{0.96}{2})(1.238)(10^{-4})}{0.0489} = 0.113 \text{ [T]}$$

步骤22. 重新计算导线尺寸, $A_{W(B)}$:

$$A_{W(B)} = \frac{W_a K_u}{N_{new}} = \frac{0.4283 \times 0.4}{74} = 0.002315 \text{ [A/cm}^2\text{]}$$

步骤23. 计算在低输入电压与期望工作频率下的趋肤深度。趋肤深度即导线的直径。

$$\gamma = \frac{6.62}{\sqrt{f}} = \frac{6.62}{\sqrt{50 \times 10^3}} = 0.02960 \text{ [cm]}$$

步骤24. 计算考虑趋肤深度情况下所需的导线面积:

$$Wire_A = \pi(r^2) = 0.0027535 \text{ [cm}^2\text{]}$$

步骤25. 参考表4选择所需面积的导线尺寸。如果导线面积不在所需面积的10%以内, 则跳到下一个最小尺寸。

AWG=#23

$$A_{W(B)} = 0.00259 \text{ [cm}^2\text{]}$$

$\mu\Omega/\text{cm}=666$

步骤26. 计算原边股线数量, S_{np} :

$$S_{np} = \frac{A_{W(B)}}{Wire_A} = \frac{0.002315}{0.00259} = 0.8938$$

这意味着, 按照步骤25选取导线AWG23已经足够, 或者说, 在反激变换器中提供原边电流已经具有足够余量。

步骤27. 计算副边线圈和辅助线圈的匝数, N_s 、 N_{aux} :

$$N_s = \frac{N_p(V_o + V_d)(1 - D_{max})}{(V_p D_{max})} = \frac{74(24 + 1)(1 - 0.35)}{(\sqrt{2} \times 90)(0.35)} = 27.05$$

$N_s=27.05$; 实际中采用27。

$$N_{aux} = \frac{N_p(V_o + V_d)(1 - D_{max})}{(V_p D_{max})} = \frac{74(15 + 1)(1 - 0.35)}{(\sqrt{2} \times 90)(0.35)} = 17.31$$

$N_{aux}=17.31$; 实际中采用17。

步骤28. 计算副边峰值电流, I_{spk} :

$$I_{spk} = \frac{2I_o}{(1 - D_{max})} = \frac{2(0.7)}{1 - 0.35} = 2.153 \text{ [A]}$$

步骤29. 计算副边有效电流, I_{srms} :

$$I_{srms} = I_{spk} \sqrt{\frac{(1 - D_{max})}{3}} = 2.153 \sqrt{\frac{(1 - 0.35)}{3}} = 1.0021 \text{ [A]}$$

步骤30. 计算副边导线面积, $A_{sw(B)}$:

$$A_{SW(B)} = \frac{I_{rms}}{J} = \frac{1.0021}{265} = 0.003781 \text{ [cm}^2\text{]}$$

步骤31. 参考表4选择所需面积的导线尺寸。如果导线面积不在所需面积的10%以内, 则转向下一最小尺寸。

AWG=#22

$$A_{W(B)} = 0.003243 \text{ [cm}^2\text{]}$$

$\mu\Omega/\text{cm}=531.4$

步骤32. 计算所需的原边股线数量, S_{np} :

$$S_{np} = \frac{A_{sw(B)}}{Wire_A} = \frac{0.003243}{0.00259} = 1.2521$$

这就要求具有双股线的AWG21导线作为反激变换器的副边绕组。

适合的磁芯尺寸		PQ-42614	AWG
匝数	原边	74	23
	副边	27	22/ 2 股
	辅助	17	
估计间隙[mm]		0.489	

B. MOSFET和二极管的选取

步骤33. 计算原边MOSFET漏极电压的最大值:

$$V_{MOSFET(off)} = V_{IN} + V_R + V_{OS} = V_{IN} + \frac{N_p}{N_s} V_o + V_{OS} = 490.54 \text{ [V]}$$

其中, 假定 V_{OS} 约为50V, 且其峰值可被外部外部缓冲电路降低。这意味着采用600V MOSFET已具有一些余量。下面对MOSFET的最低要求进行了总结。

电流额定值[A]		电压额定值[A]	
计算结果	+20%余量	计算结果	+20%余量
0.96	1.152	490.54	588.65

步骤34. 计算副边二极管最大电压。

$$V_{PK(DIODE)} = V_O + V_{IN} \frac{N_S}{N_P} = 24 + 265\sqrt{2} \frac{27}{74} = 160.74 \text{ [V]}$$

这意味着使用200V的二极管可留有一些余量。下面对副边二极管的最低要求进行总结。

电流额定值[A]		电压额定值[A]	
计算值	+20%余量	计算值	+20%余量
2.153	2.584	160.74	192.88

C. 检测电阻

FL6961的CS管脚在整个工作周期具有过电流保护(OCP)功能, 其内部钳位电平 V_{LIMIT} 为0.8V。

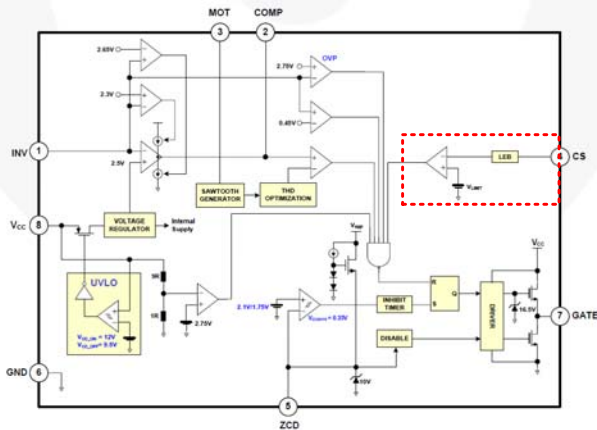


Figure 5. 估计间隙

通常情况下, 合理的选择是将OCP电平设置为原边峰值电流的1.5倍。

$$I_{LIMIT} = 1.5I_{PPK} = \frac{3TP}{\eta V_p t_{on(max)}} = 1.44$$

按下式计算检测电阻:

$$R_{sensing} \leq \frac{0.8}{I_{LIMIT}} = 0.55 \text{ } [\Omega]$$

D. 恒流/恒压功能的电压和电流反馈

利用外部无源器件和评估板上的运算放大器测量实际输出电压和电流, 并以此调节恒定的电压和电流输出。由于输出负载、高亮度LED (HB LED)和无源器件易受环境温度影响, 故使用反馈路径来实现稳定运行。

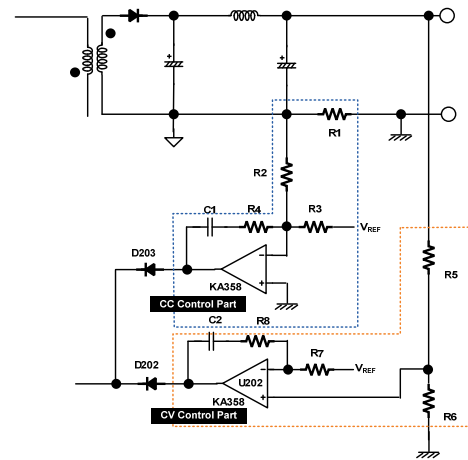


Figure 6. 恒流/恒压工作的反馈电路

通常, 在稳态下恒流模块占据主导地位, 在暂态和非正常模式下恒压模块起过电压保护(OVP)的功能, 比如无负载情况下。

恒流模块的输出信号可由下式确定:

$$V_{O_cc} = R_4 \left(\frac{V_{sensing_CC}}{R_2} - \frac{V_{ref}}{R_3} \right) + \frac{1}{C_1} \int \left(\frac{V_{sensing_CC}}{R_2} - \frac{V_{ref}}{R_3} \right) dt$$

其中, $V_{sensing_CC}$ 表示检测电阻(R1)的检测电压, 检测电阻的取值可由下式计算:

$$V_{sensing_CC} = I_o \times R_1$$

恒压模块的输出信号由下式确定:

$$V_{O_CV} = \left(\frac{R_6}{R_5 + R_6} \right) V_{sensing_CV} + \frac{R_8}{R_7} \left[\left(\frac{R_6}{R_5 + R_6} \right) V_{sensing_CV} - V_{ref} \right] + \frac{1}{C_2} \frac{1}{R_7} \int \left(\frac{R_6}{R_5 + R_6} V_{sensing_CV} - V_{ref} \right) dt$$

其中, $V_{sensing_CV}$ 表示该电路的输出电压, 该电压由两个电阻R5和R6分压, 并连接到运算放大器的非反向输入管脚。

通常情况下, 设置该分压 $\left(\frac{R_6}{R_5 + R_6} \right) V_{sensing_CV}$ 为 V_{ref} , 稳态

条件下该值略小, 这是因为该模块的主要作用是过压保护。与稳态相比, 在暂态或者异常情况下会有更高电压传输到输出级, 例如过电压输出情况。

E. 软启动/过冲防止功能

一般情况下，高亮度(HB) LED需要正向电流限制，以防止过功率损耗引起的LED烧毁。因此，整个工作周期中过冲防止功能都是必要的。尽管有恒流/恒压模块可调节输出，但是这些模块在瞬态模式下表现欠佳，因为它们响应时间过长，无法迅速动作。

图7给出了采用二极管和电阻的输出电压过冲抑制方法。启动时，电流流经电阻R9和二极管理D204，此时尚未激活恒流/恒压模块，在稳态时电流下降。旁路电流流入控制IC FL6961的反馈模块，并逐步控制输出功率。

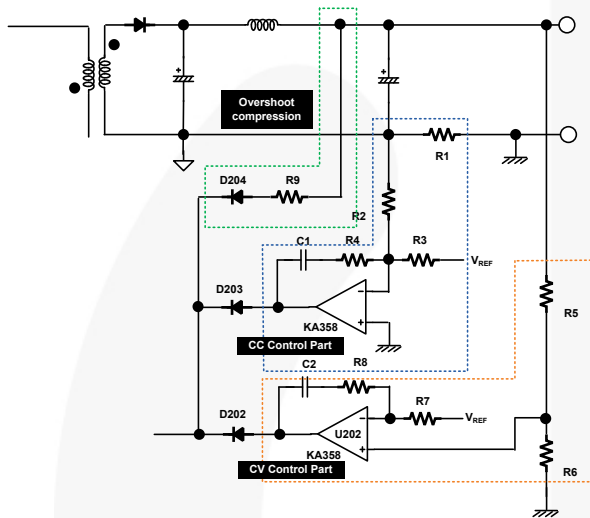
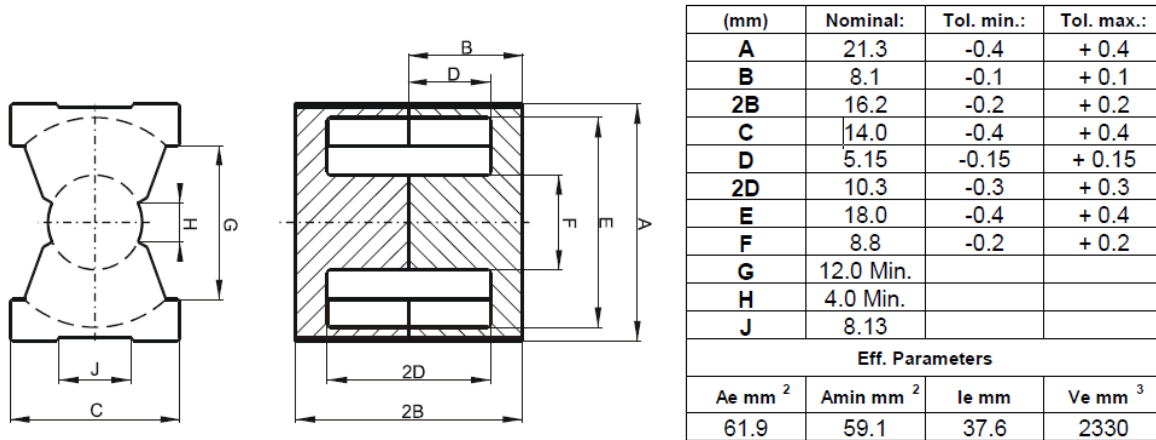


Figure 7. 软启动/过冲防止

Table 2. 各种磁芯类型与尺寸

型号#	MLT [cm]	MPL [cm]	G[cm]	A _c [cm]	W _a [cm ²]	A _p [cm ⁴]	K _g [cm ⁵]	Perm	AL	制造商
RM-42316	4.17	3.80	1.074	0.640	0.454	0.2900	0.017820	2500	2200	Magnetics
PQ-42610	5.54	2.94	0.239	1.05	0.1177	0.1235	0.00937	2500	6310	Magnetics
PQ-42614	5.54	3.33	0.671	0.709	0.3304	0.2343	0.01200	2500	4585	Magnetics
PQ-42016	4.34	3.74	1.001	0.580	0.4283	0.2484	0.01327	2500	2930	Magnetics
EPC-25	4.930	5.92	1.800	0.4640	0.8235	0.3810	0.01438	2300	1560	Magnetics
EI-44008	7.77	5.19	0.356	0.9950	0.3613	0.3595	0.018416	2500	4103	Magnetics
EFD-25	4.78	5.69	1.86	0.5810	0.6789	0.3944	0.01917	1800	1800	Philips

Table 3. PQ-42016 磁芯尺寸(Magnetics: <http://www.mag-inc.com/home/Advanced-Search-Results?pn=42016>)**Table 4. 导线表**

AWG	裸线面积		$\mu\Omega/\text{cm}$	加强绝缘		
	Cm2	CIR-MIL		Cm2	匝/cm	匝/cm2
20	0.005188	1024.0	332.3	0.006065	11.37	98.93
21	0.004116	812.30	418.9	0.004837	12.75	124.0
22	0.003243	640.10	531.4	0.003857	14.25	155.5
23	0.002588	510.80	666.0	0.003135	15.82	191.3
24	0.002047	404.0	842.1	0.002514	17.63	238.6
25	0.001623	320.40	1062.0	0.002002	19.8	299.7
26	0.001280	252.80	1345.0	0.001603	22.12	374.2
27	0.001021	201.60	1687.6	0.001313	24.44	456.9
28	0.008048	158.80	2142.7	0.0010515	27.32	570.6
29	0.0006470	127.70	2664.3	0.0008548	30.27	701.9

原理图

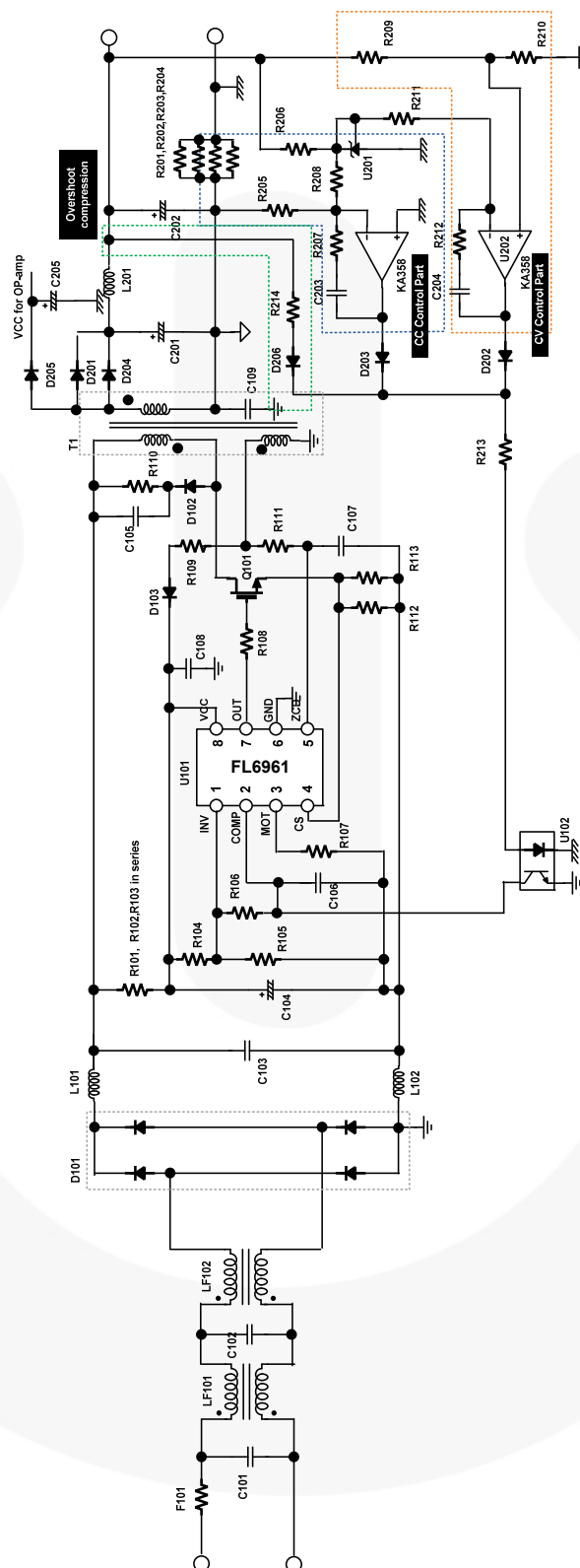


Figure 8. 原理图

材料清单

项目编号	器件标号	取值	数量	说明(制造商)
1	U101	FL6961	1	CRM PFC控制器(飞兆半导体)
2	U102	FOD817	1	光电耦合器(飞兆半导体)
3	U201	KA431	1	分流稳压器(飞兆半导体)
4	U202	KA358A(LM2904)	1	双运放(飞兆半导体)
5	Q101	FQPF3N80C	1	800V/3A MOSFET (飞兆半导体)
6	D101	DF04	1	1.5A SMD 桥式二极管(飞兆半导体)
7	D102	RS1M	1	1000V/1A超快恢复二极管(飞兆半导体)
8	D103	RS1G	1	400V/1A快恢复二极管 (飞兆半导体)
9	D201,D204	EGP30D	2	200V/3A超快恢复二极管(飞兆半导体)
10	D202,D203, D205,D206	LL4148	3	通用二极管(飞兆半导体)
11	R101,R102, R103	82K Ω	3	SMD电阻1206
12	R104	120k Ω	1	SMD电阻1206
13	R105	10K Ω	1	SMD电阻1206
14	R106	20K Ω	1	SMD电阻1206
15	R107	9.1k Ω	1	SMD电阻1206
16	R108	47 Ω	1	SMD电阻1206
17	R109	10 Ω	1	SMD电阻1206
18	R110	220K Ω	1	2W
19	R111	30K Ω	1	SMD电阻1206
20	R112,R113	1 Ω	2	SMD电阻1206
21	R201,R202, R203	1 Ω	3	SMD电阻1206
22	R204	2.2 Ω	1	SMD电阻0806
23	R205	4.3K Ω	1	SMD电阻0806
24	R206	1.5K Ω	1	SMD电阻0806
25	R207	30K Ω	1	SMD电阻0806
26	R208	51K Ω	1	SMD电阻0806
27	R209	33K Ω	1	SMD电阻0806
28	R210	3.9K Ω	1	SMD电阻0806
29	R211	120K Ω	1	SMD电阻0806
30	R212	47K Ω	1	SMD电阻0806
31	R213	4.7K Ω	1	SMD电阻0806
32	R214	47K Ω	1	SMD电阻0806

材料清单（续）

项目编号	器件标号	取值	数量	说明(制造商)
33	C101	100nF/250V	1	X-电容
34	C102	47nF/250V	1	X – Capacitor
35	C103	100nF/630V	1	薄膜电容
36	C104	33μF/35V	1	点解电容
37	C105	2.2nF/1kV	1	Y-电容
38	C106	2.2μF	1	SMD 电容0805
39	C107	30pF	1	SMD 电容0805
40	C108	100nF	1	SMD 电容0805
41	C201,C202	470μF/35V	2	点解电容
42	C203	1μF	1	SMD 电容0805
43	C204	470nF	1	SMD 电容0805
44	C205	10μF/35V	1	点解电容
45	LF101,LF102	80mH	2	线路滤波器
46	L101	27μH	1	线路滤波器
47	L102	6.8μH	1	线路滤波器
48	L201	5μH	1	输出电感
49	F101	1A/250V	1	保险丝
50	T1	PQ-42016	1	1mH

相关数据表

[FL6961 — 照明用单级反激和临界模式PFC控制器](#)

[AN-8025 — 采用AN7530的LED照明用单级反激 AC-DC 变换器的设计指南](#)

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