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应用指南AN-9041

采用模拟 PFC IC 的 PFC SPM® 设计指南

编写:

应用工程部分
电机控制系统团队
HV PCIA
飞兆半导体

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说明:

在本指南及其他飞兆文档和产品手册中, 下列术语可以互换:

DIP = SPM2、Mini-DIP = SPM3、Tiny-DIP = SPM5、 μ Mini-DIP = SPM45H、PFCM = PFC SPM®。

1. 系统配置

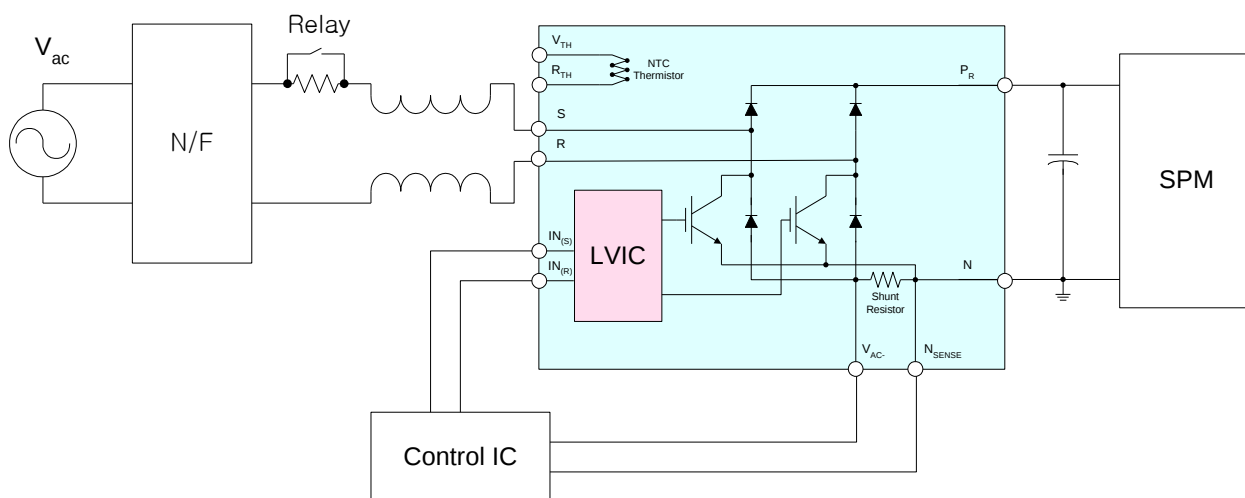


图 1 PFC SPM® 系统的典型框图

由于存在较大的直流母线电容，需要一个浪涌电流抑制电路，如图 1 所示。直流母线电容充满电后，应关闭电路中继电器。PFC SPM®、迷你 SPM 和控制 IC 可共享单个 GND 级。通常来说，PFC SPM 的 GND 和 N_{SENSE} 端子应该具有相同的电势。通过较大的电流开关，很容易在 P 和 N 端子之间产生较大的浪涌电压。为了减小过冲电压，缩短在 PFC SPM 和直流母线电容间的连线变得尤为重要。此外，应在 P 和 N 端子附近安装高频电容，如聚丙烯膜电容，用作缓冲器。

2. 保护电路

下面图 2 显示保护功能的时序图。OCP 和 OVP 各有两个保护等级。通常来说，PFC 控制 IC 自身具有 OCP 和 OVP 功能。另外，用户还可以利用 C_{SC} 输入在预置 OC 和 OV 条件下停止运行 PFC SPM® 并输出 FO 信号。

过流保护 (OCP)

[OCP 等级 1 - PFC SPM®] PFC SPM 在过流情况下具有保护功能。出现过流 (OC) 情况时，PFC SPM 停止工作并在故障输出时段（由 C_{FOD} 设定）生成故障输出信号。该时段过后，PFC SPM 根据输入命令重新开始工作。其总传输延迟时间取决于外部运算放大器的速度。我们建议使用具有快速保护功能的低成本、速度较慢的运算放大器解决方案。即下一段中介绍的 OCP 等级 2 保护。

[OCP 等级 2 (SCP) - PFC 控制 IC] 通过 PFC 控制 IC 的峰值电流限制功能，系统受到短路 (SC) 保护。OCP 等级 2 的推荐电流限值比 OCP 等级 1 的高。它不会生成故障输出信号，但响应速度非常快。在 OCP 等级传输延迟时间内，系统受到短路保护。

过压保护

过压 (OV) 保护也可以实现双重保护。由于存在较大的电容，直流母线电压变化缓慢。这样，OVP 不需要快速响应。因此，是否激活 PFC 控制器的 OVP 功能是可选的。

[OVP 等级 1 - PFC 控制器] OVP 等级 1 抑制瞬变情况下的电压击穿。不会生成故障输出信号。

[OVP 等级 2 - PFC SPM®] OVP 等级 2 的电压电平比 OVP 等级 1 的高。出现过压情况时，PFC SPM 停止工作并在故障输出时段（由 C_{FOD} 设置）生成故障输出信号。然后，PFC SPM 重新开始工作。

欠压保护

当控制电压降至 UV 断路电平以下时，IGBT 栅极会中断，若控制电压恢复至 UV 重置电平，该保护功能自动释放。

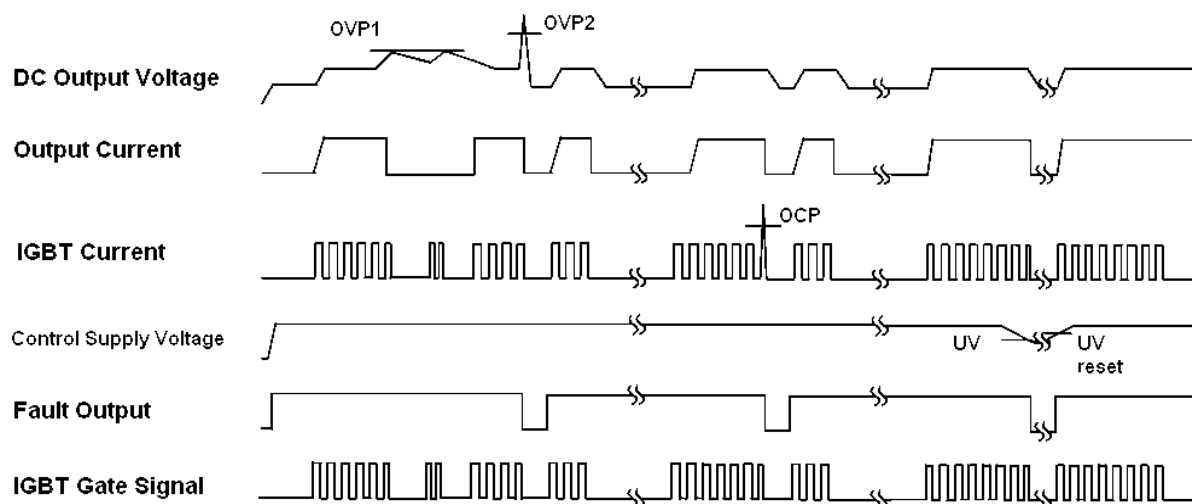


图 2 保护功能的时序图

3. 设计实例 (PFC SPM® 演示板)

一个常见的 PFC 实例是实现输入电压为 187~276[V] 的 5[kW] 空调应用。

PFC SPM® 演示板的工作条件:

表 1 工作条件

	项目	符号	数值	单位
1	开关频率	F _{sw}	40	KHz
2	最小输入电压	V _{imin}	176	Vac
3	标称输入电压	V _{inom}	220	Vac
4	最大输入电压	V _{imax}	264	Vac
5	最大输出功率	P _o	5000	W
6	最小输出电压	V _{omin}	350	Vdc
7	标称输出电压	V _{onom}	380	Vdc
8	OVP 等级 1	V _{ov1}	420	V
9	OVP 等级 2	V _{ov2}	440	V
10	峰值纹波电流	I _{ripple}	5	A
11	OCP 等级 1	I _{ocp1}	40	A
12	OCP 等级 2 (SCP)	I _{ocp2}	50	A
13	分流电阻	R _{sh}	2	MΩ
14	直流电容	C _{out}	940	μF

输出电容和电感设计

输出电压纹波 & 输出电容

$$|V_{OUTRIPPLE}|_{PEAK} = I_{OUTDC} \sqrt{\left(\frac{1}{4\pi f_L \times C_{OUT}}\right)^2 + ESR^2}$$

where:

f_L = line frequency.

ESR = the ESR of the output capacitor.

纹波电压 V_{dc} 的减少可通过采用较大的 C_{OUT} 实现。在演示板中, C_{OUT} 设置为 940[μF] (470[μF] × 2)

电感 & 输入电流纹波

$$\Delta I_{L-P-P} = \frac{V_{IN}(V_{OUTDC} - V_{IN})}{fL V_{OUTDC}}$$

其中: ΔI_{Lp-p} : PFC 电感器峰对峰电流

 V_{IN} : 输入交流电压

V_{OUTDC} : 直流母线电压

f : 开关频率

L : PFC 电感器电感

$$\Delta I_{L_{P-P}} = \frac{V_{IN} (V_{OUTDC} - V_{IN})}{f L V_{OUTDC}}$$

$$\therefore (\Delta I_{L_{p-p}})_{MAX} = \frac{V_{OUTDC}}{4fL} \quad (\because V_{IN} = \frac{1}{2}V_{OUTDC})$$

$$(\Delta I_{L_{p-p}})_{MAX} = 5A \rightarrow L = \frac{V_{OUTDC}}{20f} = \frac{380}{20 \cdot 40000} = 475[\mu H] \text{ (f_s=40kHz)}$$

电流纹波由开关频率和电感决定。为了减少电流纹波，需要较高的开关频率和较大的电感值。也就是说，采用较高的开关频率能够减少电感器尺寸。但是，功耗会增加，因而需要效率更高的散热器结构。

开环响应

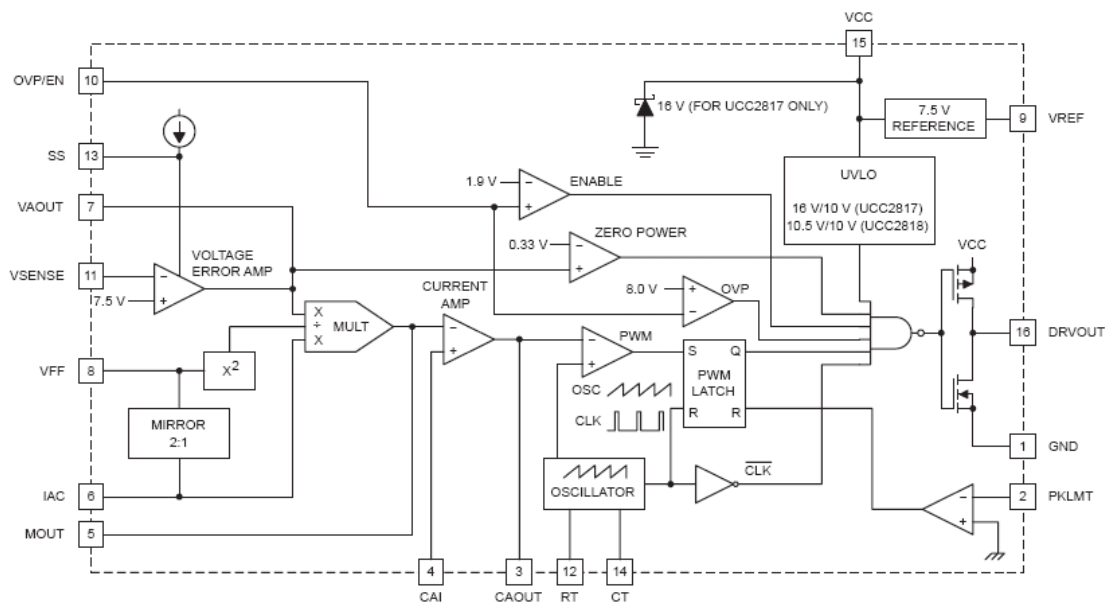


图 3 PFC 控制 IC 框图

下面是 PFC 控制器 ucc3818 的框图。平均电流模式控制包含两种环路：电压环路和电流环路。电压环路控制输出直流母线电压。它调节输出电压。输出直流母线中存在一个 120[Hz] 的纹波电压，是由 60[Hz] 的交流输入电流产生的。因此，电压环路的设计带宽必须足够低，从而抑制 120[Hz] 纹波电压。

在通用连续导通模式 (CCM) 下，存在一个乘法器。乘法器将 V_{EA} (电压环路输出) 乘以 I_{AC} (输入交流电流波形基准值)，然后除以 V_{RMS} (RMS 输入电压基准值)。乘法器的输出 ($I_{MO} = K \cdot \frac{V_{EA} \cdot I_{AC}}{V_{RMS}^2}$) 是 PFC 输入电流 (I_{AC}) 的基准值。

I_{MO} 引脚的电压 (乘法器输出) 和电流感测电阻的电压之间的差值被电流环路放大。 V_{EA} (电流环路输出) 是生成栅极信号的比较器的基准电压。电流环路应足够快，从而赶上 120[Hz] 的输入交流电流。由于存在开关噪声，速度太快会导致电流波形失真。因此，电流环路必须设计的足够快，以便赶上 120[Hz] 的整流输入电流，但又不能太快，以便抑制开关噪声。

电流环路放大器

方程式 1 显示功率级的开环响应。(请参阅 UCC3818 数据表)

$$G_{PST} = \frac{V_S(s)}{V_{IAOUT}(s)} = \frac{V_{DC} R_{SH}}{4sL} \quad (\text{UCC3818}) \quad (\text{Eq. 1})$$

其中：
 V_S : 分流电阻的电压
 V_{IAOUT} : R_{MO} 电压
 V_{DC} : 直流母线电压
 R_{SH} : 用于电流感测的分流电阻 (2 mohm)
 L : PFC 电感
 s : $j\omega (= j \cdot 2\pi f)$

电压环路放大器

方程式 2 显示功率级的开环响应。(请参阅 UCC3818 数据表)

$$G_{V.O.L.} = \frac{P_{IN}}{sC_{OUT} V_{OUTDC} \Delta V_{EAOUT}} \quad (\text{UCC3818}) \quad (\text{Eq. 2})$$

其中：
 P_{IN} : 输入功率
 C_{OUT} : 直流母线电容
 V_{OUTDC} : 直流母线电压
 ΔV_{EAOUT} : 误差放大器输出差值 ($\approx 5V$)
 s : $j\omega (= j \cdot 2\pi f)$

控制环路实现

电流环路

[步骤 1] 穿越频率

下面方程式计算理论穿越频率：

$$f_c = \frac{f_s}{6} \Rightarrow 6.7\text{kHz} \quad (\text{方程式 3})$$

[步骤 2] 确定 F_z 和 F_p

$$f_z = \frac{f_c}{2} = 3.3\text{kHz}, \quad f_p = 6f_z = 20\text{kHz}$$

[步骤 3] 确定 R_z 、 C_p 、 C_z

R_i 等于 R_{MO} 。（请参阅第 10 页上的“其它参数”）

$$R_i = 470[\Omega],$$

$$\text{在方程式 1 中, } G_{PST} \Big|_{f_c=6.6\text{kHz}} = \frac{V_{DC} R_{SH}}{4sL} = \frac{V_{DC} R_{SH}}{4(2\pi f_c)L} = 0.0103 = -39.8\text{dB}$$

因此需要以 $f_c (= 6.6 \text{ kHz})$ 的频率提高电平 40 dB。

R_z 由方程式 7 得出。

$$|G|_{dB} = 20 \log \frac{R_z}{R_i} = 40\text{dB} \rightarrow R_z = 47[\text{k}\Omega].$$

根据方程式 4 和 5，可以得到 C_p 和 C_z 。

$$C_p = 180[\text{pF}], \quad C_z = 1[\text{nF}]$$

$$f_z = \frac{1}{2\pi R_z C_z} \quad (\text{方程式 4})$$

$$f_p = \frac{C_z + C_p}{2\pi R_z C_z C_p} \quad (\text{方程式 5})$$

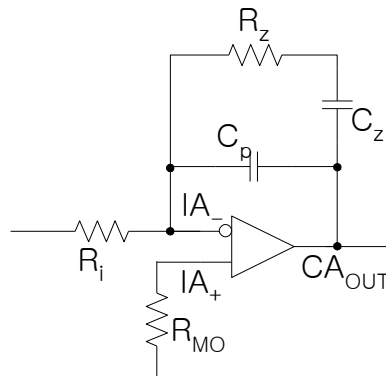


图 4 电流环路电路

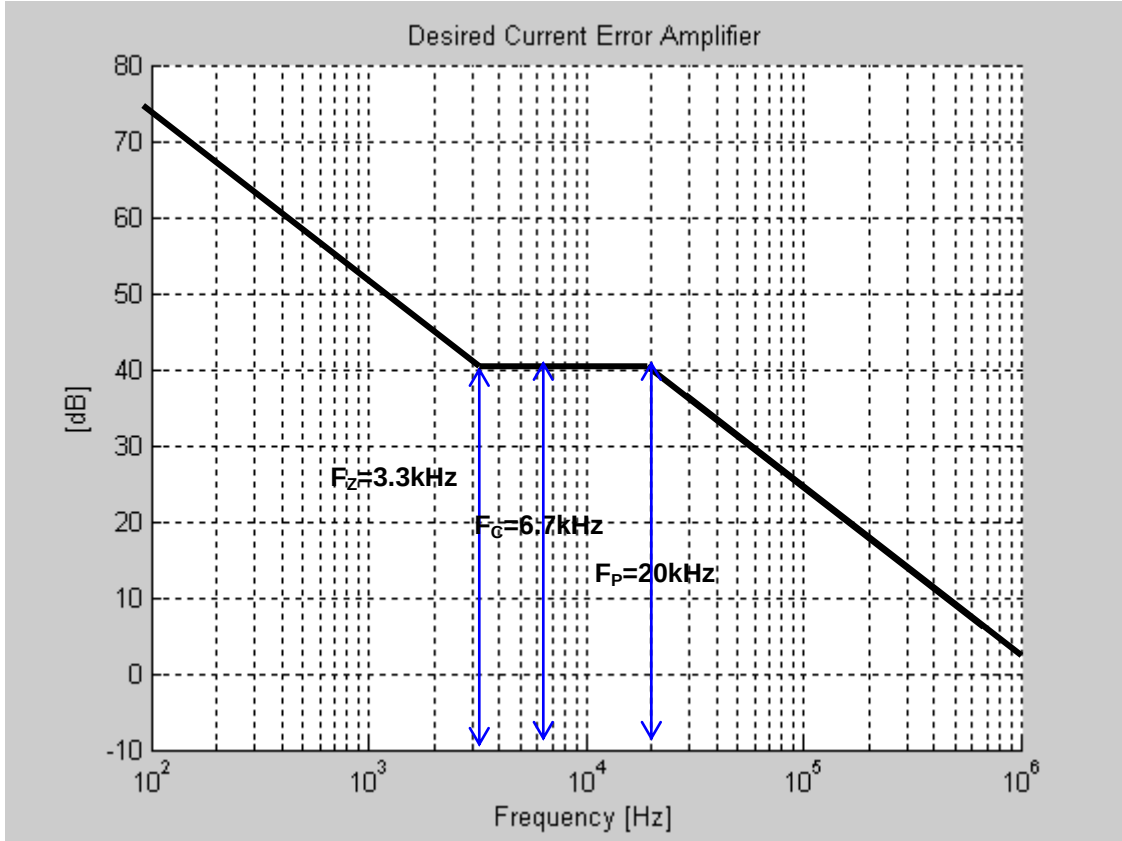


图 5 所需的电流误差放大器响应

$$[1] \quad |G|_{dB} = 20 \log \frac{1}{2\pi f R_i C_z} \quad (\text{Eq. 6})$$

$$[2] \quad |G|_{dB} = 20 \log \frac{R_z}{R_i} \quad (\text{Eq. 7})$$

$$[3] \quad |G|_{dB} = 20 \log \frac{1}{2\pi f R_i C_p} \quad (\text{Eq. 8})$$

电压环路

$$G_{V.O.L.} = \frac{P_{IN}}{s C_{OUT} V_{OUTDC} \Delta V_{EAOUT}} = \frac{5000}{2\pi f \cdot 0.001 \cdot 380 \cdot 5} = \frac{419}{f}$$

在 E/A 输入和感测电阻中间，加入了电阻 (R_{VD})。通过采用较大的 R_{VD} ，可以用较小的 SMD 电容替换掉 C_{VF} 。

$$\rightarrow R_{VD} = 120k\Omega \quad (>R_{VS})$$

$$R_{VF} = 8 \cdot R_{VD} \approx 1M\Omega \quad (>R_{VD})$$

$$f_{CV} = \frac{1}{2\pi R_{VD} C_{VF}} \ll 120 \rightarrow C_{VF} = 1\mu F \quad (f_{CV} = 1.3Hz)$$

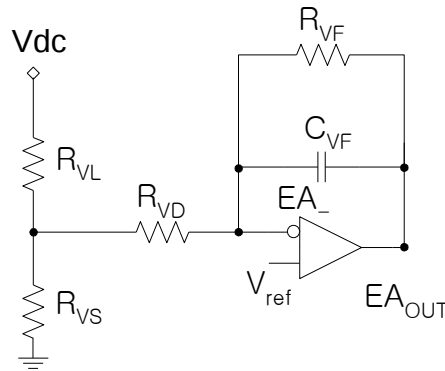


图6 电压环路电路

其它参数

R_T , C_T : 确定开关频率

$$f = \frac{0.6}{R_T C_T}$$

$$R_T = 15[k\Omega]$$

$$C_T = 1[nF]$$

$$\rightarrow F_s = 40[kHz]$$

R_{MO} : (请参阅图 4)

$$R_{MO} = \frac{I_{AC_peak} \cdot R_{sense}}{I_{GMMAX}} = \frac{50\sqrt{2} \cdot 0.002}{300 \times 10^{-6}} = 471 \approx 470[\Omega]$$

(假设输入电流是 $50 A_{RMS}$ @ $V_{AC} = 100 V_{RMS}$)

$$\rightarrow R_{MO} = 470[\Omega]$$

$R_{sense} = 0.002[\Omega]$ (在低电平电流下, 较小的电阻可能导致失真)

R_{AC} & 光电耦合器电路:

光电耦合器: TLP180

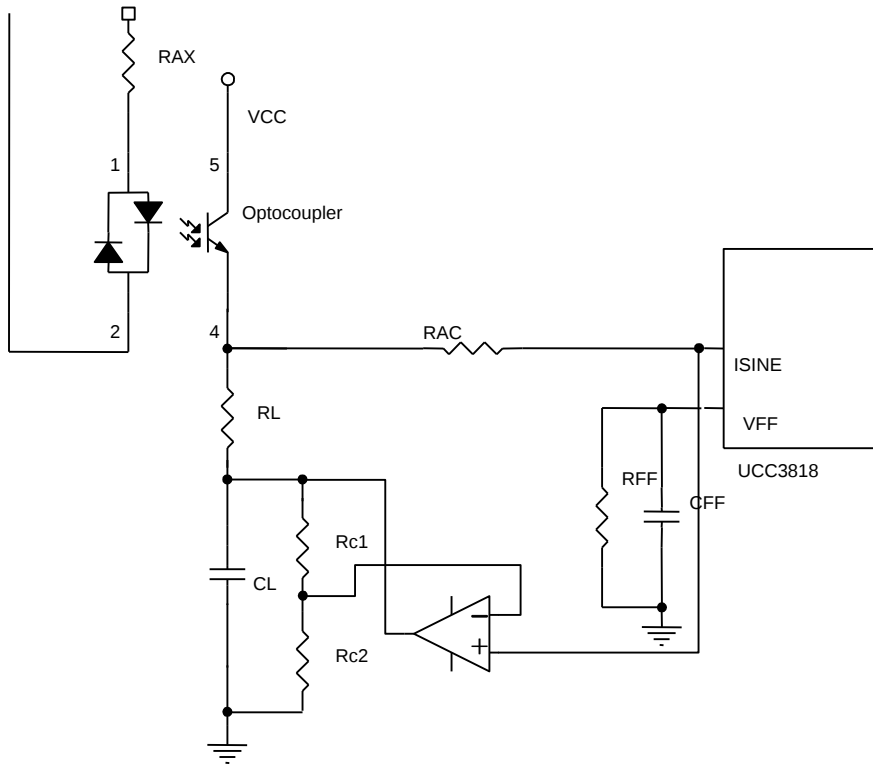


图 7 输入交流电压感测电路

R_{AX} 和 R_L 取决于光电耦合器:

$$R_{AX} = \frac{V_{RMS_max} \cdot \sqrt{2}}{I_{LINEAR_max}} = \frac{270 \cdot \sqrt{2}}{6 \times 10^{-3}} = 64[k\Omega]$$

$$\rightarrow 18 + 18 + 18 + 18[k\Omega](0.5 \times 4 = 2W)$$

$$R_{AC} = \frac{V_{RL_PEAK}}{I_{AC_max}} = \frac{9}{0.5 \times 10^{-3}} = 18[k\Omega]$$

$$R_L = 390[\Omega]$$

R_{C1} 、 R_{C2} 、 C_L 和 运算放大器 $\rightarrow I_{SINE}$ 偏移补偿

$$C_L = 1[\mu F], R_{C1} = 0[\Omega], R_{C2} = 150[\Omega],$$

V_{FF} :

$$V_{FF} = 1.4[V] \text{ (当输入电压 } V_{AC} = 90[V_{AC}])$$

$$R_{FF} = 33[k\Omega], C_{FF} = 100[\mu F]$$

过流保护

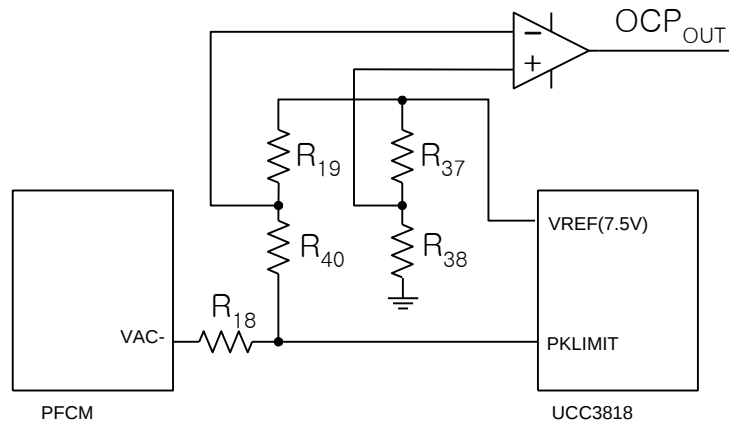


图 8 过流保护电路

实际保护等级与计算值稍有不同。取决于 PCB 布局样式。有关演示板，设计值为：

$$R_{18} = R_{40} = 1.2[k\Omega], R_{19} = R_{37} = 82[k\Omega], R_{38} = 1.5[k\Omega]$$

预期 OC 值为：

1) OCP 等级 1

$$\frac{R_{38}}{R_{37}} V_{REF} = \frac{(R_{18} + R_{40})V_{REF} - R_{SH} I_{PK} R_{19}}{R_{18} + R_{19} + R_{40}} \Rightarrow I_{PK} = \frac{V_{REF}}{R_{SH} R_{19}} \left(R_{18} + R_{40} - \frac{R_{38}}{R_{37}} (R_{18} + R_{19} + R_{40}) \right)$$

$$\therefore I_{PK} \approx 40[A]$$

2) OCP 等级 2

$$\frac{R_{19} + R_{40}}{R_{18}} = \frac{V_{REF}}{R_{SH} I_{PK}} \Rightarrow I_{PK} = \frac{R_{18} V_{REF}}{R_{SH} (R_{19} + R_{40})}$$

$$\therefore I_{PK} \approx 50[A]$$

过压保护

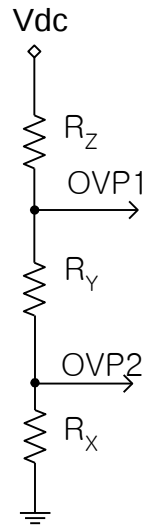


图 9 过压保护电路

有关演示板，设计值为：

$$R_X = 15 \text{ [k}\Omega\text{]}, R_Y = 1.8 \text{ [k}\Omega\text{]}, R_Z = 870 \text{ (270+270+330) [k}\Omega\text{]}$$

预期 OC 值为：

1) OVP 等级 1

$$\frac{R_X + R_Y}{R_X + R_Y + R_Z} = \frac{V_{REF_OV}}{V_{DC_PK}} \Rightarrow V_{DC_PK} = \frac{R_X + R_Y + R_Z}{R_X + R_Y} V_{REF_OV} = \frac{886.8}{16.8} \cdot 8 = 422[V]$$

2) OVP 等级 2

$$\frac{R_X}{R_X + R_Y + R_Z} = \frac{V_{REF}}{V_{DC_PK}} \Rightarrow V_{DC_PK} = \frac{R_X + R_Y + R_Z}{R_X} V_{REF} = \frac{886.8}{15} \cdot 7.5 = 443[V]$$

直流母线电压控制

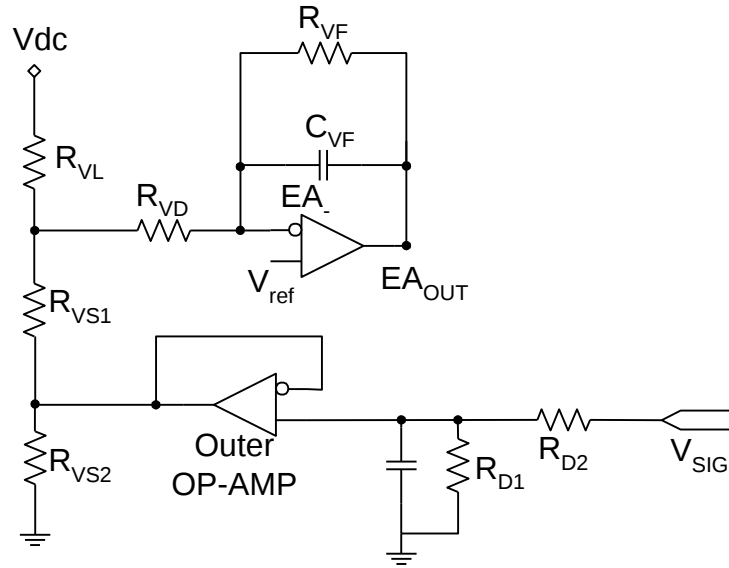


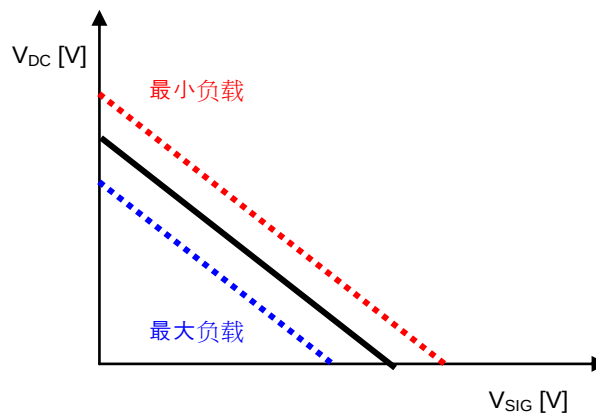
图 10 直流母线电压控制电路

V_{DC} 和参数之间的关系是：

$$V_{DC} = 7.5 \left(R_{VL} \left(\frac{R_{VD}}{R_{VF} R_{VS1}} + \frac{1}{R_{VF}} + \frac{1}{R_{VS1}} \right) + \frac{R_{VD}}{R_{VF}} + 1 \right) - \frac{1}{R_{VF}} \left(R_{VD} + R_{VL} + \frac{R_{VL} R_{VD}}{R_{VS1}} \right) V_{EA} - \frac{R_{VL}}{R_{VS1}} \left(\frac{R_{D1}}{R_{D1} + R_{D2}} \right) V_{SIG}$$

变量 V_{DC} 电压可通过调整 V_{SIG} 电压获得。电压误差放大器的输出 V_{EA} 随其负载电流在 0 至 5.5 V 间变化。在无负载条件下， V_{EA} 值几乎为零。同时， V_{DC} 的值达到最大值。下图显示 V_{SIG} 和 V_{DC} 电压。低负载条件下的电压 V_{DC} 比最大负载条件下的电压高。

图 11 直流母线电压与控制电压



4. 实验结果

图 12 显示实现 PFC 转换器的整体原理图。表 2 显示实现硬件的组件。图 13 显示输入交流电流和直流母线电压波形。表 3 详细说明这些图。

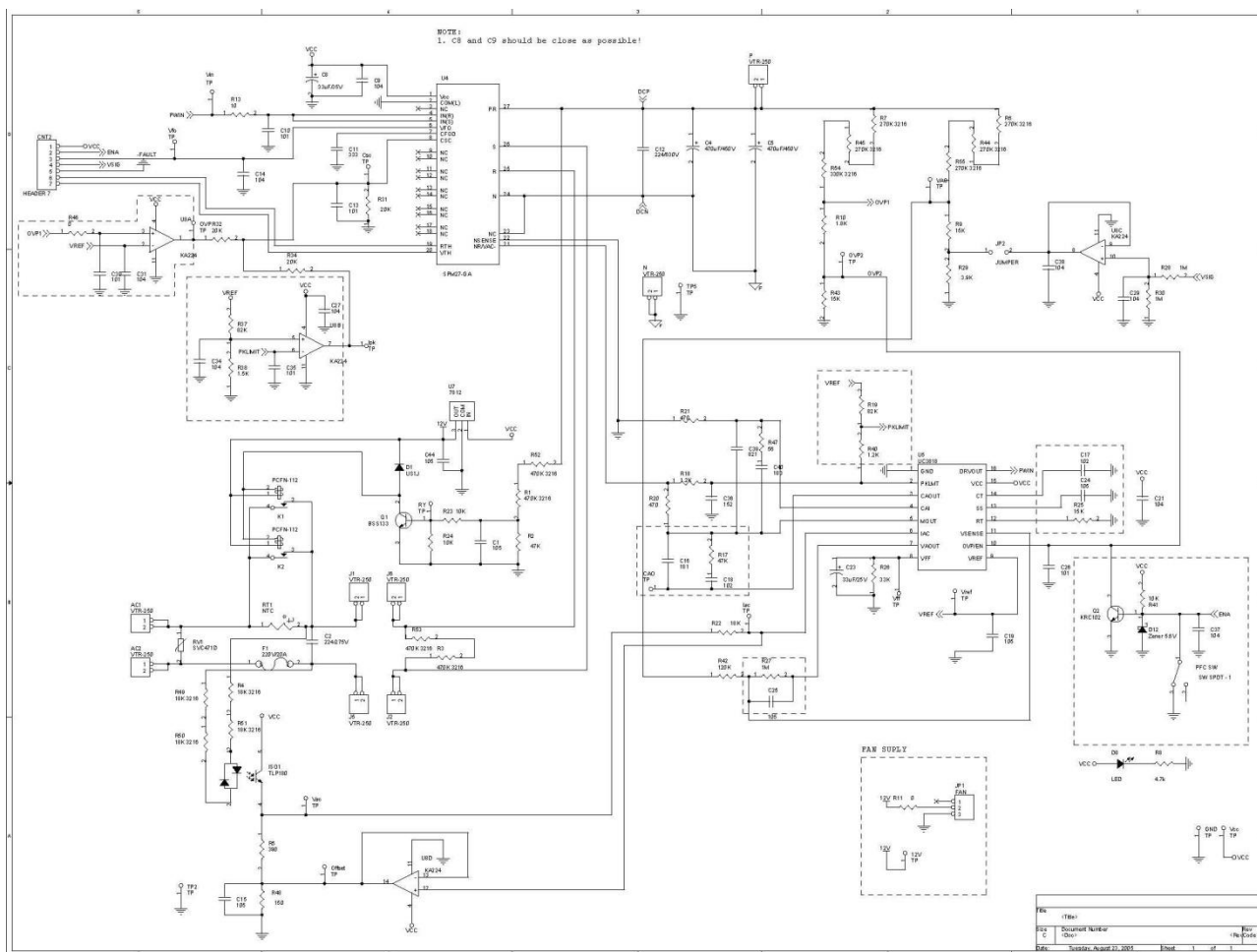


图 12 实现 PFC 转换器的原理图

表 2 PFC SPM® 演示板 BOM

Item	Part	Reference	Quantity
1	C-Ceramic : 101 2012	C10,C13,C26,C30,C35	5
2	C-Ceramic : 102 2012	C17,C18	2
3	C-Ceramic : 104 2012	SC2,SC4,C9,C14,C21,C27,C29,C31,C34,C37,C38	11
4	C-Ceramic : 105 2012	C1,C15,C19,C24,C25,C44,SC6	7
5	C-Ceramic : 152 2012	C36	1
6	C-Ceramic : 183 2012	C40	1
7	C-Ceramic : 221 2012	C16	1
8	C-Ceramic : 333 2012	C11,SC7	2
9	C-Ceramic : 821 2012	C39	1
10	C-Elec : 220uF 35V	SC5	1
11	C-ELEC : 33uF 35V	C8,C23	2
12	C-ELEC : 470uF 450V	C4,C5	2
13	C-Elec : 47uF 35V	SC3	1
14	C-FILM : 105 630V	C12	1
15	C-FILM : 220nF AC275V	C2	1
16	Connector : 7-pin, 2.54mm pitch	CNT2	1
17	DIODE : US1J	D1,SD2,SD3,SD4	4
18	FAN connector : 3-pin, 2.54mm pitch	JP1	1
19	FPS : KA5M02659RN	U10	1
20	Fuse : 220V/20A	F1	1
21	JUMPER : 2-pin, 2.54mm pitch	JP2	1
22	LED	D8	1
23	Main Relay : PCFN-112	K1,K2	2
24	Mosfet : BSS138	Q1	1
25	NTC : 6D-22	RT1	1
26	Op-Amp : KA224	U8	1
27	Opto-coupler : TLP180	ISO1	1
28	Opto-coupler : TLP181	ISO2	1
29	PFC IC : UC3818	U5	1
30	PFCM : FPDB30PH60	U4	1
31	R-Chip : 0ohm, 1/8W, J, 2012	R11,R46	2
32	R-Chip : 1.2Kohm, 1/8W, J, 2012	R40,R18	2
33	R-Chip : 1.5Kohm, 1/8W, J, 2012	R38	1
34	R-Chip : 1.8kohm, 1/8W, F, 2012	SR6,R10	2
35	R-Chip : 1.8kohm, 1/8W, J, 2012	SR2	1
36	R-Chip : 100kohm, 1/2W, J, 5025	SR7,SR8	2
37	R-Chip : 10Kohm, 1/8W, J, 2012	SR4,R23,R24,R41	4
38	R-Chip : 10ohm, 1/8W, J, 2012	R13	1
39	R-Chip : 10ohm, 1/8W, J, 2012	SR1	1
40	R-Chip : 120Kohm, 1/8W, J, 2012	R42	1
41	R-Chip : 150ohm, 1/8W, J, 2012	R48	1
42	R-Chip : 15Kohm, 1/8W, J, 2012	R9,R25,R43	3
43	R-Chip : 18Kohm, 1/4W, J, 3216	R4,R49,R50,R51	4
44	R-Chip : 18Kohm, 1/8W, J, 2012	R22	1
45	R-Chip : 1Mohm, 1/8W, J, 2012	R27,R28,R30	3
46	R-Chip : 20Kohm, 1/8W, J, 2012	R31,R32,R34	3
47	R-Chip : 270Kohm, 1/4W, F, 3216	R6,R7,R44,R45,R55	5
48	R-Chip : 3.3kohm, 1/8W, J, 2012	SR3	1
49	R-Chip : 3.9Kohm, 1/8W, J, 2012	R29	1
50	R-Chip : 33Kohm, 1/8W, J, 2012	R26	1
51	R-Chip : 330Kohm, 1/4W, F, 3216	R54	1
52	R-Chip : 390ohm, 1/8W, J, 2012	R5	1
53	R-Chip : 4.7Kohm, 1/8W, J, 2012	R8	1
54	R-Chip : 470Kohm, 1/4W, F, 3216	R1,R3,R52,R53	4
55	R-Chip : 470ohm, 1/8W, J, 2012	R20,R21	2
56	R-Chip : 47Kohm, 1/8W, J, 2012	R2,R17	2
57	R-Chip : 56ohm, 1/8W, J, 2012	R47	1
58	R-Chip : 82Kohm, 1/8W, J, 2012	R19,R37	2
59	R-Chip : 9kohm, 1/8W, F, 2012	SR5	1
60	Regulator : KA78M12	U7	1
61	Switch : SW SPDT - 1	PFC SW	1
62	Terminal : VTR-250	J1,J2,J5,J6,AC1,AC2,P,N	8
63	TR : KRC102	Q2	1
64	Transformer : EI-1916	T1	1
65	TVS : SMBJ170	SD1	1
66	Varistor : SVC471D	RV1	1
67	Voltage detector : KA431A	SD5	1
68	Zener Diode : 1N4734A, 5.6V	D12	1

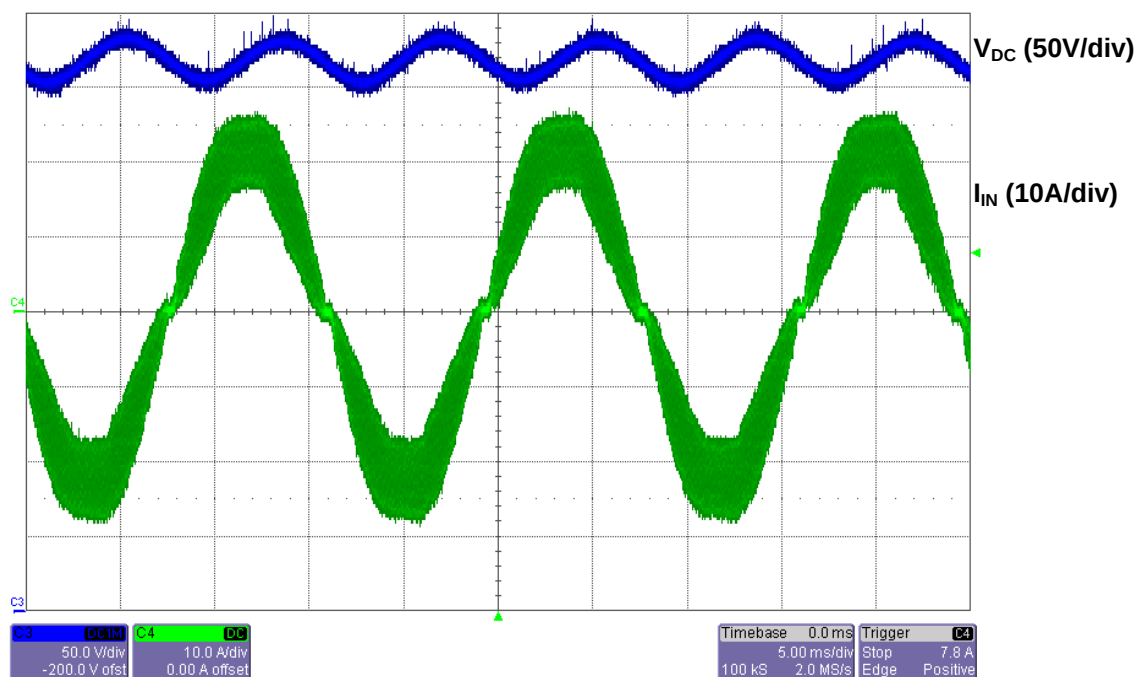


图 13 完整负载测试结果 ($I_{IN} = 16 A_{RMS}$)

表 3 功率因数和输入功率测试

	V_{AC} [V]	I_{AC} [A]	功率 [kW]	功率因数 [%]
图 13	220	16	3.5	99

* V_{AC} 和 I_{AC} 为 RMS 值

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