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采用FAN6982的功率因数校正转换器设计

本应用指南介绍采用FAN6982控制器的功率因数校正电源的工作原理以及逐步设计依据。典型应用电路如图1所示,其中电源电压 V_{DD} 由辅助电源提供,且下游转换器的电源电压由RDY引脚控制。



图1. 典型的FAN6982应用电路

功能说明

升压转换器的常用工作模式为连续导通模式 (CCM) 和临界导通模式 (BCM)。这两个具有描述性的名称指的是流经升压转换器储能电感的电流，如图2中所示。在CCM中，电感电流是连续的；而在BCM中，当电感电流归零时（即位于连续导通和不连续导通工作的边界），会开始新的开关周期。CCM PFC常用于300W以上的高功率应用，因为电感电流具有较小的纹波，相比BCM可获得更高的功率因数。由于输出二极管存在反向恢复电流，要实现高效率 and 低EMI，使用反向恢复电流低的高速二极管尤为重要。

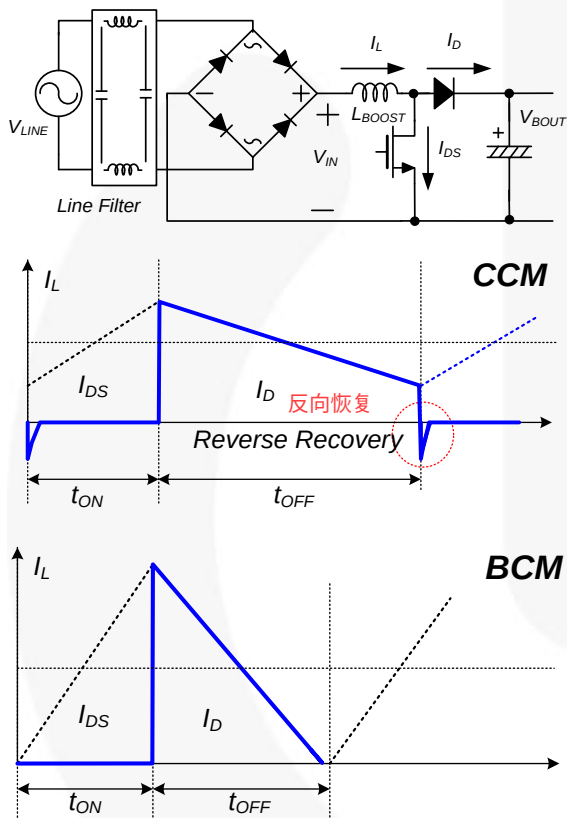


图2. CCM与 BCM控制

PFC的电流和电压控制

如图3所示，FAN6982针对功率因数校正采用两个控制环路：电流控制环路和电压控制环路。电流控制环路决定电感电流的形状，如图4所示，因此在一个开关周期内，内部电阻 R_M 上的压降等于检测电阻 R_{CS} 上的平均压降：

$$\frac{1}{T_s} \int_0^{T_s} (I_L \cdot R_{CS}) dt = I_{MO} \cdot R_M \quad (1)$$

其中，内部电阻 R_M 通常为5.7kΩ；增益调制器的输出电流 I_{MO} 为IAC pin输入电流的函数；并且VRMS和VEA引脚的电压可由下式计算得出：

$$I_{MO} = I_{AC} \times \frac{10.5 \times (V_{EA} - 0.7)}{V_{RMS}^2 (V_{EA}^{MAX} - 0.7)} \quad (2)$$

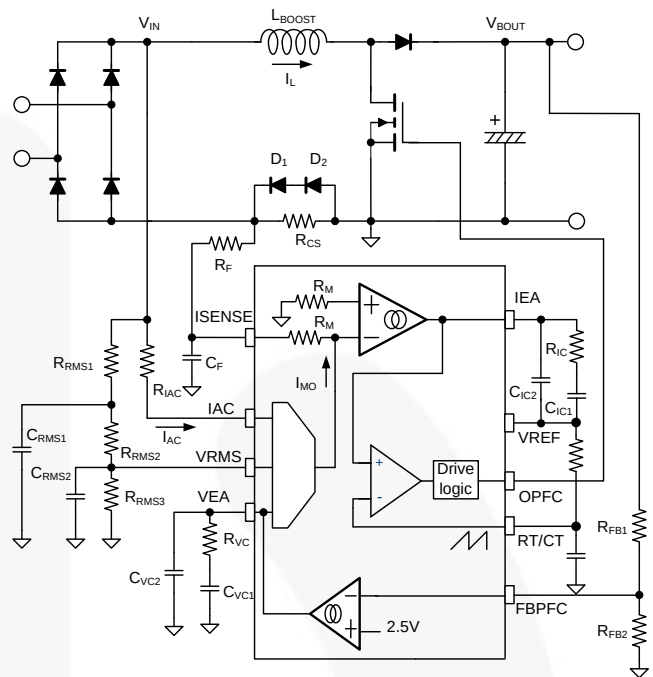


图3. 电流和电压控制反馈电路

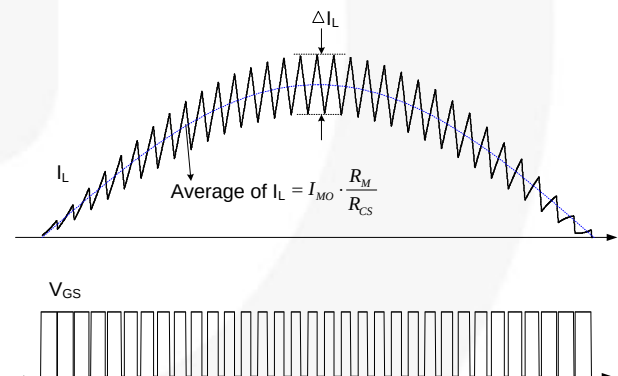


图4. CCM PFC的工作波形

电压控制环路使用内部误差放大器调节PFC输出电压，因此FBPFC电压与2.5V内部参考电压相同。需要注意的是，在等式(2)中， V_{EA} 电压应当基本保持不变，这样针对输入电流整形就能获得纯正弦参考波形。由于PFC输出电压纹波始终是线频率的两倍，因此针对输出电压控制环路应当使用较窄的带宽，以实现最小的线频率纹波。否则，控制环路会尝试消除输出电压纹波，改变误差放大器输出电压（如图5所示），造成输入电流失真。

AN-6982

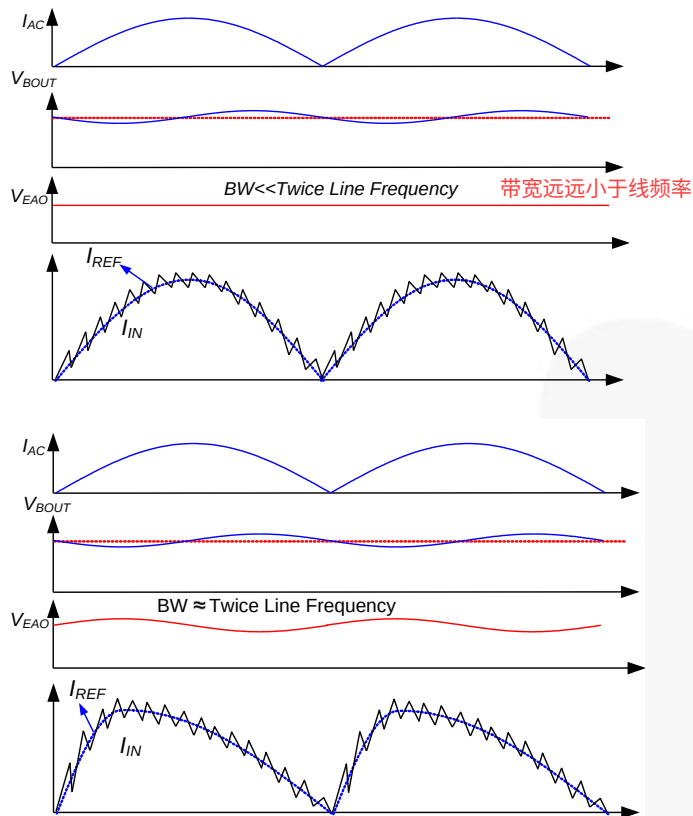


图5. 控制带宽和电感电流

线路前馈

由于整流线路电压给电流控制环路的输入电流整形提供正弦参考波形，因此增大线路电压会造成输入电流增大。然而，从输入和输出功率平衡的角度来看，当输入电压增大时，输入电流应当会减少，以保持输入功率不变。若误差放大器如同在大多数DC-DC应用中一样具有适当的带宽，则输入电压发生变化时，可保持输出电压在容差范围内的调制。然而，对于PFC应用，由于输出调制控制环路具有较窄的带宽，因此线路瞬变时某些严重的输出电压过冲/欠冲无法避免。

解决这个问题的一种措施是采用线路前馈，该方法可改变增益调制器的增益值，使其与线路电压的RMS值成反比，如图6所示。这样能抵消输入电压变化对输出电压的影响，误差放大器就无需任何校正，如图7所示。

使用线路前馈的第二个好处是误差放大器输出直接与转换器的输入功率成正比，不受线路电压变化的影响。这样就使控制到输出传递函数与线路电压无关，从而简化控制环路的设计。

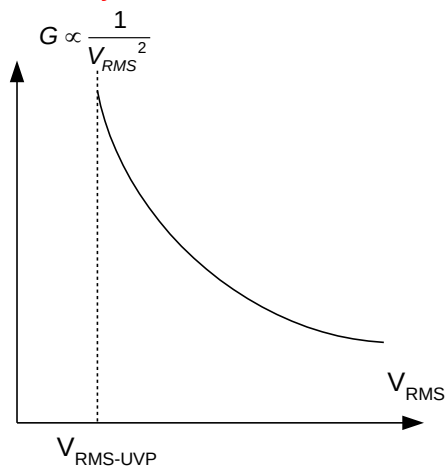


图6. 调制增益特性

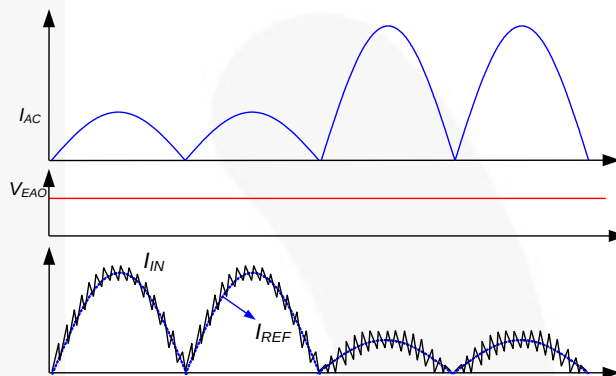


图7. 线路前馈效果

线路电压感测

由于FAN6982根据线路电压信息进行线路前馈操作并提供掉电保护，因此需感测线路电压的RMS值。为感测线路电压的RMS值，通常会采用带有两个极点的平均电路图3。PFC正常工作下的VRMS引脚电压可由下式给出：

$$V_{RMS} = V_{LINE} \frac{\sqrt{2}R_{RMS3}}{R_{RMS1} + R_{RMS2} + R_{RMS3}} \cdot \frac{2}{\pi} \quad (3)$$

其中， V_{LINE} 表示线路电压的RMS值。

PFC一停止开关动作，桥接二极管的结点电容和输入旁路电容就不放电， V_{IN} （图3）箝位在峰值线路电压，如图8所示。那么VRMS引脚电压可由下式给出：

$$V_{RMS}^{NS} = V_{LINE} \frac{\sqrt{2}R_{RMS3}}{R_{RMS1} + R_{RMS2} + R_{RMS3}} \quad (4)$$

因此，进行VRMS分压器设计时应考虑掉电保护跳变点和PFC启动阈值(1.05V/1.9V)。

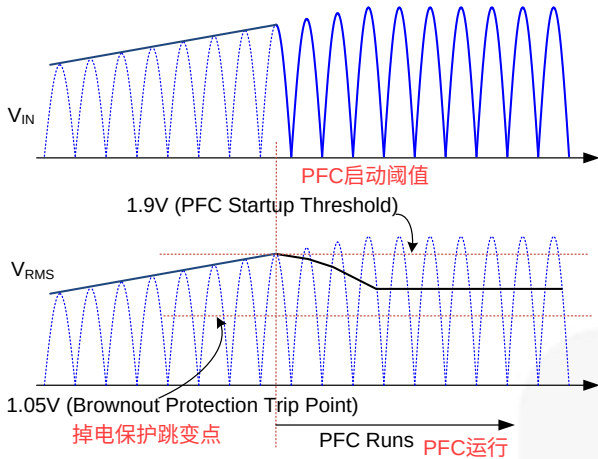


图8. 根据PFC工作情况得到的 V_{RMS}

范围功能

为了在低交流线路电压和轻负载条件下提高系统效率，FAN6982提供两级PFC输出电压。如图9所示，FAN6982监控 V_{EA} 和 V_{RMS} 电压，调节PFC输出电压。 V_{EA} 和 V_{RMS} 低于阈值时，20 μA 内部电流源会使能并流过 R_{FB2} ，从而增大FBPFC引脚电压。20 μA 电流使能时会使PFC输出电压下降，由下式计算得出：

$$V_{OPFC2} = \frac{R_{FB1} + R_{FB2}}{R_{FB2}} \times (2.5 - 20\mu A \times R_{FB2}) \quad (5)$$

通常会将第二个升压输出电压设置为340V~300V。

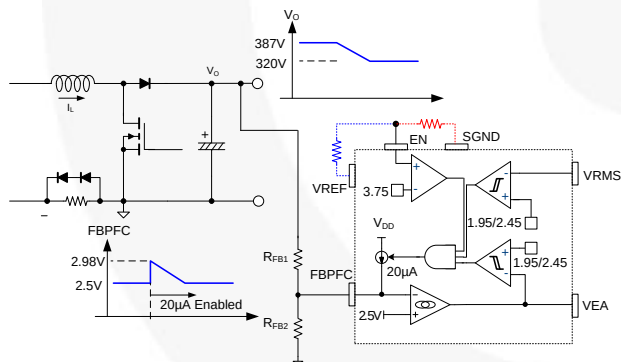


图9. 两级PFC输出模块

振荡器

内部振荡器频率由RT/CT引脚上的定时电阻和电容决定。内部振荡器频率由下式给出：

$$f_{OSC} = \frac{1}{0.56 \cdot R_T \cdot C_T + 360C_T} \quad (6)$$

PFC栅极驱动信号的死区时间由下式确定：

$$t_{DEAD} = 360C_T \quad (7)$$

死区时间应比开关周期的2%更短，这样线路过零附近的线路电流失真就会最少。

将 I_{EA} 电压与RT/CT引脚上的锯齿波形进行比较，即可确定占空比。需要注意的是，FAN6982具有前沿调制功能，占空比随 I_{EA} 电压增大而减小。

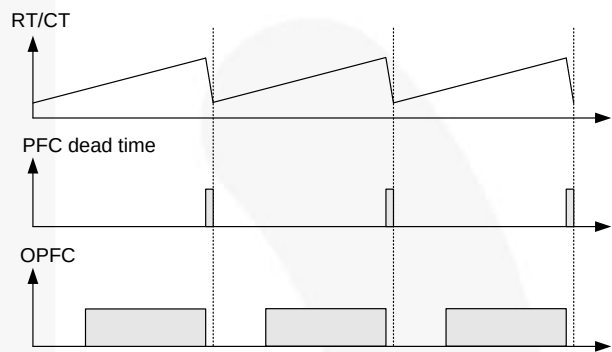


图10. 时序图

RDY功能

图11中所示的RDY功能受控于FBPFC电压。FBPFC电压超过2.5V的96%时，RDY引脚应连接SGND。同时，若FBPFC引脚电压低于2.5V的46%，则内部MOSFET关断，RDY引脚浮空。通常这一特性用来控制下游转换器的启动和关断，即连接和断开下游转换器的电源，如图11所示。通常在RDY引脚和地之间连接旁路电容，最大程度减少噪声干扰。

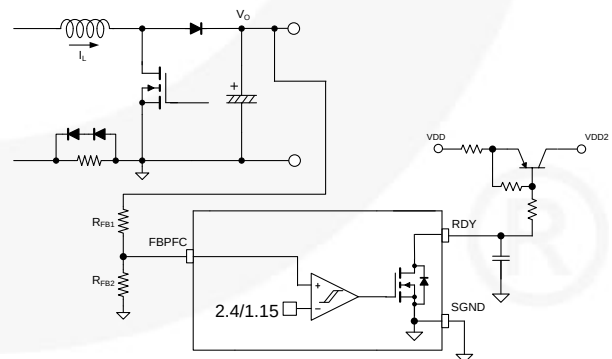


图11. RDY应用电路

软启动功能

软启动与RDY引脚操作相结合。启动时，RDY引脚保持浮空状态，直到PFC输出电压达到标称值的96%。下游转换器的电源受控于RDY引脚时，PFC级以空载开启，因为在PFC输出电压达到特定电平前，下游转换器都不会工作。

由于实际输出电压低于目标值，通常误差放大器输出 V_{EA} 会在启动期间饱和至高电平。 V_{EA} 保持饱和至高电平状态，直到PFC输出电压达到目标值。一旦PFC输出达到目标值，误差放大器即退出饱和状态。然而，对于输出调节， V_{EA} 下降到合适的值需要经过数个线路周期，为负载提供多于需要的功率，造成输出电压过冲。

为了防止因误差放大器饱和而导致的启动时间内的输出电压过冲，FAN6982将误差放大器输出电压(V_{EA})箝位在2.8V（即其最大值的一半），直到PFC输出达到标称值的96%。PFC输出电压达到其标称值的96%后， V_{EA} 的箝位功能便会被禁用。PFC输出的电压随后会由电压控制环路调节。

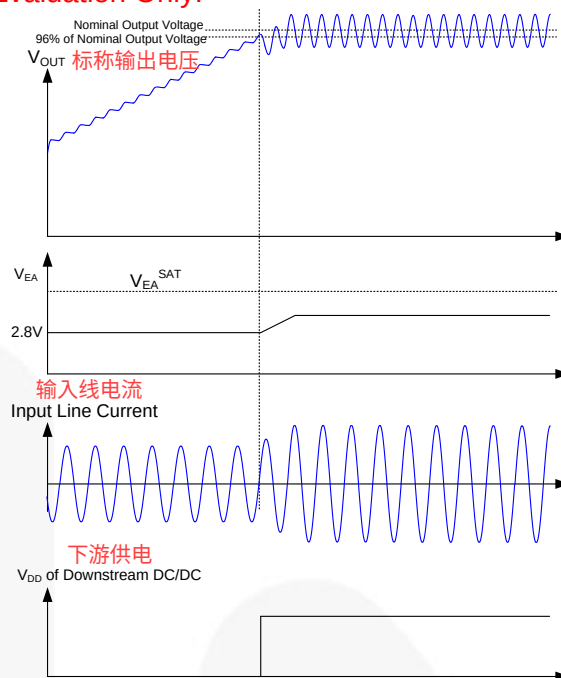


图12. PFC软启动

设计依据

本节展示是设计步骤，使用图13中的原理图作为参考。
。选择通用输入范围350W
PFC电源应用作为设计示例。有关设计规格的总结可参见表1。

表1. 设计规格

掉电保护线路电压	72V _{AC}
线路电压范围	85~264V _{AC}
交流输入电压频率	f _{line} = 50 ~ 60Hz
标称PFC输出电压	V _{BOUT} = 387V
保持时间内的最小PFC输出电压	310V
保持时间	t _{HLD} = 20ms
额定输出功率	P _{OUT} = 350W
效率	η = 0.94
开关频率	f _{SW} = 65KHz
PFC电感纹波电流	满载时最大Δ I _L 为平均电感电流的50%
PFC输出电压纹波	12V _{PP}

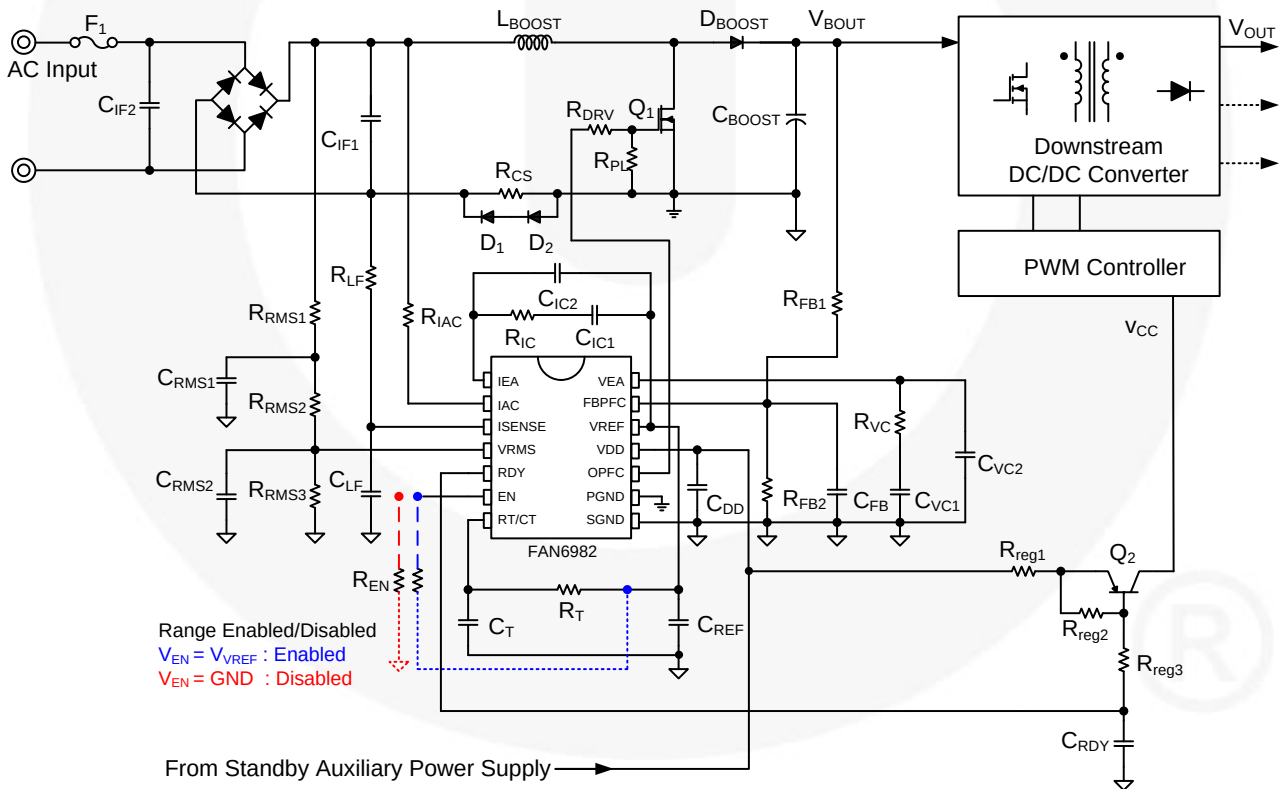


图13. 设计示例的参考电路

[步骤-1] 频率设置

开关频率由定时电阻和电容确定 (R_T 和 C_T)，如下所示：

$$f_{SW} \cong \frac{1}{0.56 \cdot R_T \cdot C_T} \quad (8)$$

定时电容值确定PFC栅极驱动信号的最大占空比，如下所示：

$$D_{MAX.PFC} = 1 - \frac{t_{DEAD}}{t_{SW}} = 1 - 360 \cdot C_T \cdot f_{SW} \quad (9)$$

对于50~75kHz开关频率，通常使用470pF~1nF电容，以便获得99~98%的最大占空比。

(设计示例) 由于开关频率为65kHz， C_T 选用1nF以获得最大占空比，如下所示：

$$D_{MAX.PFC} = 1 - 360 \cdot C_T \cdot f_{SW} = 0.98$$

随后，定时电阻可由下式确定：

$$R_T = \frac{1}{0.56 f_{SW} C_T} = 27k\Omega$$

[步骤-2] 线路检测电路设计

FAN6982使用VRMS和IAC引脚分别感测线路电压的RMS值和瞬时值，如图14所示。线路电压的RMS值通过平均电路获取，该电路使用低通滤波器，有两个极点。同时，感测流过IAC引脚的电流（通过 R_{IAC} 进行感测）便可获得瞬时线路电压信息。

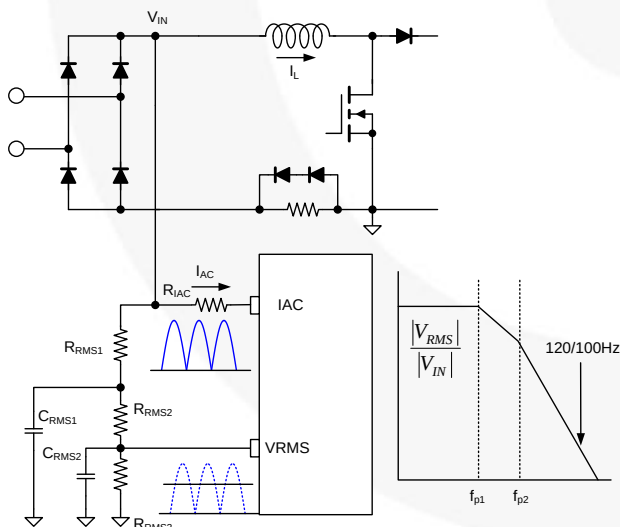


图14. 线路感测电路

RMS感测电路设计时应考虑线路电压的标称工作范围以及掉点保护跳变点，如下所示：

$$V_{RMS-UVL} = V_{LINE.BO} \frac{\sqrt{2}R_{RMS3}}{R_{RMS1} + R_{RMS2} + R_{RMS3}} \cdot \frac{2}{\pi} \quad (10)$$

$$V_{RMS-UVH} < V_{LINE.MIN} \frac{\sqrt{2}R_{RMS3}}{R_{RMS1} + R_{RMS2} + R_{RMS3}} \quad (11)$$

其中， $V_{RMS-UVL}$ 和 $V_{RMS-UVH}$ 是 V_{RMS} 的掉电/通电阈值。

通常将 R_{RMS2} 设为 R_{RMS1} 的10%。低通滤波器的极点如下所示：

$$f_{P1} \cong \frac{1}{2\pi \cdot C_{RMS1} \cdot R_{RMS2}} \quad (12)$$

$$f_{P2} \cong \frac{1}{2\pi \cdot C_{RMS2} \cdot R_{RMS3}} \quad (13)$$

为了正确衰减 V_{RMS} 中两倍的线路频率纹波，通常将极点设为10~20Hz左右。

电阻 R_{IAC} 应当足够大，以防增益调制器饱和，如下所示：

$$\frac{\sqrt{2}V_{LINE.BO}}{R_{IAC}} \cdot G^{MAX} < 159\mu A \quad (14)$$

其中， $V_{LINE.BO}$ 是掉电保护线路电压， G^{MAX} 是最大调制器增益，此时 V_{RMS} 为1.08V（通常为9，如数据手册中所示），并且159 μ A为增益调制器的最大输出电流。

(设计示例) 掉电保护阈值分别为1.05V ($V_{RMS-UVL}$) 和1.9V ($V_{RMS-UVH}$)。那么，分压器按比例缩小的因数可由下式计算得出：

$$\begin{aligned} \frac{R_{RMS3}}{R_{RMS1} + R_{RMS2} + R_{RMS3}} &= \frac{V_{RMS-UVL}}{V_{LINE.BO}} \cdot \frac{\pi}{2\sqrt{2}} \\ &= \frac{1.05}{72} \cdot \frac{\pi}{2\sqrt{2}} = 0.0162 \end{aligned}$$

PFC控制器在最小线路电压时的启动检查如下式所示：

$$\frac{V_{LINE.MIN} \cdot \sqrt{2}R_{RMS3}}{R_{RMS1} + R_{RMS2} + R_{RMS3}} = 85 \cdot \sqrt{2} \cdot 0.0162 = 1.95 > 1.9V$$

分压器网络电阻选用 $R_{RMS1}=2M\Omega$ 、 $R_{RMS2}=200k\Omega$ 以及 $R_{RMS3}=36k\Omega$ 。

要在15Hz和22Hz处设置低通滤波器极点，电容可由下式获得：

$$C_{RMS1} = \frac{1}{2\pi \cdot f_{P1} \cdot R_{RMS2}} = \frac{1}{2\pi \cdot 15 \cdot 200 \times 10^3} = 53nF$$

$$C_{RMS2} \cong \frac{1}{2\pi \cdot f_{P2} \cdot R_{RMS3}} = \frac{1}{2\pi \cdot 22 \cdot 36 \times 10^3} = 200nF$$

电阻 R_{IAC} 需满足的条件：

$$R_{IAC} > \frac{\sqrt{2}V_{LINE.BO}}{159 \times 10^{-6}} \cdot G^{MAX} = \frac{\sqrt{2} \cdot 72 \cdot 9}{159 \times 10^{-6}} = 5.8M\Omega$$

因此， ΩR_{IAC} 电阻值选择6M。

[步骤-3] PFC电感设计

峰值线路电压时升压开关的占空比可由下式确定：

$$D_{LP} = \frac{V_{BOUT} - \sqrt{2}V_{LINE}}{V_{BOUT}} \quad (15)$$

那么，峰值线路电压时升压电感的电流纹波可由下式确定：

$$\Delta I_L = \frac{\sqrt{2}V_{LINE}}{L_{BOOST}} \cdot \frac{V_{BOUT} - \sqrt{2}V_{LINE}}{V_{BOUT}} \cdot \frac{1}{f_{SW}} \quad (16)$$

峰值线路电压时上一个开关周期内升压电感的平均电流可由下式确定：

$$I_{L,AVG} = \frac{\sqrt{2}P_{OUT}}{V_{LINE} \cdot \eta} \quad (17)$$

纹波系数 (K_{RF}) 以及峰值线路电压负载下电感电流纹波和平均电感电流之比可由计算得出：

$$K_{RF} = \frac{\Delta I_L}{I_{L,AVG}} = \frac{\eta \cdot V_{LINE}^2}{P_{OUT} \cdot L_{BOOST}} \cdot \frac{V_{BOUT} - \sqrt{2}V_{LINE}}{V_{BOUT}} \cdot \frac{1}{f_{SW}} \quad (18)$$

如图15所示，线路电压为以下数值时，纹波系数达到最大值：

$$V_{LINE,MRF} = \frac{\sqrt{2}V_{BOUT}}{3} \quad (19)$$

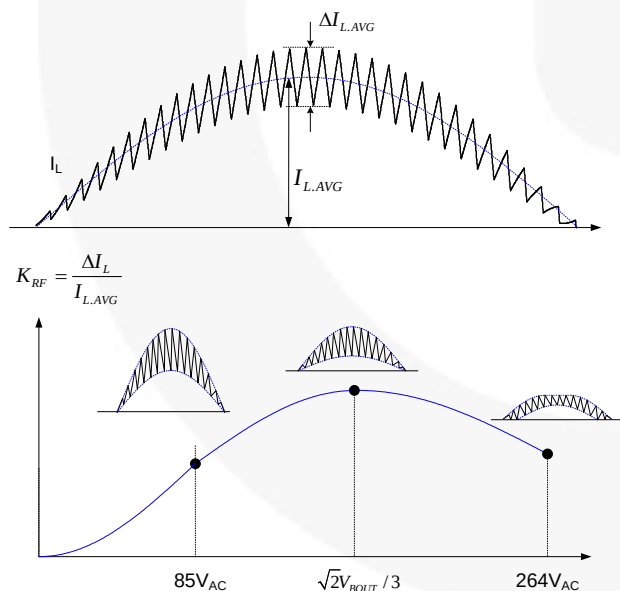


图15. 不同线路电压的纹波系数

因此，对于给定的电流纹波系数 ($K_{RF} = \Delta I_L / I_{L,AVG}$)，升压电感值可由下式获得：

$$L_{BOOST} = \frac{2V_{BOUT}^2 \cdot \eta}{K_{RF} \cdot P_{OUT}} \cdot \frac{1}{27f_{SW}} \quad (20)$$

(设计示例) 在线路电压时，最大纹波系数由下式确定：

$$V_{LINE} = \frac{\sqrt{2}V_{BOUT}}{3} = \frac{\sqrt{2} \cdot 387}{3} = 182V_{AC}$$

若纹波电流规格为50%，则升压电感可由下式获得：

$$L_{BOOST} = \frac{2V_{BOUT}^2 \cdot \eta}{K_{RF} \cdot P_{OUT}} \cdot \frac{1}{27f_{SW}} = \frac{2 \cdot 387^2 \cdot 0.94}{0.5 \cdot 350} \cdot \frac{1}{27 \cdot 65 \times 10^3} = 916\mu H$$

低压线路时的电感电流纹波可由下式计算得出：

$$\Delta I_L = \frac{\sqrt{2}V_{LINE}}{L_{BOOST}} \cdot \frac{V_{BOUT} - \sqrt{2}V_{LINE}}{V_{BOUT}} \cdot \frac{1}{f_{SW}} = \frac{\sqrt{2} \cdot 85}{916 \times 10^{-6}} \cdot \frac{387 - \sqrt{2} \cdot 85}{387} \cdot \frac{1}{65 \times 10^3} = 1.39A$$

低压线路时的峰值线路电压平均电感电流可由下式计算得出：

$$I_{L,AVG} = \frac{\sqrt{2}P_{OUT}}{V_{LINE,MIN} \cdot \eta} = \frac{\sqrt{2} \cdot 350}{85 \cdot 0.94} = 6.19A$$

低压线路时的最大电感电流可由下式计算得出：

$$I_L^{PK} = I_{L,AVG} + \Delta I_L / 2 = 6.19 + 1.39 / 2 = 6.89A$$

[步骤-4] PFC输出电容选型

选择PFC输出电容时，需考虑输出电压纹波。图16显示的是输出电压上的两倍线路频率纹波。考虑到输出纹波的特性，输出电容值可由下式计算：

$$C_{BOUT} > \frac{I_{BOUT}}{2\pi \cdot f_{LINE} \cdot V_{BOUT, RIPPLe}} \quad (21)$$

其中， I_{BOUT} 是升压PFC级的标称输出电流， $V_{BOUT, RIPPLe}$ 是峰峰值输出电压纹波规格。

确定输出电容时，还应考虑保持时间，如下式所示：

$$C_{BOUT} > \frac{2P_{OUT} \cdot t_{HOLD}}{V_{BOUT}^2 - V_{BOUT, MIN}^2} \quad (22)$$

其中， P_{OUT} 是升压PFC级的标称输出功率， t_{HOLD} 是所需的保持时间， $V_{BOUT, MIN}$ 是保持时间内允许的最小PFC输出电压。

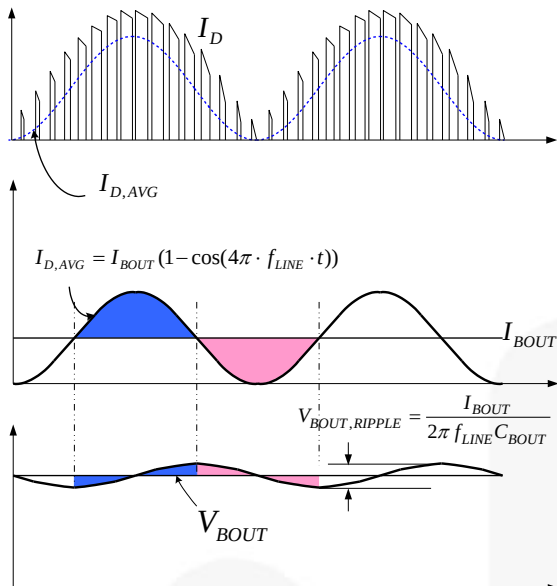


图16. PFC输出电压纹波

(设计示例) 纹波规格为12V_{PP}, 则电容应当为:

$$C_{BOUT} > \frac{I_{BOUT}}{2\pi \cdot f_{LINE} \cdot V_{BOUT,RIPPLE}} = \frac{0.9}{2\pi \cdot 50 \cdot 12} = 239\mu F$$

由于一个线路压降周期(20ms)内的最小允许输出电压为310V, 电容应当为:

$$C_{BOUT} > \frac{2P_{BOUT} \cdot t_{HOLD}}{V_{OUT}^2 - V_{OUT,MIN}^2} = \frac{2 \cdot 349 \cdot 20 \times 10^{-3}}{387^2 - 310^2} = 260\mu F$$

因此, PFC输出电容选用270μF。

[步骤-5] PFC输出感测电路

为了在低线路电压和轻负载条件下提高系统效率, FAN6982提供两级PFC输出电压。如图17所示, 范围功能可通过连接地或VREF的电阻使能或禁用。FAN6982监控V_{EA}和V_{RMS}电压, 调节PFC输出电压并使能20μA电流源。

20μA使能时PFC输出电压由下式给出:

$$V_{BOUT2} = V_{BOUT} \times \left(1 - \frac{20\mu A \times R_{FB2}}{2.5}\right) \quad (23)$$

通常将第二个升压输出电压设为340V~300V。应当检查输出电压是否高于峰值线路电压

$$\frac{R_{RMS1} + R_{RMS2} + R_{RMS3}}{R_{RMS3}} \cdot \frac{\pi}{2} \cdot 2.45 < V_{BOUT2} \quad (24)$$

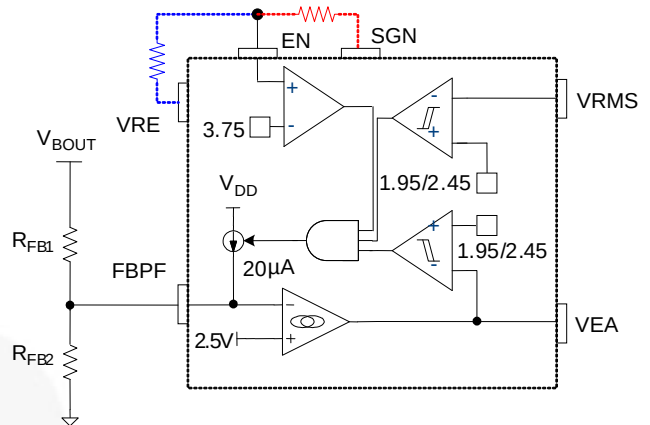


图17. 范围功能模块

用于PFC输出电压感测的分压网络应设计为FBPF在标称PFC输出电压情况下等于2.5V:

$$V_{BOUT} \times \frac{R_{FB2}}{R_{FB1} + R_{FB2}} = 2.5V \quad (25)$$

(设计示例) 假定第二级PFC输出电压为347V:

$$\begin{aligned} R_{FB2} &= \left(1 - \frac{V_{BOUT2}}{V_{BOUT}}\right) \cdot \frac{2.5}{20 \times 10^{-6}} \\ &= \left(1 - \frac{347}{387}\right) \cdot \frac{2.5}{20 \times 10^{-6}} = 12.9k\Omega \end{aligned}$$

ΩR_{FB2}选用13k。

需检查输出电压是否高于峰值线路电压:

$$\begin{aligned} &\frac{R_{RMS1} + R_{RMS2} + R_{RMS3}}{R_{RMS3}} \cdot \frac{\pi}{2} \cdot 2.45 \\ &= \frac{2 \times 10^6 + 200 \times 10^3 + 36 \times 10^3}{36 \times 10^3} \cdot \frac{\pi}{2} \cdot 2.45 \\ &= 239V < 347V \end{aligned}$$

其次, 标称PFC输出要实现387V,

$$\begin{aligned} R_{FB1} &= \left(\frac{V_{BOUT}}{2.5} - 1\right) \cdot R_{FB2} \\ &= \left(\frac{387}{2.5} - 1\right) \cdot 13 \times 10^3 = 1999k\Omega \end{aligned}$$

ΩR_{FB1}选用2M。

(b)

计算处于交叉频率时使闭环增益成为单位增益的 R_{IC} 值：

$$R_{IC} = \frac{1}{G_{MI} \cdot \left| \frac{\hat{V}_{CS}}{\hat{V}_{IEA}} \right| @ f=f_{IC}} \quad (33)$$

(c)

由于处于交叉频率时功率级的控制到输出传递函数具有 -20dB/dec 的斜率和 -90° 的相位(0dB , 如图19所示), 因此有必要将补偿网络(f_{IZ})的零点设为交叉频率的 $1/3$ 左右, 以便获得大于 45° 的相位裕量。然后, 电容 C_{IC1} 可由下式确定:

$$C_{IC1} = \frac{1}{R_{IC} \cdot 2\pi f_C / 3} \quad (34)$$

(d) 将补偿器高频极点(f_{IP})设为至少高于 f_{IC} 10个数量级, 以确保在处于其交叉频率时不会干扰电流环路的相位裕量。

$$C_{IC2} = \frac{1}{2\pi \cdot f_{IP} \cdot R_{IC}} \quad (35)$$

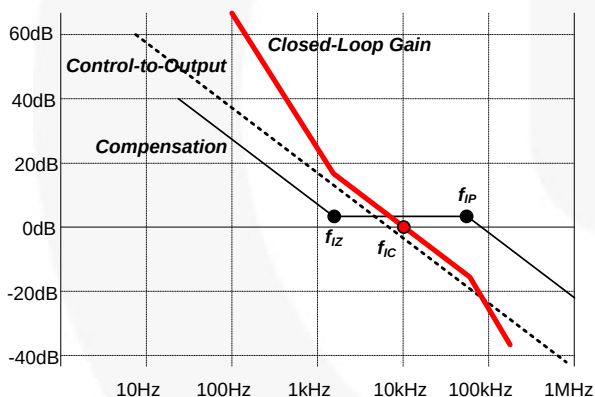


图19. 电流环路补偿

$$C_{IC1} = \frac{1}{R_{IC} \cdot 2\pi f_C / 3} = \frac{1}{26 \times 10^3 \cdot 2\pi \cdot 6 \times 10^3 / 3} = 3.1\text{nF}$$

将补偿器的极点设为 60kHz ,

$$C_{IC2} = \frac{1}{2\pi \cdot f_{IP} \cdot R_{IC}} = \frac{1}{2\pi \cdot 60 \times 10^3 \cdot 26 \times 10^3} = 0.10\text{nF}$$

实际元件值与现成元件值略有不同:

$R_{IC}=27\text{k}\Omega$, $C_{IC1}=3.3\text{nF}$, $C_{IC2}=100\text{pF}$ 。

[步骤-9] PFC电压环路设计

由于FAN6982具有线路前馈功能, 因此电源级传递函数与线路电压无关。则低频、小信号、控制至输出的传递函数为:

$$\frac{\hat{V}_{BOUT}}{\hat{V}_{EA}} \approx \frac{I_{BOUT} \cdot K_{MAX}}{5} \cdot \frac{1}{sC_{BOUT}} \quad (36)$$

其中, $K_{MAX} = P_{OUT}^{MAX} / P_{OUT}$ 和 5V 是误差放大器的控制窗口 ($5.6\text{V}-0.6\text{V}=5\text{V}$)。

带有高频极点的比例与积分 (PI) 控制通常用于补偿。补偿零点(f_{VZ})可使相位增加, 而高频补偿极点(f_{VP})可使开关纹波衰减, 如图20所示。

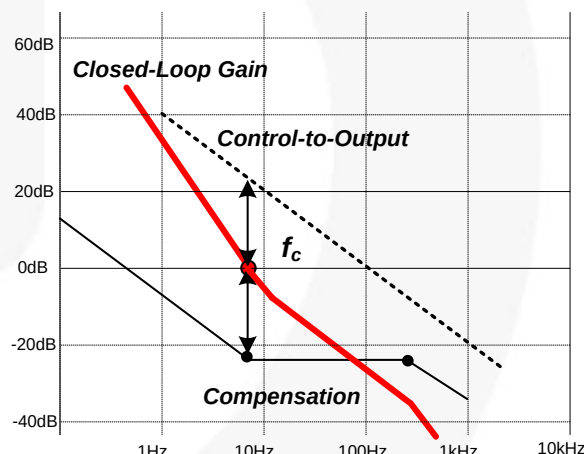


图20. 电压环路补偿

(设计示例) 将交叉频率设为 6kHz

(开关频率的 $1/10$ 左右):

$$\begin{aligned} \left| \frac{\hat{V}_{CS1}}{\hat{V}_{IEA}} \right| @ f=f_{IC} &= \frac{R_{CS} \cdot V_{BOUT}}{V_{RAMP} \cdot 2\pi f_{IC} \cdot L_{BOOST}} \\ &= \frac{0.1 \cdot 387}{2.55 \cdot 2\pi \cdot 6 \times 10^3 \cdot 916 \times 10^{-6}} = 0.44 \\ R_{IC} &= \frac{1}{G_{MI} \cdot \left| \frac{\hat{V}_{CS}}{\hat{V}_{IEA}} \right| @ f=f_{IC}} = \frac{1}{88 \times 10^{-6} \cdot 0.44} = 26\text{k}\Omega \end{aligned}$$

补偿网络的传递函数为:

$$\frac{\hat{V}_{COMP}}{\hat{V}_{OUT}} = \frac{2\pi f_{VI}}{s} \cdot \frac{1 + \frac{s}{2\pi f_{VZ}}}{1 + \frac{s}{2\pi f_{VP}}} \quad (37)$$

其中:

$$\begin{aligned} f_{VI} &= \frac{2.5}{V_{BOUT}} \cdot \frac{G_{MV}}{2\pi \cdot C_{VC1}}, \quad f_{VZ} = \frac{1}{2\pi \cdot R_{VC} \cdot C_{VC1}} \quad \text{and} \\ f_{VP} &= \frac{1}{2\pi \cdot R_{VC} \cdot C_{VC2}} \end{aligned} \quad (38)$$

设计反馈回路的步骤如下所示:

- (a) 确定约为开关频率1/10~1/5的线路频率(f_{vc})。由于处于交叉频率时功率级的控制到输出传递函数具有-20dB/dec的斜率和-90°的相位(0图20dB, 如所示), 因此有必要将补偿网络(f_{vz})的零点设为交叉频率左

(设计示例) 将交叉频率设为22Hz:

$$C_{VC1} = \frac{G_{MV} \cdot I_{BOUT} \cdot K_{MAX}}{5 \cdot C_{BOUT} \cdot (2\pi f_{VC})^2} \cdot \frac{2.5}{V_{BOUT}} = \frac{70 \times 10^{-6} \cdot 0.9 \cdot 1.27}{5 \cdot 270 \times 10^{-6} \cdot (2\pi \cdot 22)^2} \cdot \frac{2.5}{387} = 20nF$$

$$R_{VC} = \frac{1}{2\pi \cdot f_{VC} \cdot C_{VC1}} = \frac{1}{2\pi \cdot 22 \cdot 20 \times 10^{-9}} = 362k\Omega$$

将补偿器的极点设为120Hz:

$$C_{VC2} = \frac{1}{2\pi \cdot f_{VP} \cdot R_{VC}} = \frac{1}{2\pi \cdot 120 \cdot 362 \times 10^3} = 3.7nF$$

右, 以便获得大于45°的相位裕量。然后, 电容 C_{VC1} 可由下式确定:

$$C_{VC1} = \frac{G_{MV} \cdot I_{BOUT} \cdot K_{MAX}}{5 \cdot C_{BOUT} \cdot (2\pi f_{VC})^2} \cdot \frac{2.5}{V_{BOUT}} \quad (39)$$

其中, G_{MV} 是跨导误差放大器的增益, 用于输出电压调节。

在截止频率处设置补偿零点, 补偿电阻为:

$$R_{VC} = \frac{1}{2\pi \cdot f_{VC} \cdot C_{VC1}} \quad (40)$$

- (b) 将补偿器高频极点(f_{VP})设为至少高于 f_c 10个数量级, 确保在处于其交叉频率时不会干扰电压调节环路的相位裕量。它还应当远低于转换器的频率, 以便有效衰减噪声。然后, 电容 C_{VC2} 可由下式确定:

$$C_{VC2} = \frac{1}{2\pi \cdot f_{VP} \cdot R_{VC}} \quad (41)$$

1. 设计总结

应用	输出功率	输入电压	输出电压/输出电流
PFC电源	350W	85~264V _{AC}	387V/0.9A

特性

- 增益调制器的开关充电技术可提供更佳的PF和更低的THD
- 过压保护(OVP)、欠压保护(UVP)、开环保护(OLP)和最大限流保护
- 范围功能可提高低交流线路电压和轻负载条件下的系统效率
- 引脚就绪功能为下游转换器提供上电时序

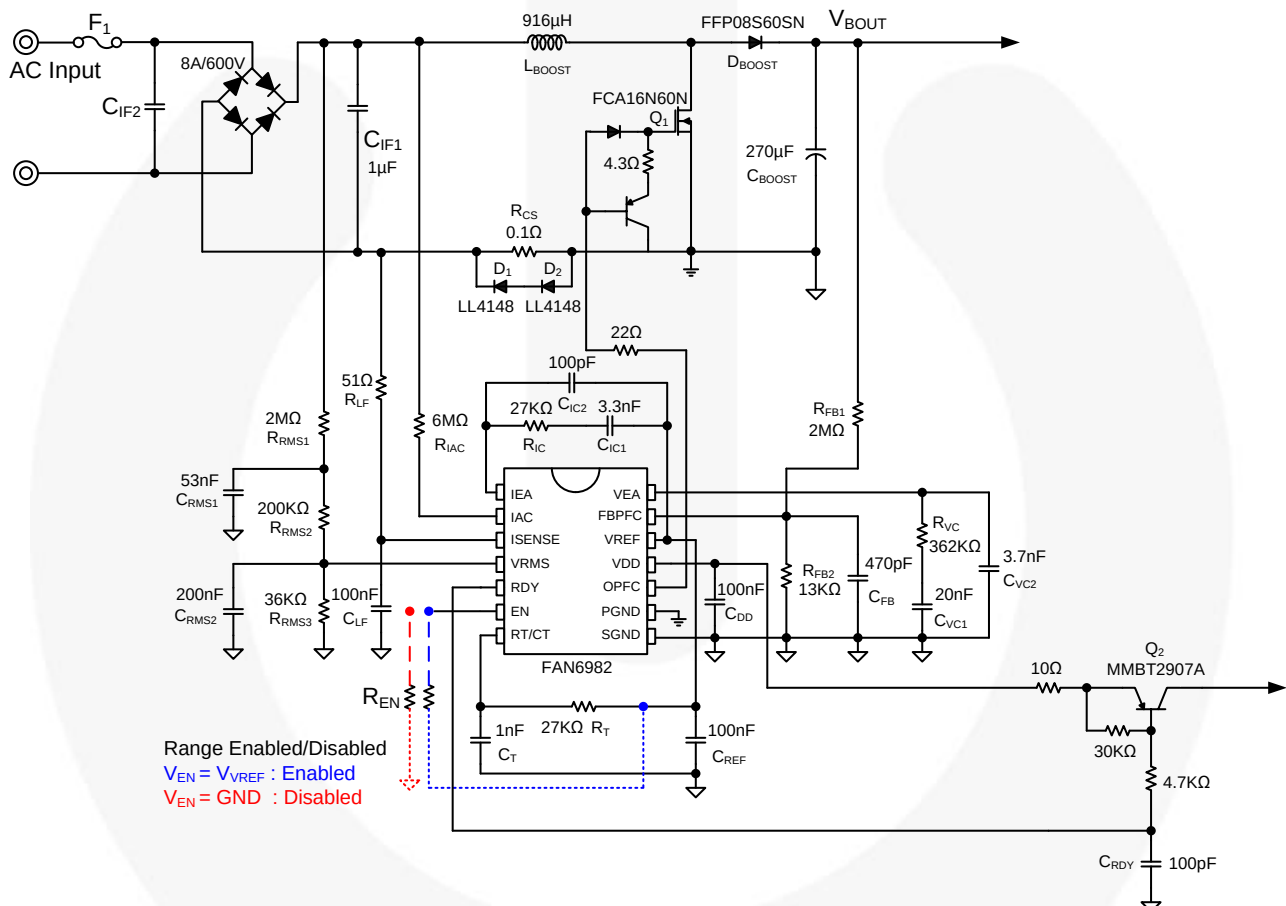


图21. 最终设计范例的原理图

附录A

MOSFET和二极管参考规格

PFC MOSFET	
电压额定值	器件编号
500V	FQP13N50C, FQPF13N50C, FDP18N50, FDPF18N50, FDA18N50, FDP20N50(T), FDPF20N50(T)
600V	FCP11N60, FCPF11N60, FCP16N60, FCPF16N60, FCP20N60S, FCPF20N60S, FCA20N60S, FCP20N60, FCPF20N60
升压二极管	
600V	FFP08H60S, FFPF10H60S, FFP08S60S, FPF08S60SN, BYC10600

参考文献

[FAN6982 - CCM功率因数校正控制器](#)

[AN-8027 - FAN480X PFC+PWM组合控制器应用](#)

[AN-6004 - 采用FAN4810的500W功率因数校正 \(PFC\) 设计](#)

[AN-6032 - FAN4800组合控制器应用](#)

[AN-42009 - ML4824组合控制器应用](#)

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