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AN-8025

採用FAN7530 LED照明用單級反激式AC-DC轉換器的設計指南

摘要

本使用手冊講述了LED照明用75W通用輸入單級功率因數校正 (PFC) 的工作原理，並提供了相應的設計指南。採用反激式變換器的拓撲，選擇臨界導通模式控制晶片 FAN7530。多重功能專門用於LED照明應用場合，例如，CV/CC模式回授電路、逐周期電流限制、軟啟動功能，等等。

簡介

儘管具有較大的輸出電壓漣波，但是從成本與功率密度的角度考量，較之兩級轉換，單級AC-DC轉換是一種頗有吸引力的解決方案，尤其在諸如電池充電器、等離子顯示幕(PDP)-持續電源、LED照明等應用場合更為如此。較大的低頻（100Hz或120Hz）輸出電壓漣波影響有限。

單級AC-DC轉換器能夠直接將交流輸入電壓轉換為直流輸出電壓，無需透過預調整器，如圖1所示。

本使用手冊推介了一種LED照明用75W單級AC-DC轉換器。作為一種電力變換拓撲，反激式轉換器通常為首選，因為這種轉換器不需要感性輸出濾波。主變壓器本身就是有感濾波器。

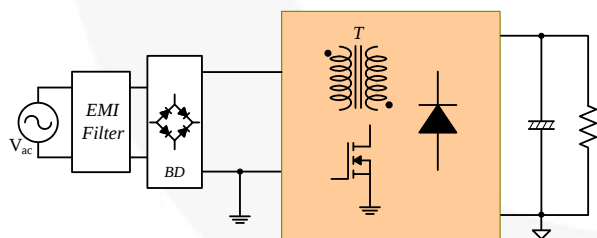


圖1 單級AC-DC轉換器

圖2為反激式AC-DC轉換器的電路圖。FAN7530作為控制器，採用CV(恒壓)與CC(恒流)模式回授電路，可以防止出現超載和過壓。對於LED照明，輸出始終處於滿載狀態。如果結溫上升，LED的正向壓降減少。因此，在正常狀態下，輸出應該受控於CC模式，CV模式僅用於過壓保護狀態。

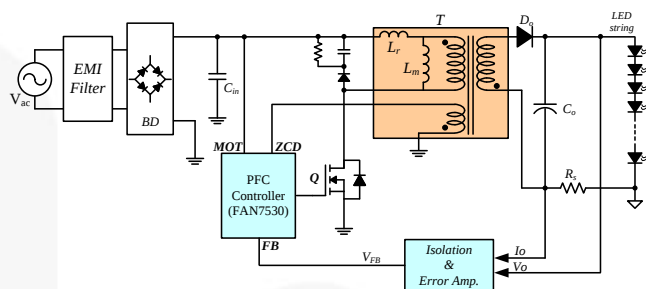


圖2 反激式AC-DC轉換器

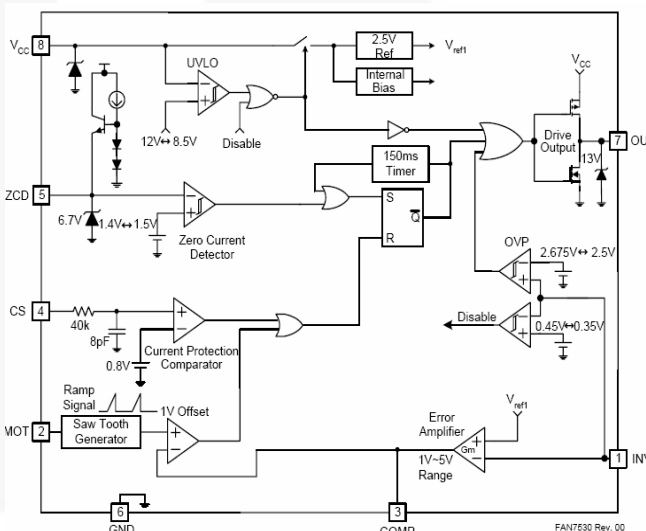


圖3 FAN7530方塊圖

圖3所示為FAN7530的框圖，其主要特徵為：

- 固定導通時間的CRM PFC控制器
- 零電流檢測（ZCS）與低谷切換
- MOSFET過電流保護
- 低啟動電流(40μA)和低工作電流 (1.5mA)
- 高態鉗位的圖騰柱輸出
- +500/-800mA 閘極驅動峰值電流

FAN7530為電壓模式CRM PFC控制器。穩態時，開關的導通時間固定不變，但是關斷時間是變化的。因而，輸入電壓變化時，開關頻率改變，如圖4所示。

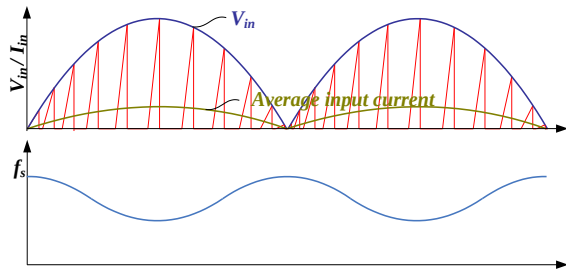


圖4 開關頻率變化

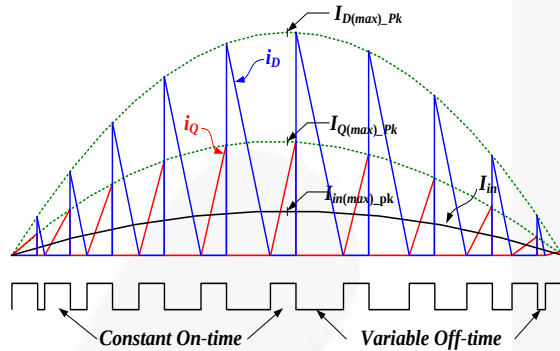


圖5 理論波形

圖5例舉了初級側開關電流、次級側二極體電流以及閘極驅動信號的理論波形。在零電流條件下，快速恢復二極體（FRD） D_o 關斷，MOSFET Q開通。Q關斷， D_o 在硬切換條件下開通。

設計範例

以下為75W單級反激式AC-DC轉換器的設計指南。應用的系統參數如表1所示。

表1 系統參數

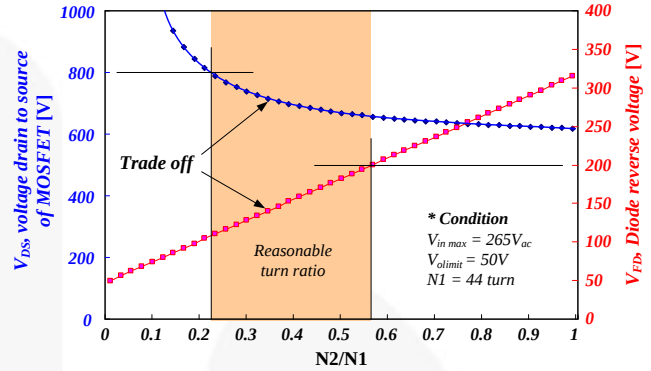
參數	取值
輸出功率	75W
輸入電壓範圍	85~265V _{AC}
輸出電壓	45V
輸出限制電壓	50V
$I_{in(max)}_{pk}$ 時工作比, $D@I_{in(max)}_{pk}$	0.6
最小開關頻率, $f_{s_min}@V_{in_min}$	50kHz
效率, η	85%

1. 反激式變壓器設計

對於反激式轉換器，變壓器很容易飽和，原因在於變壓器只能在B-H環的第一象限得到利用。此外，如若工作在臨界導通模式，其峰值電流將大大高於連續導通模式時的峰值電流。鑒於此，磁路應該加入氣隙，防止變壓器進入飽和。

對於反激式單級AC-DC轉換器，應該選擇合適的圈比 N_1/N_2 。這是因為MOSFET與快速恢復二極體（FRD）

的最大電壓與變壓器圈比密切相關。MOSFET的漏-源電壓幅度 V_{dss} 與FRD的反向電壓幅度 V_R 之間存在折中關係，依賴於變壓器的圈比。圈比 (N_2/N_1) 時較大，要求FRD的 V_R 較高，MOSFET的 V_{dss} 較低。相反，圈比較小時，要求MOSFET的電壓應力較高，FRD的 V_R 較低。圖6給出了MOSFET的 V_{dss} 與FRD的 V_R 之間的折中關係。

圖6 V_{DS} 與 V_R 之間的折中

因 $P_o = \eta V_{in} I_{in}$ ，所以最大電源電流 $I_{in(max)} = P_o / \eta V_{in(min)}$ 。鑒於開關頻率遠遠高於交流電源頻率 f_{ac} ，可以假定在一個開關週期之內輸入電流恒定不變。

如需確定變壓器的勵磁電感，必須首先確定最長開關週期。最長開關週期一般出現在施加最小輸入電壓時的輸入電流峰值 $I_{in(max)}_{pk}$ 點，可使用下列算式：

$$I_{in(max)}_{pk} = \frac{1}{T} \int_0^{DT} \frac{I_{Q(max)}_{pk}}{DT} t dt = \frac{DI_{Q(max)}_{pk}}{2} \quad (1)$$

$$I_{Q(max)}_{pk} = \frac{2}{D} I_{in(max)}_{pk} \quad (2)$$

其中 $D = D@I_{in(max)}_{pk}$ 、 $I_{in(max)}_{pk} = \sqrt{2} I_{in(max)}$ 、且 $V_{in(min)}_{pk} = \sqrt{2} V_{in(min)}$ 。

變壓器初級側電壓 V_T 為：

$$V_T = L_m \frac{\Delta I}{\Delta T} = L_m \frac{I_{Q(max)}_{pk} f_{s(min)}}{D@I_{in(max)}_{pk}} \quad (3)$$

勵磁電感值的算式為：

$$L_m \geq \frac{D@I_{in(max)}_{pk}^2 \cdot V_{in(min)}}{2 I_{in(max)} f_{s(min)}} = \frac{0.6^2 \times 85}{2 \times 1.04 \times 50 \times 10^3} \quad (4)$$

$$= 294.8 \mu H$$

依據式(5)和表1，勵磁電感計算值為294 μ H。

可以採用有多種方法確定圈數，以獲得期望電感值，最大磁通密度法是其中最為通用和簡易的方法。可以按下式得到最少匝數。

$$N \geq \frac{L_m \cdot I_{Q(max)}_{pk}}{B_m \cdot Ae} = \frac{2 \cdot L_m \cdot I_{in(max)}_{pk}}{B_m \cdot Ae \cdot D@I_{in(max)}_{pk}} \quad (6)$$

B_m 為磁性材料的最大飽和磁場強度，根據磁性材料的不同，取值範圍在0.3~0.4T之間， A_e 為磁芯的有效截面積。

採用EER3435， A_e 值為107mm²， B_m 選0.36T，計算得到的初級圈數計算值為44.5，設計時取44圈。

次級側圈數為17圈，其算式如下：

$$N_2 = \frac{\pi N_1 V_o (1 - D_{\max})}{2\sqrt{2} D_{\max} V_{in(\min)}} = \frac{\pi \times 44 \times 45 (1 - 0.6)}{2\sqrt{2} \times 0.6 \times 85} = 17 \quad (7)$$

2. MOSFET與FRD

MOSFET的電壓應力計算如下：

$$\begin{aligned} V_{ds(\max)} &= V_{in(\max)_pk} + V_{sn(\max)} \\ &= V_{in(\max)_pk} + V_f + V_{Lk} \end{aligned} \quad (8)$$

式中， V_{sn} 指緩衝電路的最大電容電壓， V_f 指反激電壓， V_{Lk} 指變壓器漏感的振盪電壓。 V_f 可以由 $N_1 V_o / N_2$ 導出， V_{Lk} 一般按反激電壓 V_f 的1.5倍估算。這樣可得MOSFET的最大電壓為：

$$\begin{aligned} V_{ds(\max)} &= \sqrt{2} V_{in(\max)} + 2.5 V_o = \sqrt{2} \times 265 \times 2.5 + \frac{44}{17} \times 45 \\ &= 665.94V \end{aligned} \quad (9)$$

最大電流有效值與電流峰值分別為：

$$I_{in(\max)} = \frac{P_o}{\eta V_{in(\min)}} = \frac{75}{0.85 \times 85} = 1.04A \quad (10)$$

和

$$I_{Q(\max)_pk} = \frac{2\sqrt{2} P_o}{\eta D_{@lin(\max)_pk} V_{in(\min)}} = \frac{2\sqrt{2} \times 75}{0.85 \times 0.6 \times 85} = 4.89A \quad (11)$$

因此，考量裕度後，選取N-溝道增強型MOSFET FQPF8N80C（800V，8A， $R_{DS_ON} = 1.55\Omega$ ）。

FRD的最大反向電壓與正向峰值電流分別為：

$$\begin{aligned} V_{R(\max)} &= V_{o_Limit} + \frac{N_2}{N_1} V_{in(\max)_pk} \\ &= 50 + \frac{17}{44} \times \sqrt{2} \times 265 = 195V \end{aligned} \quad (12)$$

$$I_{R_pk} = \frac{2}{(1 - D_{@lin(\max)_pk})} I_o = \frac{2}{(1 - 0.6)} \times \frac{75}{45} = 8.33A \quad (13)$$

因此，在考量裕度後，選取超快整流二極體(UFRD)，F06UP20S（200V，6A， $V_F = 1.15V$ ）。

3. 緩衝電路設計

對於反激式轉換器，在MOSFET關斷期間， L_{leak} 與 C_{oss} 之間的諧振會引起過電壓，導致MOSFET損壞。該電壓突波需要進行抑制，防止MOSFET被擊穿。

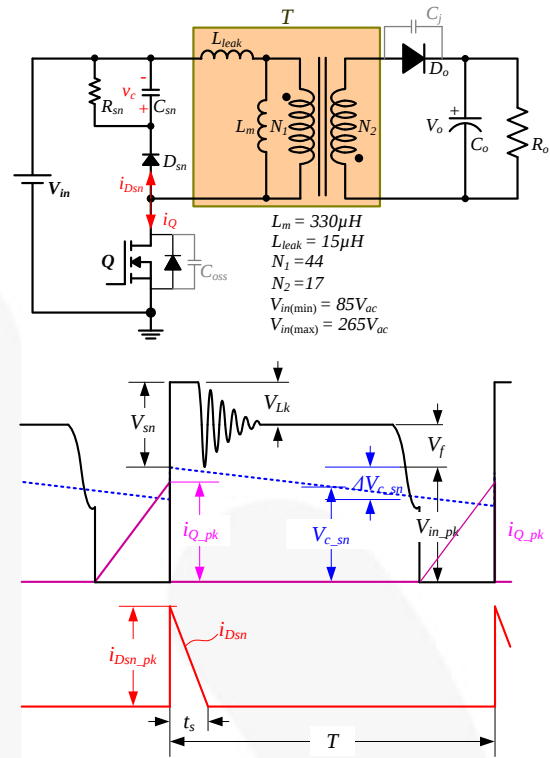


圖7 緩衝電路

緩衝器抑制的嵌位元電壓為：

$$V_{sn} = V_f + L_{leak} \frac{\Delta i}{\Delta t} = V_f + L_{leak} \frac{I_{Dsn_pk}}{t_s} \quad (14)$$

因而

$$t_s = \frac{L_{leak} \cdot I_{Dsn_pk}}{V_{sn} - V_f} \quad (15)$$

緩衝電路的最大功耗決定於：

$$P_{sn} = \frac{1}{T} \int_0^{t_s} V_{sn} \cdot \frac{I_{Dsn_pk}}{t_s} t dt = \frac{1}{2} L_{leak} I_{Dsn_pk}^2 \frac{V_{sn}}{V_{sn} - V_f} f_s \quad (16)$$

最大功率消耗為：

$$P_{sn(\max)} = \frac{1}{2} L_{leak} I_{Dsn_pk}^2 \frac{V_{sn}}{V_{sn} - V_f} f_{s@v_{in_max}} = \frac{V_{sn}^2}{R_{sn}} \quad (17)$$

式中， $V_{sn} = V_f + V_{Lr}$ 。

可得電阻 R_{sn} 為

$$R_{sn} = \frac{V_{sn}^2}{\frac{1}{2} L_{leak} I_{Dsn_pk}^2 \frac{V_{sn}}{V_{sn} - V_f} f_{s@v_{in_max}}} \quad (18)$$

可得緩衝電路的最大紋波電壓為：

$$\Delta V_{sn} = \frac{V_{sn}}{C_{sn} R_{sn} f_{s@v_{in_max}}} \quad (19)$$

緩衝電容量越大，電壓漣波越小，但是功率消耗增加。因此，選擇合適的緩衝電容十分重要。通常合理的設置為：緩衝電路的電壓突波 V_{sn} 為2~3倍的反激電壓 V_f ，紋波電壓 ΔV_c 為50V。在本應用手冊中，設置緩衝電壓

V_{sn} 為反激電壓的2.5倍。因此，緩存電阻與緩衝電容可分別由下式確定：

$$I_{Dsn_pk@V_{in}=265V} = \frac{2\sqrt{2}P_o}{\eta D_{min} V_{in}} = \frac{2\sqrt{2} \times 75}{0.85 \times 0.33 \times 265} = 2.85A \quad (20)$$

$$V_{sn} = V_f + V_{Lk} = 2.5V_f = 2.5 \times \frac{44}{17} \times 45 = 291.17V \quad (21)$$

$$t_s = \frac{L_{leak} \cdot I_{Dsn_pk}}{V_{sn} - V_f} = \frac{15 \times 10^{-6} \times 2.85}{291.17 - \frac{44}{17} \times 45} = 245.03nsec \quad (22)$$

$$f_{s@V_{in_max}} = \frac{D_{min} V_{sn}}{L_{m(measured)} I_{Dsn_pk@V_{in}=265V}} = \frac{0.33 \times 291.17}{330 \times 10^{-6} \times 2.85} = 102.03kHz \quad (23)$$

$$R_{sn} = \frac{1}{\frac{1}{2} \times 15\mu \times 2.85^2 \times \frac{291.17}{291.17 - (\frac{44}{17} \times 45)} \times 102.03k} = 8.16k\Omega \quad (24)$$

$$C_{sn} = \frac{V_{sn}}{\Delta V_{sn} R_{sn} f_{s@V_{in_max}}} = \frac{291.17}{50 \times 8.16k \times 102.03k} = 6.99nF \quad (25)$$

式中，最小工作比為：

$$D_{min} = \frac{V_o}{\frac{N_2}{N_1} V_{avg(max)} + V_o} = \frac{45}{\frac{17}{44} \times \left(\frac{2\sqrt{2}}{\pi} \times 265 \right) + 45} = 0.33 \quad (26)$$

即使 R_{sn} 計算值為8.16k Ω ，實際電阻取值也應該增加。阻值較小時，緩衝電路中功率消耗的預期過大。實際設計中，合理的選擇為：設置電阻值為計算值的兩倍。

4. 檢測電阻

FAN7530 的CS針腳可以限制電流峰值，在瞬態過程中或超載條件下，可以保護MOSFET。合理的電流限值為開關峰值電流的1.5倍。可得開關峰值電流的電流限值與檢測電阻分別為：

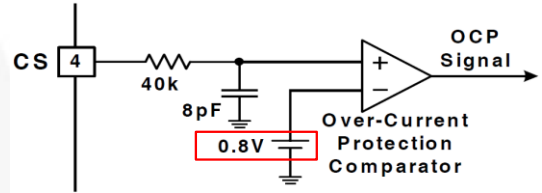
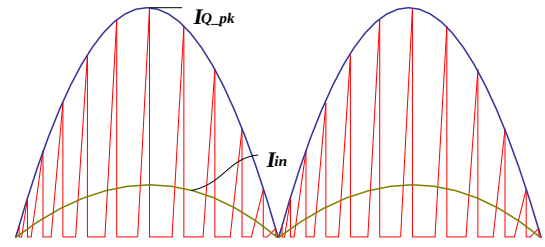


圖8 開關電流限值

$$I_{Q_Limit} = 1.5I_{Q(max)_pk} = 1.5 \times \frac{2}{D_{max}} \left(\sqrt{2} \frac{P_o}{\eta V_{in(min)}} \right) = 1.5 \times \frac{2}{0.6} \left(\sqrt{2} \frac{75}{0.85 \times 85} \right) = 7.4A \quad (27)$$

$$R_s \leq \frac{0.8}{I_{Q_Limit}} = \frac{0.8}{7.4} = 0.11\Omega \quad (28)$$

5. 軟啟動電路

鑒於FAN7530設計針對非隔離升壓PFC電路，因此需要增加一些外部電路。當FAN7530應用於非隔離升壓PFC電路時，內部的禁用放大器可以用於軟啟動功能，但若FAN7530應用於隔離升壓PFC電路時，該禁用放大器並無作用，因為針腳1的初始電壓為零，FAN7530不能啟動。為了防止該禁用放大器工作，需要通過阻斷二極體施加超過0.5V的電壓，如圖9(a)所示。

初始電壓 V_{FB} 的近似值如下：

$$V_{FB_initial} = \frac{R_1 R_{FB}}{R_{FB}(R_1 + R_2) + R_1 R_2} \cdot VCC \quad (29)$$

為防止過高的初始開關電流損壞MOSFET，有必要採取外部軟啟動功能。如圖9(b)所示，該電路可以使E/A的輸出電壓緩慢上升，結果使得導通時間漸增，轉換器能夠平滑啟動。

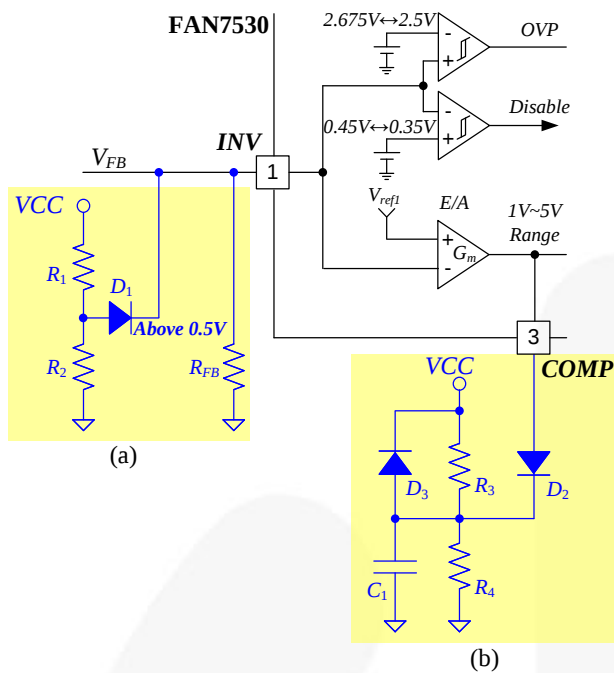


圖9 軟啟動電路

6. 電壓與電流回授

LED照明電源必須受控於恒流（CC）模式和恒壓（CV）模式。由於LED的正向壓降隨著結溫的增加而下降，導致電流劇烈增加，器件被損壞。

圖10為CC與CV模式回授電路的實例。在正常工作中，CC模式為主導。CV模式僅用於異常模式下的過電壓保護（OVP）。

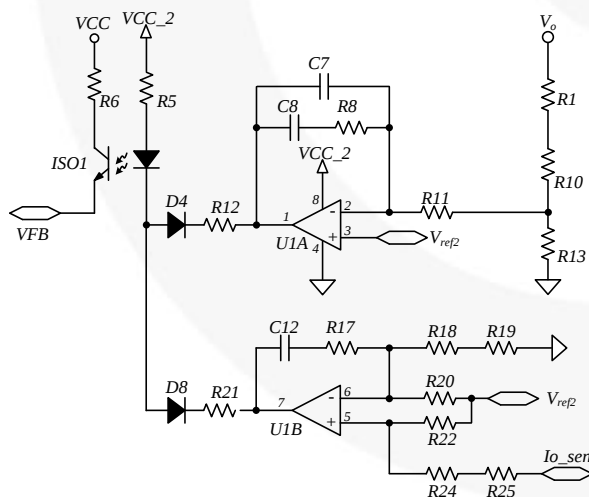


圖10 CC與CV回授電路的實例

實驗結果

為了驗證本使用手冊中設計指南的有效性，構建了原型測試電路並進行測試。關於設計參數與元件取值參見附錄。

圖11分別為輸入條件110V_{AC}和220V_{AC}時輸入電壓與電流波形。110V_{AC}和220V_{AC}時輸入功率因數的測量值分別為0.997與0.955。

圖12分別為開關電壓與電流波形。可見開關電流波形很好地跟蹤了輸入電壓波形。開關實現零電流條件下開通。

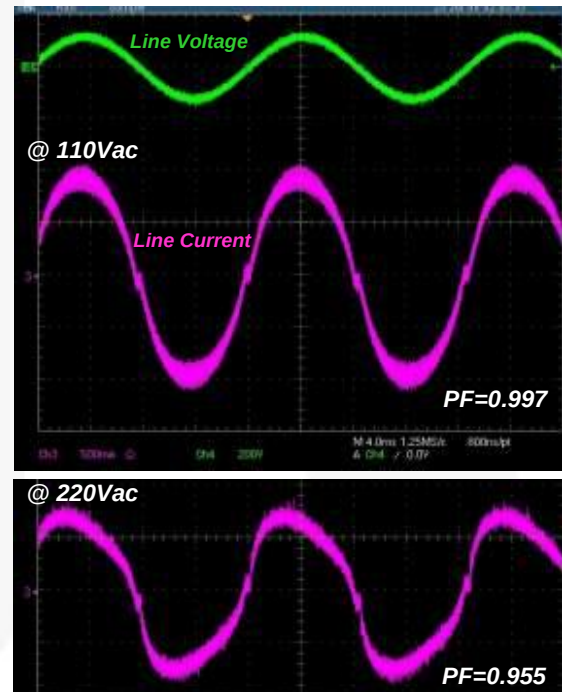


圖11 輸入電壓與電流

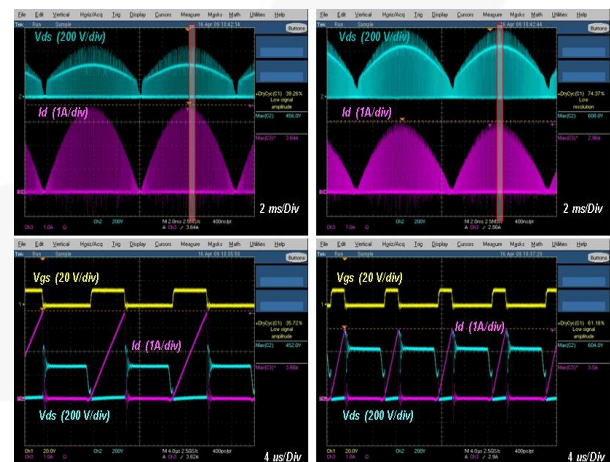
(a) 輸入 110 V_{ac} 時 (b) 輸入 220 V_{ac} 時

圖12 開關電壓與電流

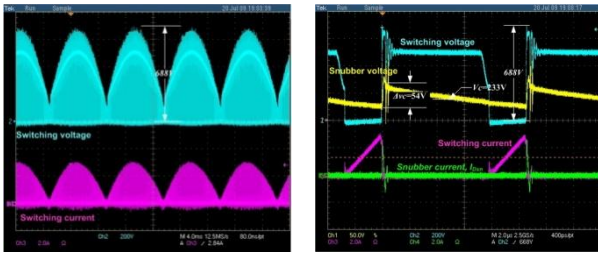
圖13 輸入條件265V_{AC}時漏-源電壓與開關電流

圖13為最高輸入電壓下，即輸入線路電壓265V_{AC}時漏-源電壓與電流波形。測得緩衝電路紋波電壓為54V，最大電壓應力為688V。鑒於最大電壓為688V，選取額定電壓800V的MOSFET，可以適應寬輸入電壓範圍。

輸入條件110 V_{ac} 與 220 V_{ac}時，根據負載的波動，繪製效率特性，如圖14所示。對於輸入電壓110 V_{ac} 和45W負載條件下，測得效率最大值為85.17%。

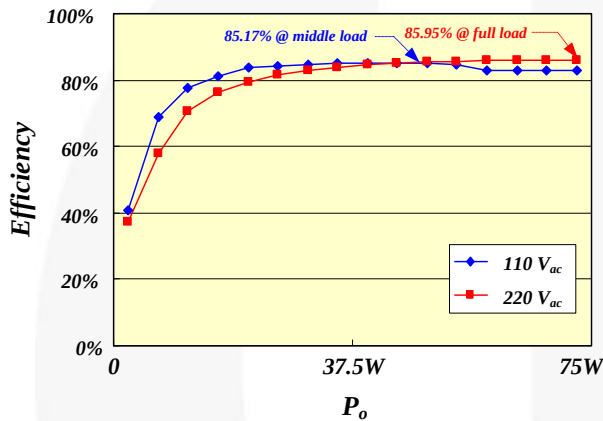


圖14 效率對比

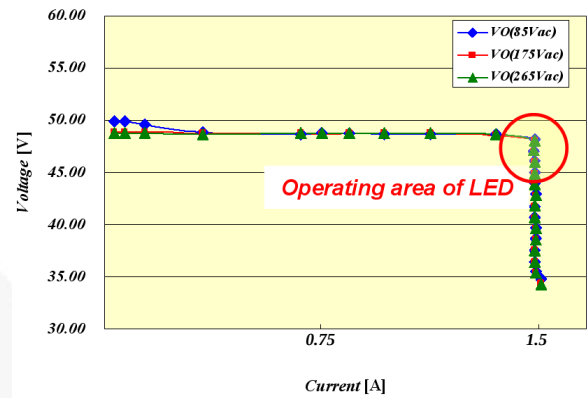


圖15 輸出V-I特性

對於輸入電壓220 V_{ac} 和75W滿載條件下，測得效率最大值為85.17%。

對於LED照明，LED燈串採取額定電流驅動，電源應工作在滿載條件下。因此，在正常條件下，電源要求處於恒流控制。圖15給出了原型實驗電路的V-I特性。所得結果驗證了在整個輸入電壓條件下，恒流控制時輸出驅動效果良好。

參考電路

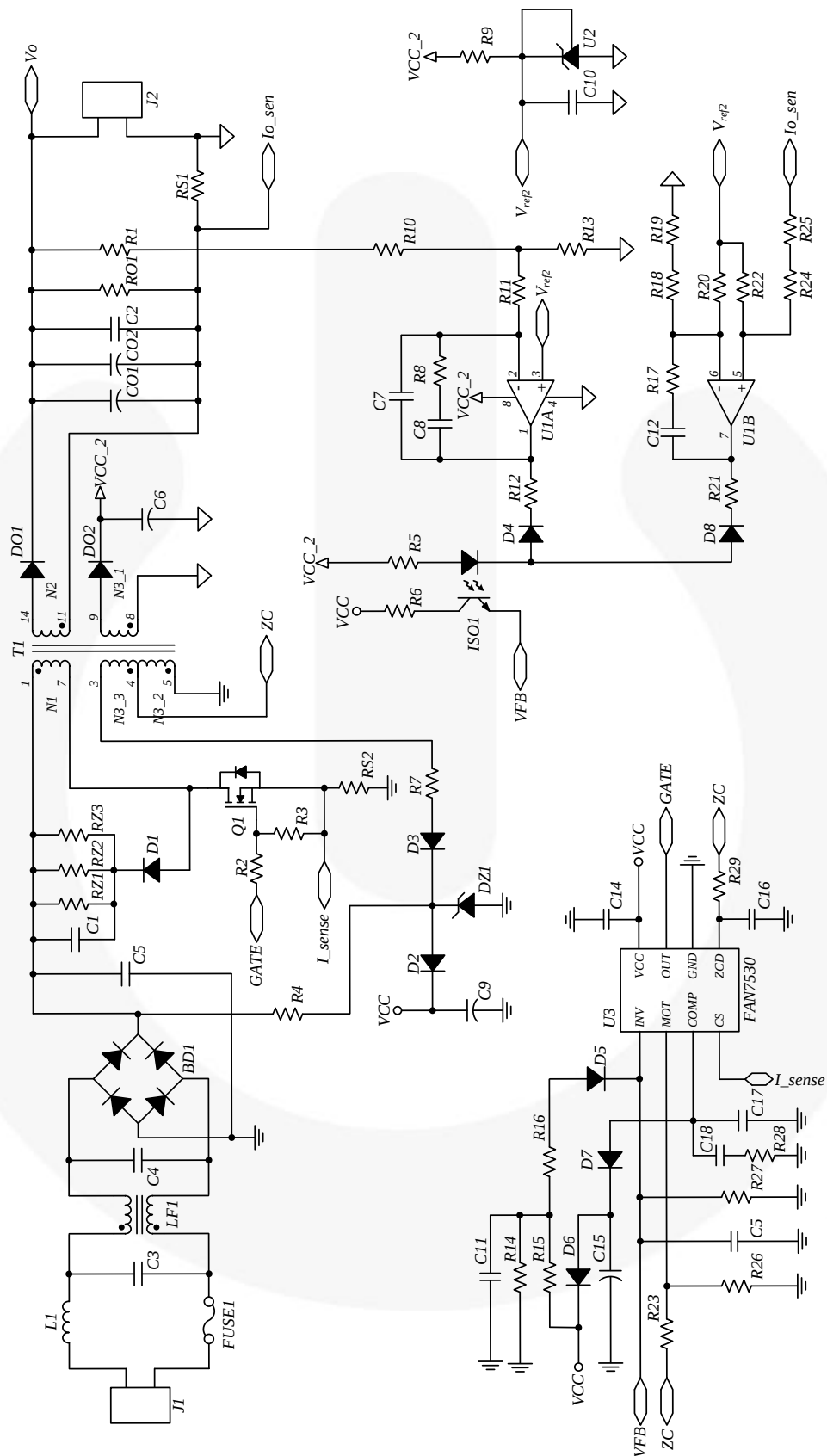


圖16 參考電路圖

物料清單

元件	符號	取值/部件編碼	元件	符號	取值/部件編碼
Rectifier	BD1	GBU8J	電阻器	R1	49.9k Ω
電容器	C1	472/1kV		R2	15 Ω
	C2	104		R3	1.5k Ω
	C3	220nF		R4	56k Ω /2Watt
	C4	440nF		R5	3.3k Ω
	C5	474/NP/630V		R6	11k Ω
	C6	33 μ /35V		R7	1.5/1W
	C7	473		R8	100k Ω
	C8	224		R9	1.2k Ω
	C9	33 μ /35V		R10	47k Ω
	C10	100p		R11	50k Ω
	C11	224		R12	11k Ω
	C12	155		R13	5.1k Ω
	C13	106		R14	1.2k Ω
	C14	105		R15	10k Ω
	C15	683		R16	33 Ω
	C16	56p		R17	10k Ω
	C17	473		R18	2k Ω
	C18	224		R19	10 Ω
	C19	105		R20	2k Ω
	CO1	2200 μ /63V		R21	8.2k Ω
	CO2	2200 μ /63V		R22	2k Ω
二極體	D1	UF4005		R23	330k Ω
	D2	RGF1J		R24	2.1k Ω
	D3	UF4005		R25	33 Ω
	D4	1N4148		R26	30k Ω
	D5	1N4148		R27	5.1k Ω
	D6	1N4148		R28	100k Ω
	D7	1N4148		R29	47k Ω
	D8	1N4148		RO1	56k Ω /2Watt
	DO1	F06UP20S		RS1	0.05 Ω /5Watt
	DO2	UF4005		RS2	0.1 Ω /5Watt
齊納二極體	DZ1	1N4746(18V)	變壓器	RZ1	56k Ω /2Watt
熔斷器	FUSE1	FUSE		RZ2	56k Ω /2Watt
光電耦合器	ISO1	PC817		RZ3	56k Ω /2Watt
連接器	J1	CON4	變壓器	T1	EER3435
	J2	CON4	運算放大器	U1A,B	KA358
電感器	L1	330 μ H	穩壓器	U2	KA431
抗流圈	LF1	EMI_CHOCK	PFC 晶片	U3	FAN7530
MOSFET	Q1	FQPF8N80C			

相關數據表

[FAN7527 — 臨界模式PFC控制晶片](#)

[FAN7528 — 雙輸出臨界導通模式控制器](#)

[FAN7529 — 臨界導通模式控制器](#)

[FAN7530 — 臨界導通模式控制器](#)

作者

by Jae-Eul Yeon/Ph. D.

HV-PCIA/Fairchild Korea Semiconductor

+82-32-680-1935

E-mail : jaeul.yeon@fairchildsemi.com

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