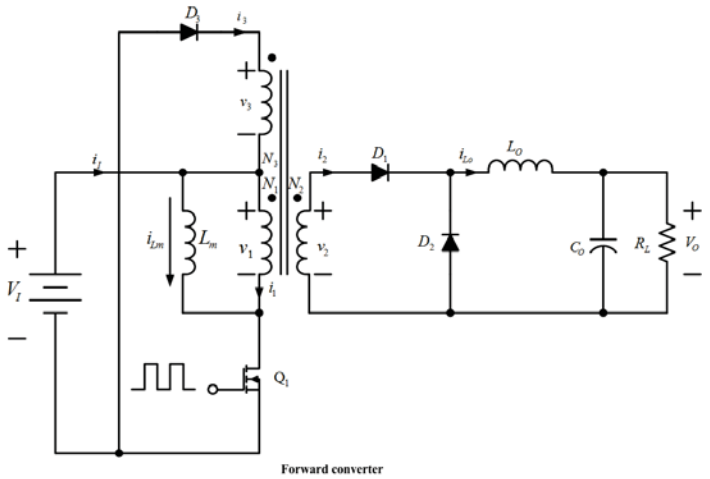
電力電子實習教具與教材製作

FORWARD CONVERTER

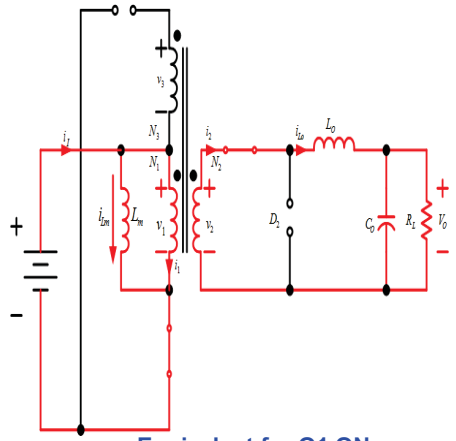
❑目錄

❑Forward Converter 介紹(1/19)



❑Forward Converter 介紹(2/19)

Analysis for the switch turn-on. (C.C.M.) :



Equivalent for Q1 ON

☐ The V_{N2} can be derived as follows:

$$V_{N2} = V_{Lo} + V_O = L_O \frac{di_{Lo}}{dt} + V_O \qquad (1)$$

❑Forward Converter 介紹(3/19)

Thus :

$$(0 \le t \le DTs)$$

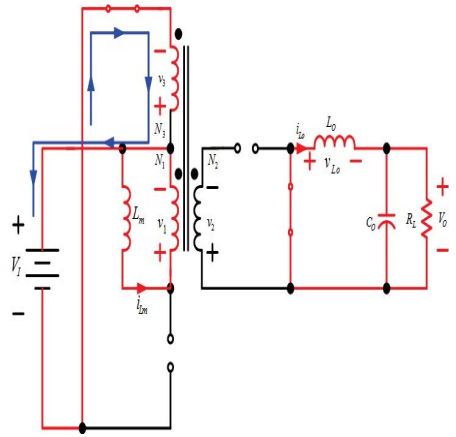
$$\frac{di_{Lo}}{dt} = \frac{V_{N2} - V_O}{L_O} \qquad (2)$$

when $t = t_{ON} = DT_S$

$$\Delta I_{Lo}^{+} = \frac{V_{N2} - V_O}{L_O} \times DT_S \qquad (3)$$

❑Forward Converter 介紹(4/19)

Analysis for the switch turn-off. (C.C.M.)



Equivalent for Q1 OFF

- **From the Fig. we have the following equations :**

$$V_{Lo} + V_O = 0 \qquad (4)$$

$$L_O \frac{di_{Lo}}{dt} + V_O = 0 \qquad (5)$$

- **Thus**

$$(DT_S \le t \le Ts)$$

$$\frac{di_{Lo}}{dt} = -\frac{V_O}{L_O} \qquad (6)$$

- **When** $t = t_{OFF} = (1-D)T_S$

$$\Delta I_{Lo}^{-} = \frac{V_O}{L_O} \times (1-D)T_S \qquad (7)$$

❑Forward Converter 介紹(5/19)

Because the i_{Lo} is C.C.M., thus :

$$\frac{V_{N2} - V_O}{L_O} \times DT_S = \frac{V_O}{L_O} \times (1-D)T_S \qquad (8)$$

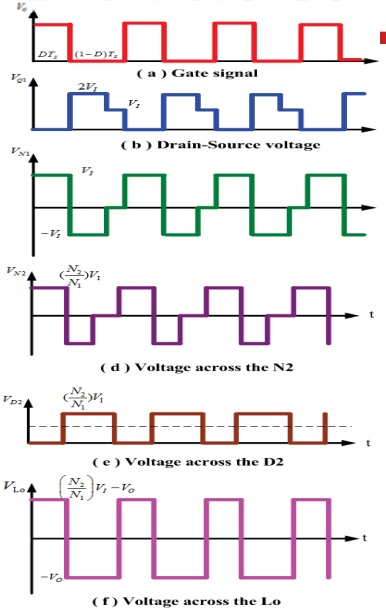
where $V_{N2} = \frac{N_2}{N_1} \times V_I$

And

$$V_O = \frac{N_2}{N_1} \times V_I D \qquad (9)$$

$$\frac{V_O}{V_I} = \frac{N_2}{N_1} D = D/n \qquad (10)$$

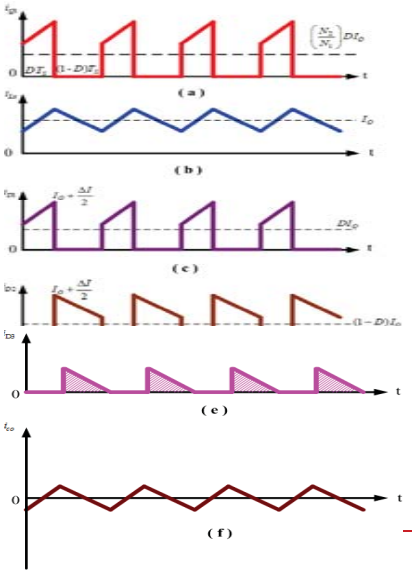
❑Forward Converter 介紹(6/19)



Various voltage waveforms of the forward converter operated in C.C.M

C.C.M:連續導通模式

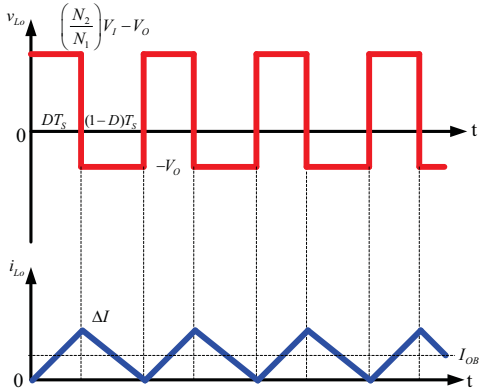
❑Forward Converter 介紹(7/19)



Various current waveforms of the forward converter operated in C.C.M

❑Forward Converter 介紹(8/19)

➢**Analysis of the forward converter in boundary mode (C.C.M/D.C.M.)**



The waveform of the forward converter in C.C.M./D.C.M. boundary

❑Forward Converter 介紹(9/19)

From the above figure, we can obtain the following equations:

$$I_{LoB} = I_{OB} = \frac{1}{2}\Delta I \qquad (11)$$

since

$$\Delta I = \frac{V_O}{L_O} \times (1-D)T_S = \frac{N_2}{N_1} \times \frac{V_I}{L_O} \times D(1-D)T_S \qquad (12)$$

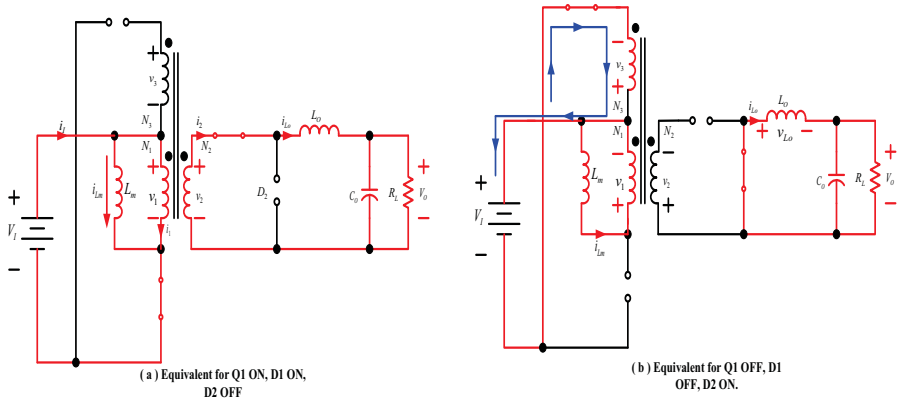
And

$$I_O > I_{LoB} = I_{OB} = \frac{N_2 V_I}{2N_1 L_O} D(1-D)T_S \quad \text{for C.C.M. condition} \qquad (13)$$

$$L_P > L_{OB} = \frac{V_O}{2I_{OB}}(1-D)T_S \quad \text{for C.C.M. condition} \qquad (14)$$

❑Forward Converter 介紹(10/19)

➢ **Analysis for the forward converter in Discontinuous Conduction Mode (D.C.M.)**

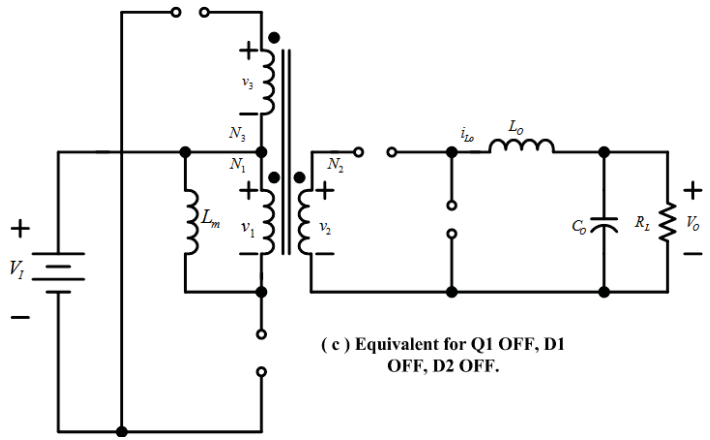


(a) Equivalent for Q1 ON, D1 ON, D2 OFF

(b) Equivalent for Q1 OFF, D1 OFF, D2 ON.

Equivalent circuit for forward converter in D.C.M

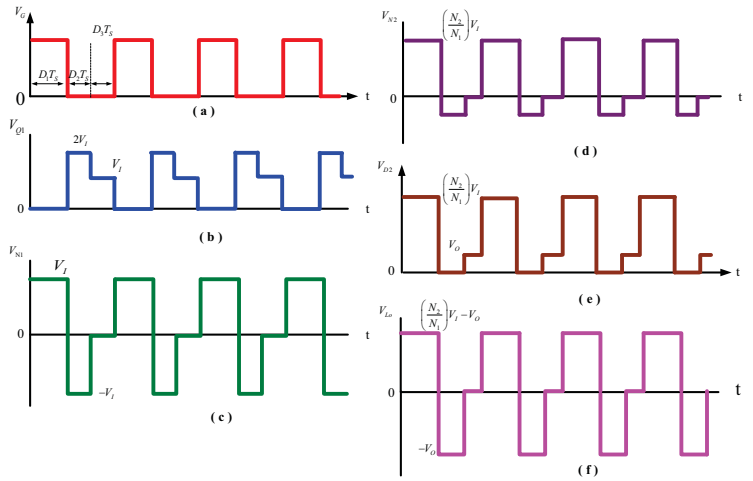
❑Forward Converter 介紹(11/19)



(c) Equivalent for Q1 OFF, D1 OFF, D2 OFF.

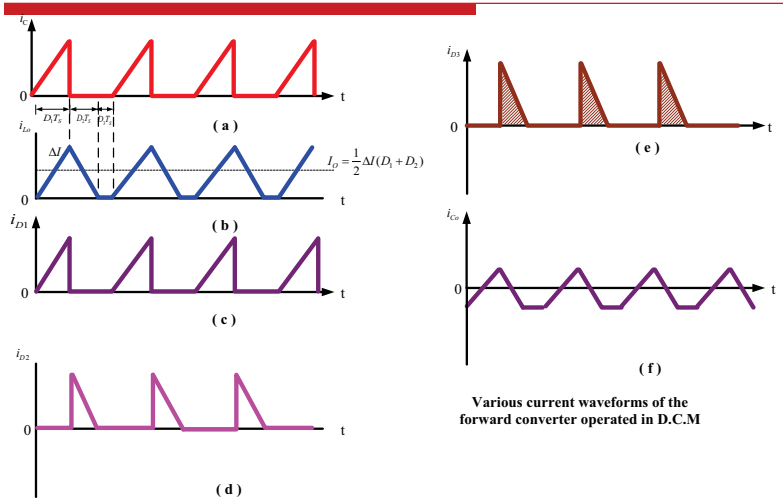
Equivalent circuit for forward converter in D.C.M

❑Forward Converter 介紹(12/19)



Various voltage waveforms of the forward converter operated in D.C.M

❑Forward Converter 介紹(13/19)



Various current waveforms of the forward converter operated in D.C.M

❑Forward Converter 介紹(14/19)

From the above figure, we can obtain the following equations:

$$\left[\left(\frac{N_2}{N_1}\right)V_I - V_O\right]D_1T_S = V_O D_2 T_S \qquad (15)$$

And

$$\frac{V_O}{V_I} = \frac{N_2}{N_1}\frac{D_1}{D_1 + D_2} \qquad (16)$$

Since

$$\Delta I = \frac{V_O D_2 T_S}{L_O} \qquad (17)$$

And

$$I_{Lo} = I_O = \frac{V_O}{R_L} \qquad (18)$$

❑Forward Converter 介紹(15/19)

From the last Fig. we have the following equations :

$$I_{Lo} = I_O = \frac{1}{2} \times \Delta I \times (D_1 + D_2) \quad (19)$$

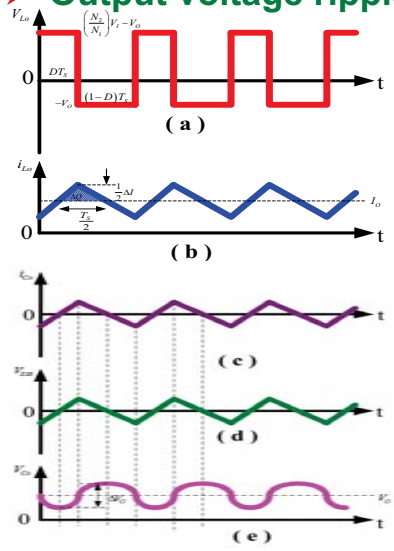
$$\frac{V_O}{R_L} = \frac{1}{2} \times \frac{V_O D_2 T_S}{L_O} \times (D_1 + D_2) \quad (20)$$

And

$$D_2 = \frac{-D_1 + \sqrt{D_1^2 + (8L_O / R_L T_S)}}{2} \quad (21)$$

❑Forward Converter 介紹(16/19)

➢ **Output voltage ripple**



Output voltage ripple of the forward converter operated in C.C.M.

❑Forward Converter 介紹(17/19)

From the above figure, we can obtain the following equations:

$$\Delta V_O = \frac{\Delta Q}{C_O} = \frac{1}{C_O} \cdot \frac{1}{2} \cdot \frac{\Delta I}{2} \cdot \frac{T_S}{2} = \frac{\Delta I T_S}{8C_O} \quad (22)$$

Thus, output voltage ripple is

$$\Delta V_O = \frac{T_S^2 V_O}{8C_O L_O}(1 - D) \quad (23)$$

❑Forward Converter 介紹(18/19)

➢ **Selection of Components**

Switch:

$$V_{DS,Q1(\max)} \geq 2V_I \quad (24)$$

$$I_{Q1(\max)} = \left(\frac{N_2}{N_1}\right)\left(I_O + \frac{\Delta I}{2}\right) + \frac{DT_S V_I}{L_1} \quad (25)$$

Diode:

$$V_{D1(\max)} \geq \left(\frac{N_2}{N_1}\right) V_I = \frac{V_O}{D} \quad (26)$$

$$I_{D1(\max)} = I_O + \frac{\Delta I}{2} \quad (27)$$

❑Forward Converter 介紹(19/19)

And

$$I_{Q1(avg)} = \left(\frac{N_2}{N_1}\right) DI_O = \frac{DI_O}{n} \quad (28)$$

$$I_{D1(avg)} = DI_O \quad (29)$$

And

$$I_{D2(\max)} = \left(\frac{N_2}{N_1}\right) V_I = \frac{V_O}{D} \quad (30)$$

$$I_{D2(\max)} = I_O + \frac{\Delta I}{2} \quad (31)$$

$$I_{D2(avg)} = (1-D) I_O \quad (32)$$

❑材料規格（1/2）

➢Input Voltage	36 VDC to 56VDC
➢Output Voltage	12VDC
➢Output Current	0.2 A to 3.6A
➢Output Ripple Voltage	100mV
➢Load Regulation	+/- 1%
➢Line Regulation	+/- 1%
➢Transient Response	1.25A to 2.5A, 0.1A/uS
➢ Overshoot / Undershoot	200mV
➢Setting Time	2mS

❑材料規格（2/2）

➢Start up

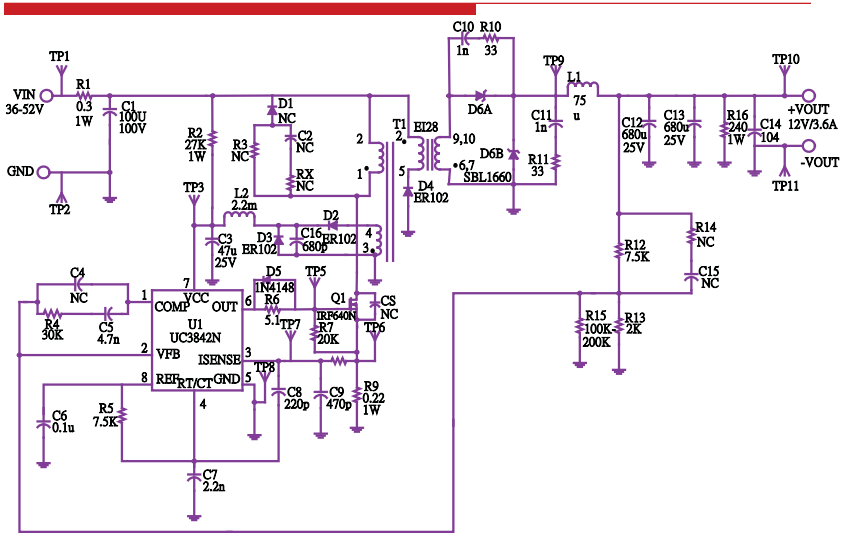
Rise Time	100 mS
Overshoot	250 mV
Delay Time	1 S

➢Short-Circuit Protection — Auto-recovery

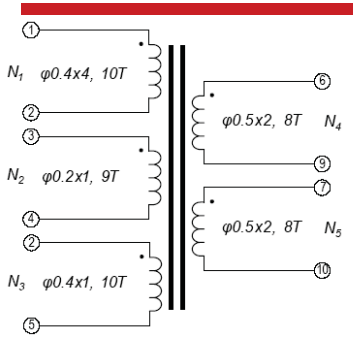
➢Efficiency — > 83%

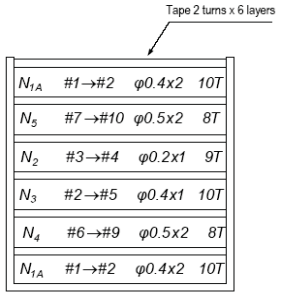
➢I/P : 48V , O/P : 3.6A

❑電路圖



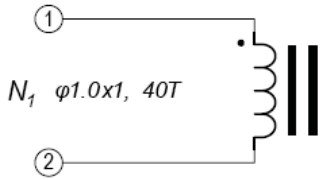
❑變壓器繞製

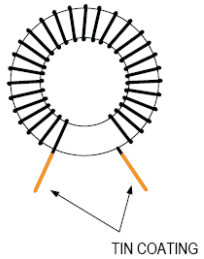




1. Core : EI-28 (PC40 OR Equivalent)
2. Bobbin : EI-28 10 Pin Vertical
3. Inductance : Without GAP, 2mH Reference
4. Cut Pin #8 After Winding

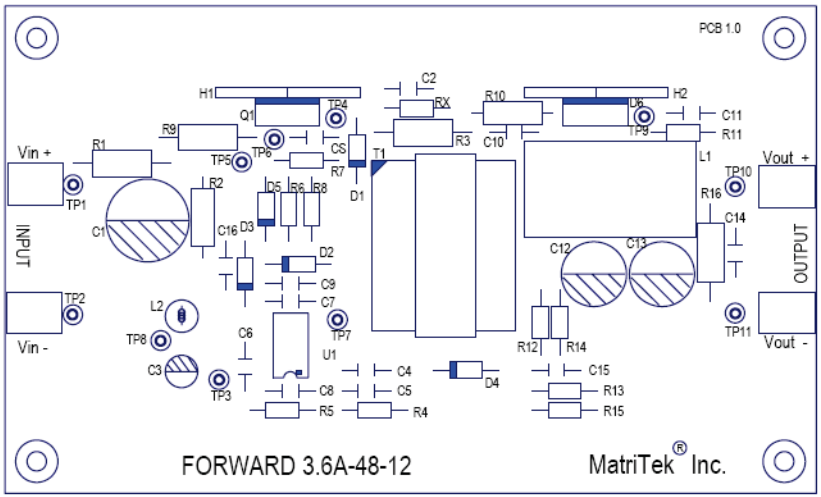
❑電感器繞製





1. Core : T90-52 (Micrometals or Equivalent)
2. Wire : ψ1.0 x 1
3. Inductance : 75 uH REFREENCE (#1 TO #2)
4. 40 TURNS

❑元件分佈



❑元件規格表（1/5）

項次	PCB位置	規格說明	數量
1	R1	RES 0R3 +/-5% 1W	1
2	R2	RES 27K +/-5% 1W	1
3	R3	RES NC +/-5% 1W	1
4	R4	RES 30K +/-5% ¼W	1
5	R5	RES 7.5K +/-5% ¼W	1
6	R6	RES 5R1 +/-5% ¼W	1
7	R7	RES 20K +/-5% ¼W	1
8	R8	RES 510 +/-5% ¼W	1
9	R9	RES 0R22 +/-5% 1W	1
10	R10	RES 33 +/-5% ¼W	1
11	R11	RES 33 +/-5% ¼W	1
12	R12	RES 7K5 +/-5% ¼W	1
13	R13	RES 2K +/-5% ¼W	1

❑元件規格表（2/5）

項次	PCB位置	規格說明	數量
15	R15	RES 180K+/-5% ¼W	1
16	R16	RES 240 +/-5% ¼W	1
18	C1	EC 100U 100V13X20	1
19	C2	MLCC NC 50V	0
20	C3	EC 47U 25V 6X11	1
21	C4	MLCC NC 50V	0
22	C5	MLCC 472 50V	1
23	C6	MLCC 104 50V	1
24	C7	MLCC 222 50V	1
25	C8	MLCC 221 50V	1
26	C9	MLCC 471 50V	1

❑元件規格表（3/5）

項次	PCB位置	規格說明	數量
27	C10	MLCC 102 50V	1
28	C11	MLCC 102 50V	1
29	C12	EC 680U 25V 10X20	1
30	C13	EC 680U 25V 10X20	1
31	C14	MLCC 104 50V	1
33	C16	MLCC 681 50V	1
35	T1	TRANSFORMER EI-28 FORWARD	1
36	L1	CHOKE T90-52 75U 3.6A	1
37	L2	CHOKE R5X7 2.2mH	1
38	Q1	NMOS IRF640N 220V/18A	1

❑元件規格表（4/5）

項次	PCB位置	規格說明	數量
40	D2	FRD SF10DG	1
41	D3	FRD SF10DG	1
42	D4	FRD SF10DG	1
43	D5	DIODE 1N4148	1
44	D6	SBD SBL1660 16A/60V TO220	1
45	U1	IC PWN CONTROLLER UC3842BN	1
46	H1,H2	HEATSINK 20X30X1	1
47	SCREW	SCREW PAN HEAD M3X7	1
48	NUT	NUT M3	1
49		INSULATOR TO-220	1
50		INSULATOR SILICON TO-220	1
51	TP1~11	TEST PIN 0.8D 10mm	1
52	IN/OUT	CONNECTOR	1

❑元件規格表（5/5）

項次	PCB位置	規格說明	數量
53		COPPER STAND	1
54	PCB	PCB 3X5 IN SS FORWARD 3.6A-48-12	1

❑組裝步驟與注意事項（1/5）

➢組裝工具

(1) 溫控電烙鐵 30W，圓尖頭

(2) 焊錫絲0.6Φ ~ 1.0Φ

(3) 梅花起子

(4) 尖嘴鉗

(5) 斜口鉗

❑組裝步驟與注意事項（2/5）

➢量測設備

(1) 直流電源 60V / 3A

(2) 電子負載 60V / 60A / 300W (Dynamic Function)

(3) 100MHZ 以上數位儲存式示波器DSO (可Hard Cpoy畫面)

(4) 100KHZ 以上 LCR Meter

(5) Digital Multimeter

(6) 電流探棒Current Probe (Optional)

(7) Gain-Phase Analyzer (Optional)

❑組裝步驟與注意事項（3/5）

➢組裝一般注意事項

(1) 對照料表，清點材料。必要時可用RLC Meter 確認電感、電容與電阻值。

(2) 階層式組立步驟：先將獨立單元組立 (如功率半導體與散熱片組合)，再依零件高低由低而高依次焊錫固定。

(3) 焊錫作業注意”三點同溫”原則，避免空焊、冷焊發生，也避免零件(特別是IC)過熱損壞。

❑組裝步驟與注意事項（4/5）

➢組裝步驟

(1) 組立MOSFET Q1 與SBD D1 與散熱片。注意絕緣片與絕緣粒子。

(2) 將最矮的零件，Zener D5 與8 顆積層陶瓷電容(MLCC)，焊於PCB 上。

(3) 其次是1/4W 的電阻，共10 顆。

(4) 其次 D2、D3 與D4。

(5) 接著焊IC (U1)，注意IC 腳位標示。

(6) 4 顆1W 電阻。

❑組裝步驟與注意事項（5/5）

(7) 焊接11 支Test Pin。

(8) 依序將所有電解電容、電感及變壓器焊上。

(9) 再來是帶散熱片的Q1 與D6 組合。

(10) 檢查零件是否已完全裝在PCB 上。

(11) 接著焊輸入與輸出的Pin (或Connector)

(12) 最後將銅柱鎖定，完成PCB 作業。

❑評估與量測（1/3）

➢ 注意：

(1) 輸入電源供應器的最大輸出電流須設定在2A 左右， 如果電源串聯輸出，先確定正確電壓。

(2) 仔細查看電路圖，明確瞭解Test Pin 是哪一點。

(3) 輸入端與輸出端要確認再開機。

❑評估與量測（2/3）

1. Conversion Efficiency
2. Load Regulation
3. Line Regulation
4. Output Ripple & Noise (DSO)
5. Dynamic Response (DSO)
6. Gate Signal And MOSFET Voltage (DSO)

❑評估與量測（3/3）

7. Start-up (Pin 10 to Pin 11) (DSO)
8. Current Sensing Voltage (U1 PIN3)
9. Secondary Diode Current (Optional) (DSO + Current Probe)
10. Others

❑靜態測試紀錄（1/2）

輸入電壓 =36 V

輸出電流	0.5A	1A	1.5A	2A	2.5A	3A	3.6A
Vo							
Iin							

輸入電壓 = 48V

輸出電流	0.5A	1A	1.5A	2A	2.5A	3A	3.6A
Vo							
Iin							

輸入電壓 = 56V

輸出電流	0.5A	1A	1.5A	2A	2.5A	3A	3.6A
Vo							
Iin							

❑靜態測試紀錄（2/2）

➢注意：

輸入電壓讀值：用DMM 量Pin 1 to Pin 2。

輸入電流讀值：可直接於電源供應器表頭讀取。

輸出電壓讀值：用DMM 量Pin 10 to Pin 11。

輸出電流讀值：可直接於電子負載表頭讀取。

❑名詞說明（1/5）

1. Conversion Efficiency :

$$\left(\eta = \frac{Vo \cdot Io}{Vin \cdot Iin}\right)$$

用量取的資料，計算出效率，並以EXCEL 作圖。

2. Load Regulation :

定義：***Load Regulation =*** $\left|\frac{Vo,\min\ load - Vo,\ fullload}{Vo,\min\ load}\right| \times 100$

用量取的資料，分別計算在三種輸入電壓下的負載穩壓率。

❑名詞說明（2/5）

3. Line Regulation :

定義：***Line Regulation =*** $\left|\frac{Vo,\min\ input - Vo,\max\ input}{Vo,\min\ input}\right| \times 100\ \%$

用量取的資料，分別計算在輸出電流為0.5A, 2A, 4A 條件下下的線電壓穩壓率。

4. Output Ripple And Noise :

條件：輸出滿載 (3.6A)

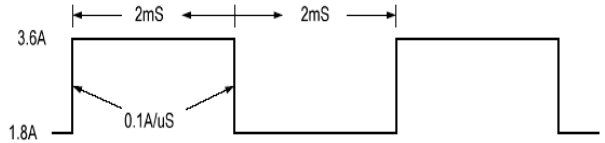
輸入電壓 = 36V，48V，56V

觀察記錄：用數位示波器觀察輸出電壓(AC Coupling)，並將波形記錄存檔。注意量測技巧，以免探棒耦合雜訊。

❑名詞說明（3/5）

5. Dynamic Response :

條件：負載設定



輸入電壓 = 36V，48V，56V

觀察記錄：用數位示波器觀察輸出電壓動態應響(AC Coupling)，並將波形記錄存檔。注意量測技巧，以免探棒耦合雜訊。

❑名詞說明（4/5）

6. Gate Signal (Duty Control) 信號與 MOSFET Voltage

條件：負載設定 = 0.2A，2A，3.8A

輸入電壓 = 48V

觀察記錄：用數位示波器觀察Pin 5 與Pin 8 的電壓，並將波形記錄存檔。

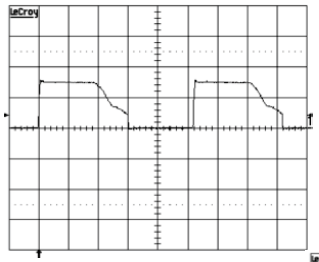
❑名詞說明（5/5）

7. Start-up

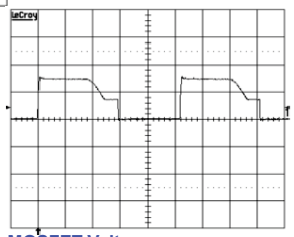
觀察從輸入電壓灌入到輸出電壓穩定的現象。

Dual Channel 量輸入與輸出電壓，以及 Soft Start 功能。

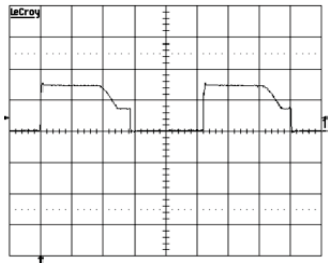
❑波形圖（1/9）



MOSFET Voltage
Vin=36V,Io=0.2A
H:2us/div. V:50V/div

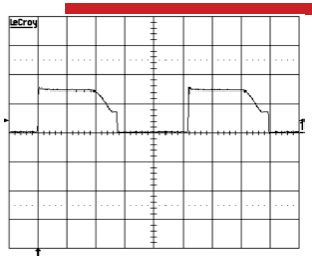


MOSFET Voltage
Vin=36V,Io=0.26A(Boundary)
H:2us/div. V:50V/div

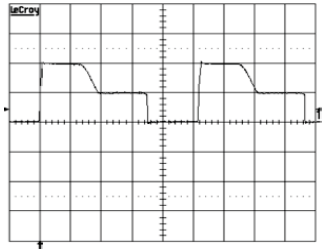


MOSFET Voltage
Vin=36V,Io=2A
H:2us/div. V:50V/div

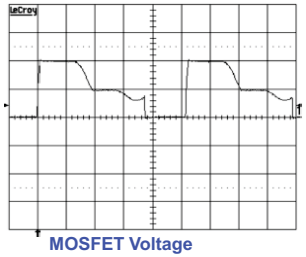
❑波形圖（2/9）



MOSFET Voltage
Vin=36V,Io=3.6A
H:2us/div. V:50V/div

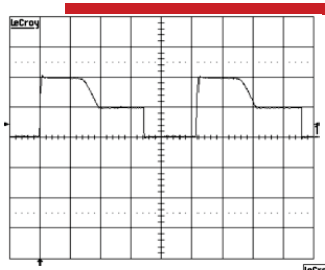


MOSFET Voltage
Vin=48V,Io=0.3A（Boundary）
H:2us/div. V:50V/div

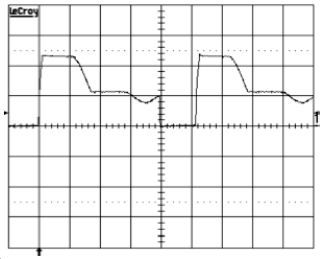


MOSFET Voltage
Vin=48V,Io=0.2A
H:2us/div. V:50V/div

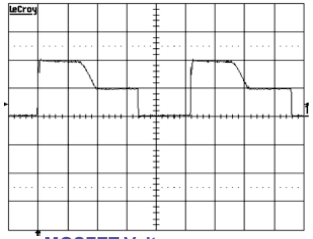
❑波形圖（3/9）



MOSFET Voltage
Vin=48V,Io=2.0A
H:2us/div. V:50V/div

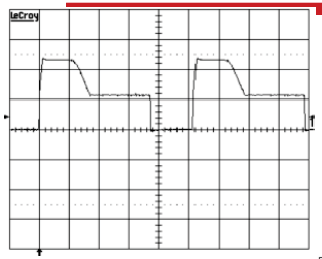


MOSFET Voltage
Vin=56V,Io=0.2A
H:2us/div. V:50V/div

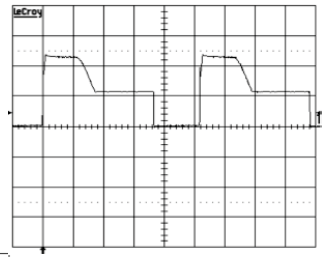


MOSFET Voltage
Vin=48V,Io=3.6A
H:2us/div. V:50V/div

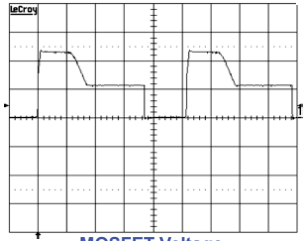
❑波形圖（4/9）



MOSFET Voltage
Vin=56V,Io=0.33A（Boundary）
H:2us/div. V:50V/div

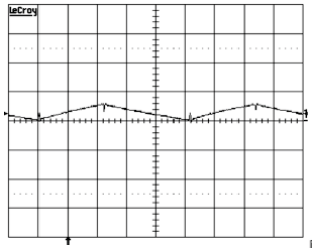


MOSFET Voltage
Vin=56V,Io=3.6A
H:2us/div. V:50V/div

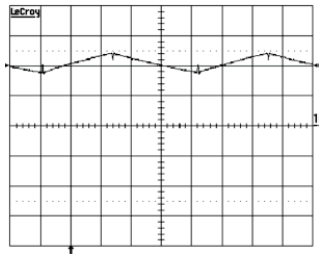


MOSFET Voltage
Vin=56V,Io=2.0A
H:2us/div. V:50V/div

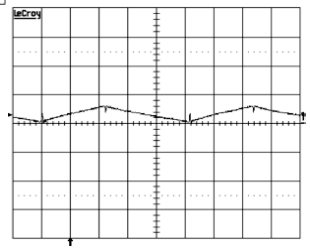
❑波形圖（5/9）



Inductor Current
@Vin=36V , Io=0.2A
H:2us/div. V:1A/div

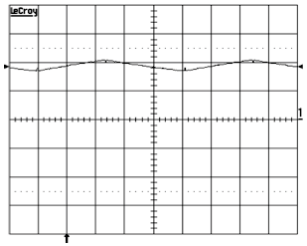


Inductor Current
Vin=36V , Io=2.0A
H:2us/div. V:1A/div

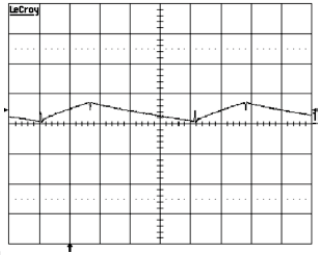


Inductor Current
Vin=36V , Io=0.26A(Boundary)
H:2us/div. V:1A/div

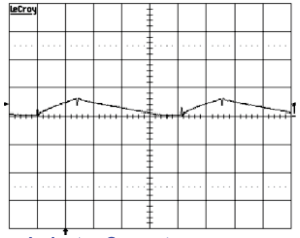
❑波形圖（6/9）



Inductor Current
Vin=36V , Io=3.6A
H:2us/div. V:2A/div

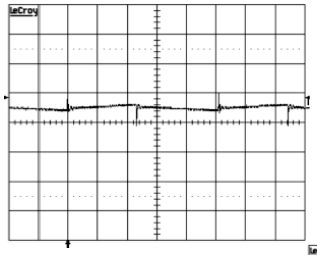


Inductor Current
Vin=48V , Io=0.3A(Boundary)
H:2us/div. V:1A/div

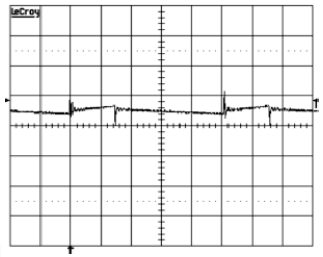


Inductor Current
Vin=48V , Io=0.2A
H:2us/div. V:1A/div

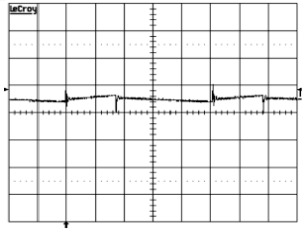
❑波形圖（7/9）



Output Transient Response
Vin=36V , Io=3.6A
H:2us/div. V:50mV/div

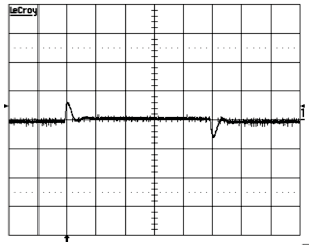


Output Transient Response
Vin=56V , Io=3.6A
H:2us/div. V:50mV/div

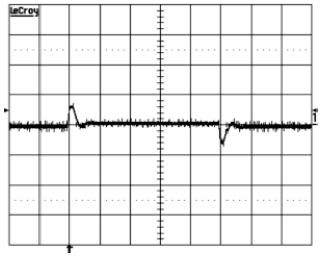


Output Transient Response
Vin=48V , Io=3.6A
H:2us/div. V:50mV/div

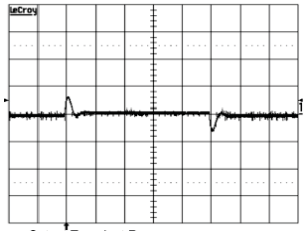
❑波形圖（8/9）



Output Transient Response
Vin=36V , Io=2.0A~3.6A
H:2us/div. V:200mV/div

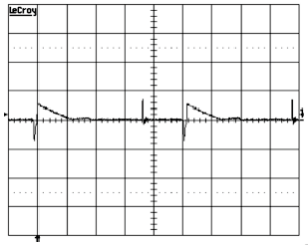


Output Transient Response
Vin=56 , Io=2.0A~3.6A
H:2us/div. V:200mV/div

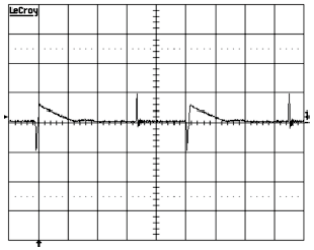


Output Transient Response
Vin=48V , Io=2.0A~3.6A
H:2us/div. V:200mV/div

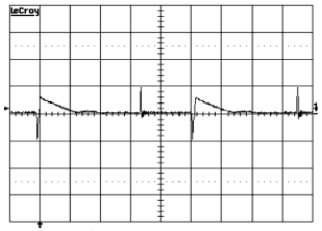
❑波形圖（9/9）



Reset Current
Vin=48V , Io=0.2A
H:2us/div. V:0.5A/div

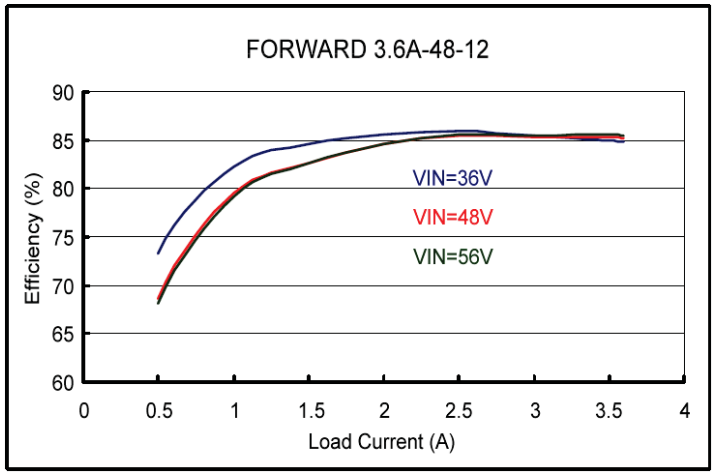


Reset Current
Vin=48V , Io=3.6A
H:2us/div. V:0.5A/div



Reset Current
Vin=48V , Io=2.0A
H:2us/div. V:0.5A/div

❑效率曲線


FORWARD 3.6A-48-12
Efficiency (%)
90
85
80
75
70
65
60
0
0.5
1
1.5
2
2.5
3
3.5
4
Load Current (A)
VIN=36V
VIN=48V
VIN=56V