

電源供應設計研討會

跨電感電壓穩壓器 (TLVR) 介紹

作者

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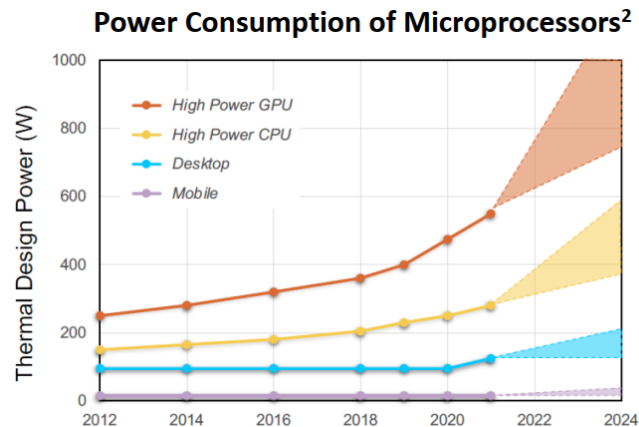
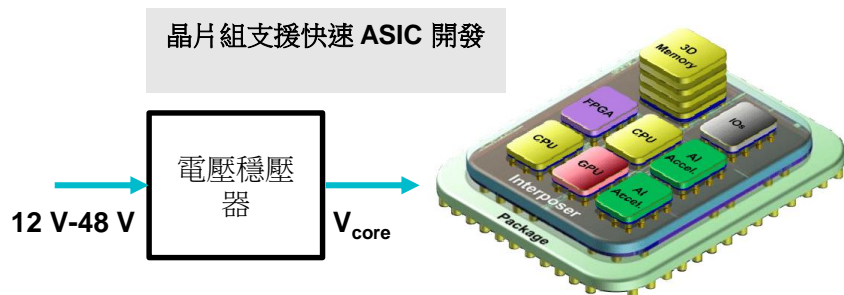


大綱/概覽

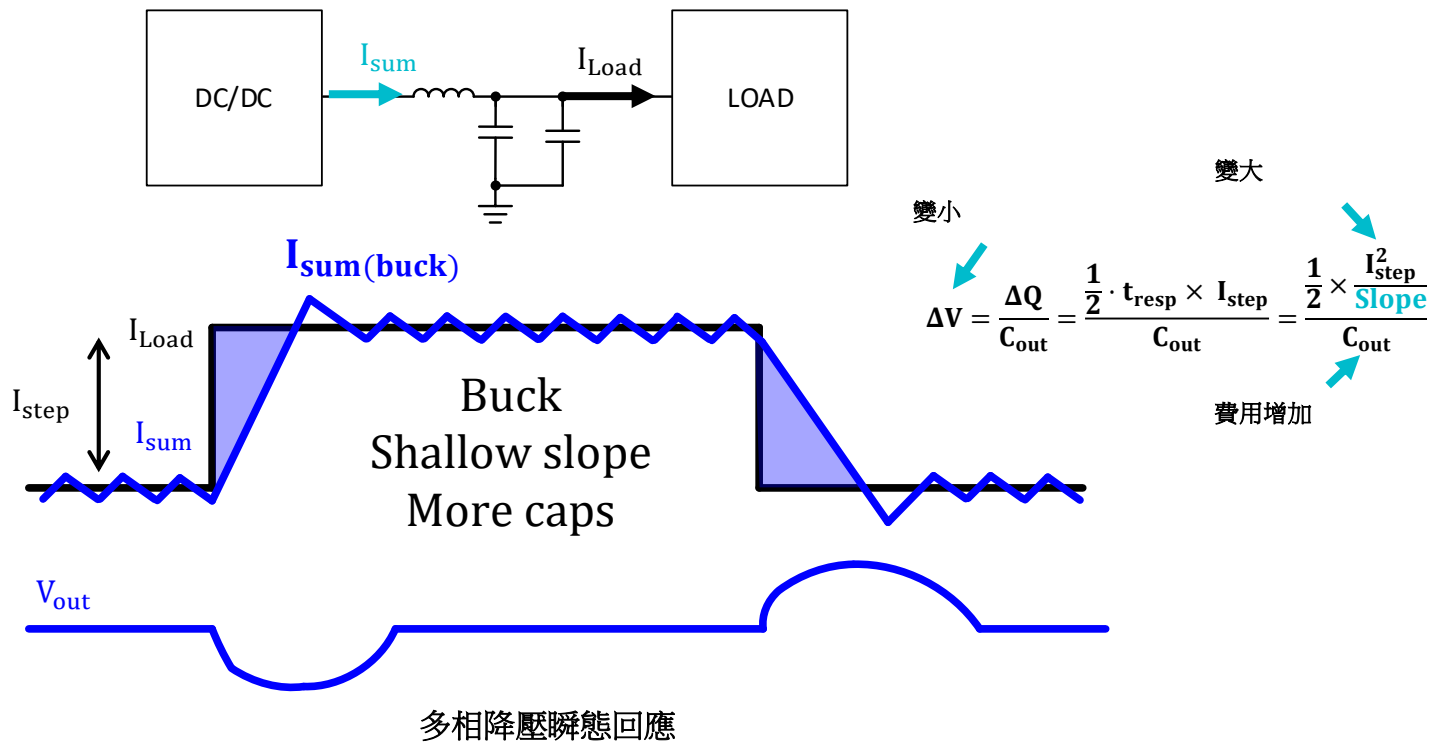
- 研究背景和研究動機
- 跨電感電壓穩壓器 (TLVR) 拓撲介紹
- 實務注意事項
- 結論

電壓穩壓器設計限制

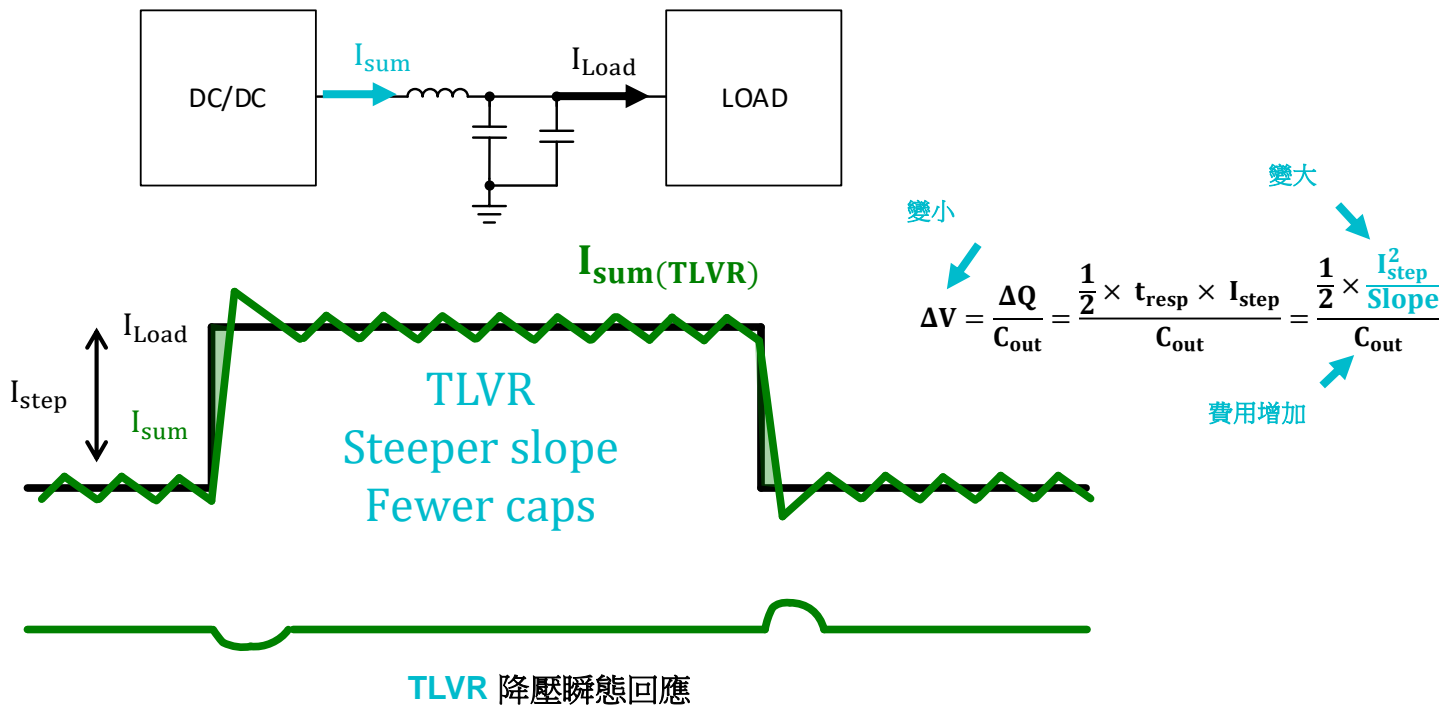
- 矽技術持續縮小晶片體積 (但速度已開始減緩) 3 奈米 → 更細微製程
- 應用特定積體電路 (ASIC) 操作電壓維持 0.7 V 至 1.0 V (最高 1.8 V)
- 高核心數設計與小晶片創新帶動操作電流快速增加 >1,000-A 設計
- 極端負載瞬態需求 1000 A/ μ s , $\pm 3\%$



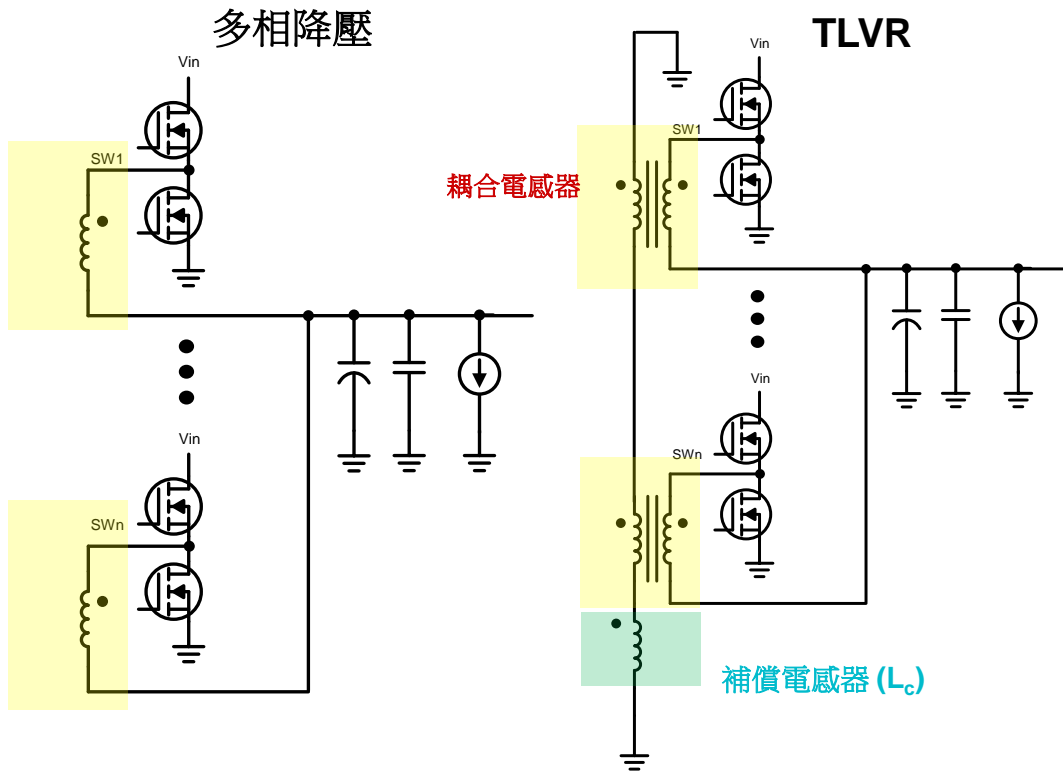
TLVR 的動機：改善瞬態回應



TLVR 的動機：改善瞬態回應



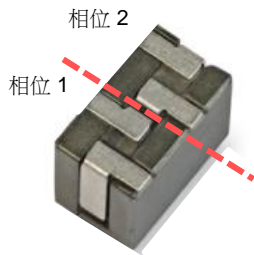
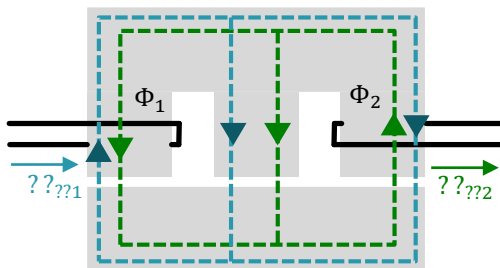
降壓轉換器與 TLVR 拓撲



- 降壓衍生的拓撲，適用於快速瞬態回應
- TLVR 是耦合電感器與降壓轉換器的新變體
- 什麼時候會派上用場：
 - 高相位數 (> 六相位)
 - 高 di/dt 負載瞬態
 - 中電壓漣波

傳統耦合電感器

傳統耦合電感器 (雙相)

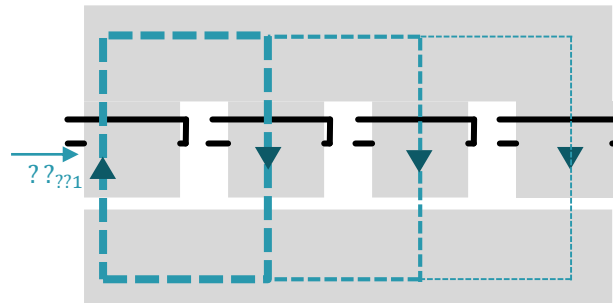


雙相耦合電感器

來源：Eaton

- 多個線圈共用單一核心
- 一般耦合係數： ≈ 0.5 至 0.7
- 高功率密度
- 相位數/配置的自訂設計

難以拓展至更高相位

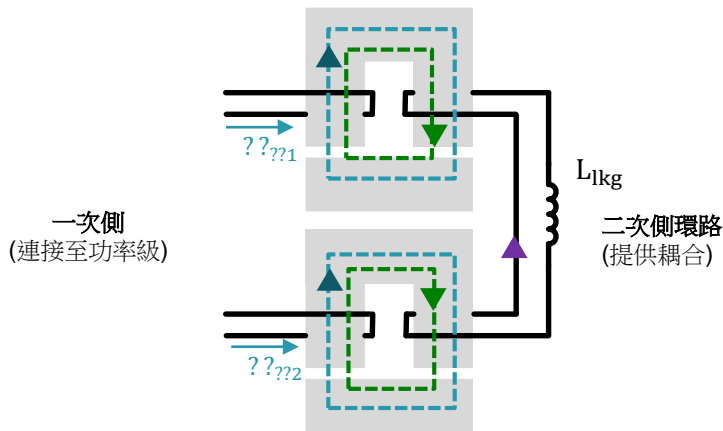


- **限制：** 相位之間的相等耦合需有對稱性
- **限制：** 在更高相位數下保持對稱性，必須借重複雜的幾何形狀

耦合允許高穩定狀態電感 (低漣波) 與低瞬態電感 (快速瞬態)

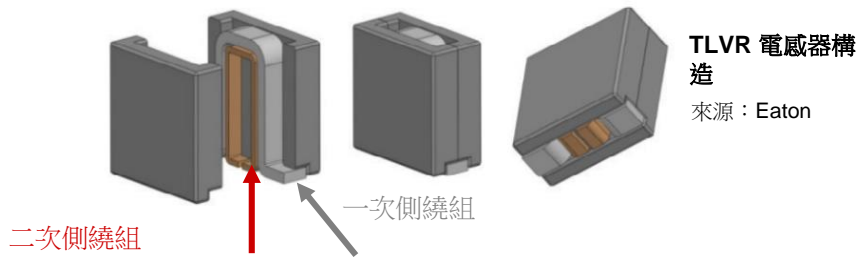
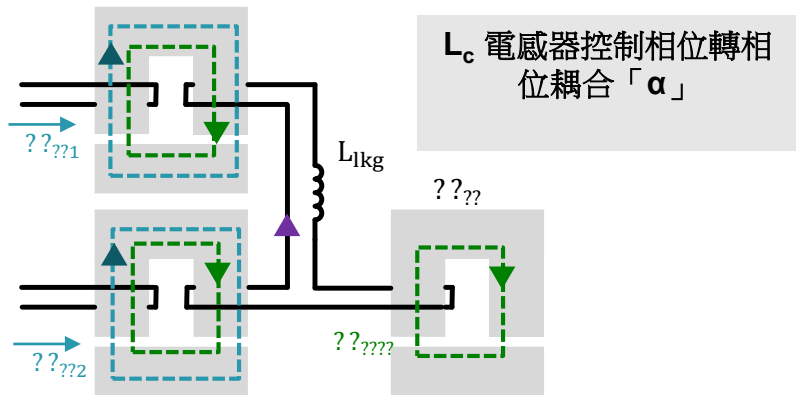
間接耦合電感器

間接耦合電感器 (雙相)



- 無需共用核心，相位也能對稱地耦合
- 簡單的核心幾何，可擴展的解決方案
- 不容易控制耦合

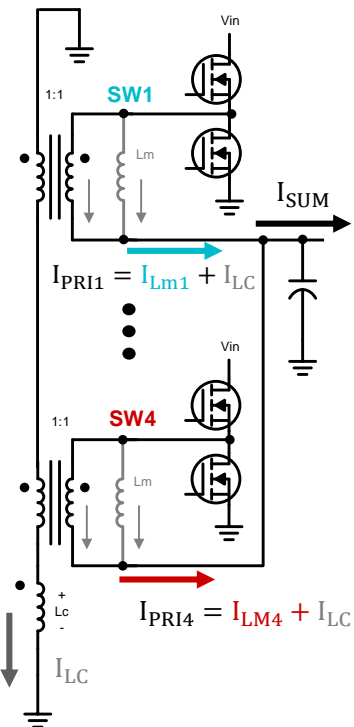
TLVR：間接耦合與補償電感器 (L_c)



TLVR 拓撲概覽

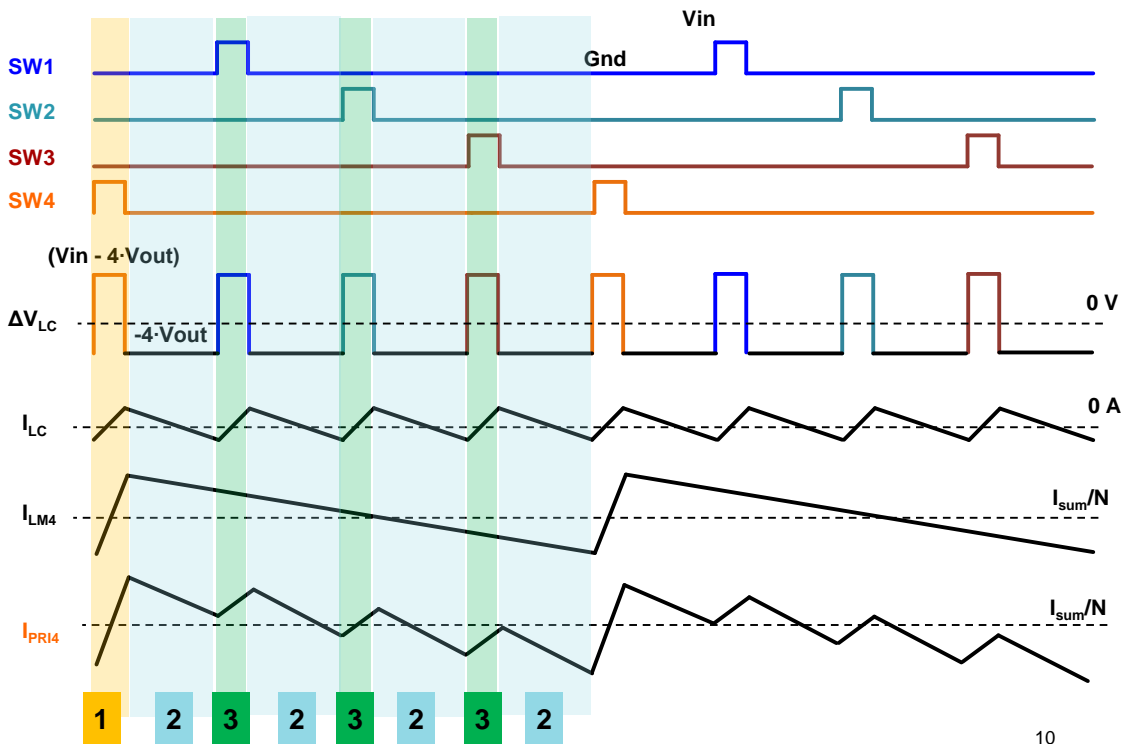
TLVR 操作原理：就緒狀態

TLVR 穩定狀態運作 (以四相為例，無重疊)

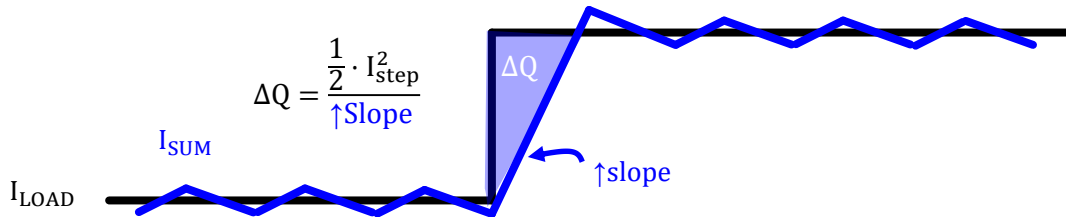
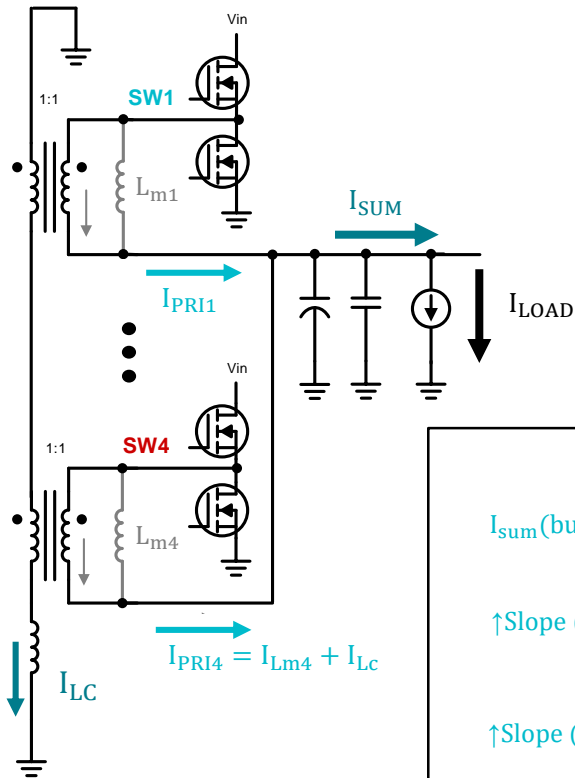


相位電流說明 (I_{PRI4})

1. 此相位 (SW4) 已開啟；其他相位均為關閉狀態
 I_{LM4} 增加 I_{LC} 增加
2. 所有相位均為關閉狀態
 I_{LM4} 減少
 I_{LC} 減少
3. 此相位 (SW4) 已關閉；但其他相位均為開啟狀態
 I_{LM} 減少 I_{LC} 增加



TLVR 操作原理：瞬態升壓



控制器開啟多個相位予以回應。

N_{ON} 相位已開啟， N_{OFF} 相位已關閉

多相降壓

$$I_{sum(buck)} = I_{L1} + I_{L2} + \dots$$

$$\uparrow Slope(buck) = \frac{\Delta V_{L1}}{L} + \frac{\Delta V_{L2}}{L} + \dots$$

$$\uparrow Slope(buck) \approx N_{on} \left(\frac{V_{in} - V_{out}}{L} \right) - N_{off} \left(\frac{V_{out}}{L} \right)$$

TLVR

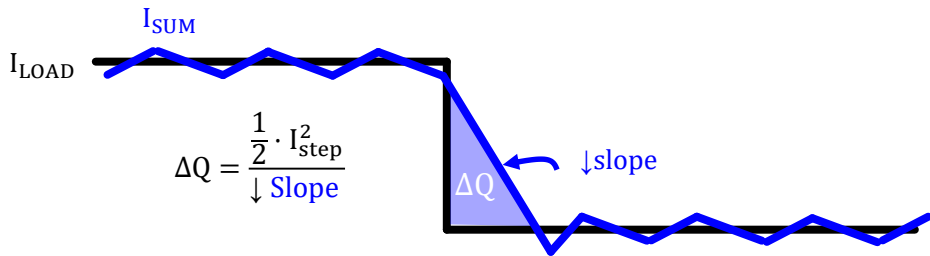
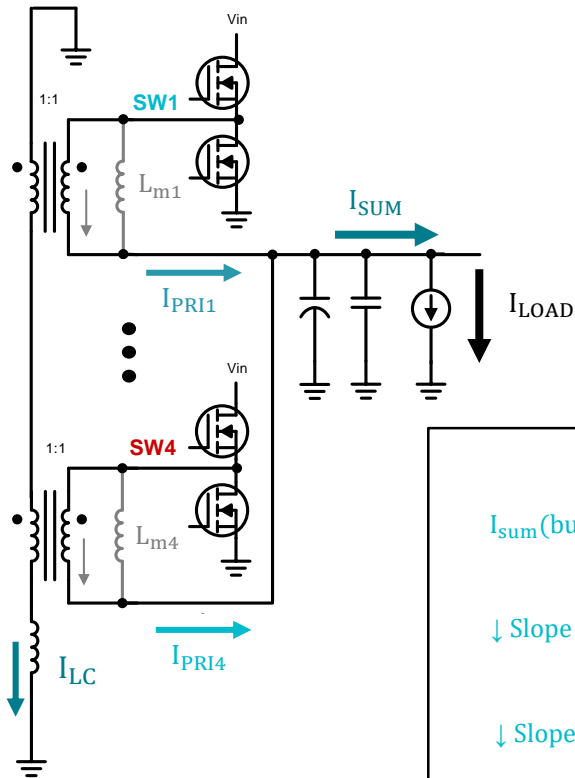
$$I_{sum(TLVR)} = I_{pri1} + I_{pri2} + \dots$$

$$I_{sum(TLVR)} = (I_{Lm1} + I_{Lc}) + (I_{Lm2} + I_{Lc}) + \dots$$

$$\uparrow Slope(TLVR) = \left(\frac{\Delta V_{L1}}{L_m} + \frac{\Delta V_{Lc}}{L_c} \right) + \left(\frac{\Delta V_{L2}}{L_m} + \frac{\Delta V_{Lc}}{L_c} \right) + \dots$$

$$\uparrow Slope(TLVR) \approx \uparrow Slope(buck) + N_{total} \left[\frac{N_{on} \cdot V_{in} - N_{total} \times V_{out}}{L_c} \right]$$

TLVR 操作原理：瞬態降壓



控制器關閉所有相位予以回應

N_{TOTAL} 相位已關閉

多相降壓

$$I_{\text{sum(buck)}} = I_{L1} + I_{L2} + \dots$$

$$\downarrow \text{Slope (buck)} = \frac{\Delta V_{L1}}{L} + \frac{\Delta V_{L2}}{L} + \dots$$

$$\downarrow \text{Slope(buck)} \approx -N_{\text{total}} \left(\frac{V_{\text{out}}}{L} \right)$$

TLVR

$$I_{\text{sum(TLVR)}} = I_{\text{pri1}} + I_{\text{pri2}} + \dots$$

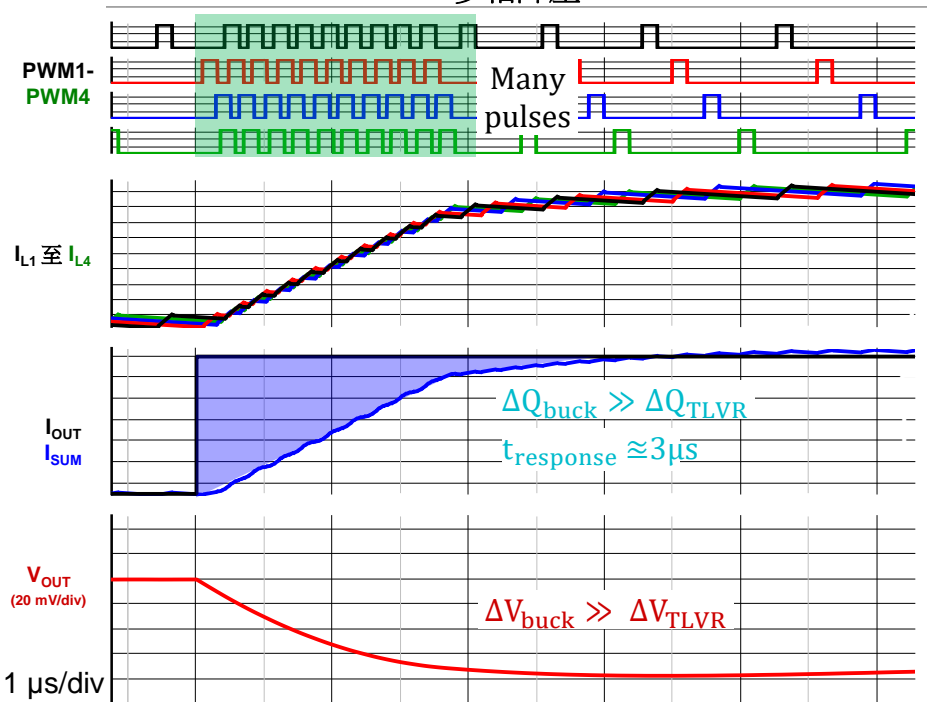
$$I_{\text{sum(TLVR)}} = (I_{Lm1} + I_{Lc}) + (I_{Lm2} + I_{Lc}) + \dots$$

$$\downarrow \text{Slope (TLVR)} = \left(\frac{\Delta V_{L1}}{L_m} + \frac{\Delta V_{Lc}}{L_c} \right) + \left(\frac{\Delta V_{L2}}{L_m} + \frac{\Delta V_{Lc}}{L_c} \right) + \dots$$

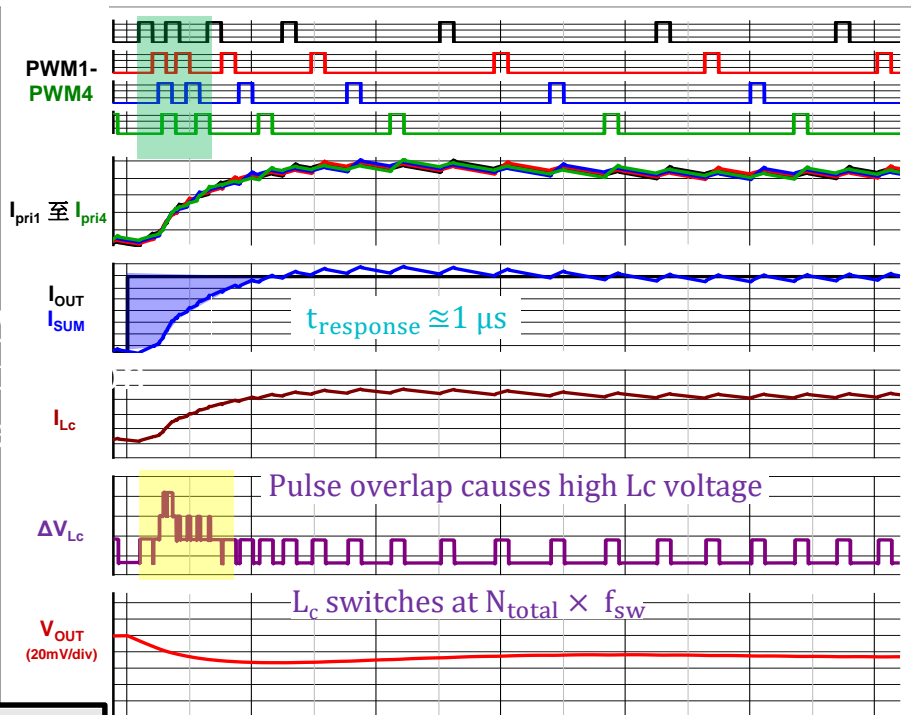
$$\downarrow \text{Slope (TLVR)} \approx \downarrow \text{Slope(buck)} - N_{\text{total}} \left[\frac{N_{\text{total}} \times V_{\text{OUT}}}{L_c} \right]$$

並排比較：負載升壓

多相降壓



TLVR

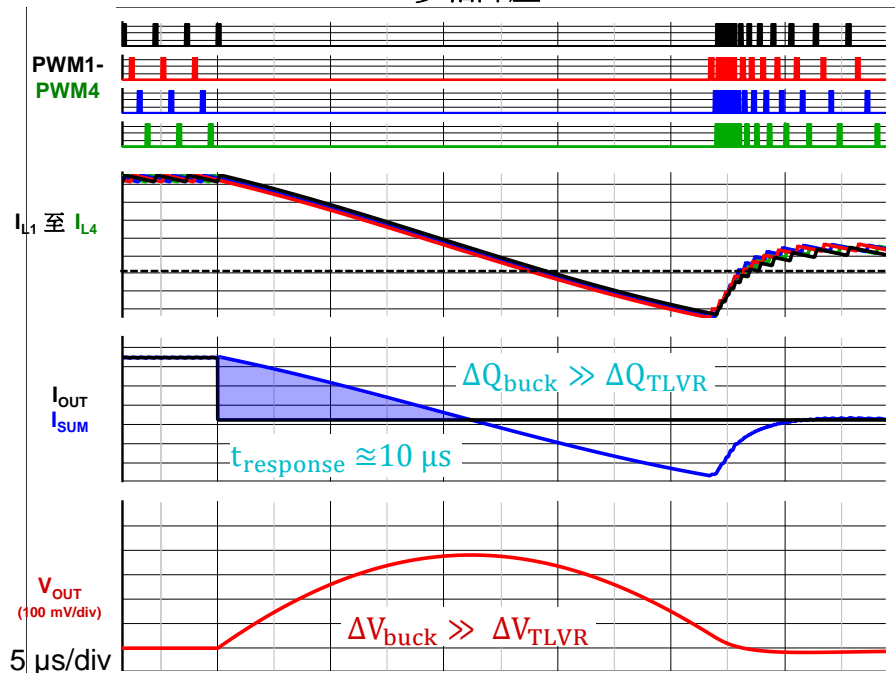


1 μs /div

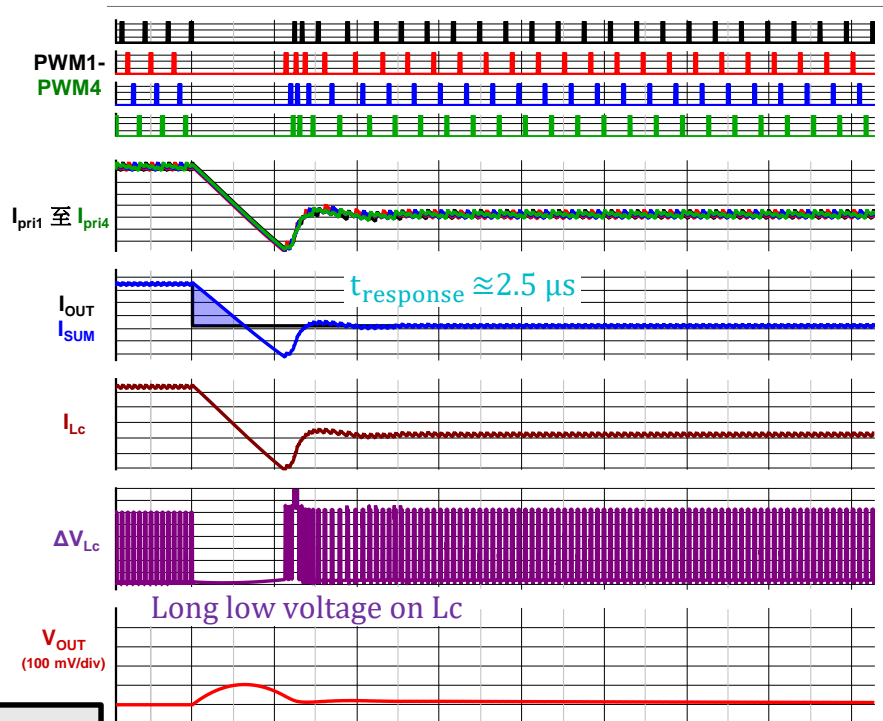
- $V_{IN} = 12 \text{ V}$
- $V_{OUT} = 0.8 \text{ V}$
- $F_{sw} = 600 \text{ kHz}$, 四相
- $I_{OUT} = 25 \text{ A}$ -325 A, 瞬時
- 降壓: $L_{buck} = 150 \text{ nH}$
- TLVR: $L_m = 150 \text{ nH}$, $L_c = 180 \text{ nH}$
- $C_{OUT} = 5 \text{ mF}$

並排比較：負載降壓

多相降壓



TLVR



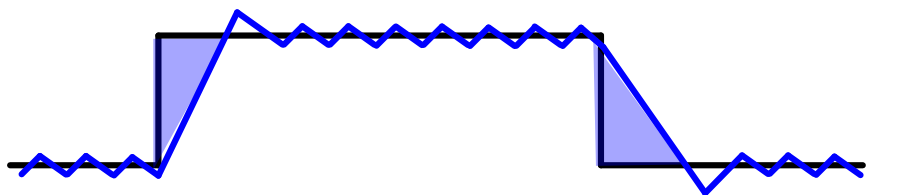
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- $C_{OUT} = 5\text{ mF}$

5 $\mu\text{s}/\text{div}$

14

DC 負載線路進一步減少輸出電容

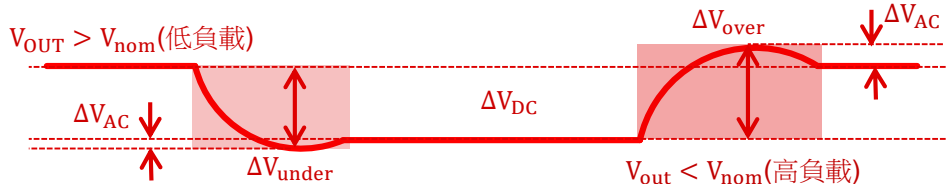
降壓與 TLVR 設計之間的 DC 負載線路 (DCLL) 行為維持相同狀態



$R_{LL} = 0 \text{ m}\Omega$



$R_{LL} \neq 0 \text{ m}\Omega$



$$R_{DCLL} = \frac{\Delta V_{DC}}{\Delta I_{step}}$$

電容器能省下

$$C_{out(min, step\ up)} = \frac{\Delta Q_{under}}{\Delta V_{under}} = \frac{\Delta Q_{under}}{\Delta V_{ac} + R_{LL} \times I_{step}}$$

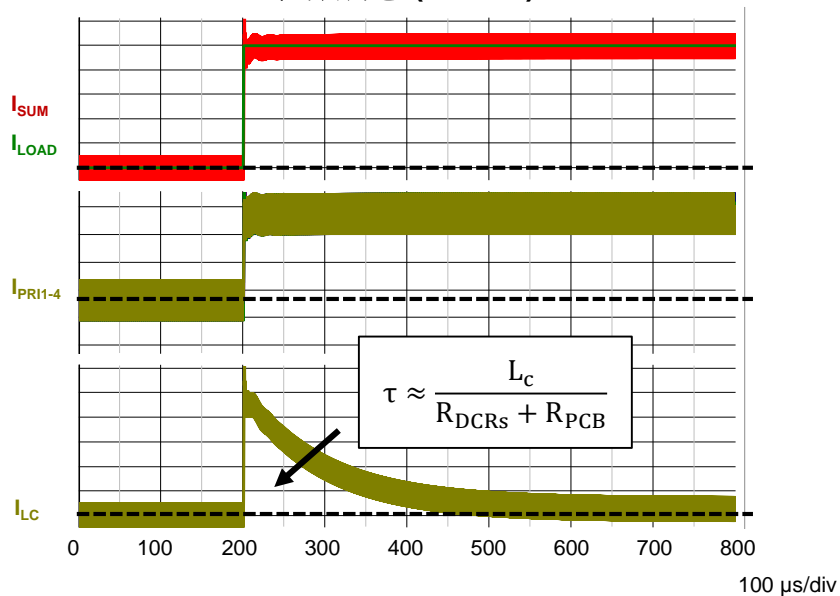
$$C_{out(min, step\ down)} = \frac{\Delta Q_{over}}{\Delta V_{over}} = \frac{\Delta Q_{over}}{\Delta V_{ac} + R_{LL} \times I_{step}}$$

輸出功率降低

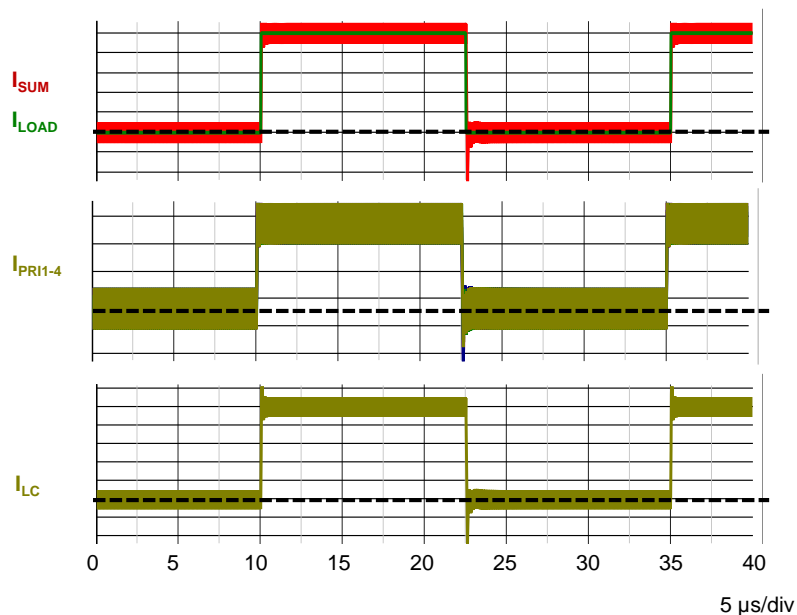
$$P_{out} = I_{out} \times (V_{out} - R_{LL} \times I_{out})$$

L_c 作為 AC 電感器 – 瞬態期間的 I_{LC}

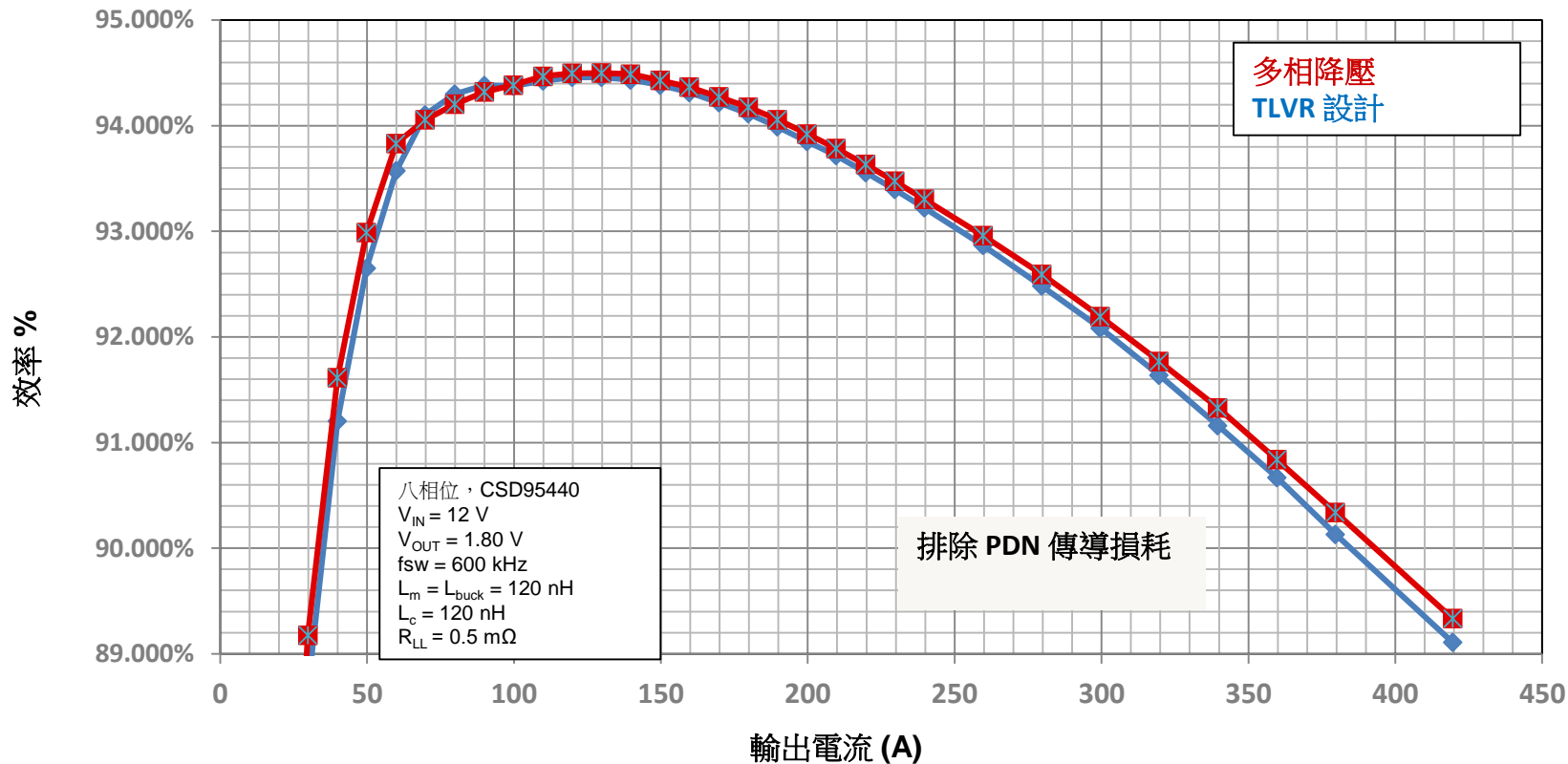
低頻瞬態 (<1 kHz)



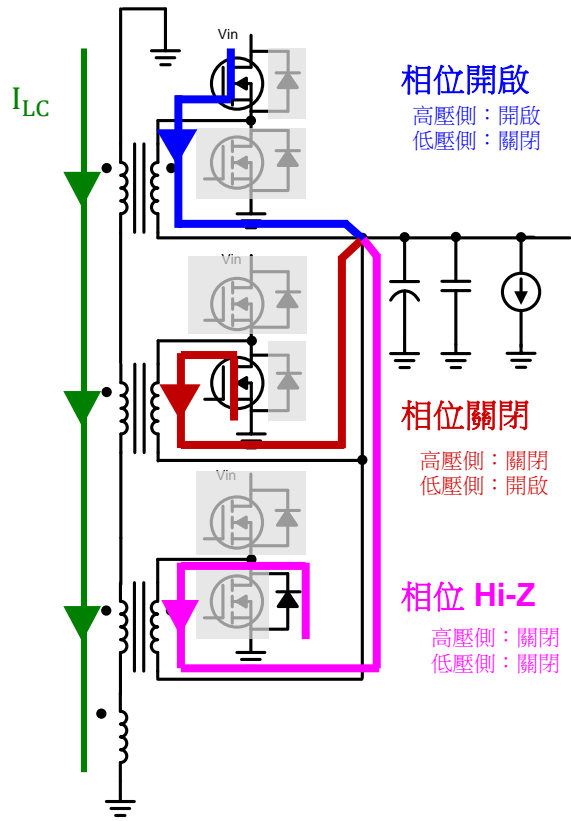
高頻瞬態 (65 kHz)



VR 與 TLVR 效率比較 ($L_{BUCK} = L_M = L_C$)



動態切相



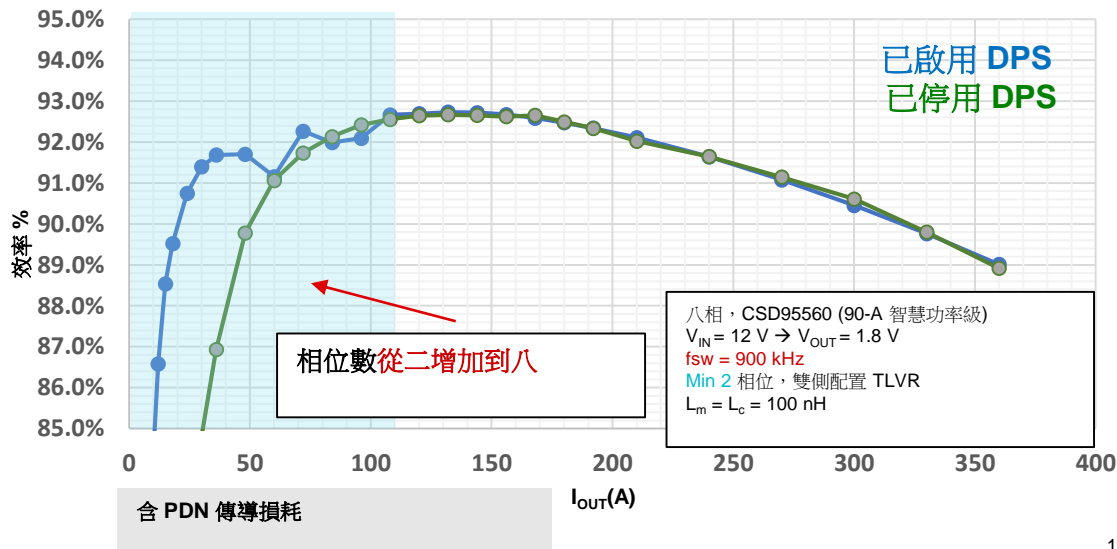
$$\Delta V_{Lc} = N_{on} \times (V_{IN} - V_{OUT}) + N_{off} \times (-V_{OUT}) + N_{HiZ} \times (V_{diode})$$

DPS 關閉時為 0

$$P_{cond,HiZ} \approx I_{rms(Lc)} \times V_{diode}$$

$$P_{cond,HiZ} \ll P_{switching}$$

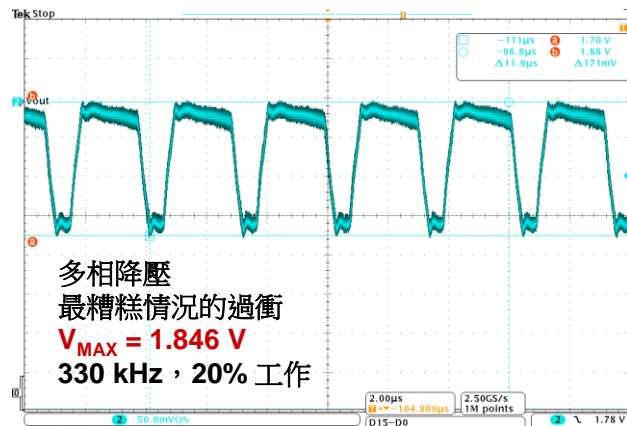
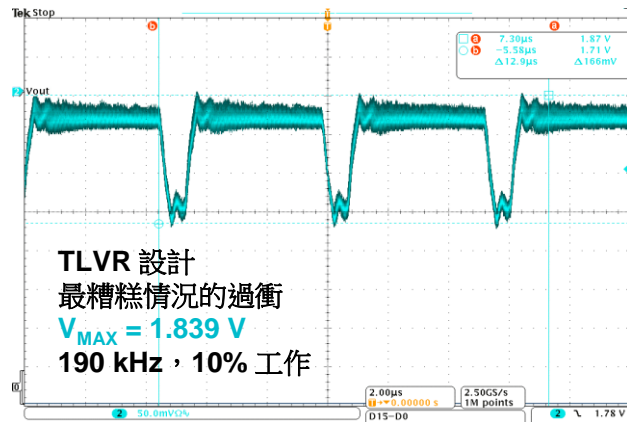
效率比較 (包括電力傳輸網路 [PDN]) 與動態相切 (DPS)



範例並排設計

參數	TLVR	多相降壓
控制器/SPS	TPS53689、CSD95440	
V_{IN}	12 V	
V_{OUT}	1.8 V	
相位數	八相位	
切換頻率	900 kHz	
載入步驟	60 A - 430 A、1000 A/ μ s、1 kHz -1 MHz	
負載線路	0.5 m Ω	
L_m/L_{buck}	150 nH	70 nH
L_c	100 nH	-
C_{bulk} (聚合物)	0 \times 470 μ F	5 \times 470 μ F
多層陶瓷電容器	80 \times 22 μ F 0402	80 \times 22 μ F 0402
	56 \times 47 μ F 0603	45 \times 47 μ F 0805
	0 \times 100 μ F 0805	15 \times 100 μ F 0805
	8 \times 0.1 μ F 0402	8 \times 0.1 μ F 0402
總 C_{out}	4.4 mF	7.7 mF

所需輸出電容降低 45%
獲得更多瞬態裕度



實務注意事項

L_c 電感器選擇

- 通常會在 L_m 以及 1.25 × L_m 之間選擇 L_c

- 所需最小均方根電流 (RMS)

$$I_{\text{rms}(L_c)} \approx \frac{\Delta I_{L_c}}{\sqrt{12}}$$

- 所需高飽和電流

$$I_{\text{sat}} \gg t_{\text{resp}} \times \left[\frac{N_{\text{on(step)}} \times V_{\text{IN}} - N_{\text{total}} \times V_{\text{OUT}}}{L_c} \right]$$

- L_c兩端的電壓可以是 ≫ V_{IN}

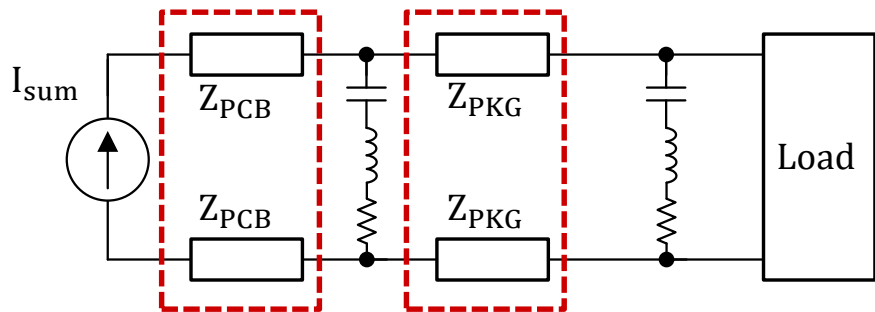
$$V_{L_c(\text{max})} = N_{\text{on(step)}} \times V_{\text{IN}} - N_{\text{total}} \times V_{\text{OUT}}$$

範例 L_c 選擇

參數	值
V _{IN}	12 V
V _{OUT}	0.8 V
F _{sw}	600 kHz
N _{total}	八相位
L _m	150 nH
L _c	180 nH
負載瞬態	50 - 500 A、1000 A/μs
ΔI _{Lc}	5.0 A
F _{LC}	4.8 MHz
I _{RMS(Lc)}	2.8 A
I _{SAT} 的裕度	25%
I _{SAT(min)}	75 A
ΔV _{Lc(max)}	30 V (N _{OVERLAP} = 3)

輸出漣波抵銷

輸出電壓漣波 (簡易模型)

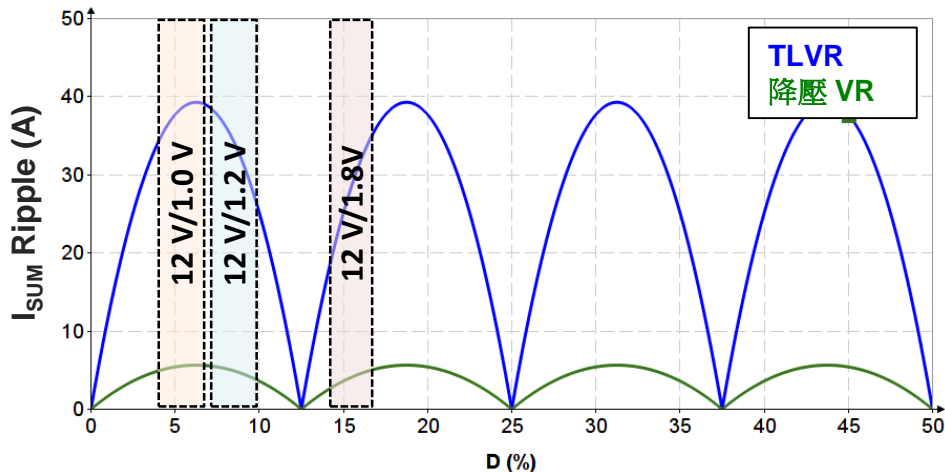


在每個相移偏移新增相同的 L_c 電流

$$I_{sum} = (I_{Lm1} + I_{Lc}) + (I_{Lm2} + I_{Lc}) + \dots$$

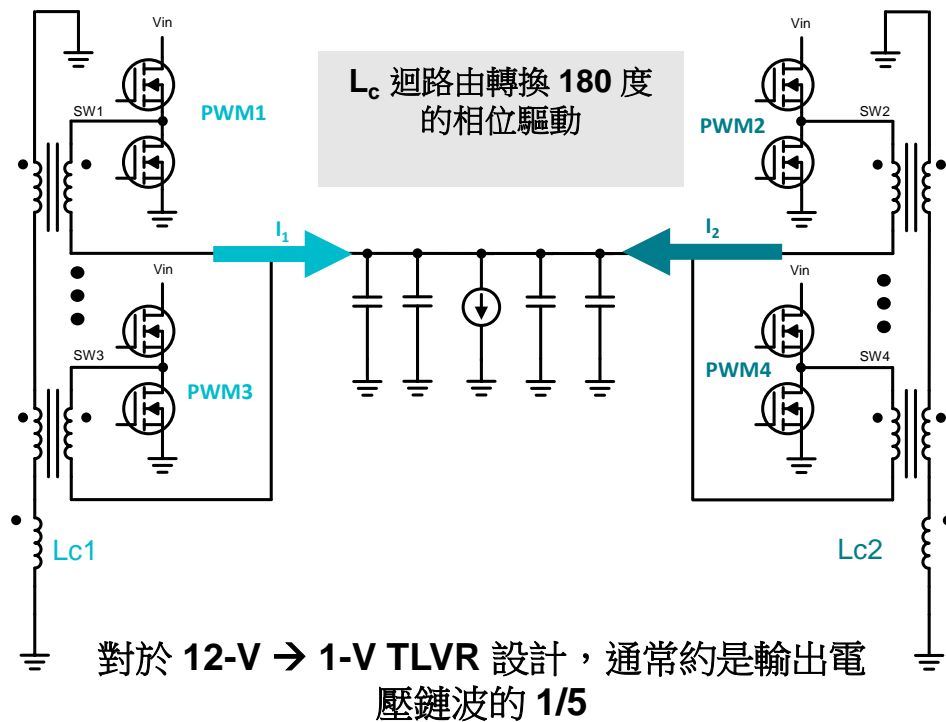
$0 \times \frac{360^\circ}{N}$ phase shift $1 \times \frac{360^\circ}{N}$ phase shift

範例：
TLVR 與多相降壓 I_{OUT} 漣波與工作週期

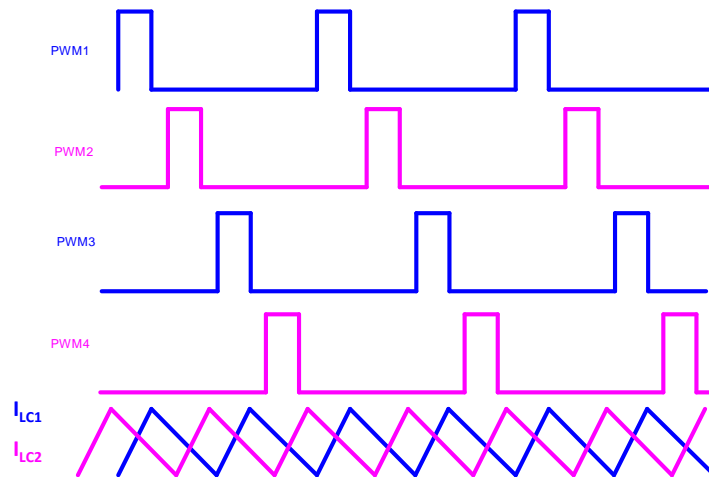


$V_{IN} = 12 \text{ V}$, $F_s = 700 \text{ kHz}$, $L_m = 150 \text{ nH}$
 $L_c = 120 \text{ nH}$, $L_{VR} = L_{eq} = 125 \text{ nH}$, 八相

鏈波電壓降低：交錯式 TLVR

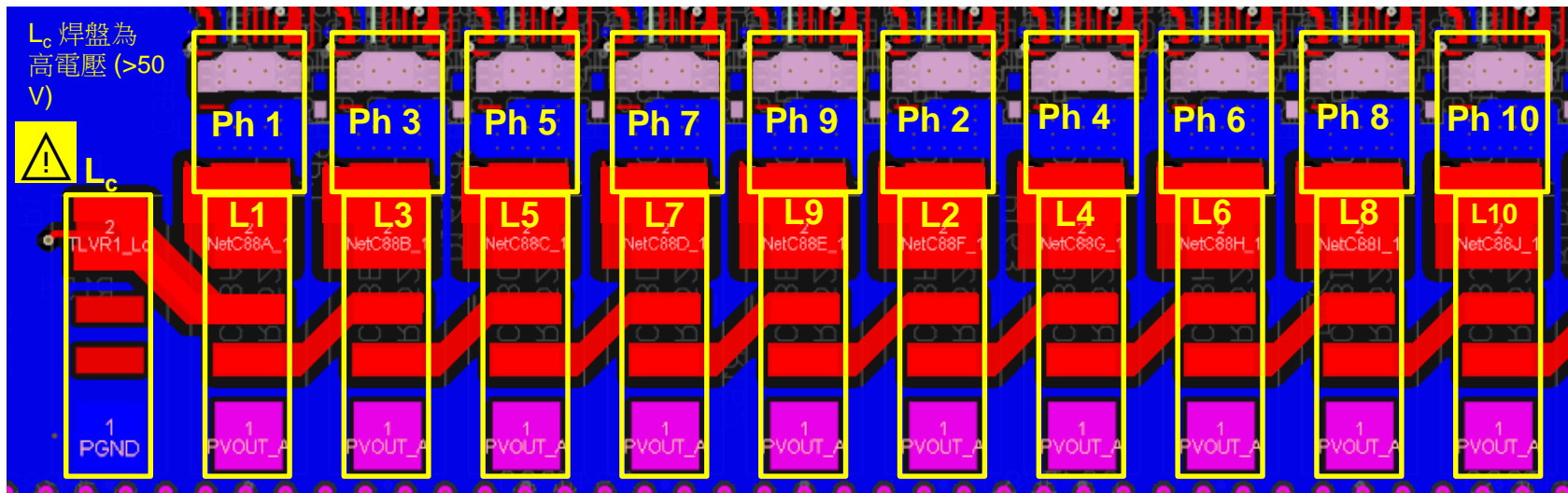


- 對於高相位數 (>12 相位) 的設計來說，建立兩個以上 L_c 迴路可實現交錯
- 對於配置與電磁干擾 (EMI) 的考量也有益處 (L_c 頻率降低，最大 L_c 電壓降低)

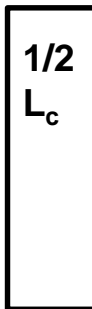


一般功率級配置

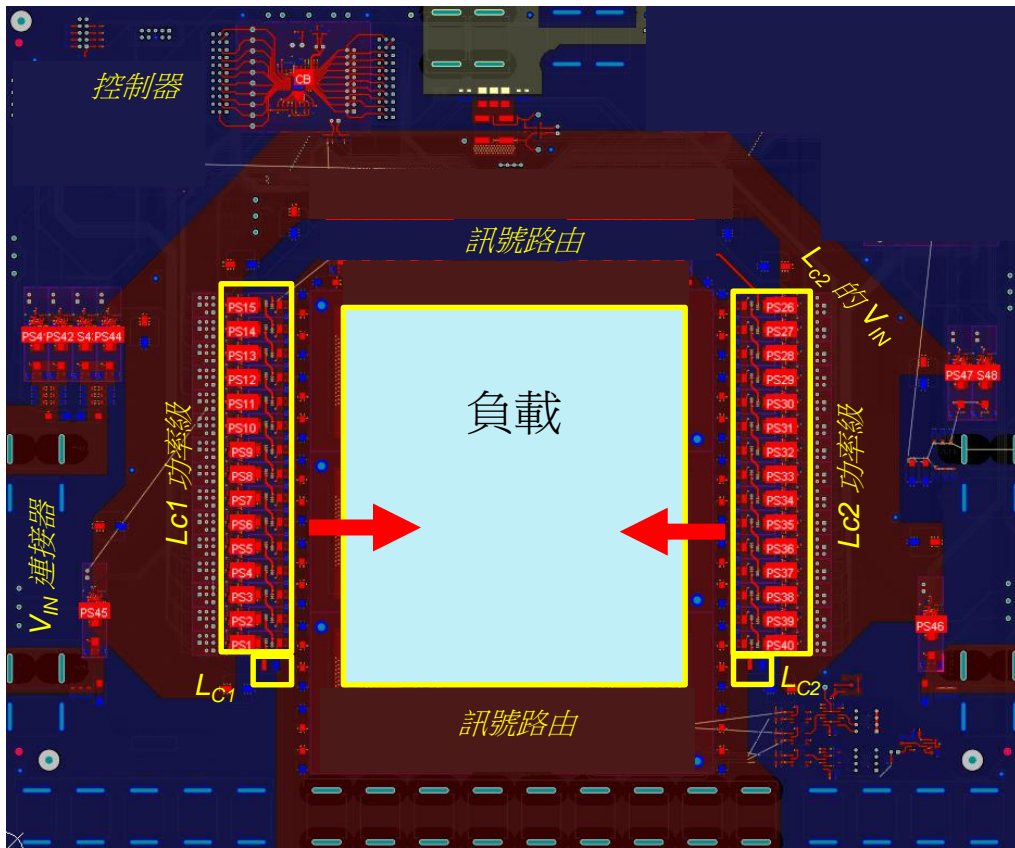
- 交叉相位開關順序可減少串音與整流器應力
- L_c 在瞬態時，仍承載高電壓
- 推薦 ≈ 50 密耳



每端可選擇減少 EMI 1/2 L_c



印刷電路板配置：多側電源傳輸



範例：

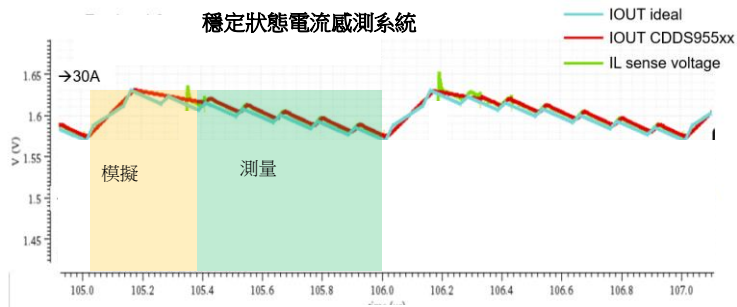
- 32 相設計
- 雙 L_c 交錯設計

建議：

- 對稱動力系統與 L_c 配置
- 去耦與輸入軌跡的電阻 (IR) 下降
- PWM 針腳軌跡電容
 - 控制器 PWM 驅動力
- 電流感測軌跡電容
 - 電流感測器 (I_{mon}) 訊號的低通濾波器效果

TLVR 最佳化的控制器和功率級

TLVR 最佳化的功率級

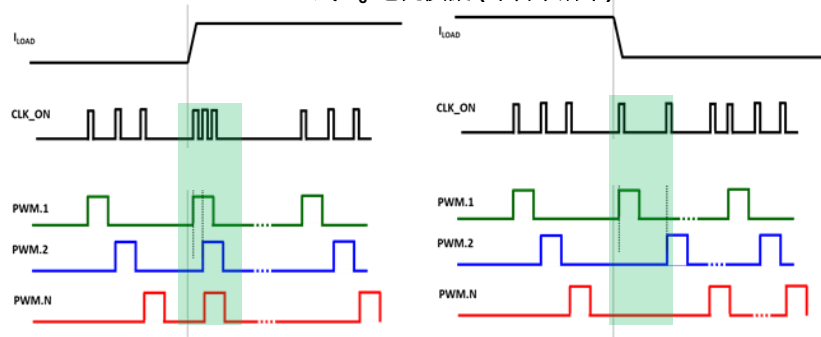


高頻寬，實際電流資訊回報

零件編號	電流額定值	封裝/功能
CSD95440	80-A 峰值、40 A _{RMS}	5 mm × 6 mm (電壓 Imon)
CSD95510	90-A 峰值、50 A _{RMS}	4 mm × 6 mm (電壓 Imon)
CSD95560	90-A 峰值、50 A _{RMS}	4 mm × 6 mm (電流 Imon)
CSD95520	60-A 峰值、30 A _{RMS}	4 mm × 5 mm (電壓 Imon)
CSD95570	60-A 峰值、30 A _{RMS}	4 mm × 5 mm (電流 Imon)

TLVR 最佳化的控制器

PWM 式 L_c 電流模擬 (專利申請中)



根據 PWM 時序的負載瞬態偵測

零件編號	相位	封裝/功能
TPS53685	8	5 mm × 5 mm AMD 介面
TPS536C5	12	6 mm × 6 mm AMD 介面
TPS53689T	8	5 mm × 5 mm Intel 介面
TPS536C9T	12	6 mm × 6 mm Intel 介面

結論

摘要

- 介紹 TLVR 拓撲
 - 降壓衍生拓撲類似於耦合電感器，適用於高相位數設計
 - TLVR 的模組化及重複使用特性更優秀，因為電感器並未共用同一核心
 - 根據耦合電感行為，能大幅省下輸出電容
- TLVR 設計的實務考量
 - 相較於降壓設計，TLVR 設計通常具備較高的鏈路電流與電壓
 - 高相位數設計交錯
 - TLVR 設計的印刷電路板配置與降壓類似，但多了 L_c 迴路
- TLVR 最佳化元件
 - 需要將高頻寬與系統級最佳化，才能實現最優化 TLVR 設計

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