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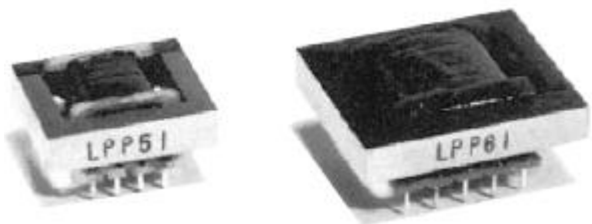
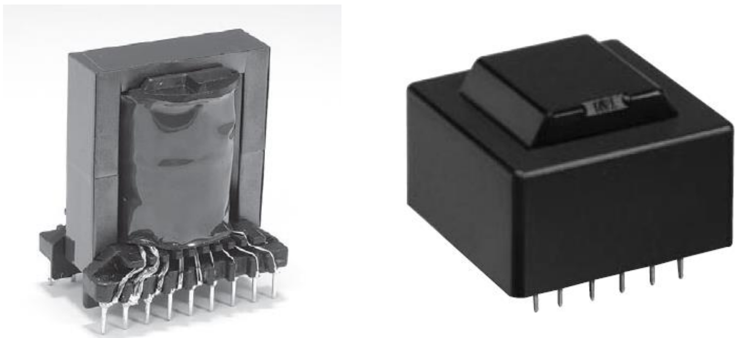
邵革良

’2014/6/21



小功率高频开关电源变压器的设计计算

Advanced Magnetics Technology



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小功率AC/DC开关电源的电路拓扑

反激电源
Flyback

正激电源
Forward

半桥电源
Half-bridge

全桥电源
Full-bridge

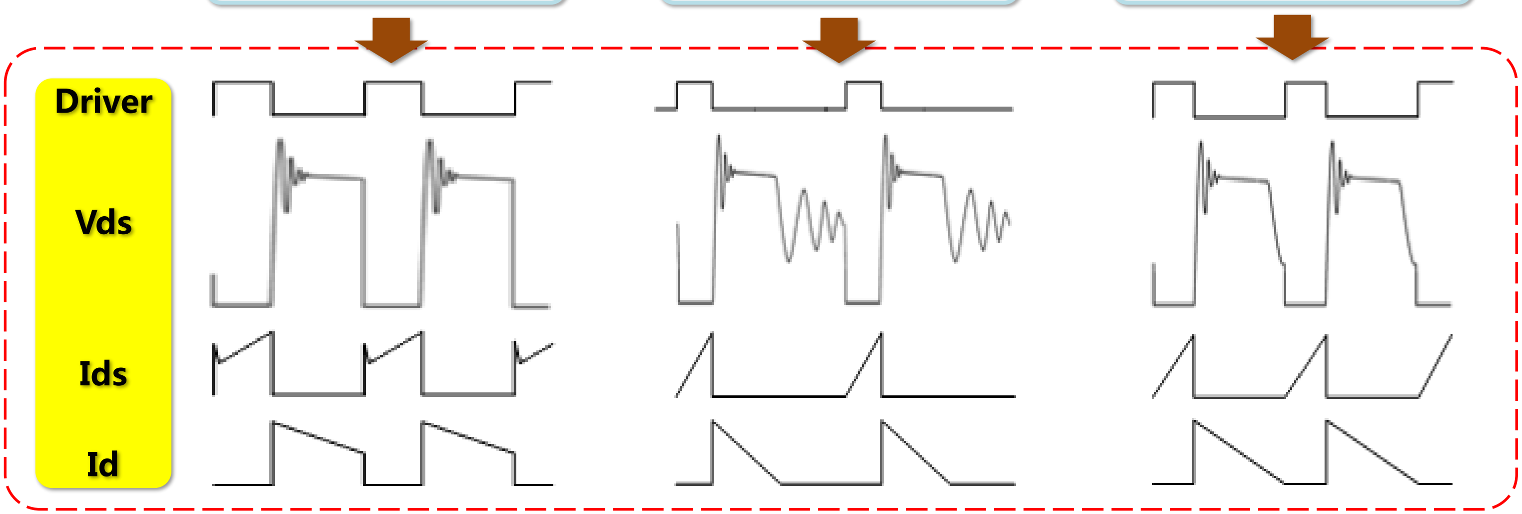
固定频率控制
Fixed Frequency

可变频率控制
Variable Frequency

电流连续模式
CCM

电流不连续模式
DCM

电流临界模式
CRM



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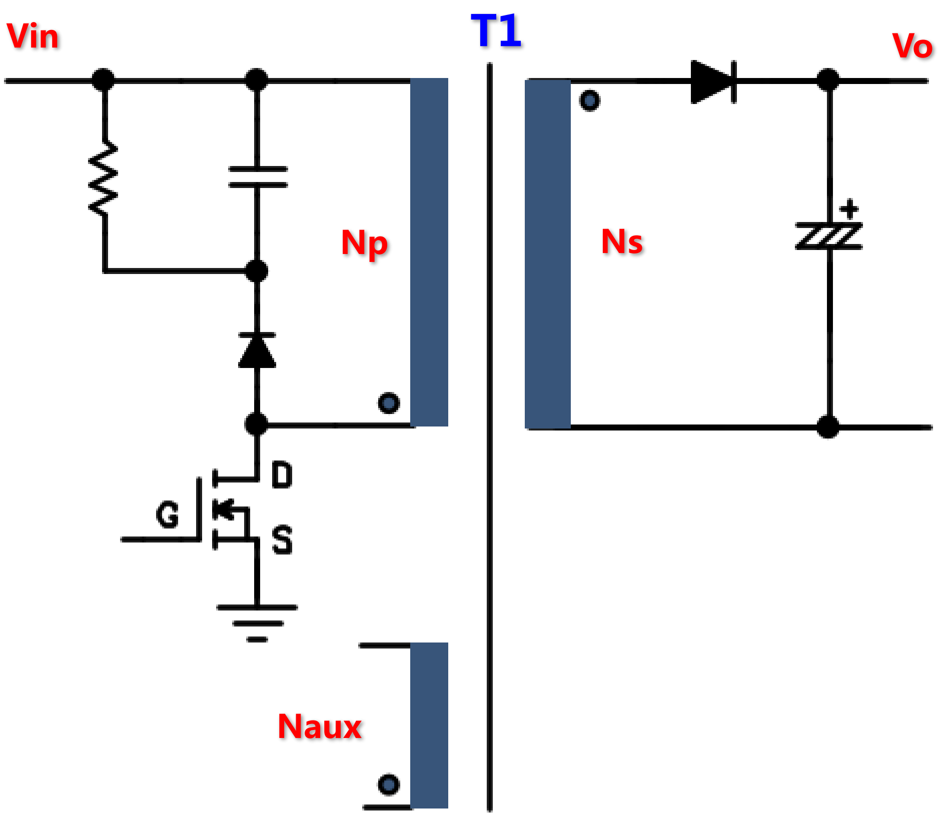
反激电源典型主电路



通用原则

- 伏秒数相等原则（磁平衡）
- T1：耦合式储能电感

两种工作模式

- 固定频率： CCM~DCM
- 准谐振模式：CRM

工作模式选定法则

- 电气性能及功能
- 成本
- EMI
- 效率
- 尺寸最优化
- 设计习惯

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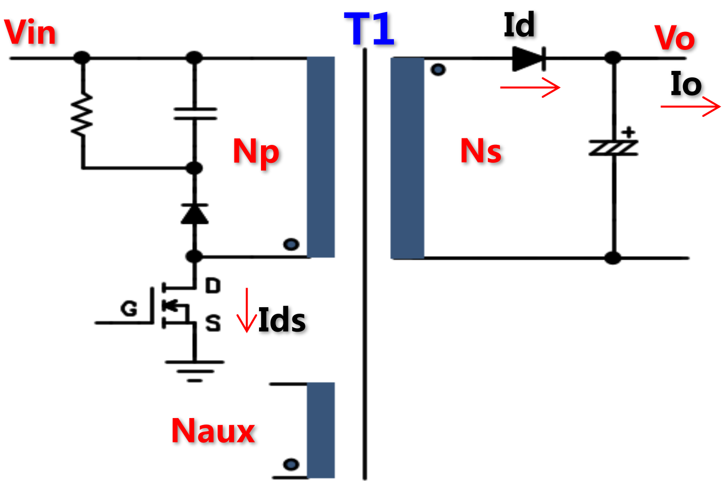
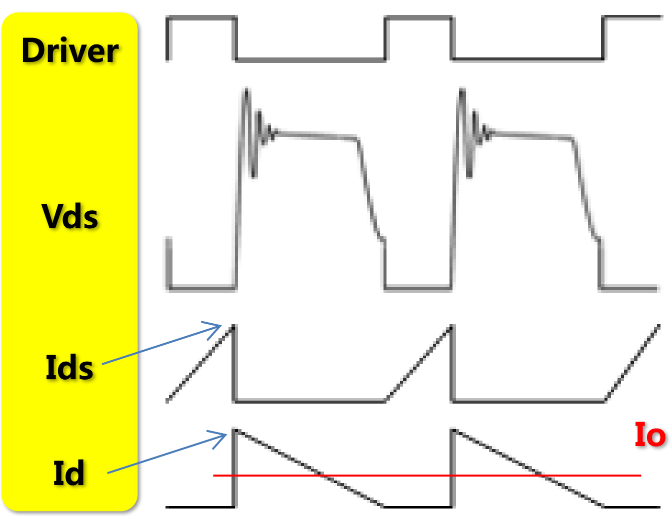
CRM反激电源的变压器设计特点





伏秒数相等

$$V_{in} \bullet T_{on} = V_o \bullet T_{off}$$

$$V_{in} \bullet D = V_o(1 - D)$$

$$\boxed{D} = \frac{V_o}{V_{in} + V_o}$$

电感储能

$$\frac{P_o}{\eta} = \frac{1}{2} \bullet I_{ds}^2 \bullet L_p \bullet f$$

$$P_o = I_o \bullet V_o$$

$$\boxed{I_{ds}^2} \bullet \boxed{f} = \frac{2P_o}{\boxed{L_p}\eta}$$

原边电流

$$\boxed{I_{ds}} = \frac{V_{in}}{L_p} \bullet T_{on} = \frac{V_{in}}{\boxed{L_p}} \bullet \frac{\boxed{D}}{\boxed{f}}$$

副边电流

$$I_o = \frac{1 - D}{2} \bullet I_D$$

储能电感续流

$$N_p \bullet I_{DS} = N_S \bullet I_D$$

$$\boxed{N_p} \bullet \boxed{I_{ds}} = \boxed{N_S} \bullet \frac{2I_o}{1 - \boxed{D}}$$

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CRM反激电源的变压器设计特点

原副边变比

$$V_C = \frac{V_O \bullet N_P}{N_S}$$

$$V_{ds} = V_{in} + V_C + \alpha(\text{spike})$$

$$\boxed{N_P / N_S = f(V_{ds}, V_{in}, V_o, \alpha)}$$

Example

$$V_{ds} = 600 \times 90\% = 540V$$

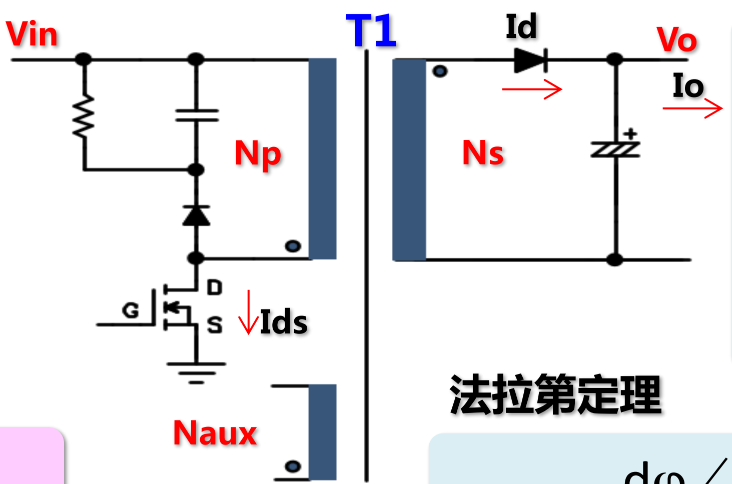
$$\alpha(spike) = 50V$$

$$V_O = 24V$$

$$V_{inmax} = 264 \times \sqrt{2} = 373.3V$$

$$N_P/N_S = 4.8625$$

Np与磁芯选取



电感量定义

$$L_P = \mu_0 \bullet \mu_e \bullet A_e/l_e \bullet N_P^2 = AL \bullet N_P^2$$

法拉第定理

$$E = N_P \bullet d\varphi/dt = N_P \bullet A_e \bullet \Delta B/\Delta t$$

$$E = L_P\, dI(L_P)/dt = L_P\, \Delta I_{DS}/\Delta t$$

$$\boxed{\Delta B = Bmax = \frac{L_P \bullet I_{DS}}{N_P \bullet A_e}}$$

➡ **360mT**

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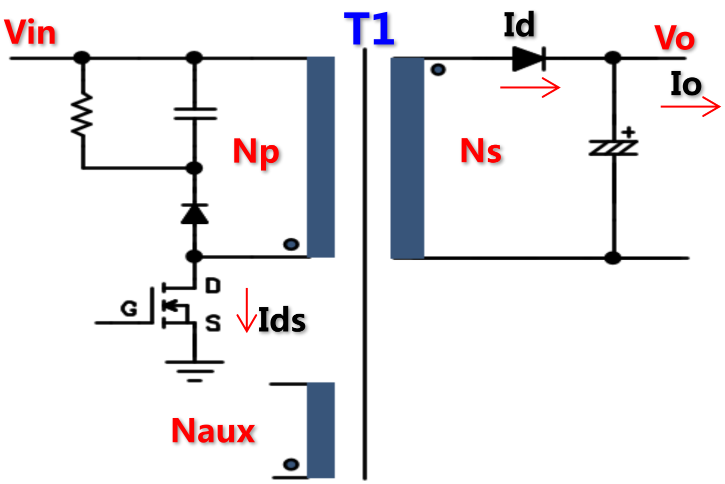
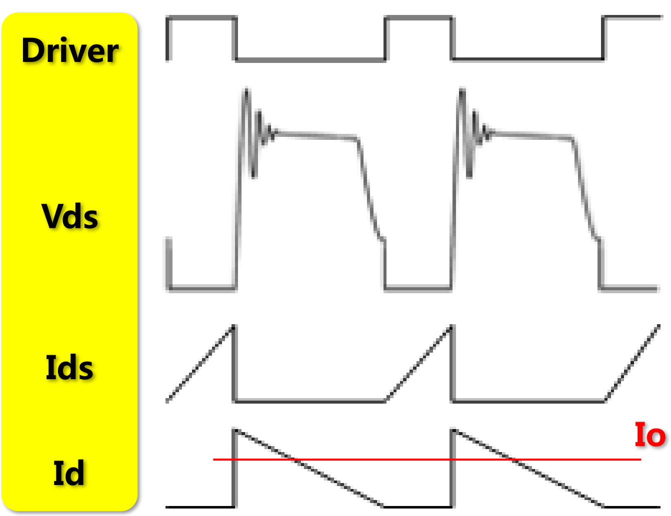
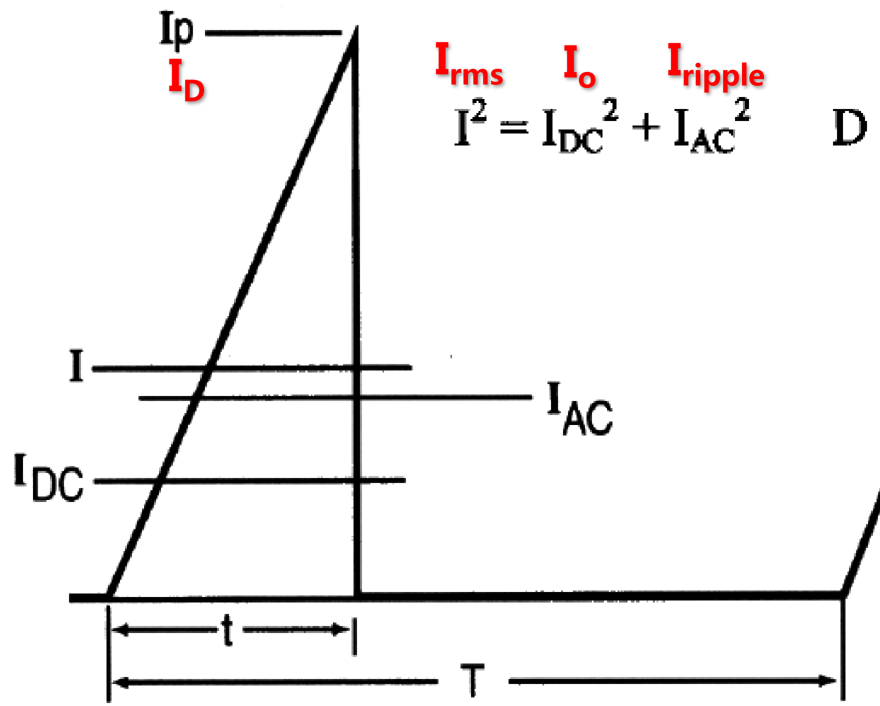
CRM反激电源的变压器设计特点







$$I^2 = I_{DC}^2 + I_{AC}^2 \qquad D = t/T$$

$$I_{DC} = I_P D/2$$

$$I_{AC} = I_P(D/3 - D^2/4)^{1/2}$$

$$I = I_P(D/3)^{1/2}$$

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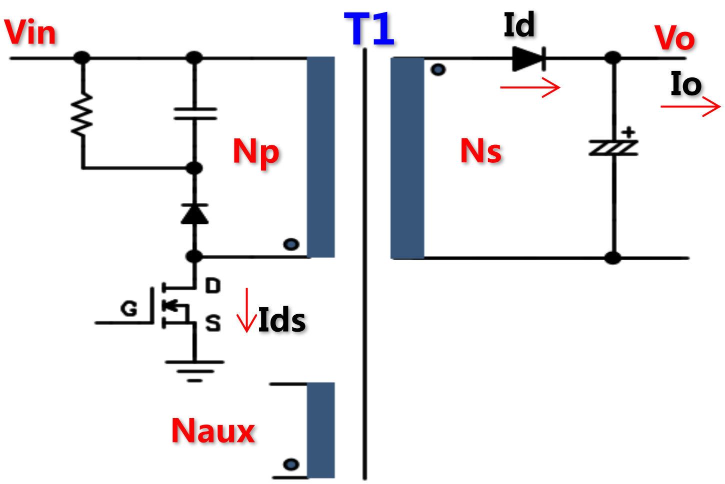
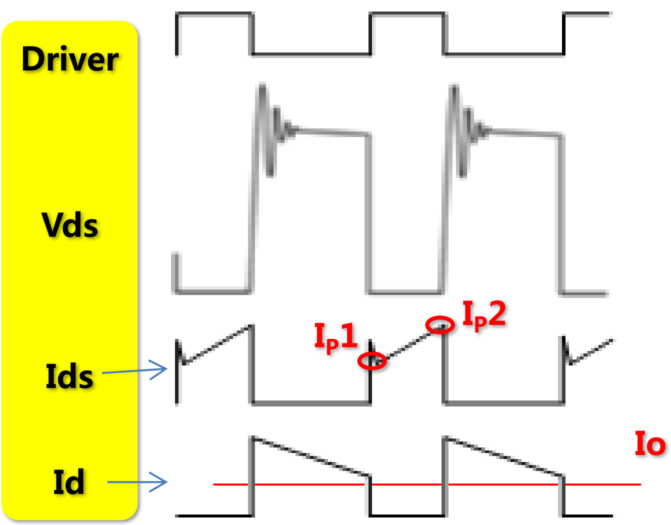
CCM反激电源的变压器设计特点





伏秒数相等

$$V_{in} \bullet T_{on} = V_o \bullet T_{off}$$

$$V_{in} \bullet D = V_o(1-D)$$

$$\boxed{D} = \frac{V_o}{V_{in} + V_o}$$

电感电流

$$\Delta I_P = \frac{V_{in}}{L_P} \bullet T_{on} = \frac{D \bullet V_{in}}{f \bullet L_P}$$

副边电流

$$I_O = \frac{N_P}{N_S} \bullet (I_{P1} + I_{P2})(1-D)$$

电感储能

$$\frac{P_o}{\eta} = \frac{1}{2} \bullet (I_{p2}{}^2 - I_{p1}{}^2) \bullet L_p \bullet f$$

$$= \frac{I_{p2} + I_{p1}}{2} \bullet (I_{p2} - I_{p1}) \bullet L_p \bullet f$$

$$= \frac{I_{p2} + I_{p1}}{2} \bullet \Delta I_p \bullet L_p \bullet f$$

$$P_o = I_o \bullet V_o$$

$$(I_{p1} + I_{p2})\Delta I_p \bullet f = \frac{2P_o}{L_p \eta}$$

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CCM反激电源的变压器设计特点

原副边变比

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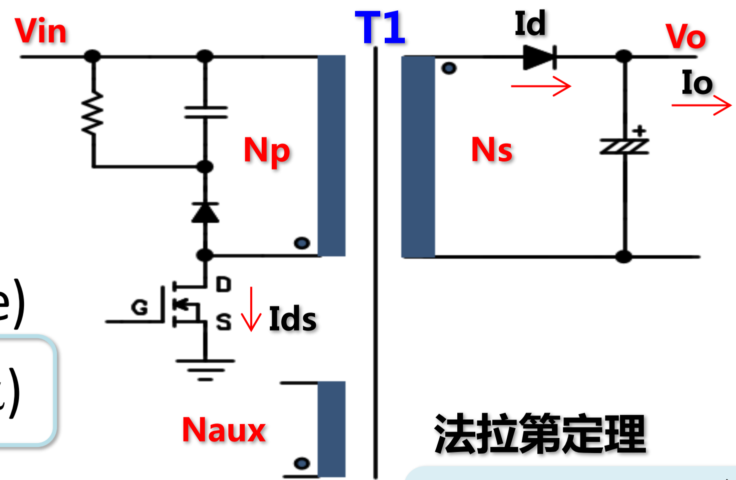

Np与磁芯选取

电感量定义

$$L_P = \mu_0 \bullet \mu_e \bullet A_e/l_e \bullet N_P^2 = AL \bullet N_P^2$$

法拉第定理

$$E = N_P \bullet d\varphi/dt = N_P \bullet A_e \bullet \Delta B/\Delta t$$

$$E = L_P\, dI(L_P)/dt = L_P\, \Delta I_P/\Delta t$$

$$\Delta B = \frac{L_P \bullet I_P}{N_P \bullet A_e}$$

$$\Delta B/B1 = \Delta I_P/I_{P1}$$

$$\Delta B/B2 = \Delta B/B_{max} = \Delta I_P/I_{P2}$$

B_{max} ➡ **360mT**

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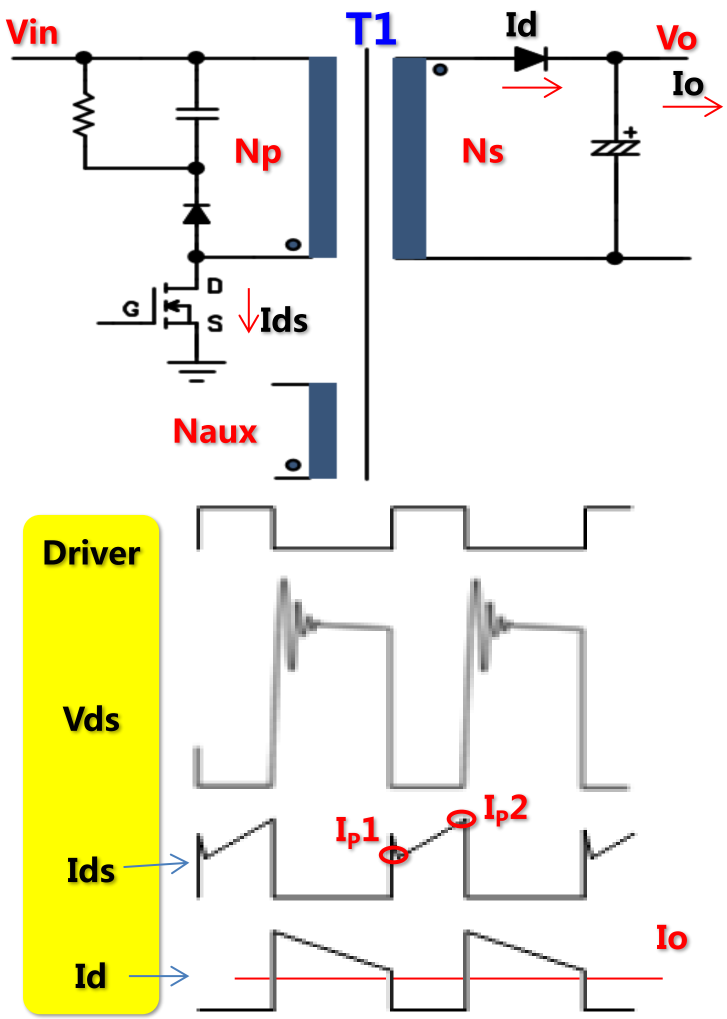
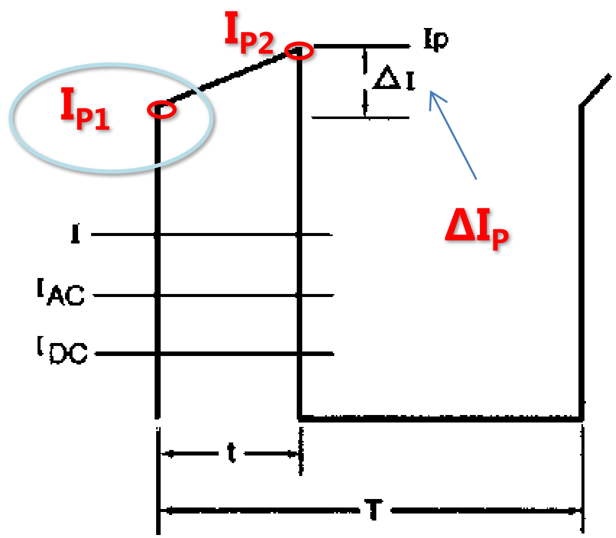
CCM反激电源的变压器设计特点



I_{rms} I_o I_{ripple}

$$I^2 = I_{DC}^2 + I_{AC}^2 \qquad D = t/T$$



$$I_{DC} = (I_P - \Delta I/2)D$$

$$I_{AC} = (I_P - \Delta I/2)[D(1-D)]^{1/2}$$

$$I = (I_P - \Delta I/2)D^{1/2}$$

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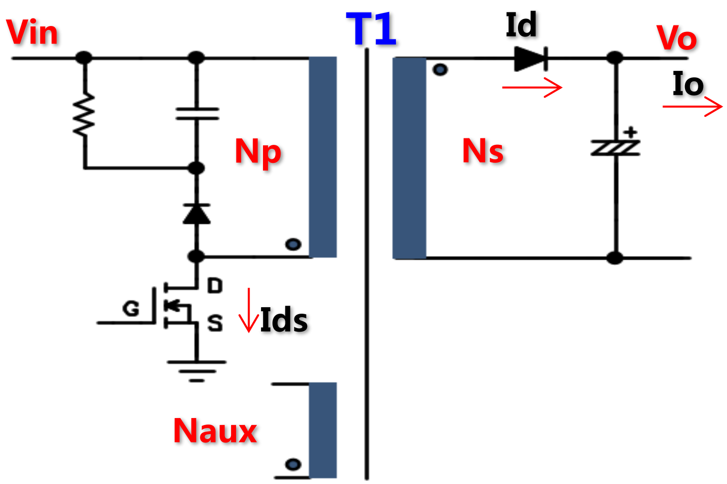
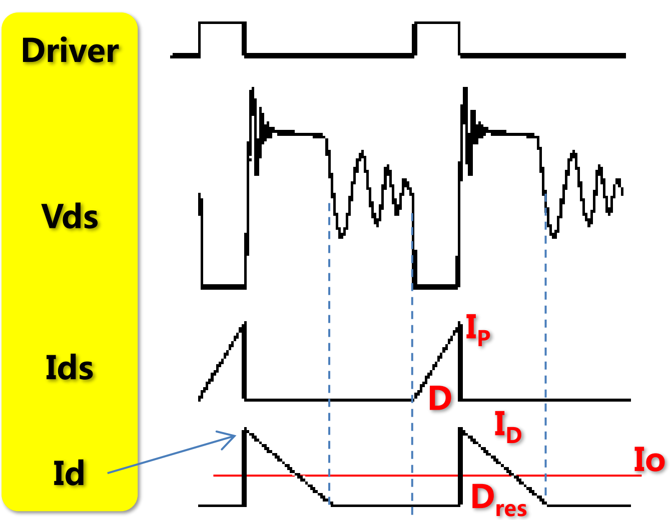
DCM反激电源的变压器设计特点





$$V_{in} \bullet D = V_O \bullet D_{res}$$

伏秒数相等

$$\frac{D}{f} \bullet \frac{V_{in}}{L_P} = I_P$$

电感峰值电流

$$\frac{I_P^{2}}{2} \bullet L_P \bullet f = \frac{I_O \bullet V_O}{\eta}$$

能量存储

$$I_O = D_{res} \bullet {}^{I_D}\!/_{2}$$

直流分量

$$I_P \bullet N_P = I_D \bullet N_S$$

电感续流

$$\frac{D_{res}}{f} \bullet \frac{V_O}{L_S} = I_D$$

电感放电电流

$$L_P / N_P^{2} = L_S / N_S^{2}$$

AL值

$$V_{ds} = V_{in} + \frac{V_O \bullet N_P}{N_S} + \alpha(\text{spike})$$

MOS耐压

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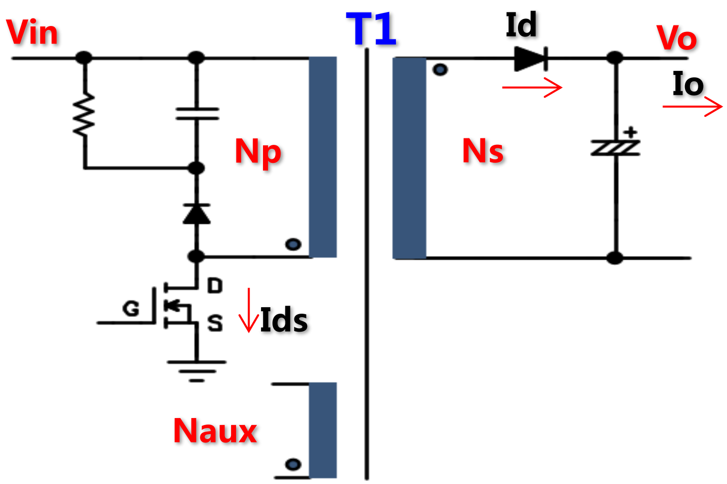
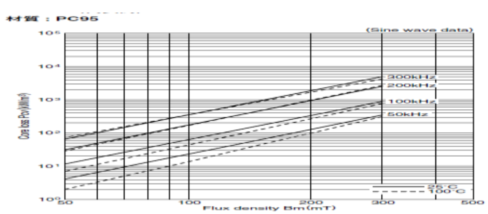
DCM反激电源的变压器设计特点



任何状态下

1）不能饱和

2）损耗（温升）OK



Np与磁芯选取

电感量定义

$$L_P = \mu_0 \bullet \mu_e \bullet A_e / l_e \bullet N_P^2 = AL \bullet \boxed{N_P}^2$$

法拉第定理

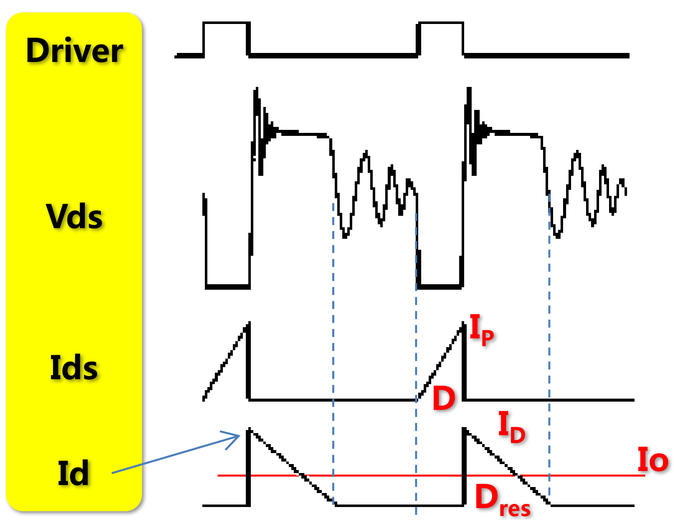
$$E = N_P \bullet d\varphi / dt = N_P \bullet A_e \bullet \Delta B / \Delta t$$

$$E = L_P\, dI(L_P) / dt = L_P\, \Delta I_P / \Delta t$$

$$\Delta B = \frac{L_P \bullet I_P}{N_P \bullet A_e}$$

$$B_{max} = \Delta B$$

➡ **360mT**



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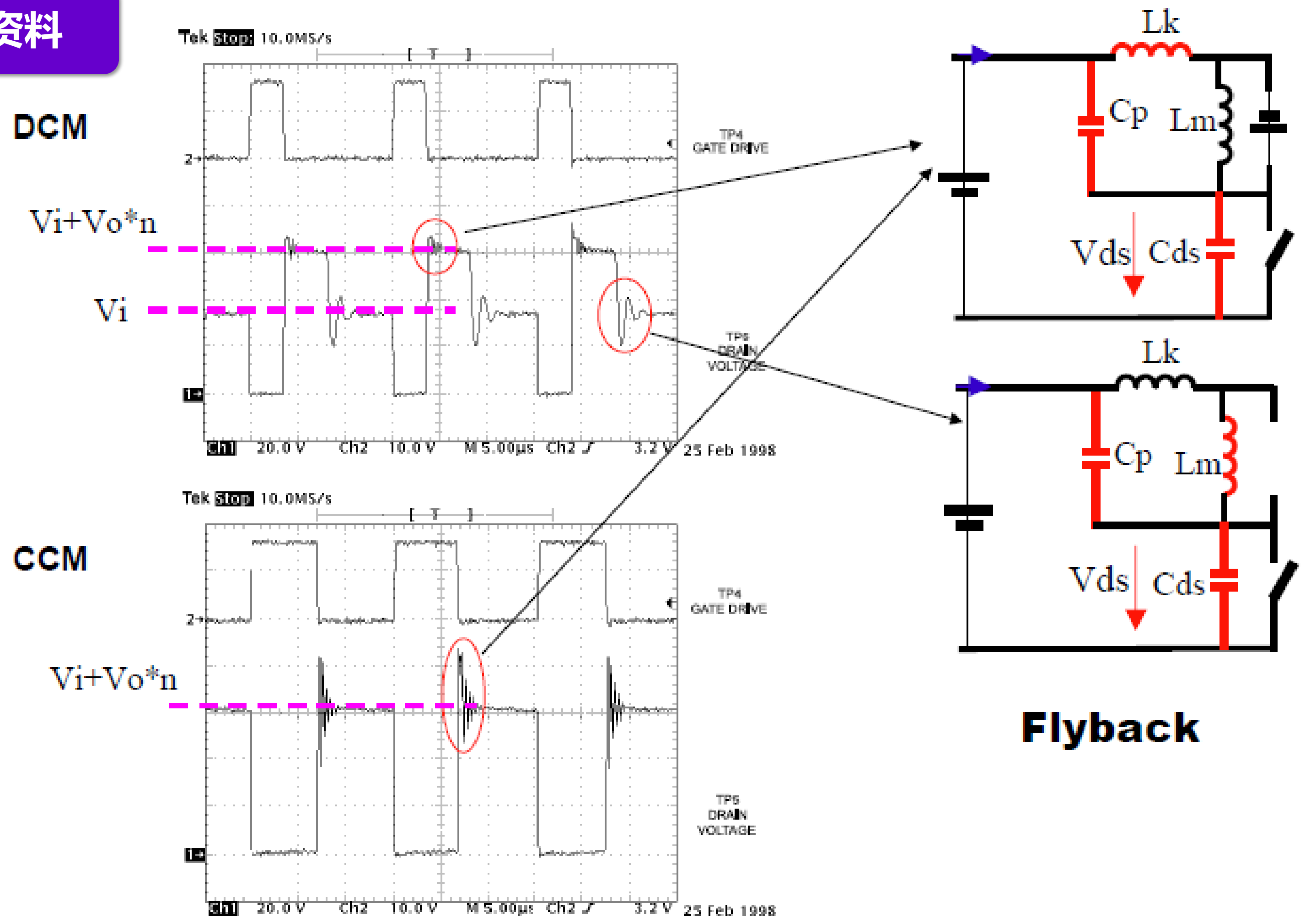
福州大学 FUZHOU UNIVERSITY

影响电压/电流应力的分布参数

陈为老师资料



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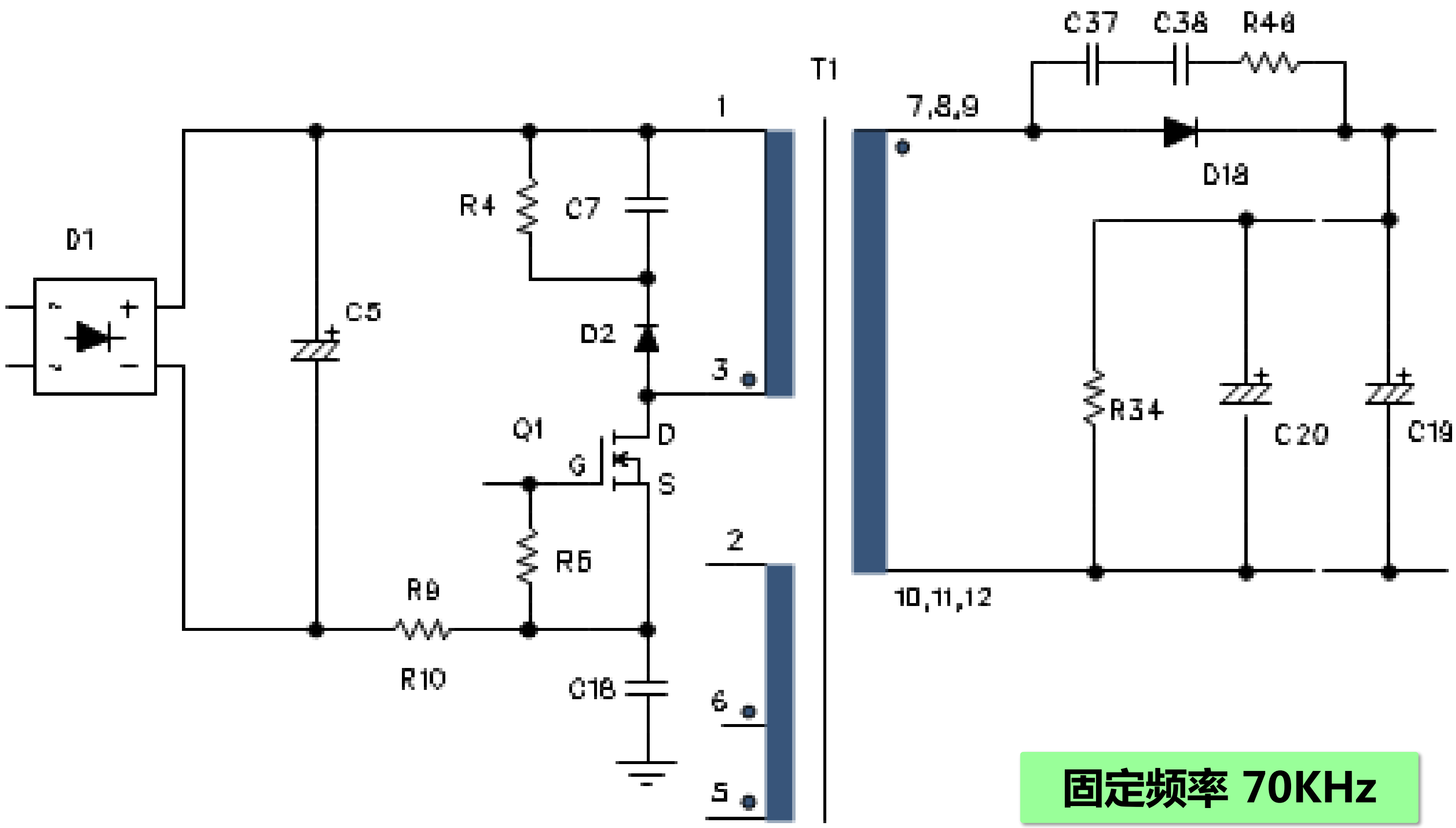
实例：24V/35W 反激电源主电路



固定频率 70KHz

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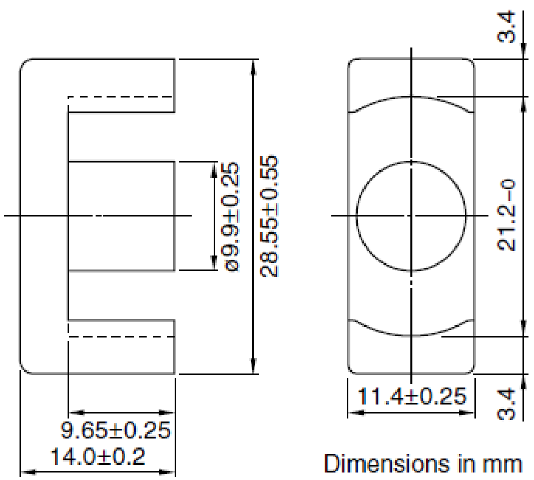
实例：24V/35W 70KHz固定频率设计

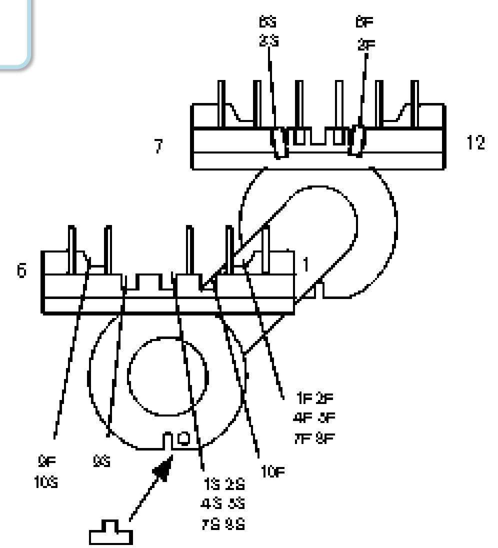
基本要求

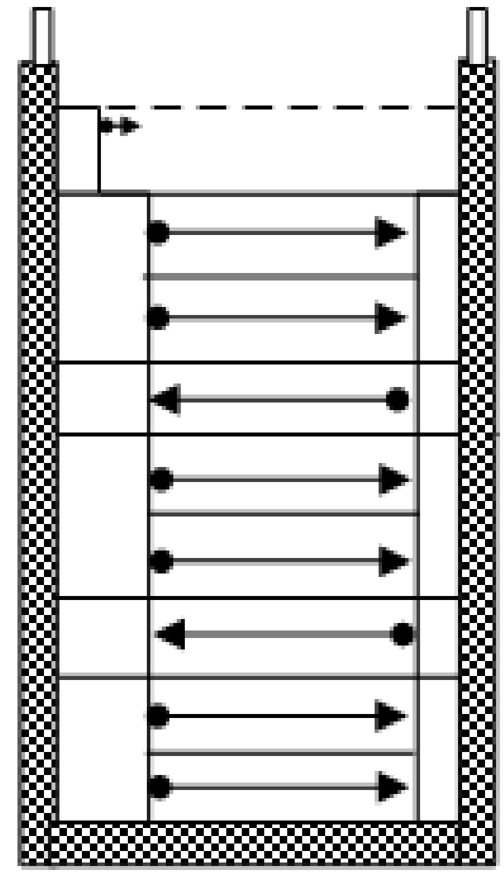
输入电压：85~264Vac
输出电压：24V±15%　35Wmax
工作频率：70KHz
MOS耐压：600V
整流管耐压：150V
电源效率：88% @100~240Vac
铁氧体磁芯：EER28 PC40
安规距离：5.5mm

C_1	mm^{-1}	0.78
ℓe	mm	64.0
Ae	mm^2	82.1
Ve	mm^3	5250
Acp	mm^2	77.0
Acp min.	mm^2	73.1
Acw	mm^2	114
	g	28



Dimensions in mm





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实例：24V/35W 70KHz固定频率设计

现场计算演示

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Frequency (KHz)	Output Power		Rectify Diode			Core Infomation					Winding Turns		
	Vo	Io	VF	VR	Sparkle	Material	Size	Ae(mm^2)	Ve(mm^3)	Rth(°C/W)	Np	Ns	Lp
70	24.0V	1.46A	0.65V	150.0V	20%	PC40	EER28	82.1	5250	22.9	**39T**	**9T**	**500uH**

Input Volatge Range					Device Derating Ratio		Tranformer Turns Trying Info.						
CL.Point	Minimum	Rating	Max.Rating	Maximum	FET(600V)	Diode	Turn Ratio	Np	15T	16T	17T	18T	19T
HoldupTime	85Vac	100Vac	**240Vac**	264Vac	**92%**	**85%**	Np:Ns	Ns	**4T**	4T	4T	4T	4T
50V	100V	120V	339V	373V	552.2V	127.5V	4.333 : 1	Err.Range	13%	8%	**2%**	4%	10%

DC Input	Duty	T_on	T_Diode_on	Working Conditions in **Core**			Bobbin	**FER28-PB20**		Others			
				Bmax	ΔB	Ploss_Core	MarginTape	Pin Side	5.5mm	Period	Ls	AL (nH/N^2)	Gap (mm)
50V	68.12%	9.73us	4.55us	0.241T	0.152T	0.11W		Wing Side	3.0mm	14.29us	26.63uH	329	0.62
100V	50.16%	7.17us	6.71us	0.224T	0.224T	0.30W	Wind.Space	8.0 mm					
120V	41.80%	5.97us	6.71us	0.224T	0.224T	0.30W	Windings	Total Lays	Wire Para.	Occupation	Max. Φ		WirePick
339V	14.78%	2.11us	6.71us	0.224T	0.224T	0.30W	P_Wire	**6 Layers**	**1 para.**	**1.0 Np**	ϕ0.200	→	**0.16U-2**
373V	13.44%	1.92us	6.71us	0.224T	0.224T	0.30W	S_Wire	**2 Layers**	**1 para.**	**1.0 Np**	ϕ0.800	→	**0.65U-2**

DC Input	Working Condition On **Primary Coil**							Working Condition On **Secondary Coil**					
	I1	I2	ΔI	Idc	Iac	Irms	Cur.Density	I1	I2	ΔI	Iac(Ripple)	Irms	Cur.Density
50V	0.57A	1.54A	0.97A	0.72A	0.54A	0.90A	7.47A/mm2	6.68A	2.47A	4.22A	2.24A	2.67A	4.03A/mm2
100V	0.00A	1.43A	1.43A	0.36A	0.46A	0.59A	4.86A/mm2	6.21A	0.00A	6.21A	1.98A	2.46A	3.70A/mm2
120V	0.00A	1.43A	1.43A	0.30A	0.44A	0.54A	4.43A/mm2	6.21A	0.00A	6.21A	1.98A	2.46A	3.70A/mm2
339V	0.00A	1.43A	1.43A	0.11A	0.30A	0.32A	2.64A/mm2	6.21A	0.00A	6.21A	1.98A	2.46A	3.70A/mm2
373V	0.00A	1.43A	1.43A	0.10A	0.29A	0.30A	2.51A/mm2	6.21A	0.00A	6.21A	1.98A	2.46A	3.70A/mm2

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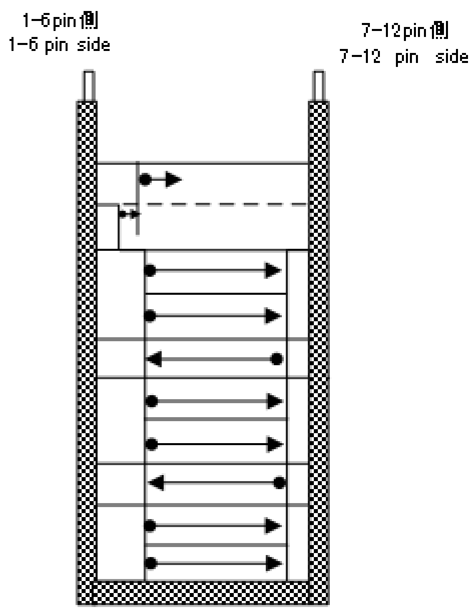
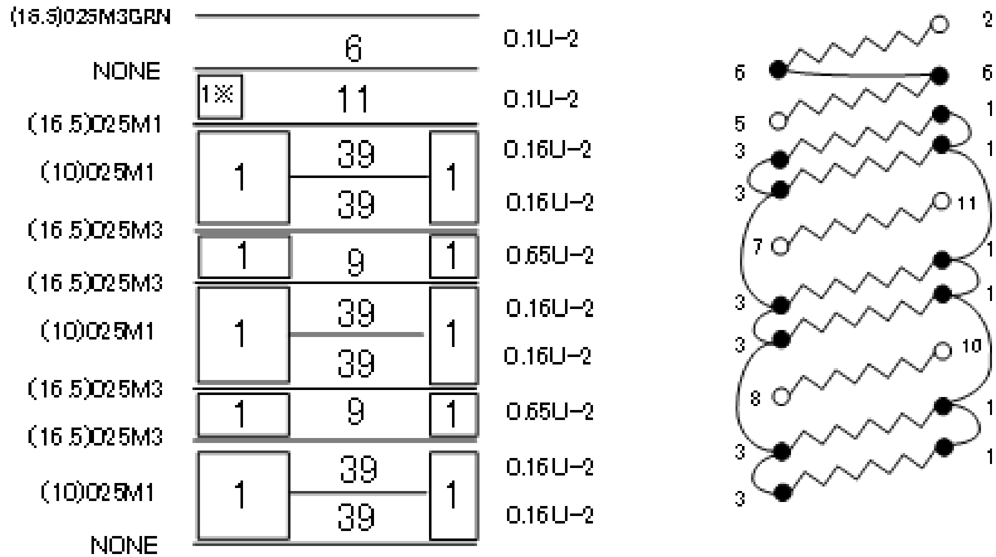
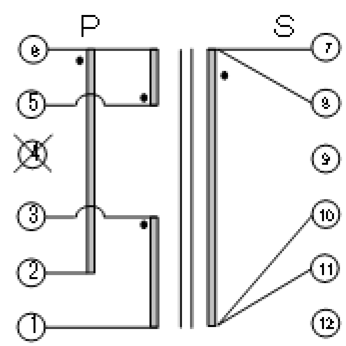
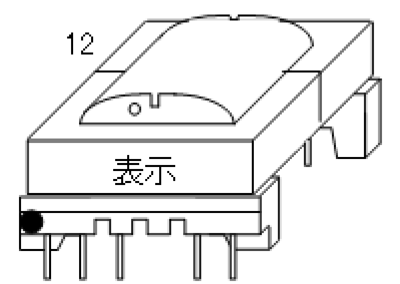
实例：24V/35W 70KHz固定频率设计

变压器绕制









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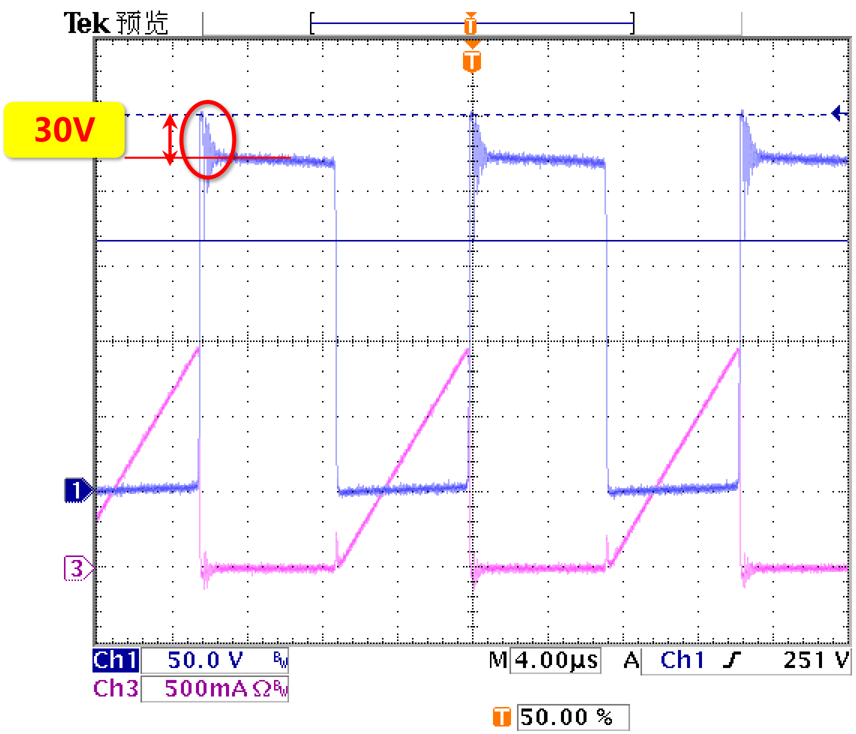
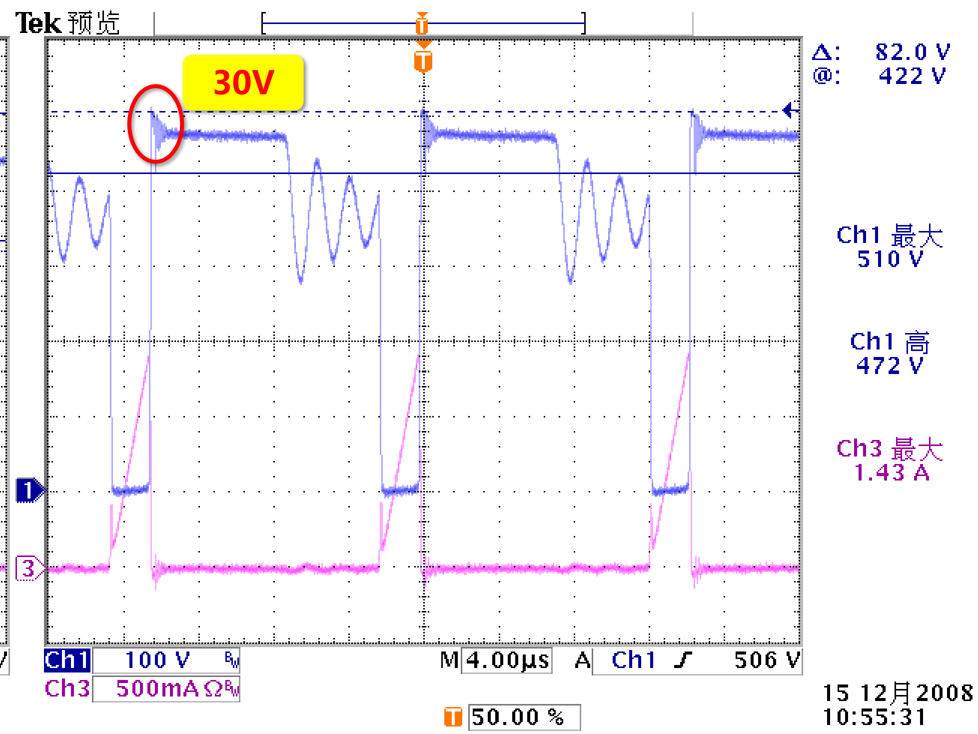
实例：24V/35W 70KHz固定频率设计

实际工作波形



85Vac 24V/35W满载



264Vac 24V/35W满载

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Change the World (Q&A)

Innovation

Cooperation

Optimization

Thank you !

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