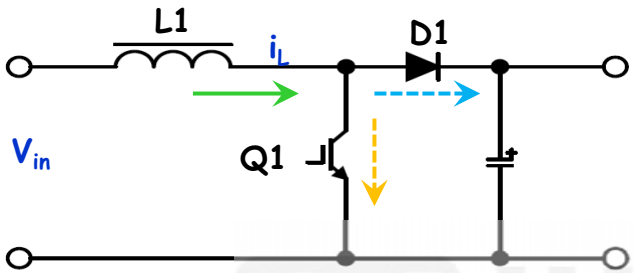
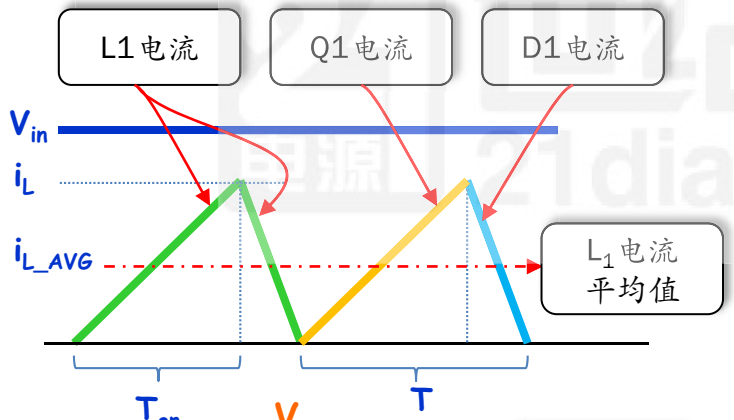
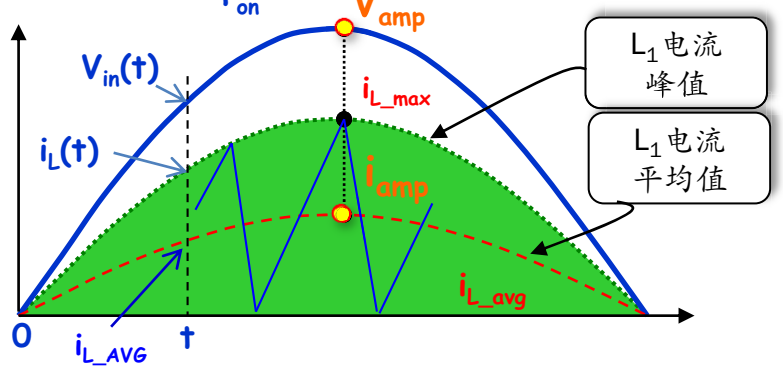
CRM模式PFC电感的设计计算







CRM PFC控制机理

$$i_{L(t)} = \frac{T_{on(Fix)}}{L} \cdot V_{in(t)} = \mathbf{Cont} \cdot Vin(t)$$

$$V_{in}(t) \cdot D = (V_o - V_{in}(t)) \cdot (1 - D) \Rightarrow D$$

$$f_{min} = \frac{D}{T_{on}} = \frac{V_o - Vamp}{V_o} \cdot \frac{1}{T_{on}}$$

$$V_{amp} = \sqrt{2} \cdot V_{AC} \qquad i_{Lmax} = 2 i_{amp}$$

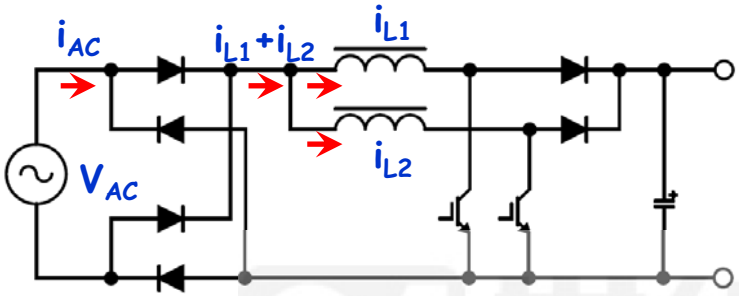
$$i_{Lmax} = \frac{V_{amp}}{L} \cdot T_{on} \qquad i_{amp} = \frac{\sqrt{2}}{V_{AC}} \cdot \frac{P_o}{\eta \cdot PF}$$

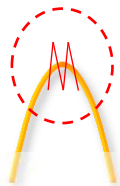
$$\Rightarrow f_{min} = \frac{V_o - \sqrt{2} V_{AC}}{V_o} \cdot \frac{V_{AC}^2}{2L} \cdot \frac{\eta \cdot PF}{P_o}$$

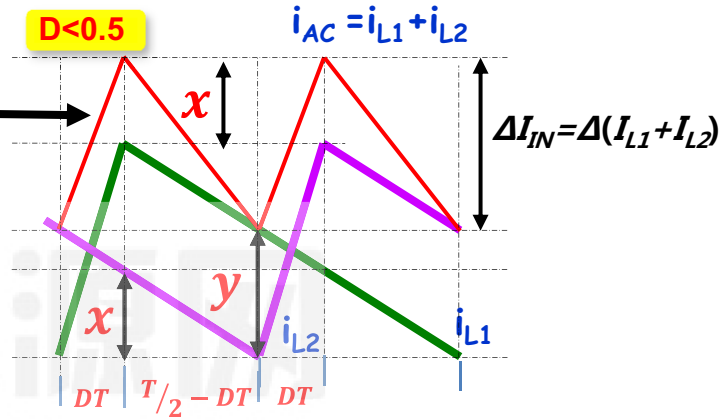
$$T_{on} = \frac{2L}{V_{AC}^2} \cdot \frac{P_o}{\eta \cdot PF}$$

$$f(t) = \frac{V_o - Vin(t)}{V_o} \cdot \frac{V_{AC}^2}{2L} \cdot \frac{\eta \cdot PF}{P_o}$$

- CCM Interleave PFC电感的设计计算







交错并联电感电流纹波叠加

D<0.5

$$\Delta I_{L1+L2} = \frac{V_{in}}{L}\cdot DT + \frac{V_{in}}{L}\cdot DT - \frac{V_o - Vin}{L}\cdot\frac{1}{2} - \left(\frac{V_{in}}{L}\cdot DT - \frac{V_o - Vin}{L}\cdot\left(\frac{1}{2} - D\right)T\right)$$

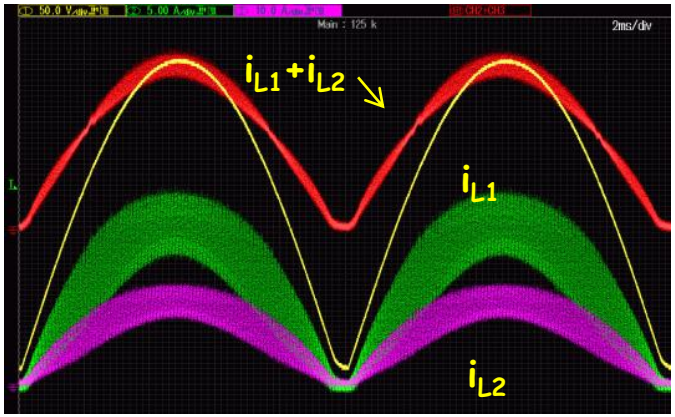
同理

$$= \frac{2V_{in} - Vo}{L}\cdot DT$$

D>0.5

$$\Delta I_{L1+L2} = \frac{V_{in}}{L}\cdot(2D-1)T$$

其中 V_{in} 交流输入工频峰值电压、
Vo PFC直流输出电压
L 单个PFC电感感量



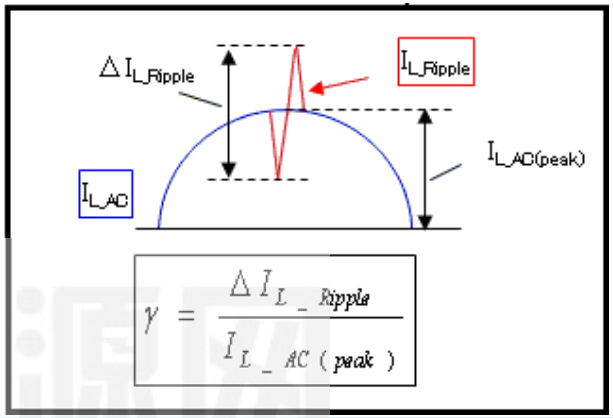
交错式PFC电感值计算（2.8KW PFC实例）

- 传导EMI低频段影响
- 滤波电容高频耐力
- 主电路开关应力损耗

例： $\gamma \le 15\%$

Vinac-nom	Vbus-nom	fsw1
220 Vac	418 Vdc	110KHz
Vo-nom	Io-nom	η
54.5 V	50.0 A	97%

180uH @11A
6.5A.rms



CCM Interleave PFC Tools

Discription	Variable Names	Vin min.		Vin nom		Vin max
Input rms Voltage	V_in_rms	176 V	200 V	220 V	240 V	264 V
Output Voltage	V_{OUT}	418 V	418 V	418 V	418 V	418 V
Output max Power	Pout(max)	2725 W	2725 W	2725 W	2725 W	2725 W
PFC Efficiency	η	95.4%	96.1%	97.0%	97.8%	98.8%
Reactor Induct	L1,L2(assume)	180 uH	180 uH	180 uH	180 uH	180 uH
Fixed Frequency	Frequency	110 KHz	110 KHz	110 KHz	110 KHz	110 KHz
Input Sine PK Current	I_in_ac_pk	23.0 A	20.0 A	18.1 A	16.4 A	14.8 A
Duty at Sine PK	Duty_sin_pk	40.5%	32.3%	25.6%	18.8%	10.7%
Max Current at sine PK of L1	Imax(L1,L2)_sin_pk	14.0 A	12.3 A	11.0 A	9.8 A	8.4 A
RMS current of each reactor	Irms(L1,L2)	8.2 A	7.2 A	6.5 A	5.9 A	5.3 A
Input current ripple (I_L1+I_L2)	ΔI(in)_pk	1.63	2.41	2.64	2.48	1.77
Boost Inductor Ripple/AC Current(pk-pk)	γ	7.1%	12.0%	14.6%	15.1%	12.0%

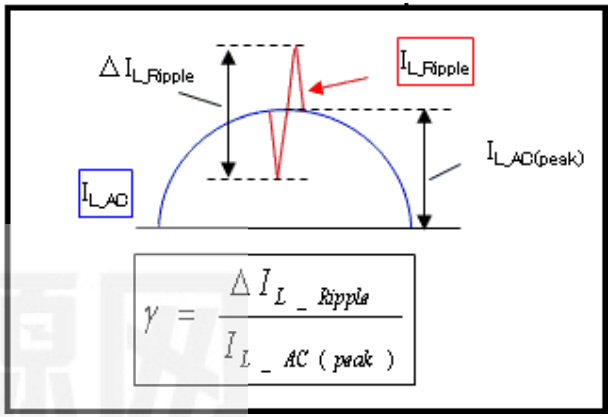
CRM Interleave PFC电感的设计计算

计算单路幅值输入电压时f_{min}和固定的T_{on}

$$f_{min} = \frac{V_o - \sqrt{2}V_{AC}}{V_o} \cdot \frac{V_{AC}^2}{2L} \cdot \frac{\eta \cdot PF}{P_o}$$

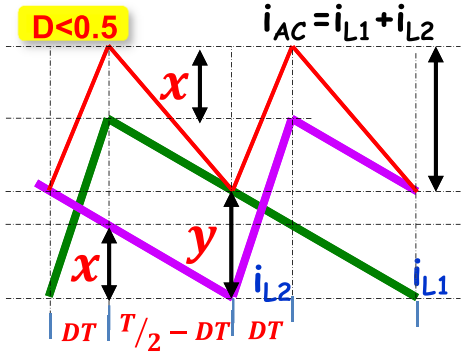
$$T_{on} = \frac{2L}{V_{AC}^2} \cdot \frac{P_o}{\eta \cdot PF}$$

P_o为1/2的总功率



$$\gamma = \frac{\Delta I_{L_Ripple}}{I_{L_AC(peak)}}$$

计算$i_{L1}+i_{L2}$的纹波



D<0.5

$$\Delta I_{L1+L2} = \frac{2Vin - Vo}{L} \cdot DT$$

D>0.5

$$\Delta I_{L1+L2} = \frac{V_{in}}{L} \cdot (2D - 1)T$$

$$\gamma = \frac{\Delta I_{L1+L2}}{i_{AC}} < 15\%$$

L1, L2

L@I_pk

I_pk

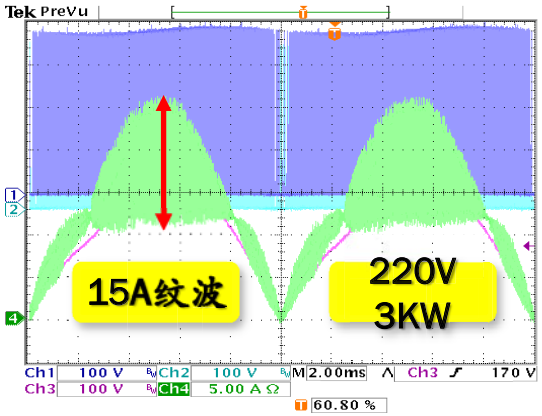
I_L_rms

21世纪电源网 21dianyuan.com

CRM Interleave PFC电感的设计计算

2-phase CRM Interleaved PFC Vin = 150~240Vac， Vo=380Vdc, Po = 3000W

Discription	Variable Names												
Input rms Voltage	V_in_rms	150 V	160 V	170 V	180 V	190 V	200 V	210 V	220 V	230 V	240 V	250 V	260 V
Output max. Power	Po	3000 W	3000 W	3000 W	3000 W	3000 W	3000 W	3000 W	3000 W	3000 W	3000 W	3000 W	3000 W
Boost Efficiency (supposed)	η	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97	0.97
Power factor (supposed)	PF	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99	0.99
Output Voltage	V_{OUT}	380 V	380 V	380 V	380 V	380 V	380 V	380 V	380 V	380 V	380 V	380 V	380 V
Reactor Inductance(supposed)	L1,L2	100 uH	100 uH	100 uH	100 uH	100 uH	100 uH	100 uH	100 uH	100 uH	100 uH	100 uH	100 uH
Input rms Current	I_in_ac_rms	20.8 A	19.5 A	18.4 A	17.4 A	16.4 A	15.6 A	14.9 A	14.2 A	13.6 A	13.0 A	12.5 A	12.0 A
Input AC Amplitude Current	I_in_ac_pk	29.5 A	27.6 A	26.0 A	24.5 A	23.3 A	22.1 A	21.0 A	20.1 A	19.2 A	18.4 A	17.7 A	17.0 A
Duty @ Input AC Amplitude Current	Duty_pk_low	44.2%	40.5%	36.7%	33.0%	29.3%	25.6%	21.8%	18.1%	14.4%	10.7%	7.0%	3.2%
Fixed Ton Time	Ton(FIX)	13.9 uS	12.2 uS	10.8 uS	9.6 uS	8.7 uS	7.8 uS	7.1 uS	6.5 uS	5.9 uS	5.4 uS	5.0 uS	4.6 uS
Frequency @ Input AC Amplitude Current	Fsw_min	31.8 KHz	33.2 KHz	34.0 KHz	34.2 KHz	33.8 KHz	32.7 KHz	30.8 KHz	28.1 KHz	24.4 KHz	19.7 KHz	13.9 KHz	7.0 KHz
Max Current ad Single Inductance	Imax(L1,L2)	29.5 A	27.6 A	26.0 A	24.5 A	23.3 A	22.1 A	21.0 A	20.1 A	19.2 A	18.4 A	17.7 A	17.0 A
RMS Current at Single Inductance	Irms(L1,L2)	12.0 A	11.3 A	10.6 A	10.0 A	9.5 A	9.0 A	8.6 A	8.2 A	7.8 A	7.5 A	7.2 A	6.9 A
Max Input Current Ripple at Vin_sin_PK	ΔI(L1+L2)	6.1 A	8.9 A	10.9 A	12.4 A	13.6 A	14.5 A	15.2 A	15.6 A	16.0 A	16.2 A	16.4 A	16.4 A
Current Ripple Ratio	γ	21%	32%	42%	51%	59%	66%	72%	78%	83%	88%	93%	97%



反激开关电源变压器设计培训

1、反激型开关电源电路的技术特征

- 固定频率反激开关电源
- 临界模式反激开关电源

2、反激开关电源变压器的设计计算

3、反激开关电源变压器的计算软件使用讲解

4、开关电源设计常见技术解答与探讨

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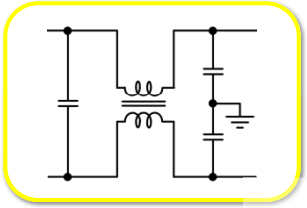
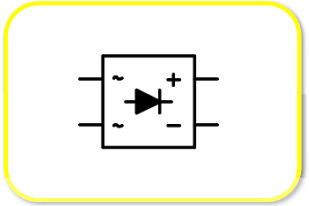
反激型开关电源电路的技术特征

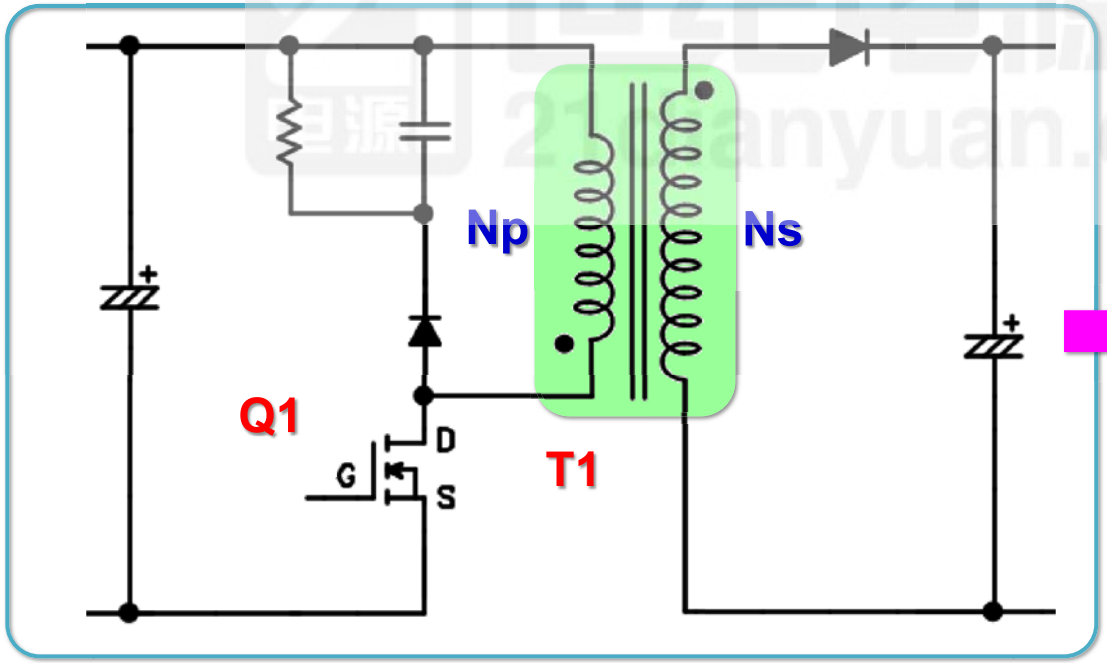
反激开关电源基本原理和电路拓扑





反激电源的实质

Q1 驱动开通时 → Np 储能充电
Q1 驱动关断时 → Ns 放电输出



反激电源的优点

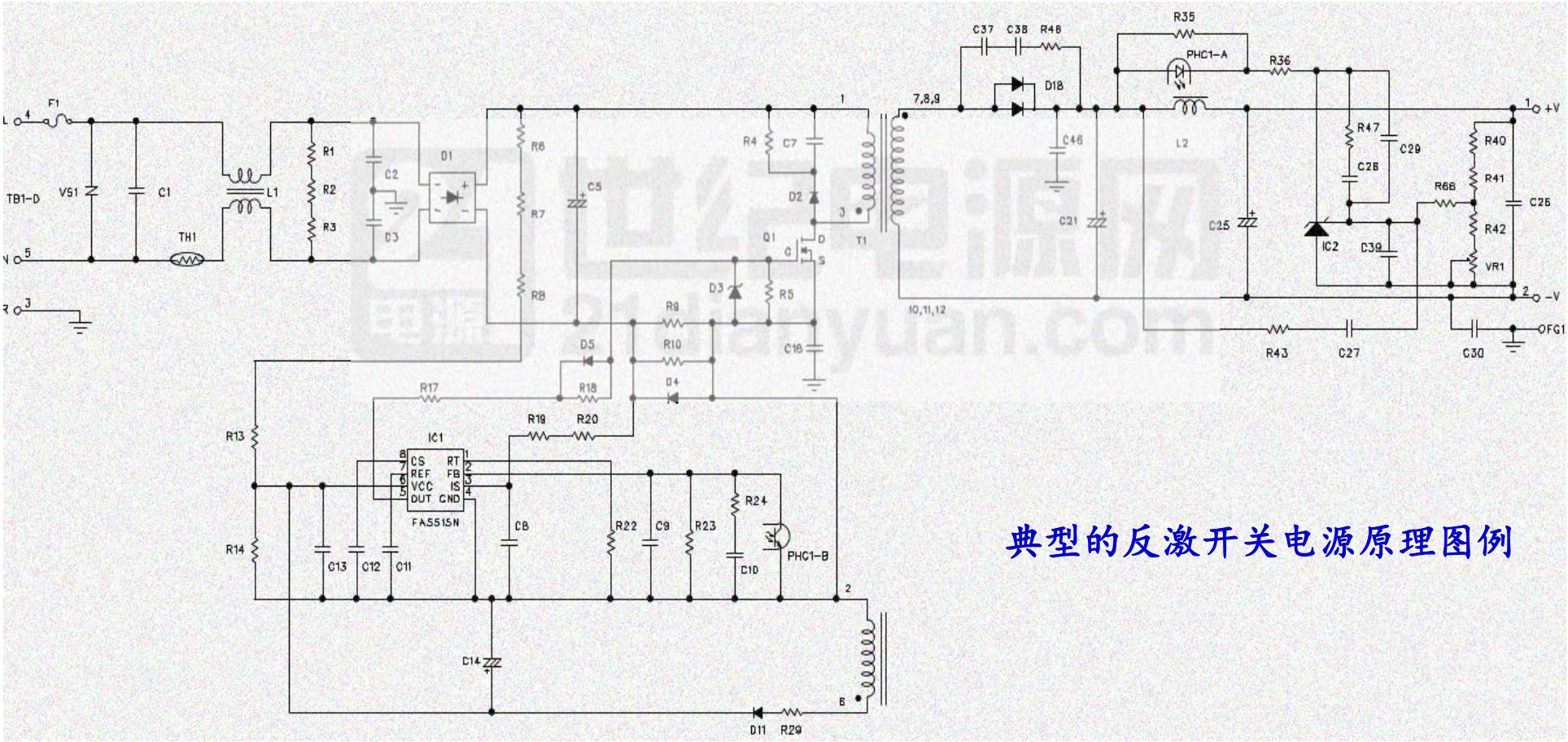
- 结构简单低成本
- 小功率 < 200W
- 宽电压输入范围
- 易实现隔离输出

非隔离方式

- DC Boost
- PFC Converter

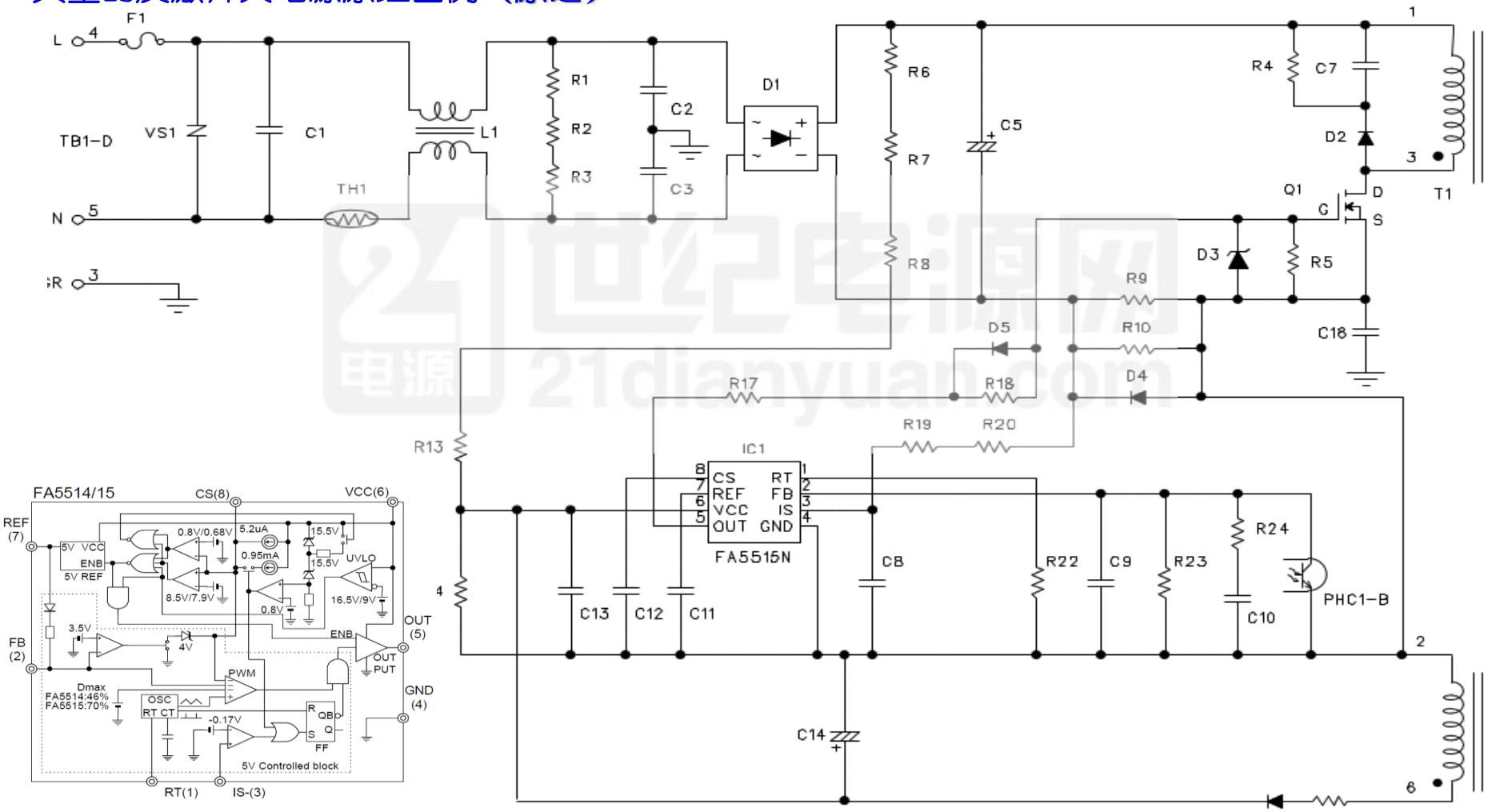
反激型开关电源电路的技术特征

反激开关电源基本原理和电路拓扑

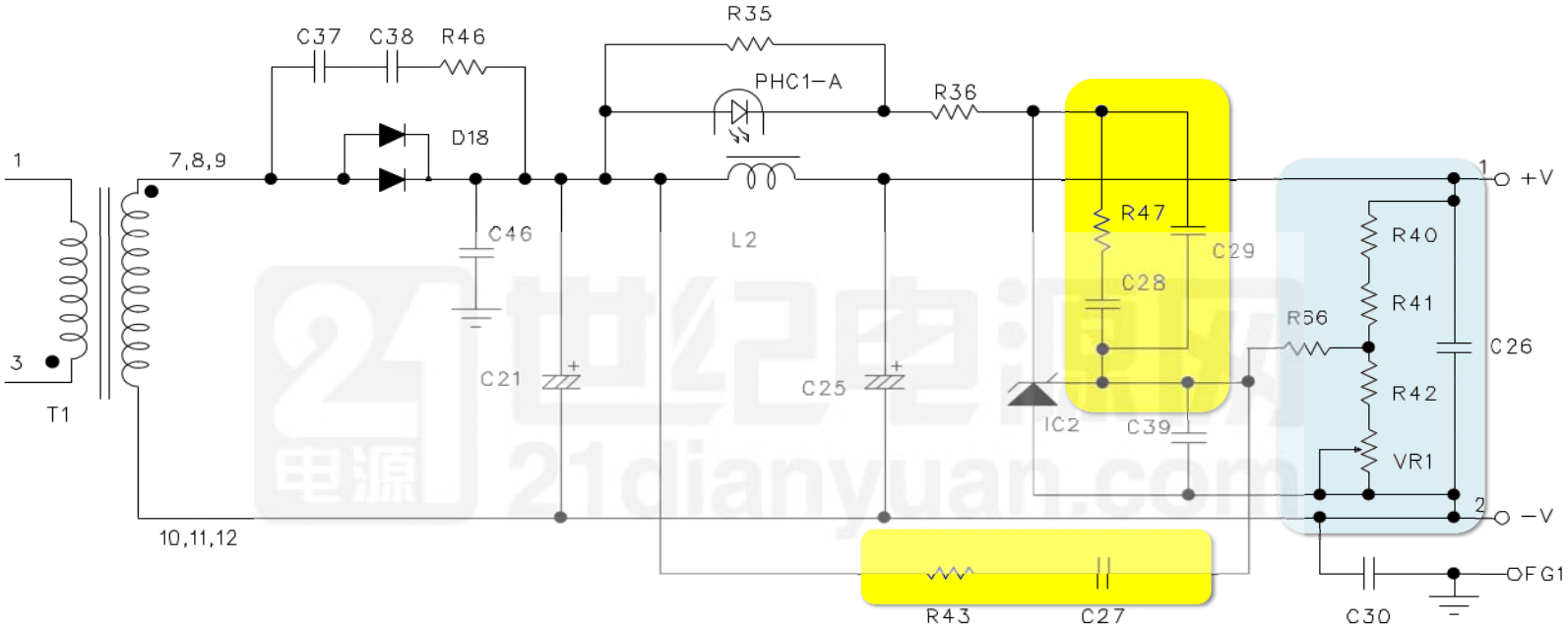


典型的反激开关电源原理图例

典型的反激开关电源原理图例（原边）

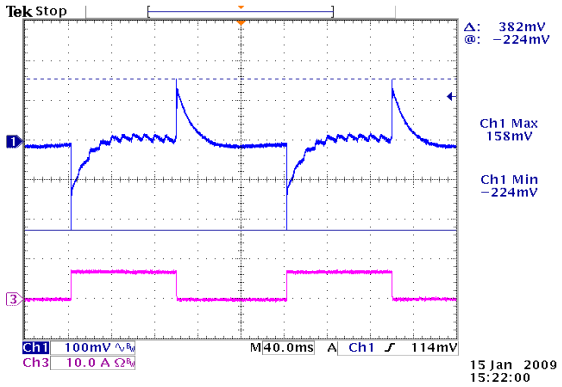


典型的反激开关电源原理图例（副边）



纹波

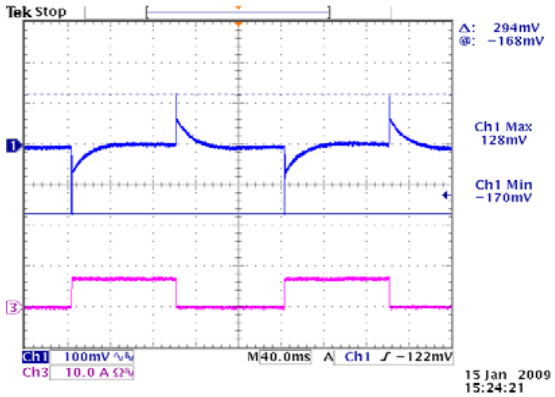
负载



动态负载响应
0~100%

← 85Vac

264Vac →

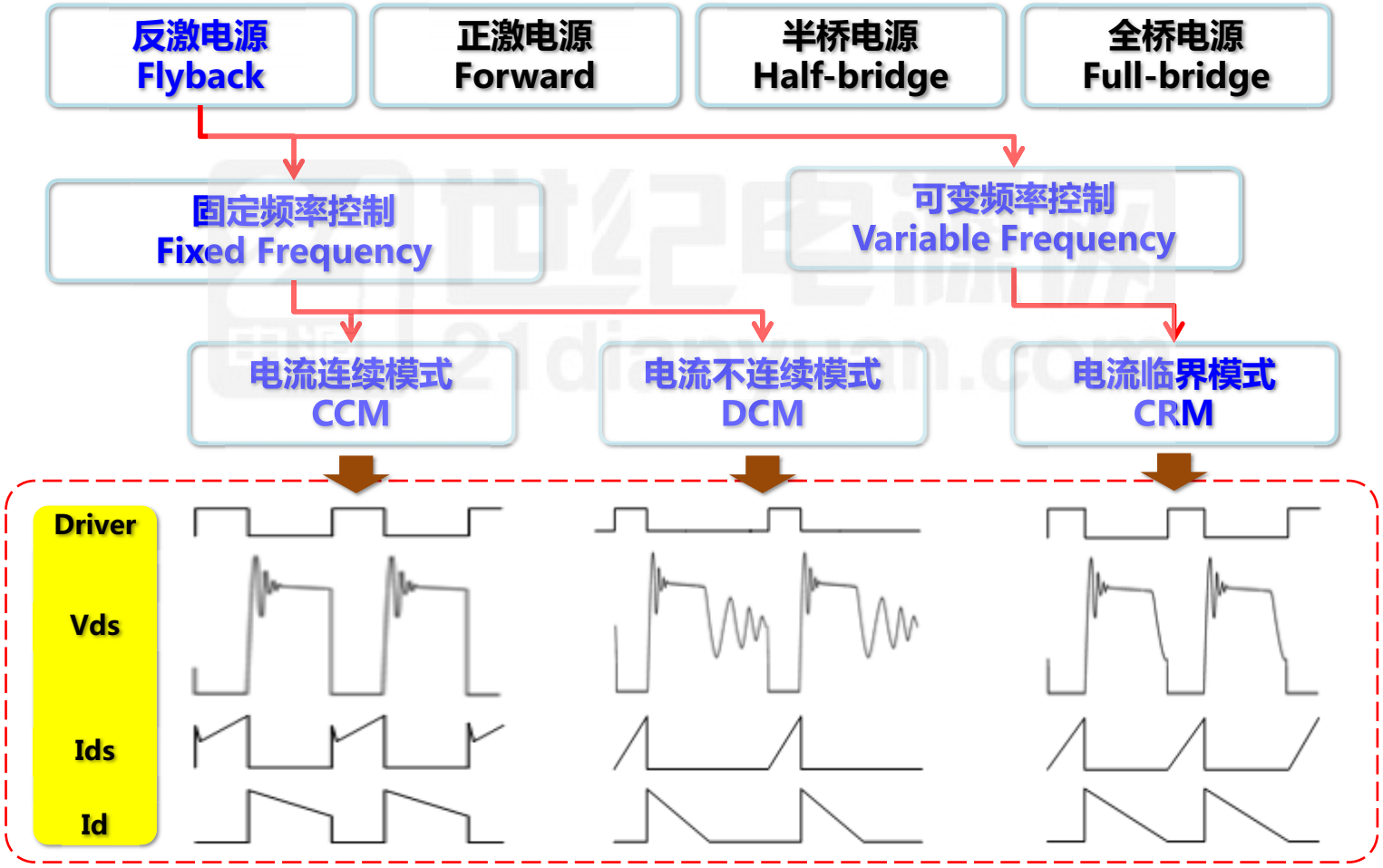


纹波

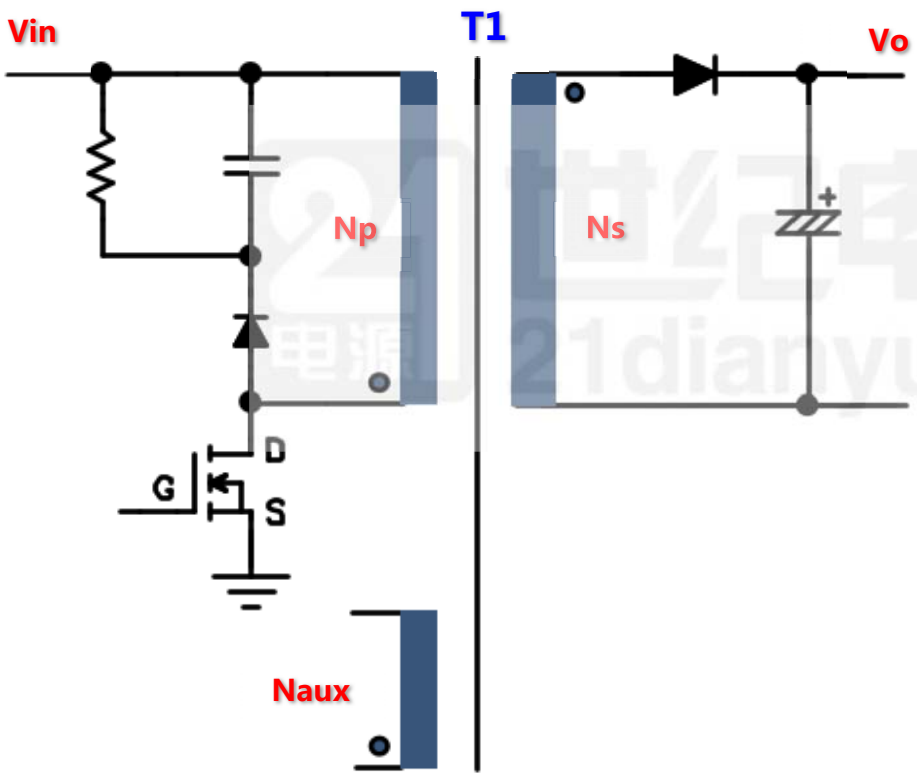
负载

反激型开关电源的工作模式

a） 固定频率控制IC及其工作机理　　b） 准谐振控制IC及其工作机理



变压器设计计算方法的掌握



通用原则

- 伏秒数相等原则（磁平衡）
- T1：耦合式储能电感

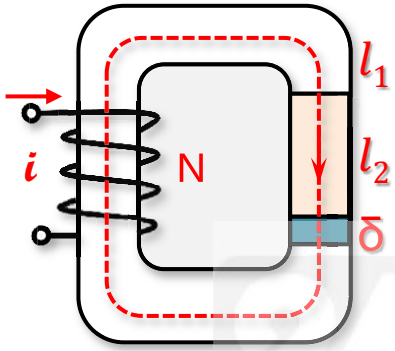
两种工作模式

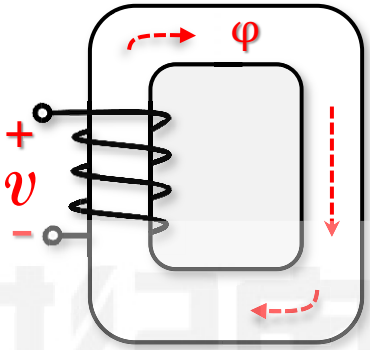
- 固定频率： CCM~DCM
- 准谐振模式：CRM

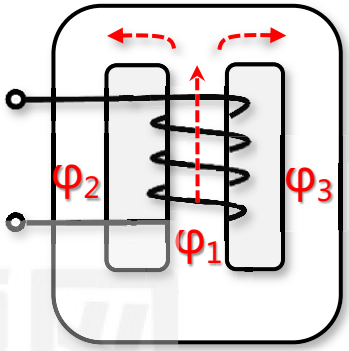
工作模式选定法则

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

磁的基本理论







安倍环路定律

$i \cdot N = H \cdot le = \mathcal{U}m$

法拉第电磁感应定律

$v = N \cdot \frac{d\varphi}{dt} = N \cdot A_e \cdot \frac{dB}{dt}$

磁通连续性定律

$\varphi_1 = \varphi_2 + \varphi_3$

$v \cdot dt = N \cdot A_e \cdot dB$ 伏秒数相等

定义 $\varphi = B \cdot A_e$ $B = \mu \cdot H = \mu_0 \mu_r H$

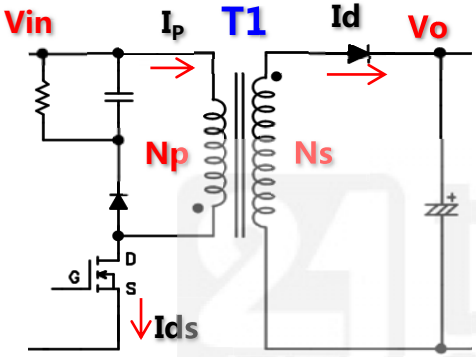
磁路欧姆定律

$$\mathcal{U}m = H \cdot le = \frac{B}{\mu_0 \mu_r} \cdot le = \varphi \cdot \frac{l_e}{\mu_0 \mu_r A_e}$$

← 磁阻$\mathcal{R}$

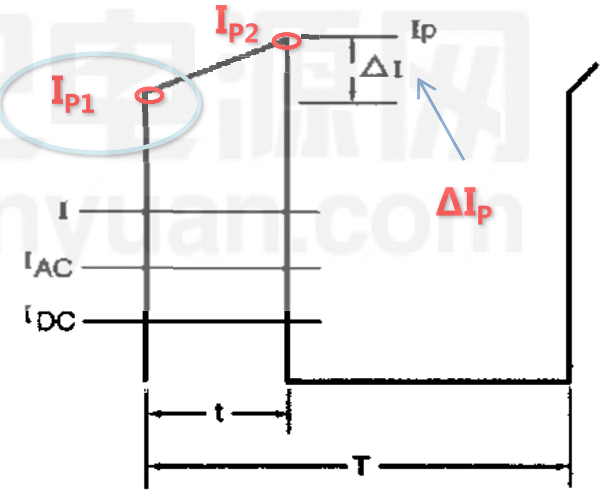
$$Ni = \sum_{k=1}^{3} H_k l_k = H_1 l_1 + H_2 l_2 + H_\delta \delta = \Phi_1 R_{m1} + \Phi_2 R_{m2} + \Phi_\delta R_{m\delta}$$

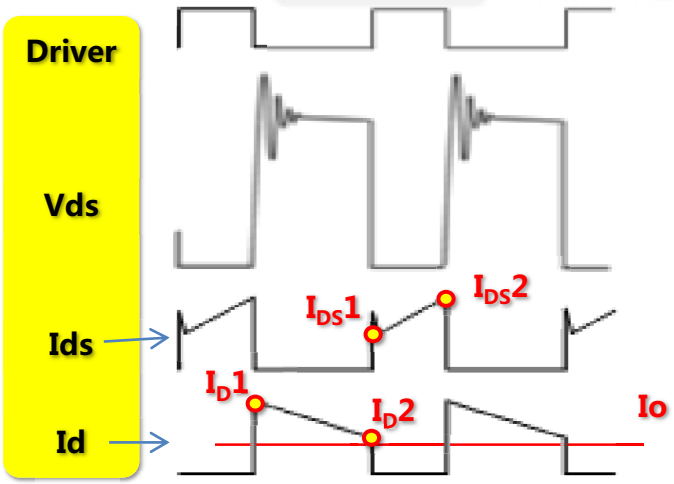
变压器设计计算方法的掌握 (固定频率CCM)



I_{rms} I_o I_{ripple}

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





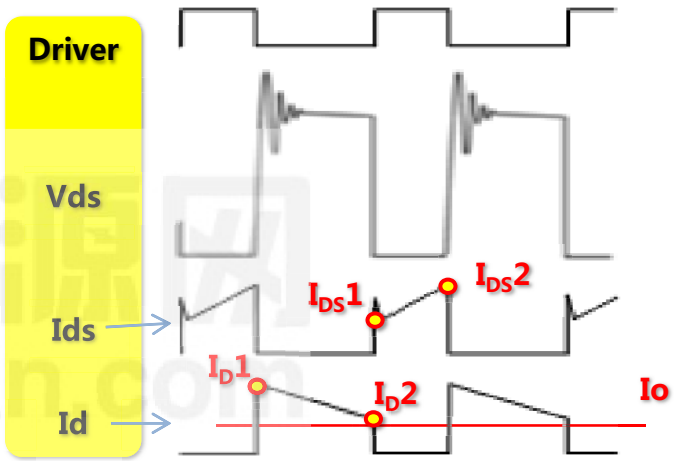
$$I_{DC} = (I_P - \Delta I/2)D$$

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

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

变压器设计计算方法的掌握 (固定频率CCM)

Fixed Frequency : fsw , T ; Duty : D



- $V_{in} \times T_{on} = V_o \times T_{off}$ 伏秒数相等

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

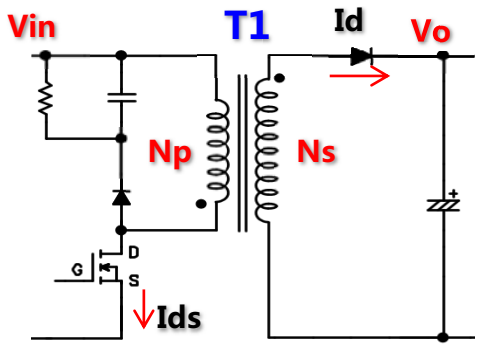
$$D = \frac{V_o}{V_{in} + V_o}$$

- $P_o/\eta = ½(I_{ds1}^2 - I_{ds2}^2) \times L_P \times f_{sw}$ 储能原则

$$P_o/\eta = \frac{I_{ds1} + I_{ds2}}{2} \bullet \Delta I_{ds} \bullet L_p \bullet f_{sw} \Rightarrow (I_{ds1} + I_{ds2}) \bullet \Delta I_{ds} \bullet f_{sw} = \frac{2P_o}{L_p \eta}$$

- $P_o = V_o \times I_o$
- $\Delta I_{ds} = V_{in}/L_P \times T_{on}$ $\Rightarrow V_{in}/L_P \times D \times f_{sw}$ 电感电流爬升
- $I_o = (I_{d1} + I_{d2}) \times (1-D)/2$ 梯形波平均值

$\Rightarrow = (I_{ds1} + I_{ds2}) \times (N_P/N_S) \times (1-D)/2$



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变压器设计计算方法的掌握 (固定频率CCM)

原副边变比 选取方法

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

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

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

$$= \frac{V_{DS} - V_{in} - \alpha(spike)}{V_O}$$

Example

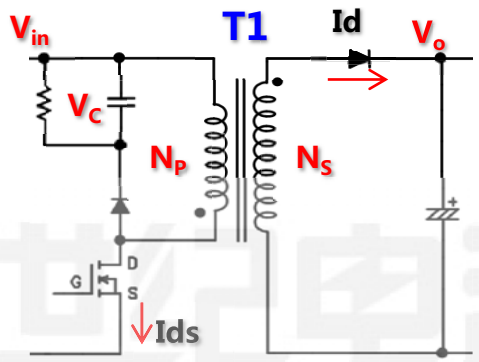
$$V_{ds} = 600 \times 90\% = 540V$$

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

$$V_O = 24V$$

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

$$N_P/N_S = 4.8625$$



法拉第定理

$$E = N_P \bullet \frac{d\varphi}{dt} = N_P \bullet A_e \bullet \frac{\Delta B}{\Delta t}$$

$$E = L_P \frac{dI(L_P)}{dt} = L_P \frac{\Delta I_P}{\Delta t}$$

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

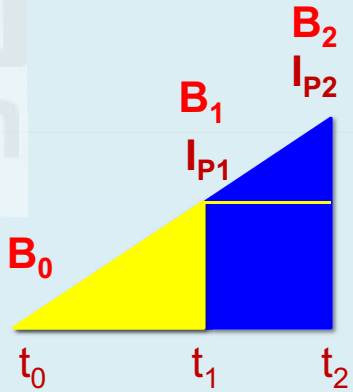
$$\frac{\Delta B}{B1} = \frac{\Delta I_P}{I_{P1}}$$

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

Np与磁芯的选取

L_P 电感量定义

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

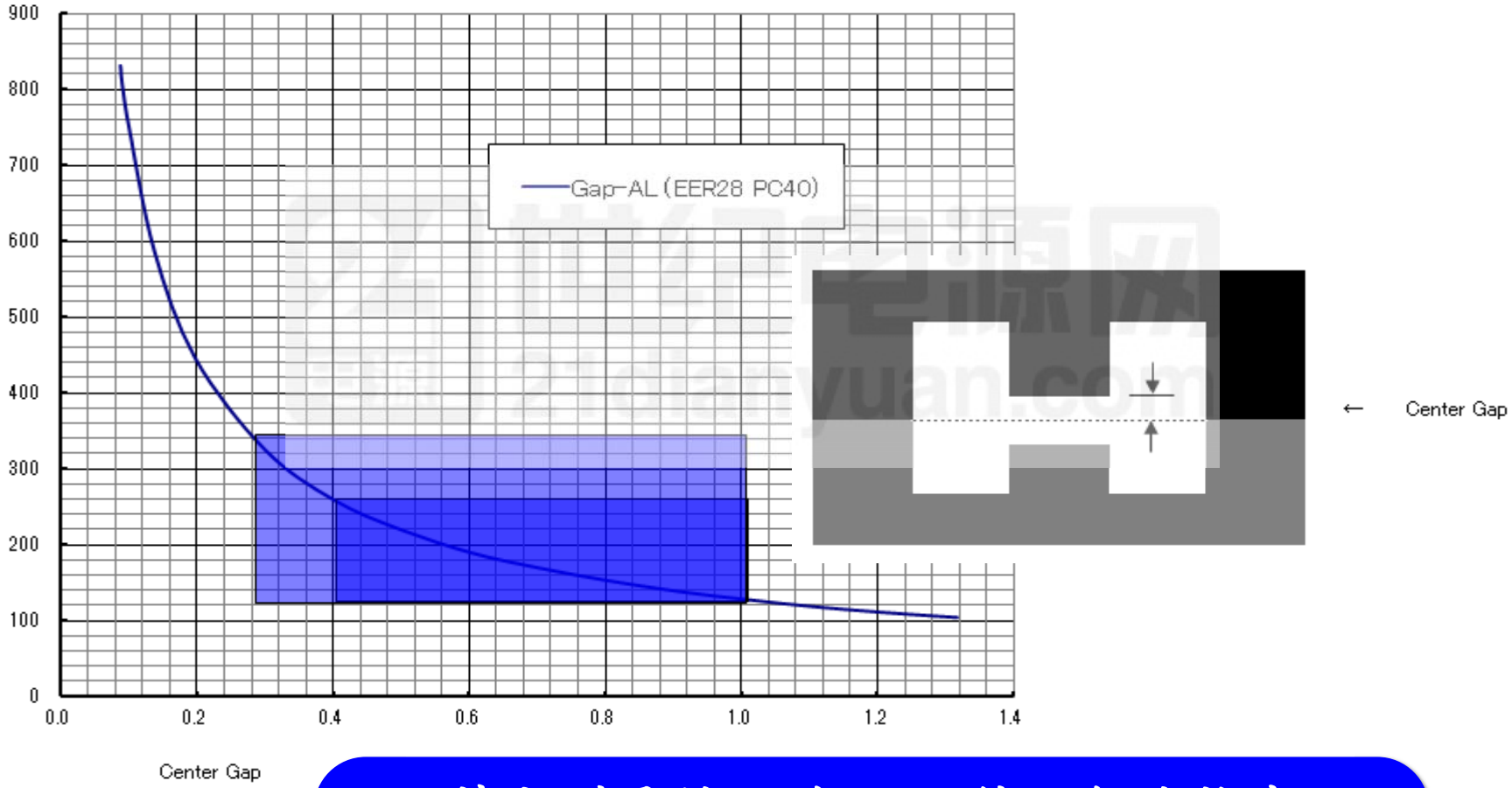


B_{max} ➡ 360mT

$$P_{core} = V \bullet P_{CV}$$

$$P_{cv} = K \bullet f_{sw}^{\alpha} \bullet \boxed{\Delta B}^{\beta}$$

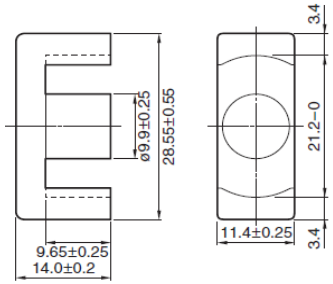
变压器设计计算方法的掌握 (固定频率CCM)



特定型号的磁芯： AL值vs气隙长度

变压器设计计算方法的掌握 (固定频率CCM)

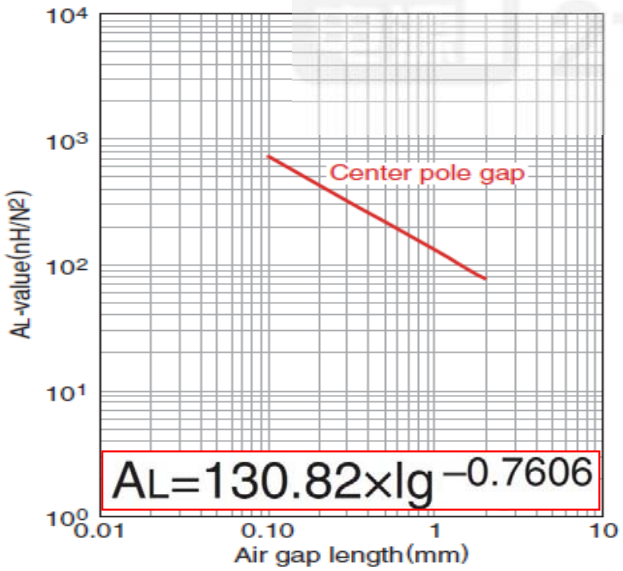
PC95EER28-Z



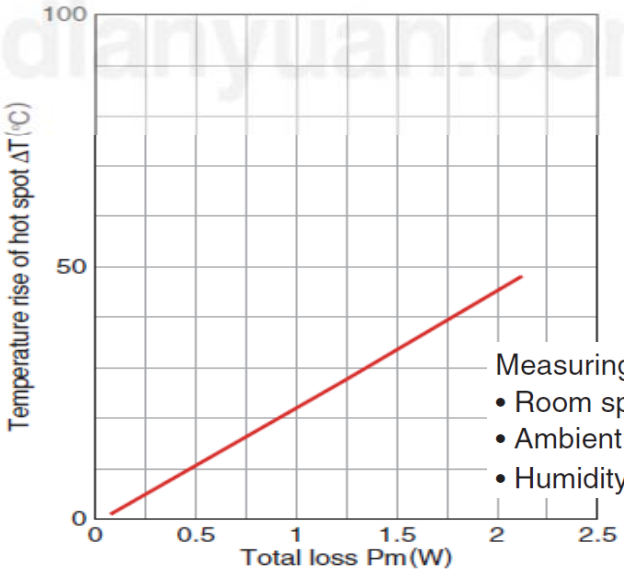
EER28-Z PC95磁芯为例------应用讲解

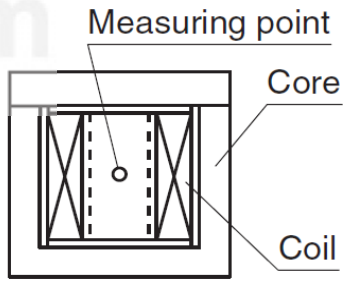
Effective parameter								Electrical characteristics				
Core factor C_1	Effective magnetic path length ℓe	Effective cross-sectional area Ae	Effective core volume Ve	Cross-sectional center pole area Acp	Minimum cross-sectional center pole are Acp min.	Cross-sectional winding area of core Acw	Weigh	AL-value *		Core loss		
(mm⁻¹)	(mm)	(mm²)	(mm³)	(mm²)	(mm²)	(mm²)	(g/set)	(nH/N²) 1kHz 0.5mA	100kHz 200mT	(W)max. 100kHz 200mT 25°C	80°C	120°C
0.78	64.0	82.1	5250	77.0	73.1	114	28	2870±25%	4000±25%	2.45	2.1	2.45

AL-value vs. Air gap length (Typ.)



Temperature rise vs. Total loss (Typ.)





Measuring conditions
- Room space: approx. 400x300x 300cm
- Ambient temperature：25°C
- Humidity：45(%)RH.

变压器设计计算方法的掌握 (固定频率CCM)

设计总结

电源规格要求

f_{SW}, V_O, I_O, V_{in}

假定目标-磁芯

V_e, A_e, A_{CW}, AL, P_{CV}, R_θ, BB

假定目标-器件

V_{DSS}, V_{RM}
De-rating, Spike

假定理想化条件

V_F $P_{Snubber}$=0
η=0.88?

设计限制条件

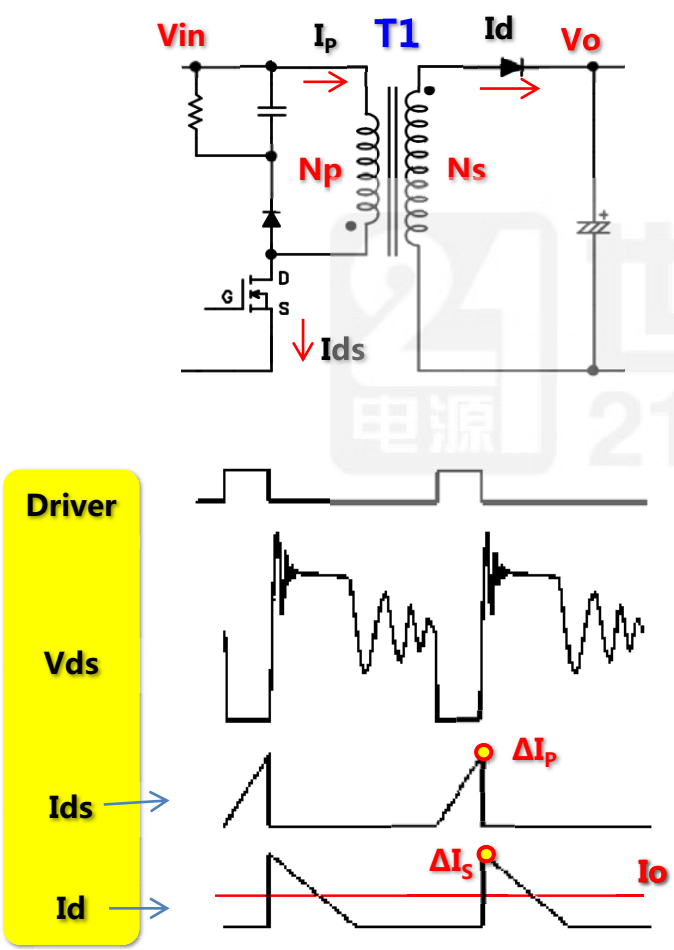
1）磁芯不饱和

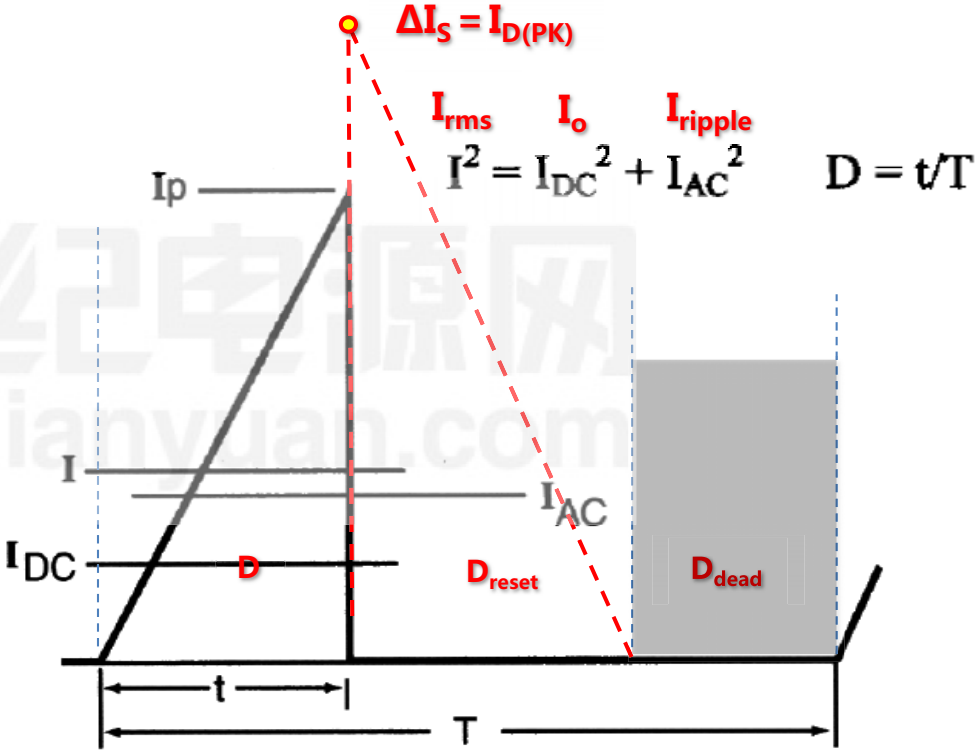
2）变压器不过热

3）符合安规

4）其他个性化要求

变压器设计计算方法的掌握 (固定频率DCM)





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

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

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

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