反激电源变压器的设计要点

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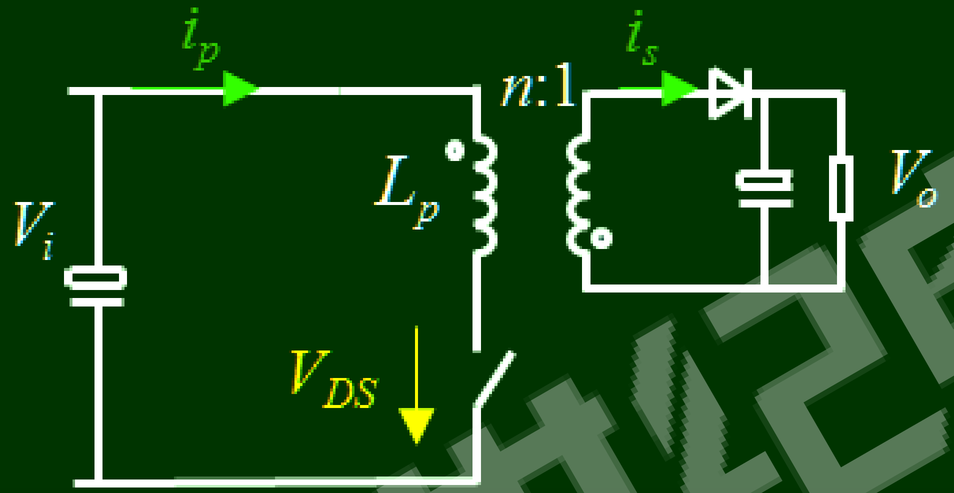
主要内容

1. 反激电源的基本原理
2. 反激变压器的电气参数设计
3. 反激变压器的一般设计方法
4. 反激变压器的杂散参数设计与控制
5. 反激变压器的损耗设计
6. 反激电源的EMI设计

反激电源的基本原理

反激变换器拓扑结构及特点



◆ **优点：**

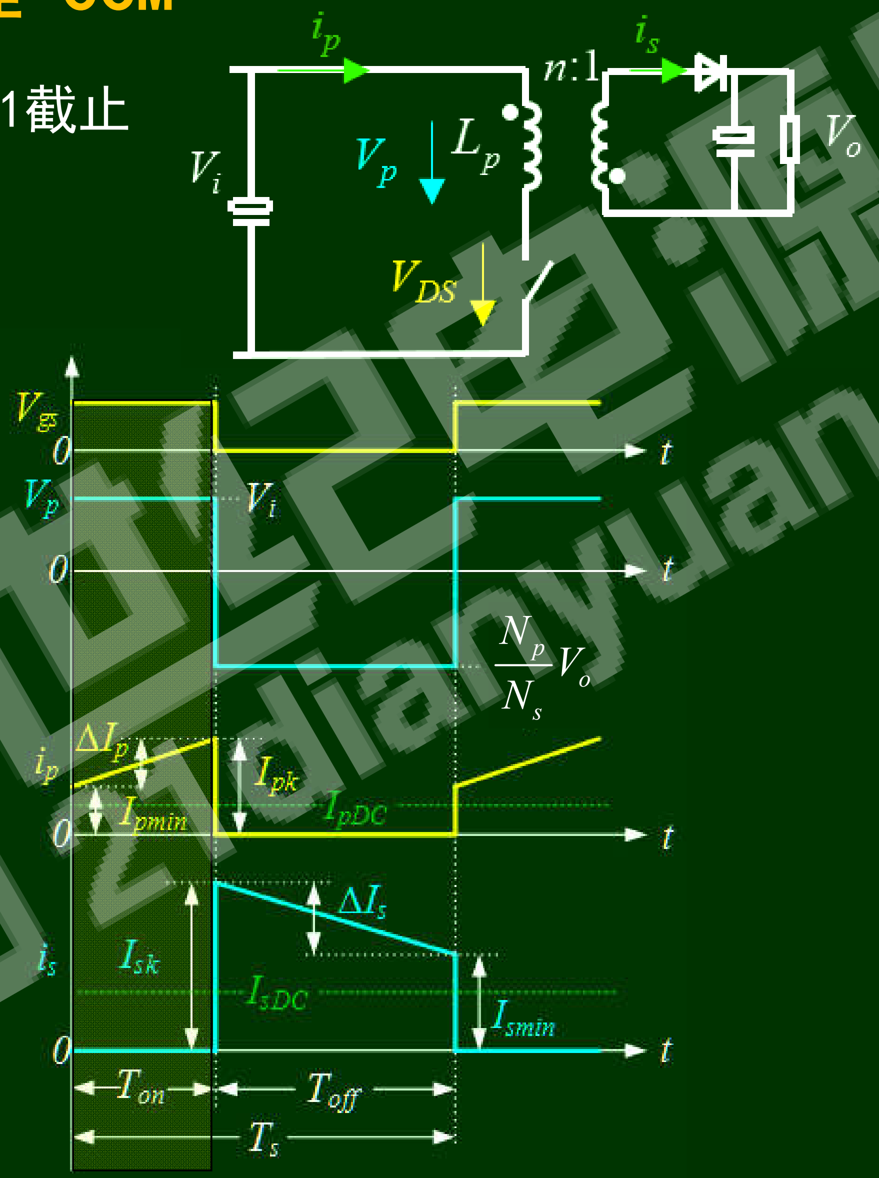
结构简单、所用的开关器件少

◆ **缺点：**

一般适用于小功率应用场合、变压器设计难度高

反激变换器的工作原理-CCM

- Ton期间:Mosfet导通，二极管D1截止



$$V_i = L_p \frac{di_p}{dt} = N_p \frac{d\Phi}{dt}$$

$$\Delta\Phi_+ = \frac{V_i}{N_p} \cdot DT_s$$

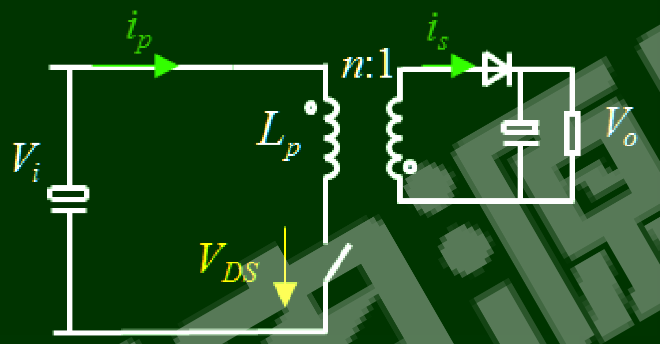
$$\Delta I_p = \frac{V_i}{L_p} \cdot DT_s$$

反激变换器的工作原理-CCM

- Toff期间： Mosfet截止，二极管D1导通

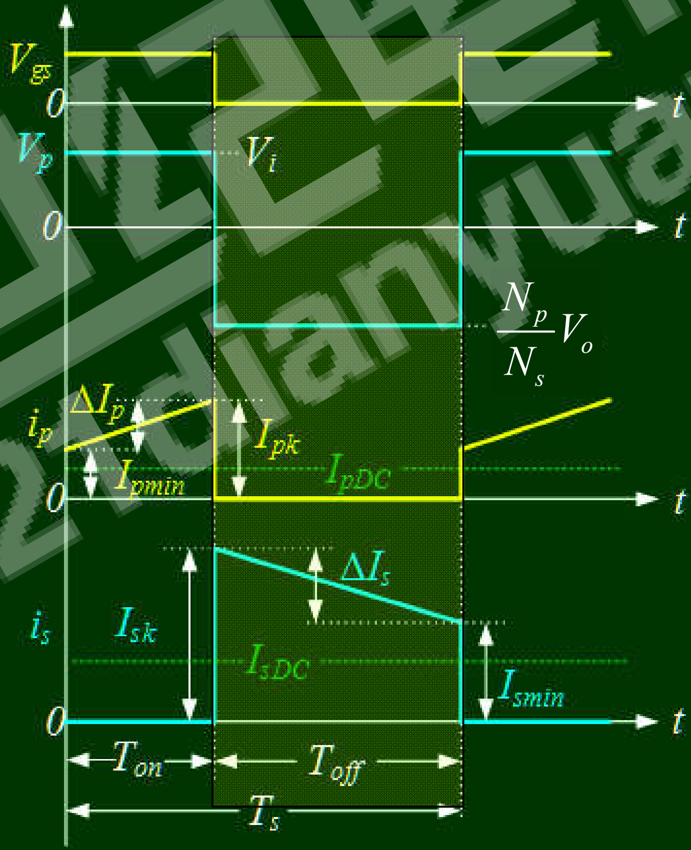
- 磁场储能不能突变： $\frac{1}{2}L_pI_{pk}^{2}=\frac{1}{2}L_sI_{sk}^{2}$

- 磁势平衡： $I_{pk}\cdot N_p=I_{sk}\cdot N_s$



$$L_s\frac{di_s}{dt}=N_s\frac{d\Phi}{dt}=-V_o$$

$$\Delta\Phi_-=\frac{V_o}{N_s}\cdot(1-D)T_s$$



输入输出电压关系

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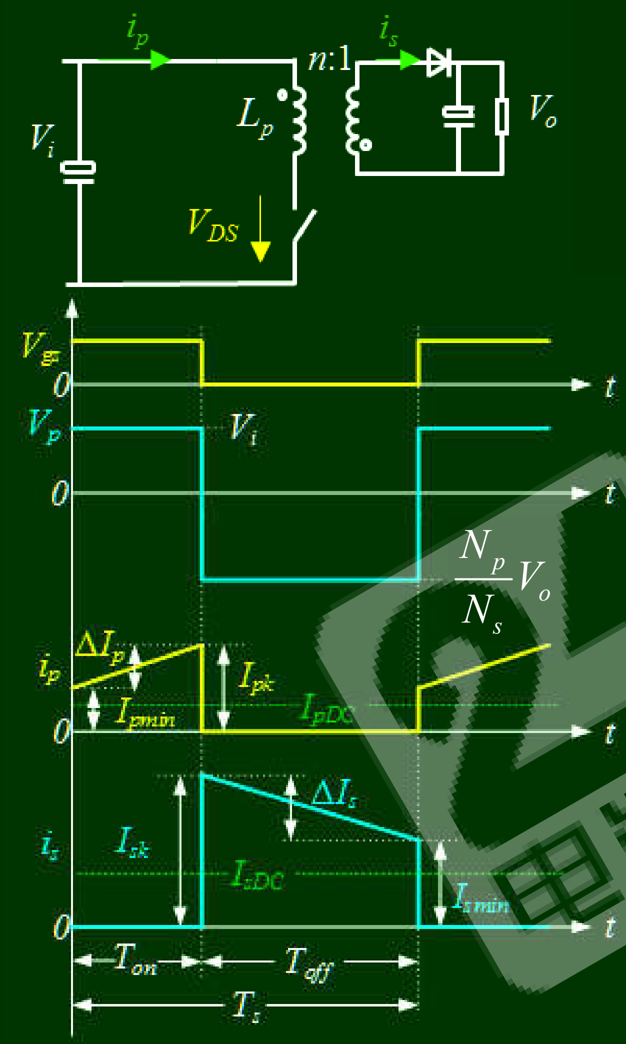


$$\Delta\Phi_+ = \Delta\Phi_-$$

$$\Delta\Phi_+ = \frac{V_i}{N_p}\cdot DT_s$$

$$\Delta\Phi_- = \frac{V_o}{N_s}\cdot(1-D)T_s$$

$$V_O = \frac{N_s}{N_p}\frac{D}{1-D}V_i$$

电压比 $M = \frac{N_s}{N_p}\frac{D}{1-D}$

升降压变换器

CCM时电流应力分析

- 电流关系式

N_p绕组的最大和最小电流：

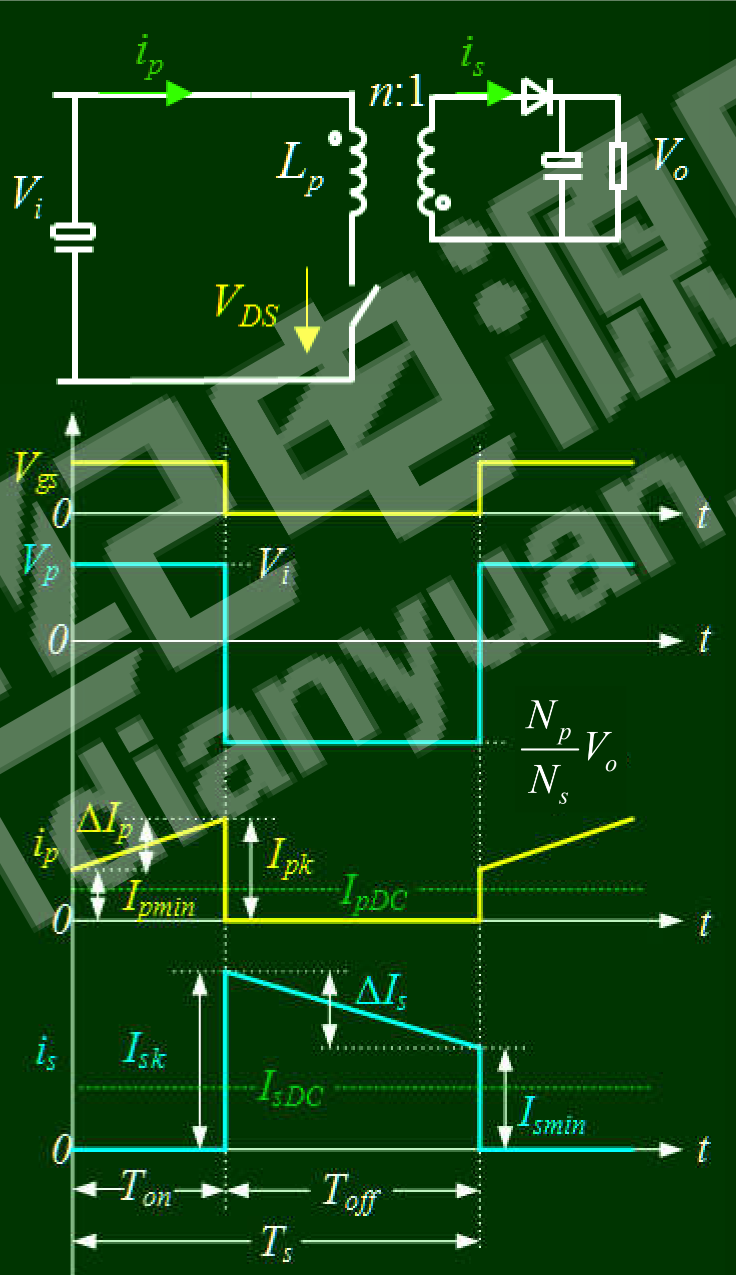
$$I_{pk}=\frac{V_O I_O}{V_i D}+\frac{V_i}{2L_p}DT_S=\frac{N_s}{N_p}\frac{I_O}{1-D}+\frac{V_i}{2L_p}DT_S$$

$$I_{p\min}=\frac{V_O I_O}{V_i D}-\frac{V_i}{2L_p}DT_S=\frac{N_s}{N_p}\frac{I_O}{1-D}-\frac{V_i}{2L_p}DT_S$$

N_s绕组的最大和最小电流：

$$i_{sk}=\frac{I_O}{1-D}+\frac{V_i}{2L_p}DT_S\frac{N_p}{N_s}$$

$$i_{s\min}=\frac{I_O}{1-D}-\frac{V_i}{2L_p}DT_S\frac{N_p}{N_s}$$



CCM时开关管电压应力分析

- Mosfet、D1阻断时承受的电压

Mosfet电压应为：

$$V_{DS}=V_i+V_p$$

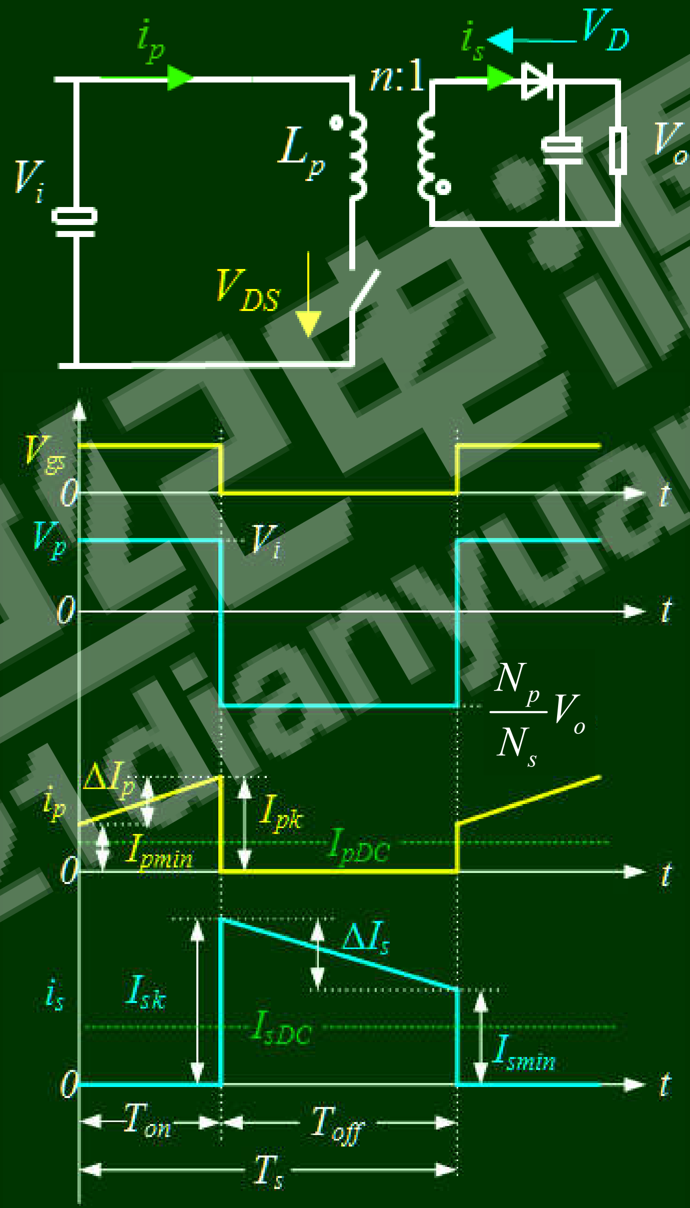
$$=V_i+\frac{N_p}{N_s}V_o$$

$$=\frac{V_i}{1-D}=\frac{N_p}{N_s}\cdot\frac{V_o}{D}$$

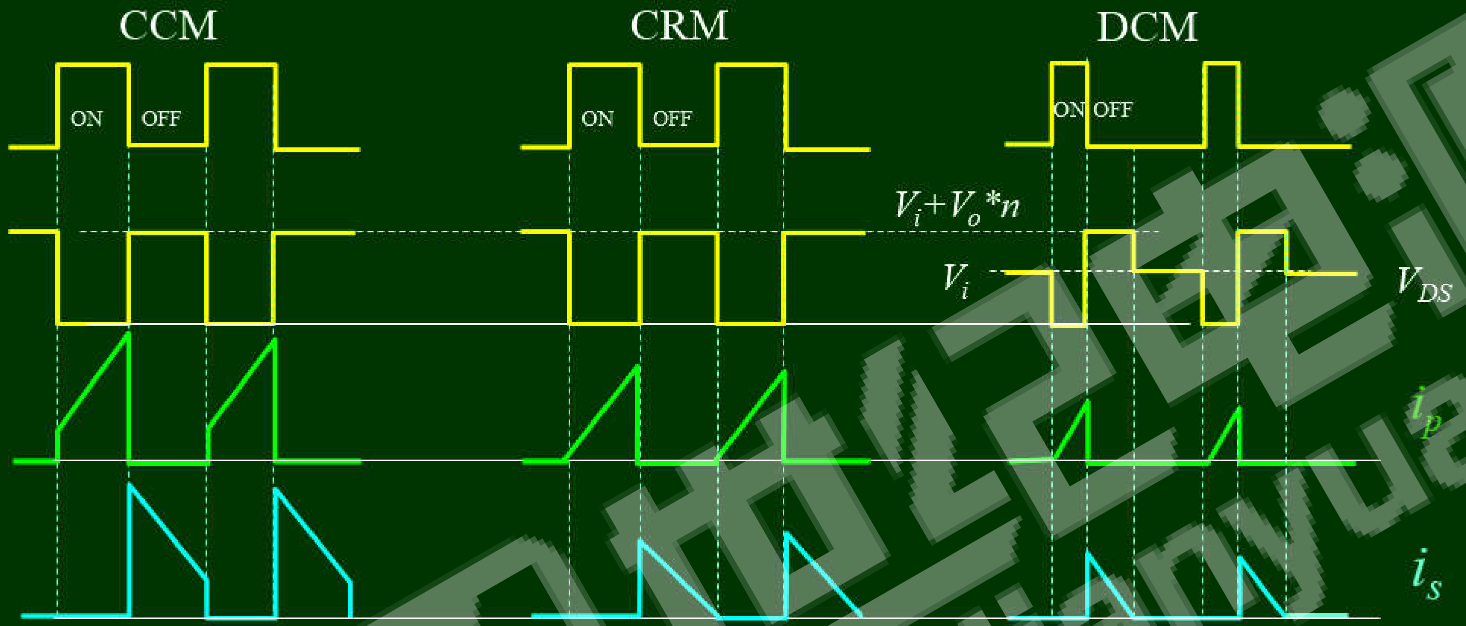
二极管电压应为： $V_D=\frac{N_s}{N_p}V_i+V_O$

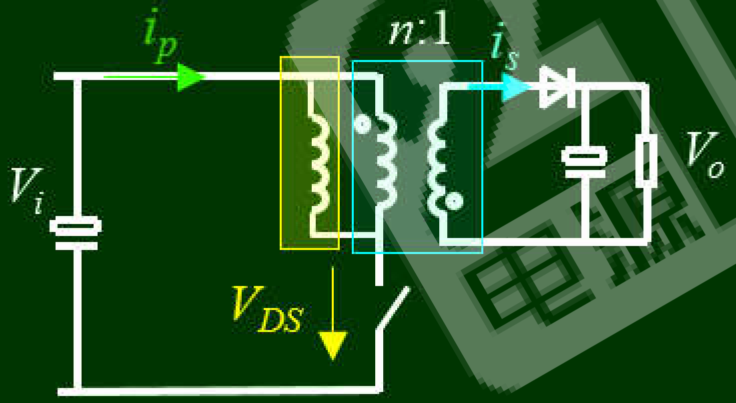
$\frac{N_p}{N_s}$ □ → V_{DS} ↓

V_D ↑



反激变换器的其它工作模式





□ 反激变压器实际上是变压器与电感器的磁集成。

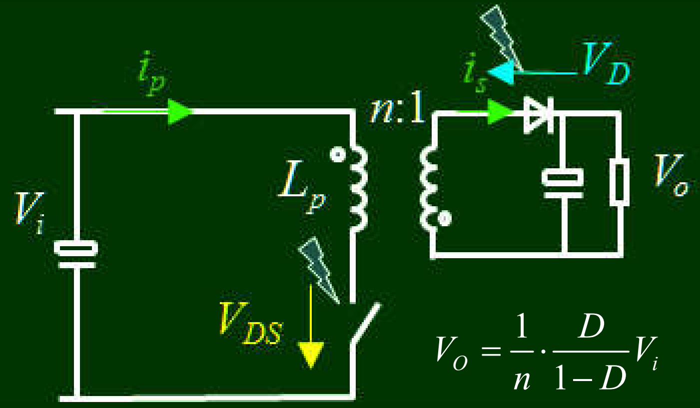
反激电路变压器的基本设计

反激变压器的设计过程

1. 反激变压器基本电气设计
   - 1.1 匝比
   - 1.2 电感量

2. 反激变压器的结构设计
   - 2.1 磁心材料选择
   - 2.2 磁心型号设计与选型
   - 2.3 绕组匝数设计
   - 2.4 气隙设计
   - 2.5 绕组线规设计
   - 2.6 窗口利用率验算
   - 2.7 磁心和绕组损耗验算
   - 2.8 温升验算

1.1 反激变压器基本电气设计 -- 匝比

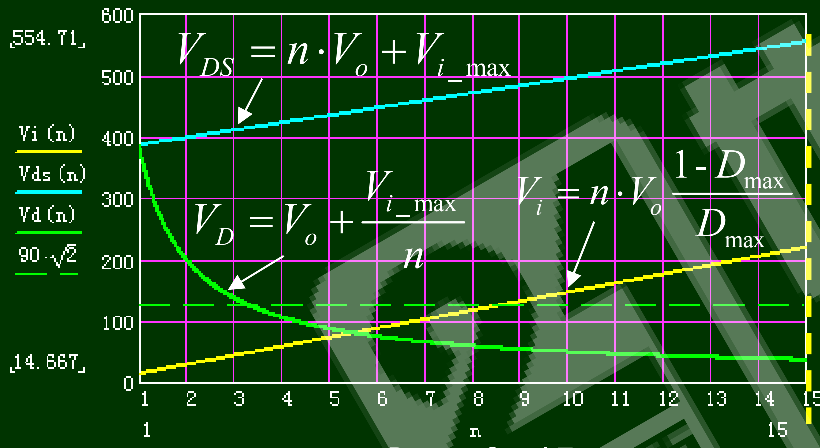


$$V_O=\frac{1}{n}\cdot\frac{D}{1-D}V_i$$

□ 确定最大占空比限制D_{max}

□ 二极管反向耐压限制V_{Dmax}

□ 开关管承受电压限制V_{DSmax}



D_{max}=0.45

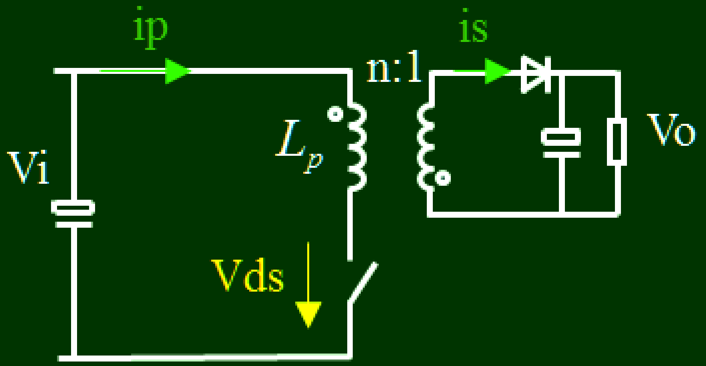
$$\begin{cases} V_i=n\cdot V_o\dfrac{1-D_{\max}}{D_{\max}}\le V_{i\_\min} \\ V_{DS}=n\cdot V_o+V_{i\_\max}\le V_{DS\max} \\ V_D=V_o+\dfrac{V_{i\_\max}}{n}\le V_{D\max} \end{cases}$$

⬇

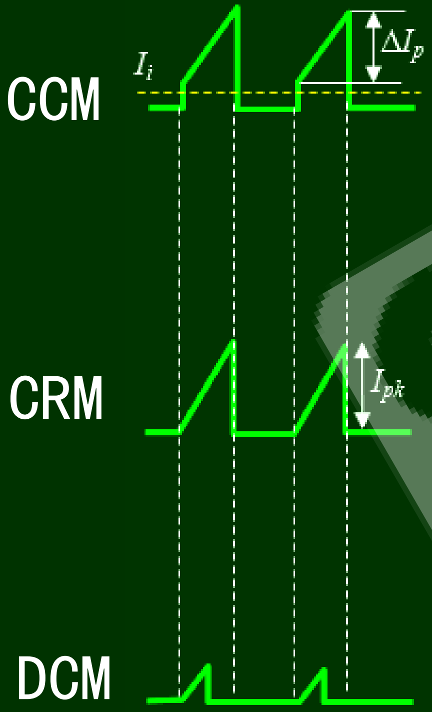
$$\frac{V_{i\_\max}}{V_{D\max}-V_{i\_\max}}\le n\le \min\left(\frac{V_{i\_\min}D_{\max}}{V_o(1-D_{\max})},\frac{V_{DS\max}-V_{i\_\max}}{V_o}\right)$$

V_o=12V, V_{i_max}=265*1.4V, V_{i_min}=90*1.4V

1.2 反激变压器基本电气设计 -- 电感量



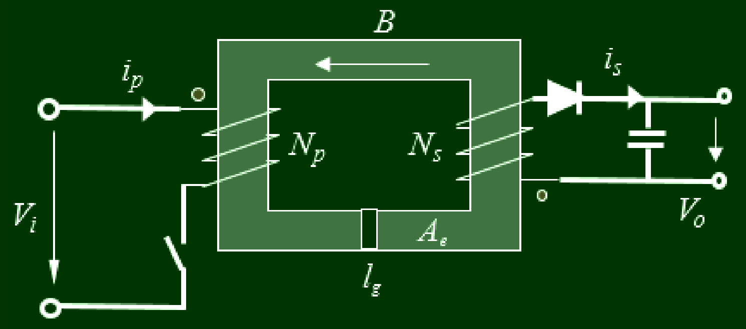
- □ 法拉第电磁感应定律
- □ 安培环路定律



$$\begin{cases} \Delta I_p = \dfrac{V_i \cdot D_{\max}}{L_p \cdot f} \\ k_{\mathrm{rp}} = \dfrac{\Delta I_p}{I_i} \end{cases} \Rightarrow L_p = \frac{V_i \cdot D_{\max}}{k_{rp} \cdot I_i \cdot f} = \frac{V_i^2 \cdot D_{\max}}{\boxed{k_{rp}} \cdot P_i \cdot f}$$

$$\begin{cases} I_{pk} = \dfrac{V_{i\_\min} \cdot D_{\max}}{L_p \cdot f} \\ P_i = \dfrac{1}{2} \cdot L_p \cdot I_{pk}^2 \cdot f \end{cases} \Rightarrow L_p = \frac{(V_{i\_\min} \cdot D_{\max})^2}{2 \cdot \boxed{P_i} \cdot f}$$

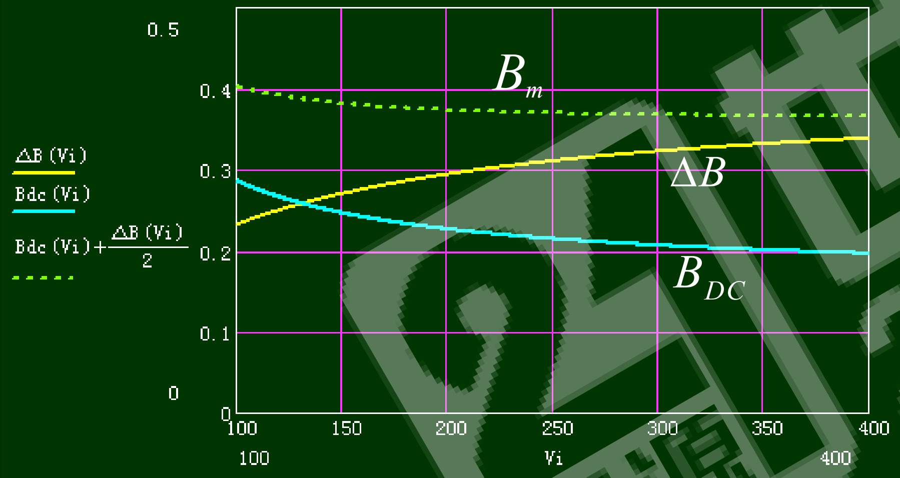
反激变压器磁心磁通特点

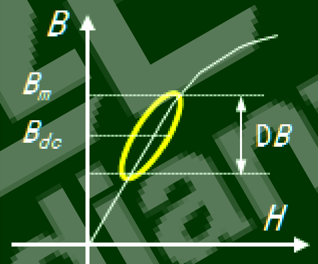


$$\Delta B = \frac{VoltSecond}{N \cdot A_e} = \frac{V_i D T_s}{N_p A_e} = \frac{V_o (1-D) T_s}{N_s A_e} \qquad \Delta B \propto 1/A_e$$

$$B_{DC} \approx \mu_a \frac{I_o N_s + I_{pDC} N_p}{l_g} \qquad B_{DC} \propto 1/l_g$$

$$B_m = B_{DC} + \frac{\Delta B}{2}$$





B_m太大 ⟶ 磁心饱和

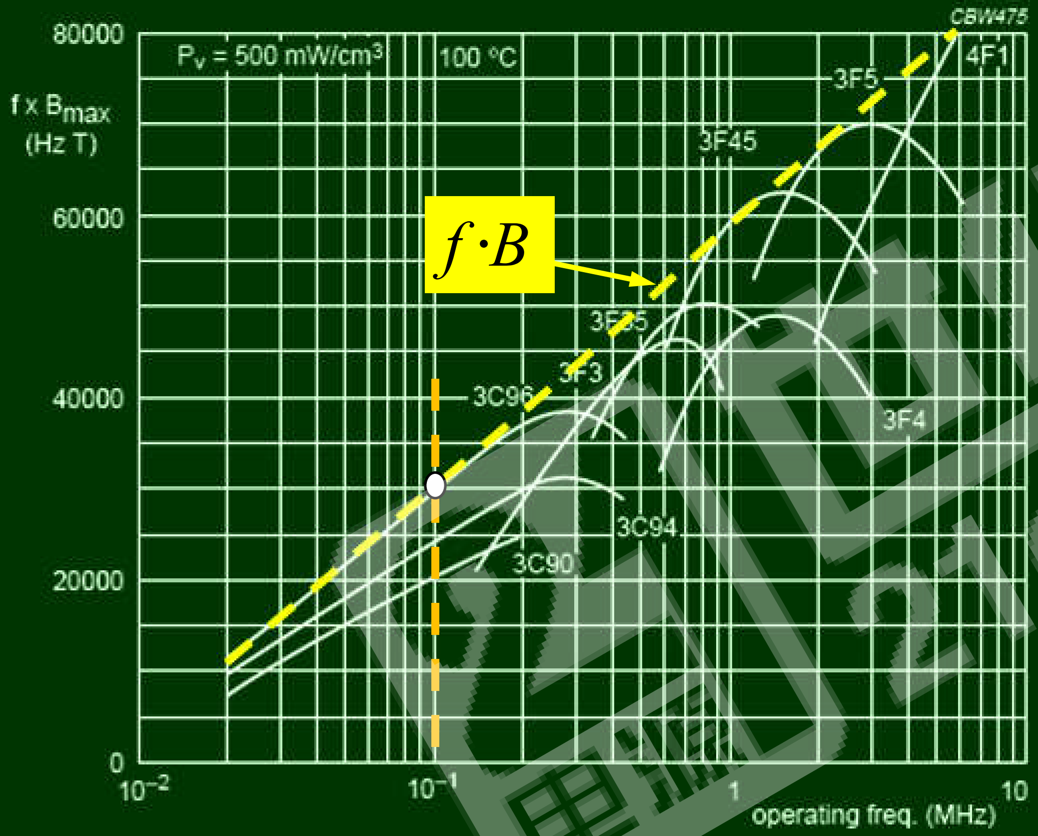
ΔB太大 ⟶ 磁心损耗太大

□ 既要考虑磁心的损耗(ΔB)，又要考虑磁心的饱和(Bm)

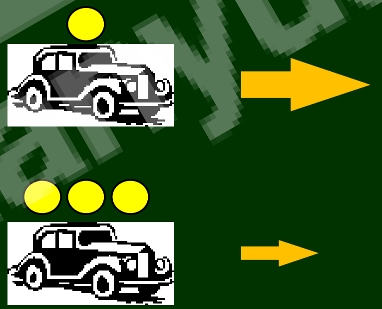
2.1 变压器磁心材料选择

$P_{传输磁能} = U\cdot I \propto (f\cdot B)\cdot N\cdot A_e\cdot I$

$(f\cdot B)$: 磁材料性能因子



B →载重　　f →速度



如开关频率为100kHz时，可选择3C96或等同的材料

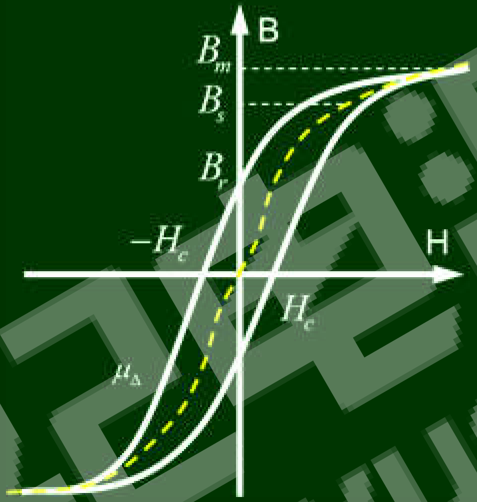
2.2 变压器磁心的设计

磁芯型号的设计考虑：

1、设计的变压器的磁芯截面积*Ae*应该保证磁芯不饱和，即$B_{max}<B_s$.

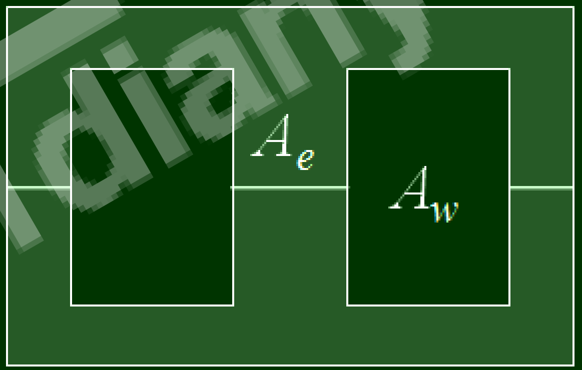
$$A_e=\frac{\Psi}{N_p\cdot B_{\max}} \qquad \Psi=L_p\cdot I_{pk}$$

$$\boxed{A_e\ge\frac{L_p\cdot I_{pk}}{N_p\cdot B_{\max}}}$$



2、设计的变压器的磁芯窗口面积*Aw*应该能保证线圈能绕得下.（S_p，S_s为原副边的导线截面积；K_u为宽口填充系数；*J*允许的电流密度大小。）

$$S_p=\frac{I_{prms}}{J} \qquad S_s=\frac{I_{srms}}{J} \qquad \boxed{n=\frac{N_p}{N_s}}$$

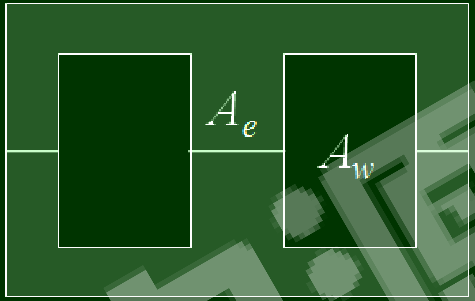


$$\boxed{A_w\ge\frac{N_p\cdot S_p+N_s\cdot S_s}{K_u}}$$

$$AP\ge A_e\cdot A_w=\frac{L_p\cdot I_{pk}}{B_{\max}}\cdot\frac{n\cdot I_{prms}+I_{srms}}{n\cdot J\cdot K_u}$$

2.2 变压器磁心的选型

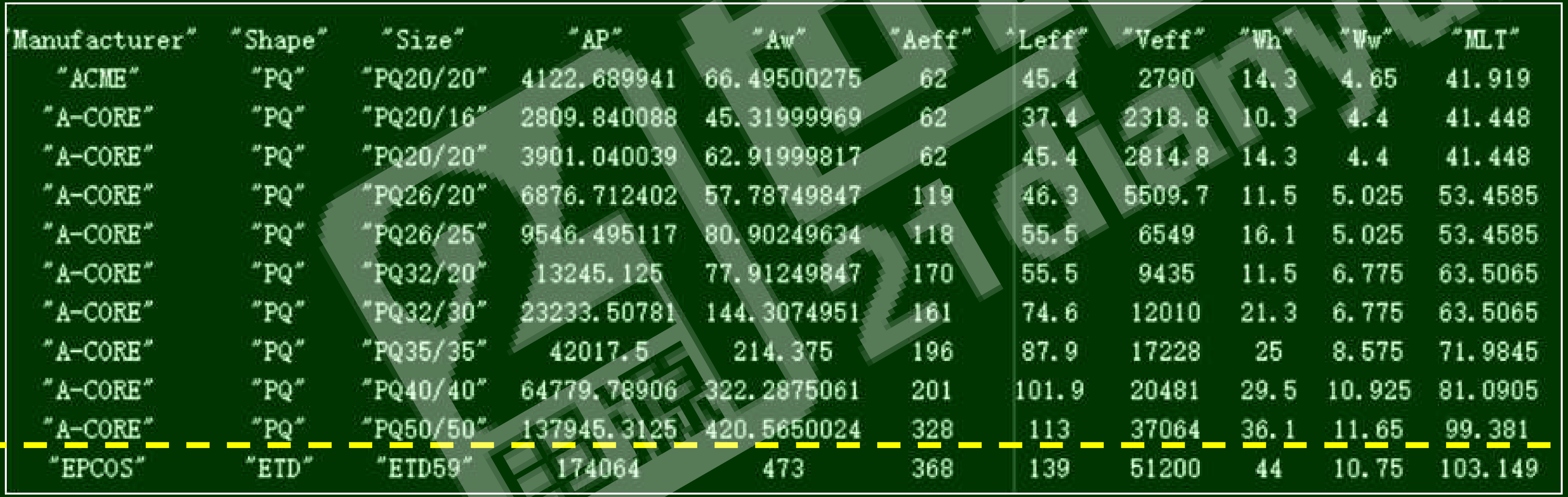
$$AP \ge A_e \cdot A_w = \frac{L_p \cdot I_{pk}}{B_{\max}} \cdot \frac{n \cdot I_{prms} + I_{srms}}{n \cdot J \cdot K_u}$$



CCM

$$\begin{cases} Iprms := \sqrt{\dfrac{Vi^2}{3Lp^2} \cdot D^3 \cdot Ts^2 + Ipmin \cdot \dfrac{Vi}{Lp} \cdot D^2 \cdot Ts + Ipmin^2 \cdot D} \\ Isrms := \sqrt{\dfrac{Vo^2}{3 \cdot Ls^2} \cdot (1-D)^3 \cdot Ts^2 + Ismin \cdot \dfrac{Vo}{Ls} \cdot (1-D)^2 \cdot Ts + Ismin^2 (1-D)} \end{cases}$$

如：Ap=1.597*10^5mm^4



"Manufacturer"	"Shape"	"Size"	"AP"	"Aw"	"Aeff"	"Leff"	"Veff"	"Wh"	"Ww"	"MLT"
"ACME"	"PQ"	"PQ20/20"	4122.689941	66.49500275	62	45.4	2790	14.3	4.65	41.919
"A-CORE"	"PQ"	"PQ20/16"	2809.840088	45.31999969	62	37.4	2318.8	10.3	4.4	41.448
"A-CORE"	"PQ"	"PQ20/20"	3901.040039	62.91999817	62	45.4	2814.8	14.3	4.4	41.448
"A-CORE"	"PQ"	"PQ26/20"	6876.712402	57.78749847	119	46.3	5509.7	11.5	5.025	53.4585
"A-CORE"	"PQ"	"PQ26/25"	9546.495117	80.90249634	118	55.5	6549	16.1	5.025	53.4585
"A-CORE"	"PQ"	"PQ32/20"	13245.125	77.91249847	170	55.5	9435	11.5	6.775	63.5065
"A-CORE"	"PQ"	"PQ32/30"	23233.50781	144.3074951	161	74.6	12010	21.3	6.775	63.5065
"A-CORE"	"PQ"	"PQ35/35"	42017.5	214.375	196	87.9	17228	25	8.575	71.9845
"A-CORE"	"PQ"	"PQ40/40"	64779.78906	322.2875061	201	101.9	20481	29.5	10.925	81.0905
"A-CORE"	"PQ"	"PQ50/50"	137945.3125	420.5650024	328	113	37064	36.1	11.65	99.381
"EPCOS"	"ETD"	"ETD59"	174064	473	368	139	51200	44	10.75	103.149

可选择ETD59的磁尺型号，确定Ae，Aw，MLT，Ve等参数。

2.3 变压器绕组匝数计算

变压器原边绕组的匝数为：

$$\Delta\Phi_{+} = \frac{V_i}{N_p}\cdot DT_s = \Delta B\cdot Ae$$

$$\boxed{N_p = \frac{V_i\cdot D}{Ae\cdot\Delta B\cdot f_s}}$$

ΔB越大磁心损耗越大！

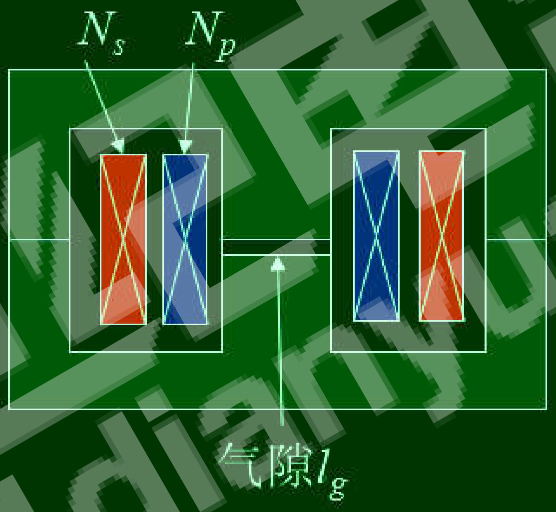
变压器副边绕组的匝数为：

$$\boxed{N_s = \frac{N_p}{n}}$$

2.4 气隙的计算

变压器的感量与气隙的关系：

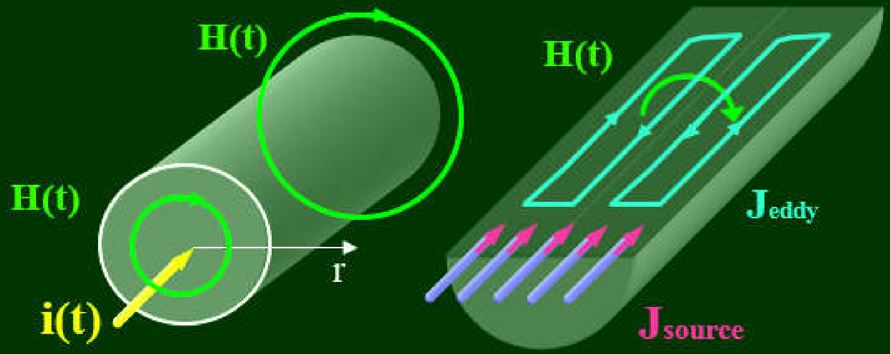
$$L_p = \frac{N_p{}^2 \mu_0 A_e}{\lg}$$

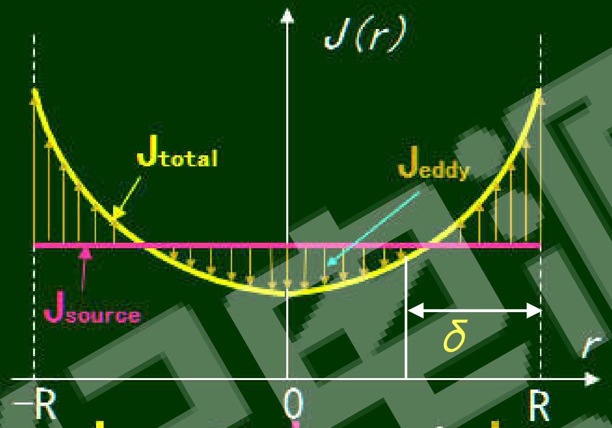


气隙的大小：

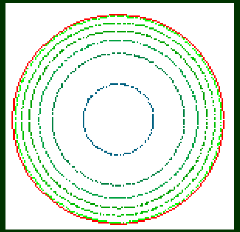
$$\boxed{\lg = \frac{N_p{}^2 \mu_0 A_e}{L_p}}$$

2.5 绕组线规设计





$J_{total} = J_{source} + J_{eddy}$



透入深度：

$$\delta = \sqrt{\frac{1}{\pi f_s \mu_0 \gamma}}$$

电流减少为表面的36.8%时的半径

为了减小其影响，可以选择线径小于透入深度。此时交流电阻可以近似用直流电阻代替。

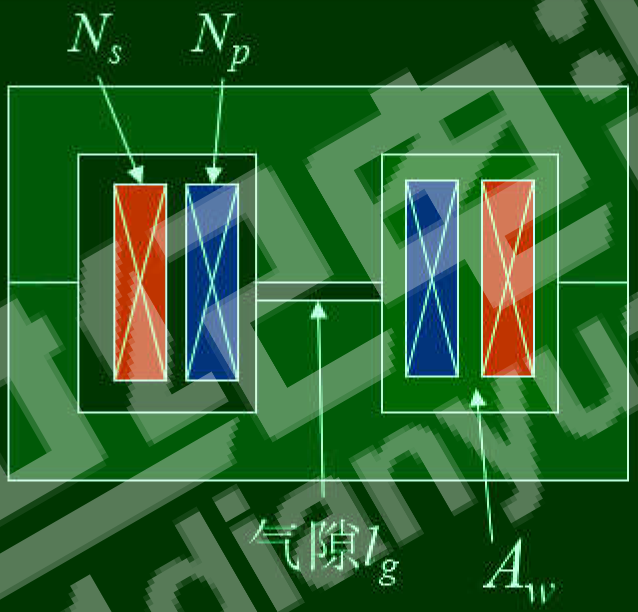
原副边线径选择
$$\begin{cases} r_p \le \delta \\ r_s \le \delta \end{cases}$$

原副边股数选择
$$\begin{cases} n_p \ge \dfrac{I_{prms}}{J \cdot \pi r_p^{\,2}} \\ n_s \ge \dfrac{I_{srms}}{J \cdot \pi r_s^{\,2}} \end{cases}$$

2.6 变压器窗口利用率验算

所设计的线规需要满足工程绕线的
窗口填充系数：

$$K_u' = \frac{N_p \cdot S_p + N_s \cdot S_s}{A_W} = \frac{N_p \cdot n_p \pi r_p^{\,2} + N_s \cdot n_s \pi r_s^{\,2}}{A_W}$$



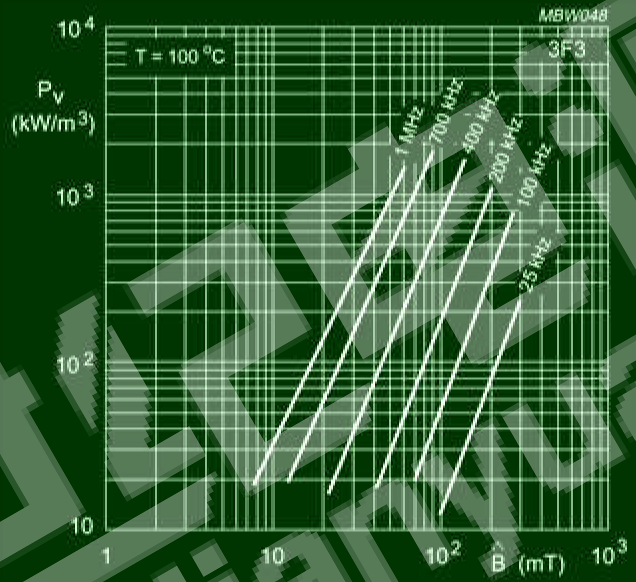
当K_u' 大于工程上允许的窗口填充系数时，说明所选的线规不合理，
需重新选型。

2.7 变压器磁心损耗和绕组损耗验算

变压器的绕组损耗计算：

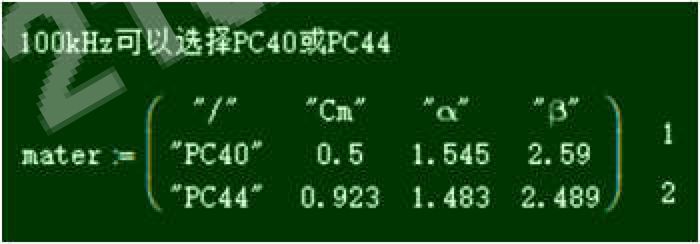
$$P_w = I_{prms}{}^2 R_p + I_{srms}{}^2 R_s$$

$$= I_{prms}{}^2 \frac{N_p MLT}{n_p \pi r_p{}^2 \gamma} + I_{srms}{}^2 \frac{N_s MLT}{n_s \pi r_s{}^2 \gamma}$$



变压器的磁心损耗计算：

$$P_c = C_m \cdot f_s{}^{\alpha} (\frac{\Delta B}{2})^{\beta} \cdot Ve$$



100kHz可以选择PC40或PC44

$$mater := \begin{pmatrix} "/" & "Cm" & "\alpha" & "\beta" \\ "PC40" & 0.5 & 1.545 & 2.59 \\ "PC44" & 0.923 & 1.483 & 2.489 \end{pmatrix} \begin{matrix} \\ 1 \\ 2 \end{matrix}$$

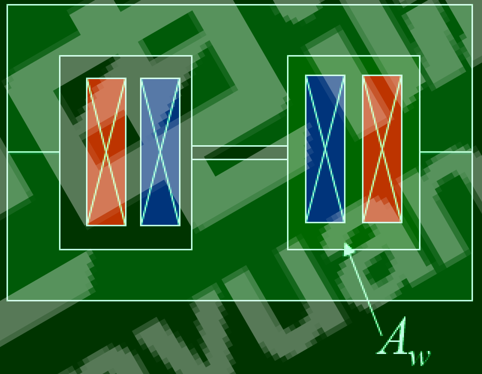
变压器的总损耗：

$$P_t = P_c + P_w$$

2.8 变压器温升验算

变压器的温升由变压器的功率损耗P_t及表面散热能力（热阻R_{th}）综合决定的。

$$\boxed{\Delta T = R_{th} P_t}$$



变压器表面到外部环境的外热阻R_{th} 可粗略计算为：

$$\boxed{R_{th} = \frac{800}{A_s(cm^2)}(^\circ C/W)}$$

A_s为磁性元件外表面面积。对于EE型磁芯，如EC，ETD，PM，PR等系列磁心的表面积可近似为窗口面积A_w的22倍 ，即：

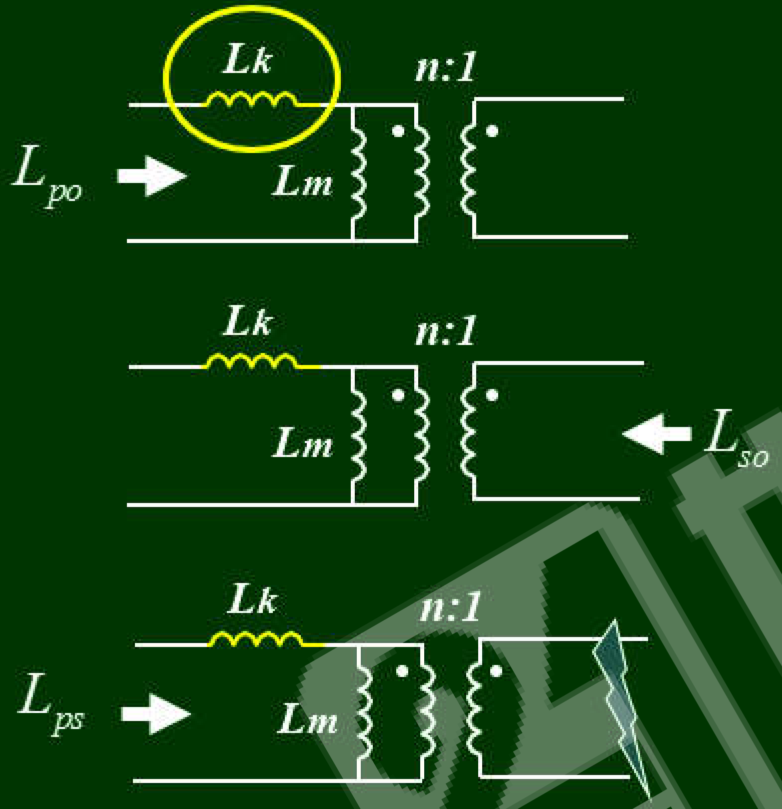
$$R_{th} = \frac{36}{A_w(cm^2)}(^\circ C/W)$$

对于PQ型磁芯，窗口较小，磁心的表面积可近似为窗口面积A_w的25-50倍。

$R_{th}=(16\sim32)/A_w$

反激电路变压器的杂散参数

变压器电路模型的参数测量



$$L_{po} = L_k + L_m$$

$$L_{so} = L_m / n^2$$

$$L_{ps} = L_k$$

➡

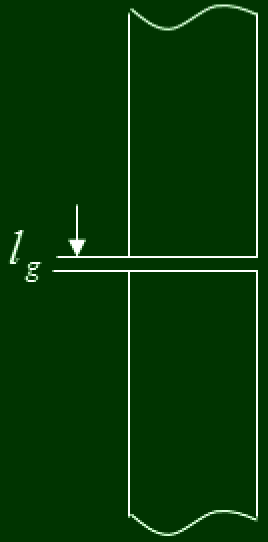
L_m

n

L_k

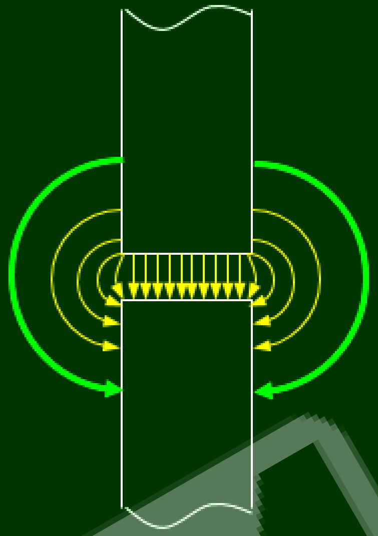
合适的模型要满足：参数可测量，便于应用分析。

气隙对电感量的影响

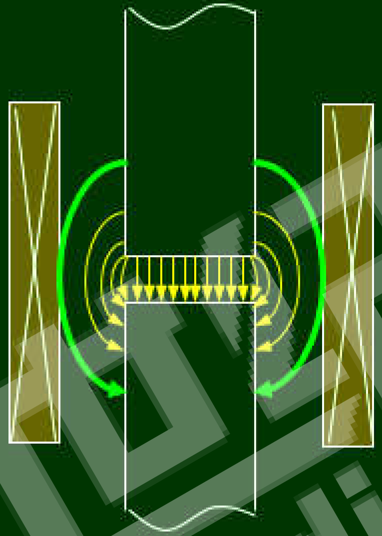


$$L = \mu_0 \frac{A_e}{l_g} \cdot N^2$$

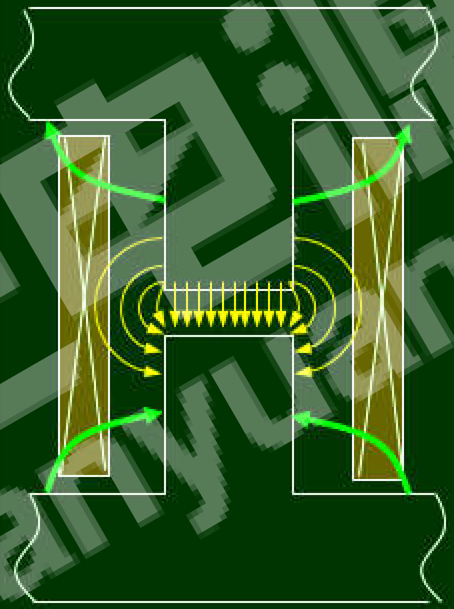
小气隙



气隙扩散效应

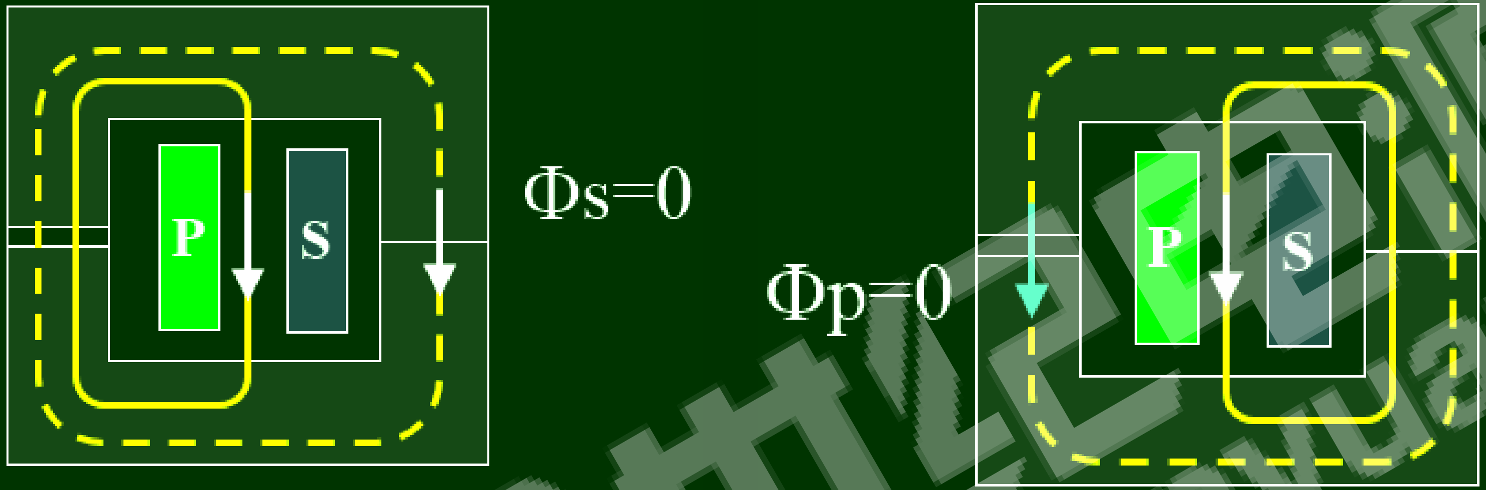


绕组涡流去磁效应



窗口高度影响

反激变压器的漏感

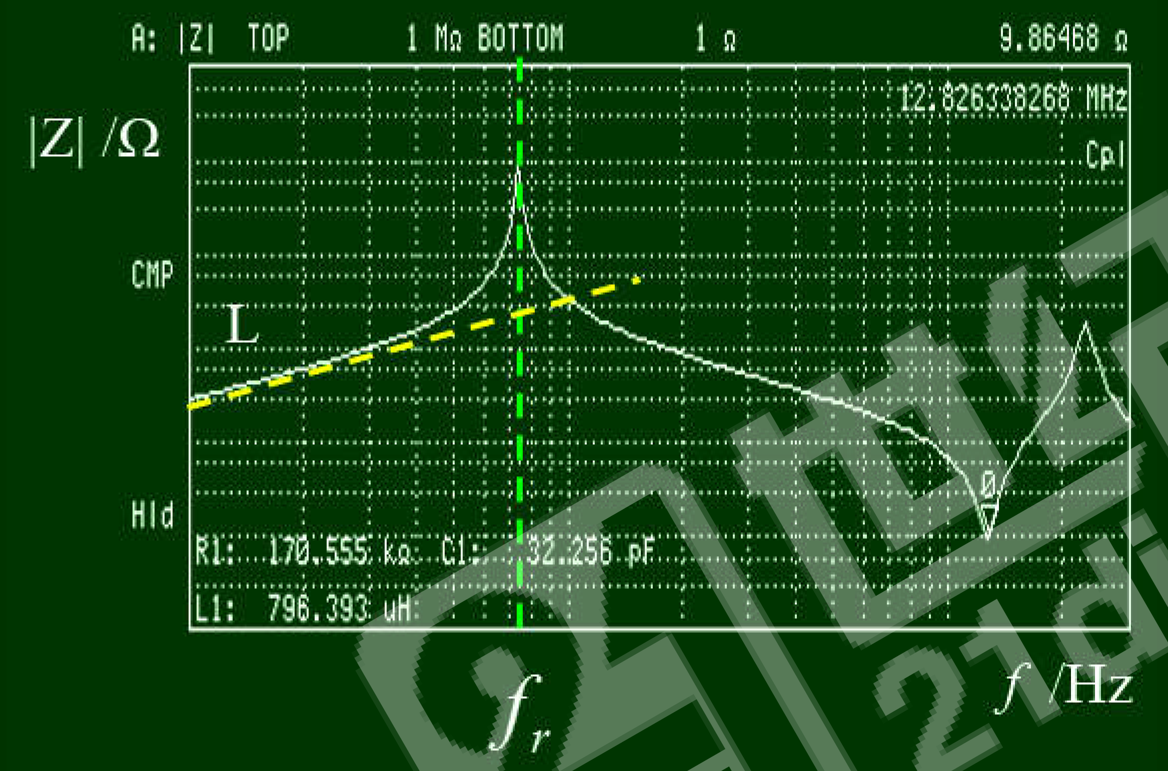


短路副边

短路原边

- □ 气隙对漏感本身值的大小影响不大
- □ 气隙影响漏感与激磁电感的比值，影响耦合系数

绕组分布电容及测量方法

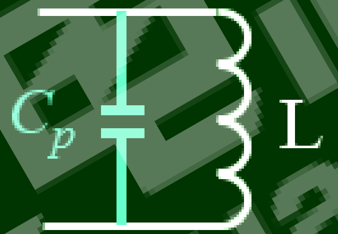


A: |Z| TOP 1 MΩ BOTTOM 1 Ω 9.86468 Ω

12.826338268 MHz

R1: 170.555 kΩ C1: 32.256 pF

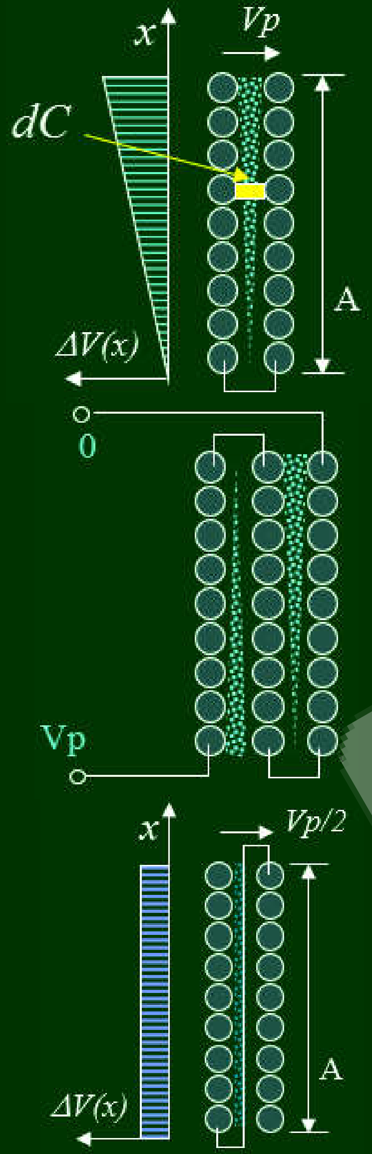
L1: 796.393 uH



$$f_r = \frac{1}{2\pi\sqrt{L \cdot C_p}}$$

□ 根据低频测量的L和谐振频率点 f_r，可以算出C_p。

绕组并联等效电容Cp



$$\Delta V(x) = V_p \frac{x}{A}$$

$$E = \int_0^A dE = \int_0^A \frac{1}{2}(dC)\Delta V(x)^2 = \int_0^A \frac{1}{2}\left(\frac{C_0}{A}dx\right)\Delta V(x)^2 = \frac{1}{2}\left(\frac{C_0}{3}\right)V_p^{\ 2}$$

$$C_P = \frac{1}{3}C_0$$

$$C_P = \frac{8}{27}C_0$$

$$C_P = \frac{1}{4}C_0$$

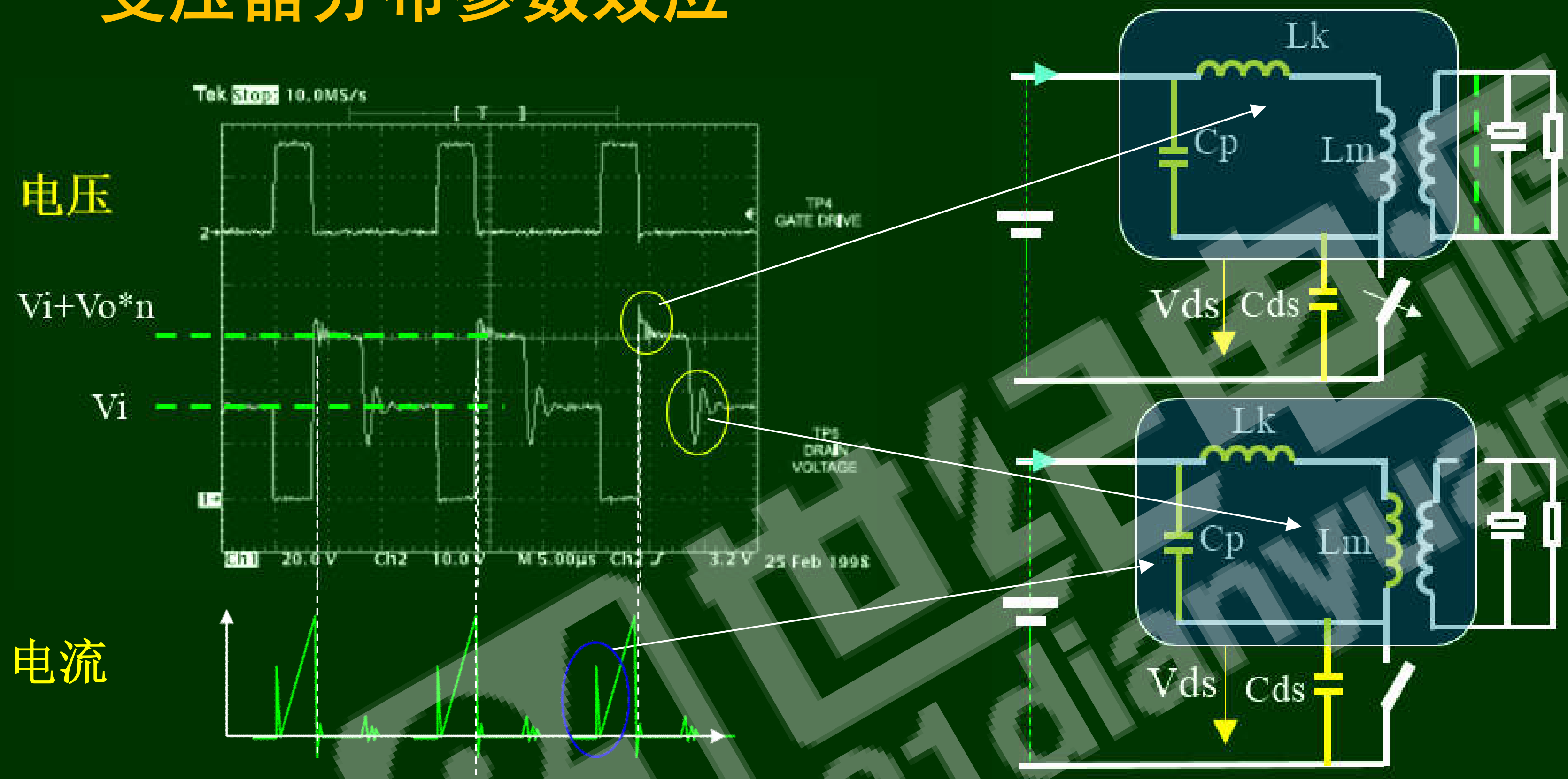
C_0：绕组层间的结构电容

C_p：绕组层间的等效电容

□ 绕组的高度、层数会影响结构电容

□ 绕组的绕线方式会影响绕组等效电容

变压器分布参数效应



影响差模噪声　影响共模噪声

影响开关应力　影响开关损耗

□ 对CM-EMI的效应 → $f_r = \dfrac{1}{2\pi\cdot\sqrt{L_k\cdot(C_p//C_{ds})}}$

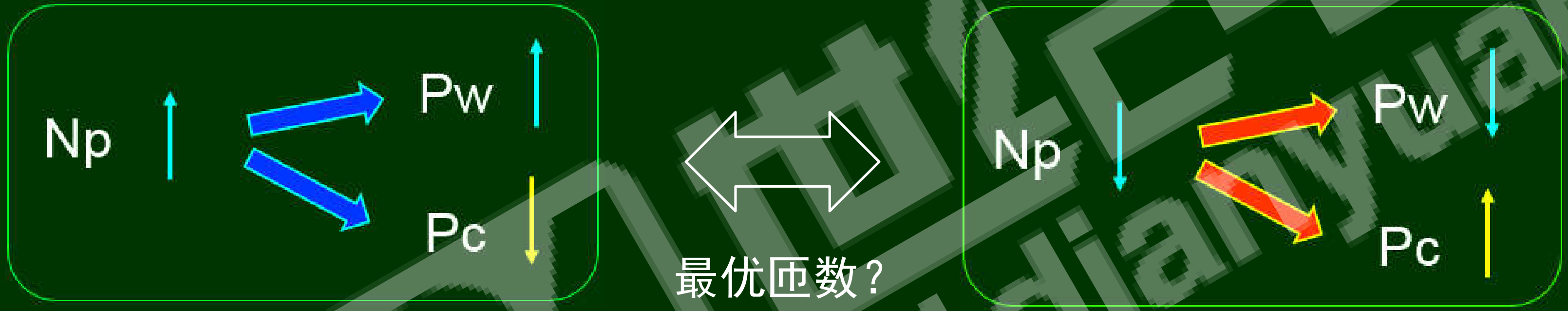
□ 对损耗的效应 → $P_{Lk} \approx (\frac{1}{2}\cdot L_k\cdot I_{pk}^{2})\cdot f$

反激电路变压器的损耗和EMI设计

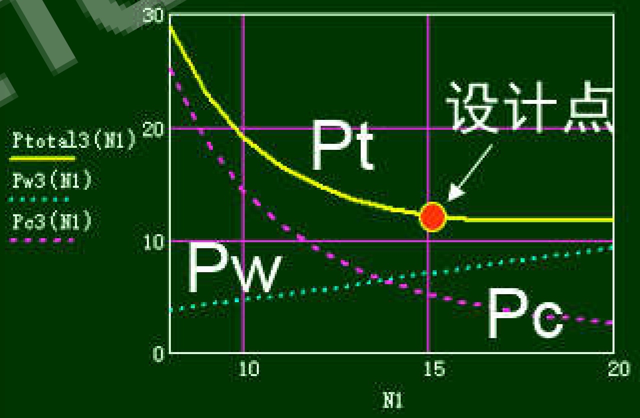
线圈匝数对变压器损耗的影响

变压器的绕组损耗计算： $P_w = I_{prms}{}^2 \dfrac{N_p MLT}{n_p \pi r_p{}^2 \gamma} + I_{srms}{}^2 \dfrac{N_s MLT}{n_s \pi r_s{}^2 \gamma}$

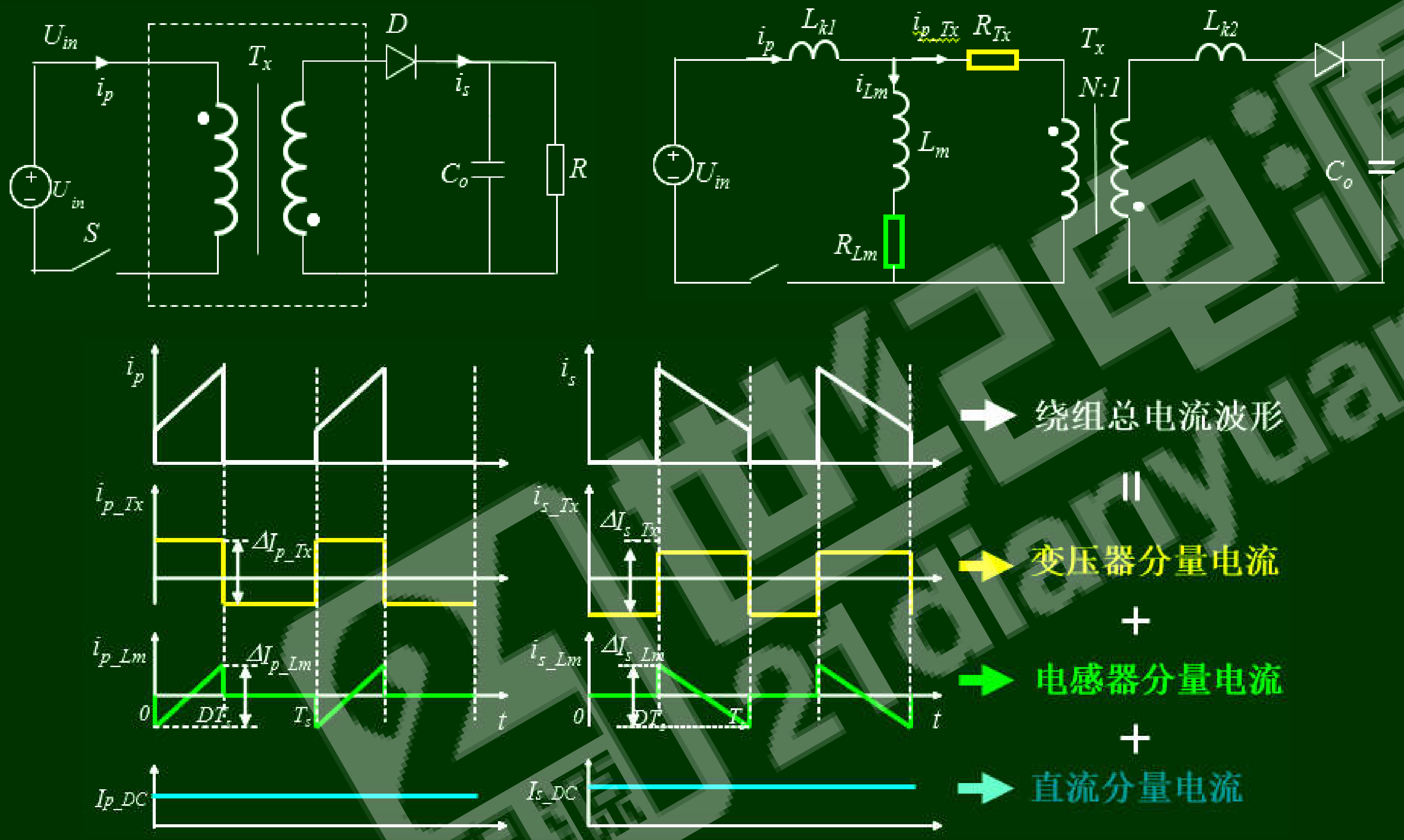
变压器的磁心损耗计算： $P_c = C_m \cdot f_s{}^{\alpha} (\dfrac{\Delta B}{2})^{\beta} \cdot Ve$ $\Delta B = \dfrac{V_i}{N_p \cdot Ae} \cdot DT_s$



$$P_w = I_{prms}{}^2 \frac{N_p MLT}{\frac{I_{prms}}{J} \gamma} + I_{srms}{}^2 \frac{N_p MLT}{n \cdot \frac{I_{srms}}{J} \gamma} + C_m \cdot f_s{}^{\alpha} (\frac{V_i}{2N_p \cdot Ae} \cdot DT_s)^{\beta} \cdot Ve$$



反激变压器绕组损耗分析–电流分解



绕组总电流波形

‖

变压器分量电流

+

电感器分量电流

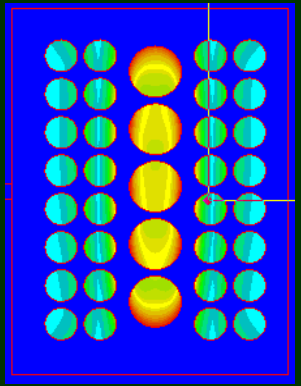
+

直流分量电流

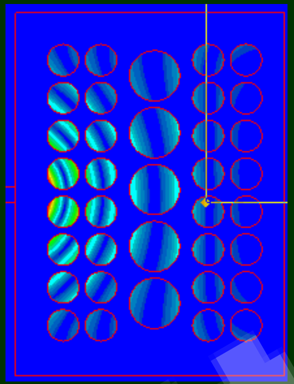
- □ 由于两个电流分量是正交的，所以损耗可以分离
- □ 变压器绕组电流可以分解为变压器和电感器分量

变压器绕组的磁场分布特点及绕组损耗优化

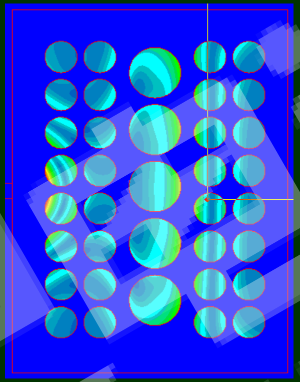
负载电流激励

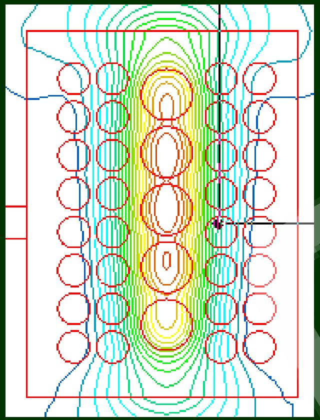


激磁电流激励

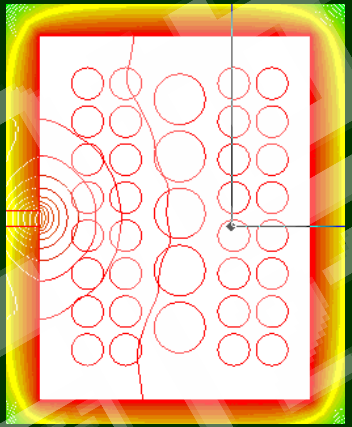


总电流激励

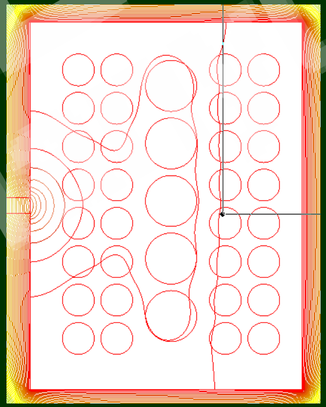




变压器漏感磁场



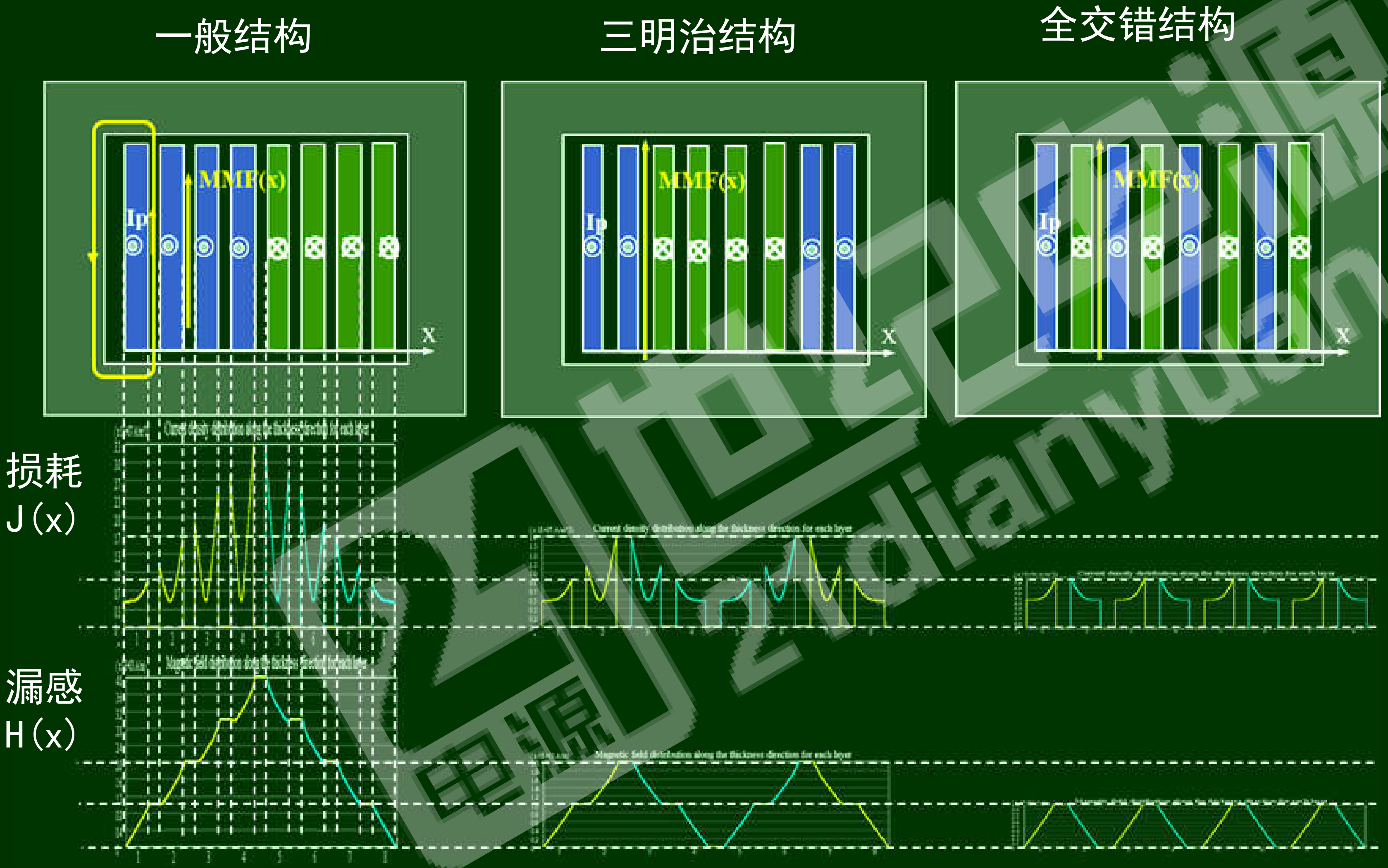
激磁电感磁场



总磁场

- □ 变压器绕组损耗的减小方法：绕组结构优化，线规优化
- □ 电感器绕组损耗的减小方法：分布气隙、气隙避让、多股绞线

变压器绕组损耗优化：绕组结构优化


一般结构
三明治结构
全交错结构
损耗
J(x)
漏感
H(x)

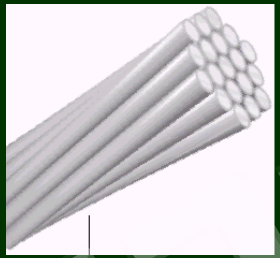
变压器绕组损耗优化：线规的优化设计

圆电磁线

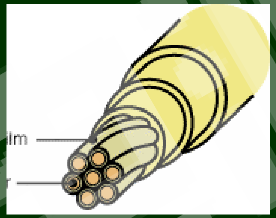
铜箔导体

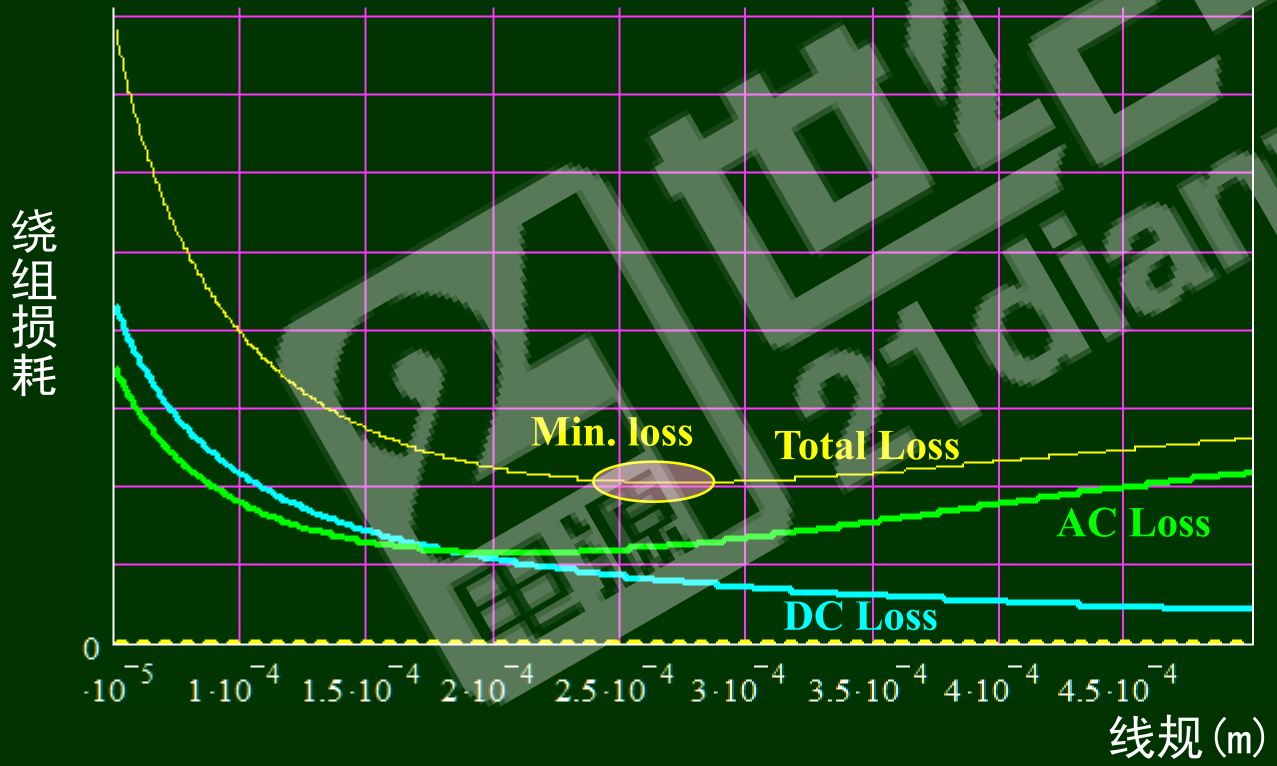
扁螺旋线圈

多股绞线

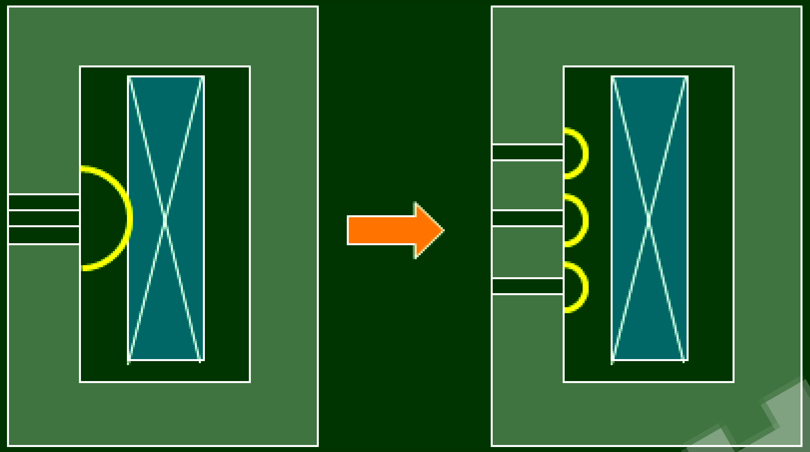


三层绝缘绞线

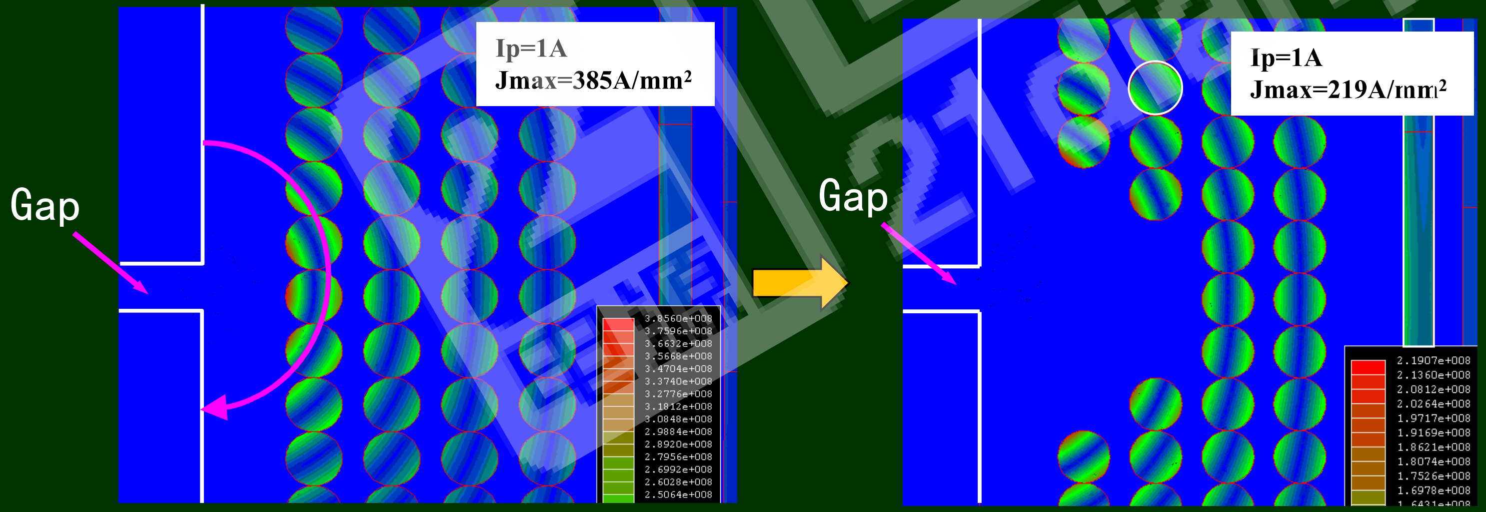




电感器损耗减小：分布气隙、气隙避让、多股绞线



多股绞线



Ip=1A
Jmax=385A/mm²

Ip=1A
Jmax=219A/mm²

反激变压器设计困难所在

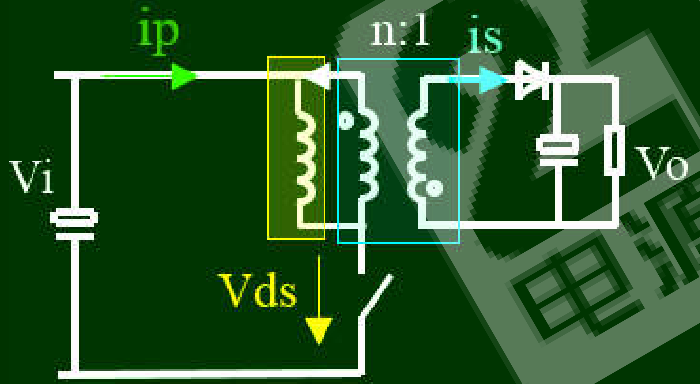
电感和变压器集成：

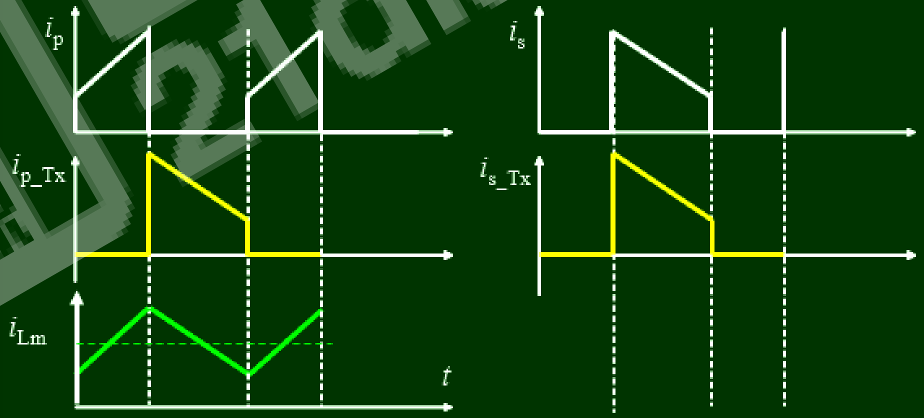
□ 交、直流电流矛盾 ➡ 绕组存在直流 线规较粗 涡流效应大

□ 交、直流磁通矛盾 ➡ 交流磁通损耗 直流磁通饱和

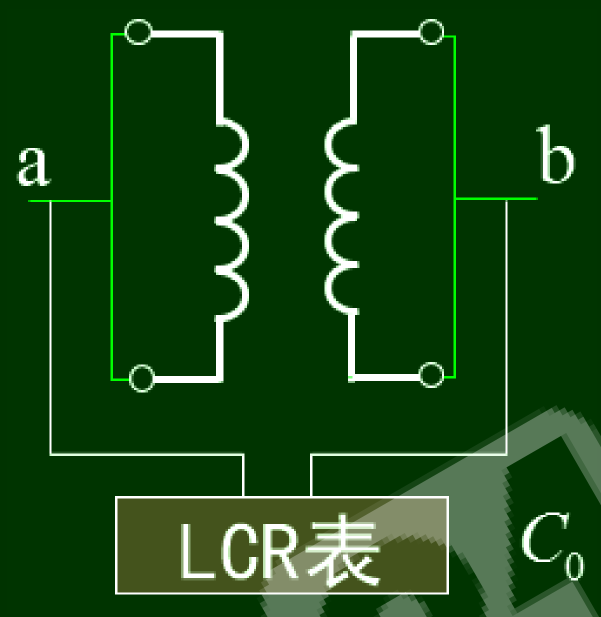
□ 电感、变压器矛盾 ➡ 磁芯需要气隙 存在扩散损耗
匝数相同 设计不易优化

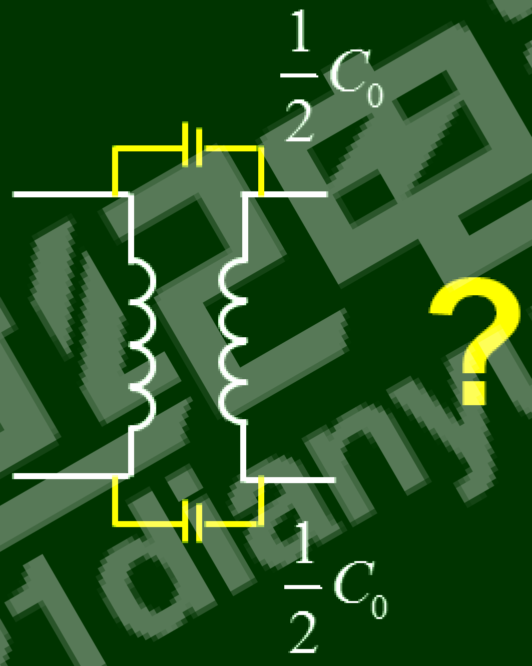
电感和变压器分立： 电感绕组纹波降低
变压器绕组电流不变，但不需气隙





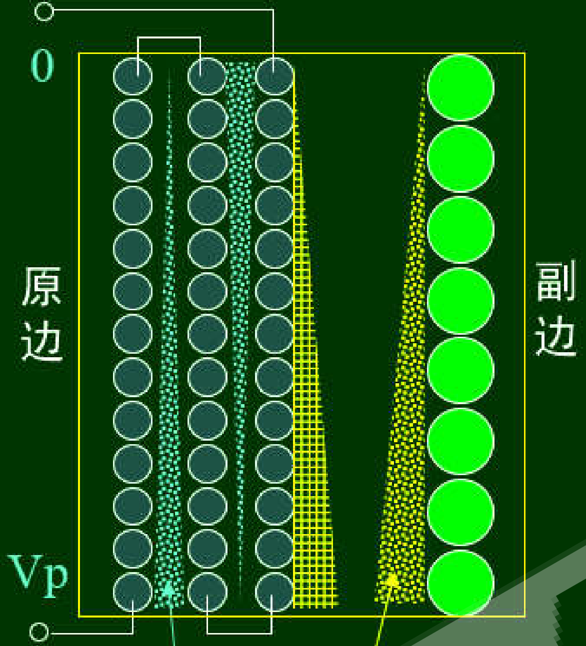
变压器原、副边绕组电容模型

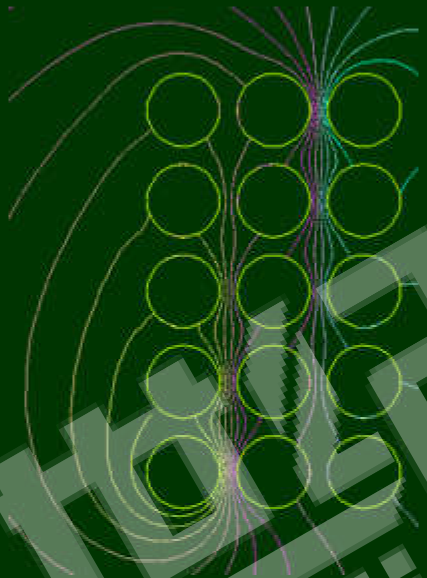


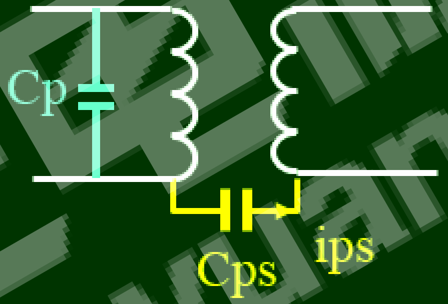


- 采用阻抗分析仪或LCR表测量的只是原、副边绕组间结构电容C_0

变压器绕组电场特性及其EMI效应







Q_{ps} → 原、副边绕组间的感应电荷 → i_{ps}

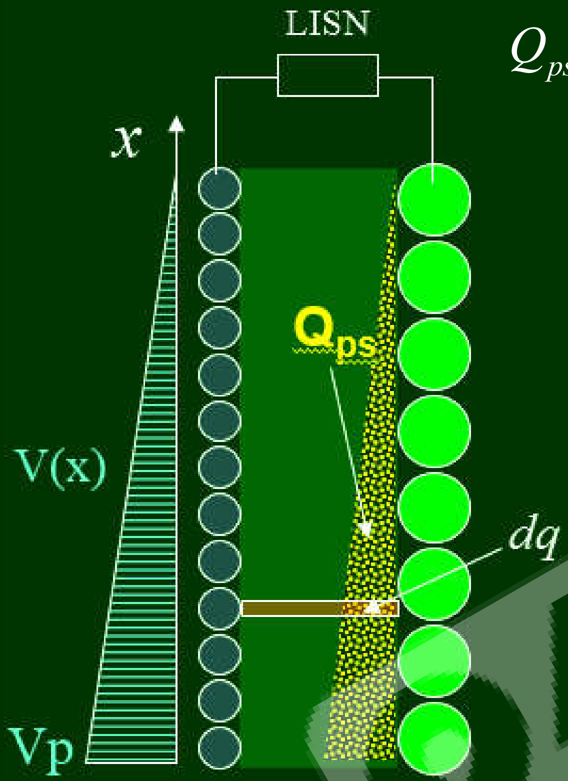
Q_p → 原边绕组储存的电场能量 → C_p

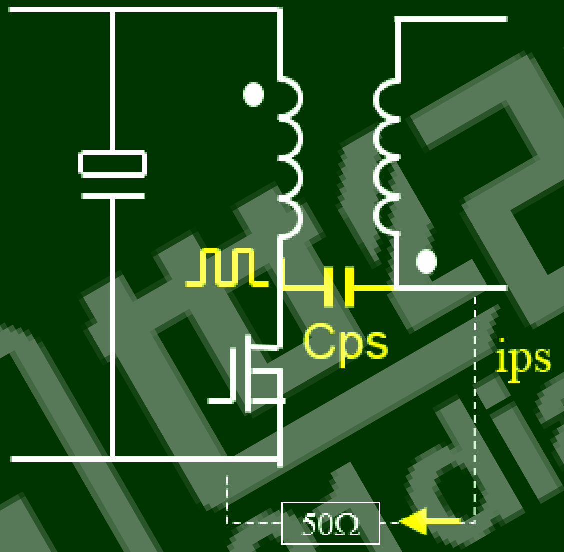
- □ Cp对 DM-EMI 的效应 → 宽频范围的差模噪音
- □ Cps对 CM-EMI 的效应 → 共模噪音
- □ Cp对损耗的效应 → $P_{Cp}=(\frac{1}{2}\cdot C_p\cdot V_p^2)\cdot f$

原、副边绕组间共模噪音电流机理

$$Q_{ps}=\int_0^A dq=\int_0^A \Delta V(x)dC=\int_0^A\left(\frac{C_0}{A}dx\right)\left(\frac{x}{A}V_p\right)=\left(\frac{C_0}{2}\right)V_p$$

*C_0为变压器原、副边间的结构电容





$$\boxed{C_{ps}=\frac{1}{2}C_0}$$

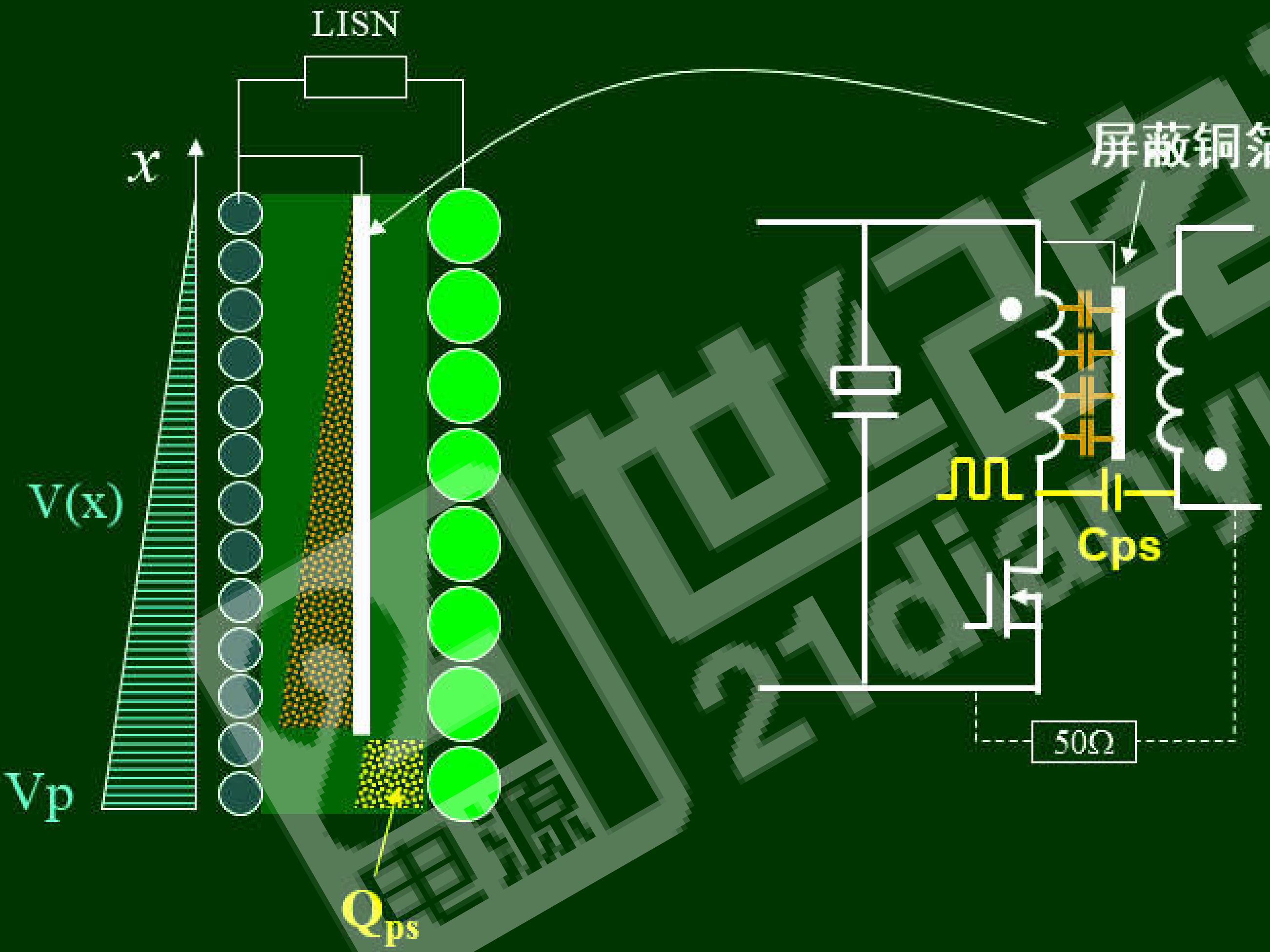
□ 副边绕组感应的电荷 Q_{ps}

→ 经副边形成回路的共模电流 i_{ps}

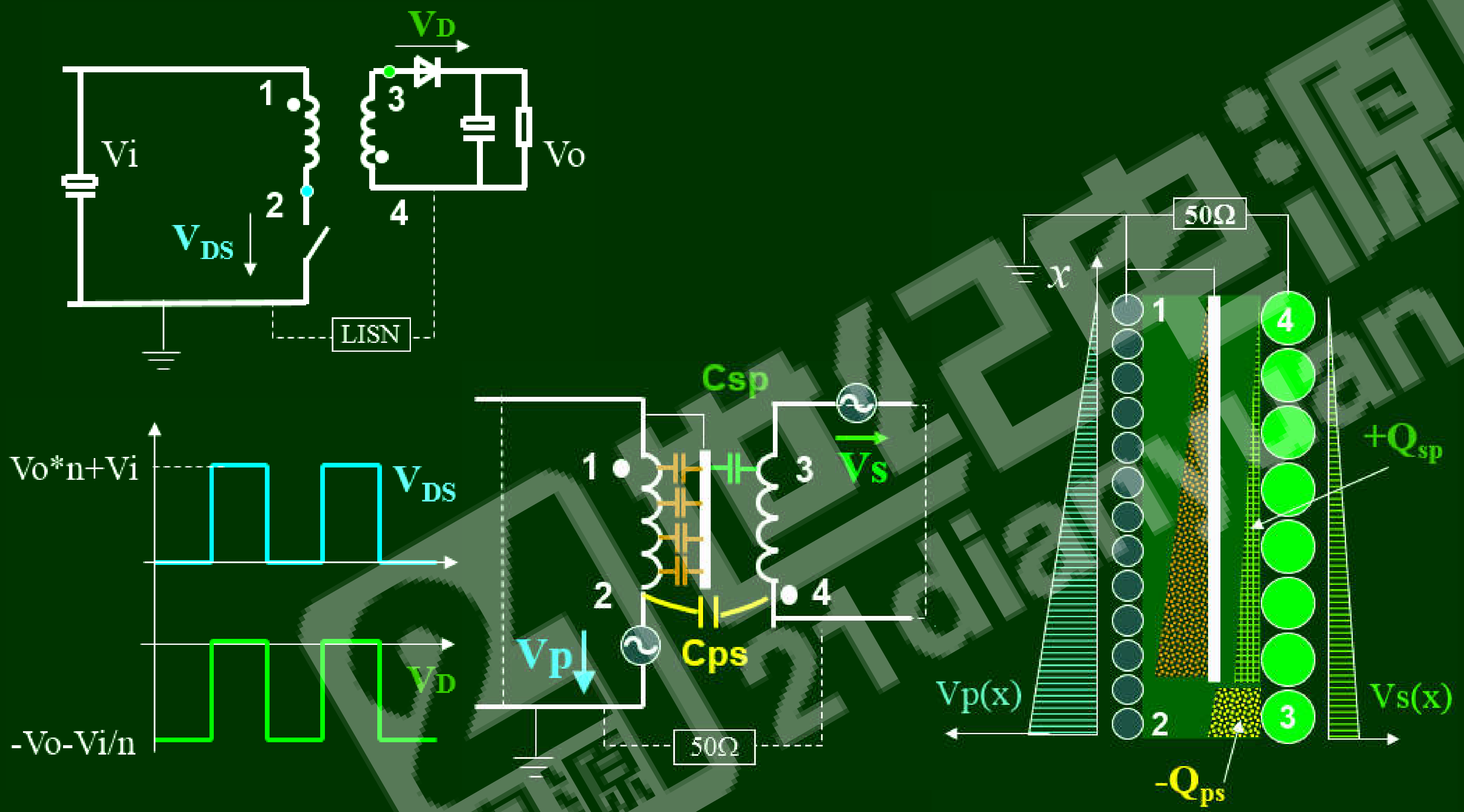
→ 表达为等效共模电容 C_{ps}

变压器副绕组导体上感应出的电荷就形成共模噪声电流

有屏蔽层变压器的绕组电场分布

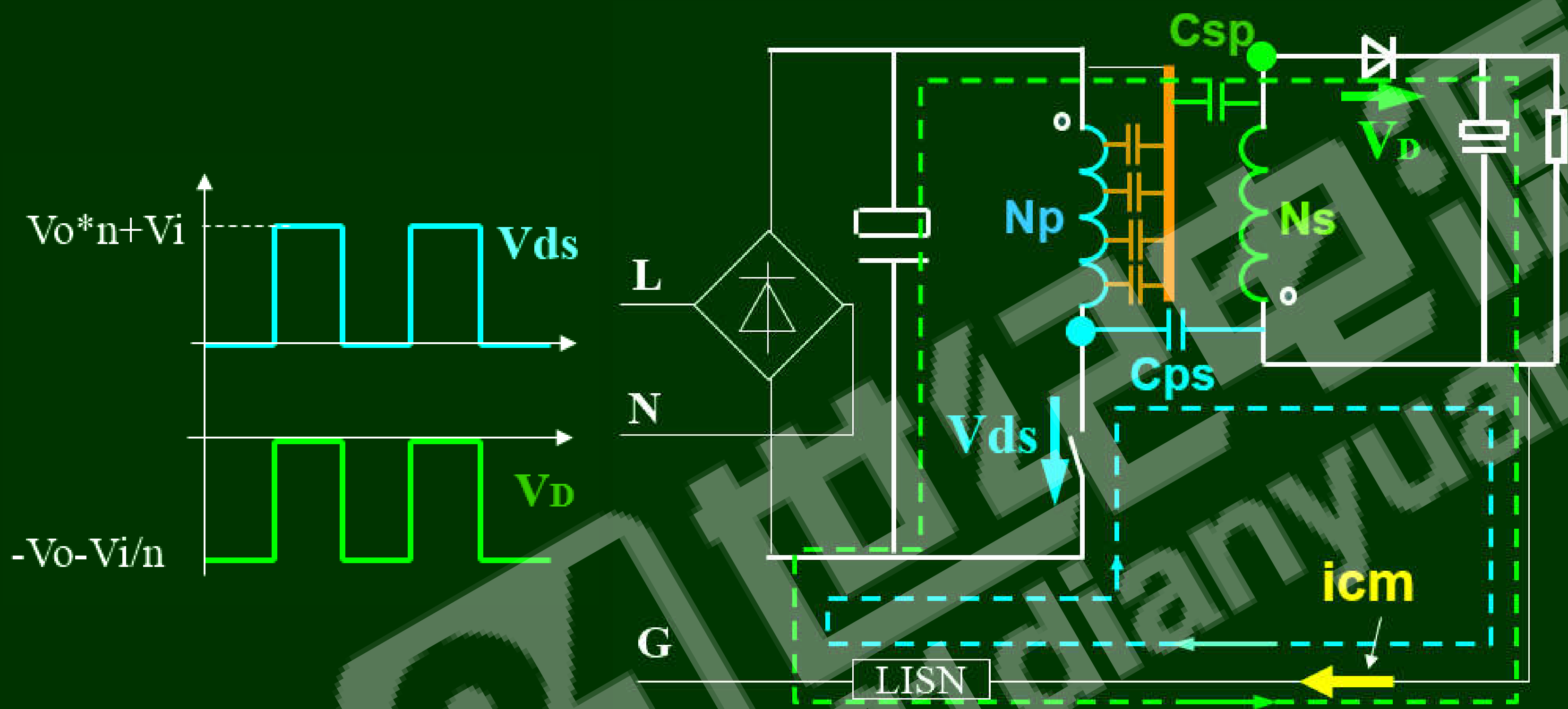


考虑副边电位的有屏蔽变压器电场分布



□ 当(-Qps+Qsp)=0 时，变压器的共模噪音相互抵消

考虑副边电位的噪声路径分析



- □ Vp和Vs相位基本相同，大小差n倍
- □ 当满足Vp*Cps=Vs*Csp时，变压器共模噪音将相互抵消为零

降低共模耦合电容的考虑

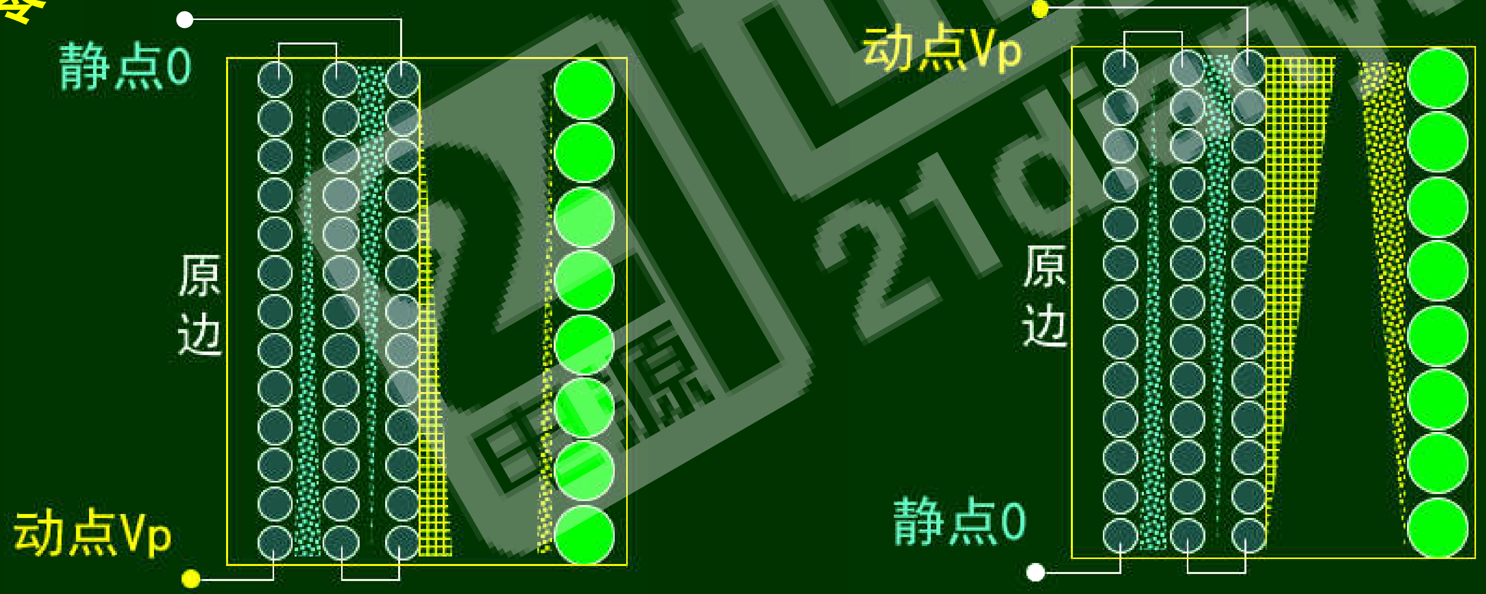
□ 增加原副边绕组间的距离 → 漏感增大， 体积增大

□ 减少原副边绕组间的面积 → 绕组层增多， 损耗增大

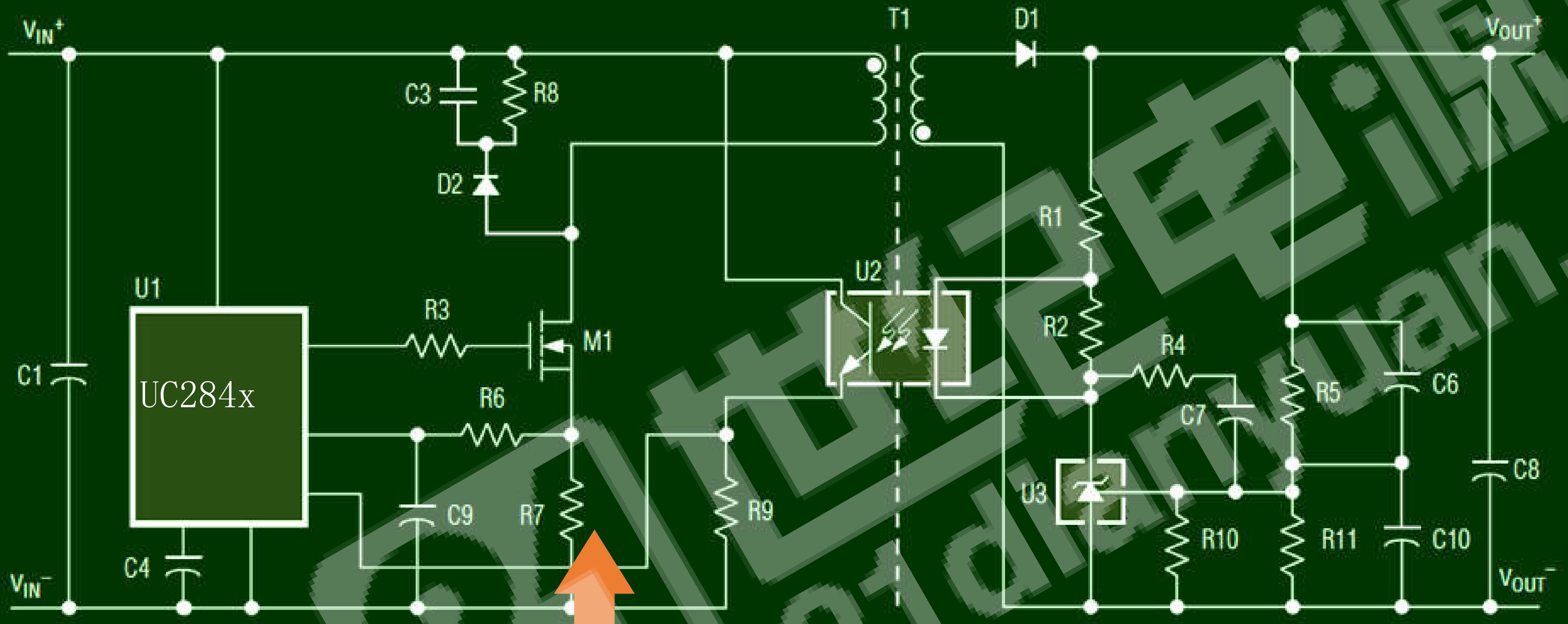
□ 采用低介电系数绝缘胶带 → 增加成本

□ 采用更完全的屏蔽 → 增加空间， 成本和损耗

□ **调整电位分布使副边电荷为零 → 很多方法**



传统光耦反馈反激变换器



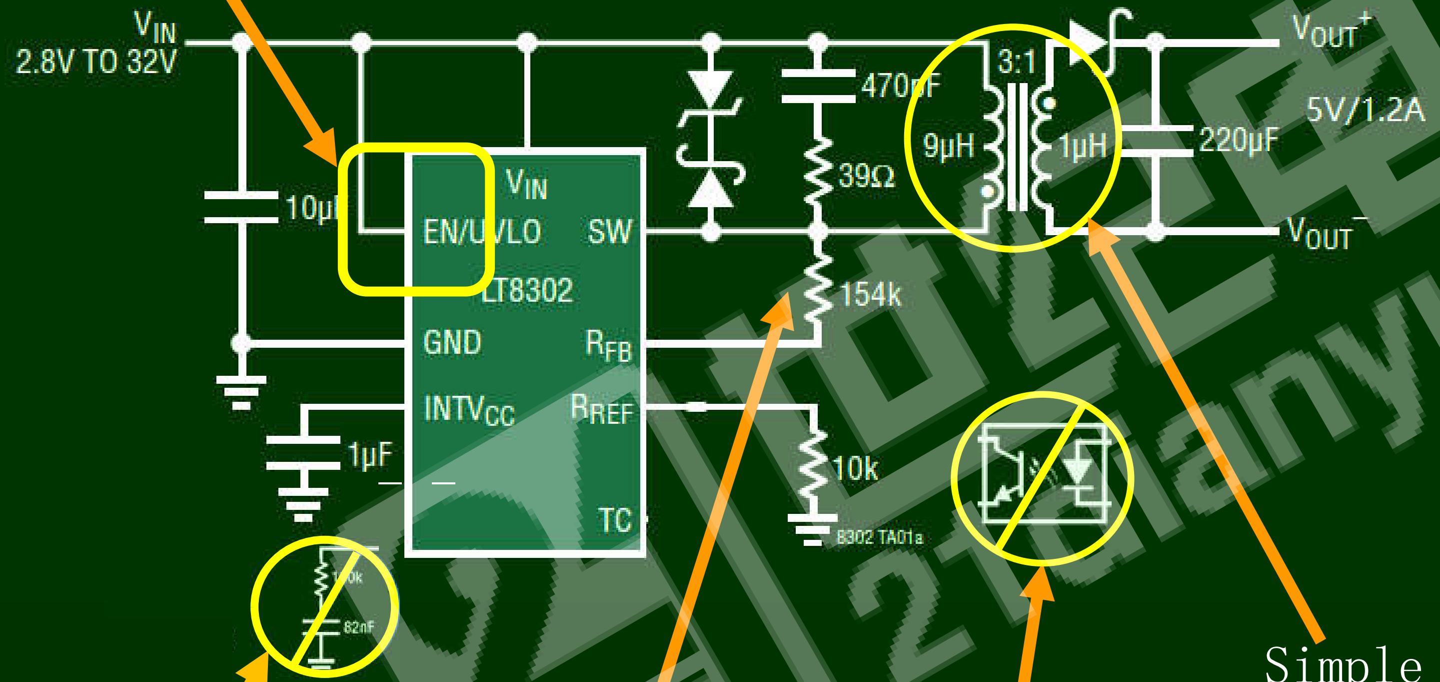
Primary Side IC

Switch FET

Opto

Secondary Side Reference and Loop Compensation

ADI绕组反馈反激变换器



Input UVLO

No Compensation

One resistor set output voltage

No Opto-coupler

Simple transformer

谢 谢大家！