



LLC谐振变换器设计与优化



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顺德会议演讲稿

2021.03

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4. LLC谐振变换器的设计与优化



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LLC谐振变换器的应用



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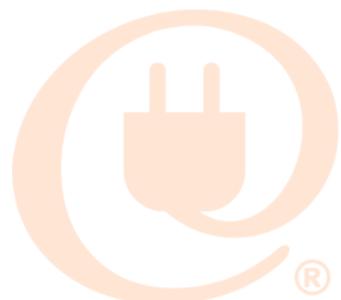
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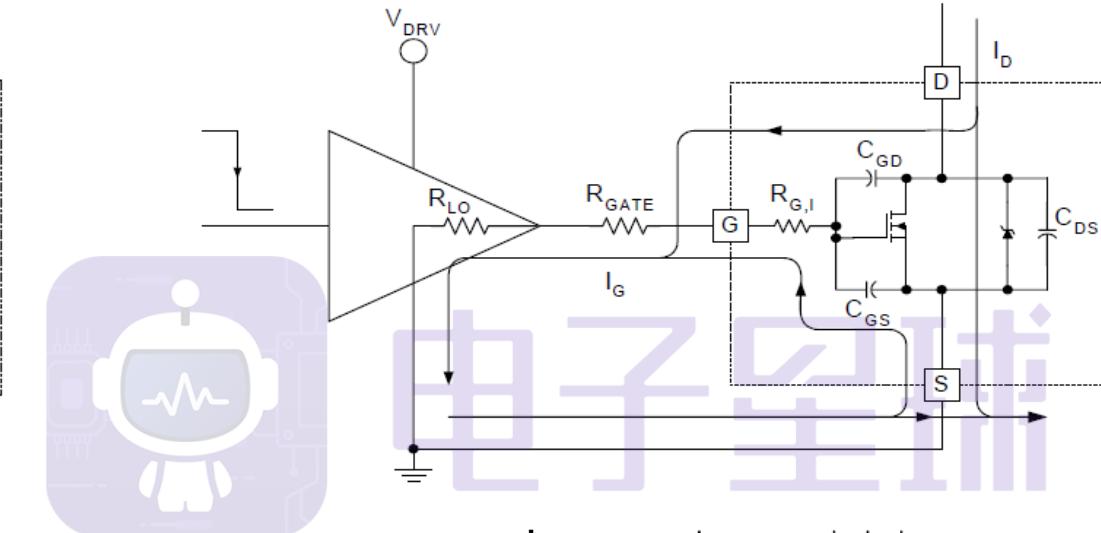
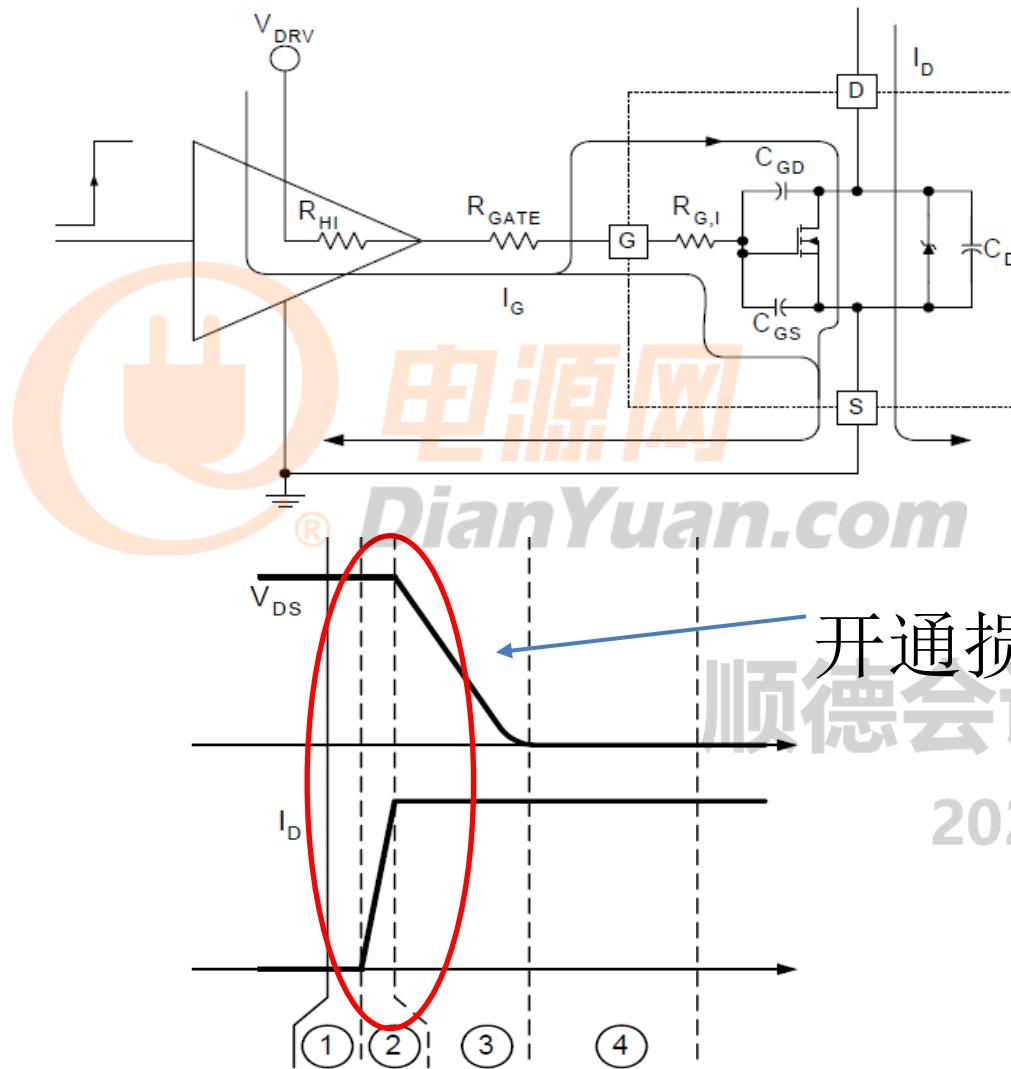
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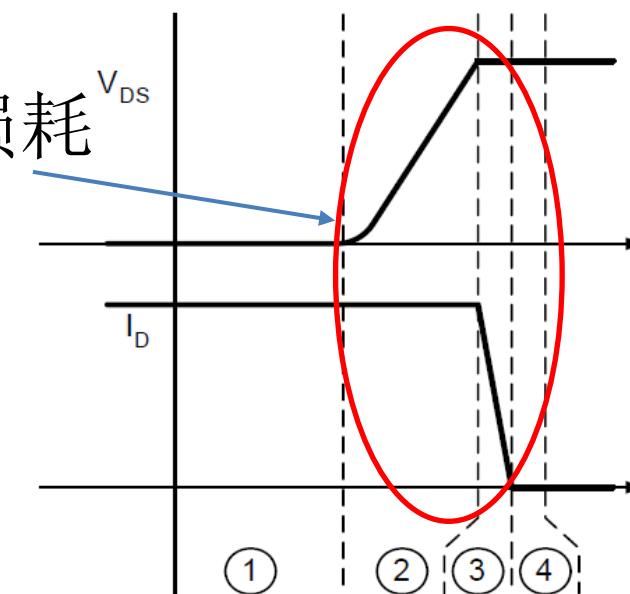
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开关损耗

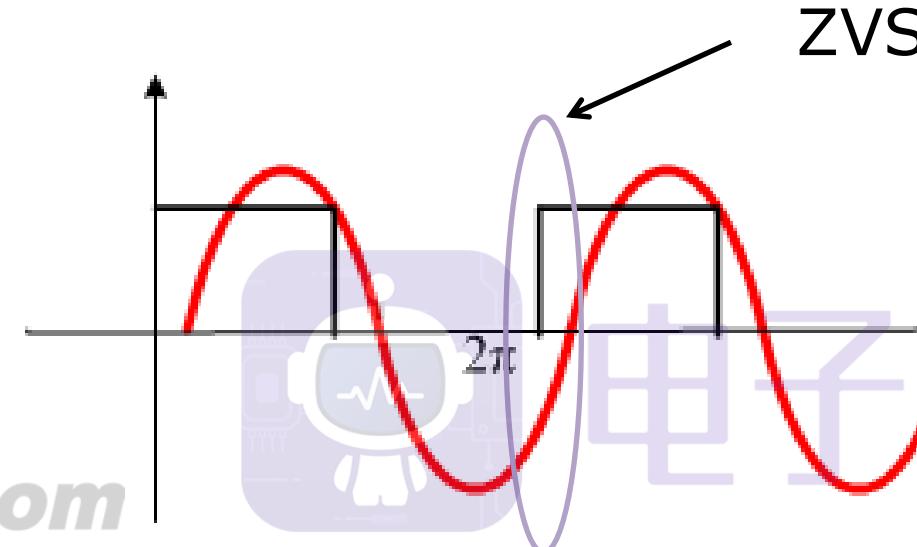
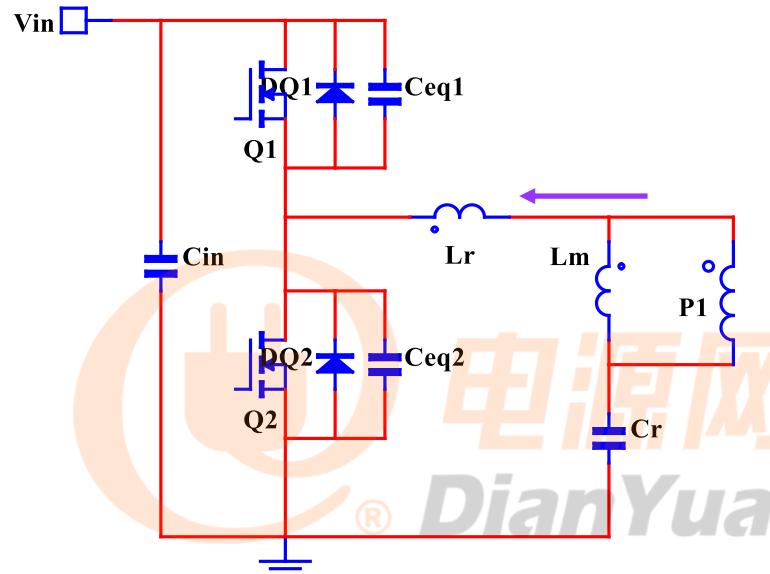


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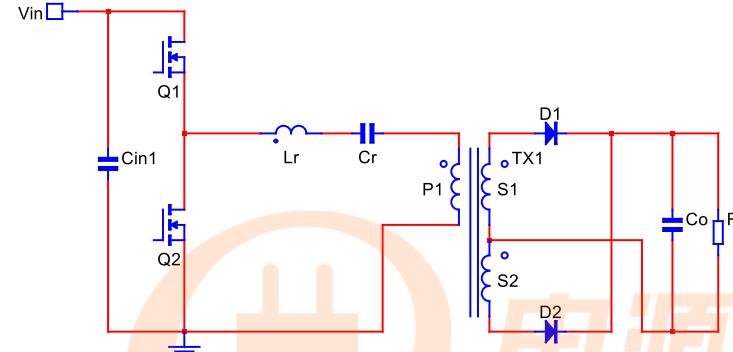
零电压谐振软开关的实现



通过改变开关频率，使谐振网络中电流滞后于电压，即谐振网络呈感性，使得开关管在开通前_③其电压已下降到零，从而实现ZVS。

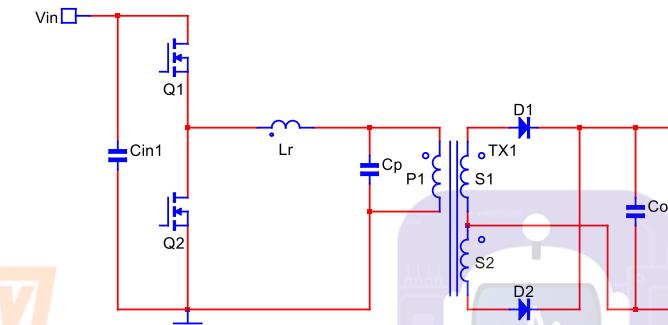


零电压谐振软开关变换器



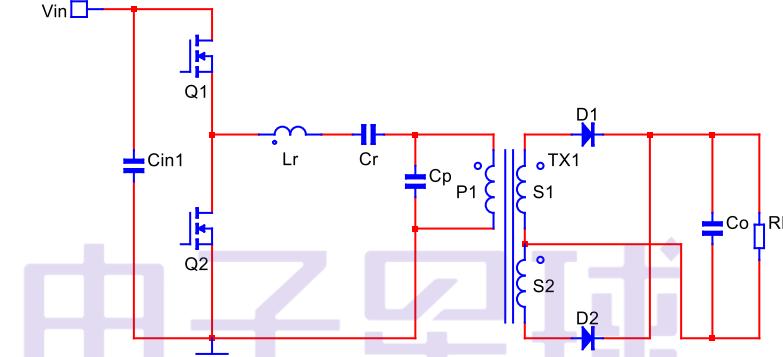
串联谐振变换器：

- 轻载调节特性不好
- 谐振网络增益不大于1



并联谐振变换器：

- 重载调节特性不好
- 轻载时无功环流大

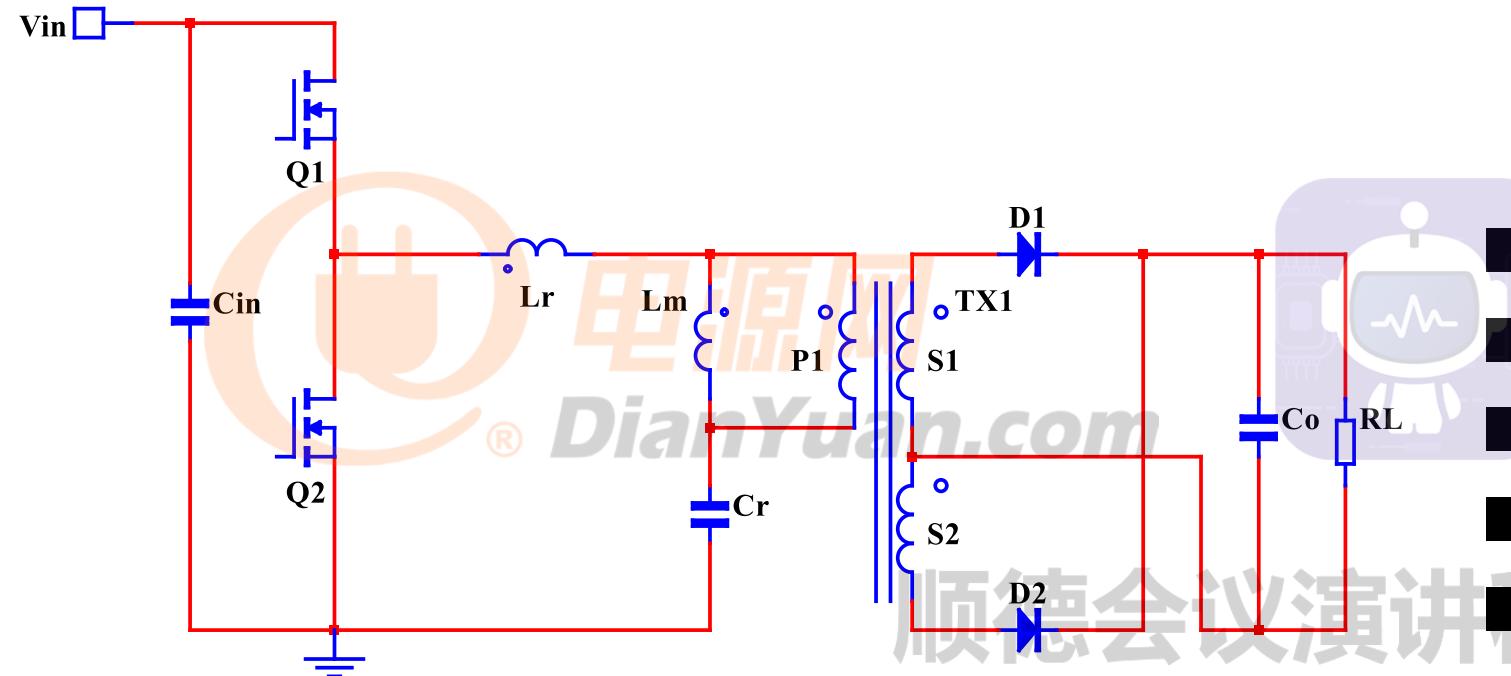


串并联谐振变换器：

- 变压器漏感不参与谐振
- 无功环流大



LLC谐振变换器

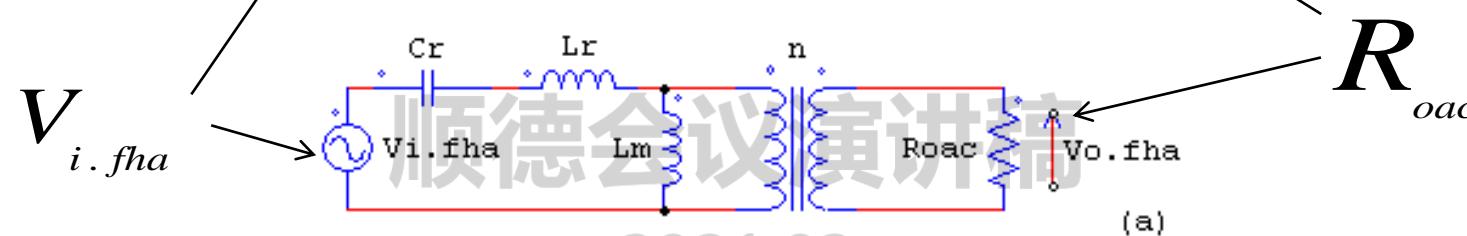
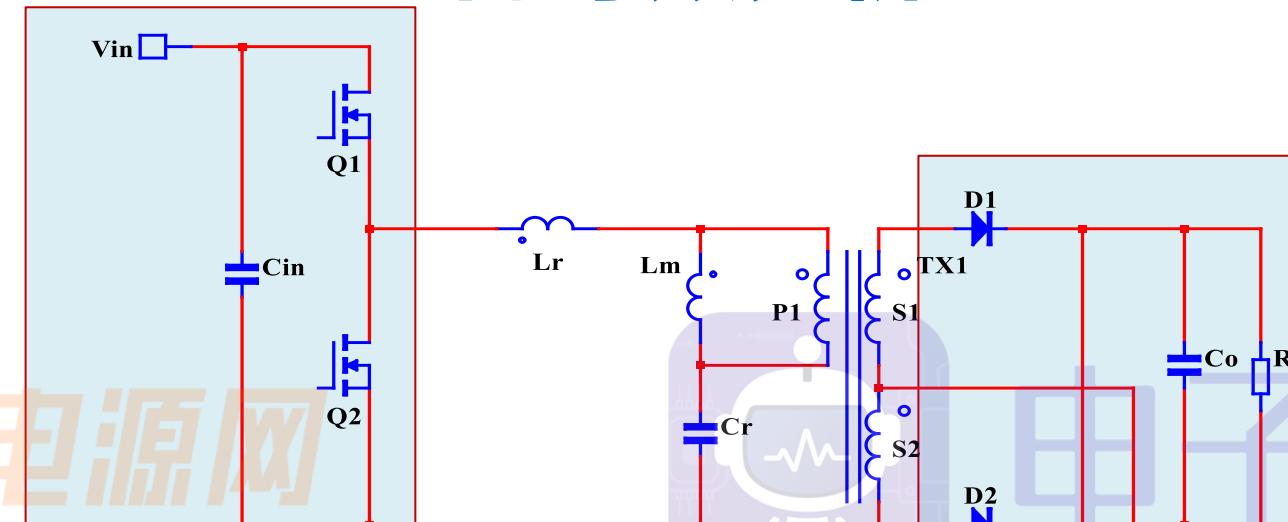


功率器件软开关，效率高
负载调节特性好
漏感参与谐振，便于磁集成
EMI小
频率高，体积小

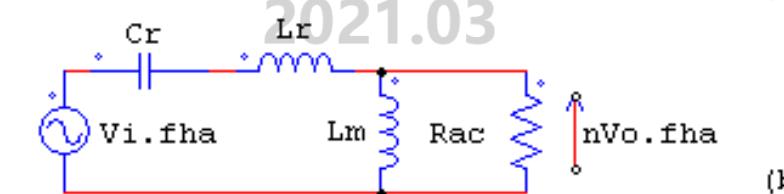
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LLC的等效分析



(a)



(b)

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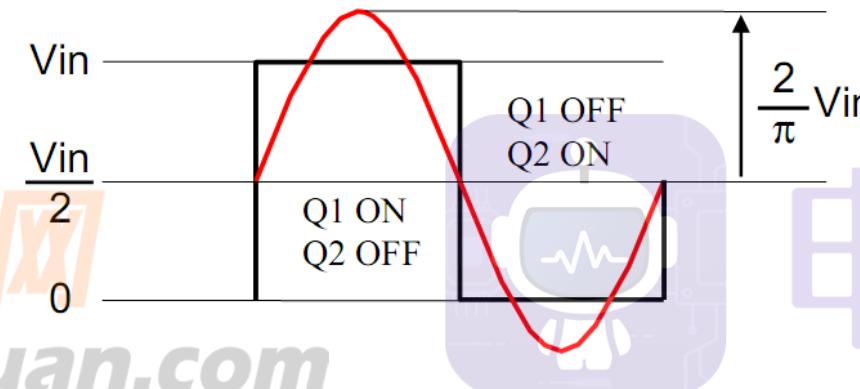
LLC的输入等效

谐振槽路的输入为方波



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通过对对其进行傅里叶分解得到其基波分量：

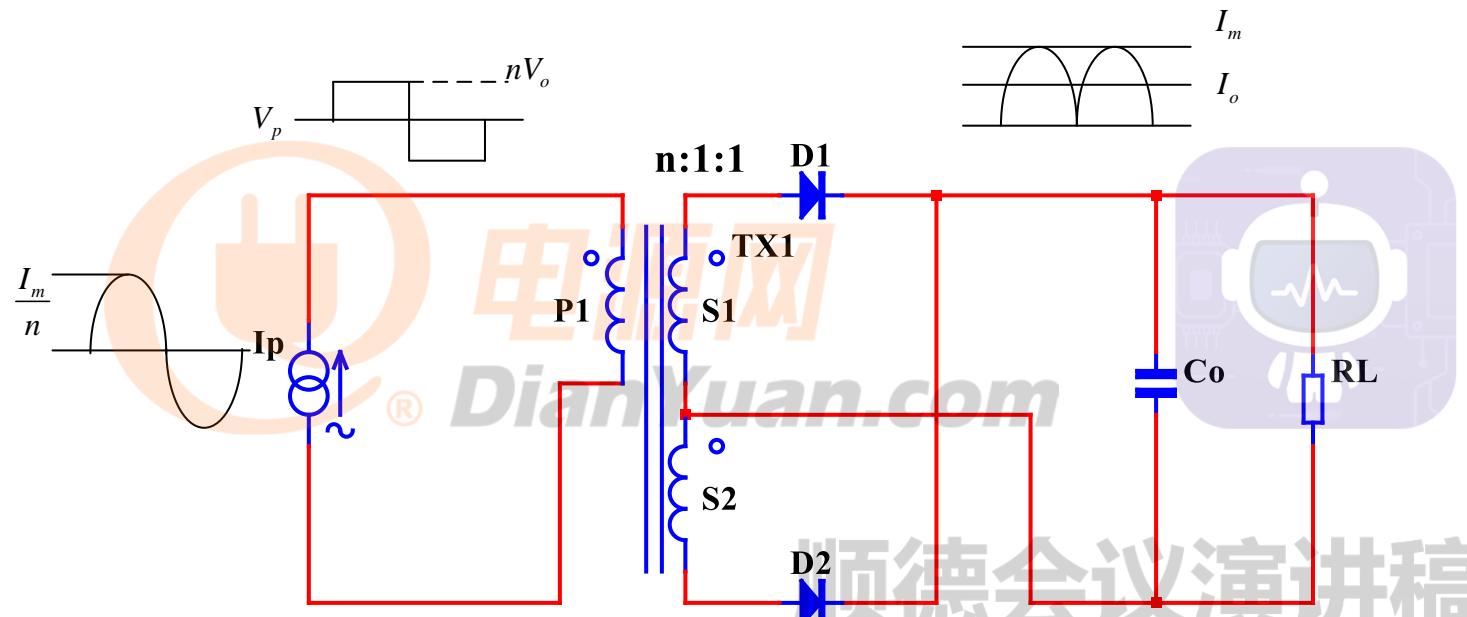
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 $V_s = \frac{2V_{in}}{\pi} \sin(2\pi f_s \cdot t)$

有效值为： $V_{iFHA} = \frac{2V_{in}}{\pi}$



LLC的输出等效

对于全波整流：



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$$V_p = \frac{4}{\pi} nV_o \sin(\omega t - \varphi)$$

$$I_p = \frac{I_m}{n} \sin(\omega t - \varphi)$$

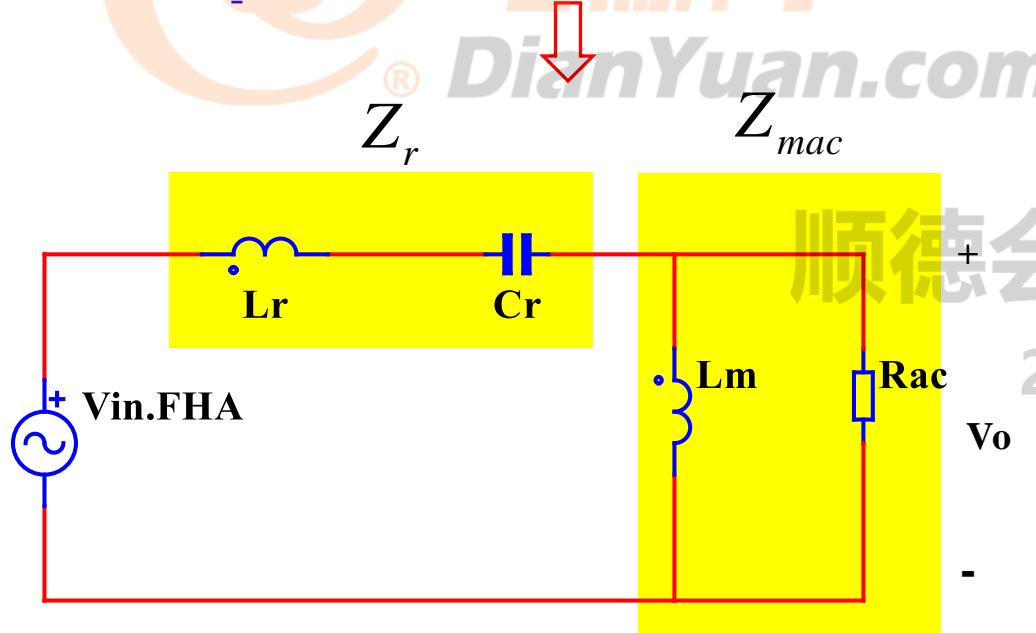
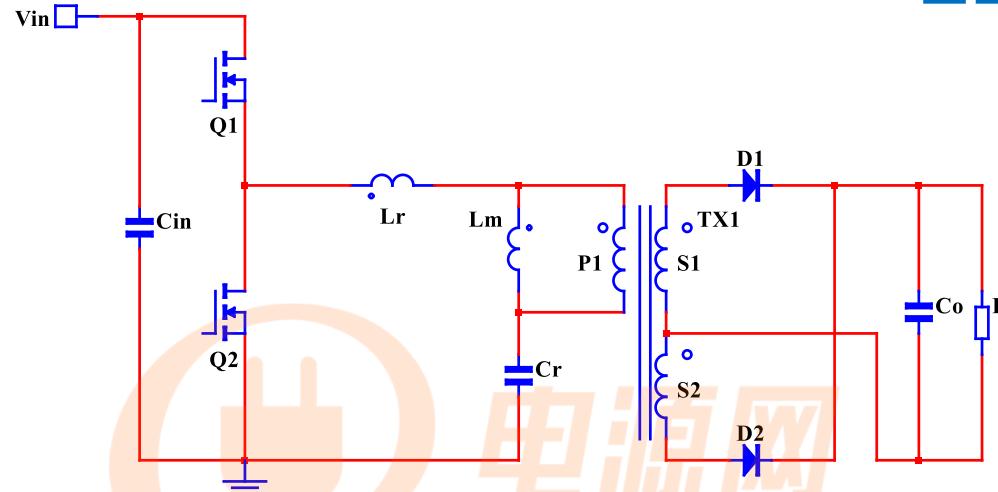
$$I_o = \frac{2}{\pi} I_m$$

$$R_{ac} = \frac{V_p}{I_p} = \frac{n^2 8}{\pi^2} R_L$$

$$R_{oac} = \frac{R_{ac}}{n^2} = \frac{8}{\pi^2} R_L$$



LLC的等效模型



谐振槽路的增益为：

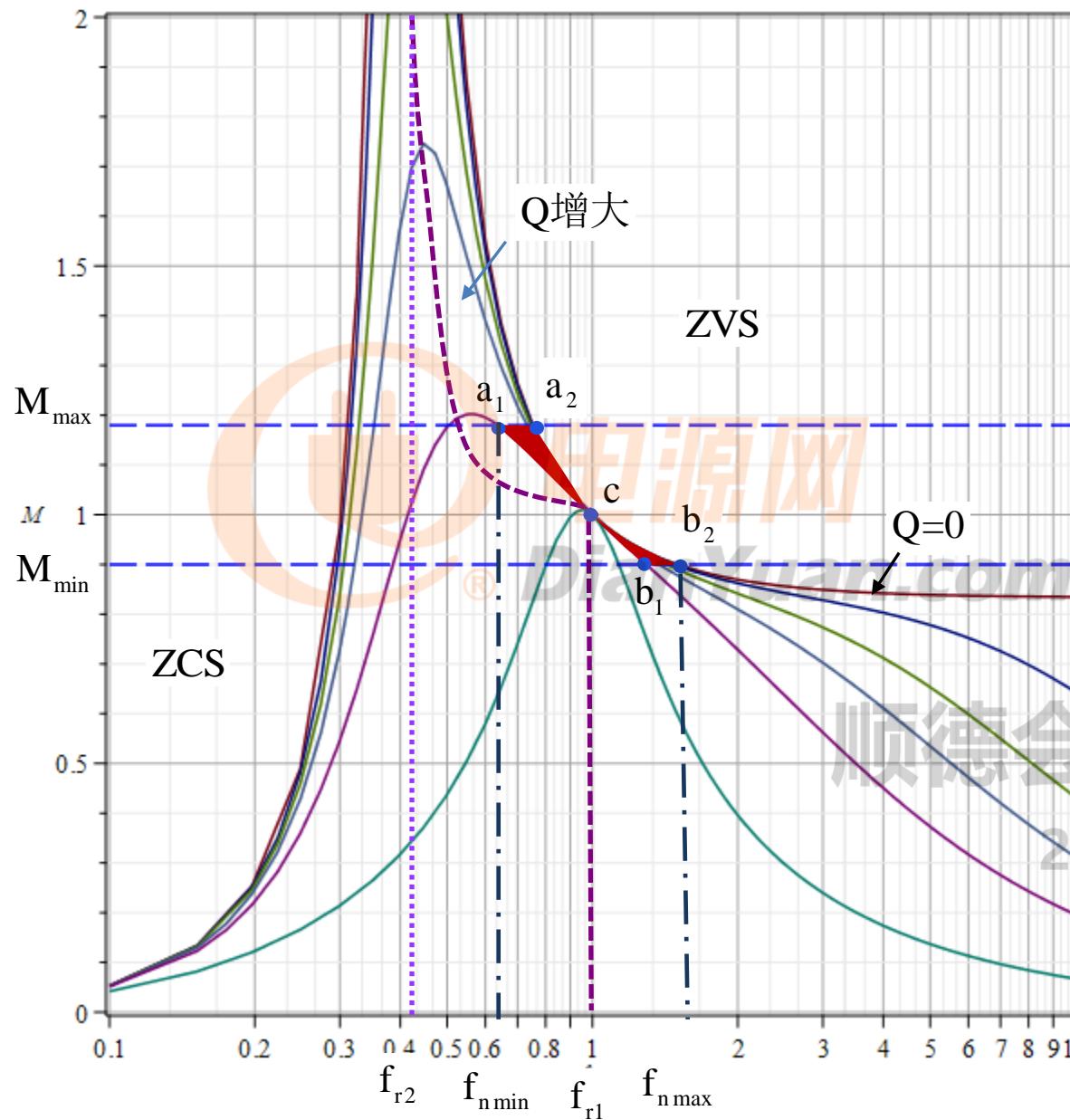
$$M = \frac{V_o}{V_{in.FHA}} = \left| \frac{Z_{mac}}{Z_r + Z_{mac}} \right| = \frac{1}{\sqrt{\left(1 + \frac{1}{k} - \frac{1}{kf_n^2}\right)^2 + Q^2\left(f_n - \frac{1}{f_n}\right)^2}}$$

其中：

$$R_{ac} = 0 \quad f_{r1} = \frac{1}{2\pi\sqrt{L_r C_r}}$$

$$R_{ac} \rightarrow \infty \quad f_{r2} = \frac{1}{2\pi\sqrt{(L_r + L_m) C_r}}$$

$$Q = \frac{Z_o}{R_{ac}} = \frac{2\pi f_{r1} L_r}{R_{ac}} \quad f_n = \frac{f_s}{f_{r1}} \quad k = \frac{L_m}{L_r}$$

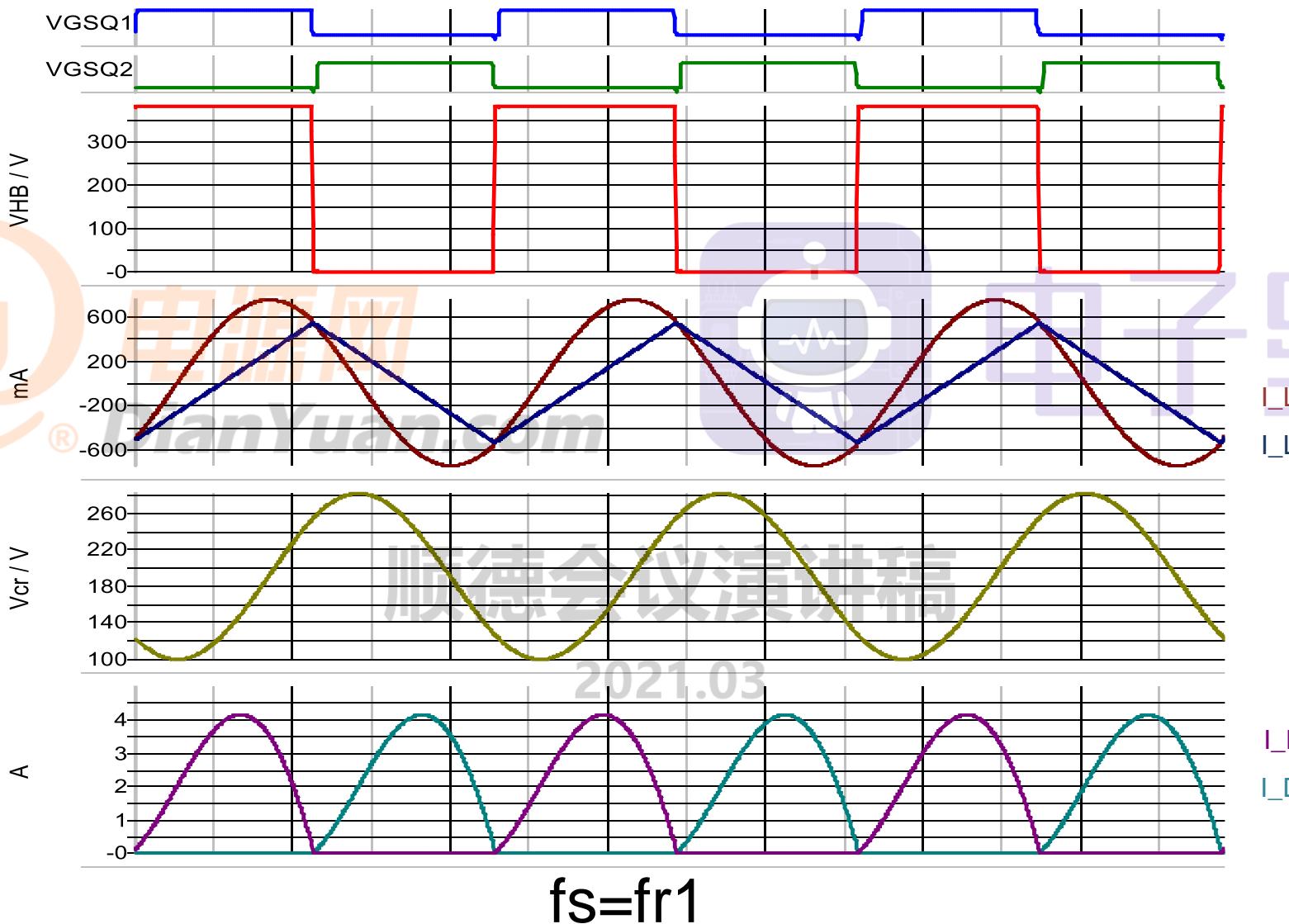


LLC的Q值曲线

- 负载变化时，工作点处于 a_1, a_2 间
- 输入电压变化，负载不变时，工作点在 a, b 间
- C点是最理想的工作点
- 满载最大增益对应最低频率
- 轻载最小增益对应最高频率

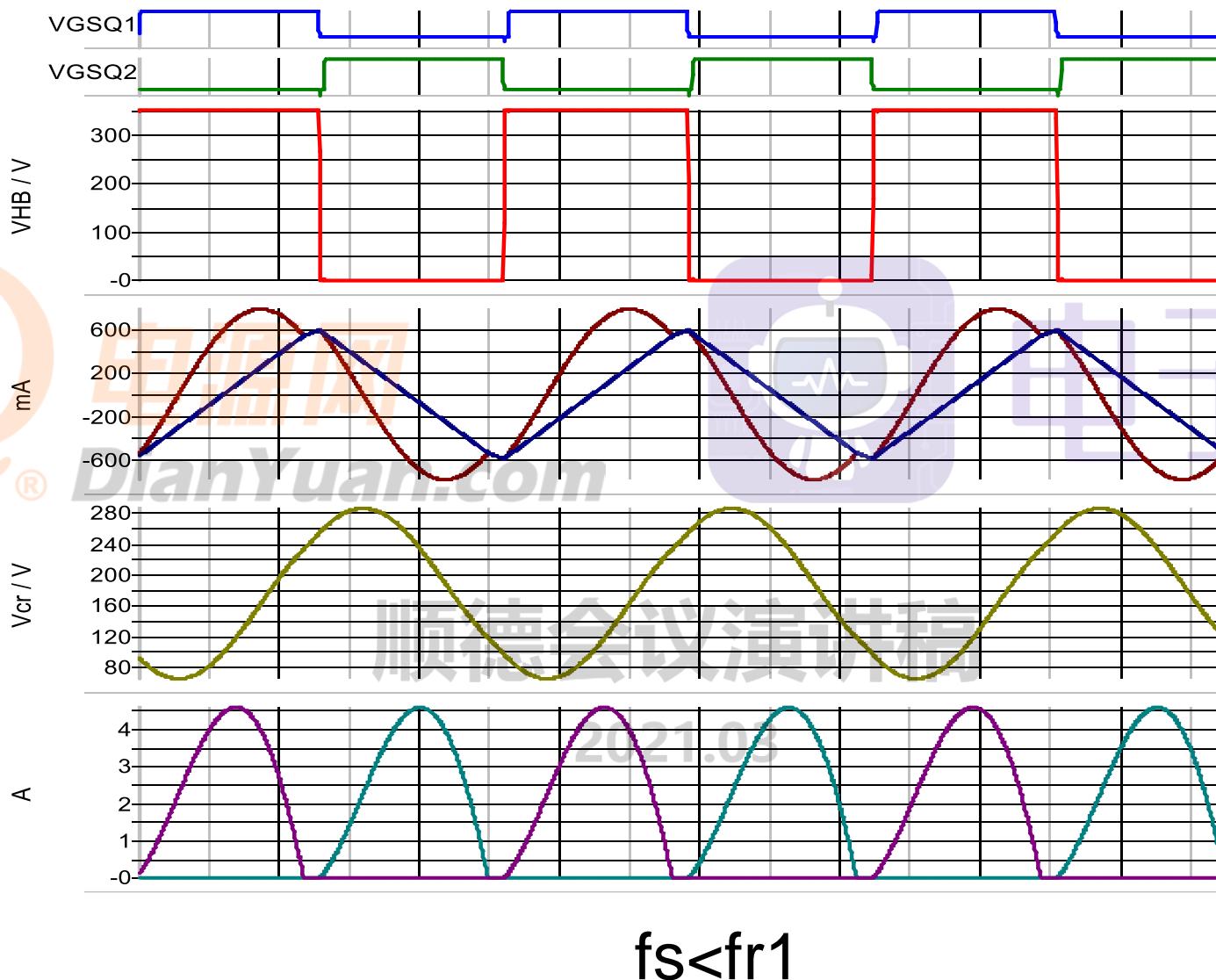


LLC谐振变换器工作波形



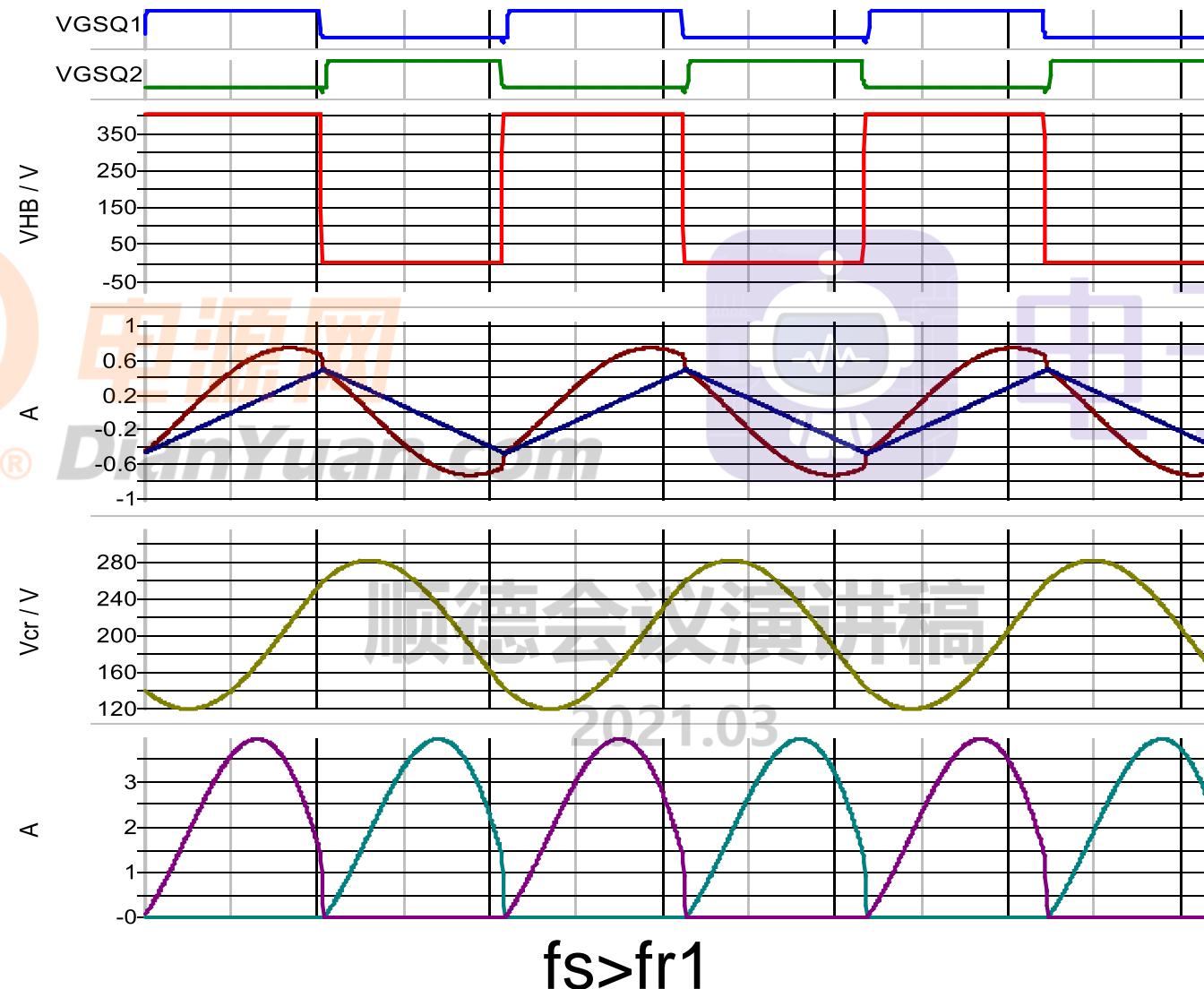


LLC谐振变换器工作波形





LLC谐振变换器工作波形



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I_Lr

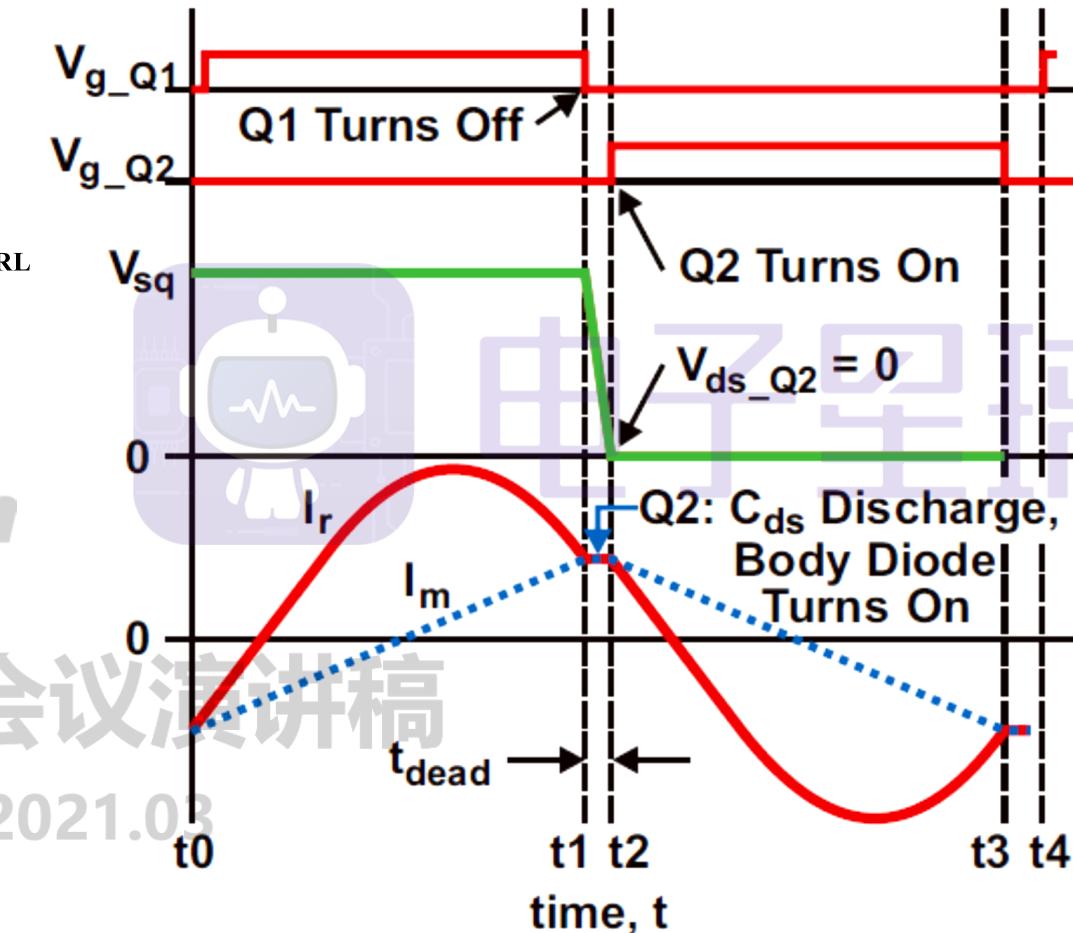
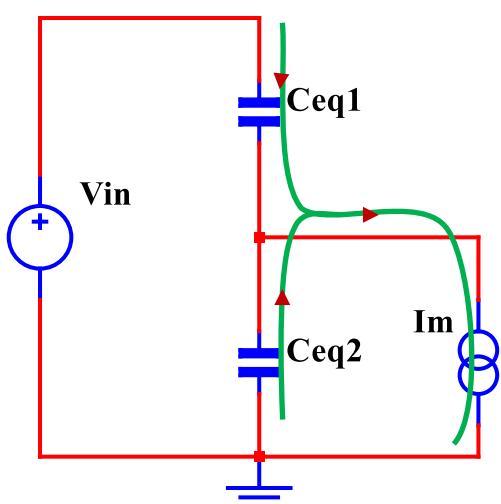
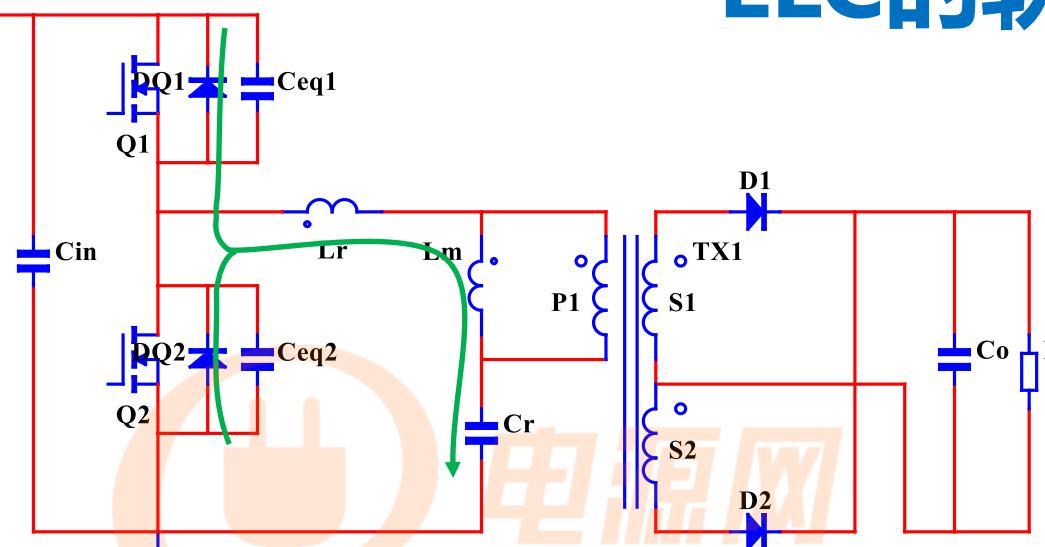
I_Lm

I_D1

I_D2



LLC的软开关过程

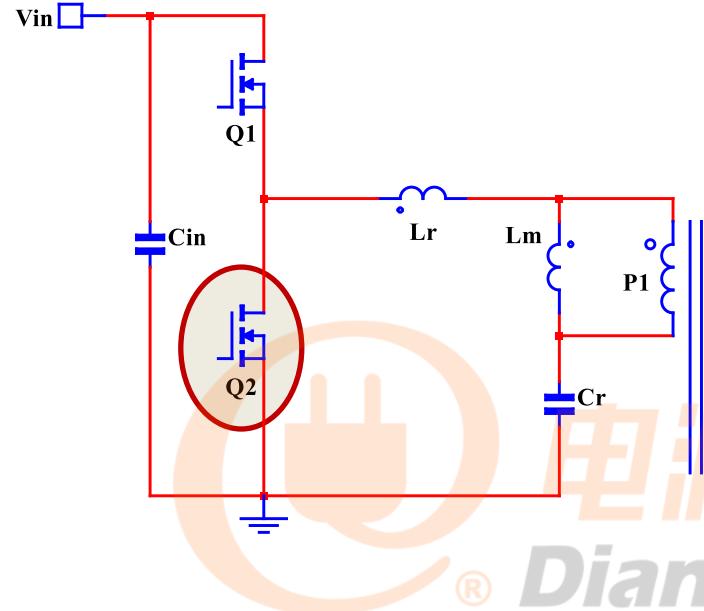


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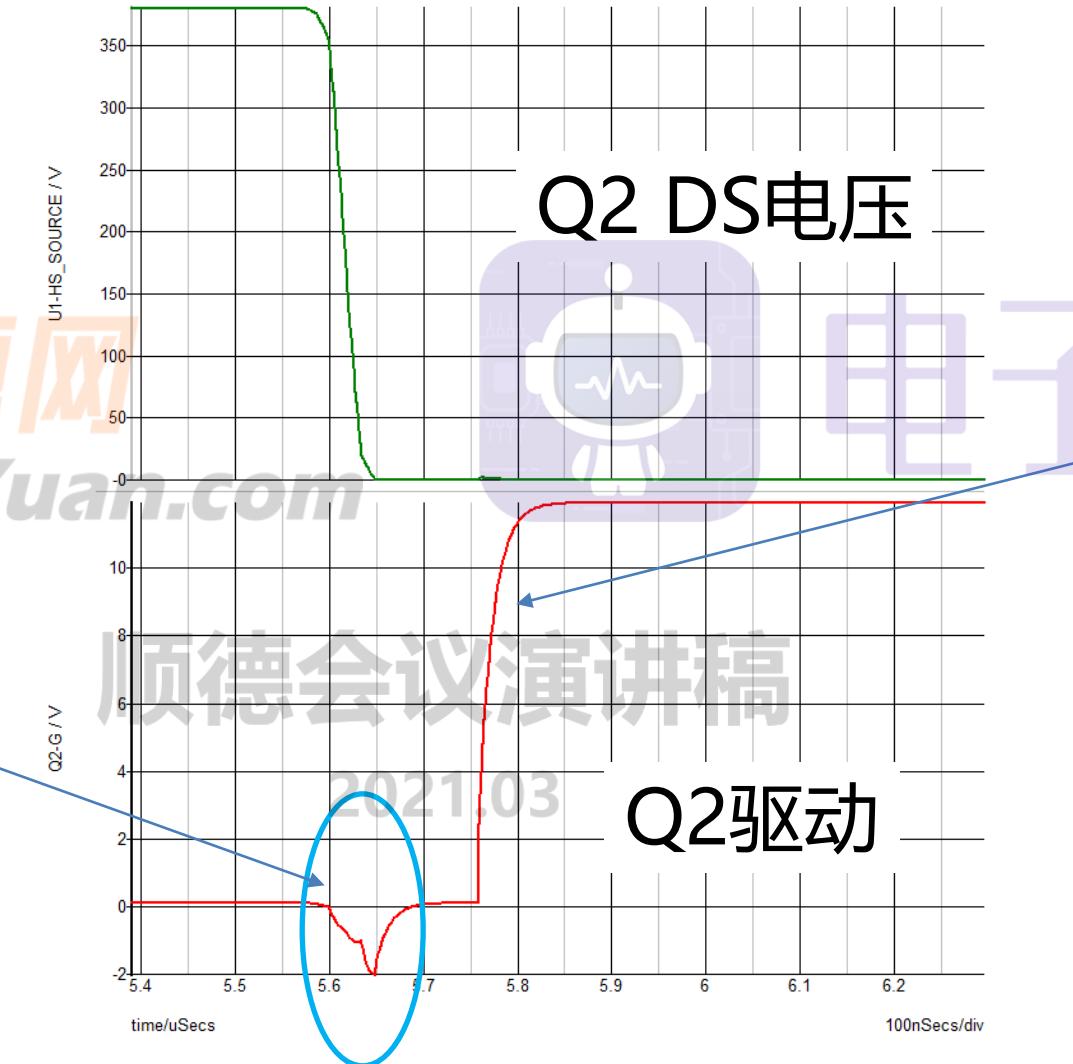
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LLC的软开关过程



DS电压到零



无米勒效应



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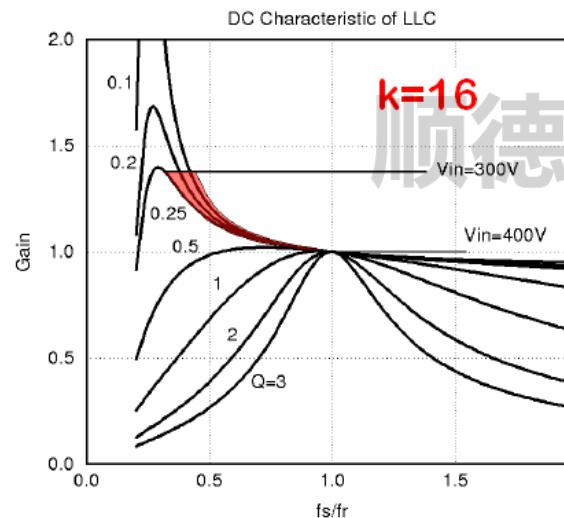
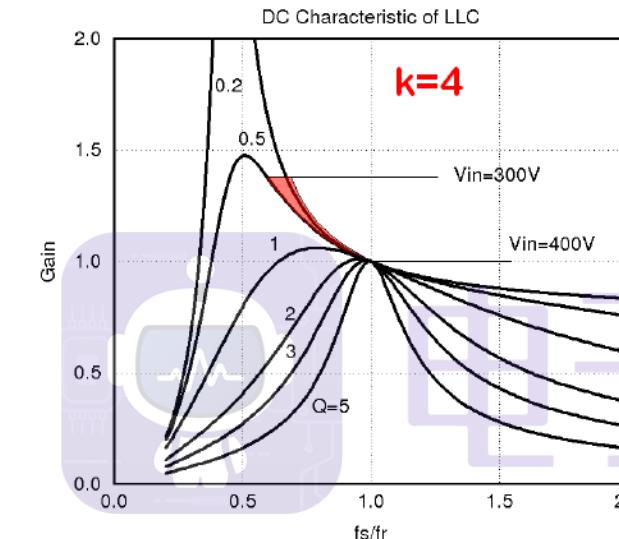
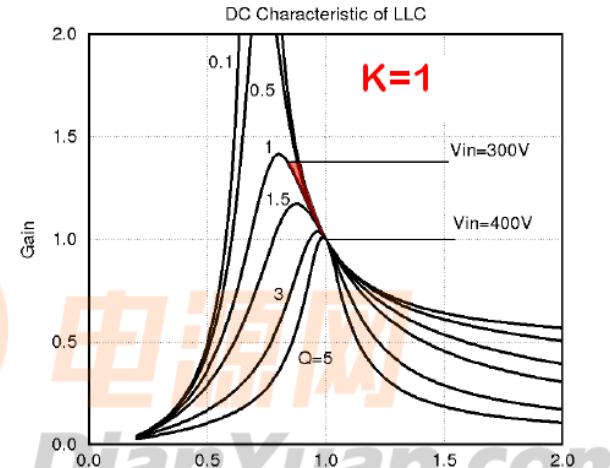
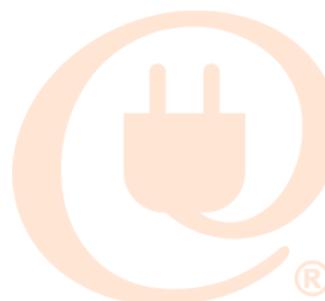
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K值对增益的影响：



K值越小，Q值曲线越陡峭，要得到相同增益时，频率变化范围越小

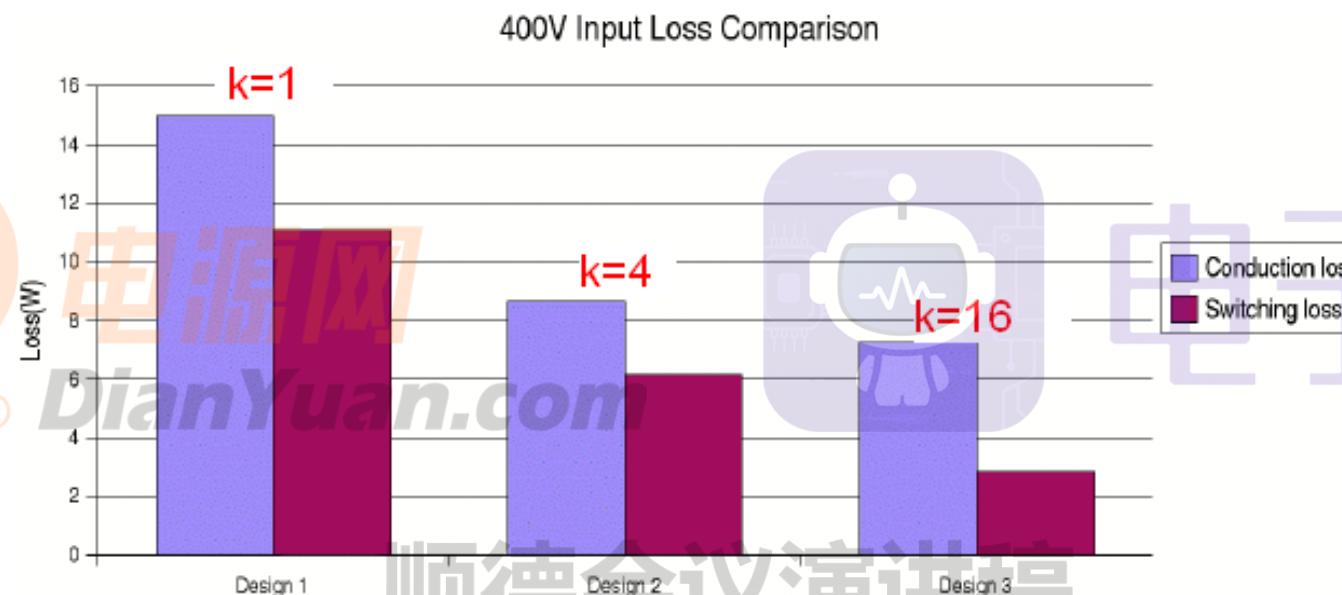
○

K值越大，Q值曲线越平缓，要得到相同增益时，频率变化范围越大

○



K值对效率的影响：



K值越小，意味着对于相同的 L_r , 其励磁电感越小，器件损耗会增大，效率降低。通常取K值在3~7之间。



Q的取值

由:
$$Q = \frac{Z_o}{R_{ac}} = \frac{2\pi f_r L_r}{R_{ac}}$$

$$k = \frac{L_m}{L_r}$$



可以得到:
$$Q = \frac{Z_o}{R_{ac}} = \frac{2\pi f_r L_m}{k R_{ac}}$$



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因此Q值越大，励磁电感越大，励磁电流越小，损耗越小。

但Q值还受到软开关条件及谐振电容电压的限制，不能过大。

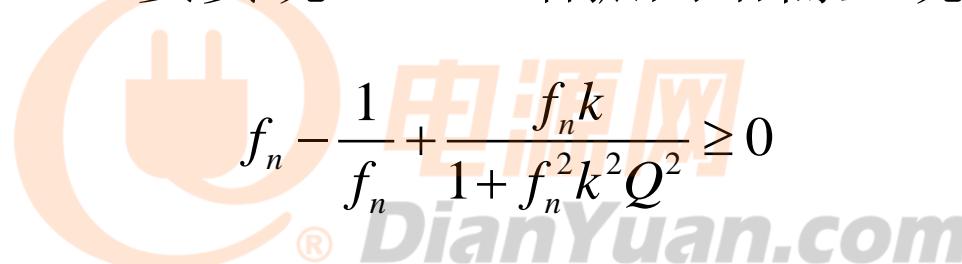
$$V_{cr} = \frac{I_r}{\omega C_r} = \frac{Q_s R_e I_r}{f_n}$$



谐振网络阻抗为：

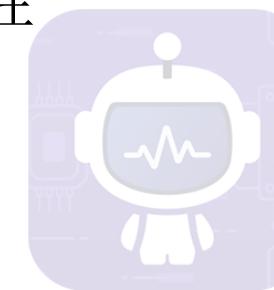
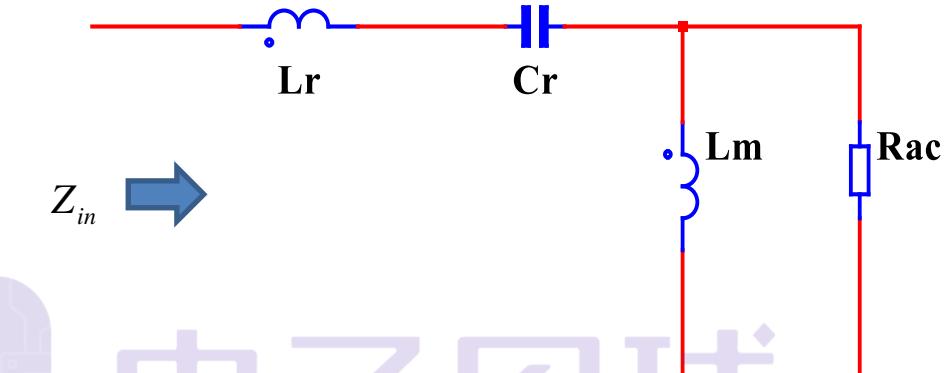
$$Z_{in} = Z_o \left[Q \frac{f_n^2 k^2}{1 + f_n^2 k^2 Q^2} + j \left(f_n - \frac{1}{f_n} + \frac{f_n k}{1 + f_n^2 k^2 Q^2} \right) \right]$$

LLC 要实现ZVS，谐振网络需呈现感性



$$\text{又由于: } M = \frac{1}{\sqrt{\left(1 + \frac{1}{k} - \frac{1}{kf_n^2}\right)^2 + Q^2 \left(f_n - \frac{1}{f_n}\right)^2}}$$

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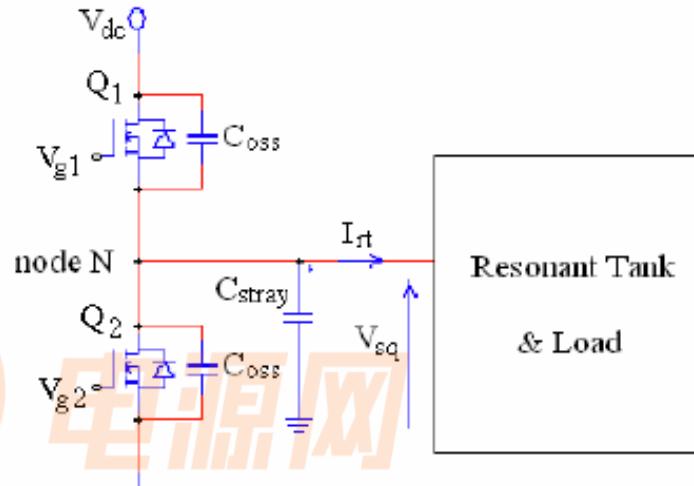
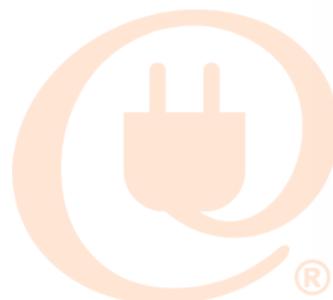


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可得:

$$Q_{max} = \frac{1}{kM_{max}} \sqrt{k + \frac{M_{max}^2}{M_{max}^2 - 1}}$$

为留一定的裕量，通常取Q为 (0.92~0.95) Qmax



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$$\frac{V_{iFHMAX}}{\|Z_{inol}(f_{n\max})\|} \geq \frac{I_{zvs(vdc\ max)}}{\sqrt{2}} \Rightarrow Q_{zvs} \leq \frac{2}{\pi} \frac{f_{n\max}}{(k+1)f_{n\max}^2 - 1} \frac{T_D}{R_{ac}C_{zvs}}$$
$$I_{zvs(vdc\ max)} = (2C_{oss} + C_{stay}) \frac{V_{dc}}{T_D}$$

当LLC运行于高输入电压，
空载的情况下时，原边电流
最小，需要确保在此情况下
，LLC仍能实现软开关。

LLC的Q值应该小于Qmax和Qzvs



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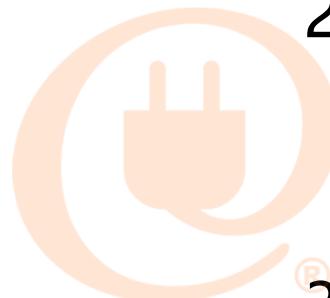
LLC的设计步骤

1.计算理论匝比(在增益为1的情况下) : $n = \frac{1}{2} \frac{V_{dc.nom}}{V_o}$

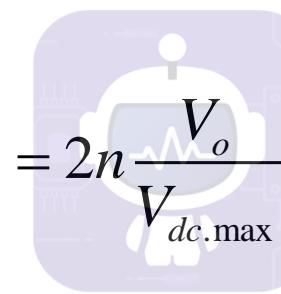
2.计算最大，最小增益:

$$M_{\max} = 2n \frac{V_o}{V_{dc.\min}}$$

$$M_{\min} = 2n \frac{V_o}{V_{dc.\max}}$$



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3.负载折算:

$$R_{ac} = \frac{8n^2}{\pi^2} \frac{V_o^2}{P_{\max}}$$

4.计算最大归一化频率: 2021.03

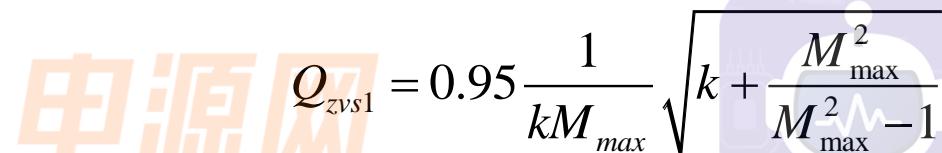
$$f_{n\max} = \frac{f_{s\max}}{f_r}$$



5.计算K值：

$$k = \frac{M_{\min}}{1 - M_{\min}} \frac{f_{n\max}^2 - 1}{f_{n\max}^2}$$

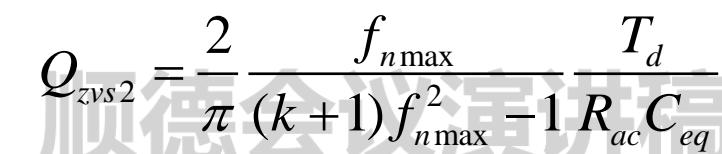
6.计算最小输入电压，最大负载时保证ZVS的Q的最大值：


$$Q_{zvs1} = 0.95 \frac{1}{kM_{\max}} \sqrt{k + \frac{M_{\max}^2}{M_{\max}^2 - 1}}$$



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7.计算最大输入电压，空载时保证ZVS的Q的最大值：


$$Q_{zvs2} = \frac{2}{\pi} \frac{f_{n\max}}{(k+1)f_{n\max}^2 - 1} \frac{T_d}{R_{ac} C_{eq}}$$

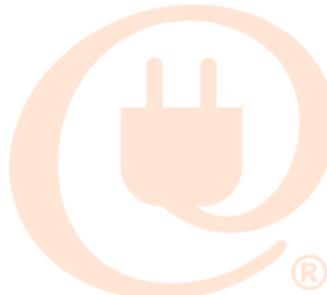
8.选择以上Q值中的最小值为最终的Q值：

$$Q_s \leq \min(Q_{zvs1}, Q_{zvs2})$$



9.计算最小开关频率：

$$f_{s\min} = f_r \sqrt{\frac{1}{1+k \left[1 - \frac{1}{M_{\max}^{1+(\frac{Q_s}{Q_{zvs}})^4}} \right]}}$$



如果计算的最小开关频率太低或者太高，需要调整设定的谐振频率，直到最小开关频率为一个合理的值。

10.计算谐振网络参数：

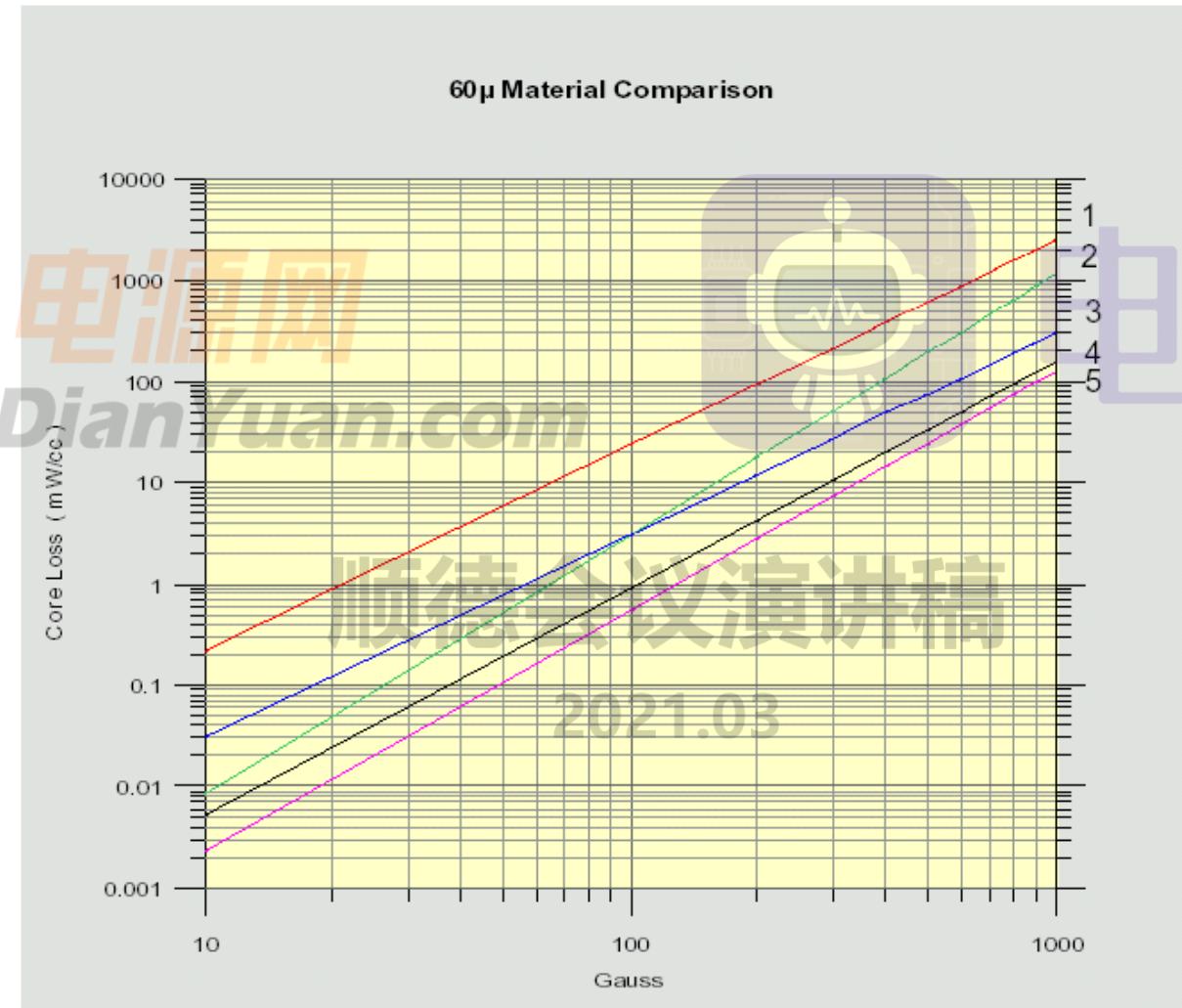
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$$Z_o = Q_s R_{ac} \quad C_r = \frac{1}{2\pi f_r Z_o} \quad L_r = \frac{Z_o}{2\pi f_r} \quad L_m = \frac{L_r}{k}$$



LLC谐振电感设计

LLC谐振电感磁通摆幅大，设计时主要受磁芯损耗限制，一般采用铁氧体磁芯





LLC谐振电感设计

谐振电感匝数:

$$N = \frac{L_r \cdot \Delta I_{pri}}{\Delta B \cdot A_e}$$



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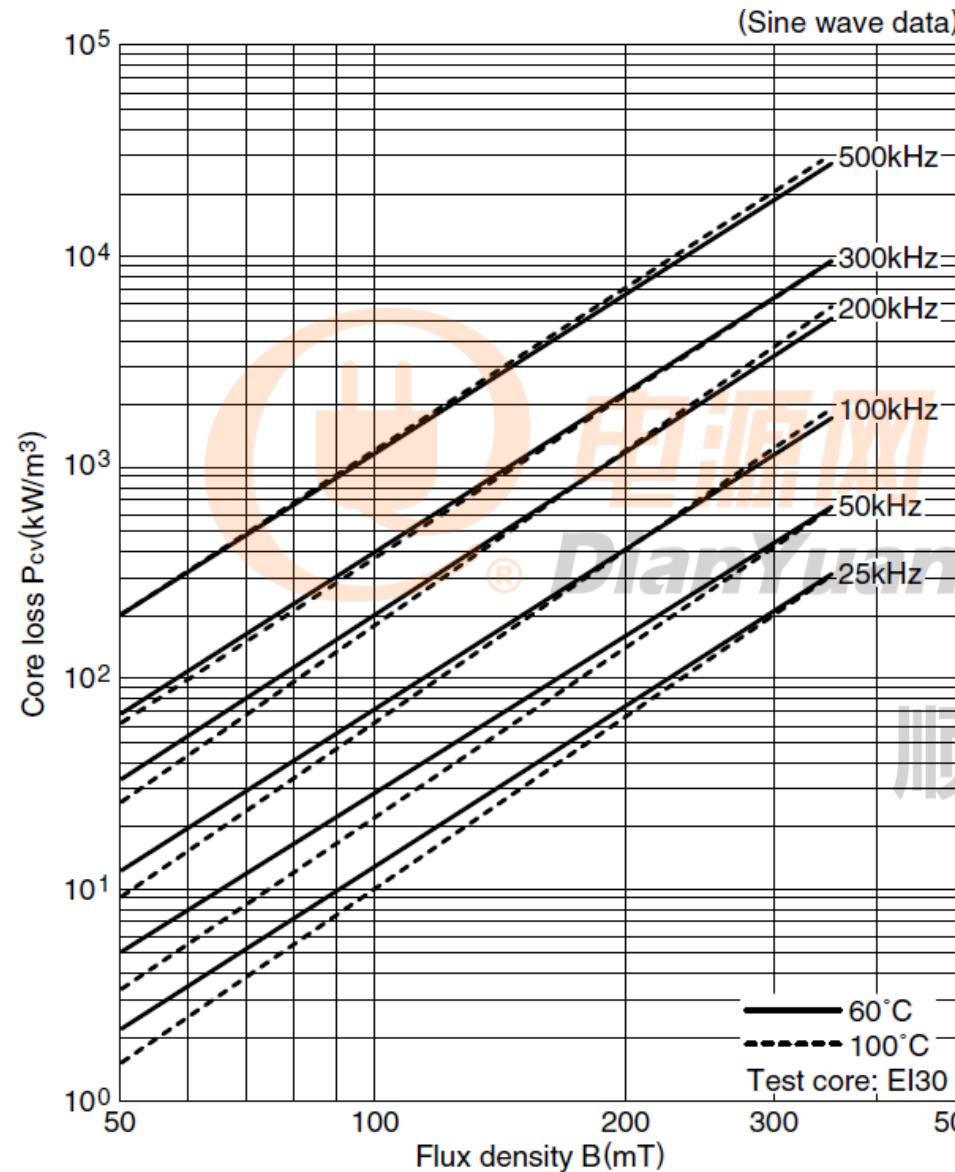
由磁芯允许损耗与温升，可以得到允许的磁通密度摆幅 ΔB

由于谐振电流近似为正弦波：

$$\Delta I_{pri} = 2I_{pri_pk} = 2\sqrt{2}I_{pri_rms} = \frac{\pi P_o}{nV_o}$$



LLC变压器参数设计



根据磁芯允许损耗与温升，确定允许的峰值磁通密度，从而确定最大磁通密度摆幅 ΔB

$$N_p = \frac{V_{in}}{4\Delta B \cdot A_e \cdot f_s}$$

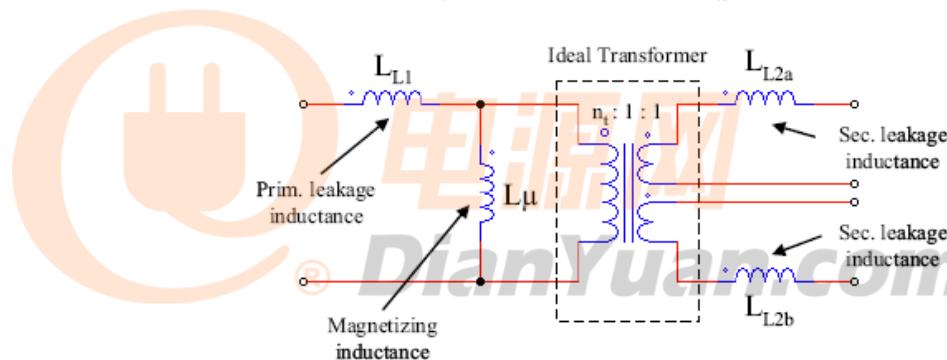
为减小线圈交流损耗，一般应采用利兹线绕制。



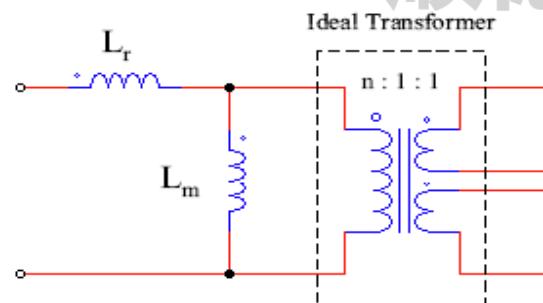
集成漏感LLC变压器设计

集成漏感的LLC变压器的实际匝比与理论匝比有较大差别

实际变压器模型:



理想变压器模型:



变压器的理论变比:

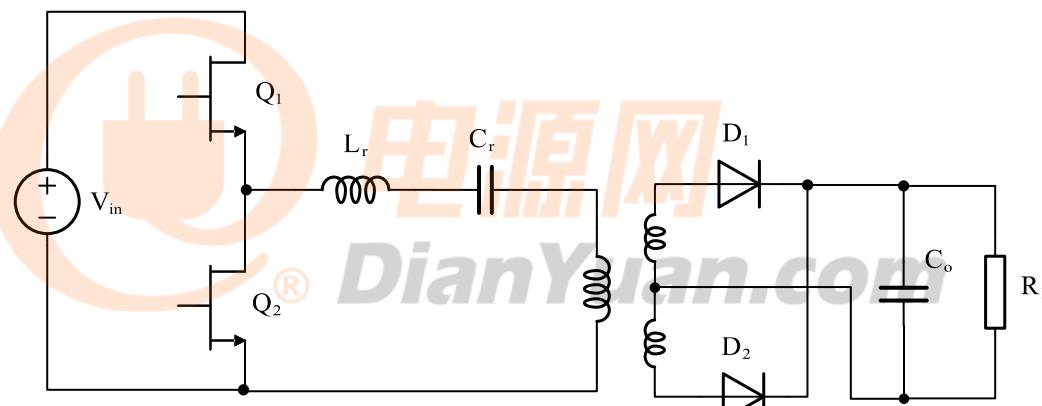
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$$n = n_t \sqrt{\frac{L_m}{L_m + L_r}}$$

因此实际变比要比理论变比大



GaN 在LLC中的应用



由于GaN-HEMT没有反向二极管，通过2DEG实现反向导通，反向导通压降大于Si-Mosfet，因此需要合理优化死区时间，减少开关时的反向导通损耗。

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