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Comparative study of typical analysis methods for the LLC resonant converter

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LLC 谐振变换器典型分析方法对比

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摘 要: LLC 谐振变换器可以在高频运行的同时实现软开关, 对于提高开关电源的功率密度和效率意义重大。基波近似法和运行模态分析法是现阶段研究 LLC 谐振变换器的 2 种经典方法, 但目前缺乏针对二者在电压增益精确性、效率、应用场合等方面的研究。该文首先分析这 2 种方法的原理; 然后, 在 PSIM 环境下对 LLC 谐振变换器工作模态进行仿真分析; 基于 LLC 运行模态, 在仿真电路中对 2 种方法下的电压增益精确性; 最后, 基于峰值电压增益选择谐振参数, 搭建 1.5 kW/28 V 输出等级的实验样机。实验结果表明, 在下谐振区, 基波近似法的电压增益比实际低 10%~15%, 而运行模态分析法迭代出的电压增益在全频率范围内与实际增益具有高度一致性, 且基于运行模态分析法得到的谐振参数应用于样机时具有更高的效率。

关 键 词: LLC 谐振变换器; 基波近似法; 模态分析; 电压增益精确性

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Comparative study of typical analysis methods for the LLC resonant converter

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Abstract: The LLC resonant converter can achieve soft-switching while it operates in high-frequency and then improves the power density and efficiency of power supply. The fundamental approximation and mode analysis are two classic analysis methods of LLC resonant converter, but the comparative studies in the voltage gain accuracy, efficiency and application is not intensively discussed. On this background, the principle of the above methods is illustrated firstly. Then, the operation mode of LLC resonant converter is analyzed in PSIM simulation environment. Based on the operation modes, the voltage gain accuracy of the two methods is compared in simulation. Finally, the resonant parameters are selected based on the peak voltage gain, and a 1.5 kW/28 V prototype is set up. The experimental results show that actual gain is higher than the gain curve based on FHA 10% to 15% below the resonant zone, and have high accordance with the voltage gain based on the mode analysis in whole frequency range. And the iterative parameters based on mode analysis have higher efficiency with the experimental prototype.

Key words: LLC resonant converter; fundamental harmonic approximation; mode analysis; voltage gain accuracy

随着开关电源功率密度的不断增加,采取高频运行以降低无源器件的尺寸势在必行。但是高频运行会带来开关损耗的增加,软开关技术的发展大大降低了开关器件高频运行的开关损耗。LLC 谐振 DC-DC 变换器具有在宽输入电压和负载波动范围内调节输出电压的优良特性,同时通过谐振软开关技术,可以降低变换器的开关损耗,对于提高开关电源的效率和功率密度,有着重要意义^[1-2]。

基波近似法(FHA)是分析、设计 LLC 谐振变换器的传统方法,简便直接。运行模态分析法是现阶段研究谐振类变换器比较全面而且精确的方法^[3],但是目前缺少对于二者分析的精确性、应用效率及应用场合的研究^[4]。该文对上述方法的原理进行研究,在 PSIM 仿真软件中搭建仿真电路,对比电压增益曲线精确性并进行量化,搭建样机对比基于 2 种方法的谐振参数的效率,最后,根据电压增益精确性和效率得出二者的应用场合。

1 基波近似法

1.1 LLC 的主要参数

半桥 LLC 谐振变换器如图 1 所示。变换器的主要参数^[4]:串联谐振频率 $f_r = 1/2\pi\sqrt{L_r C_r}$; 并联谐振频率 $f_p = 1/2\pi\sqrt{(L_r + L_m)C_r}$; 特征阻抗 $Z_c = \sqrt{L_r/C_r}$; 电感比 $k = L_m/L_r$, 归一化增益 $G = 2nV_o/V_{in}$ 。

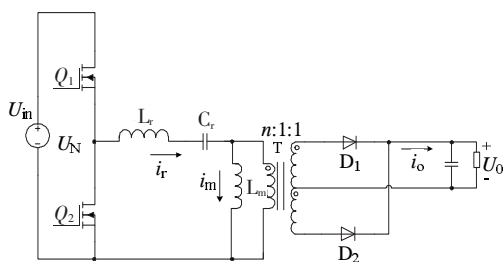


图 1 半桥 LLC 谐振变换器

Figure 1 Half-bridge LLC DC-DC converter

1.2 基波近似法原理分析

基波近似法假设只有开关频率 f_s 的基波分量输入到谐振腔,其他高次谐波能量完全被衰减,不参与能量传递。等效原理示意如图 2 所示^[5-6]。

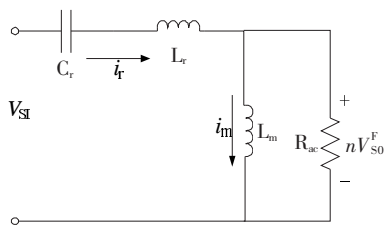


图 2 基波近似法交流等效电路

Figure 2 AC equivalence circuit of FHA

LLC 谐振变换器的 2 个开关管以 50% 的占空比交替导通,由于基波近似法只计及谐振腔电压、电流的基波成分,故需对谐振网络输入方波电压 V_{st} 、整流网络输入电流 I_{rec} 、输入电压 V_{s0} 进行傅里叶级数分解,由二次侧输出电流 I_o 是 I_{rec} 的平均值,将二次侧整流网络用交流等效电阻 R_{ac} 代替,进而得到归一化电压增益公式^[4]:

$$G = \frac{k \left(\frac{f_s}{f_r} \right)^2}{\left(1 + k \right) \left(\frac{f_s}{f_r} \right)^2 - 1 + \left(Qk \left(\frac{f_s}{f_r} \right) \left(\left(\frac{f_s}{f_r} \right)^2 - 1 \right) \right)} \quad (1)$$

其中, $Q = Z_c/R_{ac}$ 为品质因数,交流等效电阻为 $R_{ac} = 8n^2 R_o / \pi^2 R_{ac}$ 。

根据基波近似法作出的特性曲线如图 3、4 所示,为了减小开关损耗,一般设计 LLC 工作在峰值电压增益处频率以右、串联谐振频率 f_r 以左(ZVS1 区域)中,当 Q 、 k 取较小值时,峰值电压增益较高,相同的增益变化范围内频率波动较小。但是 Q 、 k 的减小不利于开关损耗的减小和效率的提高,所以需要综合所需电压增益和效率选取谐振参数。

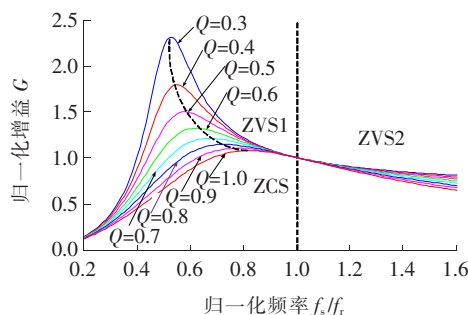
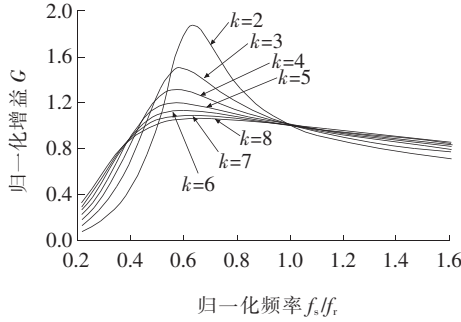


图 3 LLC 谐振变换器特性曲线 ($k=3$)

Figure 3 Characteristic curve of LLC resonant converter ($k=3$)

图 4 LLC 谐振变换器特性曲线($Q=0.5$)Figure 4 Characteristic curve of LLC resonant converter($Q=0.5$)

2 运行模态分析法

2.1 P、O、N 运行模态

LLC 谐振变换器的运行模态法是指将 LLC 的多种运行状态进行模态划分、时域描述、建模求解等,以得到精确的变换器特性及参数的方法。可分为单个模态或者几个模态的组合^[7],即①P 模态: L_m 被正向电压钳位, $U_m=nV_o$;②N 模态: L_m 被负向电压钳位, $U_m=-nV_o$;③O 模态: L_m 不被钳位, $|U_m|<nV_o$ 。

通过 PSIM 仿真可以得到 2 种典型模式电压、电流波形,如图 5、6 所示, i_r 、 i_m 分别为谐振和励磁

电流, U_m 为励磁电感电压, U_{gl} 为上管 Q_1 的漏源极电压。

2.2 运行模态分析法原理分析

P 模态下谐振网络的时域解析式为

$$\begin{cases} i_{rP}(t) = I_{rP} \sin(\omega_r t + \theta_{P0}) \\ i_{mP}(t) = I_{mP0} + \frac{nV_o}{L_m} t \\ V_{CrP}(t) = V_{in} - nV_o - L_r \frac{di_{rP}(t)}{dt} \end{cases} \quad (2)$$

式中 $i_{rP}(t)$ 为谐振电流; I_{rP} 为谐振电流的幅值; $i_{mP}(t)$ 为并联电感(变压器励磁)电流值; $V_{CrP}(t)$ 为谐振电容电压值; $\omega_r = 2\pi f_r$; θ_{P0} 为谐振电流 $i_{rP}(t)$ 的初始相位; I_{mP0} 为励磁电流 i_{mp} 的初始电流值。

令 $\theta = \omega_r t$, 且归一化变量得到 P 模态下的迭代方程^[8-11]:

$$\begin{cases} i_{rPn}(\theta) = I_{rPn} \sin(\theta + \theta_{P0}) \\ i_{mPn}(\theta) = I_{mPn} + \frac{\theta}{m-1} \\ V_{CrPn}(\theta) = \frac{2}{M} - 1 - I_{rPn} \cos(\theta + \theta_{P0}) \end{cases} \quad (3)$$

同理,可以列出单模态 N、O 的方程式,由于 i_r 、 i_m 、 v_c 在一个周期内具有对称性,故对半个周期内的组合模态进行求解。利用半个周期的电感电流和电容电压幅值相等、符号相反、功率平衡条件以及前、后模态边界值连续的条件,可以得出组合模态下的边界条件表达式。将 P 模态下的方程解作为初值,利用计算机迭代求解谐振网络方程中每个阶段的电流、电压幅值、起止相角及增益等变量,可以得出运行模态分析法的增益曲线。基于运行模态分析法对 LLC 的设计可以采用基于峰值增益的优化设计方法^[3]。

3 算例分析

3.1 仿真对比

为分析基波近似法和运行模态分析理论的精确性,谐振频率设为 105 kHz,电感比 k 取 1.76 和 5.28,在 PSIM 中搭建电路仿真模型,获得实际电压增益曲线(以 PSIM 表示),分别与采用基波近似法

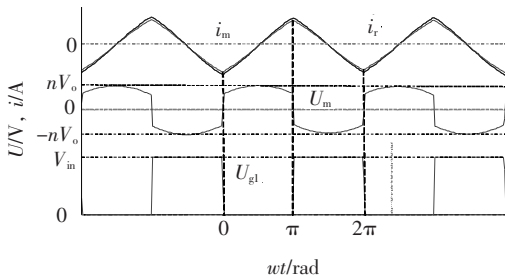


图 5 空载 O 模态

Figure 5 Mode O of no-load

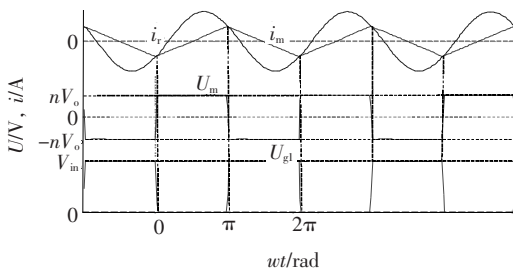


图 6 谐振频率点处 P(N) 模态

Figure 6 Mode P(N) at resonant frequency

获得的电压增益曲线(以 FHA 表示)和运行模态分析法迭代生成的电压增益曲线(以 MODE 表示)进行对比,结果如图 7、8 所示,可以看出,谐振频率附近 FHA 得出电压增益精确性高,但下谐振区的电压增益较实际低 10%~15%;而运行模态分析法得出的电压增益一直具有较高的精确性。

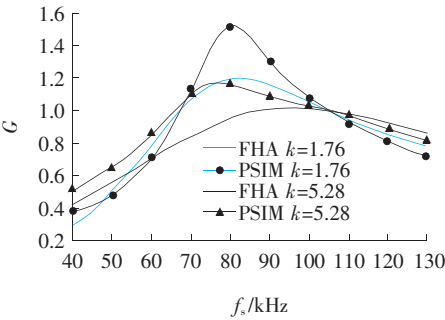


图 7 PSIM、FHA 电压增益曲线对比

Figure 7 Comparison of voltage gain curve for PSIM and FHA

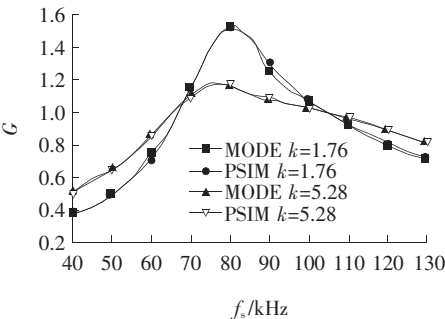
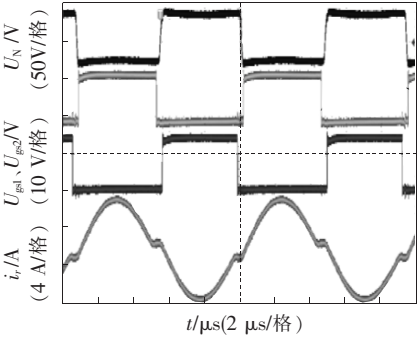


图 8 PSIM 和运行模态分析法电压增益曲线对比

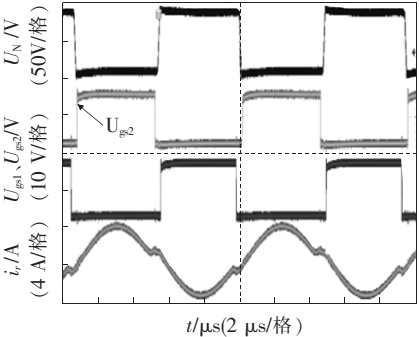
Figure 8 Comparison of voltage gain curve for PSIM and mode analysis

3.2 实验分析

基于峰值电压增益的设计方法,分别采用基波近似法和运行模态分析法得到 LLC 谐振变换器的参数,并搭建一台 1.5 kW、28 V 输出等级的样机。谐振频率设为 105 kHz,额定输入电压为 110 V,基波近似法得出 L_r 为 2.3 μH , C_r 为 1 000 nF, k 为 3;模态分析得出 L_r 为 1.53 μH , C_r 为 1 500 nF, k 为 5.26。两者相比,基于基波近似法的设计参数在相同的输入输出条件下谐振电流更大,导通损耗较大,基于运行模态分析法的样机效率可以一直保持较高,样机实验结果如图 9 所示,效率对比如图 10 所示。



(a) 基于基波近似法的样机运行波形



(b) 基于模态分析的样机运行波形

图 9 LLC 谐振变换器样机实验对比

Figure 9 Experimental comparison of LLC resonant prototype

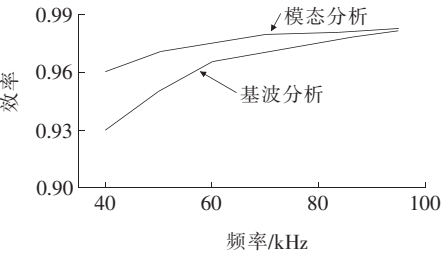


图 10 样机效率对比

Figure 10 Efficiency comparison of prototype

4 结语

该文对基波分析法和运行模态分析法的电压增益精确性进行了对比,并设计了样机对照基于 2 种方法设计的参数效率。结果表明,基波分析法的电压增益在下谐振区比实际低 10%~15%,而此时运行模态分析法得出的谐振参数应用于样机时效率更高。同时,针对 LLC 应用于只需运行在谐振频率处的电力变压器,采用基波近似分析法设计更加简单、直接。

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