Magnetic Integration Technology of LLC Resonant Converter

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Abstract

The LLC resonant converter has the advantages of high power density and high efficiency. The fundamental model is used to establish an equivalent model, and the resonant network parameters and efficiency expressions are obtained, and the parameters of the optimized efficiency are analyzed and designed. Design a suitable magnetic integrated structure through passive integration technology. In the case of constant parameters, the magnetic integration and discrete variators are compared to compare the advantages and disadvantages of the two. The saber simulation is used to verify the rationality of the parameter design. The simulation proves that the magnetic integration does not change the working characteristics of the LLC converter, which is beneficial to reduce the volume and improve the efficiency.

Keywords

LLC；DC/DC converter; parameter design;magnetic integration；fundamental analysis.

1. Introduction

In order to achieve high power density and reduce switching losses at high frequencies, LLC resonant converter has received extensive attention. The LLC resonant converter has the advantages of a conventional resonant converter. In addition, it has the advantages of being able to operate under no-load conditions and a large allowable range of input voltage[1]. The LLC resonant variator can turn off the primary side switching transistor ZVS and the secondary side rectifying diode ZCS.It solves the effect of reverse recovery of the rectifier diode and suppressses the EMI interference of the power supply.What’s more it improves efficiency of the power supply[2]. The magnetic components of conventional LLC converter are discrete in the circuit, increasing the size and mass of the converter. Magnetic integration of the magnetic components of the LLC converter can effectively reduce the number of magnetic components and increase the power density of the converter [3]. At present, the design methods of magnetic integration are mostly inconvenient for practical operation. In this paper, a simple magnetic integrated general structure is selected. Compared with the discrete LLC resonant converter with the same parameters, it is found that magnetic integration is more conducive to improving power density and efficiency.

2. Working principle and parameter analysis

The LLC resonant converter has two resonant frequencies as shown in Fig.1. The resonant frequency obtained when the resonant capacitor C_r and the resonant inductor L_r resonate together is f_{r1}.The resonant frequency obtained by co-resonating the magnetizing inductance, the resonant inductor and the resonant capacitor is f_{r2} [4]. The LLC resonant converter has three stages of circuits: a square wave generator, a resonant network, and a rectifier network. The square wave generator generates a square wave by alternately driving the switching tube with a duty ratio of 50%. To avoid common conduction between the upper and lower switching tubes, a dead time is introduced in the continuous switching. The resonant network consists of a resonant capacitor, an inductor, and a magnetizing inductor to filter the high-order harmonic current. The current flowing through the resonant network lags behind the voltage on the resonant network, satisfied the zero voltage conduction of the switching transistor. When the current flows through the body diode of the switch tube, the conduction voltage drop of the switch tube is zero, and the ZVS is turned on. The rectifier network outputs a DC voltage [5] through the rectifier diode and the filter capacitor.

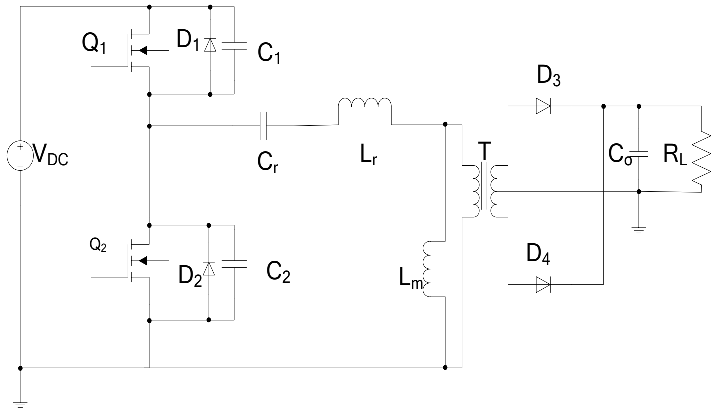


Fig.1 Converter main circuit diagram

The two resonant frequency expressions of the LLC resonant converter are as follows:

$$\mathrm{f}_{r1}=\frac{1}{2\pi\sqrt{L_r C_r}},\quad \mathrm{f}_{r2}=\frac{1}{2\pi\sqrt{(L_r+L_\mathrm{m})C_r}} \tag{1}$$

The theoretical model analysis of the LLC resonant converter is fundamental wave analysis (FHA). The voltage and current of the resonant network are approximately equivalent to a sinusoidal quantity, and the equivalent circuit obtains the expression of the voltage gain [6]. The simplified equivalent circuit of LLC is shown in Fig.2.

The voltage gain is the ratio of the input and output impedance of the resonant network. The expression is:

$$M=\frac{R_{ac}\,//\,sL_m}{1/sC_r+sL_r+R_{ac}\,//\,sL_m} \tag{2}$$

Where $R_{\mathrm{ac}}=n^2\frac{8}{\pi^2}R_L$,Rac is converted to the primary equivalent resistance.

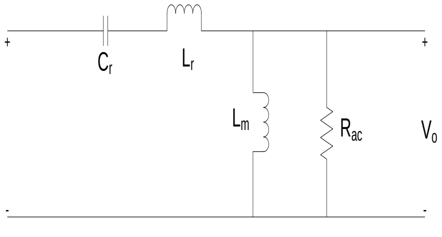


Fig.2 Equivalent circuit model

Simplified gain is as follow:

$$M\,(\mathrm{f},k,Q)=\frac{1}{\sqrt{(1+\frac{1}{k}-\frac{1}{kf^2})^2+Q^2(\mathrm{f}-\frac{1}{\mathrm{f}})^2}} \tag{3}$$

Where $Q=2\pi\mathrm{f}_r L_r/R_{ac}, k=L_m/L_r, f=f_s/f_r$.

The operating frequency of the LLC resonant converter divides into three segments: (1) $f_s < f_{r2}$; (2) $f_{r2} < f_s < f_{r1}$; (3) $f_s > f_{r1}$. In the range of $f_s<f_{r2}$, the switch can not be turned on by ZVS, and only ZCS can be turned off. The switching loss in ZVS mode is smaller than that of ZCS mode. The converter is in the range of $f_s > f_{r1}$ and the secondary rectifier diode is in the hard switching phase. Therefore, the LLC resonant converter is used to realize the soft switching of the primary and secondary sides. The most suitable working range is $f_{r2} < f_s < f_{r1}$ [7]. The curve of the voltage gain M obtained by the equation (3) is as shown in Fig.3 From the gain graph, it is known that the magnitude of the influence voltage gain mainly includes the quality factor Q, the inductance ratio k, and the frequency ratio f. At $f_s=f_r$, the gain curve passes through (1,1) and the gain is 1 and the LLC gain characteristic is independent of the load. The voltage gain varies with frequency. If the load is larger, the peak value of the voltage gain will be larger and the frequency conversion range will be wider. The tload is larger, the Q value is smaller, and the gain curve still has a higher voltage gain peak and better selectivity, so the converter can operate at no load. Reducing the inductance ratio can also achieve high voltage gain. Under a given resonant frequency and quality factor, reducing the inductance ratio means reducing the magnetizing inductance. The decrease in the magnetizing inductance leads to an increase in the circulating current, that is, an increase in conduction loss [8]. . Considering the voltage gain range and conduction loss, the inductor ratio is compromised. Generally, the inductor ratio is 3-7. Since the load increases at a frequency ratio of f=1, the gain is always 1, independent of the load, theoretically satisfying the change from no load to full load, the converter has the highest efficiency and the output voltage remains unchanged.

The output power is:

$$P_o = \frac{V_o^2}{R_L} = \frac{2(MV_{in})^2}{\pi^2 R_{ac}} \tag{4}$$

Transformer losses are:

$$P_r = \frac{2R(MV_{in})^2[1+(1+\frac{1}{k})^2 Q_L^2 f^2]}{\pi^2 R_{ac}^2} \tag{5}$$

Where $R=R_{ds}+R_{Cr}+R_{Lr}+R_{Lm}$, $Q_L=2\pi f_{r2} C_r R_{ac}$。

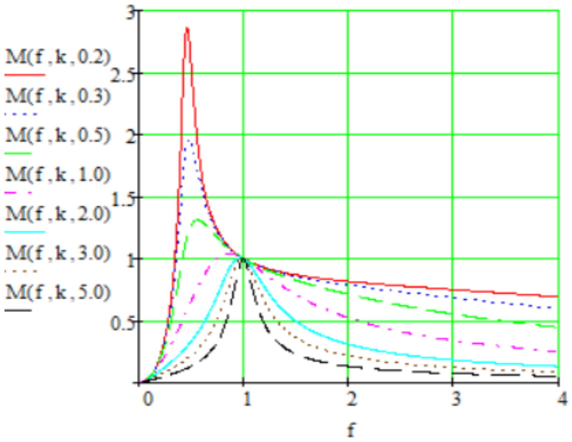


Fig.3 Voltage gain characteristic curve

Then the efficiency is:

$$\eta = \frac{P_o}{P_o+P_r} = \frac{1}{1+R\sqrt{\frac{C_r}{L_r+L_m}}[\frac{1}{Q_L}+(1+\frac{1}{k})^2 f^2 Q_L]} \tag{6}$$

From equation (6),it expresses the relationship between efficiency and load . When the load changes from light load to full load, the efficiency increases with the increase of load [9].

The resonant network parameter expression of the converter is:

$$L_r = \frac{4n^2 R_L}{\pi^3 f_s k}, \quad L_m = \frac{4n^2 R_L}{\pi^3 f_s} \tag{7}$$

$$C_{\mathrm{r}} = \frac{\pi k}{16 n^2 R_L f_s} \tag{8}$$

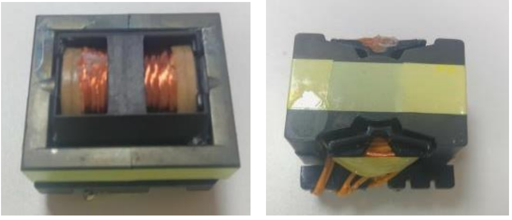
3. Magnetic integrated design

The magnetic integration technology wants to wind a plurality of discrete components in the converter on a pair of magnetic cores, and concentrate on the structure.Which can reduce the volume and quality of the magnetic components, it is important for improving the performance and power density of the power source. [10].

The design of the transformer is a manifestation of magnetic integration. Usually, the AP method is used for estimation, and then the core is selected [11]. In the design of a normal transformer, the leakage inductance is a non-negligible problem and cannot be completely eliminated. In the LLC circuit, the leakage inductance of the transformer is the required excitation inductance. The leakage inductance of the transformer means that the magnetic lines of force generated by the coil cannot pass through the secondary coil, resulting in leakage inductance. The leakage inductance is caused by the difference in the degree of coupling between the primary and secondary. The coupling is good and the leakage inductance is small. The coupling is poor and the leakage inductance is large. The leakage inductance of a common single-slot transformer often does not reach the required size. Therefore,the design selects a double-slot transformer and there is a certain gap between the two slots. One slot is wound to the primary side and the other slot is wound to the secondary side. The leakage inductance of the transformer is close to the required.

Selecting the general structure of the EE core integrated, the EE core has one winding on each of the two columns, the air cylinder has an air gap on each magnetic column and the side column air gap is smaller than the middle column, forming a stable integrated structure. The transformer of the LLC converter must have two modes of operation: (1) the magnetizing inductance does not participate in the resonance, and the primary side transmits energy to the secondary side through the transformer. (2) The magnetizing inductance participates in the resonance, and the primary side stops transmitting energy to the secondary side. Finally, the design uses the core and skeleton of ETD3945. The original secondary turns ratio is 35:9:9. The primary side uses 0.1*40 enameled wire, the secondary side uses 0.2*20 enameled wire and the secondary side two windings are wound. In order to ensure that all parameters are the same, compared with the discrete LLC resonant converter, the leakage inductance of the magnetic integrated transformer is adjusted to 107uH, which is the same as the previous resonant inductance parameter. Because the leakage inductance of the direct winding is too high, the transformer will be 4mm retaining wall is added to the skeleton slot to slightly increase the coupling level, reducing the leakage inductance to 107uH and the magnetizing inductance to 587uH. Since there are many factors affecting the magnitude of the leakage inductance, it is necessary to test the winding several times and continuously optimize the transformer.

The magnetic integrated transformer ETD3945 is shown in Figure 4(a), and the discrete transformer PQ3220 is shown in Figure 4(b).



(a) ETD3945 (b) PQ3220

Fig.4 Transformer physical map

4. Simulation design and results

According to the above design requirements, the designs a prototype with a power of 250W. The circuit parameters are as follows: input voltage range is 380V~410V, rated input voltage is 400V;

resonant capacitor Cr is 24nF; resonant inductor Lr is 107uH; excitation inductance Lm is 587uH; transformer turns ratio N = 35:9:9; output capacitance Co is 600uF. The transformer design adopts the AP method, the magnetic integrated transformer selects the ferrite core selects the skeleton of ETD3945, the magnetic core selects the skeleton of the PQ3220. The original secondary turns ratio is 23:6:6, and the primary winding is 0.1. *40 enameled wire, the secondary winding is 0.25*7*2 three-layer insulated wire. In order to make the secondary winding symmetrical, the secondary winding and winding, the whole transformer adopts the sandwich winding method. The magnetizing inductance Lm is adjusted to 587 uH by an open air gap.

The parameters of the circuit design are verified by saber simulation software. The simulation results for the LLC resonant converter pair are shown in Fig.5.

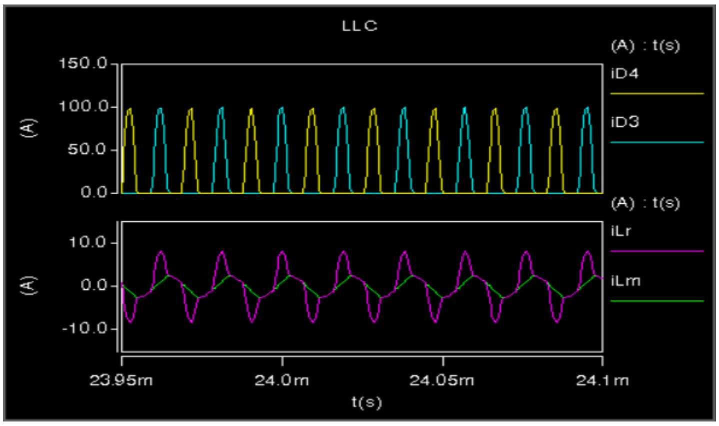


Fig. 5 simulation waveform

It can be seen from the simulation waveform diagram that the converter switch can be turned on by ZVS. The secondary rectifier diode currents D3 and D4 have an open state, and the transformer secondary diode can be turned off by ZCS. The simulation verifies the rationality of the parameter selection and makes the converter work normally.

5. Conclusion

According to the comparison of the effection of different transformer structures on the performance of LLC resonant converters, it finds that the efficiency of magnetic integration is higher than that of discrete ones. The switching losses are adjusted to be roughly equal during the experiment. The main losses are from transformers ,resonant inductors and AC loss. The resonant inductance and transformer of a common LLC resonant converter are discrete, which not only increases the volume and mass, but also increases the loss. The magnetic integrated LLC resonant converter integrates the transformer and the resonant inductor into one transformer, which not only reduces the volume and quality, but also reduces the volume and quality. Reduced losses. The magnetic integrated LLC resonant converter not only improves the power density of the converter, but also helps to reduce losses and improve efficiency.

References

[1] WANG Zejing, XU Yi, GONG Chunying. Development of multi-output DC/DC power supply with fixed on-time control[J]. Advanced Technology of Electrical Engineering and Energy, 2016, 35(3): 17-21.

[2] Wang Yue, Guo Haiping, Gao Yuan. Research on full-power range soft switching control technology for bidirectional full-bridge DC converter[J]. Advanced Technology of Electrical Engineering and Energy, 2016, 35(1): 7-12.

[3] WANG Lei, WANG Qiu-shi, ZHAO Jun-jun, et al. Multi-phase coupled staggered bidirectional DC-DC converter and its control for new energy generation systems[J]. Advanced Technology of Electrical Engineering and Energy, 2017(7).

[4] Guo Bing, Zhang Yiming, Zhang Jialin, et al. Hybrid control strategy of phase-shifted full-bridge LLC converter based on direct phase shift angle control[J]. Transactions of China Electrotechnical Society, 2018, 33(19): 4583-4593.

[5] Lü Zheng, Yan Xiangwu, Sun Lei. L-LLC Resonant Bidirectional DC-DC Converter Based on Variable Frequency-Phase Shift Hybrid Control[J]. Transactions of China Electrotechnical Society, 2017(4).

[6] YUAN Yi-sheng, ZHU Ben-yu, ZHANG Wei-ping, et al. A bridge-type secondary LC resonant converter and its modeling and design[J]. Advanced Technology of Electrical Engineering and Energy, 2015, 34(11): 63-68.

[7] Lei Ming, Zhang Fanghua, Li Shouqing, et al. Application of Matrix Transformer in LLC DC Transformer[J]. Advanced Technology of Electrical Engineering and Energy, 2016, 35(6): 54-59.

[8] Zong S , Luo H , Li W , et al. Theoretical Evaluation of Stability Improvement Brought by Resonant Current Loop for Paralleled LLC Converters[J]. IEEE Transactions on Industrial Electronics, 2015, 62(7):4170-4180.

[9] Zhao Qinglin, Liu Huifeng, Yuan Jing, et al. Interleaved Parallel Connection Technology of Full-Bridge LLC Resonant Converter Based on Phase Shift Compensation[J]. Transactions of China Electrotechnical Society, 2018, 33(12): 2777-2787.

[10] Lin R L , Huang L H . Efficiency Improvement on LLC Resonant Converter Using Integrated LCLC Resonant Transformer[J]. IEEE Transactions on Industry Applications, 2017:1-1