DESIGN AND OPTIMIZATION OF THREE-PHASE LLC RESONANT DC/DC CONVERTER

Lappeenranta–Lahti University of Technology LUT

Bachelor's Programme in Electrical Engineering, Bachelor's thesis

2024

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Examiner: Professor, Jianliang Chen, D.Sc. (Tech.)

ABSTRACT

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Design and optimization of three-phase LLC resonant DC/DC converter

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23 pages, 17 figures

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Keywords: LLC resonant, three phase, DC/DC converter

The purpose of this study is to discuss the design and optimization of three-phase LLC resonant DCDC converter. This study aims to optimize the three-phase LLC resonant DCDC converter. This study uses a literature review method to understand the working principle and application of the three-phase LLC resonant DCDC converter. Based on the literature review, the advantages of the design and optimization of the three-phase LLC resonant DCDC converter are found. The research results show that the optimized three-phase LLC resonant DCDC converter has higher energy conversion efficiency and lower power loss. It has important practical significance for improving the efficiency and stability of energy conversion systems. This will promote the development of electric vehicle charging technology and information data processing technology as well as other technologies applying LLC resonant DCDC converters.

SYMBOLS AND ABBREVIATIONS

Roman characters

I	Current	A
U	voltage	V
R	resistance	Ω
L	inductance	H
C	capacitance	F

Abbreviations

MOSFET	Metal Oxide Semiconductor Field Effect Transistor
SRC	Series resonant converter
PRC	Parallel resonant converter
SPRC	Series parallel resonant converter
ZVS	Zero Voltage Switching
ZCS	Zero Current Switching
PFC	Power Factor Correction

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1 Introduction

1.1 Research Background

Energy is the source of driving force for social development and progress. Since the 19th century, countries around the world have over exploited and used natural resources for their own development and progress. This has led to a lot of global environmental pollution and the shortage of natural resources. At the beginning of the 21st century, the world began to advocate sustainable development because of global environmental pollution and the shortage of natural resources. The development and utilization of new energy has become the focus of energy development in the 21st century. New energy vehicles stand out in the development and utilization of new energy. Electric vehicles are the representative of zero emission in new energy vehicles. Electric vehicles are powered by electricity, which reduces the car's dependence on traditional petroleum resources and relieves the pressure of energy shortages. At the same time, electric vehicles do not produce exhaust emissions, which greatly reduces the environmental pollution of cars. At the same time, the emergence of electric vehicles has promoted the reform of the modern automobile industry. Due to the zero exhaust emission of electric vehicles and the lack of reliance on traditional fossil energy, more and more automobile companies have begun to research and produce electric vehicles, which makes the automobile industry develop in a more environmentally friendly and sustainable direction. Under the current situation of global sustainable development and lack of natural resources, new energy vehicles have broad development prospects, especially the development prospects of electric vehicles. Although the development prospects of electric vehicles are very broad, the development of electric vehicles faces many challenges. For example, the fast charging technology of electric vehicles is one of the difficulties and challenges of current electric vehicle technology[1]. Since the LLC resonant DCDC converter can provide a constant and stable output voltage, the LLC resonant DCDC converter is an important part of electric vehicle fast charging technology. The design and optimization of three-phase LLC resonant DCDC converter is studied in this thesis. By discussing the design and optimization of the three-phase LLC resonant DCDC converter, the optimized characteristics are found. This will promote the development of fast charging technology for electric vehicles and thus promote the development of new energy.

1.2 Resonant converters

There are three main types of resonant converters. They are series resonant converters, parallel resonant converters and series parallel resonant converters.

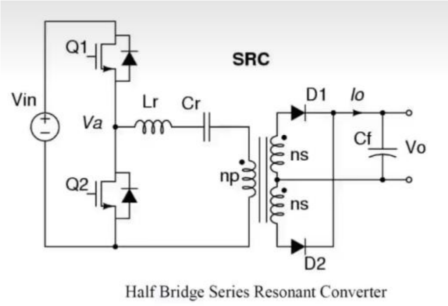

Fig. 1. Series resonant converter [2]

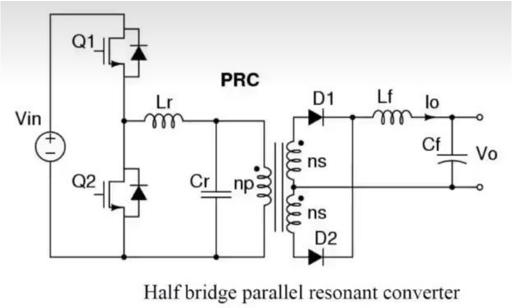

Fig. 2. Parallel resonant converter [2]

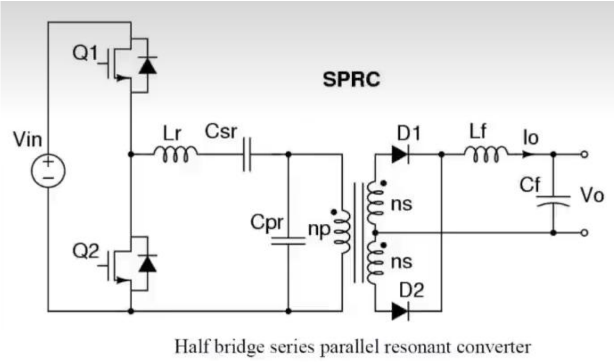

Fig. 3. Series parallel resonant converter [2]

Fig. 1. shows the series resonant converter's structure. Fig. 2. shows the parallel resonant converter's structure. Fig. 3. shows the parallel resonant converter's structure. The common denominator of the three resonant converters is that the two MOSFETS Q_1 and Q_2 form a switching network, and the two diodes D_1 and D_2 form a rectifier. There are also differences between these three resonant conversion circuits. The load and capacitor are connected in series to create a series resonant network in a series resonant converter. In a

parallel resonant converter, the load and capacitor C_r are connected in parallel to form a series-parallel resonant network. In the series-parallel resonant network, the load is not only connected with the capacitor C_{pr} but also connected with the capacitor C_{sr} to form the series-parallel resonant network[3]. The LLC resonant converter studied in this thesis belongs to the series parallel resonant converter. LCC resonant converters are also series parallel resonant converters. Compared with the LCC resonant converter, the LLC resonant converter performs better. The series resonant converter has a simple construction and a high energy transfer efficiency, but it is difficult to modify the output voltage. Compared with series resonant converters, parallel resonant converters have a wider adjustment range. At light load, the parallel resonant converter can easily adjust the output voltage. However, parallel resonant converters are not suitable for high voltage inputs. The SPRC (Series parallel resonant converter) includes the advantages of SRC (Series resonant converter) and PRC (Parallel resonant converter). Therefore, series parallel resonant converters are the most widely used.

1.3 Research contents

Although LLC resonant converters are widely used now, the LLC resonant converter still needs to be optimized and improved. The main research content of this thesis is the design and optimization of LLC resonant converter. The LLC resonant converter's structure and working principle are analyzed and optimized.

2 Design of LLC resonant DCDC converter

2.1 Single-phase LLC resonant DCDC converter

Single-phase LLC resonant converters provide a single output voltage. It is usually used in single-phase power systems. Such as high-efficiency power conversion.

2.1.1 Main circuit structure

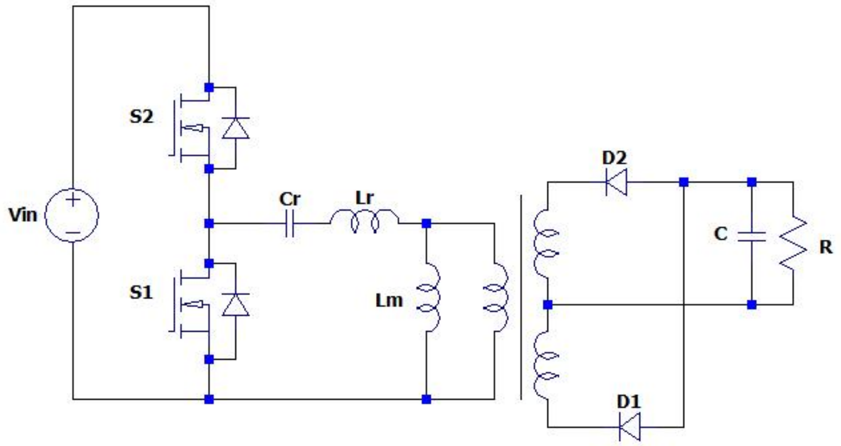

Fig. 4. Single-phase half-bridge LLC resonant converter[2]

As shown in Fig. 4, the LLC resonant converter is a single-phase half-bridge LLC resonant converter. The main components include two MOSFET switching tubes S_1 and S_2, resonant inductor L_r, resonant capacitor C_r, excitation inductor L_m, rectifier diodes D_1 and D_2, output capacitor C and load R. Both MOSFET switches have body diodes. The two diodes D_1 and D_2 form a rectifier circuit for converting AC input into DC output.

There are two resonant frequencies in the half-bridge LLC resonant converter: f_1 and f_2. When the LLC resonant works at frequency f_1, the reactive power is the smallest and the power loss is the smallest.[2] The output voltage is always equal to the input voltage. $f_1$is the resonant frequency of the resonant inductor L_r and the resonant capacitor C_r. In this case, the excitation inductor L_m does not participate in the resonance. The expression is as follows:

$$f_1 = \frac{1}{2\pi\sqrt{L_r * C_r}} \quad [2] \tag{1}$$

The excitation inductor L_m, resonant inductor L_r and resonant capacitor C_r have a resonant frequency is f_2. The expression is as follows:

$$f_2 = \frac{1}{2\pi\sqrt{(L_r + L_m) * C_r}} \quad [2] \tag{2}$$

2.1.2 Main working state analysis

The half-bridge LLC resonant converter has three working frequencies. They are greater than f_1, between f_1 and f_2, equal to f_1.[4] The working waveform of the half-bridge LLC resonant converter under three operating frequencies is shown in Fig. 5, Fig. 6 and Fig. 7. t_1 , t_2 and t_3 are several special time points of the LLC resonant converter operating waveform. Later, t_1 ,t_2 and t_3 will be introduced in detail when introducing the working principle of LLC resonant converter. i_{Lm} is excitation current. i_{Lr} is resonant current. t_{d} is the dead time. $V_{\mathrm{gsQ_1}}$ and $V_{\mathrm{gsQ_2}}$ are the voltage of MOSFETS.

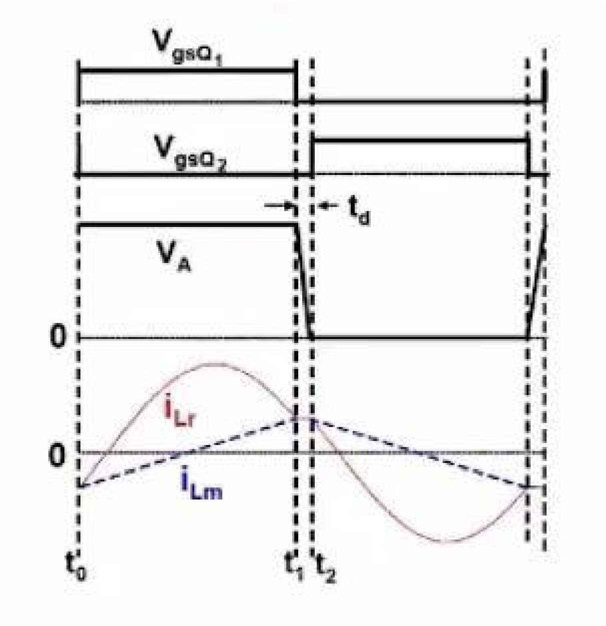

Fig. 5. Working waveform diagram when $f = f_1$[2]

ZVS can be achieved on primary side and ZCS can be achieved on secondary side when the LLC resonant converter's working frequency equal to f_1 .

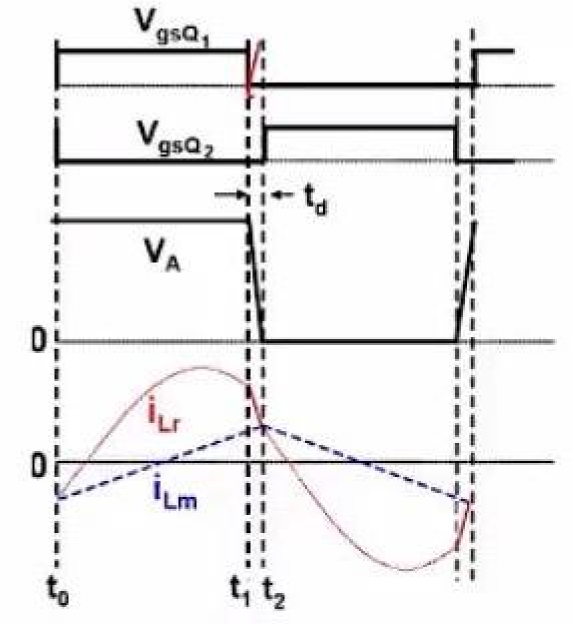

Fig. 6. Working waveform diagram when $f > f_1$[2]

ZVS can be achieved on the primary side of the transformer, but ZCS can't be achieved on the secondary the working frequency of the LLC resonant converter is greater than f_1.

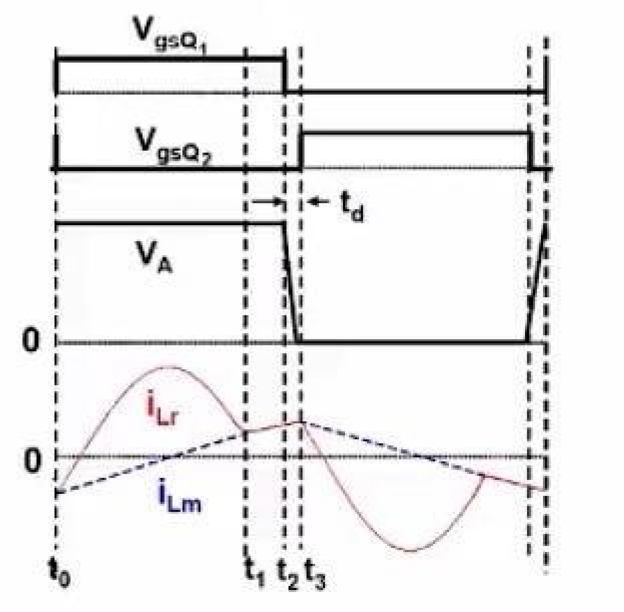

Fig. 7. Working waveform diagram when $f_2 < f < f_1$[2]

Common operating frequencies for half-bridge LLC resonant converters are between f_1 and f_2. Therefore, the main working state of LLC resonant converter between f_1 and f_2. When the working frequency is between f_1 and f_2, The LLC resonant converter's primary side can achieve ZVS (Zero Voltage Switching), and its secondary side can achieve ZCS (Zero Current Switching). ZCS and ZVS are two soft switching technologies. There are switching losses and conduction losses in the transistor of LLC resonant converter. The switching losses depend on the current and voltage during switching and on the switching frequency. ZVS is achieved by the input voltage approaching zero when the MOSFET is turned on or off. ZVS is used to reduce power loss during circuit switching, it power conversion efficiency and reliability. ZCS is achieved by the input current approaching zero when the MOSFET is turned on or off. ZCS is used to reduce power loss and electromagnetic interference during switching, which can significantly reduce power loss during switching, improve power conversion efficiency and reduce the thermal burden on switching devices.[4]

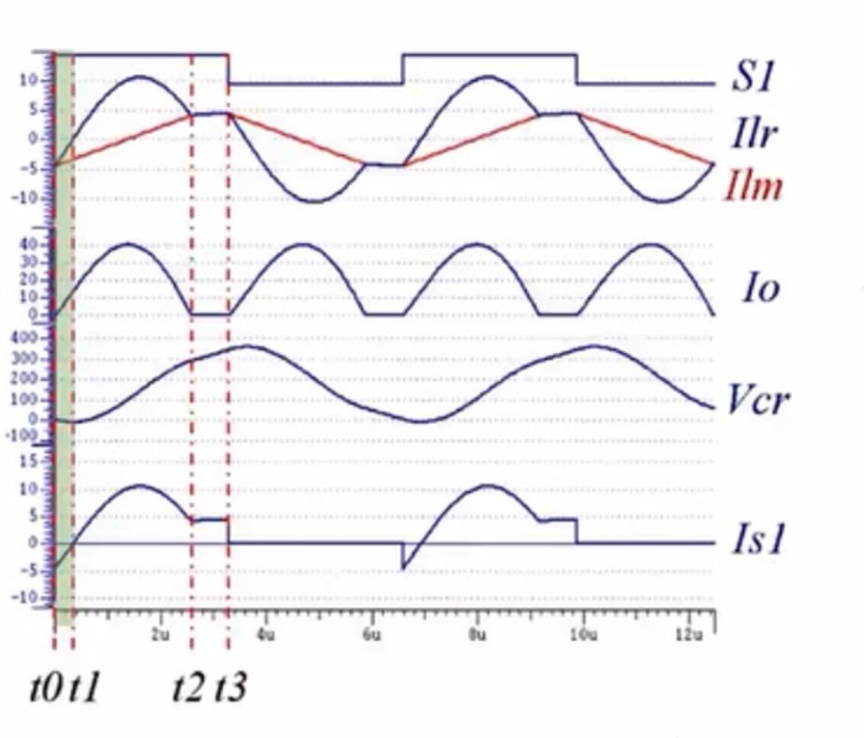

Fig. 8. Working waveform diagram[2]

Fig. 8. is a waveform diagram of the half-bridge LLC resonant DCDC converter. S_1 is the voltage of switch S_1. i_{Lm} is excitation current. i_{Lr} is resonant current. i_o is the output current. V_{cr} is the voltage of resonant capacitor. i_{s1} is the current of switch S_1. The

waveform analysis process of the half-bridge LLC resonant converter in the first half cycle and the second half cycle is similar, so only the first half cycle is taken for detailed analysis and discussion.

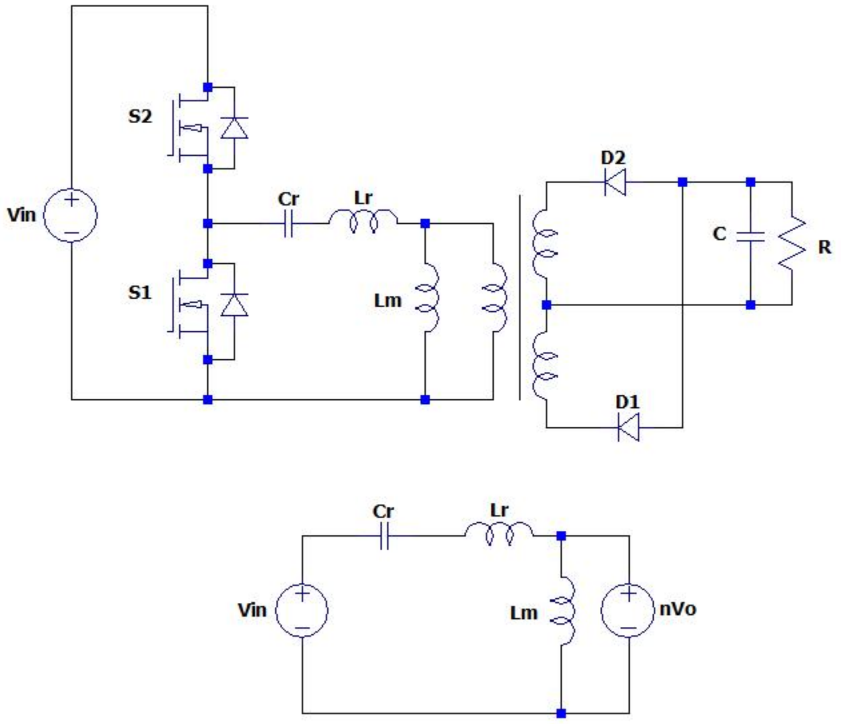

Fig. 9. Working status when t_0<t<t_1[2]

The working process during the period $t_0 < t < t_1$ is shown in Fig. 9. At time t_0, the switch S_2 is turned off instantaneously, and the voltage on switch S_2 is V_{in}. The parasitic body diode of the switch S_1 is turned on, and the voltage on switch S_1 is 0. The switch's body diode has a reverse current. The voltage on the transformer primary switch S1 is 0. The switch S_1 achieve ZVS. During this period, the excitation current I_{Lm} is also smaller than the resonant current I_{Lr}. When $t_0 < t < t_1$, the secondary diode D_1 of the transformer is turned on and D_2 is turned off. The transformer's secondary side is clamped to the primary side at a voltage of nV_o, the excitation inductor L_m is in the charging state, and the excitation current I_{Lm} increases linearly. In the resonant network, the resonant inductor L_r and resonant capacitor C_r are in the resonant working condition. The primary resonant current I_{Lr} will remain unchanged until become zero at time t_1[2].

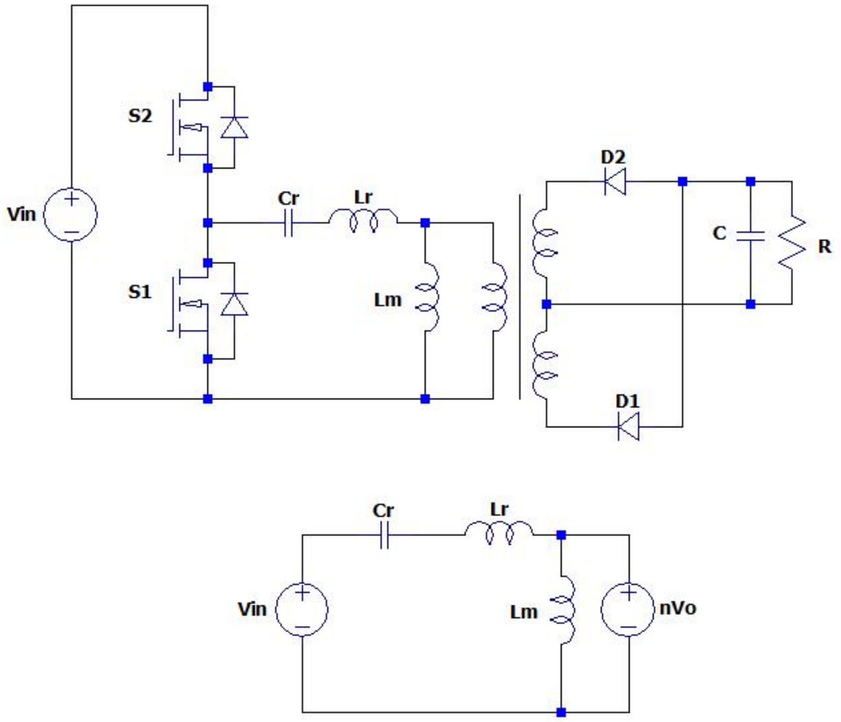

Fig. 10. Working status when t_1<t<t_2[2]

The working process during the period $t_1 < t < t_2$ is shown in Fig. 10. At time t_1, switch S_1 is turned on and switch S_2 is turned off. The secondary rectifier diode D_1 is turned on and D_2 is turned off. The resonant current I_{Lr} gradually increases from 0 to a forward current with an approximate sine wave shape. The transformer's secondary side is still clamped to the primary side at a voltage of nV_o, and the excitation current I_{Lm} continues to increases linearly. In the period of $t_1 < t < t_2$, only the resonant inductor L_r and the resonant capacitor C_r work in the resonant state, the excitation inductor L_m works in the resonant circuit as a load and it isn't participate in the resonance. At time t_2, the parallel inductor current I_{Lm} is charged until it is equal to the resonant current I_{Lr}. [2]

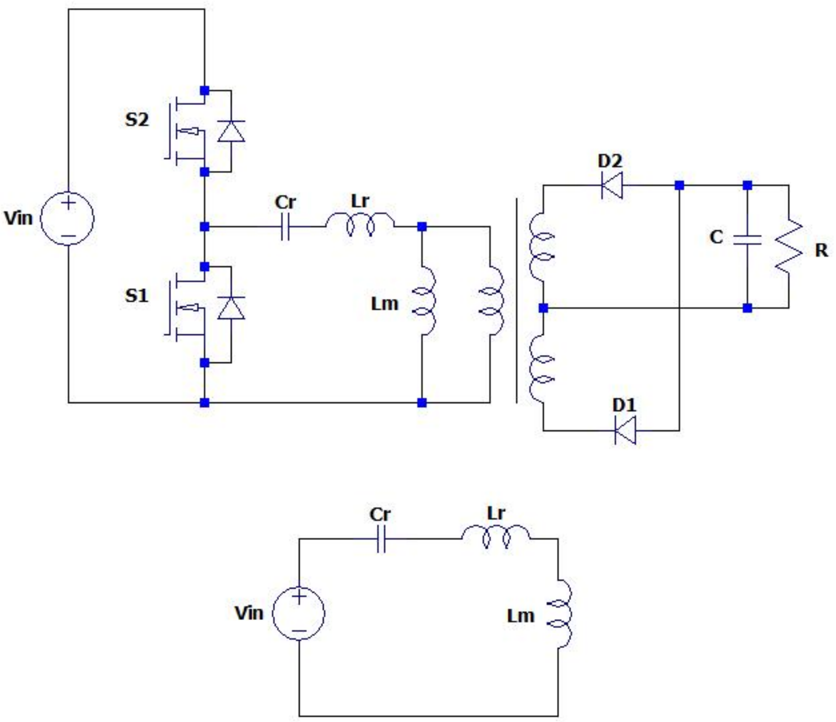

Fig. 11. Working status when t_2<t<t_3[2]

The working process during the period $t_2 < t < t_3$ is shown in Fig. 11. At time t_2, The resonant current I_{Lr} and the excitation current I_{Lm} are equal. The secondary rectifier diode D_1 is turned off and no current flows. At this time, The transformer's primary and secondary sides are not currently exchanging energy, and the load is provided with voltage by the output capacitor C. No current flows through the primary side, and the primary side switch S_1 is still turned on. The resonant inductor L_r, the excitation inductor L_m and the resonant capacitor C_r participate in the resonance. At time t_3, the switch S_1 is turned off, the resonant current I_{Lr} is greater than 0, and the switch tube's body diode is turned on.[2]

In the second half period $t_3 \sim t_6$, the switch S_2 is turned on, the working waveform of the resonant converter is symmetrical to the first half period. The analysis process is similar, but the current goes in the opposite direction. From the above analysis, it can be seen that the resonant current in the switch tube lags behind the voltage to achieve the ZVS of the MOSFET. The power loss of the switch tube is related to the excitation current I_{Lm}. The excitation current I_{Lm} is smaller, the power loss of the switch tube is smaller. By choosing a suitable resonance parameter, the excitation current can be decreased and efficiency can be increased.[5]

2.2 Three-phase LLC resonant DCDC converter

2.2.1 Main circuit structure

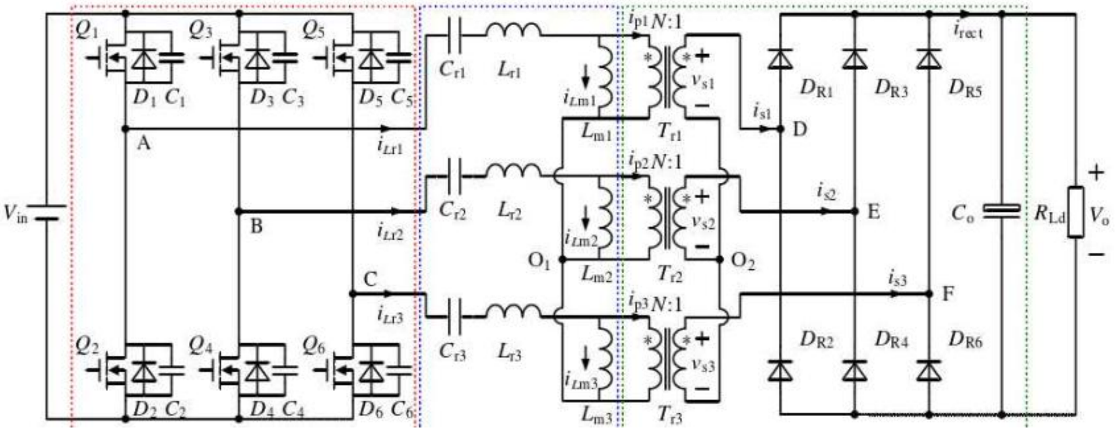

Fig. 12. Three-phase LLC resonant DCDC converter[6]

As shown in Fig. 12, the LLC resonant converter is a three-phase half-bridge LLC resonant converter. The three-phase half-bridge LLC resonant converter consists of three single-phase half-bridge LLC resonant converters. It’s main components are basically same as the component of single-phase LLC resonant converter. The main components include six MOSFET switching tubes, three resonant inductors, three resonant capacitors, three excitation inductors $\mathrm{L_m}$, six rectifier diodes, output capacitors and loads. Each of the six MOSFET switching tubes has body diodes. Six diodes form a rectifier circuit that converts AC input into DC output. The parameters of the same device are the same in the three-phase LLC resonant converter.

The three-phase half-bridge LLC resonant converter also has two resonant frequencies f_1 and f_2 . These two resonant frequencies are the same as the single-phase half-bridge LLC resonant converter.[6]

2.2.2 Main working state analysis

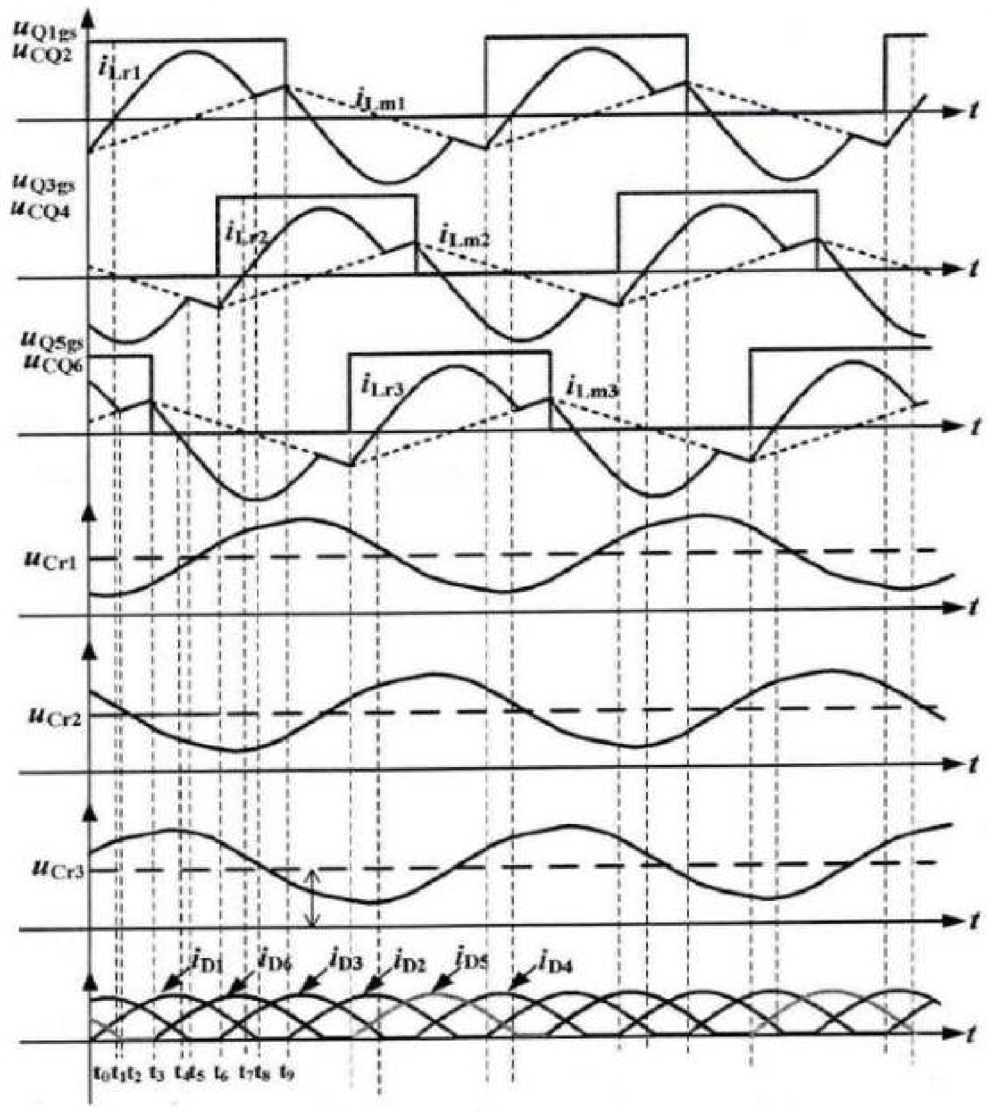

Fig. 13. Working waveform diagram[7]

The three-phase half-bridge LLC resonant converter also has three working frequencies. They are greater than f_1, betweenf_1 and f_2 and equal to f_1.

The common working frequency of three-phase half-bridge LLC resonant converters is also between $f_1$and f_2. Therefore, the main working state of the three-phase half-bridge LLC resonant converter is between f_1 and f_2. In this working state, the primary side of the three-phase half-bridge LLC resonant converter can also achieve ZVS, and the secondary side can also achieve ZCS. The achievement of ZVS and ZCS improves the power conversion efficiency of the converter.

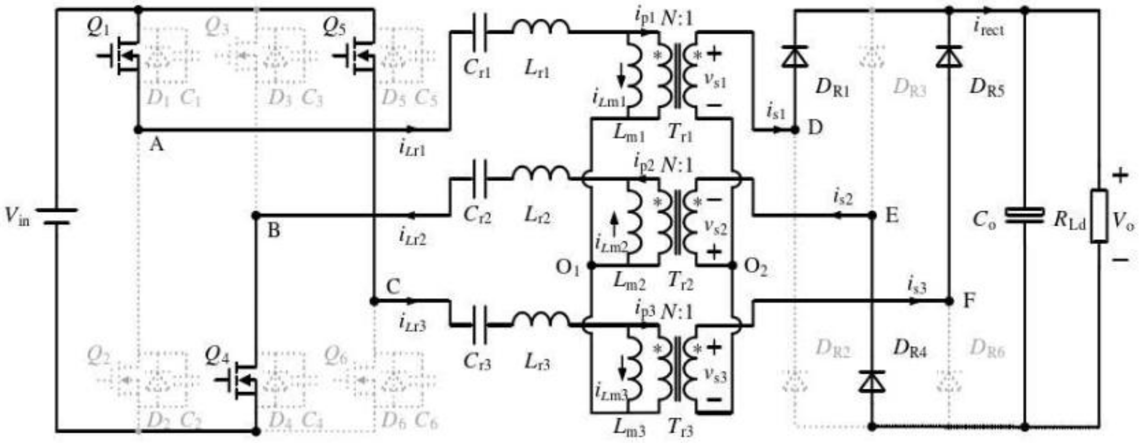

Fig. 14. Working status when t_0<t<t_2[6]

When $t_0<t<t_2$, switch tube Q_1, Q_4 and Q_5 are turned on. In each module $\mathrm{L}_{\mathrm{r}1}$ and $\mathrm{C}_{\mathrm{r}1}$, $\mathrm{L}_{\mathrm{r}2}$ and $\mathrm{C}_{\mathrm{r}2}$, $\mathrm{L}_{\mathrm{r}3}$ and $\mathrm{C}_{\mathrm{r}3}$ participate in resonance. The current flows through Q_1, $\mathrm{C}_{\mathrm{r}1}$, $\mathrm{L}_{\mathrm{r}1}$, Q_5, $\mathrm{C}_{\mathrm{r}3}$ and $\mathrm{L}_{\mathrm{r}3}$, and then through $\mathrm{L}_{\mathrm{r}2}$, $\mathrm{C}_{\mathrm{r}2}$ and Q_4. $\mathrm{D}_{\mathrm{R}1}$, $\mathrm{D}_{\mathrm{R}4}$ and $\mathrm{D}_{\mathrm{R}5}$ are turned on. The resonant current $\mathrm{i}_{\mathrm{Lr}1}$ continues to increases, and the excitation current $\mathrm{i}_{\mathrm{Lm}1}$ linearly increases. The resonant current $\mathrm{i}_{\mathrm{Lr}2}$ decreases and the excitation current $\mathrm{i}_{\mathrm{Lm}2}$ decreases linearly. The resonant current $\mathrm{i}_{\mathrm{Lr}3}$ decreases and the excitation current $\mathrm{i}_{\mathrm{Lm}3}$ increases linearly.[6]

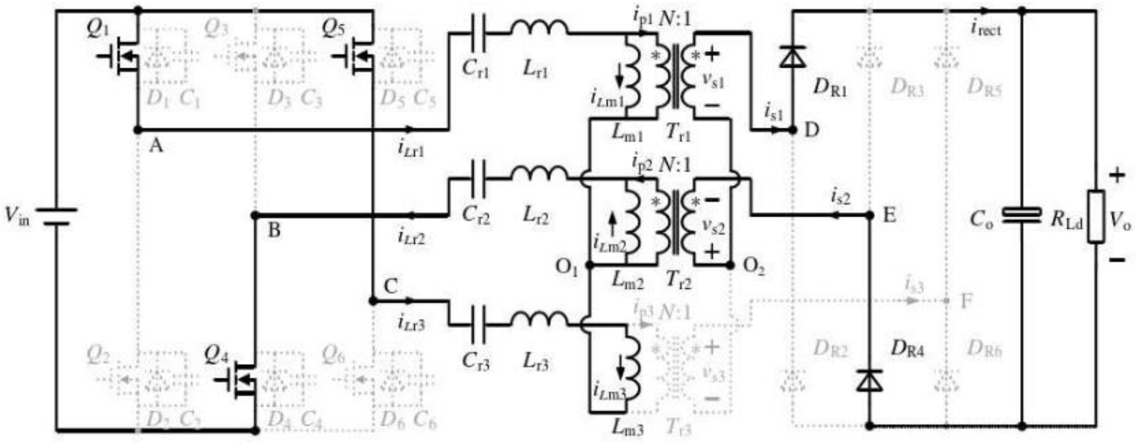

Fig. 15. Working status when t_2<t<t_3[6]

When $t_2 < t < t_3$, switch tube Q_1, Q_4, Q_5 are turned on. At this time, L_{r3}, L_{m3} and C_{r3} resonate together. The current flows through Q_1, C_{r1}, L_{r1}, Q_5, C_{r3}, L_{r3} and L_{m3} and then goes through the L_{r2}, C_{r2} and Q_4 to return the negative voltage. The resonant current i_{Lr1} continues to increase, and the excitation current i_{Lm1} continues to increase linearly. After the resonant current i_{Lr2} decreases to the minimum value, it begins to increase. The excitation current i_{Lm2} continues to decrease linearly. The resonant current i_{Lr3} is equal to the excitation current i_{Lm3}.[7]

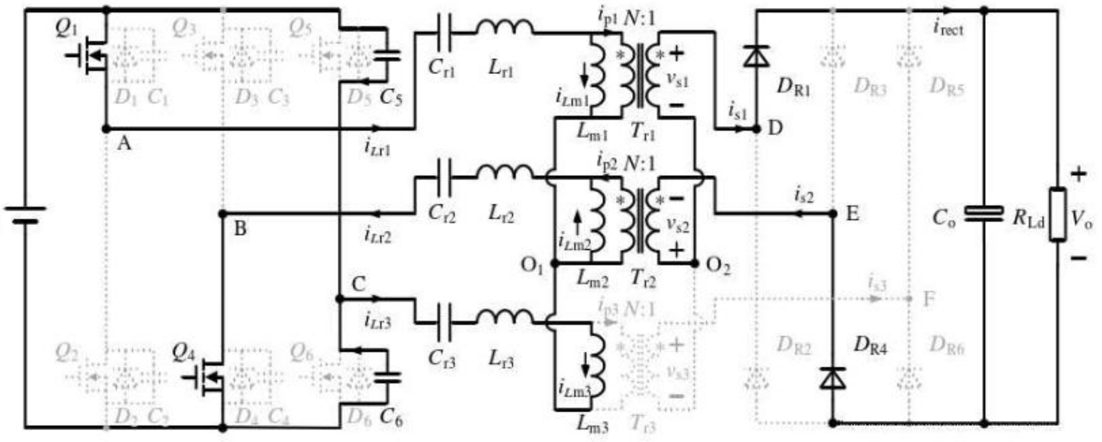

Fig. 16. Working status when t=t_3[6]

At time t_3, the switch tube Q_5 is turned off, and the excitation inductor L_{m3} charges the capacitor C_5 while discharging the capacitor C_6. Due to the buffering effect of capacitor C_5 and C_6, Q_5 is turned off when voltage is about zero. When the voltage of capacitor C_5 increases to V_{in} and the voltage of capacitor C_6 decreases to zero, the diode D_6 naturally turned on, and Q_6 can be turned on at zero voltage. The latter process is similar to the previous three.[6]

3 Design of LLC resonant DCDC converter

3.1 Applications of LLC resonant DCDC converter

LLC resonant converters have many applications, such as battery car charging, information data centers and other DCDC applications. In these applications, the LLC resonant converter is typically connected behind a capacitor, as shown in Fig. 17. AC line is the power supply network. V_o is the output voltage. In front of the capacitor C_{hdup} is often the power supply network and a PFC. PFC is used to reduce electrical energy loss and compensate the power factor due to reactive power. V_{bus} is the voltage provided by the power supply network and adjusted by PFC. The function of the capacitor C_{hdup} is to still supply power to the load for a short time after the AC input suddenly disappears. The short time is called hold-up time. During this time, the voltage supplied by the capacitor gradually decreases to the minimum input voltage of the LLC resonant converter. The role of the LLC resonant DCDC converter is often to regulate and maintain a stable voltage output for a short time after there is no power input, ensuring that the load can work normally for a short time when the power supply disappear suddenly.[2] Besides, the role of capacitor bank is to smoothen the grid power flow and also provide enough energy to output in the transients.

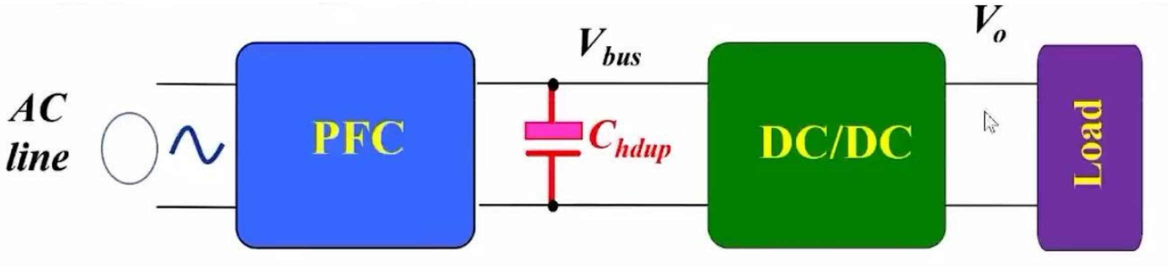

Fig. 17. Application scenario of LLC resonant converter[2]

3.2 Design process of LLC resonant DCDC converter

The most commonly used LLC resonant converter is the half-bridge LLC resonant converter. Three-phase LLC resonant converters generally use Y-Y type connection. There are generally five steps to design an LLC resonant converter. The first step is to determine the voltage input range of LLC resonant DCDC converter. The voltage input range of LLC resonant DCDC converter is often determined by the hold-up time. Because the designed LLC resonant converter needs to meet a specific hold-up time. Up time is larger, the voltage input range of the LLC resonant converter is larger, and the capacitor in front of the LLC resonant converter is larger.[2]

The second step is to select the appropriate transformer turns ratio and resonant frequency. Formula (4) is derived from formula (3). In half-bridge LLC resonant DCDC converter, half the input voltage V_{in} is equal to the load voltage multiplied by the turns ratio of the transformer. Therefore, the LLC resonant converter's input voltage range and the load operating voltage can be used to approximate the transformer turns ratio. The resonant frequency is generally chosen subjectively by humans.[2]

$$M = \frac{NV_0}{V_{in}/2} = 1 \ \ [2] \tag{3}$$

$$N = \frac{V_{in}}{2V_0} \ \ [2] \tag{4}$$

The third step is to choose the appropriate excitation inductor L_m. ZVS was mentioned before when discussing the working principle of LLC resonant converter. During the period when the excitation current i_{Lm} is equal to the resonant current i_{Lr}, the charge in the parasitic capacitor of the MOFEST tube is reduced to zero and ZVS is achieved to reduce power losses. In this process, all the charge of the MOFEST tube's parasitic capacitor is transferred to the excitation inductor L_m. Therefore, the value of the excitation inductor L_m can be obtained by equalizing the charge amount of the capacitor and the charge amount of the exciting inductor.

The fourth step is to determine the resonant inductance L_r and quality factor Q.

$$L_n = \frac{L_m}{L_r} \quad [2] \tag{5}$$

$$Q = \frac{\sqrt{L_r/C_r}}{N^2 R_L} \quad [2] \tag{6}$$

In formulas (5) and (6), L_n is inductor ratio. L_m is excitation inductor. L_r is resonant inductor. Q is quality factor. C_r is resonant capacitor. N is the turn ratio of the transformer. R_L is load. The purpose of LLC resonant converter to reduce power loss. Therefore, the current stress is smaller and the working range is smaller. The selected inductor ratio L_n is larger, the resonant inductor L_r is smaller and the power factor Q is larger.

The last step is to determine the resonant capacitor C_r. This value can be calculated by formula (7).

$$f_1 = \frac{1}{2\pi\sqrt{L_r * C_r}} \tag{7}$$

4 Optimization of LLC resonant DCDC converter

4.1 Advantages of LLC Resonant Converter

LLC resonant converters have many advantages. The LLC resonant converter can improve the power conversion efficiency. The LLC resonant converter can improve the conversion efficiency of electrical energy mainly due to its unique design and working principle. LLC resonant converters are designed to achieve soft switching. This means that the switch turns off and on when the voltage is zero or the current is zero, significantly reducing power losses. This soft switching reduces the energy loss caused by the switch tube during the on and off processes, improving the power conversion efficiency. LLC resonant converters are also maintain high efficiency over a wide load range. LLC resonant converters can work at different frequencies and can be optimized at different working frequencies to achieve high efficiency.[2]

LLC resonant converters can work in several different voltage input ranges. The resonant circuit in the LLC resonant converter plays an important role in adapting to different input voltage ranges. Compared to other resonant converters, LLC resonant converters can work over a wide frequency range. Most importantly, the LLC resonant converter allows the load to work normally for a short time after the power supply is disappeared. This plays an important role in information data processing technology. It can enable the machine to provide emergency protection for some important data when the power supply is disappeared suddenly.[2]

4.2 Limitations and challenges of LLC resonant converter

LLC resonant converters also have many limitations. Designing and optimizing LLC resonant converters is a complex process. Because it involves the selection and calculation of multiple electronic component parameters. For example, excitation inductor, resonant inductor, resonant capacitor, transformer turns ratio, power factor and so on. These parameters need to be calculated and adjusted according to different conditions. The transformer is a key component in the LLC converter. It’s design is complex and involves the selection of leakage inductance, turns ratio and so on. The efficiency and performance of the converter are directly impacted by the transformer's design. At the same time, the optimization of the physical size needs to be considered. If the physical size is small, the power density will be high.

4.3 Optimization of LLC resonant converter

The LLC resonant converter can be optimized by selecting and designing the most suitable input voltage range, inductor, switches, capacitor and transformer. In LLC resonant converter, MOSFETS are usually used as switching tubes because the conduction loss of MOSFETS is low. When selecting an inductor, the inductor value needs to be determined through calculation to achieve the expected hold-up time, gain and other conditions. The inductor is capable of carrying maximum load current without saturation. When selecting the capacitor, it should be chosen based on the resonant frequency and input voltage range of the LLC resonant converter. The input voltage range is larger, the capacitor value is larger. In addition, the capacitance value can also be obtained based on the resonant frequency of the LLC resonant converter, increasing the accuracy of the LLC resonant converter. The rated voltage of each electronic component should be higher than the corresponding working voltage to ensure the safety and reliability of the circuit. LLC resonant converters are isolated converters. Compared with non-isolated converters, LLC resonant converters are safer. The transformer in the LLC resonant converter provides electrical isolation between the input and output. The use of electrical isolation avoids the occurrence of leakage current, making the LLC resonant converter safer.[8]

5 Conclusion

Through analysis and optimization of the converter's main circuit structure and its working status, the performance of the converter can be significantly improved. The three-phase LLC resonant converter after optimized can maintain high efficiency and has good adaptability to input voltage changes. The optimized LLC converter can maintain efficient operation at different operating frequencies. At the same time, the load can still work normally for a short time after a power supply interruption, which is particularly important for data processing technology. Through the precise selection and design of key components such as inductors, capacitors and transformers, LLC resonant converters can achieve efficient energy conversion and high reliability. In addition, electrical isolation in the converter provides additional safety in various applications. In the background of the global promotion of sustainable development and new energy vehicles, the research and development of LLC resonant converters has important practical significance and application prospects. In addition, LLC resonant converters are also of great significance to the development of information data technology.

6 References

[1] Ailing, D, 2023. Research on challenges and opportunities of electric vehicle charging infrastructure development. In: Vehicle test report. Beijing, Beijing Science and Technology Journal Society P. 145-147

[2] Minfan, F. 2022. Principle and optimal design of LLC resonant converter. Bilibili. https://www.bilibili.com/video/BV14e4y1E7PW/?spm_id_from=333.1007.top_right_bar_window_history.content.click&vd_source=84f8adac6d6fe6724b319dbbbde43d6b

[3] Weixing, L. 2020. Research on half bridge LLC resonant DC-DC converter. Beijing Jiaotong University

[4] Xiaobo, Y. 2021. Design and research on half-bridge LLC resonant converter. Harbin Institute of Technology.

[5] Jie, L. 2018. Research on half-bridge LLC resonant converter. Beijing Jiaotong University

[6] Yang, C. 2021. Three-phase LLC resonant converter with integrated magnetics. Nanjing University of Aeronautics and Astronautics

[7] Yan, X. 2015. Research on three phase LLC resonant converter. Southwest Jiaotong University.

[8] Xuefeng, H. Xin, L. Zikang, L. 2022. A photovoltaic inverter without transformer and leakage current. High Voltage Technique. 48 2045-2053