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Analysis of A Bidirectional Resonant Converter Applied in High/Low Voltage Conversion

Journal of Electrical Systems

Abstract: - In order to ensure the safe and reliable operation of the ship, the emergency power supply of the ship can provide short-term power supply when the main power supply of the ship fails. This paper proposes a two-way LLC resonant converter to be used in marine emergency power supplies. While ensuring the high efficiency and soft switching performance of the converter, it realizes high and low voltage conversion and bidirectional energy flow. By analyzing the topology, working principle and gain under variable frequency control of the two-way LLC resonant converter, and constructing the principle prototype and verifying its performance, the experiment shows that the application of the two-way LLC resonant converter in the emergency power supply can achieve high and low voltage The conversion and has good soft switching characteristics.

Keywords: Bi-directional DC/DC Converter (BDDC), LLC Converter (LC), Soft Switching (SS), High and Low Voltage Conversion (HLVC).

I. Introduction

With the development of ship integrated electric propulsion system, its excellent performance has become the mainstream mode of ship propulsion system in the world. However, due to the change of navigation conditions at any time, the ship's main power supply electric propulsion system may fail. In order to ensure the normal operation of the ship's power supply system, the ship has attached an emergency power supply electric propulsion system. When the main power supply electric propulsion system cannot work normally due to the failure of the ship, the emergency power supply electric propulsion system provides short-term power supply [1,2] to ensure the safe operation of the ship.

In order to drive the normal operation of the ship, several emergency power supplies are equipped on the ship to work at the same time when the ship is running in fault. However, the voltage requirements of different high-power power power electronic equipment and systems are different, and the application of these equipment leads to EMI (electromagnetic interference) problems in the return circuit when the emergency power supplies operate at the same time. At present, the EMI problem can be solved by isolated DC/DC converter [3,4]. With the development and utilization of new energy, bidirectional DC/DC converter [5,6] has attracted more and more attention. With the advantages of its topology, bidirectional DC/DC converter can not only realize the bidirectional flow of energy at high and low pressure sides [7], but also has the advantages of high efficiency and good performance. Therefore, bidirectional DC/DC converters have been applied to many fields, especially in electric vehicle power supply system, emergency power supply [8-10] and other fields.

Based on the research of marine emergency power supply device, this paper proposes a bidirectional LLC resonant converter suitable for marine emergency power supply device. Through theoretical analysis, it is concluded that the bidirectional LLC resonant converter not only has wide input, high-low voltage conversion and soft switching performance, but also has the advantages of good controllability, wide soft switching range and high efficiency. A 500W principle prototype is built to verify the correctness of the theory, and achieved good results.

II. Ship Emergency Power Supply

The ship emergency power electric propulsion system is one of the energy sources of the ship integrated electric propulsion system, its main function is to provide short-term power supply for the emergency load of the ship when the main power supply of the ship fails [11,12].The emergency power supply is divided into high-power power supply and low-power supply according to the power [13]. The small power supply is mainly composed of battery pack, and its working mode has two kinds: charging and discharging mode.

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The composition of the marine power supply system is shown in Figure 1. The main power supply is mainly composed of generators, AC/DC converters and loads; The emergency power supply is mainly composed of storage battery, bidirectional LLC resonant converter and load.

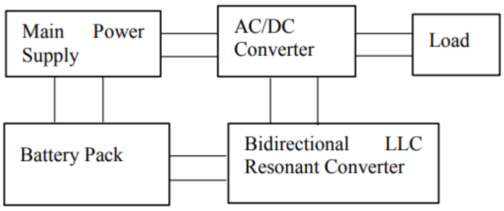

Figure 1: Diagram of Ship Power Supply System

III. Bidirectional LLC Resonant Converter

A. *Topology*

The topology of isolated bidirectional LLC resonant converter proposed in this paper is shown in Figure 2. The primary and secondary sides of the converter are all full bridge structures, which can realize the bidirectional flow of energy. Among them, the switches Q_1-Q_4 are the primary side bridge arms, Q_5-Q_8 are the secondary side bridge arms, and D_{Q1}-D_{Q8} are the diodes of Q_1-Q_8 in reverse parallel. The turns ratio of the primary and secondary sides of the transformer is n:1, realizing the conversion of high and low voltage. L_m is the excitation inductor, L_r and C_r form the resonant circuit of the primary and secondary sides, which can realize the wide range of soft switching performance of the switch, reduce the electromagnetic interference in the circuit loop and the switching loss of the switch to ensure the high efficiency and high power density of the converter. The converter adopts frequency modulation frequency conversion control mode. From the symmetry of the forward and reverse working principle, when transmitting energy in the forward direction, it controls the primary side switch and blocks the secondary side switch drive, which can be equivalent to a rectifier; When the reverse energy is transferred, the working condition is the same as that in the forward direction.

Due to the symmetry of the structure, the forward and reverse working principles of the converter are consistent, and the analysis and control methods of the circuit in different directions are completely consistent, simplifying the design complexity.

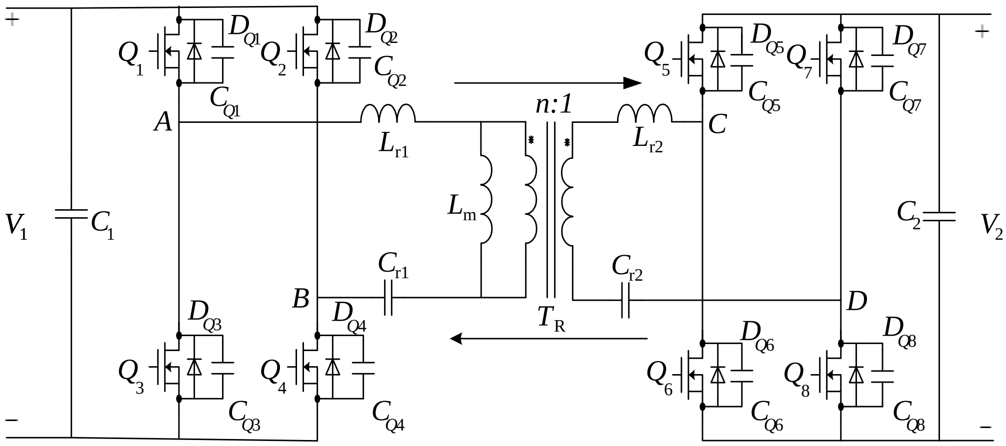

Figure 2: Bidirectional Resonant Converter

B. *Working Principle*

Two way DC/DC has the advantage of two-way flow of energy [14,15]. The ship emergency power supply uses its characteristics to work in two modes of charging and discharging. Its working characteristics are as follows: when the main power supply system of the ship works normally, the AC output from the main power supply is converted into the voltage required by the DC bus through the AC/DC converter to provide power for the load. At the same time, due to the bidirectional fluidity of energy in the bidirectional LLC resonant converter, the main power supply is connected to charge the battery pack until it is full, and the bidirectional LLC resonant converter will stop working for emergency use to optimize the energy utilization rate. When the main power supply system fails, the storage battery converts the stored electric energy into DC bus voltage to supply power to the load through the bidirectional LLC resonant converter.

The traditional marine emergency power electric propulsion system directly connects the battery pack with the DC bus of the power supply system. However, due to the different voltage requirements of different equipment, the battery pack has been in the mode of charging and discharging, and it can not ensure that a battery in the battery pack works in the same state as other batteries, which greatly reduces the efficiency and service life of the battery pack. The bidirectional LLC resonant converter proposed in this paper is applied to the marine emergency power supply electric propulsion system. It uses its advantages of good controllable performance and wide soft switching range to realize wide input, high and low voltage conversion, so as to ensure the stability of the bus voltage of the power supply system. At the same time, it can also flexibly charge and discharge the battery pack, and improve the service life of the battery pack.

C. Gain Characteristic Analysis

Based on the analysis of the gain characteristics of LLC resonant converter by fundamental analysis method, the equivalent circuit of bidirectional LLC resonant converter is obtained as shown in Figure 3, where $V_{AB,FHA}$ and $V_{CD,FHA}$ is the fundamental component of the voltages at points A and B and points C and D, $R_{eq}=8n^2R_O$, R_O is the output load, converting the parameters of the secondary side of the transformer to the primary side of the transformer, where $L_{r2}'=n^2.L_{r2}$, $C_{r2}'=C_{r2}/n^2$.

Using the equivalent circuit diagram obtained by the fundamental analysis method to calculate the relationship between the output voltage V_2 and the input voltage V_1 of the converter, the transfer function $H(jw)$ of the equivalent circuit can be expressed as equation (1).

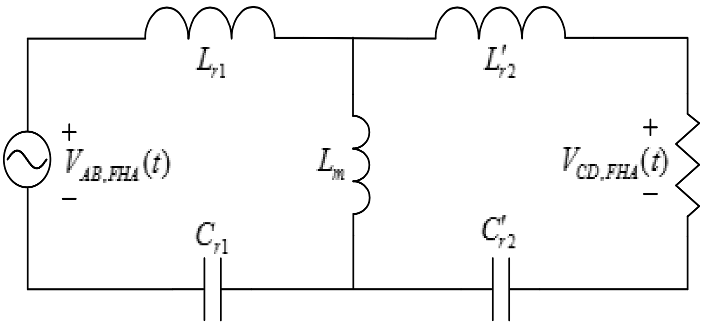

Figure 3: Equivalent Circuit Diagram of Bidirectional LLC Converter

$$H(jw)=\frac{nV_2}{V_1}=\frac{nV_{CD,FHA}(t)}{V_{AB,FHA}(t)}=\frac{jwL_m//(jwL_{r2}'+\frac{1}{jwC_{r2}'}+R_{eq})}{jwL_{r1}+\frac{1}{jwC_{r1}}+(jwL_m//(jwL_{r2}'+\frac{1}{jwC_{r2}'}+R_{eq}))}\cdot\frac{R_{eq}}{jwL_{r2}'+\frac{1}{jwC_{r2}'}+R_{eq}} \tag{1}$$

Where j is the imaginary unit, w is the switching angular frequency and $w=2\pi f$, f is the switching frequency.

The parameters of the secondary resonant element of the bidirectional LLC converter are equal to those of the primary resonant element. According to the above formula, the expression obtained is as shown in equation (2), where the ratio of the excitation inductance and the primary resonant inductance $k=L_m/L_{r1}$, the characteristic impedance $Z_r=\sqrt{L_r/C_r}$, and the quality factor $Q=Z_r/R_{eq}$.

$$M(f_n)=\frac{1}{\sqrt{(1+\frac{1}{k}-\frac{1}{kf_n^2})^2+(\frac{Q}{k})^2[f_n(2k+1)-\frac{1}{f_n}(2k+2)+\frac{1}{f_n^3}]^2}} \tag{2}$$

According to this, the expression of converter gain is obtained. Figure 4 shows the relationship between converter gain and frequency when Q is 0.3 and inductance ratio K changes; Figure 5 shows the gain curve under different Q when k=4.

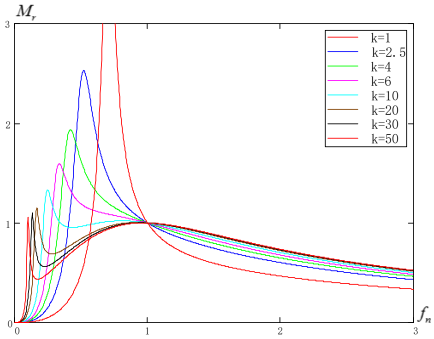

Figure 4: The Relationship between Normalized Resonance Frequency and Converter Gain under Different k Values (Q=0.3)

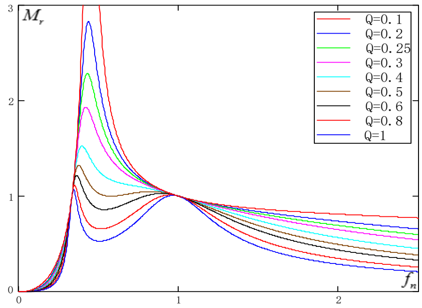

Figure 5: The Relationship between Normalized Resonance Frequency and Converter Gain under Different Q Values (k=4)

IV. Experimentation

According to the above analysis, a bidirectional LLC resonant converter is designed. Figure 6 shows the experimental waveform of the converter under forward full load operation at 100kHz. The figure shows the driving voltage v_{gs1} of Q_1, the drain source voltage v_{ds1} of Q_1, and the primary resonant inductance current i_{Lr1}. Figure 7 shows the experimental waveform of the converter under reverse full load operation at 100kHz. Where v_{gs5} is the driving waveform of the secondary side switch, v_{ds5} is the drain source voltage of the secondary side switch, and i_{lr2} is the secondary side resonant inductance current. The experimental results show that the converter can achieve good soft switching characteristics in the forward and reverse operation.

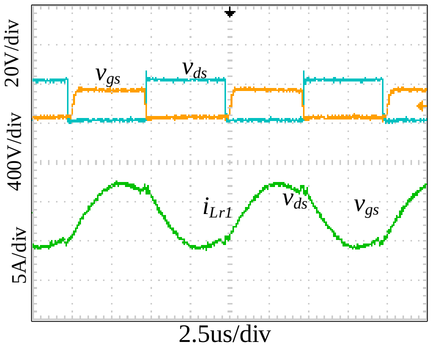

Figure 6: Full-load Operating Waveform at 100kHz Forward

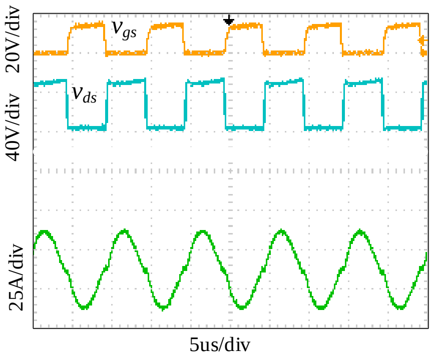

Figure 7: Full-load Operating Waveform at 100kHz Reverse

V. CONCLUSION

In this paper, a bidirectional LLC Resonant Converter Based on bidirectional DC/DC converter is proposed through the research of marine emergency power supply electric propulsion system. The converter is applied to the emergency power supply electric propulsion system, which not only realizes the soft switching performance of switches and rectifiers under wide input, high-low voltage conversion and load conditions, but also has the advantages of good controllability, wide soft switching range and high efficiency. In order to prove the above theoretical analysis, a 500W principle prototype was built, and its main parameters and waveforms were tested to verify the correctness of the above theoretical analysis and the feasibility in the application of ship emergency power supply electric propulsion system.

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