2023 4th International Conference on Mechatronics Technology and Intelligent Manufacturing (ICMTIM) | 979-8-3503-1443-4/23/$31.00 ©2023 IEEE | DOI: 10.1109/ICMTIM58873.2023.10246744

Development of bi-directional CLLLC resonant converter

Sen Wang
Department of Electrical and Control Engineering North China University of Technology Beijing, China
17862075307@163.com

***Abstract*—In order to promote the development of new energy and reduce the pollution caused by traditional fossil energy sources to the environment, bidirectional DC/DC converters, as the key link of energy conversion, are actively promoted in the fields of distributed energy, uninterruptible power supply systems and new energy storage systems. Among them, the bidirectional DC converter can achieve high efficiency power conversion and has a small switching tube voltage stress. In addition, the converter can realize high-power transmission, which can be widely used in the field of power electronics. In this paper, the bi-directional CLLLC resonant converter is studied in depth, and its circuit structure and operation principle are analyzed, and digital control technology is adopted to further improve the efficiency and accuracy of the converter, which will positively promote the development and application of bi-directional DC converter in the new energy field. In order to make the resonant converter operate stably, small-signal modeling of the converter is carried out, based on which the PI controller is designed and verified by forward and reverse closed-loop simulation, and a commutation control strategy based on the judgment of current and voltage magnitude is proposed.**

Keywords- Bidirectional CLLLC resonant converter; small-signal modeling; dual-loop control

I. INTRODUCTION

With the rapid development of science and technology, people's quality of life is growing, but at the same time also brings more environmental and energy problems. Power electronics technology will continue to develop at a high speed to achieve the purpose of energy saving, emission reduction and environmental protection. Among them, DC/DC converter is an important power electronic conversion device, which has been widely used in many industries such as aerospace and industrial automation to meet the requirements of various loads [1]. The bidirectional DC/DC converter is capable of forward and reverse power transfer and can replace two unidirectional DC/DC converters in applications where bidirectional energy flow is required. Thus, it can reduce the size and cost of the device while improving the reliability and stability of the system.

At the same time, the control strategy of bidirectional DC/DC converter has been gradually developed, shifting from traditional analog control to digital control, improving the accuracy and stability of the system. Using intelligent control algorithms, the control performance and adaptability of bidirectional DC/DC converters can be further improved to meet the needs of different occasions.

In order to reduce the switching losses of the DC/DC converter, several schemes are available. For the losses occurring in the switching loop, the existing zero-current switches can achieve zero-current turn-on at both the input and output, but their operating losses are large and poor at high input voltages.

LLC resonant technology has been widely used in unidirectional DC/DC converters, however, with the increasing requirements for bidirectional DC/DC converters, how to use LLC resonance to improve their performance is still under continuous research. Currently, there are two main approaches: traditional topology bidirectional LLC resonant converter and non-traditional topology bidirectional LLC resonant converter with additional components. The conventional topology bidirectional LLC resonant converter uses two LLC resonant circuits to realize the bidirectional flow of current by controlling the on and off of the switching tubes. This structure has the advantages of simplicity, reliability, low cost and high efficiency, but there are still certain switching losses and harmonic losses at high frequencies. In order to overcome these shortcomings, a non-traditional topology of bi-directional LLC resonant converter with added components was created. This converter structure adds resonant capacitors, resonant inductors, switching tubes and other components, which can achieve zero-voltage switching and lower switching losses in the full frequency band. In addition, the non-traditional structure can achieve higher voltage conversion ratio and higher output power. The converter based on CLLLC resonant technology has a wide application prospect in electric vehicle chargers, solar inverters, wind power generation systems, etc., but the appropriate topology and components need to be selected according to the specific requirements.

Various mature modulation strategies exist, and in the literature [2] an open-loop fixed-frequency control method is used to control the CLLLC resonant converter, which has the advantages of easy implementation and high efficiency and stability. In the literature [3], the method is improved on the basis of the control method of the CLLLC resonant converter, which effectively improves the efficiency of the converter under light load operation, and is experimentally verified. In the intermittent operation mode, the method employs a Bang-Bang charge control strategy, which is effective. To cope with applications requiring a wide voltage gain range, a multimodal control strategy including frequency control, phase shift control, and topology switching is proposed in the literature [4]. Specifically, full-bridge frequency modulation mode, full-bridge phase-shift mode, and half-bridge frequency modulation mode are used when the switching frequency is greater than, equal to, or less than the resonant frequency, respectively. Although this method is effective, it increases the control complexity of the converter, reduces its reliability, and increases the size and cost.

II. TOPOLOGICAL STRUCTURE

According to Figure 1, the main circuit topology of the bidirectional CLLLC resonant converter is completely symmetrical. The operation mode of this converter is divided into two categories according to two different ways: with excitation inductance and without excitation inductance. When the excitation inductance is introduced in the resonant tank, the resonant devices of the resonant tank are C_{r1}, L_{r1}, L_m. and when the excitation inductance is clamped, the resonant elements of the resonant tank are C_{r1}, L_{r1}. therefore, two resonant frequencies exist in this converter, the first resonant frequency and the second resonant frequency, respectively.

$$f_{r1} = \frac{1}{2\pi\sqrt{L_{r1}C_{r1}}} \tag{1}$$

$$f_{r2} = \frac{1}{2\pi\sqrt{(L_{r1}+L_m)C_{r1}}} \tag{2}$$

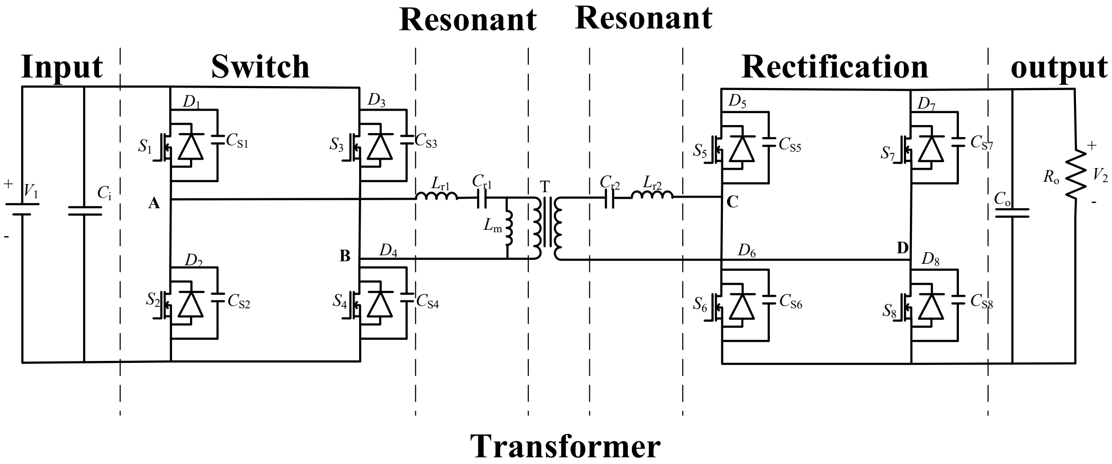

Figure 1. Bi-directional CLLLC resonant converter main circuit structure

From Figure 1, we can see that this converter is a symmetrical CLLLC resonant circuit, which can realize bidirectional power conversion. Set S_1-S_8 as the switching tubes in the circuit, C_{S1}-C_{S8} as the parasitic capacitance in the switching tubes, L_m, L_{r1}, L_{r2} as the excitation inductance and resonant inductance in the resonant circuit, C_{r1}, C_{r2} as the resonant capacitance in the resonant circuit, and n as the transformer ratio value. The left side of the main circuit is the DC bus and the right side is the load. In the forward operating mode, S_1-S_4 is on and S_5-S_8 is not operating, and in the reverse operating mode, S_5-S_8 is on and S_1-S_4 is not operating. This structure has the ability of ZVS turn-on and ZCS turn-off, which enables efficient power conversion.

III. CONTROLLER DESIGN

A. Small Signal Model

In DC/DC converters, the output voltage is dominated by the low frequency component of small signals. For this reason, it is necessary to perform small-signal modeling and analyze its control-output performance when performing controller design. Using the equivalent circuit modeling method, the system was modeled in small signal and studied in simulation. The small-signal analysis of the system allows for proper control of the system to provide better control. The small signal model of the converter is obtained by replacing the devices in the original position in the switching network, the energy storage devices in the resonant network and the energy storage devices in the rectifier network of the converter.

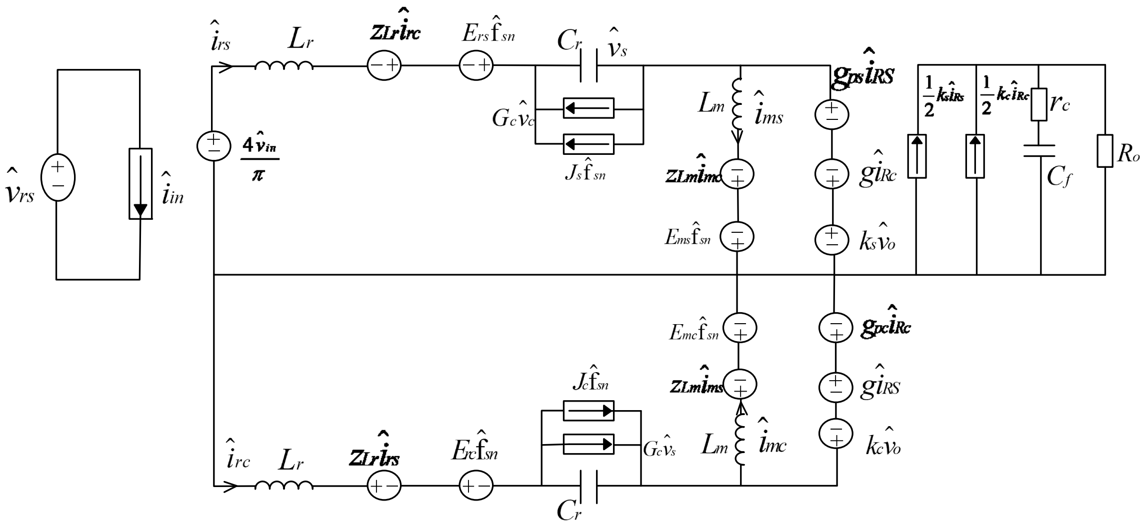

Figure 2. Bidirectional CLLLC resonant converter small signal equivalent circuit model

On this basis, the transfer function of the bidirectional CLLLC resonant converter can be obtained. The frequency-output relationship of the bidirectional CLLLC resonant converter is

$$G_{vw} = \frac{\hat{v}_o}{\hat{\omega}_s} = \frac{\left[\frac{V_{in}Q^2}{\omega_r}\left(\frac{\Omega_s}{\omega_r} - \frac{\omega_r^3}{\Omega_s^3}\right) - \frac{2\omega_r^2}{k\Omega_s^3}\left(1+\frac{1}{k}-\frac{\omega_r^2}{k\Omega_s^2}\right)\right]\left(1+r_cC_fs\right)}{\left[\left(1+\frac{1}{k}-\frac{\omega_r^2}{k\Omega_s^2}\right)^2 + \frac{Q^2\omega_r^2}{k\Omega_s^2}\left(\frac{\Omega_s^2}{\omega_r^2}-1\right)^2\right]^{3/2}\left(1+R_LC_fs\right)\left(1+\frac{s}{Q\Omega_s}+\frac{s^2}{\Omega_s^2}\right)} \tag{3}$$

The control frequency-resonant current function of the bidirectional CLLLC resonant converter is

$$G_{iw} = \frac{\hat{i}_r}{\hat{f}_{sn}} = C(sI-A)^{-1}B + D \tag{4}$$

The use of dual-loop control can improve the static and dynamic performance of the system, while also ensuring the reliability and safety of the system. This type of control is very common in practical applications and can be widely used in various electronic devices to improve the control accuracy and response speed of the system and reduce the cost and maintenance difficulty of the system. The control block diagram of this topic is shown in 3 Fig:

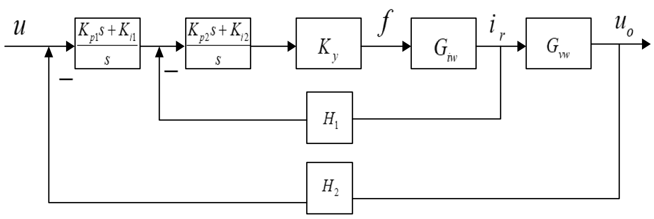

Figure 3. Bidirectional CLLLC resonant converter control block diagram

where G_{iw} represents the converter current control-output transfer function and G_{vw} represents the converter voltage control-output transfer function. K_y is the transfer function of V_{CO}, H_1, H_2 is the sampling circuit, the input is the voltage signal u, and the output is the frequency f of the switching tube.

From the above figure, we can obtain the inner loop transmission letter G_1

$$G_1 = \frac{\frac{k_{p2}s+k_{i2}}{s}k_yG_{iw}}{1+\frac{k_{p2}s+k_{i2}}{s}k_yG_{iw}H_1} \tag{5}$$

After calculating the appropriate inner loop pi parameters, they are then substituted into the outer loop to obtain the transfer function G_2

$$G_2 = \frac{\frac{k_{p1}s+k_{i1}}{s}G_1G_{vw}}{1+\frac{k_{p1}s+k_{i1}}{s}G_1G_{vw}H_2} \tag{6}$$

The outer loop pi parameter is obtained from G_2.

The system simulation parameters are substituted into the requested transfer function and a Bode plot analysis is performed.

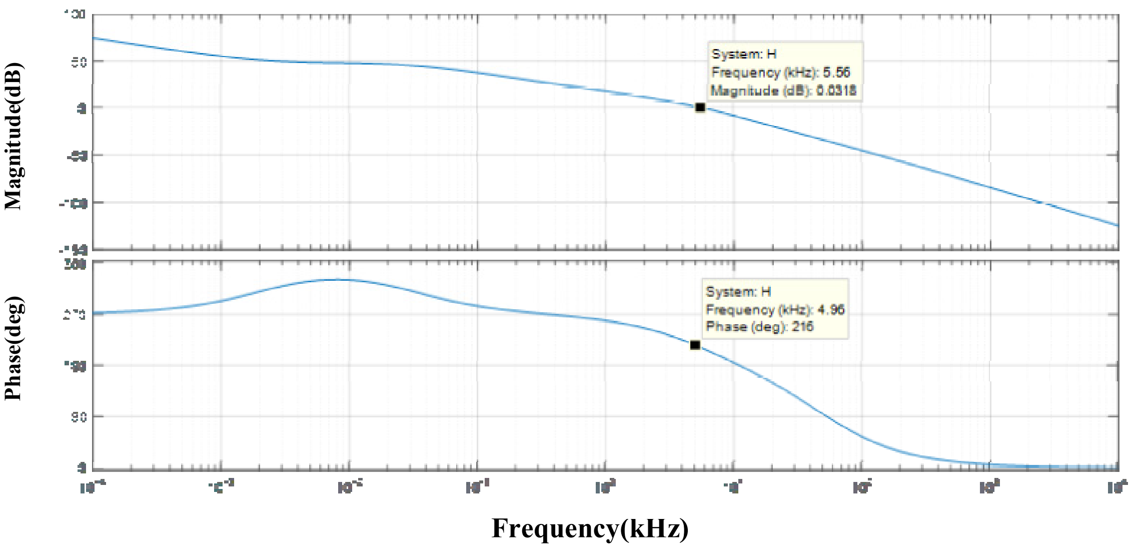

Figure 4. Control frequency-output Bode plot after adding PI regulation

Low frequency band open loop gain, small steady-state error, crossed by -20dB/dec, indicating good tracking ability of the input signal; medium frequency band slope is wide and slow, crossing frequency is about 1/20 of the switching frequency, good dynamic performance; high frequency band slope is large, low gain, enhance the system's ability to suppress high frequency disturbances. And the phase angle margin is greater than 35°, the system has good stability.

B. Bidirectional control strategy

In this paper, a new method of commutation using the low voltage side capacitor voltage hysteresis loop is proposed. Using the voltage information of the output capacitor without any external device, the power delivery direction can be switched smoothly. When the output current of the converter is greater or less than the set value, the output capacitor voltage changes accordingly. Using the method of detecting the voltage across the low-voltage side capacitor of the converter, the capacitor voltage information is then used as a basis to determine the operating state of the converter and thus to adjust the direction of power flow.

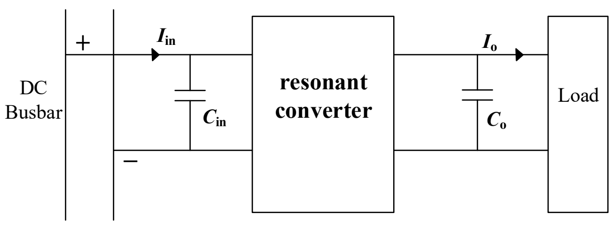

Figure 5. Energy flow diagram

Assuming that the converter initially works in forward mode, when the output current at the low-voltage side is lower than 0.8 times the rated output current at light load, its output capacitor voltage will rapidly increase until its output voltage bandwidth reaches the upper limit, at which point the converter's operation mode will change to reverse mode;

Similarly, assuming that the converter works in reverse mode at first, when the input current on the low side is greater than 1.2 times the rated input current at heavy load, the input capacitor voltage on the low side will drop rapidly until the capacitor voltage reaches the lower limit of the output voltage bandwidth, and then the converter's operating mode will be changed to forward mode. In this way, the operating mode can be judged by measuring the capacitance voltage at its low side.

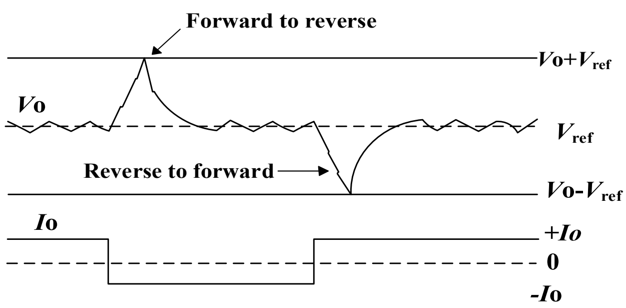

Figure 6. Voltage hysteresis waveform

The control method requires the setting of the voltage bandwidth on the low voltage side. Firstly, the bandwidth should provide sufficient margin for the low voltage side voltage to avoid misjudgment caused by reasonable voltage fluctuation. Secondly, it is also necessary to avoid the long switching time caused by too large bandwidth, which reduces the efficiency and affects the stable operation of the converter.

Considering the above issues, the voltage bandwidth of the low voltage side is taken to be 5% fluctuation around the rated voltage of the low voltage side.

In this paper, the control process of the commutation control strategy combining current and voltage is proposed. The control strategy takes the current size or the LV side capacitor voltage as the judgment basis to control the commutation work of the converter according to the size of the LV side current. When the low-voltage side current is between $0.8I_{on}$ and $1.2I_{on}$, the current magnitude is used to judge, which can control the commutation of the converter efficiently; when the low-voltage side current is not within this range, the low-voltage side capacitor voltage is used as the judgment basis, which avoids the problem that the current commutation strategy cannot control accurately. The combined use of both current and voltage information improves the accuracy and efficiency of commutation control.

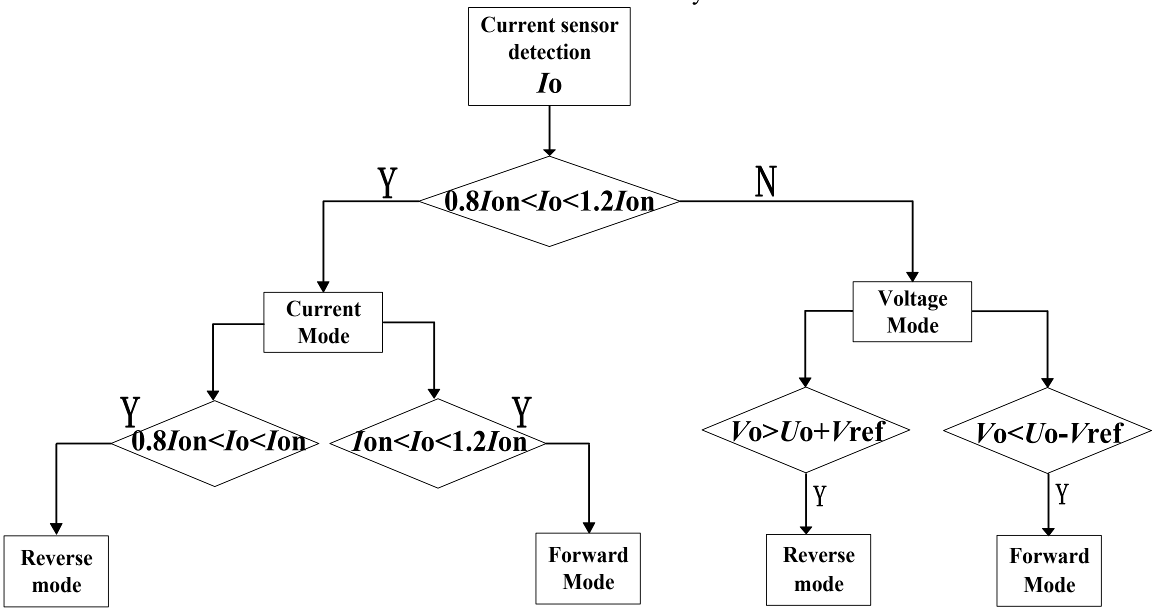

Figure 7. Commutation control strategy flow chart

IV. ANALYSIS OF SIMULATION

The forward and reverse simulation of the bidirectional CLLLC resonant converter is performed with Matlab software to verify the symmetry and consistency of the forward and reverse operation of the converter.

A. Forward Simulation

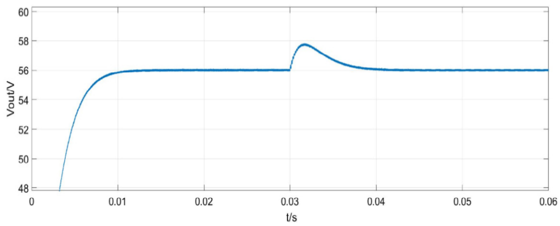

Figure 8. Forward closed-loop workload abrupt change

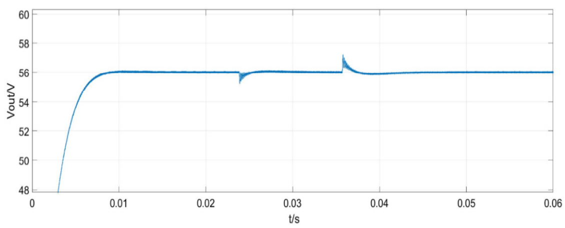

Figure 9. Sudden change in input voltage for positive closed-loop operation

Figure 8 shows the simulation waveform of the output voltage change when the converter switches from heavy load state to light load state at 0.03 seconds. It can be seen that the output voltage is stabilized at 56V after 0.01 seconds of regulation, and the closed-loop control is realized. Figure 9 shows that the input voltage drops at 0.024 seconds, and the output voltage immediately recovers to 56V through frequency regulation, and the input voltage raises at 0.036 seconds, and the output voltage immediately recovers to 56V after frequency regulation, realizing the closed-loop control.

B. Reverse Simulation

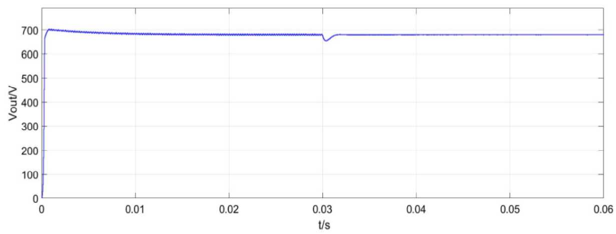

Figure 10. Reverse closed-loop workload abrupt change

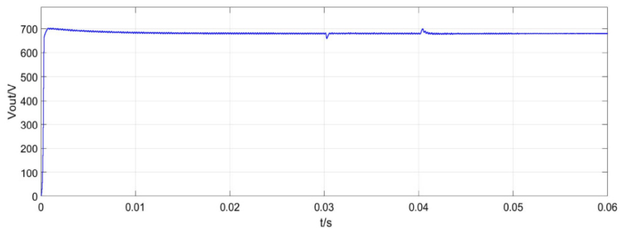

Figure 11. Reverse closed-loop operation with sudden changes in input voltage

Figure 10 shows the simulation waveform of the output voltage change when the converter switches from light load state to heavy load state at 0.03 seconds, it can be seen that the output voltage is stabilized at 680V after regulation, and the closed loop control is realized. Figure 11 shows that the input voltage drops at 0.03 seconds, and the output voltage is immediately restored to 680V by frequency regulation, and the input voltage is raised at 0.04 seconds, and the output voltage is immediately restored to 680V by frequency regulation to realize closed-loop control.

C. Bidirectional flow simulation

In order to verify the correctness of the principle of bidirectional power flow control, the following simulation waveform of commutation control is shown in Fig. 11. the total simulation time is 0.06s, at the beginning, the converter works forward with a current of 53A, and when t=0.033s, it is converted into the load to return energy to the bus with a current of -53A. it can be found that the simulation waveform is the same as the commutation principle in Fig. 6, when the output voltage touches the voltage When the output voltage touches the upper limit, the converter changes from the forward operating state to the reverse operating state. The correctness and feasibility of this control method are thus verified.

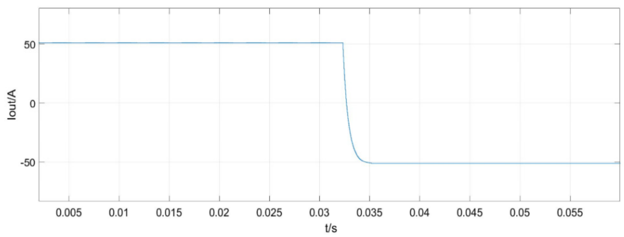

Figure 12. Inverter commutation operation simulation waveform

V. CONCLUSIONS

This paper presents an in-depth theoretical and technical analysis of a bidirectional DC/DC converter in the context of new energy technologies. Based on this structure, this paper carries out the analysis of the working principle of the converter based on this structure, the study of the control method, and the verification by Matlab simulation. The final results are as follows:

(1) For the bidirectional CLLLC resonant converter, the small-signal modeling is carried out to derive its output characteristics that change with the change of switching frequency, so as to realize the design of the PI controller of the converter, thus laying a theoretical foundation for the digital control of the converter.

(2) With the closed-loop simulation of the forward and reverse operating processes of the bidirectional CLLLC resonant converter, a regulation scheme for the bidirectional flow of converter energy is given and simulated to prove that the regulation scheme is feasible.

REFERENCES

[1] R Liu,C Q Lee. Analysis and design of LLC-type series resonant convertor[J]. **Electronics Letters**.2018, 24(24):1517-1519.

[2] Chen Qichao, Ji Yanchao, Wang Jianze. Analysis and design of bi-directional CLLLC resonant dc transformer[J]. **Chinese Journal of Electrical Engineering**, 2014, 34(18): 2898-2905.

[3] Chen Qichao. Research on some key issues of CLLLC resonant bidirectional DC-DC converter[D]. **Harbin Institute of Technology**, 2015.

[4] Huang Linghang. Research on multimodal control CLLLC resonant converter[D]. **Beijing Jiaotong University**, 2018

[5] H Park,M Kim,J Jung. Spread spectrum technique to reduce EMI emission for an LLC resonant converter using a hybrid modulation method[J]. **IEEE Transactions on Power Electronics**.2018, 33(5): 3717-3721.

[6] Y. Wei, Q. Luo and A. M a n t o o t h . O v e r v i e w of Modulation Strategies for LLC Resonant Converter[J]. **IEEE Transactions on Power Electronics**.2020,35(10):10423-10443.

[7] Jiang T, Zhang J, Wang Y. New control strategy for bidirectional LLC resonant converter in energy storage systems[C]. **Energy Conversion Congress and Exposition (ECCE)**, 2013 IEEE. IEEE, 2013: 27 -34.

[8] Yan X, Zhao H, Zhang Q, et al. An efficient isolated bi-directional half bridge resonant DC/DC converter[C]. **2012 IEEE Third International Conference on Sustainable Energy Technologies (ICSET). IEEE**, 2012: 48-53.

[9] Jiang T, Zhang J, Wu X, et al. A Bidirectional LLC Resonant Converter with Automatic Forward and Backward Mode Transition[J]. **IEEE Transactions on Power Electronics**.2015, 30(2): 757-770.

[10] W. Feng, F. C. Lee and P. Mattavelli. Optimal Trajectory Control of Burst Mode for LLC Resonant Converter[J]. **IEEE Transactions on Power Electronics**.2013,28(1): 457-466.

[11] W. Feng, F. C. Lee and P. Mattavelli. Simplified Optimal Trajectory Control (SOTC) for LLC Resonant Converters[J]. **IEEE Transactions on Power Electronics**.2013,28(5): 2415-2426.