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Comparative analysis of modulation strategies of bidirectional isolated AC-DC Matrix Converter

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Comparative analysis of modulation strategies of bidirectional isolated AC-DC Matrix Converter

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Abstract—Bidirectional isolated AC-DC matrix converter is a new topology which has potential advantages in many aspects. But the topology of bidirectional isolated AC-DC matrix converter is complex, the front and rear circuits are coupled and interact with each other, it is difficult to decouple it directly, and it is difficult to modulate. So it is necessary to study its modulation strategy. In this paper, several existing modulation strategies are analysed and compared from three aspects: switching process, current stress and transmission power, and a relatively optimal modulation strategy is obtained. The superiority and correctness of the modulation strategy are verified by simulation.

1. Introduction

With the increasing demand and consumption of electric energy, traditional non-renewable energy sources such as coal, oil and natural gas are becoming increasingly scarce. More and more people begin to pay attention to the use of cleaner renewable energy sources such as solar energy, wind energy and tidal energy for power generation. In order to ensure power grid stability and power supply reliability, power generation equipment must be equipped with energy storage system[1]. As the interface equipment between energy storage components and power grid, bi-directional energy storage converter is undoubtedly the most core and key link in the whole system. Its performance will affect the future development of many technologies such as electric vehicle and smart grid. Therefore, in-depth study of high-performance bidirectional energy storage converter has important theoretical significance and practical value. The performance of bidirectional energy storage converter usually has the following requirements[2]-[3]: ensure that the three-phase current on the grid side is sinusoidal, and the power factor is close to 1; keep the voltage and current on the DC side stable with small ripple; realize soft switching and low switching loss as far as possible to ensure high efficiency; compact structure and high power density.

Bi-directional isolated AC-DC matrix converter is a new topology derived from the traditional AC-AC matrix converter. It has the advantages of high power density, low current harmonic, small volume and lightweight. At the same time, it can realize the bi-directional flow of power and unit power factor. There is electrical isolation between the front and rear circuits with high safety, which has attracted the attention and favor of the majority of scientific researchers. Bidirectional isolated AC-DC matrix converter has good development prospects in many application fields, especially in the field of vehicle to grid (V2G) technology, which can be well used as a high-performance power converter. However, its topology is complex, and the front and rear circuits cannot be decoupled, so it is difficult to modulate directly. In this paper, a variety of modulation strategies for this topology are studied and compared, and a relatively optimal modulation strategy is analysed to optimize the performance of the converter.

2. Circuit topology and working principle

The circuit topology of the bidirectional isolated AC-DC matrix converter used in this paper is shown in Figure 1. The main five components are: network side filter, front stage matrix conversion circuit, high-frequency transformer, rear stage full bridge circuit and DC side output filter. The front stage device adopts SiC MOSFET and the rear stage device adopts GaN HEMT. Observing the circuit topology of bidirectional isolated AC-DC matrix converter, it can refer to the control idea of dual active bridge (DAB) converter[4] to simplify the equivalent form of series connection of left and right voltage sources and intermediate inductors. Where u_p is the high-frequency AC voltage generated by the front stage matrix circuit, u_s is the high-frequency AC voltage generated by the rear stage full bridge circuit, n is the transformer transformation ratio, L_S is the sum of the equivalent leakage inductance of the front stage series inductance and the high-frequency transformer. The two AC sources act on the middle equivalent inductance together, and the power can be adjusted by adjusting the phase difference of AC sources on both sides. As shown in equation (1), the current through the equivalent inductance L_S is i_L (t).

$$L_s \frac{di_L}{dt} = (u_p - nu_s) \tag{1}$$

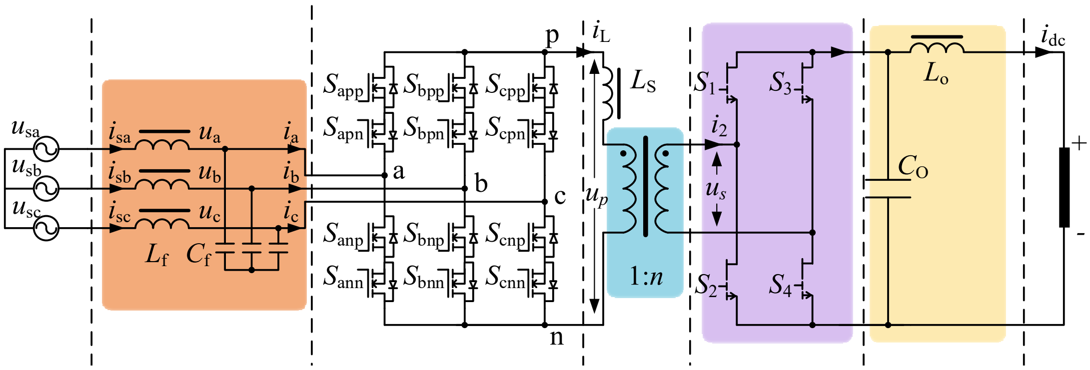


Fig.1 Bidirectional isolated AC-DC Matrix Converter Topology

Because the topology can be conducted in both directions, it can be divided into rectifier mode and inverter mode according to different energy transmission directions. When working in the rectification mode, energy is transferred from the network side to the load side through the bidirectional isolated AC-DC matrix converter, and the inductance current direction is from left to right; when working in the inverter mode, energy is transferred from the load side to the grid side, and the inductance current flows from right to left.

3. Comparative analysis of modulation strategies

Based on the above analysis of the working principle of bidirectional isolated AC-DC matrix converter, due to the particularity of the topology, the more reasonable modulation stratyge is that the front stage matrix converter circuit adopts two-wire voltage modulation[5], the rear stage full bridge circuit adopts segment complementary control[5], and the front and rear stages adopt phase-shifting control for coordination[6].

According to the above modulation ideas, many scholars have proposed a variety of modulation methods for bidirectional isolated AC-DC matrix converter, as shown in Fig. 2(a)~(f). Type A shown in Fig. 2(a) is the phase-shifting mode between the front and rear stages [4], which makes the switch of the rear stage circuit turn on after a certain time lag behind the front stage, that is, a phase-shifting angle is formed between the front and rear stages. Type B shown in Fig. 2(b) is the front stage single phase shift mode[5], and Type C shown in Fig. 2 (c) is the rear stage single phase shift mode[5], which is a layout mode formed by embedding a zero vector of a certain length of time into the front stage or rear stage circuit. Fig.2(d)~(f) shows the combination of two different phase-shifting modes. Type D is the arrangement mode formed by embedding the front and rear stages into zero vectors for a period of time.

Type E is the piecewise synchronous control based on zero vector embedding[6], the combination mode of embedding the front stage into zero vector and phase-shifting between the front and rear stages, and Type F is the combination of embedding zero vector and phase-shifting between the rear stages. Due to the addition of a phase-shifting angle, it makes the control more flexible.

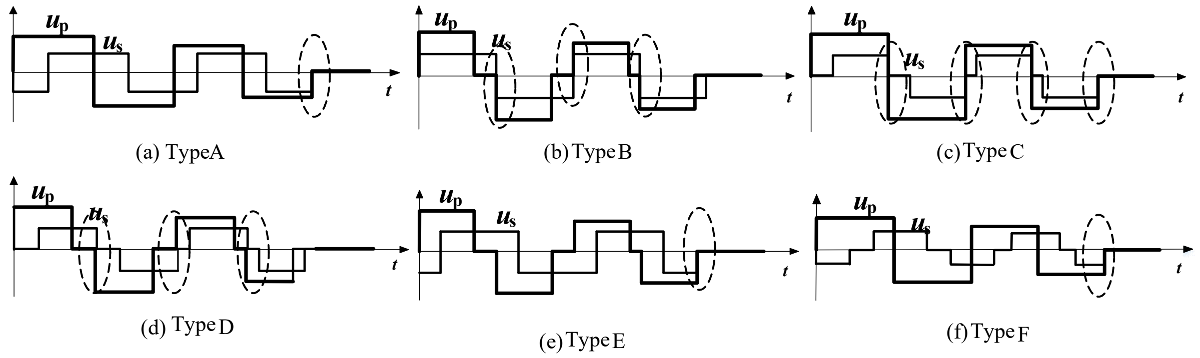


Fig.2 Voltage distribution of front and rear stages under six modulation strategies

Different combined phase-shifting modes and zero vector arrangement will lead to great differences in switching loss and input-output performance of the converter. Therefore, this paper compares the above six arrangement modes shown in Fig. 2 from three aspects: switching process, current stress and transmission power for further analysis and discussion.

3.1. Switching process analysis

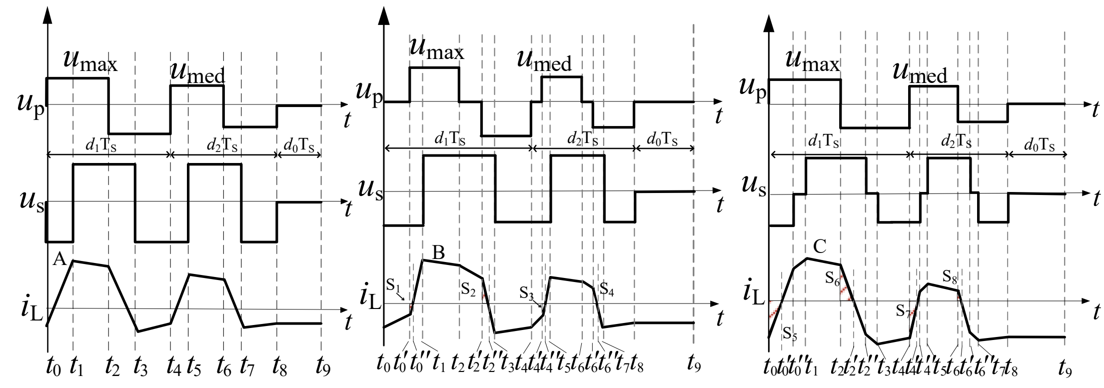
In the topology of bidirectional isolated AC-DC matrix converter, the front stage circuit adopts SiC MOSFET with extremely fast switching speed. In the closing process, most of the channel current is used to charge the parasitic capacitance and stored in the parasitic capacitance of the device, which can be reasonably used in the follow-up through reasonable control. Therefore, it can be considered that SiC MOSFET itself has zero voltage switching characteristics[7]. The post stage full bridge circuit adopts GaN HEMT device, which has many characteristics similar to MOSFET. Its static on resistance is smaller and its on state loss is lower. For GaN HEMT, the literature[8] describes in detail that its off loss itself is very small, which is only generated in the second stage of off, and is similar to the characteristics of MOSFET. Its parasitic capacitance can also store the energy of the device during off to a certain extent. Therefore, for its opening process, if the soft switching technology can be used to realize zero voltage opening, the overall loss will be very small and the system efficiency can be improved. The commutation conditions necessary to realize soft switching are obtained from literature [9]: when the rising edge of the front stage voltage u_p, the required inductance current i_L is less than 0; when the falling edge of the previous stage voltage u_p, the required inductance current i_L is more than 0; when the rising edge of the later stage voltage u_s, the required inductance current i_L is more than 0 and when the falling edge of the later stage voltage u_s, the required inductance current i_L is less than 0.

According to the ZVS realization conditions, at the same time, the inductance current required by the switching devices of the front and rear stage circuits to realize ZVS is in the opposite direction. When the rising edge or falling edge of the current rear stage voltage coincides, no matter what working state, all devices of the front and rear stage circuits can not realize ZVS at the same time, as shown in the dotted circle in Fig. 2(a)~(f), where the rising edge or falling edge of the front and rear stage voltage coincides, ZVS cannot be implemented at the same time. It can be seen that only one of the three modulation strategies A, E and F can not realize ZVS at one point, while the other three have multiple points, and the switching loss is relatively larger.

3.2. Current stress comparison

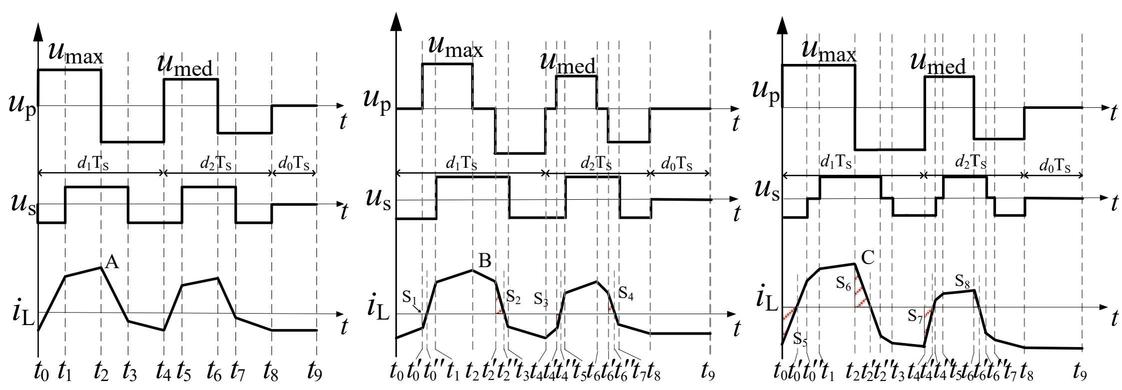
Taking the rectifier mode as an example, the inductance current peaks under three modulation strategies of Type A, E and F are compared. A control cycle T_S is divided into three parts: d_1T_S, d_2T_S and d_0T_S.

The action time period of d_1T_S is composed of the maximum line voltage with positive and negative symmetrical distribution and the embedded zero vector, the action time period of d_2T_S is composed of the secondary line voltage with positive and negative symmetrical distribution and the embedded zero vector, and d_0T_S is the action time of zero vector. u_{max} represents the maximum voltage amplitude in one cycle, and u_{med} represents the second largest voltage amplitude in a cycle. The distribution of inductive current in each time period can be determined according to the distribution mode of front and rear stage voltage and the equivalent circuit diagram, as shown in Figure 3. It can be seen from equation (1) that the external voltage will affect the slope of the inductive current, and then affect the peak value of the inductive current. A large current stress will increase the loss and reduce the service life of the switching device. Therefore, the peak value of the inductive current under different modulation methods is compared according to the different voltage of the front and rear stages.



(a) Type A (b) Type E (c) Type F

Fig.3 The voltage of the front stage is greater than that of the rear stage



(a) Type A (b) Type E (c) Type F

Fig.4 The voltage of the later stage is greater than that of the previous stage

According to the equivalent circuit of the converter and equation (1), the slope of the inductive current is directly proportional to the voltage difference at both ends of the transformer, that is, the greater the voltage difference, the faster the inductive current increases or decreases. It can be seen from the distribution of the voltage vectors of the front and rear stages shown in Fig. 3 and 4 that Type E embeds a zero vector in the voltage of the front stage, which slows the rise speed of the inductance current between t_0 and t_1 compared with Type A, so that the inductance current value at t_2 is smaller. Therefore, under the same voltage conditions, the value of point B is smaller than that of point A. Similarly, the inductance current peak of Type F is smaller than that of Type A. Under the same voltage conditions, the value of point C is smaller than that of point A. It can be seen that the current stress of

Type A is the largest, but for Type E and F, different results will be obtained under different voltage conditions, and the only conclusion cannot be obtained.

3.3. Transmission power comparison

Because the topology of bidirectional isolated AC-DC matrix converter has similar characteristics to double active bridge (DAB), it can be analysed by analogy. Taking the rectification mode as an example, due to the phase shift between the front and rear stage voltages, there is a phase opposite phase between the inductive current and the front stage voltage in the process of power transmission, such as t_0'~ t_0'', t_2'~ t_2'', t_4'~ t_4'' and t_6'~ t_6'' in Fig. 3 (b), (c) and Fig. 4 (b), (c). During this period, the direction of transmission power is opposite to the reference direction, making the power return to the power supply. Part of the literature on dual active bridge (DAB) defines this power as circulating or return power [10], which is represented by shaded parts in Fig. 3 (b), (c) and 4 (b), (c). Larger return power will lead to larger circulating current and current stress, which also increases the loss of power devices and magnetic components and reduces the efficiency of the converter.

To sum up, as shown in Fig.3 and Fig.4, when using Type E for modulation, the shadow area under the same conditions of any working condition is significantly smaller than that of Type F, indicating that the return power of Type E is smaller, the loss of converter is relatively lower and the modulation effect is better under this modulation strategy.

4. Simulation results

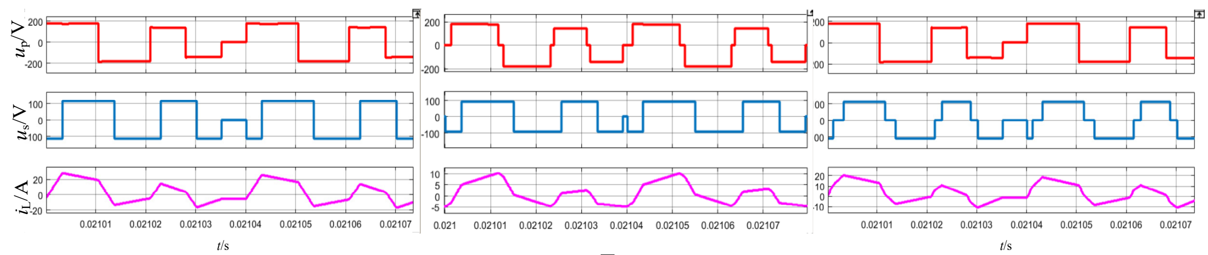
In order to verify the correctness of the theory deduced and analysed, relevant simulation verification is carried out in this paper. The simulation model of bidirectional isolated AC-DC matrix converter is built by using MATLAB / Simulink. The electrical parameters of the main circuit are shown in table 1.

Table 1 Simulated electrical parameters of main circuit

parameter	value	parameter	value
L_f/μH	200	n	85 : 64
C_f/μF	4	L_o/μH	10
L_s/μH	87	C_o/μF	24

4.1. Rectification mode

When the converter works in the rectification mode, the energy is transmitted from the AC side to the DC side. The setting: three-phase AC input phase voltage u_i = 110V, post stage DC power supply voltage u_o = 100v, control frequency 25kHz. The figure shows the simulation results of front and rear stage voltage and inductance current waveforms under three modulation strategies in rectifier mode.



(a) Type A (b) Type E (c) Type F

Fig.5 Waveforms of front and rear stage voltage and inductance current of three modulation strategies in rectifier mode

As shown in Figure 5, by comparing the waveforms of front and rear stage voltage and inductance current under the three modulation strategies, it can be seen that Type E has obvious advantages in soft switching range, current stress and transmission power in rectification mode, which verifies the theoretical derivation.

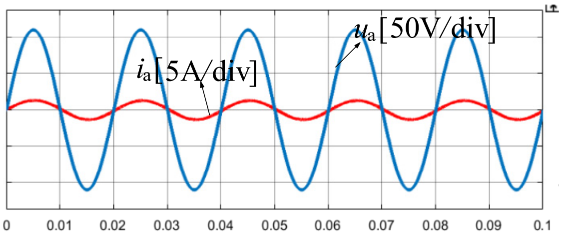
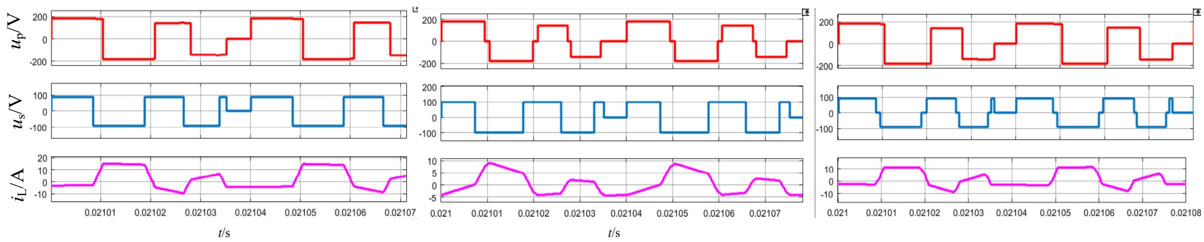


Fig.6 Phase A voltage and current waveform at grid side

As shown in Figure 6, the phase a voltage and current on the grid side under Type E, and the input current and voltage on the grid side have the same phase.

4.2. Inverter mode

When the converter works in the inverter mode, the energy is transmitted from the DC side to the AC side. The setting: three-phase AC input phase voltage u_i = 110V, post stage DC power supply voltage u_o = 100v, control frequency 25kHz. The figure shows the simulation results of three kinds of inverter mode.



(a) Type A (b) Type E (c) Type F

Fig.7 Waveforms of front and rear stage voltage and inductance current of three modulation strategies in inverter mode

As shown in Fig.7, comparing the waveforms of front and rear stage voltage and inductance current under the three modulation strategies, it can be seen that Type E has obvious advantages in soft switching range, current stress and transmission power under the inverter mode, which verifies the theoretical derivation.

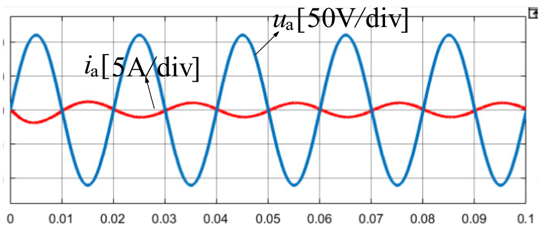


Fig.8 Phase A voltage and current waveform at grid side

As shown in Fig.8, the phase a voltage and current on the grid side under Type e, and the input current and voltage on the grid side have opposite phases.

5. Conclusion

Bidirectional isolated AC-DC matrix converter is considered to be a promising topology in AC-DC applications because of its advantages such as high power density, low current harmonic, small volume, light weight, bidirectional power flow, unit power factor and so on. In this paper, a variety of modulation schemes used in this topology are studied, analyzed and compared. Based on the theoretical analysis and simulation results, it is concluded that Type E has more advantages in current stress, return power and soft switching degree than other modulation strategies under the same conditions. Under this modulation strategy, the loss of the converter is relatively low and the modulation effect is better.

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