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A Simplified-ISOP-CLLLC Converter with Wide Voltage Gain for Auxiliary Power Supply Systems of Urban Rail Vehicles

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Abstract

An input-series-output-parallel (ISOP) CLLLC bi-directional converter with a reduced number of switches is proposed for the auxiliary power supply system of urban rail transit vehicles. Unlike the conventional ISOP structure, the two transformer outputs on the secondary side is in parallel, connected to one resonant tank and one synchronous rectifier circuit. A novel control strategy is proposed to realize zero voltage switching (ZVS) for all switches. A novel control strategy is proposed to realize wide voltage gain, adapted to the fluctuation of DC bus. The principle of operation during forward power operation is analyzed and soft switching is analyzed taking into account the junction capacitance of all switches. A 40kW simulation prototype is built to verify the effectiveness of the proposed solution. The simulation results prove the correctness of the converter with the proposed control strategy and show that it is capable of achieving ZVS turn-on at full load and light load.

1 Introduction

In order to reduce global carbon emissions, saving electricity used in urban rail vehicles is urgently needed. The electricity consumption of air-conditioning auxiliary power supply system in urban rail vehicles accounts for a major part of the total energy consumption[1]. Optimizing the mode of the power supply system, by reducing the energy conversion links and improving the efficiency of the converters, can save important means of electric energy in urban rail vehicles. Due to the excessive conversion links, changing the AC power supply system to the DC power supply system achieves higher efficiency. In addition, the use of the new generation of power semiconductor devices can significantly improve the efficiency of the system. SiC MOSFET has lower conduction loss because of the lower R_{dson}. SiC MOSFET can also reduce the size and quality of the core element because of the higher switching frequency[2].

A new DC system is proposed,which a medium-voltage battery is connected to the 650V DC bus to provide energy when the 1500V DC bus is in emergency, as it's shown in Fig.1. The selection of bidirectional isolated converter should meet the high efficiency and the ability to adapt the high voltage of the primary side.

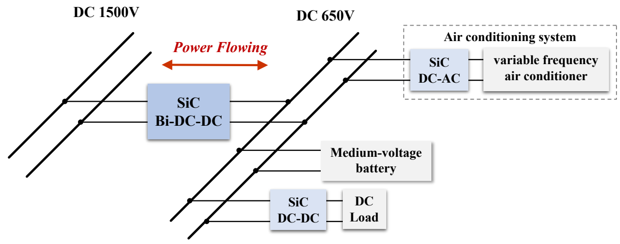

Fig. 1: The proposed DC power supply system structure for urban rail vehicles with SiC MOSFET.

In the context of moving towards high-frequency light weighting, soft-switching technology is an important means of achieving overall efficiency improvements. The use of efficient converter circuits and control methods is more helpful to maximize the realization of small and lightweight design. A common bidirectional isolated DC-DC converter that can realize soft switching by relying on its own operating characteristics. In [3]uses a phase-shifted full-bridge topology to power a 110V bus with an 8% efficiency improvement in a single-stage DC-DC converter. However, phase shifted full bridge circuits are gradually not adopted due to their disadvantages such as loss of duty cycle and small soft switching implementation range. Dual Active Bridge (DAB) and CLLLC resonant converters are gradually becoming more readily adopted today. Both of these converters can inherently realize soft switching, but each has its own advantages and disadvantages when used[4]. DAB are often used in

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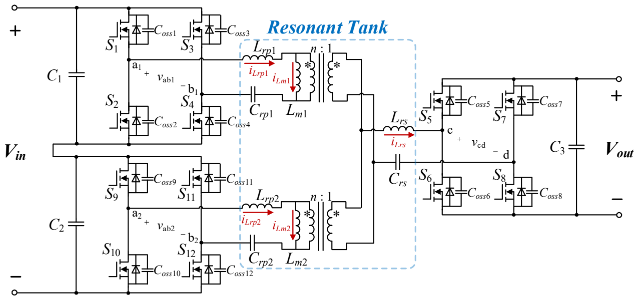

Fig. 2: Circuit topology of Simplified-ISOP-CLLLC.

the engineering use of a single phase-shift strategy, this control strategy under the DAB converter can achieve a large gain range, but the zero-voltage turn-on range of the primary and secondary edges is limited, and in the light-load situation can not realize the zero-voltage turn-on of the primary and secondary edges at the same time; In addition, the current at the primary side of the switches turn-off DAB converter is at the peak of the inductance current, the turn-off current is large, the turn-off loss is large and brings serious electromagnetic interference (EMI) problems. The CLLLC resonant converter is able to realize the zero-voltage turn-on of the full-range primary switch and the zero-current turn-off of the secondary switch under the premise of reasonable design. From the above analysis, it can be seen that the CLLLC resonant bidirectional converter has a better efficiency advantage when the gain range can be satisfied.

The current methods to improve the voltage stress are input-series output-parallel (ISOP), multi-electrode and other techniques, among them, ISOP is more widely used because of its structural stability, simplicity of control, and the ability to interleave control to achieve smaller ripple. In [5], a new topology is proposed, which simplifies the ISOP DAB-LLC parallel connection and suggests that the multiplexing of the secondary synchronous rectifier bridge can make the current output from the secondary side of the transformer larger and help the secondary switches turn on more easily with zero voltage. However, the article targets the combination of LLC and DAB, which is not easy to control and is of little significance for engineering guidance. However, its method of simplifying the number of switches can be taken.

Accordingly, in this paper, the ISOP-CLLLC is based on changing the point of parallelism, combining the use of the secondary devices, and reducing the overall number of switches and the number of devices. The proposed converter, i.e. Simplified-ISOP-CLLLC is obtained as shown in Fig.2. This converter sets the shunt point at the output of the transformer's secondary winding, which is then given to a resonant tank connected to the synchronous rectifier bridge. Since the energy of the two resonant tank on the primary side is converged to one resonant tank on the secondary side, it makes the secondary full bridge switches easier to realize zero voltage switching-on (ZVS-on), which is more loss-reducing for high-current rectifier tubes.

Facing the need of 1500V to 650V bidirectional current conversion, a novel all-switches ZVS-on topology with reduced number of switches, i.e. Simplified-ISOP-CLLLC is proposed for the air conditioning auxiliary DC power supply system in urban rail vehicles, which enables voltage conversion from 1500V to 650V. In this paper, the operation of the proposed converter in forward operation is analyzed, and the novel improved control strategy for realizing ZVS-on of the secondary switches is analyzed. On the basis of the above analysis, the principle verification of the proposed converter is carried out using PSIM software with rated power of 40 kW, which proves that this converter can realize bidirectional power flow and all switches can realize ZVS-on, and the feasibility and advantages of the proposed converter are proved.

2 Simplified-ISOP-CLLLC Converter with proposed control strategy

The Simplified-ISOP-CLLLC has two full bridges in series on the primary side, passing through the resonant tank and transformer of the primary, the outputs are paralleled at the secondary side of the transformer, and the currents are summed up to the secondary resonant tank and connected to one synchronous rectifier bridge, as shown in Fig.2.

The following assumptions are made before the analysis:

– *all the switches and body diodes, inductors, capacitors and other passive devices are ideal devices;*

– *the oscillation caused by the C_{oss} of the switches is ignored during the dead time;*

– *the primary and secondary dc side filtering capacitance is infinite.*

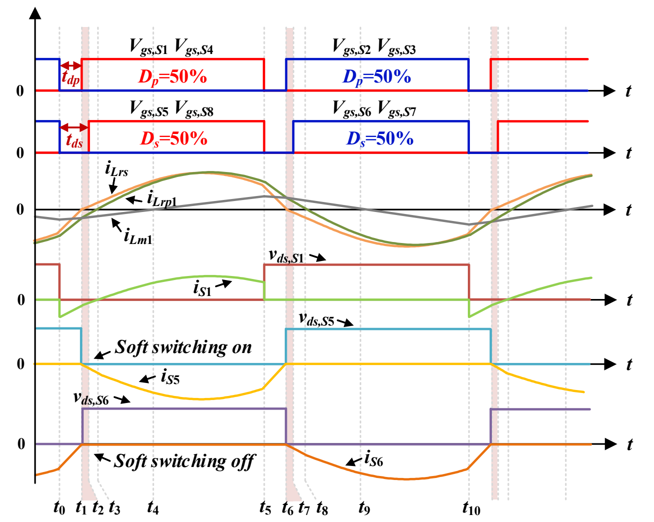

Fig. 3: Key waveforms of Simplified-ISOP-CLLLC in forward operation with the proposed improved control strategy.

The switches on the primary side are $S_1 \sim S_4$, $S_9 \sim S_{12}$, and the switches on the secondary side are $S_5 \sim S_8$. The output capacitor of the switches are $C_{oss1} \sim C_{oss12}$. The resonant tank consists of two resonant inductors and capcitors on the primary side, and one resonant inductor and capcitor on the secondary side. The primary resonant current are i_{Lrp1} and i_{Lrp2}, the magnetizing current are i_{Lm1} and i_{Lm2}. The secondary resonant current is i_{Lrs}. The positive directions of i_{Lrp1}, i_{Lrp2}, i_{Lm1}, i_{Lm2} and i_{Lrs} are shown in Fig.2. The two transformers are ideal transforemer, which the magnetizing inductors are L_{m1} and L_{m1}. The turns ratio of the transformers are both n:1. The Simplified-ISOP-CLLLC uses the pulse frequency modulation (PFM) control strategy, where the switches on the secondary side are driven in synchronization with the primary side. The power and the voltage gain of the converter can changed by the switching frequency, f_s.The key waveforms of Simplified-ISOP-CLLLC in forward operation is shown in Fig.3. When the converter works in the forward direction, the duty cycle of the transformer switches on the primary side is 50%, the switches on the secondary side driving signal is synchronized with the switches on the primary side, the switch S_1 and S_4 conduct synchronously, the switches S_2 and S_3 conduct synchronously, and the switches of the different bridge arm have the same dead time, as shown in Fig.3. When the converter works in the backward direction, the duty cycle of the transformer's switches on the secondary side is 50%, the two switches on the primary side signals are synchronized with

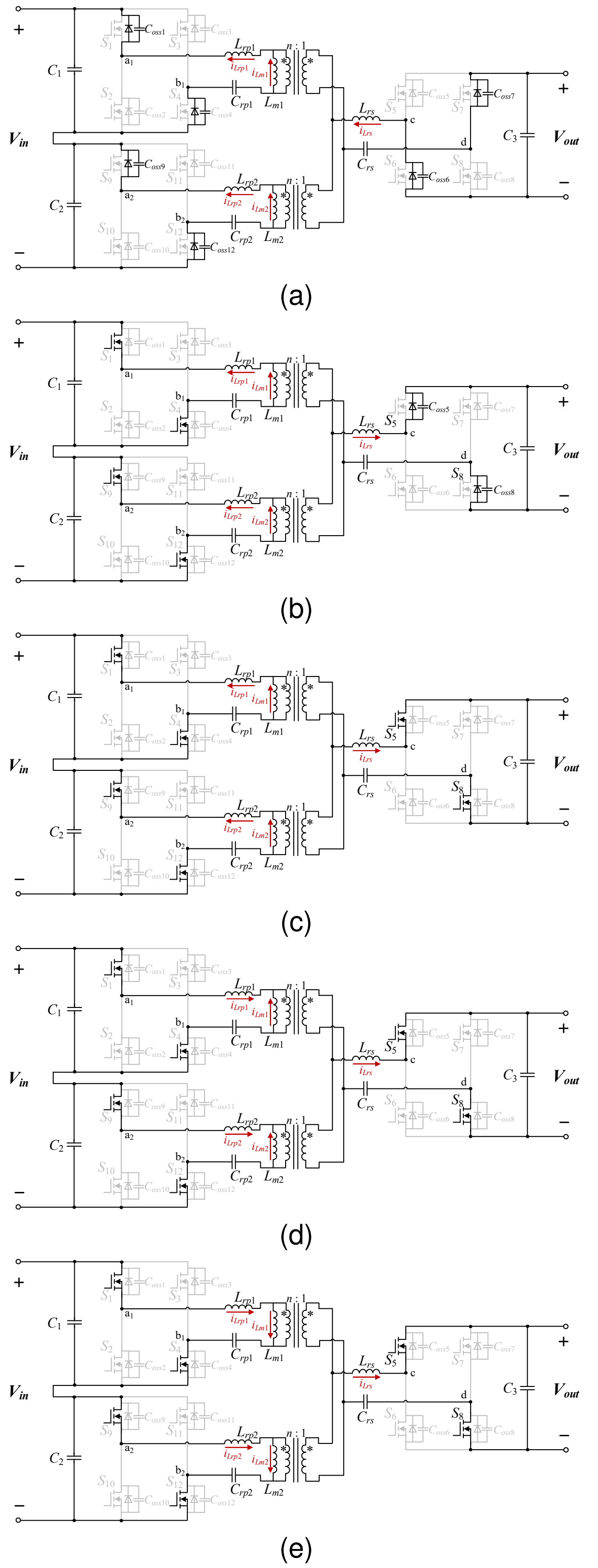

Fig. 4: Operating equivalent circuit with the proposed improved control strategy in forward operation.(a)Stage 1.(b)Stage 2.

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the switches on the secondary side, the switches S_5 and S_8 conduct synchronously, the switches S_6 and S_7 conduct synchronously, and the switches of the same bridge arm conduct in a complementary manner.

The following assumptions are made before the analysis:all the switches and body diodes, inductors, capacitors and other passive devices are ideal devices; the oscillation caused by the C_{oss} of the switches is ignored during the dead time; the primary and secondary dc side filtering capacitance is infinite.

When the converter power operates in the forward operation, there are 5 operating modes in half a cycle in this case, the equivalent circuit of each state are shown in Fig.4(a)∼(e).

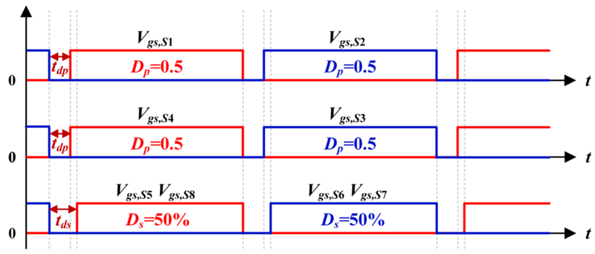
Stage **1 (*t_0*, *t_1*):** as shown in Fig.4(a), this period is the dead time of the converter, all switches are turned off. During this period, i_{Lrp1}, i_{Lrs1}, i_{Lm1} is opposite to the reference direction and gradually decreases.Taking one of the primary full bridge as example, because i_{Lrp1} is opposite to the reference direction, i_{Lrp1} flows through the body diode of S_1 and S_4, which cause C_{oss1} and C_{oss4} are both discharged. $V_{ds,S1}$ and $V_{ds,S4}$ are zero, which provides conditions for S_1 and S_4 to implement ZVS-on. On the secondary side, i_{Lrs} is opposite to the reference direction, and i_{Lrs} flows through the body diode of S_6 and S_7, which makes C_{oss6} and C_{oss7} discharged.

Stage **2 (*t_1*, *t_2*):**as shown in Fig.4(b), during this period, i_{Lrp1} is opposite to the reference direction and gradually decreases, i_{Lrs1} is the same as the reference direction and gradually increases from zero, i_{Lm1} is opposite to the reference direction and gradually decreases. S_1, S_4 turn on at t_1, i_{Lrp1} flows through S_1 and S_4. S_1 and S_4 achieve ZVS-on. During this period, S_5 and S_8 is still turned off, i_{Lrs} flows through the body diode of S_5 and S_8, which cause C_{oss5} and C_{oss8} are both discharged. $V_{ds,S5}$ and $V_{ds,S8}$ are zero, which provides conditions for S_1 and S_4 to implement ZVS-on.

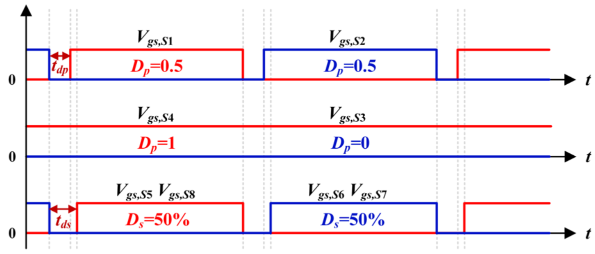
Stage **3 (*t_2*, *t_3*):** as shown in Fig.4(c), during this period, i_{Lrp1} is opposite to the reference direction and gradually decreases to zero, i_{Lrp1} flows through the S_1 and S_4. i_{Lrs} is the same as reference direction and increases gradually. i_{Lm1} is opposite to the reference direction and decreases. At t_2, S_5 and S_8 turn on, and achieve ZVS-on. i_{Lrs} is same as the reference direction, the power is flow to the load side.

Stage **4 (*t_3*, *t_4*):** as shown in Fig.4(d), ZVS-on of the primary side and secondary have both realized, and the current is flowing to the load side. During this period, i_{Lrp1} and i_{Lrs} is the same as the reference direction and increases gradually. i_{Lm1} is opposite to the reference direction and gradually decreases until t_4 decreases to zero.

Stage **5 (*t_4*, *t_5*):**as shown in Fig.4(e), i_{Lm1} is the same as the reference direction and gradually increases from zero. The converter is delivering energy to the load side.



(a)



(b)

Fig. 5: Operating equivalent circuit with the proposed improved control strategy in forward operation.(a)Stage 1.(b)Stage 2.

3 An Improved Control strategy of Simplified-ISOP-CLLLLC for wide voltage gain

Since the conventional control strategy leads to hard turning-on and turn-off of the switches on the secondary of the Simplified-ISOP-CLLLC, this paper proposes an improved control strategy to realize ZVS-on of the switches on the secondary side, which will not affect the ZVS-on of the switches on the primary side.The improved control strategy of Simplified-ISOP-CLLLC uses a PFM control strategy. The switches on the secondary side are still driven in synchronization with the primary side, but with the different dead time. The key waveforms of Simplified-ISOP-CLLLC in forward operation is shown in Fig.5.

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Tab. 1: Simulation parameters

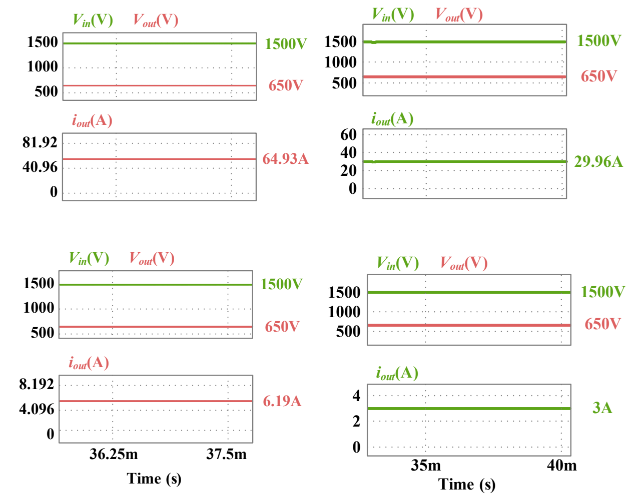
Parameter	Variable	Value
Rated output power	P_{out}	40kW
Input DC voltage	V_{in}	1500V
Output DC voltage	V_{out}	650V
Resonant inductor (primary side)	L_{rp1}	19.32μH
Resonant capacitor (primary side)	C_{rp1}	58.28μF
Resonant inductor (secondary side)	L_{rs}	14.51μH
Resonant capacitor (secondary side)	C_{rs}	77.59μF
Magnetizing inductor	L_{m1}	30.9μH
turns ratio	n	1.15:1
Switching frequency	f_s	150kHz
Resonant frequency	f_r	146kHz
Dead time (primary side)	t_{dp}	200ns
Dead time (secondary side)	t_{ds}	300ns

4 Simulation Results

Simulation of the Simplified-ISOP-CLLLC in both forward and backward operation is build in PSIM software considering values in Table1.The simulation assumes identical circuit parameters for the two full bridges and resonant tanks on the primary side. The analysis of both forward and backward simulation results reveals that the converter's operational modes, voltage gain and ZVS-on features, align with theoretical predictions. The symmetry remains intact in both forward and backward scenarios.The improved control strategy is proved, and the detailed waveforms in full load in forward operation are as shown in Fig.6 (a) and (b).

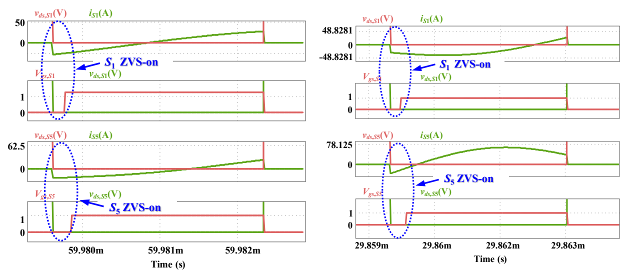
The simulation results of both forward and backward operation reveals that the converter's operational modes, voltage gain and ZVS-on features align with theoretical analysis. The symmetry remains intact in both forward and backward scenarios. With 1500V as input voltage and 650V as output voltage, the proposed converter is capable of achieving the necessary voltage conversion in bidirectional power flow in full load (40kW) and light load (4kW), as shown in Fig.7 (a) and (b).(a)The input voltage is 1500V and the output voltage is 650V. (b)The input voltage is 1950V and the output voltage is 450V.

In Fig.7 (a), the converter's simulation waveforms in full load with conventional control strategy in forward operation are displayed. As is shown, i_{S5} and $v_{ds,S5}$ is overlapping when is S_5 turns on, which shows that the switches in the secondary side with conventional control strategy cannot realize ZVS-on. The simulation results about the hard switching of the switches of the secondary side are consistent



(a) (b)

Fig. 6: ZVS-on of Simplified-ISOP-CLLLC with full load in forward operation.



(a) (b)

Fig. 7: ZVS-on of Simplified-ISOP-CLLLC with full load in forward operation.

with the analysis in Section II.

As a comparison, the simulation results in full load with the proposed improved control strategy in forward operation are shown in Fig.7 (b). As is shown, i_{S5} and $v_{ds,S5}$ is non-overlapping when is S_5 turns on, which shows that the switches in the secondary side with the proposed improved control strategy realize ZVS-on. The simulation results about the hard switching of the switches of the secondary side are consistent with the analysis in Section III.

The detailed waveforms of the ZVS-on state of the primary and the secondary switches are shown in Fig.8 (a), when the converter is operating in the forward operation in light load. The detailed waveforms of the ZVS-on state of the primary and the secondary switches are shown in Fig.8 (a) and (b), when the converter is operating in the backward operation with the full load and light load.

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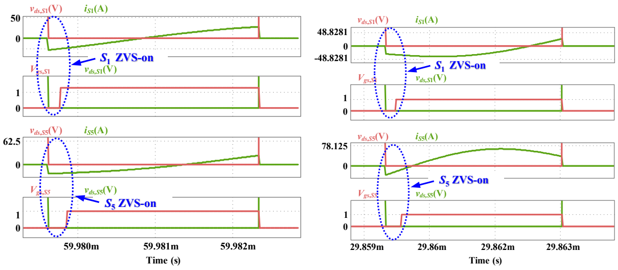

(a) (b)

Fig. 8: ZVS-on of Simplified-ISOP-CLLLC with light load in forward operation.

5 Conclusion

Based on the bidirectional power conversion from 1500V to 650V in the DC power supply system assisted by air conditioning in urban rail vehicles, this paper compares the advantages and disadvantages of different isolated DC-DC converters, analyzes the characteristics of the converter structure adapted to high voltage stress. A new Simplified-ISOP-CLLLC bidirectional converter with a novel control strategy is proposed, which has two advantages: simplifying the number of MOSFET and helping the secondary switches to realize ZVS-on. The simulation results prove the feasibility of Simplified-ISOP-CLLLC, and demonstrate the ZVS-on of the primary side and the secondary side.

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