

Active Power Filter for Single-Phase Quasi-Z-Source Integrated On-Board Charger

Tuopu Na, Qianfan Zhang, Jiaqi Tang, and Jinxin Wang

Abstract—Single-phase quasi-Z-source rectifiers have second harmonic currents and corresponding ripple voltages on the dc bus. To filter the voltage ripple, bulky capacitor bank is needed. This paper proposed an active power filter (APF) for single-phase quasi-Z-source rectifier. It eliminated the second harmonic power with small capacitor and inductor. This topology is suitable for integrated electric vehicle (EV) on-board charger, which can use EV's inverter hardware as its own rectifier hardware. Thus, this proposed topology can save much space and weight. Simulation and experimental results verified the proposed system.

Index Terms—Active power filter, integrated charger, quasi-Z-source, single-phase rectifier.

I. INTRODUCTION

ELECTRICAL vehicles (EVs) have been widely used recently. The charger of EVs plays an important role in EVs system. An onboard charger makes it convenient for customers to charge. Thus, an onboard charger is necessary for EVs. An integrated onboard charger is proposed in [1]. The integrated charger and the EV's traction system share the hardware including three IGBT bridges, circuits and sensors. Besides, the integrated charger uses motor windings as filter inductor. The integrated charger costs less and takes less space. The quasi-Z-source network is suitable for single-phase integrated charger because it can realize bi-directional power flowing.

Since single-phase PWM rectifier has dc-side second harmonic current, it needs not only larger dc-side capacitor but also larger quasi-Z-source inductor and capacitor to suppress ripple. These inductors and capacitors will increase the charger's weight and take much space. And the dc-side second frequency ripple will reduce the battery life. So it is necessary to eliminate second frequency ripple. Many APFs [2]-[10] have been proposed to solve the problems for traditional single-phase converters. APF uses auxiliary circuit to convert the ripple power from the dc link to other energy storage components. [10] uses an inductor as energy storage, which includes one bridge circuit and one inductor. [6] also uses inductor as energy storage. In this system, a third IGBT bridge is added and one inductor is used which cost much. Capacitor is also can be used as energy storage for APF. [9] proposed a topology which adds a third IGBT bridge, a capacitor and an inductor. Two capacitors are used as energy storage in [8]. These APFs are suitable for single-phase

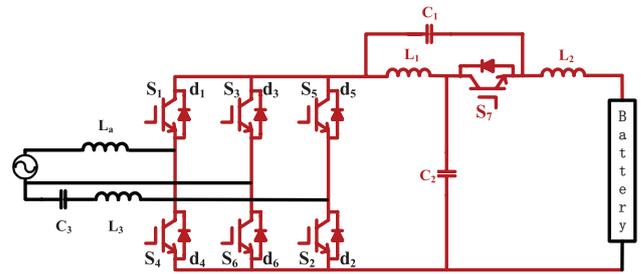


Fig. 1. The topology of single phase quasi-Z-source integrated charger with APF control.

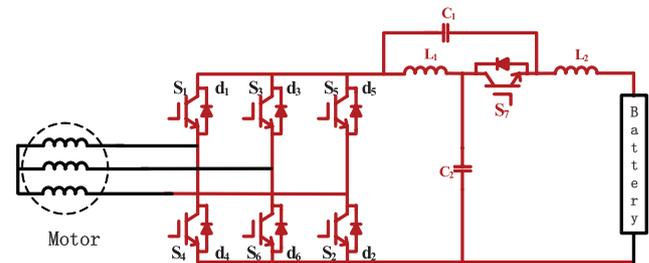


Fig. 2. The topology of EV traction system.

PWM rectifier, and some methods have been proposed to solve the second harmonic current in single-phase z-source inverters [11]-[13].

However, there is not a method proposed for single-phase z-source PWM rectifier. In this paper, a topology is proposed for eliminating the second harmonic current of the system, as shown in Fig. 1. And this topology is suitable for single-phase EV on-board integrated charger. The proposed topology uses extra IGBT S5 and IGBT S2 to control C3 and L3 to absorb the second harmonic power. The traction system of one electric vehicle is shown in Fig. 2. So the proposed APF single-phase z-source rectifier can use three IGBT bridges and the quasi-Z-source network to eliminate the second harmonic. The red topologies in Fig. 1 and Fig. 2 share the hardware including three IGBT bridges, quasi-Z-source network and control circuits. The integrated single-phase on-board charger saves much space, costs less and reduces weight.

II. PROPOSED APF SINGLE-PHASE QUASI-Z-SOURCE RECTIFIER

A. Existing Problem Analysis

The topology of traditional single-phase quasi-z-source rectifier is shown in Fig. 3. With PFC, the grid-side voltage and cur-

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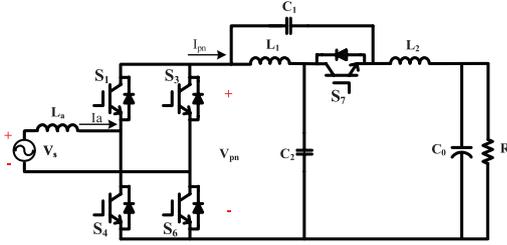


Fig. 3. The traditional quasi-Z-source single-phase rectifier.

rent can be controlled in the same phase. And the voltage and current are

$$v_s = V_s \sin(\omega t) \quad (1)$$

$$i_a = I_a \sin(\omega t) \quad (2)$$

and we can get the input power

$$p_{in} = v_s i_a - L_a \frac{di_a}{dt} i_a = \frac{V_s I_a}{2} - \frac{V_s I_a}{2} \cos(2\omega t) - \frac{\omega L_a I_a^2}{2} \sin(2\omega t) \quad (3)$$

so the dc component and the second harmonic component are,

$$p_0 = \frac{V_s I_a}{2} \quad (4)$$

$$p_{2\omega} = -\frac{V_s I_a}{2} \cos(2\omega t) - \frac{\omega L_a I_a^2}{2} \sin(2\omega t) \quad (5)$$

The second harmonic voltage and current will flow through the quasi-Z-source network, the huge capacitor and inductor of the quasi-Z-source network are needed to make the second harmonic voltage and current ripple small. It costs much and takes much space. The input power of quasi-Z-source network is

$$p_{pn} = (1-D)v_{pn} i_{pn} \quad (6)$$

where D is the shoot-through duty cycle[12]. [13] has analyzed the second harmonic ripple of quasi-Z-source network, that is

$$\begin{aligned} i_{L1} = i_{L2} &= I_{L1} + i_L \cos(2\omega t - \lambda) \\ v_{C1} &= V_{C1} + v_C \sin(2\omega t - \lambda) \end{aligned} \quad (7)$$

where I_{L1} and V_{C1} are the average current of inductor L1 and the average voltage of capacitor C1, respectively. The amplitudes of the second ripple of voltage and current are

$$i_L = \frac{1-2D}{\sqrt{[4\omega^2 LC - (1-2D)^2 + [\frac{4\omega L I_{pn} (D-1)}{V_{pn}}]^2]}} \cdot \frac{V_s I_a}{2V_{pn}} \quad (8)$$

$$v_C = \frac{2\omega L}{\sqrt{[4\omega^2 LC - (1-2D)^2 + [\frac{4\omega L I_{pn} (D-1)}{V_{pn}}]^2]}} \cdot \frac{V_s I_a}{2V_{pn}} \quad (9)$$

where L and C are the inductor and capacitor of the quasi-Z-

source network.

When the parameters of the system have been designed, the quasi-Z-source network inductor and capacitor can be calculated by

$$L = \frac{v_c^* (1-2D)}{2\omega i_L^*} \quad (10)$$

$$C = \frac{(1-2D)^2 + \sqrt{(1-2D)^2 \left(\frac{V_s I_a}{2V_{pn} i_L^*}\right)^2 - \left[\frac{4\omega L I_{pn} (D-1)}{V_{pn}}\right]^2}}{4\omega^2 L} \quad (11)$$

where v_c^* is the voltage ripple amplitude, i_L^* is the desired current ripple amplitude.

B. Proposed System Design

The APF circuit has no relationship with the quasi-Z-source network, so we only need to analyze APF single-phase rectifier at first. And the APF circuit is shown in Fig. 4.

Suppose the capacitor C3 and inductor L3 to be

$$v_{C3} = V_{C3} \sin(\omega t + \theta) \quad (12)$$

$$i_{C3} = I_C \cos(\omega t + \theta) = \omega C_3 V_{C3} \cos(\omega t + \theta) \quad (13)$$

We can get the power of the APF

$$p_{APF} = L_3 \frac{di_{C3}}{dt} i_{C3} + v_{C3} i_{C3} = \left(\frac{1}{2\omega C_3} - \frac{\omega L_3}{2}\right) I_C^2 \sin(2\omega t + 2\theta) \quad (14)$$

To eliminate second harmonic power in DC link, the power of APF should be

$$p_{APF} = p_{2\omega} \quad (15)$$

Submitting (5) and (14) into (15) yields

$$\frac{V_s I_a}{2} + \left(\frac{1}{2\omega C_3} - \frac{\omega L_3}{2}\right) I_C^2 \sin(2\theta) = 0 \quad (16)$$

$$\frac{\omega L_a I_a^2}{2} + \left(\frac{1}{2\omega C_3} - \frac{\omega L_3}{2}\right) I_C^2 \cos(2\theta) = 0 \quad (17)$$

The voltage of the capacitor C3 is controlled in the APF single-phase rectifier system, and the voltage and current of C3 can be get based on (16) and (17)

$$v_{C3} = \sqrt{\frac{V_s^2 I_a^2 + \omega^2 L_a^2 I_a^4}{\omega C_3 - \omega^3 L_C C_3^2}} \sin(\omega t + \theta) \quad (18)$$

$$i_C = \sqrt{\frac{V_s^2 I_a^2 + \omega^2 L_a^2 I_a^4}{1/\omega C_3 - \omega L_C}} \cos(\omega t + \theta) \quad (19)$$

$$\theta = \frac{\pi}{2} + \frac{1}{2} \tan^{-1}\left(\frac{V_s}{\omega L_a I_a}\right) \quad (20)$$

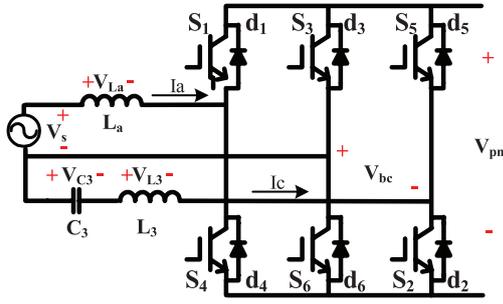


Fig. 4. The APF circuit.

When the voltage and current of the C3 satisfy the above conditions, the second harmonic power on DC link can be eliminated.

Because the second harmonic power ripple has been completely eliminated, the capacitor and inductor of the quasi-Z-source network are designed only to limit the switching frequency ripple. Therefore, the value of capacitor and inductor can be smaller, and the value will be

$$L_1 = L_2 = \frac{D(1-D)V_{pn}}{2f_s(1-2D)I_{L1}\delta_{\Delta i}} \quad (21)$$

$$C_1 = C_2 = \frac{I_{L1}D(1-2D)}{f_s V_{pn} \delta_{\Delta v}} \quad (22)$$

where $\delta_{\Delta v}$ and $\delta_{\Delta i}$ are the ratio of peak to peak ripple.

III. CONTROL STRATEGY AND MODULATION

A. Control Strategy for APF

In section two, we have got the reference voltage of the capacitor C3. Then we can control this voltage to make the system working with no second harmonic power.

First, we can get the transfer function

$$G_v(s) = \frac{V_{C3}}{V_{bc}} = \frac{1}{L_3 C_3 s^2 + 1} \quad (23)$$

where V_{bc} is the voltage between phase B and phase C, and the equivalent resistance has been ignored. Because the proposed APF single-phase rectifier quasi-Z-source network is used as electric vehicle on-board integrated charger, the voltage and current sensors are enough to get the voltage and current of C3. Then we can use the V_{C3} and I_C as the poles to get a very stable system. The capacitor voltage control system is shown in Fig. 5. When the V_{bc} is obtained, it is easy to get the voltage of phase C. Then we can control the S2 and S5 to modulate the voltage.

B. Modulation for Quasi-Z-Source Network

The modulation for the quasi-z-source network is shown in Fig. 6. In the paper [14], a novel modulation for soft-switching three-phase quasi-Z-source rectifier was proposed. The pro-

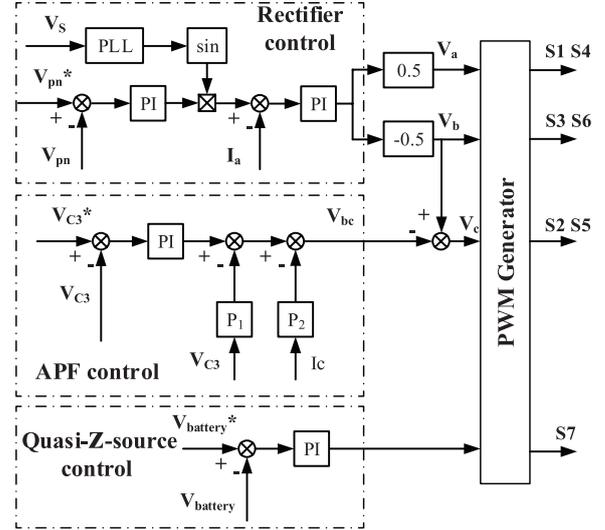


Fig. 5. The control strategy.

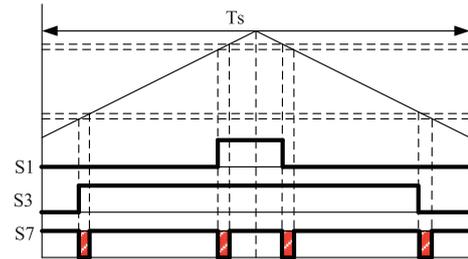


Fig. 6. The modulation for quasi-Z-source network.

posed modulation can be used in this APF single-phase quasi-Z-source system. When the S7 is turned off, the voltages across other switches (S1-S6) are clamped to zero. So the switches can be turned on or turned off under ZVS at the beginning of the system working in shoot-through state.

IV. SIMULATION AND EXPERIMENTAL VERIFICATION

The simulation and experimental results have been done to verify that the proposed APF single-phase quasi-Z-source rectifier can eliminate the second harmonic power.

A 750-W system has been designed with the parameters: $V_s = 50$ V, $I_a = 30$ A, $L_a = 3$ mH, $V_{pn} = 190$ V, $R = 30$ Ω , $D = 0.1$, $f_s = 10$ k. According to (10) and (11), the single-phase rectifier without APF needs quasi-Z-source impedance with $L = 43$ mH and $C = 780$ μ F to make the second harmonic ripple smaller than 5%. The inductors and capacitors are huge. While, based on (21) and (22), the capacitance and inductance are $C = 26$ μ F and $L = 0.85$ mH, respectively. In this paper, the values of $C = 50$ μ F and $L = 1$ mH were used as the quasi-Z-source impedance.

A. Simulation Results

The traditional single phase quasi-Z-source rectifier suffers from the second harmonic ripple, so the voltage of C2 and the current of L1 have the second harmonic ripple. Fig. 7 shows the simulation result. The current of L1 and the voltage of C2 have

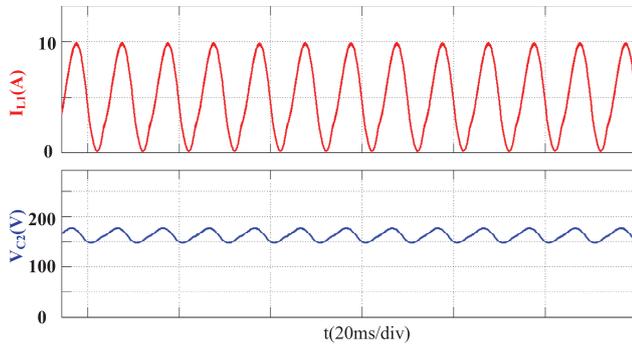


Fig. 7. Simulation results without APF: the inductor L1 current and the capacitor C2 voltage.

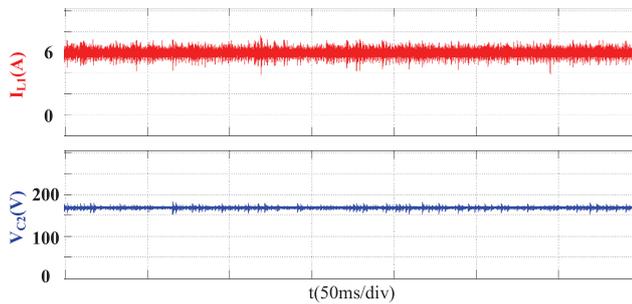


Fig. 8. Simulation results with APF: the inductor L1 current and the capacitor C2 voltage.

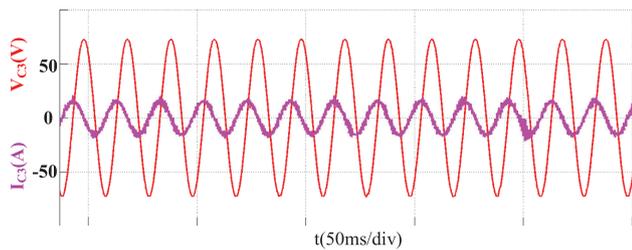


Fig. 9. Simulation results with APF: the current and voltage of C3.

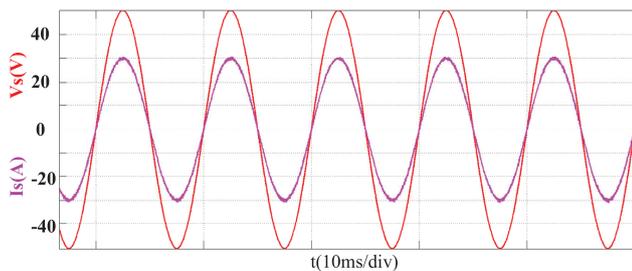


Fig. 10. Simulation results: grid-side voltage and grid-side current.

the large second harmonic ripple. Large capacitor and inductor are needed to suppress ripple. And when we use the proposed APF topology, the harmonic ripple can be eliminated, and the simulation result is shown in Fig. 8. From the simulation results, it can conclude that the APF topology absorbs all the second harmonic power.

The current and the voltage waveforms of the APF topology are shown in Fig. 9. And when the proposed APF single-phase

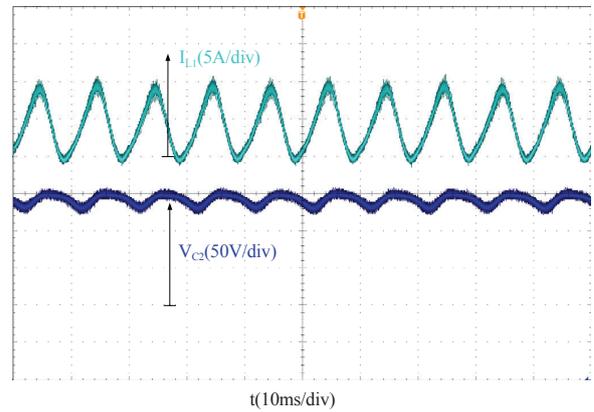


Fig. 11. Experimental results: L1 current and C2 voltage.

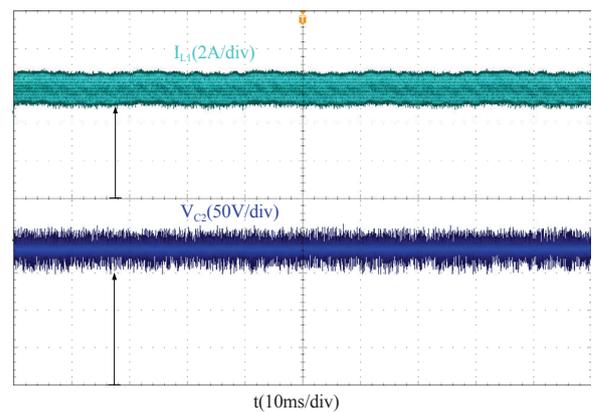


Fig. 12. Experimental results: L1 current and C2 voltage.

quasi-Z-source rectifier works, the grid-side current and voltage are with the same phase angle, as shown in Fig. 10. The efficiency of the system is high, and the harmonic of the grid-side current is small.

B. Experimental Results

Fig. 11 shows the experimental result of the quasi-Z-source single-phase rectifier without APF. From the Fig. 11, we can see that the current ripple of L1 and the voltage ripple of C2 are huge. And the waveforms are the same as the simulation result. The large current ripple will increase device loss and decrease the efficiency of the system. The APF topology is used to eliminate the second harmonic power, so the second harmonic current and voltage ripple can also be eliminated, the experimental result is shown in Fig. 12.

The experimental results of the current through APF and the voltage across C3 are shown in Fig. 13. Fig. 14 shows the grid-side current and voltage waveforms.

V. CONCLUSION

This paper proposed an APF quasi-Z-source single-phase integrated on-board charger which can eliminate the second harmonic power on DC link. Compared with the quasi-Z-source single-phase rectifier without APF, the quasi-Z-source network

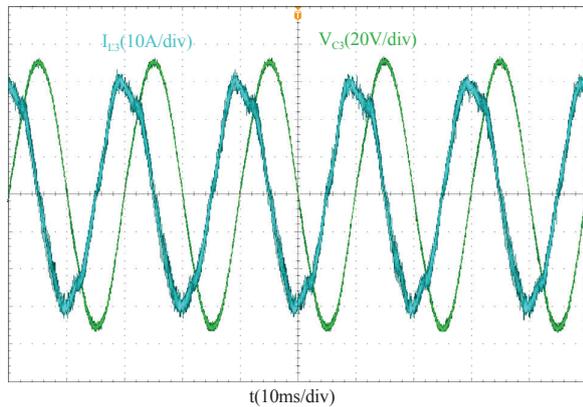


Fig. 13. Experimental results: C3 current and C3 voltage.

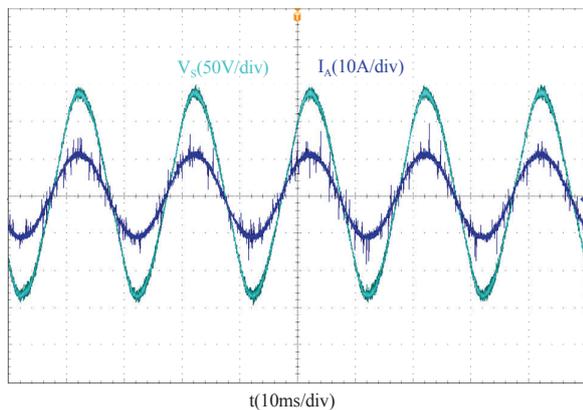


Fig. 14. Experimental results: grid-side current and grid-side voltage.

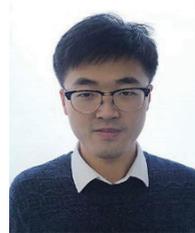
of the proposed system only need very small inductor and capacitor. The paper has provided the method how to design the parameters. Because this system can be used as an integrated on-board electric vehicle charger, it can make full use of the devices. Therefore, another advantage is that it saves much space and costs less. And a 750-W prototype has been designed. The simulation and experimental results have verified the theory of the proposed system.

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