Charging Topology and Low Frequency Interharmonic Suppression of Bidirectional Electric Vehicle On-board Converter

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Abstract. Bidirectional DC/DC converters are widely used in hybrid DC power supply systems. Aiming at the hybrid power supply system of electric vehicle supercapacitor and battery, the article takes the new interleaved parallel Buck/Boost converter as the research object and uses the state space averaging method to establish the AC small signal model under the Boost state continuous mode (CCM). We get the open-loop transfer function of the circuit model. Aiming at the V2G load characteristics of electric vehicles, an optimal configuration model of harmonic suppression devices with the smallest sum of investment and network loss for harmonic suppression was established. The research shows that the model effectively improves the operating voltage level and reduces the network loss.

Key words: Two-way electric vehicles, on-board converters, charging, harmonic suppression, reactive power compensation.

1. Introduction
With the rapid development of electric vehicles (EV), the non-linearity, impact and harmonics generated by asymmetric loads in charging facilities cause deterioration of power quality indicators and interfere with the normal operation of power equipment and electrical loads. The research is imperative. The charger converts the three-phase alternating current into a high-voltage direct current, and then converts it into a low-voltage direct current that the battery can accept through a DC/DC conversion [1]. The vehicle-mounted charging system mainly includes two parts: the rectifier of the charging station and the reversible DC/DC converter of the vehicle-mounted charging device. The current charging system has the limitations of conversion efficiency, reliability, and unidirectional energy flow. The impedance source converter provides a solution to the above problems. Therefore, this article proposes a fast charging method using AC/DC matrix converters. This method can solve the problems of low efficiency of traditional topologies and control methods, large energy storage capacitors, low power density, large current distortion, and inability to achieve fast charging. The simulation results show that the matrix V2G bidirectional fast charging double closed-loop control strategy can realize V2G fast charging and discharging, and the grid-side current harmonic distortion rate during pulse charging and constant current discharge is less than 5%, and the power factor can reach 1.0. The system has a compact structure, high power density and high efficiency.
2. Overall system plan

2.1. The overall structure of the system

The system structure of this article to realize the V2G function is shown in Figure 1. The system is composed of four parts: electric vehicle battery pack, electric energy calculation unit, converter and smart microgrid. The main research object of this article is electric energy calculation unit, which can realize data collection and analysis, through logical operation output instructions to control the charging and discharging mode of the charging pile [2]. When an electric car is connected to the two-way charging pile, firstly, the working mode of the charging pile will be determined according to the user's selection; secondly, if the user is not detected Input, the charging pile will automatically select the working mode according to the actual working conditions.

![System structure diagram](image)

**Figure 1. System structure diagram**

2.2. Topological diagram of system circuit structure

Today's V2G bidirectional charging and discharging system topology can generally be divided into single-stage and two-stage structures. The single-stage structure is simple, but the control is difficult, the power is small, and the charging time is relatively long; the two-stage structure uses more power electronic devices and the structure is relatively complex, but the power is larger, which can increase the endurance of electric vehicles in a short time [3]. The topology selected in this paper is shown in Figure 2. This topology is composed of a bidirectional PWM rectifier and Buck-Boost and, as shown in the figure Q is power switch IGBT, D is freewheeling diode, D1-D6 are connected in parallel with Q1-Q6 respectively to provide reverse voltage blocking capability. Given AC side grid voltage 380V, frequency 50Hz; AC side filter capacitor L2-L4 is 0.5H; the large capacitance C on the DC bus side is 4000μF; the battery side capacitance L1 is 0.5H; the battery selected is the lithium-ion model that comes with Simulink, the open circuit voltage is 300V, and the rated capacity is 135Ah.
3. Control Strategy

Taking the voltage-type circuit topology as an example, the steady-state principal characteristics of a single-phase Z-source AC-AC chopper controlled by the instantaneous voltage value PWM are analysed [4]. Since the power switch $S_1$, $S_2$ complementary conduction and the inductance and capacitance of the output filter are small, the equivalent circuit of the switching state of this type of chopper in a high-frequency switching cycle is shown in Figure 3.

$$i_{L1} = i_{L2} = i_L = \sqrt{2} I_L \sin(\omega t + \varphi_L)$$ (1)

$$u_{C1} = u_{C2} = u_C = \sqrt{2} U_c \sin(\omega t + \varphi_C)$$ (2)

$$i_{C1} = i_{C2} = i_C = \sqrt{2} \omega CU_c \sin(\omega t + \varphi_C + 90^\circ)$$ (3)
φ_L, φ_C and are the initial phase angles of the inductor current and capacitor voltage of the Z source network, respectively. Let the input and output voltages be

\[ u_i = \sqrt{2}U_i \sin \omega t \]

\[ u_0 = \sqrt{2}U_0 \sin(\omega t + \varphi_0) \]  

(4)

(5)

In (5), \( \varphi_0 \) is the initial phase angle of the output voltage. Power switch \( S_1 \) is turned on and \( S_2 \) is turned off. Input AC power \( u_i \) to charge the capacitor \( C \) in the Z source network, and the inductor \( L \) releases energy to the load, there is

\[ u_C = u_i - u_L \]  

\[ u_{AB} = u_i - 2u_L \]  

(6)

(7)

During \( (1-D)T_s \), power switch \( S_1 \) is off and \( S_2 \) is on. The capacitor \( C \) in the Z source network discharges, and the inductor \( L \) stores energy. Have

\[ u_C = u_L \]  

\[ u_{AB} = 0 \]  

(8)

(9)

In the steady state, the fluctuation of the input voltage is ignored, and the average value of the inductor voltage in the same power cycle is zero. Have

\[ \frac{U_C}{U_i} = \frac{D}{2D-1} \]  

(10)

Since the output filter inductance \( L_1 \) and the Z source network inductance \( L \) are both small, their fundamental voltage can be ignored. The load voltage \( u_0 \), the output filter front-end voltage \( u_{AB} \), and the Z source network capacitor voltage \( u_C \) are equal, so there is

\[ U_0 = \frac{D}{2D-1}U_i \]  

(11)

Which is

\[ u_0 = \frac{D}{2D-1}u_i \]  

(12)

It can be seen from (12) that the output voltage \( u_0 \) can be adjusted by controlling the duty cycle \( D \) of the chopper. When \( D < 0.5 \), \( u_0 \) and \( u_i \) are in phase, \( \varphi_0 = \pi \); when \( D > 0.5 \), \( u_0 \) and \( u_i \) are in phase, \( \varphi_0 = 0 \). This is also the unique feature of the Z source chopper [5]. The single-phase voltage type Z source AC-AC chopper has two working areas: when \( D < 0.5 \), the chopper works in the negative gain area, and the phase difference between \( u_0 \) and \( u_i \) is 180; when \( D < 0.5 \), the chopper enters the positive gain area, \( u_0 \) and \( u_i \) are in phase. The single-phase current type Z source AC-AC chopper also has two working areas. When \( D < 0.5 \), the chopper works in the positive gain area, and
$u_0$ and $u_i$ are in phase; when $D < 0.5$, the chopper enters the negative gain area, that is, $u_0$. It is 180 degrees out of phase with $u_i$.

4. Steady state principal characteristics
Taking the voltage-type circuit topology as an example, the steady-state principal characteristics of the three-phase Z source AC-AC chopper are analysed. For easy analysis, suppose the three-phase input grid voltage is symmetrical, that is, the input line voltage is

$$
\begin{bmatrix}
    u_{ab} \\
    u_{bc} \\
    u_{ca}
\end{bmatrix} = \sqrt{2}U_i
\begin{bmatrix}
    \sin(\omega t) \\
    \sin(\omega t - 120^\circ) \\
    \sin(\omega t + 120^\circ)
\end{bmatrix}
$$

(13)

When the 3 inductors and 3 capacitors in the Z source network have the same size, the Z source network is a symmetric network, and the source network inductance voltage can be derived

$$
\begin{bmatrix}
    u_{La} \\
    u_{Lb} \\
    u_{Lc}
\end{bmatrix} = \sqrt{2}\omega LI_i
\begin{bmatrix}
    \sin(\omega t + \varphi_L) \\
    \sin(\omega t + \varphi_L - 120^\circ) \\
    \sin(\omega t + \varphi_L + 120^\circ)
\end{bmatrix}
$$

(14)

Z source network capacitor voltage

$$
\begin{bmatrix}
    u_{Ca} \\
    u_{Cb} \\
    u_{Cc}
\end{bmatrix} = \sqrt{2}U_C
\begin{bmatrix}
    \sin(\omega t + \varphi_C) \\
    \sin(\omega t + \varphi_C - 120^\circ) \\
    \sin(\omega t + \varphi_C + 120^\circ)
\end{bmatrix}
$$

(15)

Output line voltage

$$
\begin{bmatrix}
    u_{a'c} \\
    u_{b'c} \\
    u_{c'a}
\end{bmatrix} = \sqrt{2}U_0
\begin{bmatrix}
    \sin(\omega t + \varphi_0) \\
    \sin(\omega t + \varphi_0 - 120^\circ) \\
    \sin(\omega t + \varphi_0 + 120^\circ)
\end{bmatrix}
$$

(16)

The chopper has two working modes: on $DT_s$ and off $(1 - D)T_s$. When $0 < t < DT_s$, the three-phase Z-source AC-AC chopper is in conduction $DT_s$ working mode. Have

$$
\begin{bmatrix}
    u_{ab} \\
    u_{bc} \\
    u_{ca}
\end{bmatrix} = \begin{bmatrix}
    u_{Ca} \\
    u_{Cb} \\
    u_{Cc}
\end{bmatrix} - \begin{bmatrix}
    u_{La} \\
    u_{Lb} \\
    u_{Lc}
\end{bmatrix}
$$

(17)

$$
\begin{bmatrix}
    u_{a'c} \\
    u_{b'c} \\
    u_{c'a}
\end{bmatrix} = \begin{bmatrix}
    u_{Ca} \\
    u_{Cb} \\
    u_{Cc}
\end{bmatrix} - \begin{bmatrix}
    u_{La} \\
    u_{Lb} \\
    u_{Lc}
\end{bmatrix}
$$

(18)

When $DT_s < t < T_s$, the three-phase Z-source AC-AC chopper is in cut-off $(1 - D)T_s$. Have
In one input power cycle, the average voltage across the inductor is zero during steady state.

\[
\begin{bmatrix}
L_c u_c \\
L_b u_b \\
L_a u_a
\end{bmatrix} = \begin{bmatrix}
L_c u_{c1} \\
L_b u_{b1} \\
L_a u_{a1}
\end{bmatrix}
\]  

\[\text{(19)}\]

\[
\sqrt{2}U_c \begin{bmatrix}
D \cos(\omega t + \phi_c) + (1 - D) \cos(\omega t + \phi_c - 120^\circ) \\
D \cos(\omega t + \phi_c - 120^\circ) + (1 - D) \cos(\omega t + \phi_c + 120^\circ) \\
D \cos(\omega t + \phi_c + 120^\circ) + (1 - D) \cos(\omega t + \phi_c)
\end{bmatrix}
\]

\[\text{(20)}\]

\[
= \sqrt{2} DU_j \begin{bmatrix}
\cos(\omega t + 30^\circ) \\
\cos(\omega t - 90^\circ) \\
\cos(\omega t + 150^\circ)
\end{bmatrix}
\]

\[\text{(20)}\]

5. Experimental results and analysis in charging mode

Since 3 constant AC voltage sources are used in the simulation to replace the microgrid, the grid operation status cannot be judged by the grid-side voltage change, so the grid status is simulated by artificial setting: the given voltage \(U=210V<U^*\) to simulate the grid valley load status. In this case, set the battery SOC to 20%, and then input a signal with a lower current electricity price, and then simulate [6]. This situation is equivalent to the user inputting a charging command. The simulation result is shown in Figure 4. In the charging mode, the SOC of the battery increases steadily with time during charging, indicating that the battery is in a charging state. The grid-side voltage and current waveforms can achieve the same phase at \(t=0.02s\), indicating that the electric vehicle is connected to the charging mode in the charging mode. The adjustment time after the pile is short; the battery can be charged with constant current at \(t=0.1s\), and the current steady point is at the rated current of 34A. At this time, the voltage of the lithium-ion battery slowly rises to about 220V, and the DC bus voltage is at \(t=0.2s\) When it can be stabilized to 700V, the active power \(P\) flows from the grid side to the battery side, and the reactive power \(Q\) can be stabilized near zero at \(t=0.25s\). Currently, the system realizes charging with unit power factor. The current drops from 34A Up to 5A, to achieve low current charging effect.

![Figure 4. Simulation waveform in charging mode](image-url)
6. Conclusion
This paper studies an electric vehicle charger with a two-way high-efficiency quasi-impedance source converter. Using its unique impedance network, the main circuit of the converter and the power supply are coupled together, and unique characteristics that cannot be obtained by traditional voltage source and current source converters can be obtained. By adopting the power feed-forward deadbeat control method with through state, the fast tracking and response of the current are realized. The experiment proves the correctness of the electric vehicle charger topology and control method of the bidirectional high-efficiency impedance source converter studied in this paper. However, the charger structure is only suitable for small and medium power situations, so the structure needs to be improved to adapt to high-power charging occasions.

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