Research on Train Secondary Pulsation Elimination Method

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Abstract. In the train traction system, the single-phase four-quadrant converter achieves the same frequency and phase of the voltage and current on the grid side, but it cannot avoid generating secondary pulse power of the same magnitude as the DC side load. The traditional method is to connect the LC secondary resonance circuit in parallel on the DC side, but the volume and weight of the resonance circuit are relatively large, which reduces the power density, which does not meet the development trend of lightweight trains and the requirements of energy saving. The active filtering method of the secondary pulsation can not only effectively eliminate the secondary pulsation, but also cancel the bulky LC filter, reduce the axle load, increase the passenger capacity, and realize green energy saving.

1. Introduction

In the field of rail transit, most of the high-speed trains adopt modern AC drive system, that is, AC-DC-AC structures. The first part of the AC-DC conversion process is mostly a single-phase four-quadrant-running PWM rectifier, that is, four-quadrant converter. Therefore, the grid-side voltage and current will generate corresponding ripple power that is twice the grid voltage frequency. The AC ripple power will flow to the intermediate DC link support capacitor to generate a secondary ripple voltage. The presence of ripple voltage will affect the system. It poses a threat to the safety and stability of the vehicle, and at the same time will cause the beat frequency phenomenon of the motor of the rear-stage traction system, which affects the stability of the train [1].

For the method of suppressing the secondary pulsation on the DC side, a large capacitor or a secondary LC resonant circuit is connected in parallel on the bus. The method of paralleling the large capacitor can’t completely eliminate secondary pulsation. In the field of rail transit, the secondary resonance branch method has a wide range of applications due to its simple design and easy implementation. Electric locomotives usually use the DC-side parallel LC resonance method. Since the frequency of the secondary ripple is 100 Hz, the volume and weight of the required capacitance and inductance are very large, greatly reducing the power density of the system, increasing the construction cost of the train. In actual operation, there may be a problem that the harmonic elimination frequency does not match the resonance point [2]. Due to the many shortcomings of the passive filtering method, some scholars have proposed active filtering methods, including active power factor correction technology, active power filtering technology, etc. [3]. Reference [4] proposed a DC ripple suppression circuit, and reference [5] proposed an AC measurement active filter circuit. The basic idea of active filtering is to transfer the secondary pulsating power to a smaller energy storage element through an additional active switching circuit. Since the energy storage element is not directly connected to the DC bus, the volume of the energy storage element can be reduced. Power density will increase [6]. At present,
most active filter circuits are connected in parallel. Due to the structure and working characteristics of the main circuit of the traction drive system, the active filter method of series mode is not suitable for high power [7]. In reference [8], an active filter topology using a Buck circuit is proposed. The voltage command of the filter capacitor is the secondary pulsating current, and the secondary pulsating power is absorbed by the energy storage capacitor. When the rectifier power increases, the filtering effect becomes worse, which limits the application range.

Aiming at the shortcomings of [8], this paper uses a half-bridge bidirectional Buck / Boost topology for active filter control, and proposes a voltage loop plus current loop control strategy. In this paper, the generation mechanism of the second pulse is described, and the active filter method is proposed. Then the control strategy is introduced. Finally, the simulation and experimental results verify the feasibility of the active filter method.

2. Generation mechanism of secondary pulsating power

![Figure 1. Four-quadrant converter system.](image)

Figure 1 shows the topology of a voltage-type single-phase four-quadrant rectifier. Set its AC power voltage and current to be power-frequency sinusoidal inputs:

\[
\begin{align*}
  u_s &= U_s \sin(\omega t) \\
  i_s &= I_s \sin(\omega t - \phi)
\end{align*}
\]

The input power at the grid side is shown in equation (2):

\[
p_{in} = u_s i_s = \frac{U_s I_s}{2} \cos \phi - \frac{U_s I_s}{2} \cos(2\omega t - \phi)
\]

Active power portion of rectifier input power is shown in equation (3):

\[
p_o = \frac{U_s I_s}{2} \cos \phi
\]

Because the inductance power of the traction network side is usually not negligible under high power conditions, the inductance power on AC side can be expressed as equation (4):

\[
p_L = \omega L_s i_s = \frac{\omega L_s I_s^2}{2} \sin(2\omega t - 2\phi)
\]

The rectifier AC side input power can be expressed as equation (5):
\[ p_s = p_{io} - p_i = \frac{U_s I_s}{2} \cos \phi - \left[ \frac{U_s I_s}{2} \cos(2\omega t - \phi) + \frac{\omega L_s I_s^2}{2} \sin(2\omega t - 2\phi) \right] \] (5)

Then the input power ripple component can be expressed as equation (6):

\[ p_r = \sqrt{p_{io}^2 + \left( \frac{\omega L_s I_s^2}{2} - p_s \tan \phi \right)^2 \sin^2(2\omega t - 2\phi + \arctan \frac{p_s}{(\omega L_s I_s^2/2) - p_s \tan \phi})} \] (6)

Because the four-quadrant converter can achieve the same phase of voltage and current on the grid side, so the power factor angle \( \phi = 0 \), the input pulsating power can be expressed as equation (7):

\[ p_r = p_{r-peak} \sin(2\omega t + \gamma) \] (7)

In the above formula:

\[ p_{r-peak} = \sqrt{p_{io}^2 + (\frac{\omega L_s I_s^2}{2})^2} \] (8)

\[ \gamma = \arctan \frac{p_s}{(\omega L_s I_s^2/2)} \] (9)

3. Analysis of Active Filtering Ideas

Figure 2 is the main circuit topology used in this article. Based on the four-quadrant converter, the bridge arm of Buck / boost type DCDC module is added to the topology. By controlling the opening and closing of the bridge arm, the secondary pulse component can flow into the LC bridge arm of DCDC completely, so there is no secondary pulse voltage on the DC side, and then the active filtering function can be realized.

The idea of active filtering is to assume that current above \( L_{cs} \) is \( i_{cs} = I_{cs} \sin(2\omega t + \alpha) \), and a dc voltage bias \( U_{cs} \) is given at the initial stage. The capacitor voltage includes dc voltage bias and secondary pulsation components. The specific expression is shown in equation (10):

\[ u_{cs} = U_{cs} + u_{cs-ripple} = U_{cs} - \frac{I_{cs} \cos(2\omega t + \alpha)}{2\omega C_{cs}} \] (10)

At the same time, the voltage on the \( L_{cs} \) of the filter inductance can be expressed as equation (11):
\[ u_{LS} = L_{cs} \frac{di_{cs}}{dt} \]  

(11)

Combined with the three formulas, the power flowing into the bidirectional DCDC converter can be calculated as in equation (12):

\[ P_{APF} = i_{cs} \times (u_{cs} + u_{LS}) \]  

(12)

The aim of active filter is to control the secondary power flowing into the bidirectional DCDC converter equal to the DC side secondary pulse power, that is, to eliminate the DC side secondary pulse power.

\[ I_{cs} U_{cs} \sin(2\alpha t + \alpha) = p_{r-peak} \sin(2\alpha t + \gamma) \]

(13)

Since the current output by the four-quadrant rectifier \( i_m \) can be divided into three components: dc component \( i_d \), secondary ripple component \( i_r \), and switching harmonic component \( i_{ \text{switch}} \), the secondary ripple power can be expressed as in equation (14):

\[ p_r = i_2 U_d = p_{r-peak} \sin(2\alpha t + \gamma) \]

(14)

Therefore, the capacitor current instruction value in the filter circuit can be obtained:

\[ i_{cs}^* = \frac{p_r}{U_{cs}} = \frac{p_{r-peak} \sin(2\alpha t + \gamma)}{U_{cs}} = \frac{i_2 U_d}{U_{cs}} \]

(15)

4. Control strategy research

Figure 3 is the block diagram of the control strategy adopted in this paper. The control objects are the voltage of the filter branch capacitance and the current of the filter inductance. The output power of the four-quadrant converter is obtained by multiplying the output current and DC bus voltage of the four-quadrant converter. Through the band-pass filter, the secondary pulse component in the output power can be obtained, that is, the target secondary power that the active filter needs to filter out. The target value of inductor current can be obtained by the formula, and the proportional resonance control is used to realize the tracking without static error. At the same time, the detected capacitor voltage is filtered out of the secondary component and the high-frequency component to obtain the DC component. For the control of the DC flow, the PI control is used to realize no static error tracking, and the control duty cycle is obtained by adding the two control outputs, the elimination of secondary pulsation component in DC side is realized.

![Figure 3. Active Filter Control Block Diagram.](image-url)
5. Simulation results
Based on the actual parameters of the hybrid EMU, this paper uses Matlab / Simulink to build a
simulation model to simulate the active filtering process during the actual train operation. Table 1 shows
the parameters used in the simulation, and figure 4 (a) shows the secondary pulsation at the DC side
under the condition of no LC resonance branch. It can be seen from the figure 4(a) that the peak-peak
value of the secondary pulsation reaches about 90V. After the above active filtering control, the The
peak-peak value of secondary pulsation is reduced to about 10V, and the effect is remarkable. From the
Fourier analysis of the two methods, it can also be concluded that the second pulse component after
active filtering is greatly reduced, which verifies the feasibility of the active filtering method.

| Parameter | Value         |
|-----------|---------------|
| $P_e$     | 300Kw         |
| $T_s$     | 1e-5s         |
| $f_{switch}$ | 1KHz       |
| $L_s$     | 2.08mH        |
| $L_{cs}$  | 1mH           |
| $U_{dc}$  | 1500V         |
| $U_{cs}$  | 1100V         |
| $C_{cs}$  | 2mF           |
| $C_{dc}$  | 4mF           |

![Simulation Waveform](image1)

![FFT of Simulated Waveforms](image2)

6. Experimental waveform
In this paper, the experiment is carried out on the traction converter experimental platform of the hybrid
EMU. The figure below shows the active filter experiment under the DC bus voltage of 1500V. It can
be seen from the figure that the experimental waveform is basically similar to the simulation waveform.
In figure 6 (a), the DC voltage secondary pulse component is obvious, and in figure 6 (b), the DC voltage
secondary pulse component is basically eliminated, and the filtering effect is obvious. And the actual
filter power can accurately track the power command value, which verifies the rationality of the control
strategy. It can also be seen from Figure 6 that the system stability is good when the active filter method
is put into operation.
7. Conclusion

In this paper, through the research and analysis of the traction converter system without LC resonator, an active filter method without LC resonance branch is proposed, and the feasibility of this method is verified by simulation and experiment. The method of active filter can effectively reduce the adverse effects of LC resonance branch. By replacing the secondary resonance branch with active filter, the volume weight of capacitance and inductance used in active filter is far less than the volume weight of LC secondary resonator, so the axle load of the train is reduced, the passenger capacity of the train is increased, and the goal of green energy saving is realized.

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