SINGLE-PHASE ACTIVE FILTER FOR HIGH ORDER HARMONICS COMPENSATION

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Abstract: *A single-phase active power filter for high-order harmonic current compensation is presented in this paper. In modern railway locomotives, multi-paralleled PWM converters provide unity power factor operation with low THD, but their high-order harmonics current may provoke interference problems with the railway track signal and public telecommunication lines. A band-pass digital filter is proposed to extract the harmonic reference currents to be compensated in the active filter. A prediction algorithm to compensate the delay in the deadbeat current control is also proposed to produce a predicted harmonic reference current. The effectiveness of the proposed algorithms is verified through simulations and experiments.*

Key words: *Active filter, harmonics, single-phase systems, locomotives.*

1. Introduction

PWM converters are employed as the line-side converters of traction motor drives in modern locomotive applications. Multi-paralleled PWM converters give unity-power factor operation and move the dominant harmonic components of the overhead line current up to high-order regions. Such harmonic currents drawn by railway traction locomotives provoke electromagnetic interference to the railway track signals and the public telecommunication lines. This interference might be amplified to be more harmful to the surrounding communication system if certain frequencies of the harmonic currents coincide with the resonance frequencies of the overhead lines [1, 2].

In order to suppress the high-order harmonic currents, most of the railway locomotives are equipped with passive filters consisting of inductors, capacitors, and resistors. This passive filter reveals some drawbacks such as bulky size and weight. Considering these problems, a single-phase active filter is regarded as an alternative to give an attractive solution. Active filters for railway application have been investigated and have shown several outstanding results [1-5]. Harmonic compensation method uses only the gating signals of the main power converters on the base of feed-forward control scheme [3]. The resonance properties of the distributed overhead lines may produce an amplification of the specific harmonic currents generated by PWM converter-fed locomotives [3, 5]. This paper aims at developing an algorithm for controlling single-phase active filter parallel-connected with PWM converters [6]. A band-pass filter to generate the reference waveforms of the harmonic currents flowing through the active filter is employed [7]. A predictive reference generation algorithm is proposed in order to compensate one-step delay in the deadbeat current control scheme.

2. System configuration

Fig. 1, which is composed of parallel-connected PWM converters, active filter, and input transformer, shows the power circuit dealt with in this paper. In practice, main converters feed inverters following traction motors. We pay major focus on the harmonics generated by the PWM converters, which operate with unipolar sinusoidal PWM in which their carriers are phase-shifted at 90 degrees to minimize the resulting switching current ripple. The switching frequency of each PWM converter is equal to 540Hz and then the effective switching frequency is seen as 2160Hz in the primary side of the transformer. Fig. 2 shows experimental results of parallel-connected PWM converters in the upper line the transformer secondary two currents is1 and is2 and in the lower line the primary current.

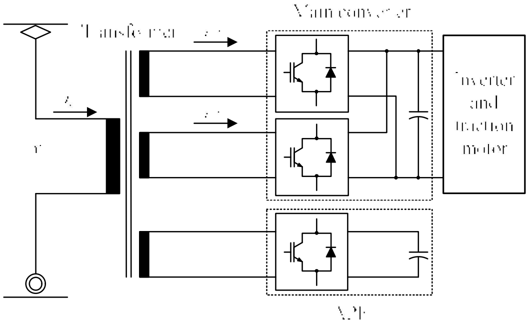


Fig. 1. Main power circuit block diagram.

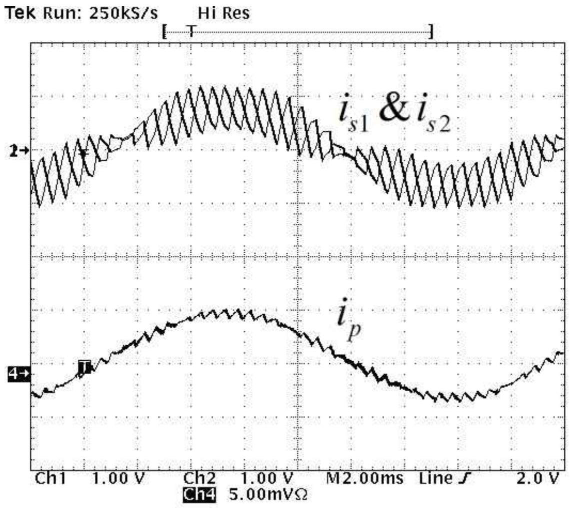


Fig. 2. The current waveform of the primary-side transformer.

The power circuit of active filter is shown in Fig. 3, where the inductance *L* means the leakage component of the transformer secondary winding connected to the active filter. The power conversion circuit of the active filter is the same as those of the PWM main converters.

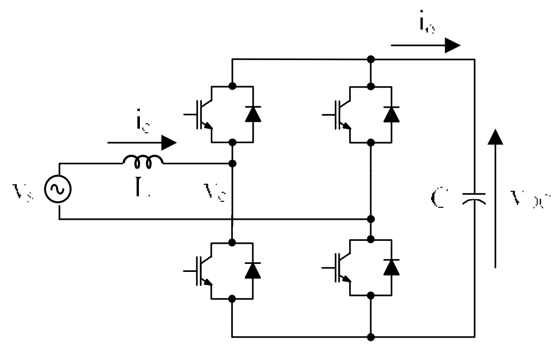


Fig. 3. Single-phase active filter.

3. Control scheme

The basic control scheme of the active filter composed of the reference generation block of the harmonic current, the respective current-control block, and the sinusoidal PWM block is as shown in Fig. 4. A DC voltage PI-controller block is provided to regulate the DC capacitor voltage of the active filter and to draw the active current equivalent to the power losses occurring in the power conversion stage. This paper mainly deals with a generation method to extract the harmonics components, i_h^*, in the line current of the PWM converters and a prediction algorithm to compensate the delay appeared in the deadbeat current control scheme.

3.1 Extraction of harmonics reference current

In the main power circuit configuration considered in this paper, harmonic currents in the range of 1-3 kHz may provoke interference with public telecommunications and railway track signaling. Hence, it is necessary to extract accurately the harmonic components existing in this range. For that purpose, several filter structures are considered for performance evaluation. Please note that if the unnecessary fundamental component remains in the generated reference, this component makes the active filter oversized in capacity. Considering the filter performance of a 4th-order Butterworth digital filter taken as a primary reference, three types of filter configurations are investigated in aspect of the estimation accuracy.

Fig. 5 shows the digital filter structure using the 4th low pass filter to acquire the desired harmonic reference current from the primary current. Fig. 6 shows the digital filter structure using the 4th high pass filter to acquire the desired harmonic reference current from the primary current. Fig. 7 results from a combination of 2nd order low-pass filter and 2nd order high-pass filter to form a 4th order Butterworth digital filter. In this configuration, the inherent merits of each filter can be fully utilized such that the low-pass filter is designed to keep a small phase error in the pass band and the high-pass filter is designed to provide a high attenuation rate in the stop band. Such design process makes it possible to extract the desirable harmonic reference current in which a small fundamental component and a negligible phase-error are involved. The overall transfer function is described as shown in (1)-(3).

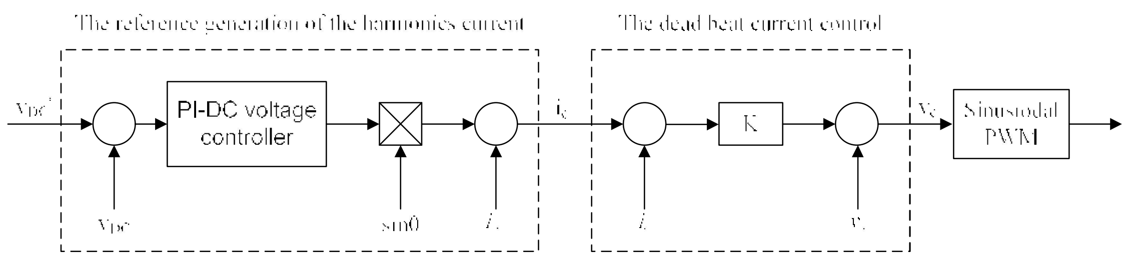


Fig. 4. Control block diagram.

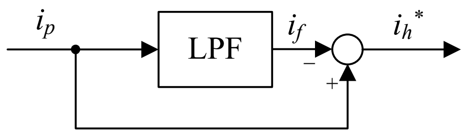


Fig. 5. Filter configuration using a low-pass filter; case 1

Fig. 6. Filter configuration using a high-pass filter; case 2

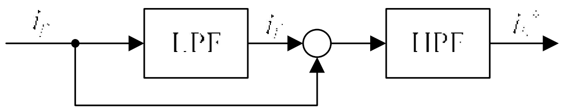


Fig. 7. Filter configuration with a band-pass filter; case 3

$$
\begin{aligned}
H(s) &= [1 - LPF(s)] \cdot HPF(s) \\
&= \left[1 - \frac{\omega_{CL}^2}{s^2 + \sqrt{2}\omega_{CL}s + \omega_{CL}^2}\right] \cdot \frac{s^2}{s^2 + \sqrt{2}\omega_{CH}s + \omega_{CH}^2} \\
&= \frac{s^2 + \sqrt{2}\omega_{CL}s}{s^2 + \sqrt{2}\omega_{CL}s + \omega_{CL}^2} \cdot \frac{s^2}{s^2 + \sqrt{2}\omega_{CH}s + \omega_{CH}^2}
\end{aligned} \tag{1}
$$

$$
|H(j\omega)| = \sqrt{\frac{(\omega^4)^2 + (-\sqrt{2}\omega_{CL}\omega^3)^2}{(\omega^4 + b_2\omega^2 - \omega_{CH}^2\omega_{CL}^2)^2 + (-b_1\omega^3 - b_3\omega)^2}} \tag{2}
$$

$$
\angle H(j\omega) = \tan^{-1}\frac{-a_1\omega_{CL}}{\omega} - \tan^{-1}\frac{-b_1\omega^3 - b_3\omega}{\omega^4 + b_2\omega^2 - \omega_{CH}^2\omega_{CL}^2} \tag{3}
$$

where,

$$
\begin{aligned}
b_1 &= \sqrt{2}\omega_{CH} + \sqrt{2}\omega_{CL} \\
b_2 &= \omega_{CH}^2 + 2\omega_{CL}\omega_{CH} + \omega_{CL}^2 \quad . \\
b_3 &= \sqrt{2}\omega_{CH}^2\omega_{CL} + \sqrt{2}\omega_{CH}\omega_{CL}^2
\end{aligned}
$$

The frequency-response characteristics of the three cases are shown in Fig. 8, where the primary design criterion is to suppress the fundamental component to the level of 1%. It can be seen in this figure that the band-pass filter of Fig. 7 shows the best results among three types. This result from the property to determine separately the cutoff frequencies of the low-pass filter and the high-pass filter, respectively. The cutoff frequency of the low-pass filter is determined based on extracting only the fundamental component, not considering the phase error of the harmonic reference current compensated. Meanwhile, the cutoff frequency of the high-pass filter is designed only by considering the phase error of the harmonic reference current.

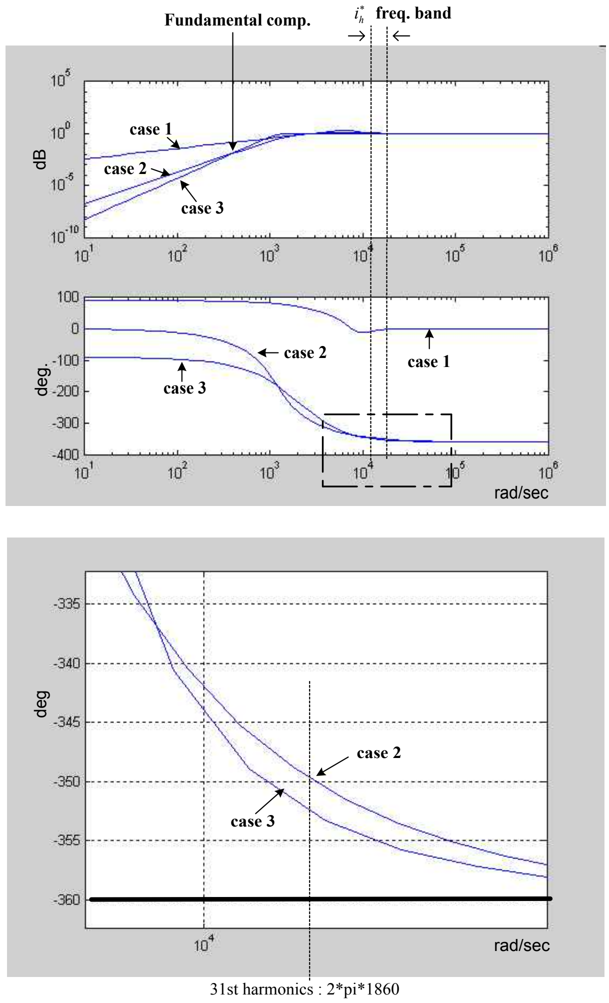


Fig. 8. Frequency response of the filter configurations.

3.2 Simple prediction algorithm

As a current controller, a deadbeat control algorithm is employed to force actual harmonic current coinciding with the above-mentioned reference current through the active filter [8]. Because the underlying harmonic current waveform shows the dominant frequency of around 2 kHz, one-step delayed response inherently appearing in the deadbeat controller provokes a critical problem in the high frequency current waveform. Fig. 9 shows simulation results of the harmonic reference current and the actual line current considering one-step delay.

In order to compensate the delay, a prediction algorithm of the harmonic reference current is devised as follows:

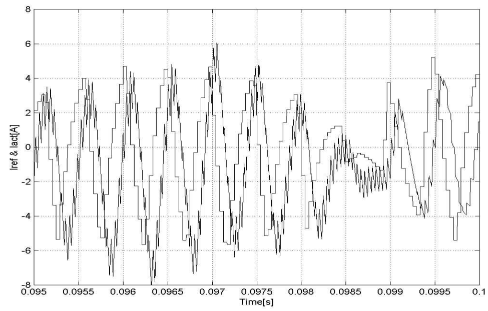
$$V_s(k) \approx 2V_s(k-1) - V_s(k-2) \tag{4}$$

$$i_{ref}(k) \approx (2-\alpha)i_{ref}(k-1) - (1+\alpha)\,i_{ref}(k-2) \tag{5}$$

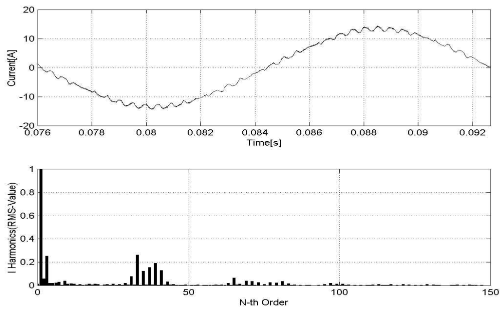
$$V_i(k) = V_s(k) - \frac{L}{T_s}\{\, i_{ref}(k) - i(k) \,\} \tag{6}$$

$$i(k) - i(k-1) = \frac{T_s}{L}\left\{V_s(k-1) - V_i(k-1)\right\} \qquad (7)$$

$$V_i(k) = -\frac{L}{T_s}\left\{2\, i_{ref}(k-1) - i_{ref}(k-2) - i(k-1)\right\} + 2V_s(k-1) - V_i(k-1). \qquad (8)$$

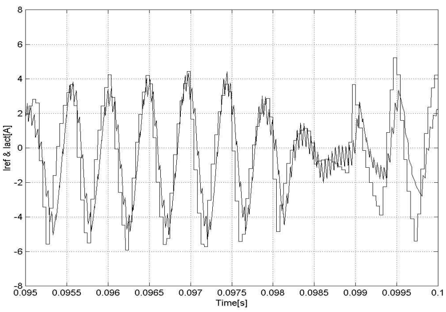


(a) Reference and line current

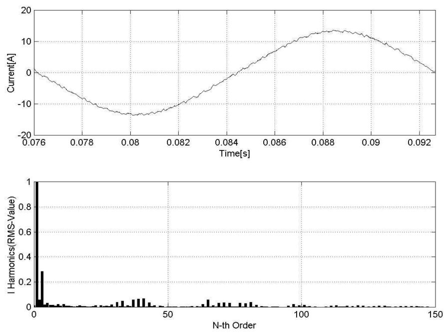


(b) Harmonic spectrum of line current

Fig. 9. Reference and line current without delay compensation.



(a) Reference and line current



(b) Harmonic spectrum of line current

Fig. 10. Reference and line current with prediction scheme.

In this predictive deadbeat control, the control input at the k[th] sampling time is predicted by using the system values at the (k-1)[th] sampling time. In (8), the modulation signal at the k[th] sampling time for SPWM is calculated by using the harmonic reference current, the actual active filter current, the input voltage, and the modulation signal at the (k-1)[th] sampling time or before. Fig. 10 shows the results of active filter current when the prediction deadbeat control algorithm is used. Fig. 11 shows simulation results of the DC-link voltage with and the actual line current.

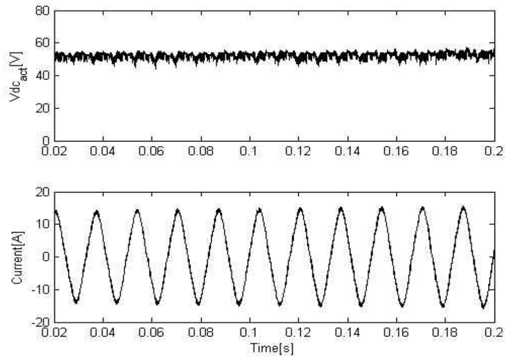


Fig. 11. DC-link voltage and actual line current.

4. Experiment

An experimental setup is established based on a controller TMS320C31; the sampling period is about42μs. The system parameters used in experiment are listed up in Table 1.

Table 1. System parameters.

Parameter	Value
Primary-side voltage	100 Vdc
Secondary-side voltage (converters)	50 Vac
Secondary-side voltage (active filter)	14 Vac
Leakage inductance (converter)	3.6 mH
Leakage inductance (active filter)	0.2 mH
DC capacitor (converter)	3300 uF
DC capacitor (active filter)	470 uF
DC voltage (converter)	100 Vdc
DC voltage (active filter)	50 Vdc
Switching frequency (converter)	540 Hz
Switching frequency (active filter)	12 kHz

Fig.11 shows the experimental results of the active filter current when the proposed prediction algorithm is used. The proposed prediction algorithm has a satisfactory tracking performance without delay. Fig.12 (a) shows the current waveform of the primary-side of transformer when the active filter is not in operation. The current waveform is shown in Fig.13 (a) when the active filter is in action with PWM converters. Fig 12 (b) and Fig. 13 (b) show the harmonic spectrum when active filter is not in operation and when it is in action with the proposed PWM converter, respectively. It is to be noted in Fig

12 (b) and Fig. 13 (b) that the current harmonic components existing in the region of 1-3 kHz are suppressed by the active filter control system proposed in this paper. The THDs of the input currents are 9.4% and 5.1% respectively.

The experimental results are similar to the respective simulation results in Fig. 10. From these experimental results, it can be said that the proposed active filter scheme shows relatively small harmonics in the region of 1-3 kHz that provoke electromagnetic interference with railway track signals and public telecommunication lines.

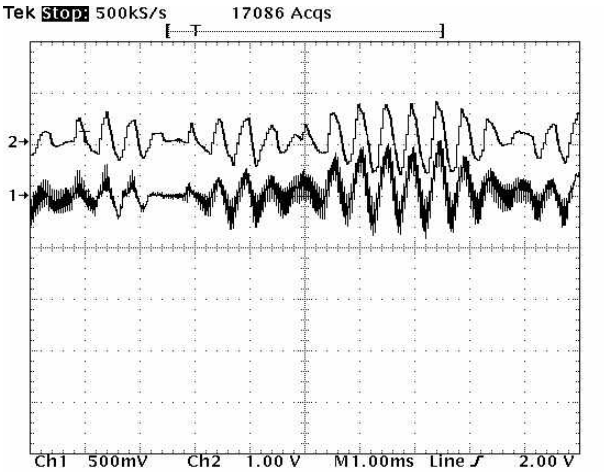
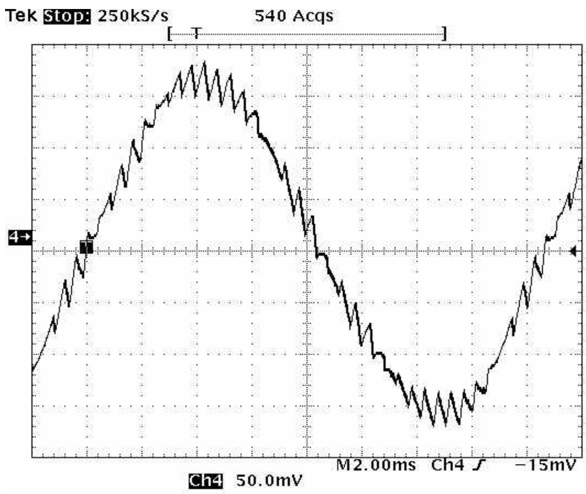
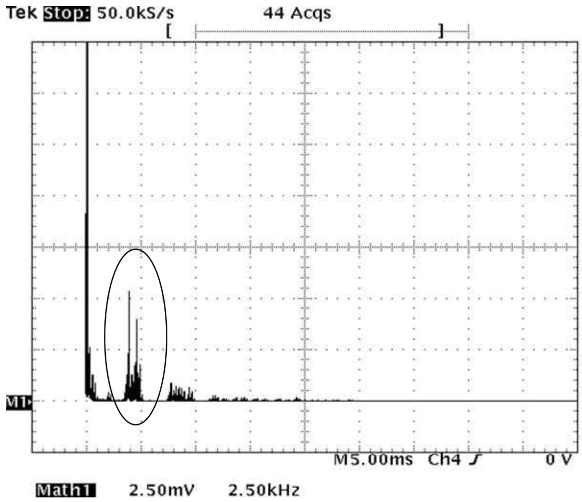


Fig. 11. Reference and line current of active filter.

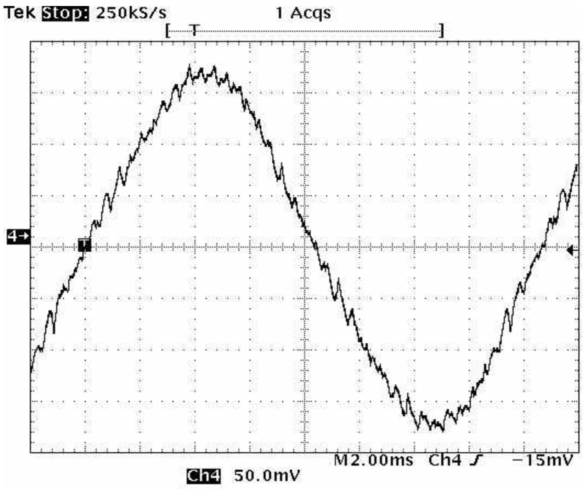


(a) Primary-side current (2ms/div, 5A/div)

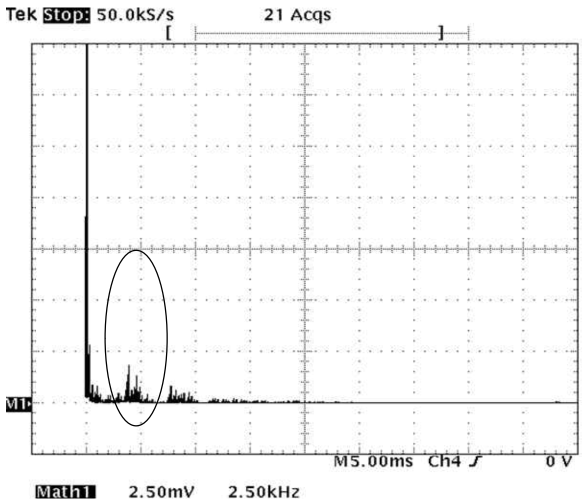


(b) Harmonics spectrum (2.5kHz/div)

Fig. 12. System input current waveform without active filter.



(a) Primary-side current (2ms/div, 5A/div)



(b) Harmonics spectrum (2.5kHz/div)

Fig. 13. System input current waveform with active filter

5. Conclusion

A single-phase active filter for effective compensation of high-order harmonic currents generated by railway locomotive PWM line converters is investigated in this paper. A band-pass digital filter to accurately extract the harmonic reference current in a selected frequency range is presented and a predictive deadbeat-control algorithm makes it possible to compensate the delay inherently appearing in the current control.

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