RESEARCH ARTICLE

Interference mechanism analysis and mitigation measures with railway signalling equipment from harmonics in the traction system.

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Abstract

With the development of high-speed railway and heavy-haul rail transport in China, a large number of new types of electric locomotives and electric multiple units have been put into operation, improving the efficiency and equipment quality of railway transportation. However, harmonics emitted from the traction system and locomotives often interfere with the railway signalling equipment, which can lead to critical malfunction of the equipment. Based on field test data, this paper analyses the interference coupling mechanism and magnitude of traction harmonics to the signalling equipment using a three-element method of interference. It examines the three essential elements of electromagnetic interference, studies harmonic mitigation measures and proposes to solve the problem of interference with signalling equipment by installing a passive high-pass filter in the coupling path. After comparing the effects of several types of filters using simulation tests, this paper verified the validity of the method and concluded that a second-order passive filter is the optimal solution for harmonic interference mitigation.

Keywords: heavy-haul railway; traction harmonics; interference; signalling equipment

1. Introduction

The AC-DC-AC electric drive locomotives, represented by HXD3C locomotives and CRH (China Railway Highspeed) series EMUs, are widely used in the operation of heavy-haul rail transport and high-speed railways in China. Thanks to the use of gate turn-off power devices and PWM modulation technology, the AC-DC-AC drive system has the characteristics of a high power factor, low

Received: 27 April 2020; Revised: 8 July 2020; Accepted: 12 July 2020

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voltage distortion and regenerative braking in the full power range; meanwhile, its content of low-order harmonics such as 3rd, 5th and 7th harmonics (the fundamental frequency is 50 Hz) is reduced, and the content of high-order harmonics close to the switching frequency (mainly between 20th and 50th) is increased, overlapping with the carrier frequency of the signal (1700Hz–2600Hz) [1, 2]. The traction power supply and signalling systems of locomotives and EMUs both use steel rails as the transmission carrier. Thus, when a traction backflow current containing a large number of high-order harmonics is transmitted through the rails, various factors such as longitudinal and lateral imbalance will cause unbalanced current to be generated. As the harmonic content exceeds the threshold, the on-board and ground equipment may erroneously identify the unbalanced current's harmonics as a carrier frequency signal, rather than reporting the erroneous low frequency signal and producing an abnormal braking.

There are many cases of signalling equipment malfunction resulting from harmonic interference, potentially causing abnormal fluctuations in monitoring curve of track circuit and abnormal braking of the electric locomotive in codeless sections. This in turn will directly affect the normal operation and safety of the railway [3]. It is therefore very important to employ harmonic mitigation measures to reduce the harmonic interference.

2. Analysis of the coupling mechanism between harmonics in the traction system and on-board signalling equipment

The coupling mechanism of harmonics in the on-board signalling equipment is analysed according to the three essential elements of EMI, namely the source, the coupling path and the receiver, as shown in Fig. 1. The source of traction system harmonic interference is mainly non-linear equipment, such as electric locomotives. Meanwhile, the coupling path is the traction network and the unbalanced sections of the turnout in the station, and the receiver is the on-board and ground signalling equipment. In what follows, the interference coupling mechanism between harmonics in the traction system and on-board equipment will be demonstrated from these three aspects.

2.1 Source

AC drive electric locomotives and EMUs generally utilize the AC-DC-AC main circuit structure. The AC-DC-AC electric drive system uses a four-quadrant pulse converter as the rectifier of the system. Since it can operate in four quadrants after adopting the PWM technology, it can implement pulse-width modulation as well as the conversion of active power and reactive power, and thus can work as either a rectifier or an inverter.

The four-quadrant converter of the AC-DC-AC electric drive system usually includes two-level and three-level structures, as shown in Figs 2 and 3, respectively. Of these, the CRH1 uses a two-level four-quadrant converter, the CRH2 uses a three-level four-quadrant converter and the CRH5 uses a pair of two-level four-quadrant converters connected in parallel [4, 5].

The four-quadrant converter uses PWM control technology, which greatly reduces the low-order harmonic content. The output voltage only contains the harmonics of certain frequencies, which include the working frequency range of signalling equipment.

2.2 Coupling path

As the common channel of traction current and signal current, rail has the characteristics of common impedance coupling. In the actual field environment, due to the factors of lateral imbalance and longitudinal imbalance [6], there will be traction current imbalance between the two rails. The difference module component in the unbalanced traction current will cause disturbance to the locomotive signal. Fig. 4 is a schematic diagram of unbalanced current received by locomotive induction coil. The receiving coil receives signals from the ground track circuit through the
Fig. 2: Two-level four-quadrant converter: (a) Main circuit diagram of single-phase two-level four-quadrant rectifier; (b) Voltage and current waveforms of single-phase two-level four-quadrant rectifier

principle of electromagnetic induction. The differential current will couple the induced voltage in the coil and act on the locomotive signal loop together with the differential track circuit voltage.

2.3 Receiver

The track circuit TCR receiving coil receives the current information in the ground rail through the principle of electromagnetic induction. Receiving coils are connected in pairs by a group of homonymous ends [7]. The magnetic flux received by the coil is shown in Fig. 5.

The magnetic flux received by each coil consists of three parts: Self-inductance of rail 1, self-inductance of rail 2 and mutual inductance of another coil on the same core [8]. Suppose the flux of the NTH coil is \( \phi_n \) (n = 1, 2, 3, 4), then

\[
\phi_n(t) = \phi_{n1}(t) + \phi_{n2}(t) + \phi_{nm}(t) \quad (1)
\]

The total magnetic flux in the two route circles can be expressed as:

\[
\begin{align*}
\phi_{LA}(t) &= \phi_1(t) + \phi_3(t) \\
\phi_{LB}(t) &= \phi_2(t) + \phi_4(t)
\end{align*}
\quad (2)
\]

The induction voltage of the two locomotive signal receiving antennas is:

\[
\begin{align*}
\varepsilon_{LA}(t) &= -\frac{d\phi_{LA}(t)}{dt} \\
\varepsilon_{LB}(t) &= -\frac{d\phi_{LB}(t)}{dt}
\end{align*}
\quad (3)
\]

Ignoring the loss of cables and other equipment in the on-board equipment, the equivalent circuit of the host machine receiving signals through circuit partial voltage is shown in Fig. 6.

Suppose the input impedance of the locomotive signal host is \( z_h \), and the impedance of a single receiving coil is \( z_c \), then the input voltage of the
Fig. 3: Three-level four-quadrant converter: (a) Main circuit diagram of single-phase three-level four-quadrant rectifier; (b) Voltage and current waveforms of single-phase three-level four-quadrant rectifier

The actual host can be expressed as:

\[
\begin{align*}
\varepsilon_{rA} &= \varepsilon_{LA} \times \frac{Z_s}{Z_s + Z_c} \\
\varepsilon_{rB} &= \varepsilon_{LA} \times \frac{Z_s}{Z_s + Z_c}
\end{align*}
\]

According to the minimum short-circuit current of ZPW-2000 series rail and locomotive signal sensitivity (Table 1), when the interfered harmonic voltage value reaches the receiving voltage sensitivity of the host, it will be recognized and received by the vehicle, which will interfere with the normal operation of signal equipment.

In summary, the coupling mode between harmonics in the traction system and the on-board equipment involves harmonics generated by nonlinear equipment, such as electric locomotives, near the carrier frequency range transmitted on the steel rail as traction current; meanwhile, the
on-site factors unbalance the traction current, which results in the on-board host erroneously recognizing the harmonic interference signal as a carrier frequency signal, causing the vehicle processing logic to report no low frequency and brake the vehicle.

3. Traction harmonic mitigation measures and mechanism analysis

3.1 Research on harmonic mitigation measures

According to the above mechanism analysis, traction harmonic interference with on-board equipment is formed by specific combinations of the source, the coupling path and the receiver. As long as any one of these factors is missing, interference cannot occur. The harmonic interference mitigation measures therefore will be considered from these three aspects.

3.1.1 Measures focusing on the source. The traction converter and the transmission device of locomotives are the main sources of harmonics in railway transport. By adjusting the control parameters of the traction system, using multiple phase shift control technology or adding an RC filter device on the main circuit of the traction drive [9], harmonics could be mitigated from the source. Filtering and mitigating harmonic injection from the sources is a very effective local harmonic mitigation measure. However, due to the wide spectrum coverage of different harmonic sources, the above method can only filter a certain part of the harmonic source, and in some practical cases the best filtering effect cannot always be achieved. There is also the risk of affecting the performance of other aspects of the locomotive.

3.1.2 Measures focusing on the coupling path. Codes can be added to the individual sections where traction harmonic interference has occurred; a fixed low frequency of 27.9 Hz can be sent to solve the problem of no working signal on the coupling path and susceptibility to interference [10]. However, such interference occurs highly randomly, thus it is difficult to effectively pin down the target. Such an approach constitutes a relatively complete solution when building new lines, but cannot be implemented on existing lines.

Some scholars have suggested that passive filtering devices can be installed in traction substations or switching stations to mitigate high-order
harmonics in specific frequency bands, and to reduce high-order harmonics in rails and traction networks [11, 12]. The method is simple in terms of needed equipment, requires a small investment, is convenient in maintenance and remarkable in effect and is currently the most widely used harmonic mitigation method.

3.1.3 Measures focusing on the receiver. The anti-interference ability of the on-board equipment can also be enhanced by optimizing the on-board processing logic, not allowing it to recognize single-frequency signals without low-frequency information. This measure requires specific adjustment for different locomotive models, thus cannot fundamentally solve the problem of harmonic interference.

3.2 Mechanism analysis and design of passive filter to mitigate harmonic interference

Passive filters are widely used in industrial electrical systems. They are a simple, reliable and cost-effective harmonic mitigation solution. At the same time, their convenience and economy make them useful in high-speed and heavy-haul railways. A ready-made parallel passive filter design is a more appropriate solution when the harmonic distortion is not particularly serious. This filter is intended to reduce the harmonic pollution of the system and the harmonic distortion rate, yet it is also used to suppress systemic harmonic resonance [13] and to eliminate the impact of harmonics on the vehicle equipment and signalling system from the coupling path.

Passive filters are filter devices composed of a proper combination of filter capacitors, reactors and resistors; there are many types of such filters. Electrified railways commonly use single-tuned, first-order, second-order, C-type and band-rejection high-pass filters, as shown in Fig. 7.

Fig. 7: Schematic diagram of the topological structure of passive filters: (a) Single-tuned; (b) First order; (c) Second order; (d) C-type; (e) Band-rejection

Comparing these five filters, a single-tuned filter can only filter out harmonics of a specific frequency [14]. First-order and second-order high-pass filters have better filtering effects in terms of resonance and high frequency, however, the resistance branch of the first-order filter must carry all its working current, which generates more heat due to a large active power loss, and the second-order filter’s reactance branch shunt produces a small fundamental loss [14]. The filtering performance of the C-type filter, which has certain engineering applications, is close to that of the second-order filter, with a smaller fundamental loss, but it is also more sensitive to fundamental frequency detuning and component parameter drift [15]. The band-rejection high-pass filter has no fundamental frequency loss and no reactive power under ideal conditions, but the designed capacitors and inductors not only occupy a large space but also have a high cost [16].

The results of the above analysis indicate that the structural characteristics of filters differ, thus the most suitable filter type must be selected based on the actual situation and needs. The second-order high-pass filter is used as an example to introduce the working principle of harmonic mitigation.

The impedance of the second-order high-pass filter is shown in equation (5),

\[
Z_n = \frac{R + (n\omega_0L)^2}{R^2 + (n\omega_0L)^2} + j \left( \frac{R^2\omega_0L}{R^2 + (n\omega_0L)^2} - \frac{1}{n\omega_0C} \right)
\]

According to the structure and impedance expression of the second-order high-pass filter, it can be seen that when \( R \to \infty \), the high-pass filter will become a single-tuned filter, whose resonance frequency is \( \omega = 1/\sqrt{LC} \), when \( \omega \to \infty \), \( Z_n = R \), and the impedance of the filter is limited by \( R \). In fact, if the harmonic frequency is higher than a certain value, the filter achieves high-pass filtering via its low impedance characteristic (\(|Z_n| \leq R \)) in a wide frequency band.

The tuning sharpness of the high-pass filter \( Q \) is defined [15] as

\[
Q = \frac{R}{X_0}
\]

Where \( X_0 \) is the reactance value of \( L \) or \( C \) at the tuning frequency. Equation (6) indicates that the
larger the resistance value, the sharper the tuning curve.

When designing a high-pass filter, the harmonic order to be suppressed must first be determined. The characteristics of the high-pass filter are described by the following two parameters:

\[ f_0 = \frac{1}{2\pi RC} \]  
\[ m = \frac{L}{R^2C} \]  

In equation (7), \( f_0 \) is called the cut-off frequency; the cut-off frequency of the high-pass filter is generally selected to be slightly higher than the highest characteristic harmonic frequency of the installed single-tuned filter. When the frequency \( f \) lies between \( f_0 \) and infinite, the filter has a low impedance smaller than its resistance \( R \). In equation (8), \( m \) is related to \( Q \), which directly affects the shape of the filter tuning curve. The general value of \( Q \) lies between 0.7 and 1.4, and the corresponding \( m \) is 2~0.5. Since the operating characteristics of the high-pass filter are not sensitive to frequency detuning, and its impedance is approximately equal in a relatively wide frequency band, there is no problem in selecting the optimal \( Q \) value.

Of the three parameters of the high-pass filter, \( R \), \( L \) and \( C \), the investment is the least when the filter capacitor installation capacity is the smallest [14]. Following the minimum installation capacity requirements of the filter capacitor, the capacity can be determined to be

\[ C^* = C_{min}^* \approx \sqrt{\sum_{i=k}^{n} \frac{I_{f(n)}^*}{n_i}} \]  

The standard unit values are used in the formula where \( n_i (i = k, \ldots, n) \) is the order of harmonics filtered by the high-pass filter and \( I_{f(n)}^* \) is the \( n \)th harmonic current passing through the filter. After the \( C \) value is determined, the \( R \) and \( L \) can be determined. First, set \( n_k = \frac{f_0}{f_{(1)}} = \frac{1}{2\pi f_{(1)}RC} = \frac{1}{\omega_{(1)}RC} \)  

Then

\[ R = \frac{1}{\omega_{(1)}C} \]  

Using formula (8) and formula (11), the loss is

\[ L = mR^2C = \frac{m}{\omega_{(1)}^2C} \]  

Thus, the smaller the \( m \) or the larger the \( Q \), the smaller the loss of the filter. In formula (12), \( m = 0.5 \) is therefore generally taken.

![Fig. 8](https://academic.oup.com/tse/advance-article/doi/10.1093/tse/tdaa002/6259410)  

Fig. 8: Harmonic characteristics of locomotive under traction conditions: (a) Voltage and current waveforms under traction conditions; (b) Harmonic spectrum distribution under traction conditions
Fig. 9: Current imbalance caused by insulation joint misalignment

Fig. 10: The path of traction current of the emu through the unbalanced section process: (a) Before the first pair enters the unbalanced section; (b) The first pair is in the unbalanced section; (c) After the first pair passes the unbalanced section

Fig. 11: 2000 Hz interference signal displayed in the CF card record (The experimental interface is in Chinese.)
Table 2: The parameters of the four passive high-pass filters

| Type          | C1/uF | C2/uF | L/H | R/Ω |
|---------------|-------|-------|-----|-----|
| First-order   | 2.165 | –     | –   | 120 |
| Second-order  | 2.165 | –     | 0.035 | 120 |
| C-type        | 2.165 | 287.28| 0.035 | 120 |
| Band-rejection| 2.165 | –     | 4.68 | 120 |

4. Field measurement and simulation verification

In this section, a first-order, a second-order, a C-type and a band-rejection high-pass filter will be designed based on actual cases, and a simulation environment of a harmonic interference system will be built based on the passive filter model in Simulink, so that the filters’ mitigation effect can be compared and analysed.

Case analysis: Starting from Sept. 2015, before entering 20G of a station on the Daqin line, the on-board host received 2000 Hz carrier frequency interference in the codeless section of the turnout, and there was no low frequency, which caused the vehicle to judge that the train had entered the station track and set the brake to stop the vehicle.

The voltage and current of the main transformer of the emu, the ground rail side turnout section and the induction coil of the locomotive are tested and analysed comprehensively from the interference source, path and receiver.

Fig. 8 shows the harmonic characteristics of AC-DC-AC locomotive under the actual test traction condition. It can be seen from the figure that the harmonics of the AC-DC-AC locomotive are widely distributed and that the high harmonics in the signal working frequency band are relatively high.

Fig. 9 is a schematic diagram of current imbalance caused by insulation joint misalignment in the turnout section.

Fig. 10 shows the path of the traction current of the emu in the unbalanced section of the turnout. Before the first locomotive pair enters the unbalanced section (Fig. 10(a)), the current released by the wheelset flows back through the rail, and the locomotive induction coil has no current induction. When the first pair is pressed into the unbalanced section (Fig. 10(b)), the current is 100% unbalanced and the harmonic interference is transmitted to STM through the induction coil. After the first pair passes through the insulation (Fig. 10(c)), the traction current is rebalanced and the harmonic induced voltage is offset through the coil.

The yellow circle in Fig. 11 indicates an event during which the induction coil received a wideband interference signal in the codeless section, together with a considerable amount of 2000 Hz interference signal. Field test data showed that the maximum value of the 2000 Hz harmonic in the traction backflow through the unilateral choke transformer lead wire was 559 mA, which was within the locomotive signal sensitivity range.

According to the harmonic test results of the switching station, the designed filter capacity is 1200 kVar, harmonics above 11th order are filtered and the parameter design of the first-order, second-order, C-type and band-rejection filters is shown in Table 2.

Using the multi-conductor transmission line model, the double-line direct supply and backflow traction network model from the substation to the power supply arm of the district substation is built [17, 18]. Fig. 12 is a traction network model of...
Fig. 13: Comparison of the effects of the four filters before and after input: (a) Comparison of voltage and current values before and after the input of the four filters; (b) FFT comparison of current values after the input of the four filters

As shown in Fig. 13(a), after the four filters are put into operation, the network voltage and feeder current distortion have been significantly improved. As can be seen from Fig. 13(b) and Table 3, near the signal frequency band the system needs to focus on the 34th to 52th harmonics, and the filtering effects of the second-order filter and of the C-type filter are close, slightly better than the first-order and band-rejection filters (the filter effect of which is the worst).
Table 3: Comparison of harmonic current values before and after the input of the filters

| Harmonic order | Before filter input | First-order | Second-order | C-type | Band-rejection |
|---------------|---------------------|-------------|--------------|--------|----------------|
| THD of bus voltage | 10.25% | 2.62% | 2.39% | 2.39% | 2.63% |
| Fundamental wave | 27.45 | 34.91 | 33.83 | 33.83 | 38.78 |
| 3rd | 4.96 | 5.07 | 5.08 | 5.08 | 7.15 |
| 7th | 2.99 | 3.27 | 3.55 | 3.55 | 4.63 |
| 9th | 1.28 | 1.44 | 1.68 | 1.68 | 2.04 |
| 11th | 1.26 | 1.46 | 1.63 | 1.63 | 2.06 |
| 13th | 1.15 | 1.35 | 1.29 | 1.29 | 1.91 |
| 31th | 2.51 | 0.66 | 0.55 | 0.55 | 0.94 |
| 33th | 1.32 | 0.25 | 0.23 | 0.23 | 0.36 |
| 34th | 0.28 | 0.06 | 0.05 | 0.05 | 0.08 |
| 35th | 2.45 | 0.61 | 0.56 | 0.56 | 0.86 |
| 37th | 1.07 | 0.39 | 0.37 | 0.37 | 0.55 |
| 39th | 1.10 | 0.53 | 0.52 | 0.52 | 0.75 |
| 40th | 0.52 | 0.27 | 0.27 | 0.27 | 0.38 |
| 41st | 1.15 | 0.63 | 0.63 | 0.63 | 0.89 |
| 46th | 0.04 | 0.02 | 0.02 | 0.02 | 0.03 |
| 52nd | 0.17 | 0.12 | 0.13 | 0.13 | 0.17 |

Table 4: Active loss of the filters

| Active loss | First-order | Second-order | C-type | Band-rejection |
|-------------|-------------|--------------|--------|----------------|
| P (kW)      | 41.29       | 0.35         | 0.36   | Approx. 0       |

According to research on the traction backflow test results of high-speed railways, rail backflow current accounts for 50% to 60% of the total backflow current [19]. The simulation results indicate that, after the four filters are put into operation, the 34th, 40th, 46th and 52nd harmonic currents of the signal flowing through the rails and their nearby subharmonic currents are reduced to below 0.40 A, less than the locomotive signal sensitivity. This verifies the effectiveness of the filter in mitigating harmonics.

The active power loss of the four filters obtained from simulation analysis is shown in Table 4.

Of the four filters, the first-order filter has the largest active loss (118 times that of the second-order filter) and the band-rejection filter has the smallest loss (almost 0). There is a certain amount of active loss in the second-order and C-type, but the loss value is small.

Based on the above analysis, the four filters can effectively filter out high-order harmonics; the second-order and C-type filters have better filtering effects, and the band-rejection filter has the smallest active loss value, but the C-type filter has an additional capacitor, while the inductance value of the band-rejection filter is large. Considering the filtering effect, active loss and cost, the second-order filter is the best choice for resolving harmonic interference.

4. Conclusions

This paper analyses the interference coupling mechanism of traction harmonics to signalling equipment based on the three essential elements of EMI, and studies the harmonic mitigation measures around the three elements. Finally, through comprehensive comparison and analysis, it is concluded that the installation of passive filters in the interference path is the simplest and most effective solution for harmonic mitigation, and the effectiveness of the method is verified by example simulation. The specific conclusions are as follows:

(1) Interference with on-board equipment from harmonics in the traction system is mainly caused by traction current imbalance. When harmonics near the signalling carrier frequency are coupled to the locomotive induction coil through the unbalanced current and mistakenly received by the on-board equipment, the on-board host will identify the harmonic interference signal without low frequency as an indication that the vehicle’s brakes should be activated.

(2) By conducting research into measures of mitigating harmonics in the traction system from the three aspects of source, coupling path and receiver, it is concluded that installing a passive filter on the coupling path is the simplest
and most effective harmonic mitigation measure. (3) This paper used a harmonic mitigation simulation test based on a passive filter scheme to analyse and verify the effectiveness of the passive filter in mitigating the interference of traction system harmonics with on-board signalling equipment. The four different filters are compared and analysed, and the second-order passive filter is determined as the best choice for resolving harmonic interference.

Conflict of Interest statement. The authors have declared that no conflict of interest exists.

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