Postprint: Railway Harmonic Suppression Based on High-Pass Filters

Authors: Ma Qizhi, Xie Xuqin, Deng Zhuohui, Ruan Baishui, ZHANG Gang

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Abstract

With the extensive deployment of AC-DC-AC electric multiple units (EMUs) in electrified railways, the issues of traction network harmonic amplification and resonance induced by high-order harmonics generated from EMUs have become increasingly severe. To address this problem, this paper establishes an equivalent circuit model of the traction network, performs theoretical analysis and simulation verification on the resonance and harmonic amplification characteristics, and introduces a method for suppressing harmonic current gain by installing a high-pass filter on the auxiliary winding of the traction transformer within the locomotive. Finally, the effectiveness of the proposed method in suppressing harmonic gain is verified through theoretical calculations and simulations, offering valuable reference for mitigating harmonic hazards to the traction network.

Full Text

Preamble

Research on Railway Harmonic Suppression Based on High-Pass Filter

Ma Qizhi[1], Xie Xuqin[2], Deng Zhuohui[3], Ruan Baishui[1], Zhang Gang[1]

[1]Beijing Jiaotong University, School of Electrical Engineering, Beijing 100044, China
[2]Beijing Jiaotong University, Beijing Engineering Technology Research Center of Rail Transit Electrification, Beijing 100044, China

Author Biographies:
Ma Qizhi (female, born 1968) holds a master' s degree. Her research focuses on power electronics and electric drives.

Xie Xuqin (male, born 1990) holds a master' s degree. His research focuses on EMU key technologies and traction networks.

Abstract: With the extensive deployment of AC-DC-AC electric multiple units (EMUs) in electrified railways, the harmonic amplification and resonance problems in traction networks caused by high-order harmonics generated by EMUs have become increasingly severe. To address this issue, this paper establishes an equivalent circuit model of the traction network, conducts theoretical analysis and simulation verification of traction network resonance and harmonic amplification characteristics, and introduces a method for suppressing harmonic current gain by adding a high-pass filter to the auxiliary winding of the traction transformer onboard the locomotive. Finally, the effectiveness of this method in suppressing harmonic gain is verified through theoretical calculations and simulations, providing valuable reference for preventing harmonic hazards to traction networks.

Keywords: Railway traction power supply system, harmonic transmission characteristics, high-pass filter, Matlab simulation

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1 Introduction

The widespread adoption of AC-DC-AC EMUs in electrified railways has altered the harmonic characteristics of railway traction power supply systems. In addition to low-frequency harmonics (3rd, 5th, 7th, 9th, etc.), numerous high-order harmonics have emerged in the high-frequency band. Although the content of these high-frequency harmonics is not high, they significantly increase the likelihood of harmonic resonance in the system. When traction network parameters match the high-order characteristic harmonics of the locomotive, resonance and severe harmonic amplification occur, generating substantial overvoltage and overcurrent that endanger traction substations and insulation equipment such as Scott locomotives, causing equipment burnout and affecting safe system operation. Cases of accidents caused by severe harmonic current amplification at traction substations due to system resonance have been reported.

Currently, there are two main methods for harmonic suppression in traction networks [1]. The first method involves installing compensation devices at traction substations. Shunt passive filters are connected at traction substations to change the impedance characteristics of the traction network and suppress harmonic gain. However, since the traction network rated voltage is 25 kV, this approach requires additional step-down transformers, substantially increasing costs. The second method involves installing compensation devices on the auxiliary winding of the traction transformer onboard the locomotive, achieving the same harmonic suppression effect. Compensation devices are mainly divided into two categories: active filter devices that compensate for harmonics generated by the locomotive to fundamentally eliminate harmonic effects, and passive filter windings composed of capacitors, inductors, and resistors that change traction network impedance characteristics to reduce harmonic gain. The former is difficult to implement and costly, with limited current applications, while the latter is relatively simple to implement, offering advantages of low cost, simple structure, and stable operation.

This paper establishes a joint simulation model of the traction network equivalent circuit, conducts theoretical analysis and simulation verification of traction network resonance and harmonic amplification characteristics. Since high-pass filters can eliminate high-order harmonic bands, this paper introduces a method for suppressing harmonic current gain by adding a high-pass filter to the auxiliary winding of the traction transformer onboard the locomotive. The effectiveness of this method is verified through theoretical calculations and simulations, providing valuable reference for preventing harmonic hazards to traction networks.

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2 Railway Traction Power Supply System Equivalent Circuit Model

2.1 Railway Traction Power Supply System

The Auto-Transformer (AT) power supply method is widely adopted in China's high-speed railways. The system structure is shown in Fig. 1 [Figure 1: see original paper]. The main components include [2-3]: (1) Scott transformers installed in traction substations, which convert three-phase 110 kV or 220 kV voltage into two-phase 55 kV voltage with a 90° phase difference. In AT power supply mode, a traction substation is typically installed every 30–50 km to connect the entire traction network through sections; (2) Auto-transformers. In AT power supply mode, an AT is installed approximately every 10 km, with its two ends connected to the feeder line and contact wire, and its neutral point connected to the rail. The auto-transformer steps down the 55 kV voltage to approximately 27.5 kV to supply the locomotive; (3) Traction network system. The traction network system has a complex geometric structure composed of contact wires, messenger wires, negative feeder lines, protective lines, rails, and buried ground wires, as shown in Fig. 2 [Figure 2: see original paper].

As seen in Fig. 2, the traction network system is complex with numerous conductors. Literature [4] introduces a multi-conductor transmission line model to simplify the number of conductors. During modeling, messenger wires and reinforcement lines can be equivalently merged into contact wires using the multi-conductor transmission line inductance matrix method, while buried ground wires can be equivalently merged into rails, ultimately simplifying into a three-conductor equivalent circuit without affecting model accuracy. Literature [5] presents the equivalent degradation process for multi-conductor transmission line systems, through which the overall external impedance Z and admittance Y of the multi-conductor transmission line system can be obtained through iterative calculations. The traction network system can be simplified into the equivalent circuit shown in Fig. 3 [Figure 3: see original paper], where ZSS is the substation equivalent impedance (including source reactance and traction transformer reactance); Ix is the traction network current at distance x from the substation; I1 is the locomotive current flowing toward the substation (SS) direction; I2 is the locomotive current flowing toward the section post (SP) direction; IT is the locomotive current; L1 is the distance from locomotive to substation; L2 is the distance from locomotive to section post; Z1 and Z2 are the equivalent impedances seen from the locomotive position toward the substation and section post directions, respectively [6].

2.2 Traction Network System Equivalent Circuit Model

According to the steady-state equations and equivalent circuit of distributed-parameter power transmission lines, the distributed-parameter circuits on both sides of the locomotive are equivalently represented as T-type circuits, as shown in Fig. 4 [Figure 4: see original paper]. In Fig. 4, the expressions for ZT1, ZT2, YT1, and YT2 are:

$$ZT1 = \frac{Z_0(\cosh\gamma L_1 - 1)}{\sinh\gamma L_1}, \quad YT1 = \frac{\sinh\gamma L_1}{Z_0}$$

$$ZT2 = \frac{Z_0(\cosh\gamma L_2 - 1)}{\sinh\gamma L_2}, \quad YT2 = \frac{\sinh\gamma L_2}{Z_0}$$

where Z0 is the line characteristic impedance, $Z_0 = \sqrt{Z/Y}$; is the line propagation coefficient, $\gamma = \sqrt{ZY}$; Z and Y are the per-unit-length equivalent impedance and admittance of the traction network line, respectively.

Treating the locomotive as a current source, the voltage and current at the beginning end are determined. According to the uniform transmission line characteristic equations, the voltage and current at a distance x from the beginning end are:

$$\dot{U}_x = \dot{U}_1\cosh\gamma x - \dot{I}_1 Z_0\sinh\gamma x$$

$$\dot{I}_x = \dot{I}_1\cosh\gamma x - \frac{\dot{U}_1}{Z_0}\sinh\gamma x$$

The locomotive current source impedance relative to the entire traction network is the parallel combination of the above impedances. Treating the section post as an open circuit, the impedances Z1 and Z2 from the locomotive toward the traction substation and section post can be obtained using circuit principles, as shown in Fig. 5 [Figure 5: see original paper]:

$$Z_1 = Z_0 \frac{Z_{SS} \cosh \gamma L_1 + Z_0 \sinh \gamma L_1}{Z_{SS} \sinh \gamma L_1 + Z_0 \cosh \gamma L_1}$$

$$Z_2 = Z_0 \frac{\cosh \gamma L_2}{\sinh \gamma L_2}$$

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3 Harmonic Transmission Characteristics Analysis

Substituting the locomotive as a current source, the voltage and current at the beginning end are:

$$\dot{U}_1 = \frac{Z_1 Z_2}{Z_1 + Z_2} \dot{I}_T, \quad \dot{I}_1 = \frac{Z_2}{Z_1 + Z_2} \dot{I}_T$$

Substituting Eq. (5) into Eq. (6), the harmonic current at distance x from the locomotive is:

$$\dot{I}_x = \dot{I}_T \frac{\cosh \gamma L_2 [Z_{SS} \sinh \gamma (L_1 - x) + Z_0 \cosh \gamma (L_1 - x)]}{Z_{SS} \sinh \gamma L + Z_0 \cosh \gamma L}$$

The traction network harmonic current gain expression is:

$$G = \frac{\dot{I}_x}{\dot{I}_T} = \frac{\cosh \gamma L_2 [Z_{SS} \sinh \gamma (L_1 - x) + Z_0 \cosh \gamma (L_1 - x)]}{Z_{SS} \sinh \gamma L + Z_0 \cosh \gamma L}$$

When the denominator of Eq. (8) approaches zero, the harmonic gain reaches its maximum and the line experiences resonance. Eq. (8) shows that the main factors affecting the harmonic resonance frequency of the traction power supply system include the per-unit-length impedance and admittance of the traction network, traction network length, locomotive position, and substation equivalent impedance.

Fig. 6 [Figure 6: see original paper] shows the harmonic current gain measured at the substation for different traction network lengths with the locomotive position fixed (20 km from the substation). Figs. 6a–6c illustrate the harmonic gain for traction network lengths of 20 km, 30 km, and 40 km, respectively, demonstrating that longer traction networks result in lower resonance frequencies.

Fig. 7 [Figure 7: see original paper] shows the harmonic current gain measured at the substation when the locomotive is at different positions for a 30 km traction network. Figs. 7a–7c correspond to locomotive distances of 10 km, 20 km, and 30 km from the substation, respectively, showing that locomotive position does not affect the resonance frequency, but harmonic gain increases with distance from the substation.

Fig. 7 reveals that for a 30 km traction network, the resonance point occurs near the 40th harmonic. When the harmonic current frequency band generated by the network-side converter coincides with this point, the locomotive' s harmonic current is severely amplified in the traction network, causing extremely adverse effects on the traction power supply system. To verify the effectiveness of the harmonic suppression measures, subsequent simulations in this paper primarily focus on a 30 km traction network, with the filter frequency band set to the 37th–43rd harmonics.

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4 Harmonic Suppression Method Based on High-Pass Filter Branch

This paper employs a high-pass filter installed on the auxiliary winding of the traction transformer onboard the locomotive to suppress harmonic current amplification, as shown in Fig. 8 [Figure 8: see original paper]. Here, US and US1, US2 represent the primary and secondary transformer voltages, respectively, while C, L, and R denote the filter capacitor, inductor, and resistor.

The distributed-parameter traction network equivalent model after filter installation is shown in Fig. 9 [Figure 9: see original paper], where ZF is the equivalent impedance of the filter branch (referred to the primary side of the traction transformer).

Applying circuit theorems, the network input current and voltage from the locomotive toward the traction substation direction are:

$$\dot{I}_1 = \frac{Y_1}{Y_1 + Y_2 + Y_F}\dot{I}_T, \quad \dot{U}_1 = \frac{1}{Y_1 + Y_2 + Y_F}\dot{I}_T$$

where Y1, Y2, and YF are the admittances of Z1, Z2, and ZF, respectively.

The harmonic current gain after filter installation can be derived from the uniform transmission line characteristic equations as:

$$G' = \frac{\dot{I}_x}{\dot{I}_T} = \frac{\cosh\gamma L_2[Z_{SS}\sinh\gamma(L_1 - x) + Z_0\cosh\gamma(L_1 - x)]}{Z_{SS}\sinh\gamma L + Z_0\cosh\gamma L + (Z_{SS}\cosh\gamma L_1 + Z_0\sinh\gamma L_1)Z_0\cosh\gamma L_2 Y_F}$$

To filter high-order harmonics, the high-pass filter is analyzed. The impedance expression for the high-pass filter is:

$$Z_F = \frac{R \cdot j\omega L}{R + j\omega L} + \frac{1}{j\omega C}$$

The characteristic angular frequency 0 of the high-pass filter is set as:

$$\omega_0 = 2\pi f_0 = \frac{1}{\sqrt{LC}}$$

The quality factor Q is defined as:

$$Q = \omega_0 CR = \frac{R}{\sqrt{L/C}}$$

Letting = / 0, Eq. (11) can be simplified to:

$$Z_F = \frac{(\omega_0 L)^2}{R} \cdot \frac{\lambda^2 + jQ\lambda}{1 + jQ\lambda} = \frac{R}{Q^2} \cdot \frac{\lambda^2 + jQ\lambda}{1 + jQ\lambda}$$

Squaring both sides of Eq. (14) yields the squared magnitude of the high-pass filter impedance:

$$|Z_F|^2 = \frac{R^2}{Q^4} \cdot \frac{\lambda^4 + Q^2\lambda^2}{1 + Q^2\lambda^2}$$

Differentiating the above expression reveals the minimum impedance frequency:

$$\omega_{\min} = \omega_0 \sqrt{\frac{Q^2 - 2}{2Q^2 - 2}} \quad (Q > 0.64)$$

When Q > 2, min 0, meaning the minimum impedance frequency approximately equals the characteristic frequency.

From Eq. (12), the relationship between inductance L and capacitance C for the high-pass filter is:

$$C = \frac{1}{(2\pi f_0)^2 L}$$

Fig. 10 [Figure 10: see original paper] shows the impedance variation trend of the high-pass filter with quality factor Q. For small Q values, the filter exhibits poor frequency selectivity with minimum impedance frequency at infinity, enabling filtering of broad harmonic bands. For large Q values, frequency selectivity improves with a defined minimum impedance frequency, but high-order harmonic impedance increases, making high-order harmonic filtering less effective [7-8]. To achieve effective filtering, Q is selected in the range of 2–8.

From the above analysis, smaller L values result in smaller high-pass filter impedance ZF and better filtering performance. Based on this analysis, with Q = 2–8, characteristic frequency f0 = 50 × 40 Hz, and small L values, typical parameters for C, L, and R (on the transformer secondary side) are selected as shown in the table below.

Table: Typical Parameters of High-Pass Filter

Inductance (H)	Capacitance (F)	Resistance (Ω)
50	316	2.0
100	158	4.0

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5 Simulation and Verification

During locomotive operation, in addition to low-order harmonics (3rd, 5th, 7th, 9th), the high-order harmonic current frequency band is primarily determined by the switching frequency of the four-quadrant converter. This paper references the CRH1 four-quadrant converter to build a Matlab simulation model with a switching frequency of 1 kHz, using double-edge natural sampling modulation. The main characteristic harmonics are the 37th, 39th, 41st, and 43rd. Fig. 11 [Figure 11: see original paper] shows the converter grid-side current waveform, and Fig. 12 [Figure 12: see original paper] presents its spectrum analysis.

When establishing the traction network simulation model, multiple 1 km distributed-parameter lines are selected to build the complete traction network circuit model, making it closer to reality [9]. Fig. 13 [Figure 13: see original paper] shows the unit-length three-conductor line model. Based on previous calculations, when the line length is 30 km, the resonance point occurs near the 40th harmonic, close to the locomotive' s high-order harmonic band. To verify harmonic suppression effectiveness, a total line length of 30 km is selected.

Connecting the traction substation, traction network, auto-transformer, and other models according to the AT traction network operation mode yields the traction power supply system model. When the traction network length is 30 km and the locomotive generates high-order harmonics near the 40th, the traction network experiences resonance. Fig. 14 [Figure 14: see original paper] shows the AC voltage and current measured at the traction substation during resonance, and Fig. 15 [Figure 15: see original paper] presents the current spectrum analysis. The results show severe distortion of the AC current at the substation, with lost sinusoidal characteristics, extremely high harmonic content, and THD reaching 42.76%. Voltage exhibits large fluctuations, seriously endangering the traction network and other locomotives.

Fig. 16 [Figure 16: see original paper] shows the contact wire current measured at the traction substation after installing the high-pass filter. The results demonstrate that AC current harmonic content is significantly filtered, restoring sinusoidal characteristics.

Fig. 17 [Figure 17: see original paper] presents the current spectrum analysis after installing two groups of high-pass filters. The results show that harmonic gain is greatly reduced after adding the filter branch, verifying the effectiveness of the filter branch. Moreover, the second parameter set shows more obvious filtering effects, confirming the rationality of the high-pass filter design.

6 Conclusion

This paper establishes an equivalent circuit model of the traction network and conducts theoretical analysis and simulation verification of traction network resonance and harmonic amplification characteristics. Simulation results demonstrate that when the traction network resonance point coincides with the locomotive' s high-order characteristic harmonics, severe resonance occurs, causing current distortion. To address this problem, this paper introduces a method for suppressing harmonic current gain by adding a high-pass filter to the auxiliary winding of the traction transformer onboard the locomotive. Calculation and simulation results show that after adding the filter winding, locomotive high-order harmonic current gain is significantly reduced, verifying the effectiveness of the method. This provides valuable reference for preventing harmonic hazards to traction networks.

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