Influence of electric traction system on power grid harmonics

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Abstract. This paper analyzes the traction power supply system and traction substation of electrified railway. Due to the use of a large number of power electronic devices, the electric locomotive has strong nonlinear characteristics. Focusing on harmonics, this paper studies the harmonics generated by AC-DC and AC-DC-AC electric locomotives respectively. Based on this, the mathematical model of the power supply system of electrified traction locomotive is established, and the harmonic model is established. The simulation results are in good agreement with the actual conditions.

1. Introduction
Nowadays, electrified traction locomotive combines lots of new technologies in many fields. It has big transport capacity, high volume, speediness, energy-saving, environment-friendly, and many other advantages [1]. With the rapid development of high-speed railway electrification in China, by the end of 2017, the length of railroad lines in service has reached 127,000km, of which 25,000km is high-speed railway, accounting for 66.3% of the world's total high-speed railway, and ranking first in the world. According to the 13th Five-Year Plan for Railway Development, by the year of 2020, the length of railroad lines in service nationwide will reach about 150,000 kilometres, and the electrification rate will reach about 70%.

Heavy-haul and high-speed railway are the main development directions of railway in China in the future. The conventional external voltage classes of the system are mainly 110kV and 220kV, most of which are 110kV. At present, the major locomotive used in heavy-haul railway in China is AC-DC electric locomotive, whose control mode is phase-controlled rectifier. When getting electric energy from the power grid, the locomotive will generate low-order harmonics of 3, 5, 7, and so on, these will be injected into the power system through the traction network. The single-phase modulation technology–PWM is adopted in AC-DC-AC electric locomotive, thus the third and fifth harmonics are reduced, but the higher harmonics near the switching frequency increase. Harmonics will do great harm to the whole power supply system, mainly: reduce the efficiency of power generation, power transmission and electricity consumption, leading to the increase of electrical loss; make noise, which will affect the normal life of the surrounding residents; and the traction electric network is distributed parameter element, so that resonance may occur when harmonic current passes through the traction network., causing fold increase of the harmonic current, overvoltage, affecting the safe and stable operation of power supply equipment. Therefore, it is of great necessity to conduct in-depth analysis and research on harmonics of electric traction system.
At present, the research results on harmonics of electric traction system mainly focus on deriving the harmonic content of a certain locomotive from the mechanism, most of which simplify the locomotive load into harmonic current source; analyzing the influence of electrified traction locomotives on power quality based on the field measured data; establishing the electromagnetic transient simulation models according to the different research objects by simulation software; modelling of the harmonic source and negative sequence source and power flow calculation of harmonic and negative sequence based on the field measured data; the resonance characteristics of traction power supply system, etc. This paper establishes a harmonic model for the power supply system of electrified traction locomotive, and simulates and analyzes the traction conditions. The simulation results show that the model is typical.

2. Harmonic of Electrified traction locomotive

2.1. Traction power supply system

Power systems and transmission lines transfer power from power plants to traction power supply systems. The voltage level of power grids, to which traction power supply systems are connected, is generally 110kV or 220kV. At present, most of general electrified railways in China are connected to 110kV power grids, while high-speed passenger dedicated lines are connected to 220kV power grids [2].

The simple principle of the electrified railway power supply system is shown in Fig.1. In Fig.1, 1 is a three-phase AC high-voltage transmission line; 2 is a traction substation; 3 is a feeder line; 4 is a contact line; 5 is track or ground as a traction current regression channel; 6 is a return line; 7 is an electric locomotive.

In general traction power supply system is composed of traction substation and traction network, in which the traction network includes feeder line, contact line, track circuit, return line and other parts [3].

![Figure 1. Structure diagram of traction power supply system](image)

In the whole traction power supply system, traction substation plays a key role, and the biggest role of it is to realize varying voltage and phase transformation. It can convert the three-phase high-voltage (110kV or 220kV) power supply of the upper power grid into a low-voltage (25 kV or 27.5 kV) power grid which can supply electric locomotives and meet the needs of locomotive traction. Traction substation is usually installed near the railway, ordinarily using more than one disconnected power to supply electricity, or by a single power to supply power through double circuit transmission line, to raise the efficiency of the power supply system. Combined with the current situation in foreign countries, the key types adopted are: single-phase traction substation, three-phase YN, d11 connected traction substation, three-phase-two-phase traction substation.

The single phase traction substation includes single phase connected traction substation and single phase V, v connected traction substation. Single-phase connected traction substation is simple in structure and low in investment in comparison and can increase capacity utilization greatly, especially when the loads of two power supply arms is consistent, which are mostly used in China at present. As is shown in Fig2, this type of substation is only connected by two phases from the power system, so there is obvious negative sequence current in the power grid. While single phase V, v connected traction substation adopts 2 single phase traction transformers, the connection form is V, v.
2.2. AC-DC electric locomotive

AC-DC electric locomotive first transforms three-phase electric energy into two single-phase electric energy supply arms through three-phase-two-phase traction converter (such as three-phase YNd11 connection and balanced connection transformer), and then transmits electric energy to the train through the traction network of direct power supply or direct power supply with reflux power supply. Converter-driven DC motors, which have nonlinear, mobility and high-power load characteristics, will inject a large number of latent wave and negative sequence current through the traction network and traction transformer network, which will pose a greater threat to the safety and stability of power grid operation.

At present, the main electric locomotive used in Chinese electrified railway is the Shaoshan series electric locomotive, which is developed independently by China.

The harmonic content diagram of SS-4G electric locomotive is shown in Fig. 4.
Table 1. Measured harmonic currents of 8K AC-DC electric locomotives

| order | 3   | 5   | 7   | 9   | 11  | 13  | 15  |
|-------|-----|-----|-----|-----|-----|-----|-----|
| content (%) | 21.47 | 13.98 | 5.85 | 5.25 | 5.28 | 3.76 | 3.193 |

The spectrum of current on line side is shown in Fig 5.

Figure 5. Measured spectrum of current on line side

It can be concluded that the AC-DC electric locomotive mainly generates odd harmonics of 3 and 5 order in the low frequency band. As the order of harmonics increases, the content of harmonics generated by the AC-DC electric locomotives gradually decreases. The 3-order harmonic content is the largest.

2.3. AC-DC-AC electric locomotive

Different from the general speed railway, the traction transformer of the high speed railway adopts V, v connection transformer, and the installation capacity is larger. The traction electric network adopts full parallel AT power supply mode to reduce electromagnetic interference, but the structure is more complex and the power supply interval is longer. The AC-DC-AC electric locomotive, compared with the general speed railway, runs faster and the power is higher, the power factor is close to 1. With PWM rectifier, the harmonic current of AC side is smaller, the low-frequency harmonic component is smaller, low frequency harmonic components are smaller, and the low-order harmonic is improved, but the current frequency band becomes wider, the high-order harmonic distribution is wider.

Table 2. Measured harmonic currents of 8K AC-DC electric locomotives

| Type | Voltage level number | Switching frequency/Hz | Low-order harmonics | High-order harmonics |
|------|----------------------|------------------------|---------------------|---------------------|
| CRH1 | 2                    | 450                    | 3, 5, 7             | 31, 33, ...41      |
| CRH2 | 3                    | 1250                   | 3, 5, 7             | 45, 47, ...55      |
| CRH3 | 2                    | 1250                   | 3, 5, 7             | 95, 97, ...105     |
| CRH5 | 2                    | 250                    | 3, 5, 7             | 15, 17, ...25      |

In China, AC-DC-AC electric locomotives are mainly "Harmony" series of freight electric locomotives, such as HXD1, HXD2, HXD3 etc. And currently the widely used CRH China Railway High-speed is CRH1, CRH2, CRH3 and CRH5 etc.

Table 2 shows the basic data and characteristic harmonic frequencies of various types of Harmony EMUs which are widely used at present.

According to document [4] Fig.6 shows the measured harmonic current content of the net side.
Figure 6. Measured harmonic current content of the net side

Theoretical analysis shows that low-frequency harmonic component of AC-DC-AC electric locomotive should be small, while high-frequency harmonic component large, but in reality the effect is not ideal enough, because the control of low harmonics is subject to certain conditions. However, generally, compared with AC-DC electric locomotive, the high-frequency harmonic components generated by AC-DC electric locomotive are very small.

3. Harmonic model of traction power supply system

3.1. Load harmonic source modelling

Modelling harmonic source of electric traction locomotive load is the basic premise of harmonic analysis and harmonic control of traction power supply system. Previous analysis shows that traction load is a typical high-power harmonic source, which has the characteristics of asymmetry and fluctuation compared with general power system load.

Figure 7. Equivalent structure model of traction power supply system

In the modelling of harmonic source of traction power supply system, the magnitude of DC side current and the waveform of AC side current of traction load are mainly determined by its own characteristics, which are basically independent of AC side grid parameters and can be regarded as harmonic current source [5]. The equivalent structure model of traction power supply system is shown in Fig.6. A simplified harmonic current source model is used to describe the harmonic characteristics of traction loads. The real and imaginary parts of each harmonic current in Fig.6 are expressed as functions of fundamental positive sequence voltage, current RMS and phase difference.

According to the working principle of traction load control system of electrified traction locomotive, the traction control system of electric locomotive determines the armature current of traction motor by the speed and level of train running. The voltage equation of traction circuit is shown in equation (1).

\[
U_j = C_{\phi n_j} + I_j (R_s + R_u)
\]  \hspace{1cm} (1)

In the formula, \( R_s \) is armature resistance, \( R_u \) is stray resistance of traction circuit, \( \phi \) is main pole magnetic flux, \( n_j \) is traction motor speed. The DC voltage of the rectifier circuit can be determined by equation (1), and according to the working principle of the rectifier circuit, the working state of the rectifier bridge can be determined, and then the trigger angle of the thyristor can be determined. That is, the amplitude and phase angle of harmonic current generated by traction load under this working condition are constant. Therefore,
the harmonic generated by traction load of electrified traction locomotive can be determined only by the traction load operation condition.

In order to make the model more practical in engineering and to make the harmonic source model more descriptive under the test of measured data, a three-phase fundamental positive sequence power exchanged between locomotive and grid-side power supply system is proposed as the excitation of the model to evaluate the harmonic characteristics of traction load, and the basic form of the model is given as follows:

\[ \hat{i}_h = F_h(P_1, Q_1, C), h = 1, 2, \ldots, N \]  

(2)

In the formula, \( \hat{i}_h \) is the phasor of h-order harmonic current injected into the network side, \( P_1, Q_1 \) are the fundamental positive sequence active and reactive power exchanged between locomotive and power supply system; \( C \) is a set of model parameters. It can be seen from equation (2) that by this model \( \hat{v}_h \) can be obtained without fundamental power flow calculation when solving harmonic current because of the use of three-phase fundamental power as excitation, which brings great convenience to practical engineering application.

3.2. Traction condition

The measured data collected from three 110kV traction substations in reference [6] classify the traction conditions into seven typical categories, while some traction conditions have several sets of data samples, which are listed as events, as shown in Table3.

The data samples of the same type of traction condition are different from each other in the starting time of sampling, sample size and the average power \( P \) of the locomotive during this period, it gives:

\[ P = \frac{P_1 + P_2 + \ldots + P_n}{n} \]  

(3)

In the formula, \( n \) is sampling point number; \( P_n \) is active power of sampling point \( n \).

| Event | Average power (MW) | Traction substation | Traction side load distribution | Operation state |
|-------|--------------------|---------------------|--------------------------------|----------------|
| 1     | 10.39              | V/V                 | Two armed                      | Level          |
| 2     | 9.47               | V/V                 | Single armed                   | Level          |
| 3     | 3.23               | balance             | Single armed                   | Level          |
| 4     | 3.36               | balance             | Single armed                   | Level          |
| 5     | 1.72               | balance             | Single armed                   | Level          |
| 6     | 1.92               | balance             | Single armed                   | Over compensation |
| 7     | 1.27               | Y–Δ                 | Single armed                   | Over compensation |
| 8     | 1.29               | Y–Δ                 | Single armed                   | Over compensation |
| 9     | -6.0               | Y–Δ                 | Single armed                   | regenerative braking |
| 11    | -6.04              | Y–Δ                 | Single armed                   | regenerative braking |
| 12    | -6.12              | Y–Δ                 | Single armed                   | regenerative braking |

Table 3. Classification of traction conditions

3.3. Harmonic source modelling of traction conditions

On the premise of guaranteeing the accuracy of the polynomial model, minimize the order of the polynomial model as far as possible to improve its engineering practicability. Based on the principle that the correlation coefficient is not less than 0.9, the order of polynomial is determined to be 5. For any harmonic on the net side, the positive and negative sequence currents are:

\[
\begin{align*}
\hat{i}_h^{(0)} &= I_{h_n}^{(0)} + jI_{h_n}^{(0)} \\
\hat{i}_h^{(2)} &= I_{h_n}^{(2)} + jI_{h_n}^{(2)}
\end{align*}
\]  

(4)

In the formula, \( I_{h_n} \) is real part of sequence current, \( I_{h_n} \) is imaginary part of sequence current. The harmonic source model expression is given for the real part or the imaginary part of the sequence current.
In the formula, \( P_1, Q_1 \) are active and reactive power of three phase fundamental wave positive sequence on net side, which is determined by the load level of a given locomotive or measured. \( c_1, c_i \) is parameters of the model.

In particular, when the locomotive is stopped, that is, when the active power and reactive power are 0, take \( c_1 \) to be 0. In order to identify the parameters of the model, the objective function is given:

\[
J = \min \sqrt{[I_m - F_h(P_m, Q_m, C)]^T [I_m - F_h(P_m, Q_m, C)]} \tag{6}
\]

In the formula, \( I_m \) is the measured effective value of \( h \)-order harmonic current. \( P_m, Q_m \) are measured power. The parameter set \( C \) of the polynomial model can be determined only when the minimum value of the objective function \( J \) is obtained. The quasi-Newton method is used for parameter identification, and the iteration number is set to 1000. Convergence criterion is \( \sqrt{J(C^{(i)})} \leq 10^{-10} \). Take the reference current \( I_{r}=10A \) and the reference power \( S_{r}=19053.3kVA \).

Detailed identification results of the real and imaginary parts of the positive and negative sequence components of the third harmonic currents under various operating conditions can be found in reference [6].

4. Harmonic simulation of electrified traction locomotive

After obtaining the identification results of the model parameters of each traction condition, the positive sequence active power and reactive power of the three-phase fundamental wave on the original network side are substituted into the model as excitation, and the model response is obtained. According to reference [6], taking the positive and negative sequence current amplitudes of 3-order harmonic as an example, the model responses of two typical events are compared with the measured data, as shown in Fig.8 and Fig.9.

![Figure 8. Measurement and model response of event 3](image)

![Figure 9. Measurement and model response of event 7](image)

The remaining 30 groups of measured harmonic current and power data under various traction conditions are taken as samples to test the harmonic source model. The maximum average relative error of the 3-order harmonic currents under different traction conditions is

\[
\max \sigma = \frac{1}{30} \sum_{n=1}^{30} \left| \frac{I_m - F_h(P_{m,n}, Q_{m,n}, C)}{I_m} \right| = 6.91\% \tag{7}
\]

In the formula, \( I_m \) is the real or imaginary part of the 3-order harmonic of positive sequence or negative sequence in group \( n \) under a certain working condition. The maximum average relative error of the other harmonics is within 8%. The accuracy of the model is verified.
3-order harmonic model parameters of AC-DC electric locomotive are given here. It is known from the previous section that the amplitude of harmonics generated by AC-DC-AC electric locomotive is very small compared with that of AC-DC electric locomotive because of its PWM control mode. For AC-DC electric locomotive, the 3-order harmonic current value is the largest, so this model is representative.

5. CONCLUSIONS
Firstly, the traction power supply system and traction substation of electrified railway are analyzed in this paper. It is known that the electric locomotive has strong nonlinear characteristics due to the use of a large number of power electronic devices, which brings a lot of power quality problems to the traction network and power system. This paper focuses on harmonics. On this basis, the harmonics generated by AC-DC and AC-DC-AC electric locomotives are studied respectively. It is concluded that compared with AC-DC electric locomotives, the high-frequency harmonics generated by AC-DC electric locomotives are very small. The mathematical model of the power supply system of electrified traction locomotive is established, and the harmonic model is established. The simulation results are in good agreement with the actual conditions. The model is typical and suitable for the follow-up harmonic analysis of various electrified traction locomotives.

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