Analysis of Frequency Domain Characteristics of Crosstalk for Train Network Control Communication Cable

Yang Liu*
College of Automation and Electronic Engineering, Dalian Jiaotong University, Dalian Liaoning China
liuyang_82@163.com

Changxian Li
National and Local Joint Engineering Research Center for Rail Transit Equipment, Dalian Jiaotong University, Dalian Liaoning China
lichangxianzju@163.com

Bozhen Ma
College of Automation and Electronic Engineering, Dalian Jiaotong University, Dalian Liaoning China
13213167157@163.com

ABSTRACT

Aiming at crosstalk problem of communication cable in train network control, mechanism of crosstalk generation is analyzed based on multi-conductor transmission lines (MTL) theory, and calculation method of distributed parameter of shielding cable in homogeneous dielectric is given. Frequency domain method of generalized two-port network is used. Frequency domain solution of the coupling response in the cable terminal is derived by solving shielded twisted pair (STP) chain-parameter matrix. Finally, influence factors of crosstalk is simulated. The results show that crosstalk is inversely proportional to the distance between lines and is directly proportional to the height from the ground and the coupling length, and the amplitude of variation increases significantly when the frequency is greater than 80MHz. For shielding layer, double-end grounding has the strongest anti interference ability. Single-end grounding has a significant inhibitory effect on low frequency interference, but has limited suppression of high-frequency interference. Double-end floating has a worse anti interference effect.

CCS CONCEPTS

• **Applied computing**; • **Operations research**; • **Industry and manufacturing**; • **Command and control**;

KEYWORDS

Train network control, Communication cable, Crosstalk, Frequency-domain

ACM Reference Format:
Yang Liu, Changxian Li, and Bozhen Ma. 2021. Analysis of Frequency Domain Characteristics of Crosstalk for Train Network Control Communication Cable. In *The 5th International Conference on Computer Science and Application Engineering (CSAE 2021), October 19–21, 2021, Sanya, China.* ACM, New York, NY, USA, 5 pages. https://doi.org/10.1145/3487075.3487180

1 INTRODUCTION

Energy transmission and information exchange are carried out between different onboard electrical systems through cables in the train. With the improvement of electrification and automation, a large number of strong and weak current cables are interwoven in the limited vehicle space [1] [2]. Although electromagnetic protection of cables has been considered in train design stage, due to constraints of space and routing methods, crosstalk between cables still exists to varying degrees [3] [4]. To ensure safe and stable operation of trains, it is necessary to predict the electromagnetic compatibility characteristics of key cables in train design stage. Communication cables of train control and monitoring system (TCMS) are electromagnetically coupled by the interference of strong electric cables in the vehicle, which will generate induced voltage and current on the core of communication cables, and excessively high induced voltage and current. It will cause distortion of the communication signal and invalidate the control. In severe cases, electronic components of the equipment will also be burned, causing the train to fail to operate normally [5] [6]. In response to this problem, theory of multi-conductor transmission line (MTL) is used to derive the frequency domain solution of coupling response in the cable terminal, and simulation analysis about factors affecting the crosstalk is carried out within the frequency domain. The research is helpful to the wiring design of communication cables for train network control.

2 TRANSMISSION LINE EQUATION

Crosstalk is a main source of interference in TCMS. Since the electromagnetic interference inside of the train can reach more than 100 MHz, and the length of the communication cable is comparable to the wavelength, the multi-conductor transmission line (MTL) can be used to study the crosstalk. Its wave equation is [7]:

$$\begin{cases} \frac{d^2\mathbf{V}(x)}{dx^2} + \mathbf{P} \cdot \mathbf{V}(x) = 0 \\ \frac{d^2\mathbf{I}(x)}{dx^2} + \mathbf{Q} \cdot \mathbf{I}(x) = 0 \end{cases} \quad (1)$$

In the formula:V(x) is the voltage vector.$\mathbf{I}(x)$Is the current vector.$\mathbf{P} = \mathbf{Z}' \times \mathbf{Y}'$,$\mathbf{Q} = Y' \times Z'$,$\mathbf{Z}'$ and $\mathbf{Y}'$are respectively $N \times N$ matrices of unit-length impedance and unit-length admittance. For lossless transmission lines,$\mathbf{Z}' = j\omega\mathbf{L}'and\mathbf{Y}' = j\omega\mathbf{C}'$. $\mathbf{L}'$and$\mathbf{C}'$are matrices of distributed inductance and capacitance of transmission lines.

The coupling interference voltage and current on the cable can be obtained by solving the equation.

CSAE 2021, October 19–21, 2021, Sanya, China

ACM ISBN 978-1-4503-8985-3/21/10…$15.00
https://doi.org/10.1145/3487075.3487180

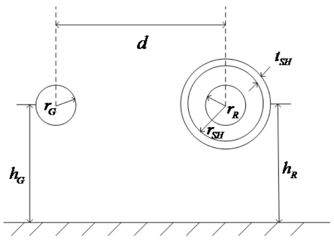


Figure 1: Sectional View of Shielded Cable.

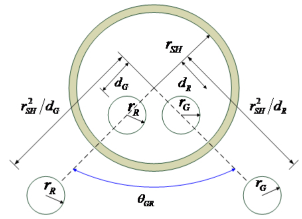


Figure 2: Sectional View of Dual-Conductor Transmission Line Inside of the Shielding Layer.

3 CALCULATION OF DISTRIBUTION PARAMETERS OF SHIELDED CABLE

To solve above wave equation, distribution parameters need to be calculated. Here, two conductor transmission line is studied as an example.

3.1 Distributed Inductance

As shown in Figure 1, r_{SH} is the radius of the shielding layer. t_{SH} is the thickness of the shielding layer, and its distributed inductances are listed as follows [8]:

Self-inductance of emission line G is:

$$L_G = \frac{\mu_0}{2\pi} \ln\left(\frac{2h_G}{r_G}\right) \tag{2}$$

Self-inductance of disturbed line R is:

$$L_R = \frac{\mu_0}{2\pi} \ln\left(\frac{2h_R}{r_R}\right) \tag{3}$$

Self-inductance of shielding layer is:

$$L_S = \frac{\mu_0}{2\pi} \ln\left(\frac{2h_R}{r_{SH} + t_{SH}}\right) \tag{4}$$

Mutual inductance L_{GS}between line G and shielding layer, and the mutual inductance L_{GR}between line G and line R are:

$$L_{GS} = L_{GR} = \frac{\mu_0}{4\pi} \ln\left(1 + 4\frac{h_G h_R}{d^2}\right) \tag{5}$$

Mutual inductance between the shielding layer and line R is:

$$L_{RS} = L_S = \frac{\mu_0}{2\pi} \ln\left(\frac{2h_R}{r_{SH} + t_{SH}}\right) \tag{6}$$

As shown in Figure 2, $d_G$andd_R are distances between centers of core line and shielding layer, and mutual inductance between transmission lines in the shielding layer is [9]:

$$L_m = \frac{\mu_0}{2\pi} \ln\left[\frac{d_R}{r_{SH}}\sqrt{\frac{(d_G d_R)^2 + r_{SH}^4 - 2d_G d_R r_{SH}^2 \cos\theta_{GR}}{(d_G d_R)^2 + d_R^4 - 2d_G d_R^3 \cos\theta_{GR}}}\right] \tag{7}$$

3.2 Distributed Capacitance

Extending above methods to the case of multiple conductors, unit-length inductance matrix$\mathbf{L}'$can be obtained. When line is an ideal conductor and surrounding medium is uniform, the relationship between unit-length inductance and the capacitance matrix is [10]:

$$\mathbf{L}'\mathbf{C}' = \frac{1}{v^2}\mathbf{E_n} \tag{8}$$

In the formula:$\mathbf{E_n}$is unit matrix.$v = \frac{1}{\sqrt{\varepsilon\mu}}$ is wave velocity along the line.$\mu$is permeability, and$\varepsilon$is permittivity.

Unit-length capacitance matrix can be obtained according to the above formula:

$$\mathbf{C}' = \frac{1}{v^2}\mathbf{L}'^{-1} \tag{9}$$

4 SOLUTION OF CROSSTALK IN FREQUENCY DOMAIN

4.1 Generalized Two-Port Network

In practical applications, we usually only care about the terminal response of transmission lines. Chain parameter equation of the transmission line can be written as [11-13]:

$$\begin{aligned}\begin{bmatrix}\mathbf{V}(x)\\ \mathbf{I}(x)\end{bmatrix} &= \begin{bmatrix}\mathbf{\Phi}_{11}(x) & \mathbf{\Phi}_{12}(x)\\ \mathbf{\Phi}_{21}(x) & \mathbf{\Phi}_{22}(x)\end{bmatrix}\begin{bmatrix}\mathbf{V}(0)\\ \mathbf{I}(0)\end{bmatrix}\\ &= \mathbf{\Phi}(x)\begin{bmatrix}\mathbf{V}(0)\\ \mathbf{I}(0)\end{bmatrix}\end{aligned} \tag{10}$$

$\mathbf{\Phi}(x)$is chain parameter matrix, and its expression is:

$$\begin{cases}\mathbf{\Phi}_{11}(x) = \frac{1}{2}\mathbf{Z}_\mathrm{C}\mathbf{T}_\mathrm{I}\left(e^{\gamma x} + e^{-\gamma x}\right)\mathbf{T}_\mathrm{I}^{-1}\mathbf{Y}_\mathrm{C}\\ \mathbf{\Phi}_{12}(x) = -\frac{1}{2}\mathbf{Z}_\mathrm{C}\left[\mathbf{T}_\mathrm{I}\left(e^{\gamma x} - e^{-\gamma x}\right)\mathbf{T}_\mathrm{I}^{-1}\right]\\ \mathbf{\Phi}_{21}(x) = -\frac{1}{2}\left[\mathbf{T}_\mathrm{I}\left(e^{\gamma x} - e^{-\gamma x}\right)\mathbf{T}_\mathrm{I}^{-1}\right]\mathbf{Y}_\mathrm{C}\\ \mathbf{\Phi}_{22}(x) = \frac{1}{2}\mathbf{T}_\mathrm{I}\left(e^{\gamma x} - e^{-\gamma x}\right)\mathbf{T}_\mathrm{I}^{-1}\end{cases} \tag{11}$$

In the formula: $\mathbf{Z}_\mathrm{C} = v\mathbf{L}' = \mathbf{L}'/\sqrt{\mu\varepsilon} = \sqrt{\mathbf{L}'/\mathbf{C}'}$is characteristic impedance of the transmission line.$\mathbf{T}_\mathrm{I}$is diagonal matrix of$\mathbf{Q}$. $\gamma = j\omega\sqrt{\mathbf{L}'\mathbf{C}'}$.

4.2 Solution of Crosstalk for Shielded Twisted Pair

Since$\mathbf{Q}$is already a diagonal matrix, $\mathbf{T}_\mathrm{I} = \mathbf{T}_\mathrm{V} = \mathbf{E_n}$.The propagation constant of each mode of the system i$\gamma_n = \alpha + j\beta = \sqrt{\mathbf{Y}' \cdot \mathbf{Z}'} = j\omega\sqrt{\mu\varepsilon}$, and characteristic impedance $\mathbf{Z}_\mathrm{C}$is a real number. Substituting equation (11), chain parameter matrix can be obtained. Shielded twisted pair can be regarded as a cascade of N twisted rings, and the total chain parameter matrix after cascading is:

$$\mathbf{\Phi}(x) = \begin{bmatrix}\mathbf{\Phi}_{11} & \mathbf{\Phi}_{12}\\ \mathbf{\Phi}_{21} & \mathbf{\Phi}_{22}\end{bmatrix} = \begin{cases}\mathbf{\Phi}(\Delta x)[\mathbf{P\Phi}(\Delta x)]^{N-1}, \mathrm{N: odd}\\ [\mathbf{P\Phi}(\Delta x)]^{N}, \mathrm{N}: even\end{cases} \tag{12}$$

In the formula: the transformation matrix of the twisted part is:

$$\mathbf{P} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 \\ 0 & 0 & 1 & 0 \end{bmatrix}$$

Hybrid method using Norton and Thevenin equivalent are to establish the constraint equation:

$$\mathbf{V}(0) = \mathbf{V} - \mathbf{Z_0}\mathbf{I}(0) \tag{13a}$$

$$\mathbf{I}(L) = \mathbf{Y_L}\mathbf{V}(L) \tag{13b}$$

$$\begin{aligned}&[\mathbf{Y_L}\mathbf{\Phi_{11}}(L)\mathbf{Z_0} - \mathbf{Y_L}\mathbf{\Phi_{12}}(L) - \mathbf{\Phi_{21}}(L)\mathbf{Z_0} + \mathbf{\Phi_{22}}(L)]\cdot \\ &\mathbf{I}(0) = [\mathbf{Y_L}\mathbf{\Phi_{11}}(L) - \mathbf{\Phi_{21}}(L)]\mathbf{V}\end{aligned} \tag{14a}$$

$$\mathbf{I}(L) = \mathbf{\Phi_{21}}(L)\mathbf{V} + [\mathbf{\Phi_{22}}(L) - \mathbf{\Phi_{21}}(L)\mathbf{Z_0}]\mathbf{I}(0) \tag{14b}$$

$$\boldsymbol{V} = \begin{bmatrix} V \\ 0 \\ 0 \\ 0 \end{bmatrix}., \boldsymbol{Z_0} = \begin{bmatrix} Z_{NG} & 0 & 0 \\ 0 & Z_{NS} & 0 \\ 0 & 0 & Z_{NR} \\ 0 & 0 & 0 \end{bmatrix},$$

$$\boldsymbol{Y_L} = \begin{bmatrix} \left(\frac{1}{Z_{FG}}\right) & 0 & 0 \\ 0 & \left(\frac{1}{Z_{FS}}\right) & 0 \\ 0 & \left(\frac{1}{Z_{FR}}\right) & -\left(\frac{1}{Z_{FR}}\right) \\ 0 & -\left(\frac{1}{Z_{FR}}\right) & \left(\frac{1}{Z_{FR}}\right) \end{bmatrix}$$

In the formula: $V$is excitation source voltage. Z_{NG} is internal resistance of the excitation source. Z_{NS}andZ_{FS}respectively represent near-end and far-end resistance of the shielding layer. Z_{NR}andZ_{FR}respectively represent near-end and far-end resistance of the twisted pair.

$\mathbf{I}(0)$and $\mathbf{I}(L)$ can be obtained by formula (14). Then, substituting them into formula (13) can obtain terminal voltage $\mathbf{V}(0)$ and $\mathbf{V}(L)$. Extending above solving process, terminal response of communication cable can be obtained in frequency domain.

In summary, general steps for solving the frequency domain response of the train network control communication cable terminal are:

(1) Solve distribution parameters$\mathbf{C'}$and$\mathbf{L'}$to determine characteristic impedance $\mathbf{Z_C}$and propagation constantγ.
(2) Use similar transformation of the matrix to decouple wave equation of the transmission line and determine transformation matrix$\mathbf{T_I}$.
(3) Find the chain parameter matrix$\mathbf{\Phi}(x)$.
(4) Substitute boundary conditions to obtain terminal responses$\mathbf{I}(0)$,$\mathbf{I}(L)$,$\mathbf{V}(0)$ and$\mathbf{V}(L)$.

5 SIMULATION AND RESULT ANALYSIS

According to previous solution, it can be seen that distribution parameter between cables is the direct cause of crosstalk, and it is affected by cable radius, height from the ground and distance between cables. At the same time, the cable length and shielding layer grounding method may also affect the crosstalk. In view of the similar electromagnetic characteristics of MVB and WTB cable,

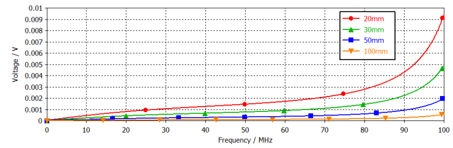


Figure 3: The Influence of the Distance between Cables on the Near-End Crosstalk Voltage.

this article only conducts simulation experiments and analysis on WTB cable.

Parameters of WTB cable commonly used in TCMS are shown in Table 1 [14]. Suppose interference excitation source is a voltage source with an amplitude of 10V and a frequency of 100MHz. Load at the near end of the interfering line is$Z_{NG} = 0$. Load at the far end is$Z_{FG} = 120\Omega$. Load at the near and far end of the shielding layer is$Z_{NS} = Z_{FS} = 1\Omega$. Load at the near and far end of the cable is$Z_{NR} = Z_{FR} = 120\Omega$.

(1) Cable spacing influence

The cable length is L=1m, and distance from the ground is 10mm. The distance between interference cable and WTB cable is 20mm, 30mm, 50mm and 100mm respectively. As can be seen from Figure 3, as the distance between cables increases, crosstalk voltage of the WTB cable coupling from interference line gradually decreases. This is because mutual inductance and capacitance between lines are inversely proportional to the line spacing. With the increase of line spacing, mutual inductance and capacitance decrease and coupling decreases. And the larger the distance between lines, the weaker the rising trend of coupling voltage with frequency. At the same time, the amplitude of the crosstalk voltage in Figure 3 increases with the increase of the frequency. When the frequency is greater than 80MHz, the amplitude of change increases significantly. When the line spacing is 100mm, the coupling voltage is less affected by the frequency.

(2) Influence of the height of the cable from the ground

The length of the cable is L=1m, and the distance between interference cable and WTB cable is 20mm. The height of the cable from the ground is respectively 10mm, 15mm, 20mm and 40mm. As can be seen from Figure 4, as the height of the cable from the ground increases, the voltage coupled on WTB cable gradually increases. This is because the height from the ground is proportional to the mutual inductance. On the other hand, the increase of the height is equivalent to the increase in the loop area between cable and ground, and mutual inductance increases, so the coupling increases. At the same time, it can be seen that the coupling voltage on WTB cable increases with the increase in frequency, and the increase trend is slow in low frequency band and significant in high frequency band.

(3) Influence of cable length

The length of the interference cable is L=1m, and distance between the cable and WTB cable is 20mm. The height of the cable from the ground is 10mm, and the length of WTB cable is respectively 1m, 0.75m, 0.5m and 0.25m. There is no direct relationship between cable length and mutual capacitance and inductance, but it can be seen from Figure 5 that as cable length grows, the coupling voltage on the cable gradually increases. And the longer the cable

Table 1: WTB Cable Parameters

Outer diameter(mm)	Core radius(mm)	Conductor cross-sectional area(mm2)	Core spacing(mm)
6.4	0.4886	0.75	2.2
Material	Number of twists per meter	Shield braid material	Insulation layer material
copper	20	copper	PE

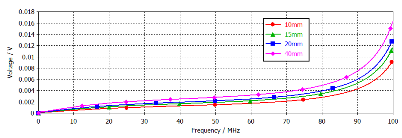


Figure 4: The Influence of the Height of the Cable from the Ground on the Near-End Crosstalk Voltage.

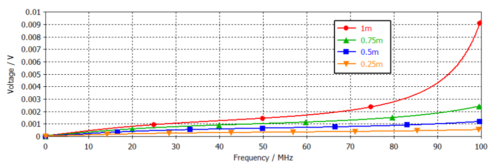
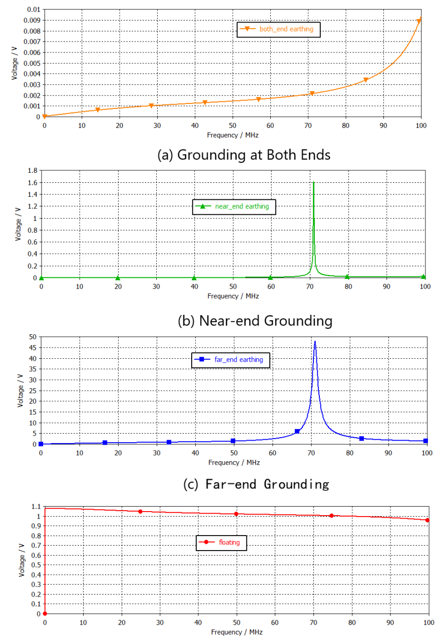


Figure 5: The Influence of Cable Length on Near-End Crosstalk Voltage.



(a) Grounding at Both Ends

(b) Near-end Grounding

(c) Far-end Grounding

(d) Double-ended Floating

Figure 6: The Influence of Shielding Layer Grounding on Near-End Crosstalk Voltage.

length is, the more obvious the increasing trend of coupling voltage in high frequency band. When the cable length exceeds 1m, the coupling voltage increases sharply as the frequency increases.

(4) The influence of shielding layer grounding method

Above studies are all carried out under the condition of double-ended grounding of the shielding layer. The following analyzes the crosstalk under different grounding methods. The cable length L=1m, the cable spacing is 20mm, and the height between cables and ground is 10mm. Since the near-end and far-end crosstalk characteristics of WTB cable are basically the same, only the near-end crosstalk is analyzed here.

It can be seen from Figure 6 that when the ground plane is ideal, there is no potential difference between the two grounding points. At this time, the double-ended grounding has a better interference suppression effect. From Figure 6 (b) and (c), it can be seen that when shielding layer is grounded at a single end, it can attenuate electromagnetic interference in low frequency range. However, the suppression in the high frequency range is limited, and large oscillations may even occur near the frequency of 70MHz. When the far-end is grounded, the non-grounded and near-end crosstalk voltage fluctuates more. From Figure 6(d), when the two ends are floating, a larger crosstalk voltage will appear on WTB cable in the entire frequency range.

6 CONCLUSION

The root cause of crosstalk is the distribution parameters between cables, which are affected by such factors as the relative position of cables, coupling length, interference source frequency, and grounding mode of shielding layer. The simulation results show that the crosstalk on communication cable can be reduced by adopting the following measures. In the limited space of the train, spacing between interference line and communication cable greater than 100mm is appropriate. Communication cables should be arranged as close as possible to the car body or the public grounding plane such as the cable trough. If restricted by the layout of on-board electrical equipment, the coupling length of interference line and communication line should be reduced as far as possible. With the increase of frequency, both metal loss and medium loss increase rapidly. And the transverse size of the transmission line cannot be ignored compared with the wave length. The coupling between circuits becomes more serious. Therefore, communication cables should be wired away from high-frequency radiation areas as far as possible, such as traction and auxiliary converters. The shielding layer of the communication cable shall be double-grounded. These measures have certain engineering application value to guide the communication cable wiring of train network control system.

ACKNOWLEDGMENTS

This research was supported by scientific research project of Liaoning Provincial Department of Education. (Project: Research on EMC design and simulation technology of traction converter.). The authors gratefully acknowledge the financial support.

REFERENCES

[1] Xie Lifeng, Lv Jifang, Jiang Zhongcheng, *et al.* (2016). Simulation analysis and test verification of subway cable crosstalk[J]. Urban Mass Transit, 5: 78-82.

[2] Li Kangxu, Li Donghui, Li Changxian, *et al.* (2020). Research on Simulation and Electromagnetic Compatibility of External Traction to Electromagnetic Radiation of Train Traction Converter[J]. Journal of Dalian Jiaotong University, 40(1), 110-115.

[3] He Xiaodong (2016). Research on electromagnetic compatibility of EMU cable coupling[D]. Beijing: Beijing Jiaotong University.

[4] Zhang Lu (2011). Research on the crosstalk mechanism of shielded cables of EMUs[D]. Beijing: Beijing Jiaotong University.

[5] Yu Dinghua, Wang Yimin (2005). Research on anti-electromagnetic interference of locomotive cables [J]. Locomotive Electric Drive, 6: 32-6.

[6] Zhang Hongjiang, Wu Donghua, Zhang An (2011). Design technology of electromagnetic compatibility for rail vehicles[J]. Locomotive Electric Drive, 3: 61-76.

[7] An Zhanyang (2015). Research on the prediction of automobile wiring harness crosstalk and its dynamic characteristics[D]. Jilin: Jilin University.

[8] Shan Qin (2013). Research on key technologies of electromagnetic compatibility for high-speed EMUs[D]. Beijing: Beijing Jiaotong University.

[9] Zhang Gang (2009). Research on the coupling mechanism of space transient electromagnetic field to shielded cable[D]. Harbin: Harbin Institute of Technology.

[10] Paul C R, Feather A E (1976). Computation of the Transmission Line Inductance and Capacitance Matrices from the Generalized Capacitance Matrix[J]. IEEE Transactions on Electromagnetic Compatibility, 18(4),175-183.

[11] Paul C R (1981). Computation of cross-talk in a multi-conductor Transmission Line[J]. IEEE Trans EMC, 23(4), 352-358

[12] Sun Yaxiu, Zhuo Qingkun, Jiang Qinghui, *et al.* (2015). Research on a new type of crosstalk model of differential mode excitation based on multi-conductor transmission line theory[J]. Acta Physica Sinica, 64(4),1-12.

[13] Paul C R (2007). Analysis of Multiconductor Transmission Lines[M]. New York: Wiley-Interscience.

[14] Liu Jianqiang, Zheng Qionglin, Zhang Yongfeng, *et al.* (2010). Research on the electrical characteristics of the transmission medium of the CRH3 EMU train network[J]. Locomotive Electric Drive, 6: 7-11.