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REVIEW ARTICLES

Modelling and Simulation of Stray Current in Urban Rail Transit—A Review

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Abstract With the rapid development of urban rail transit, the issue of stray current due to incomplete insulation between the rail and the earth is attracting increasing attention. Stray current seriously affects the safe operation of urban rail transit, pipelines and power grids, and pose challenges to the development of urban energy security. However, there are significant differences among the various methods for the analysis and verification of stray currents, and existing research works thus lack a mature theoretical framework. To address this, this paper presents an in-depth review on the study of stray current including the mechanism, technical standards, modelling, simulation and mitigation technologies. Firstly, the principle and standards of stray current are introduced from multiple perspectives (i.e. metro side, pipeline side and grid side). Then, the typical modelling and simulation of stray current are summarized and compared in detail. The representative stray current mitigation measures, together with the stray current hardware simulation technologies, are also discussed. In conclusion, this paper provides a comprehensive overview of key technologies involved in the modelling and simulation of stray current, and highlights the valuable research direction in stray current mitigation.

Keywords Urban rail transit · DC traction power supply · Stray current · Modelling and simulation

1 Introduction

Urban rail transit has developed rapidly in cities around the world [1], because of its advantages of punctuality, high speed, large volume and low pollution. The direct current (DC) traction power supply system is widely adopted in urban rail transit [2]. However, conventional DC traction power supply systems generally employ running rail as the return path for traction current, which not only results in high rail potential, threatening equipment and personal safety [3], but also leads to stray current leakage and corrosion on the underground metal pipelines [4]. Meanwhile, the stray current may enter the neighbouring power grid [5], which flows into the transformer winding through the neutral wire and generates DC bias, thereby affecting the safety and stable operation of the power grid.

Ideally, the traction current of a conventional DC traction power supply system flows back to the traction substation through the running rail (hereafter "rail" for simplification). However, due to the incomplete insulation between the rail and the earth, part of the current inevitably leaks from the rail, resulting in so-called stray current as shown in Fig. 1, and then returns to the traction substation through multiple uncertain paths. Obviously, the stray current mainly flows through low-resistance paths such as underground metallic pipelines or structural steel bars [6].

At this time, the rail including its stray current collection mat (SCCM), soil and metal pipelines form the primary battery near the traction substation and train. The primary battery will cause electrochemical corrosion in the anode area. Moreover, metal pipeline corrosion can

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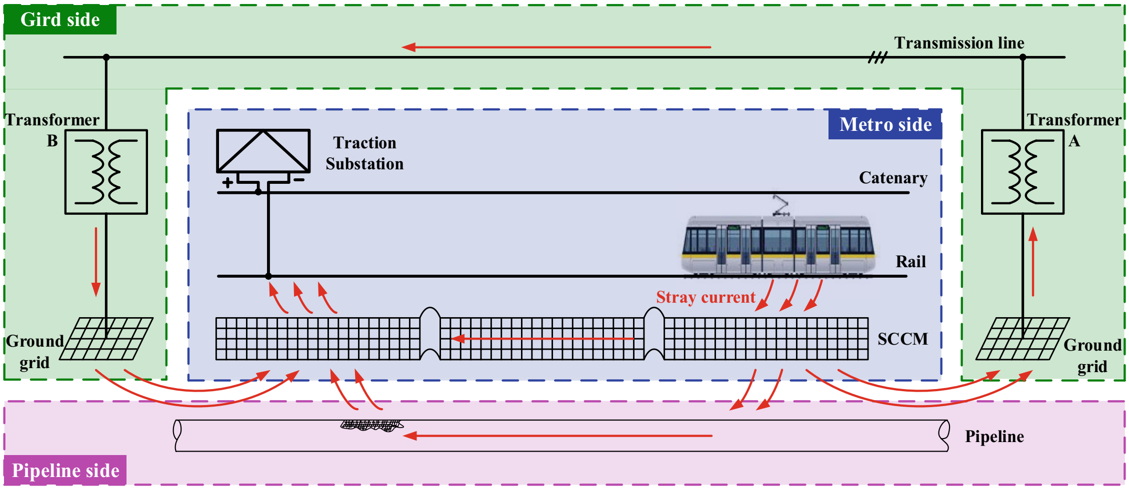


Fig. 1 Typical distribution of stray current in urban rail transit

lead to internal leakage such as natural gas and oil, which not only causes economic losses but also threatens public safety. For the chemical reaction of corrosion, the principle of metal iron in the anode area of the primary battery is shown in Eq. (1), while various reactions can occur in the cathode area due to the different oxygen and electrolyte pH values [7]. In anaerobic environments, acidic electrolytes (pH<7) and neutral and alkaline electrolytes (pH≥7) can exhibit hydrogen evolution corrosion as shown in Eq. (2), while in aerobic environments, different electrolytes exhibit oxygen absorption corrosion as shown in Eq. (3).

$$2\mathrm{Fe} \rightarrow 2\mathrm{Fe}^{2+} + 4\mathrm{e}^{-} \tag{1}$$

$$\begin{cases} 4\mathrm{H}^{+} + 4\mathrm{e}^{-} \rightarrow 2\mathrm{H}_2 \uparrow, \quad \mathrm{pH} < 7 \\ 4\mathrm{H}_2\mathrm{O} + 4\mathrm{e}^{-} \rightarrow 4\mathrm{OH}^{-} + 2\mathrm{H}_2 \uparrow, \quad \mathrm{pH} \geq 7 \end{cases} \tag{2}$$

$$\begin{cases} \mathrm{O}_2 + 4\mathrm{H}^{+} + 4\mathrm{e}^{-} \rightarrow 2\mathrm{H}_2\mathrm{O}, \quad \mathrm{pH} < 7 \\ \mathrm{O}_2 + 4\mathrm{H}_2\mathrm{O} + 4\mathrm{e}^{-} \rightarrow 4\mathrm{OH}^{-}, \quad \mathrm{pH} \geq 7 \end{cases} \tag{3}$$

Due to the spatial overlap between the urban rail transit and power grid, the stray current flows into the earth and leads to potential differences among nearby substations. The stray current will flow into the ground grid of the alternating current (AC) power grid system as shown in Fig. 1 [8]. Here, DC stray current flows through the power grid transmission line path, from the neutral point of transformer A to the neutral point of transformer B, and finally returns to the traction substation. Then, when the neutral current approaches its saturation threshold, transformer DC bias will occur [9]. With the continuing growth of urban rail transit, the risk of transformer DC bias is now affecting many urban power grid substations. Taking Shenzhen, which had 13 urban rail transit lines in 2022, as an example, more than 80% of 220 kV substations have transformer neutral current greater than 5 A, with maximum current even reaching 83 A, resulting in serious DC bias [10]. Unfortunately, DC bias greatly increases the excitation current of the transformer and worsens the saturation degree of the iron core, which may cause local overheating and fire accidents. Meanwhile, DC bias also increases the mechanical vibration of the transformer and leads to higher transformer noise, loss and harmonics [11, 12].

The stray current issue has seriously affected the safe and normal operation of systems in many fields, which indicates that urgent action is needed. Many scholars have studied stray currents. Memon and Fromme [13] introduced the principle of stray current corrosion and the development history of mitigation measures, and Paul [14] focused on the cathodic protection measure on the basis of the work of Memon and Fromme [13]. In addition to studies on typical mitigation measures, Pires [15] introduced an empirical formula for calculating stray currents and the measurement scheme of a rail–earth resistance network, and techniques for monitoring stray current distribution were discussed in detail by Charalambous et al. [16] and Mariscotti [17]. Wang et al. [18] also studied stray current modelling, but only two representative models were discussed, which lacked detailed analyses and comparisons with other models. Obviously, there is significant potential for improvement in modelling and simulation review of stray current, and a more comprehensive theoretical system for stray current is needed.

Therefore, this paper focuses on the review of key technologies involved in the study of stray current such as modelling, simulation and mitigation. The layout of the paper is illustrated in Fig. 2, and the remainder of the

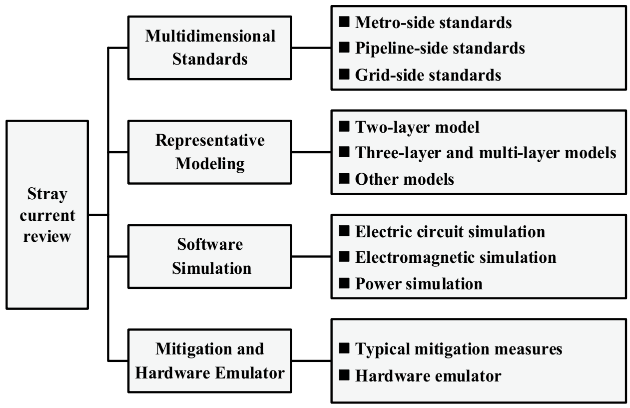


Fig. 2 Layout of paper structure

paper is organized as follows. Section 2 discusses the relative standards of stray current from the train, pipeline and grid sides, and representative modelling schemes and simulation software are presented in Sects. 3 and 4, respectively. Section 5 briefly introduces stray current mitigation measures and hardware emulator technology. Finally, conclusions are presented in Sect. 6.

2 Multidimensional Standards

With the increasing attention to stray current issues, relevant standards have gradually been proposed and promoted. Due to the uncertain path of stray current flow in the earth, different fields have issued relevant standards from different perspectives. In addition to urban rail transit (such as the representative “metro”) as the stray current leakage source, nearby areas affected by stray current include the metallic pipeline and power grid. Therefore, the following will briefly introduce the worldwide standards as shown in Table 2 from these three perspectives:

2.1 Metro-Side Standards

For the metro side, both IEC 62128-2:2013 [19] and EN 50122-2:2022 [20] propose measurement schemes for rail resistance, conductance between rail and structure, and conductance between rail and earth, and [19, 20] propose methods for estimating the stray current passing from rail to earth through continuous monitoring of rail potential. In China, CJJ/T 49-2020 [21] has been recommended and applied to the design, construction, monitoring and maintenance of metro stray current protection. Here, [19–21] recommends that the average stray current per unit length not exceed 2.5 mA/m. Furthermore, GB 50157-2013 [22] proposes specific requirements for a stray current mitigation and grounding scheme, where the maximum rail potential of the platform should be limited to 120 V and the traction power supply should be a floating system.

2.2 Pipeline-Side Standards

For the pipeline side, ISO 21857:2021 [23] establishes the principles for the evaluation and minimization of the effects of stray current corrosion on the pipeline system, introduces the identification and measurement of stray current interference on pipelines, and puts forward proposals on the acceptance and reduction of stray current interference. EN 50162:2004 [24] establishes the general principles for minimizing stray current corrosion on long buried horizontal structures (e.g. pipeline and metal sheathed cable), which helps reduce stray current interference from the modifications to both current source and interfered structure. Meanwhile, GB 50991-2014 [25] focuses on mitigation measures for buried steel pipeline corrosion, such as drainage protection and cathodic protection, while GB/T 19285-2014 [26] provides inspection standards for pipeline corrosion protection, which include investigating the interference sources, conducting interference tests and evaluating the performance of mitigation measures.

2.3 Grid-Side Standards

For the grid side, IEC/TS 60076-23:2018 [27] specifies the device requirements for suppressing DC magnetic bias of transformers, adopting a DC current-limiting device and DC current-blocking device to suppress transformer bias current. IEEE C57.163-2015 [28] introduces evaluation techniques to determine the performance characteristics of power transformers under the influence of geomagnetically induced current, which could be regarded as a special type of stray current. Meanwhile, DL/T 1786-2017 [29] provides a technical guideline for monitoring DC bias current distribution, which specifies the technical requirements for distribution principles, monitoring devices and synchronous monitoring of DC bias current in the power grid. Extending from [29], DL/T 1957-2018 [30] further provides a guideline for risk assessment and active defence of DC bias current, emphasizing key technologies such as the process, principles and indicators of risk assessment, and representative defence measures (Table 1).

In summary, stray current standards have been widely adopted in the field, but these multidimensional standards are relatively independent and lack integration with each other. For instance, [19–22] lack an evaluation of the stray current performance outside the metro, and [23–26] only

Table 1 Multidimensional standards of stray current around the world

Field	Code	Title	Organization/country
Metro side	IEC 62128-2:2013	Railway applications—fixed installations—electrical safety, earthing and the return circuit—part 2: provisions against the effects of stray currents caused by DC traction systems	IEC
	EN 50122-2:2022	Railway applications—fixed installations—electrical safety, earthing and the return circuit—part 2: provisions against the effects of stray currents caused by DC traction systems	Europe
	CJJ/T 49-2020	Technical standard for stray current corrosion protection in metro	China
	GB 50157-2013	Code for design of metro	China
Pipeline side	ISO 21857:2021	Petroleum, petrochemical and natural gas industries—prevention of corrosion on pipeline systems influenced by stray currents.	ISO
	EN 50162:2004	Protection against corrosion by stray current from direct current systems	Europe
	GB 50991-2014	Technical standard for DC interference mitigation of buried steel pipeline	China
	GB/T 19285-2014	Inspection of corrosion protection for buried steel pipelines	China
Grid side	IEC/TS 60076-23:2018	Power transformers—Part 23: DC magnetic bias suppression devices.	IEC
	IEEE C57.163-2015	IEEE guide for establishing power transformer capability while under geomagnetic disturbances	IEEE
	DL/T 1786-2017	Technical guideline for the synchronous monitoring of DC bias current distribution	China
	DL/T 1957-2018	Guide for risk assessment and active defense of DC bias of power grids	China

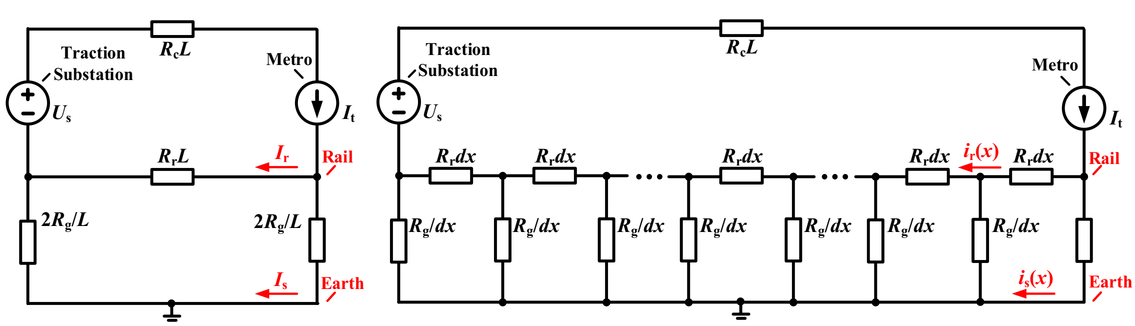
consider stray current as one of the factors contributing to pipeline corrosion, while [27–30] even ignore the origin of stray current and discuss DC bias current performance directly. Stray current standards should involve not only the electrical engineering discipline but also other related disciplines, such as civil engineering and electrochemistry, which means that further development of stray current standards should be approached from an interdisciplinary perspective.

3 Representative Modelling

In recent years, mathematical modelling of stray current has been used to determine its distribution characteristics. Stray current distribution is generally obtained with the equivalent circuit through the simplification of urban rail transit power supply systems, particularly the electrical connections between rail and earth. The representative models and their comparisons are then given as follows.

3.1 Two-Layer Model

The two-layer model employs the "rail-to-earth" resistance network to analyse the stray current distribution, where the network mainly includes rail resistance and rail-to-earth resistance. To simplify the analysis, a unilateral power supply is adopted, and the configurations of the two-layer model are shown in Fig. 3. The global scheme performs π-type equivalence on the entire section, while the differential element scheme first divides the entire section into



(a) Global scheme (b) Differential element scheme

Fig. 3 Configurations of two-layer model

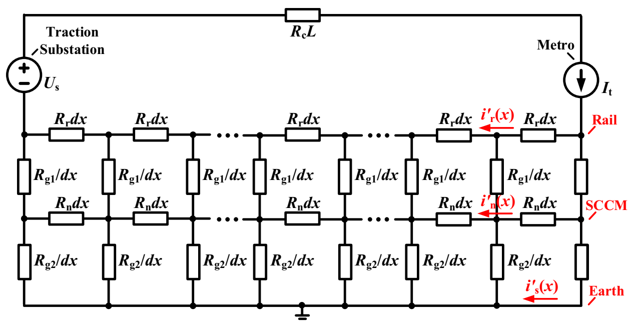


Fig. 4 Typical configuration of three-layer model

Table 2 Comparison of accuracy and simplicity of representative models

Field	Accuracy	Simplicity
Two-layer model with global scheme	★	★★★★★
Two-layer model with differential element scheme	★★	★★★★
Three-layer model	★★★	★★★
Multi-layer model	★★★★	★★
Electromagnetic model	★★★★★	★

multiple small sections, then performs π-type equivalence on each small section. Thus, the stray currents of the global scheme and differential element schemes can be expressed as Eqs. (4) and (5) respectively, where R_c (Ω/km), R_r (Ω/km), R_g (Ω km), L (km), x (km), and I_t (A) refer to the catenary resistance, rail resistance, rail-to-earth resistance, distance between the metro and traction substation, distance between the observation point and traction substation, and train current.

$$I_s = \frac{RL^2}{4R_g + RL^2} I_t \tag{4}$$

$$i_s(x) = I_t \left[1 - \frac{ch\alpha\left(x - \frac{L}{2}\right)}{ch\frac{\alpha L}{2}} \right], \quad \alpha = \sqrt{\frac{R}{R_g}} \tag{5}$$

3.2 Three-Layer and Multi-Layer Models

Stray current collection mats (SCCM), including the structural steel bars, pipelines and other structures between the rail and the earth, generally have a significant impact on the stray current distribution. Therefore, further three-layer and multi-layer models are investigated on the basis of the two-layer model [31]. These models generally adopt a differential element scheme, and the typical three-layer model with a "rail–SCCM–earth" network is shown in Fig. 4, where R_n (Ω/km), R_{g1} and R_{g2} (Ω km) refer to SCCM resistance, rail-to-SCCM resistance and SCCM-to-earth resistance, respectively. Furthermore, on the basis of the three-layer model, extra consideration of pipelines and structural steel bars will obtain a stray current model with more layers. Although the multi-layer model may show better stray current distribution characteristics, the derivation and calculation of stray current $i'(x)$ will become more complex.

3.3 Other Models

Besides the models described above, stray current modelling can be further upgraded and optimized. On the one hand, the improved model can consider more details of the actual system, such as the uneven electrical resistivity of soil, overvoltage protection devices (OVPD), or stray current drainage devices (SCDD). On the other hand, the modelling of stray current can be extended from the electric circuit model to the electromagnetic model, which means that the stray current distribution changes from two-dimensional to three-dimensional [32].

A comparison of the accuracy and simplicity of representative models is shown in Table 2. Obviously, as a greater number of factors are considered (i.e. increasing the number of layers, upgrading from the electric circuit model to the electromagnetic model), the accuracy of the model increases, but with increased complexity. Therefore, researchers studying stray current should select the appropriate model according to their specific needs. For instance, two-layer or three-layer models may be the best choice when only measuring the total leaked stray current from rail to earth, but if analysis of the stray current in the pipelines is needed, the multi-layer model or even the electromagnetic model should be used to obtain greater detail.

4 Software Simulation

Studies on the simulation of stray current distribution have continuously explored methods to verify the correctness of the modelling analysis. Nowadays, stray current simulation is mainly divided into three types, including electric circuit simulation, electromagnetic simulation and power simulation. The principles, characteristics and representative software of these simulations are briefly discussed as follows.

4.1 Electric Circuit Simulation

Based on the electric circuit model, circuit simulation generally divides the entire section into multiple small sections in the software and adopts modelling equivalence to obtain the resistance network of the system, which can further simulate the stray current distribution. Here, the representative software of circuit simulation includes MATLAB/Simulink [33] and PSIM. Other software simulates the train running performance by continuously varying the rail resistance on both sides of the train. Additionally, the system may adopt added switches to allow the train to move from any section to its adjacent section. Therefore, the circuit simulation can effectively obtain the stray current distribution performance in the various applications, but its computational complexity increases along with the scale of the simulation.

4.2 Electromagnetic Simulation

The electromagnetic model is adopted by considering the soil resistivity, SCCM, structural steel bars and pipelines of actual urban rail transit in three-dimensional space, and representative simulation software includes CDEGS [34], ANSYS and PSCAD. Compared with circuit simulation, electromagnetic simulation can reproduce the stray current performance more accurately in three-dimensional space. However, due to enormous calculations, the simulation is generally limited to a single power supply section (i.e. one train and two adjacent traction substations), and the position and current of the train are generally fixed to provide enough time for the calculation, which makes it impossible for electromagnetic simulation to obtain stray current distribution performance with the train operation.

4.3 Power Simulation

Unlike circuit simulation and electromagnetic simulation, power simulation mainly focuses on the power flow of the DC traction power supply system, and it generally neglects the complex connection between rail and earth. Representative software such as DCTPS [35] is generally adopted by metro design and research institutes, which can evaluate the power and current distribution of the entire line during its planning stage. However, although the power simulation covers the entire line and multiple trains, strictly speaking, the simulation does not obtain the underground stray current. Instead, it roughly estimates the stray current from rail to earth by simulating the rail potential distribution and reproduces the simulated rail potential to derive the stray current.

A comparison of the different software simulations is shown in Table 3. Here, the electromagnetic simulation focuses on the stray current details of a single power supply interval, while the power simulation studies the rail potential distribution along the entire line with multiple trains, and it evaluates the relationship between rail potential and stray current to indirectly estimate the leaked stray current across the entire line. Meanwhile, the circuit simulation may be considered as a compromise between these two simulations. The circuit simulation can increase the details between rail and earth to more closely emulate electromagnetic simulation, or expand the system to the whole line and multiple trains to approach power simulation, but this significantly increases its computational complexity. Therefore, the simulation should also be selected cautiously based on the requirements, and more accurate simulation is recommended to validate the modelling analysis.

5 Mitigation and Hardware Emulator

Stray current mitigation measures were first proposed by the National Association of Corrosion Engineers of the United States in the first half of the nineteenth century [36]. Although these mitigation measures have been improved through follow-up studies around the world, the stray current issue in urban rail transit has not yet been completely resolved. Stray current corrosion in the United States is estimated to cost nearly $500 million annually [37]. Various measures have been employed to reduce stray current in urban rail transit. According to the operating principles, these measures can be divided into the following schemes: increasing the resistance of leakage path to earth, reducing the rail-return circuit resistance, installing a stray current collection mat, and adopting specific current-returning rail/cable. Other measures such as increasing the power supply voltage and installing energy storage devices [38, 39] can also reduce the stray current with smaller traction current.

Table 3 Comparison of different software simulations

Simulation	Advantages	Disadvantages
Electric circuit simulation	Wide application range Simulates train operation	Computational complexity increases with simulation range
Electromagnetic simulation	More accurate simulation of stray current distribution	Fixed position and current Limited simulation range
Power simulation	Whole line and multiple trains Actual operating conditions	Estimated stray current Lack of stray current details

5.1 Increasing Resistance of Leakage Path to Earth

The traction current flows back to the traction substation through the running rail, and incomplete insulation between the running rail and earth is the one of the main reasons for stray current leakage to the earth. Obviously, the worse the insulation between the running rail and earth, the greater the current leakage from running rail to earth [40]. Therefore, increasing the resistance of the leakage path to earth can effectively reduce the stray current leakage. Typical measures to increase leakage resistance include adopting high-resistivity concrete sleepers and ballast beds [41], avoiding water accumulation [42] and applying insulation coating on the rail surface [43]. However, the mitigation performance of these measures generally deteriorates over time, and it is difficult to renovate the running rail or ballast bed to increase leakage resistance for existing railway lines.

5.2 Reducing the Rail-Return Circuit Resistance

When the traction current flows back to the traction substation, the running rail and earth can be simplified as two parallel return paths. Therefore, increasing the earth return resistance (i.e. increasing the resistance of the leakage path to earth) can effectively reduce stray currents. Meanwhile, reducing the rail-return circuit resistance, which increases the components of the running rail path in the traction current return, can also effectively reduce the earth-return current and solve the stray current issue [44]. Typical measures for reducing rail-return resistance include adopting high-duty running rails [45], paralleling cables for the running rails [46] and shortening the distance between adjacent traction substations [47]. However, the cost of these measures is generally high, while the mitigation performance is limited, especially with worse insulation conditions due to water accumulation.

5.3 Installing a Stray Current Collection Mat

The stray current leaked from the running rail can be collected by setting up a stray current collection mat (SCCM). Here, the stray current leaks from the running rail to the ballast bed, and the structural steel bars inside the ballast bed are welded and formed as a SCCM to collect a part of the stray current [48]. A stray current drainage device (SCDD) is generally installed at the traction substation, which transmits the stray current collected by the SCCM back to the traction substation. Ideally, the SCCM can achieve collection efficiency of 50–80%, but its actual effectiveness may be limited. On the one hand, the SCCM and SCDD will increase the total amount of stray current leaking from the running rail to the ballast bed; on the other hand, the non-standard welding during the SCCM installation generally results in high resistance at the welded joints of the steel bars, which greatly reduces the collection efficiency of the SCCM.

5.4 Adopting Specific Current-Returning Rail/Cable

The fundamental cause of stray current is attributed to the conventional DC traction power supply scheme adopting the running rail as the traction current return path. Thus, compared with the conventional scheme, the specific current-returning rail/cable scheme as shown in Fig. 5 can fundamentally solve stray current issues. For the specific current-returning rail scheme, the traction current is transmitted to the additional return rail (also known as the fourth rail) rather than the running rail by renovating the train structure [49]. Here, the traction current returns to the traction substation through a highly insulated return rail, while the running rails only serve as a guiding device. However, due to the train renovation and the added return rail, the railway clearance and tunnel cross-section are expanded, making the specific current-returning rail scheme costly and impractical for existing railway line applications.

For the specific current-returning cable scheme, the virtual reflow point (VRP) is constructed on the running rail by adding power electronic devices and return cables [50]. The actual reflow point (ARP) and VRP are always equipotential, which ensures that there is no current on the running rail between ARP and VRP. Then the current return distance of the running rail is shortened and stray current leaked from the running rail is reduced [51–53]. The traction current of the specific current-returning cable scheme is still directly injected into the running rail, which avoids the need for train renovation. In addition, compared with the return rail, the return cable is generally more convenient for installation, so there is no need to expand the railway clearance and tunnel cross-section due to the cable installation, which suggests good application prospects for the scheme in existing railway lines.

5.5 Stray Current Hardware Emulator

To further verify the software simulation of stray current and the mitigation performance of specific current-returning cable schemes, research works on hardware emulator verification have been developed in recent years. The hardware emulator adopts power electronic variable resistors (PEVRs) to simulate the resistance network changes when the train is running on the rail. The typical hardware emulator as shown in Fig. 6 consists of eight PEVRs, which can reproduce the stray current and rail potential distribution of the DC traction power supply system [51].

Ibrahem [54] introduced a stray current hardware emulator with PEVRs. However, the current direction of proposed PEVRs is fixed, which means these PEVRs are not

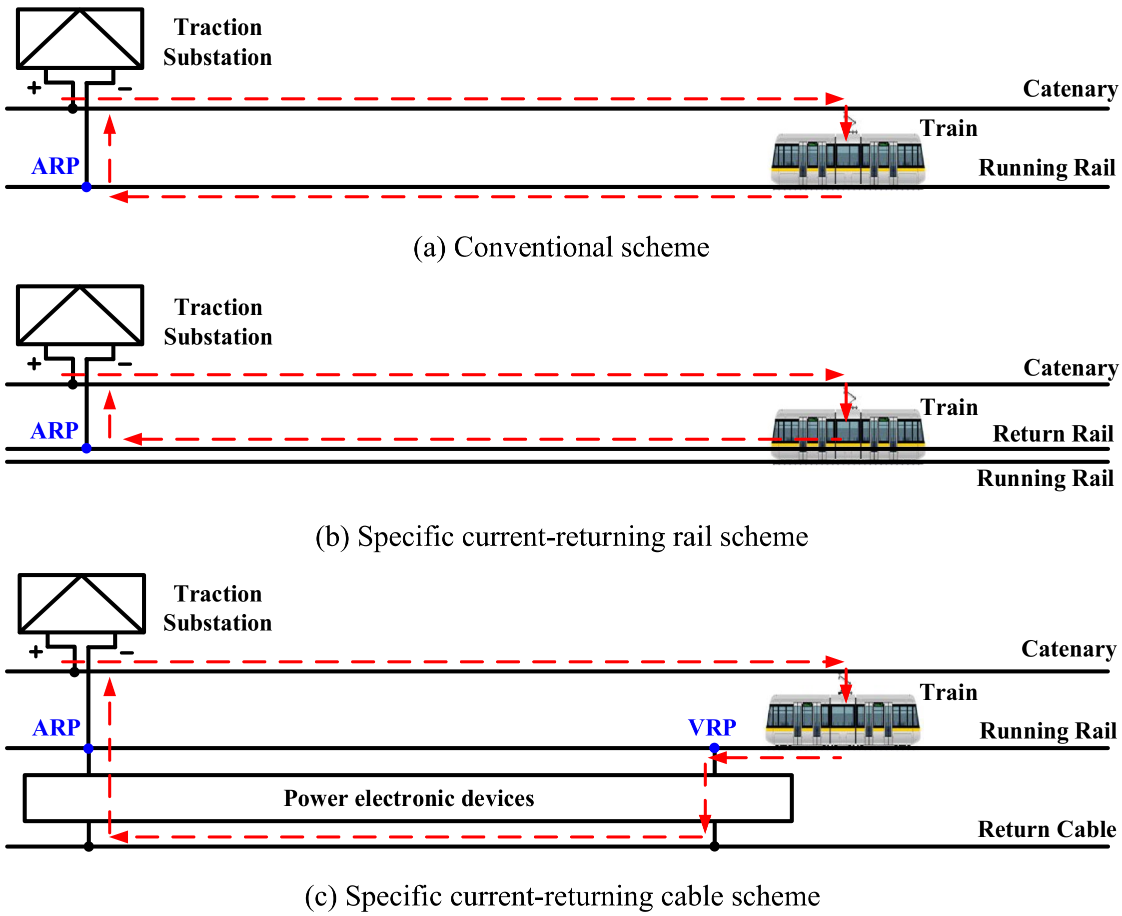


Fig. 5 Configuration of specific current-returning rail/cable scheme

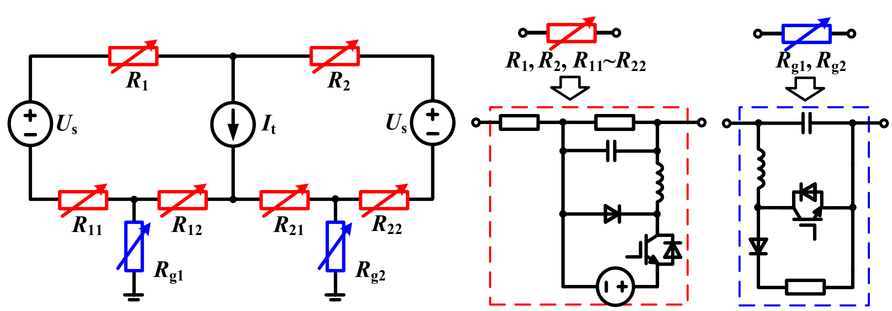


Fig. 6 Typical configuration of a stray current hardware emulator

applicable under braking conditions with current direction reversal. Yang et al. [55] then further improved the structure of the PEVRs and achieved bidirectional energy flow. However, the hardware emulators in these works [54, 55] can only simulate the conventional traction power supply system, because the emulator cannot provide access points for the added power electronic devices of the specific current-returning cable scheme. To deal with these limitations, Shao et al. [56] further improved the hardware emulator scheme by dividing the running rail into multiple sections to provide fixed access points. Unfortunately, this emulator cannot accurately simulate changes in rail-to-earth resistance, and the required number of PEVRs increases with the number of sections. Therefore, to reduce the PEVRs number, Xue et al. [57] proposed a new topology for hardware emulators by multiplexing PEVRs, and innovatively used the voltage sources to replace the resistors in each PEVR for reducing the power loss. Meanwhile, to accurately simulate the rail-to-earth resistance, Wang [58] also improved the hardware emulator structure, and the stray current and rail potential distribution of the specific current-returning cable schemes were effectively verified by coordinating with power electronic devices and return cables.

Importantly, compared with actual urban rail transit, the above hardware emulators still have a certain degree of simplification for the convenience of design. More complex factors should be considered in new emulators, such as the finite boundary fringe effect beyond the running section [59], up-line/down-line and their current sharing lines [60], and distribution difference in rail-to-earth resistance [61]. Therefore, further research to develop a more accurate hardware emulator is still critical.

6 Conclusions

This paper presents an in-depth review of urban rail transit stray current research on the principle, standards, modelling, simulation, mitigation and hardware emulator. This review will be helpful in selecting appropriate methods for stray current research and obtain more comprehensive theoretical research and simulation verification. The key conclusions of this paper are summarized as follows:

(1) Stray current is an area of multidisciplinary research, and its standards should be gradually developed from a single field (such as metro) to multi-field cooperation.
(2) The modelling and simulation of stray current includes multiple solutions, and the appropriate scheme should be selected based on the specific requirements.
(3) The mitigation measures with the adoption of a specific current-returning rail/cable can solve the stray current issue, and the specific current-returning cable could have good application prospects in existing lines due to convenient installation and low cost.
(4) The hardware emulator plays an important role in stray current reproduction and verification of the mitigation measures, which has good research value in the stray current field.

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Declarations

Conflict of interest No potential conflict of interest was reported by the authors.

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