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STRAY CURRENT CALCULATION AND MONITORING IN DC MASS-TRANSIT SYSTEMS

Interpreting Calculations for Real-Life Conditions and Determining Appropriate Safety Margins

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Digital Object Identifier 10.1109/MVT.2015.2477419
Date of publication: 31 March 2016

This article delivers useful practical contemplation of stray current calculation and monitoring endeavors in dc mass-transit systems. We focus on interpreting stray current calculations—carried out at the design stage for real-life conditions—and on determining safety margins to cope with calculations following oversimplifying assumptions. We also discuss the general specifications and benefits of the direct stray current monitoring method, through addressing the implications that arise from implementing the alternative rail potential monitoring method informatively quoted in European (EN) Standards.

Introduction

Over the past few decades, the stray current modeling and monitoring endeavors in dc mass-transit systems can be broadly summarized as follows:

- Existing railway stray current model applications have the ability to compute rail voltage to remote earth and current flow [1], [2] in the modeled components under various scenarios, depending on their design and level of complexity [3], [4].
- Assessments of the corrosion impacts are made as qualitative assessments using a mix of engineering judgment and simple spreadsheet applications of Faraday's laws to assess the cumulative mass of metal loss over the target operating period [5].
- Application of Faraday's law requires consideration of current flows, whereas the most common site of validation measurement is corrosion potentials in railway system structures and utility assets to a local reference [6], [7].
- Railway stray current flows are time-variable in response to timetabled train operations and bidirectional as a function of dynamic changes in multiple train positions and train regeneration characteristics [8], [9].
- The impacts measured on affected structures and services present the net effect from these variable factors.
- Current impact assessment techniques are limited to simple time averaging and linear extrapolation of current flows from either static or dynamic model outputs [10].

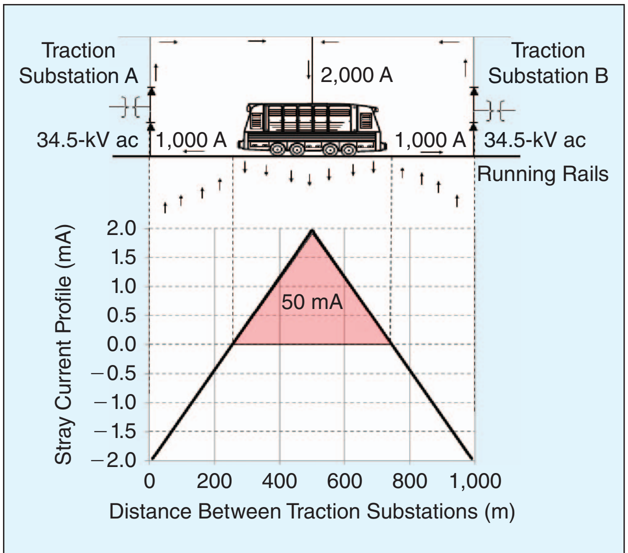

FIGURE 1 The stray current profile under the worst static conditions in a floating system.

- By contrast, current standards (e.g., EN 50122-2 [11] and EN 50162 [12]) apply criteria based on exceedance of absolute or averaged corrosion potential thresholds without regard to current flows.

In particular, EN 50122-2 specifies requirements for protective provisions against the effects of stray currents, which result from the operation of dc traction systems. This applies to all metallic fixed installations, which form part of the traction system, and also to any other metallic components located in any position in the earth, which can carry stray currents, resulting from the operation of the railway system. To this end, EN 50162:2004 completes EN 50122-2 by establishing the general principles to be adopted for minimizing the effects of dc stray current corrosion on buried or immersed metal structures.

Stray Current Calculations

Interpreting Stray Current Magnitude

Stray current magnitude depends on the traction current, the rail resistance, and the resistance to the earth value. Applying the equation in the EN 51022-2:2010 Annex C to a data set with a maximum expected traction current of 2,000 A that is equally returning through a 500-m section of two rails (i.e., 1,000 A on each side) with a resistance of 40 mW/km of rail and a resistance to earth of 100 W/km results in a I_{stray} of 50 mA.

However, care should be taken when interpreting any simulation outputs. For example, Figure 1 illustrates the stray current profile simulated (under a resistive type model [1]) along the same 1-km section of floating track with two substations at remote ends, supplying a train with 2,000 A at the midpoint. This profile constitutes a snapshot of the worst distribution stray current along the length of the rail (0–1,000 m). In the floating system, modeled by means of an example, this profile will appear on the rails as +2 mA near the train and −2 mA near the two substations. A positive figure implies a current leaking out of a conductor by corrosion, and a negative figure implies a current leaking into a conductor. At 250-m down the track, the voltage to remote earth will be 0 V, thus no leakage current activity occurs. Although the maximum stray current under the static condition simulated is about 2 mA at 500 m along the rail (see Figure 1), the sum of total stray current leaving the rails, between 250 and 750 m, is 50 mA.

The principles previously described for interpreting the stray current simulation outputs equally hold for diode-bonded systems, albeit for their intrinsic characteristics. In such systems, the diodes can either be in turn-on or turn-off status. When the rail is at negative potential with respect to the earth, the system is floating (i.e., the diode is turned off). The diode, however, will appear as a short circuit (i.e., the diode is turned on) when the rail potential moves positive with respect to the earth. The general effect is to increase the stray current level because it holds the negative potential of the rail at or near earth potential and raises the peak rail voltage, with respect to the floating mode of the system.

Applying Scaling Factors for Real-Life Conditions

A determination of the stray current levels under real-life conditions can be achieved by applying scaling factors to the modeling results. A variation in track current will influence the leakage current distribution due to the resulting alteration of rail-to-earth potential. A doubling in track current will lead to a doubling in voltage and, hence, doubling of leakage current density along the rail. This is a linear effect.

The rail-to-earth potential is determined by the currents flowing through the rail. Unless there is significant leakage that causes a change in the rail current flow, the leakage current density is proportional to the resistance of the rail insulation. Variations in the rail-to-earth resistance can, therefore, be taken to have a linear relationship with the leakage current density.

The 50-mA stray current value in Figure 1 may be lower when compared to measured numbers on some systems; however, it is realistic at rail-to-earth resistance levels of 100 Ω km, which is driven by design and construction targets. To this end, it is noted that the whole track system is usually planned, installed, and maintained to ensure particular insulation levels (e.g., 40 or 10 Ω km) can be sustained under operational conditions. However, industrial practice suggests using a value of insulation level higher than the aforementioned values as a benchmark for the design—that is, to ensure that when the track is new, clean, and dry (i.e., just after the installation process), it has a typical value of 100 Ω km. If, however, the rail-to-earth resistance is pushed to 2 Ω km, (specified as minimum in EN 51022-2) or any other value lower than 100 Ω km, then the numbers from the model would come out significantly higher (see Table 1).

The linear scaling rule does not apply when adjusting the expected maximum stray current to account for varying distances between two supplying traction substations. To this end, we note the total stray current leaking from a floating system can be conveniently described using

$$I_{\text{stray}} = \frac{I \cdot r_t \cdot l^2}{8 r_c}, \tag{1}$$

where I is the traction current in amperes, r_t is the resistance of the track (i.e., two parallel rails) in ohms per kilometer, l is the distance between the train and the two supplying substations in kilometers when the train is at the midpoint, and r_c is the resistance to the earth of the tracks. Thus, doubling the distance between any two supplying substations, (l) will result in increasing the stray current level (I_{stray}) by a factor of four. The concept is clearly illustrated in Figure 2, where the maximum stray current level expected is interpolated for different equal distances between the train and the supplying traction substations (i.e., the train sits at midpoint).

Interpreting Stray Current Leakage Density

EN 50122-02:2010 states that there is no damage in the tracks over a period of 25 years, if the average stray current $(I_{\max})$ per unit length, that is, current leakage density, does not exceed 2.5 mA/m. In particular, Annex C of the EN 50122-02:2010 specifically states that the 2.5 mA/m is a conservative figure based on simplifying assumptions and prompts for more detailed investigation.

In relevant modeling endeavors identified in the literature, as well as the method described in EN 50122-02, the stray current density calculation assumes that the rail-to-earth resistance at each baseplate along a section of track is uniform, and it provides a combined effective resistance to the earth (e.g., 100 Ω km) for the entire traction section considered. However, this is an improbable condition and the real resistance is more likely to result from a small proportion of baseplates with a lower than expected resistance. Furthermore, the longitudinal rail resistance is also uniform—i.e., there is even wear along the length of the rail and the welded joints are all of uniformly low resistance. It is important to note that variation in longitudinal rail resistance may also arise due to track bonding issues (stolen bonds and degraded connections. The method described in EN 50122-02 also assumes the track bed reinforcement and concrete, together with the tunnel systems, are also electrically uniform and that the external soil environment is uniform.

Given that this degree of system uniformity across all of the infrastructure components is highly unlikely, especially once the system is in operation, it is more reasonable to assume that there will be a concentration

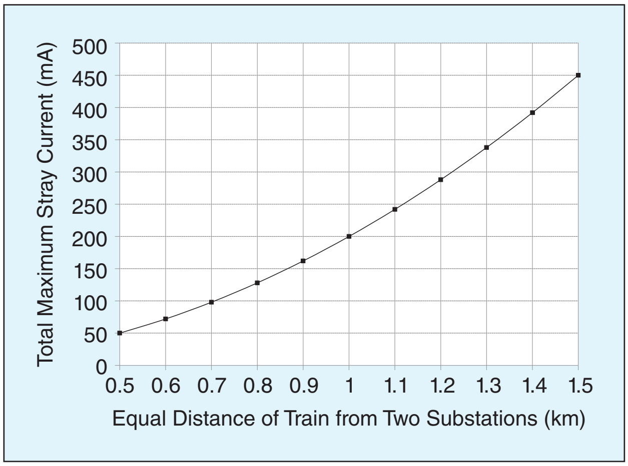

FIGURE 2 The stray current level variation for different substations locations in the floating system.

of stray current return to the rail over a possibly short distance. To apply a more realistic case, a range of scenarios can be investigated based on a more credible method for calculating the average stray current per length of a single-track line, illustrated in the following equation:

$$J = \frac{p \times I_s}{d}, \tag{2}$$

where p is the percentage (%) of the stray current that will return to the rails within a specified shorter length d and I_s is the total stray current flow from the rails. If, for example, the total calculated stray current flow is 200 mA (1-km section), the worst case stray current leakage under a design level of 50 Ω km into the track bed concrete would be 2 mA/m when it is assumed that 30% of the total stray current flow will have a concentrated return to the rails within 3% of the rail length (see Figure 3).

Similarly, when it is assumed that 30% of the total stray current flow will have a concentrated return to the rails within a 30% section of the rail length, then the stray current leakage would be at 0.25 mA/m. Figure 3 provides the results for two more scenarios that investigate smaller percentages (e.g., 10% and 20%) of stray currents' concentrated returns to the rails. Thus, the method shown in (2) may facilitate stray current control designers to determine safety margins to credibly test a number of configurations of their designs as well as service conditions.

Stray Current Monitoring Methods

Stray current performance monitoring is a recommended requirement in EN standards covering dc railway systems. The performance monitoring is utilized to enable proactive maintenance. It merely relies on the system's condition data and ensures continued stray current control over railways and third-party infrastructure.

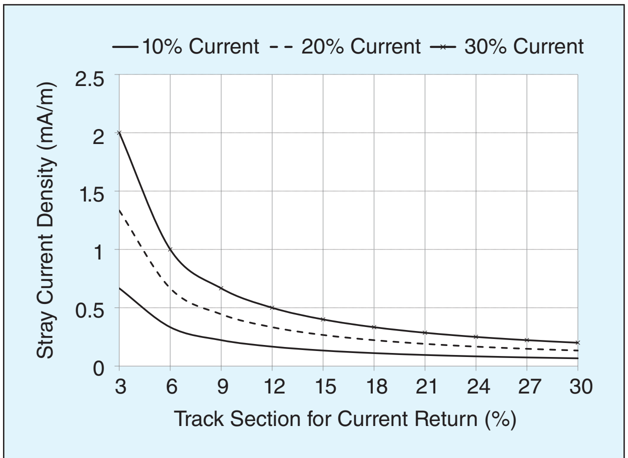

FIGURE 3 The leakage current density (amperes per meter length of the rail) assuming concentrations of stray current return to the rail over shorter distances.

Rail Potential Monitoring Method

A basic specification for continuous monitoring is given in EN 50122-2 as an informative (not normative) Annex B, and on this a number of commercial systems have been developed and marketed. The philosophy of these systems is that direct measurement of stray currents is difficult; therefore, they are based on measurements of the resistance of the return circuit to the earth or the voltage against the earth resulting from train operation (see Figure 4).

These rail potential measurements are providing information to the systems' operators and owners to restore their systems back into line with a reference condition. Thus, such endeavors do not measure the effects of stray current but they merely concentrate on its source. The drawback of this endeavor lies in identifying an appropriate reference condition that will serve as a healthy condition-benchmarking metric. The reference condition should be able to account for elements that are semideterministic but also varying. These elements include scheduled daily or seasonal traffic trends, occasional traffic peaks (e.g., a major sporting event), weather/environmental conditions, rail insulation condition, faults, and track pollution. Most importantly, the reference healthy condition should be defined once all third-party measurement issues have been resolved and should be under occasional reassessment. Therefore, to acceptably interpret any arising alarms under the rail potential monitoring method, a mix of engineering judgment and experience is required.

Direct Stray Current Monitoring Method

To partially lift the uncertainties associated with the rail potential monitoring method, a direct stray current monitoring method can be deployed. The objective of the stray current monitoring method is to determine the performance of the package of protective measures used to control stray current, measure the impact of stray current

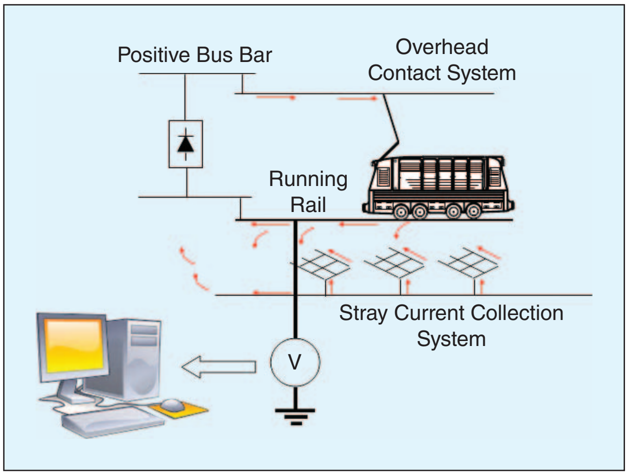

FIGURE 4 The rail potential monitoring method.

on the corrosion of the system structures, and allow the location of stray current faults to be determined.

The reference specification of a stray current monitoring method for a tunnel metro system can be summarized as follows.

- In each rectifier substation of the traction system, a wall-mounted stray current cabinet is usually provided. This cabinet is equipped with a sufficient number of suitable size terminals to terminate the necessary cables carrying the potential of specific parts of the traction earth and structural earth systems according to the stray current monitoring design. After completion of construction and putting into operation of the tunnel stretch, measurements have to be carried out via the stray current cabinet to check if the maximum allowable value of 0.1 V for the longitudinal voltage drop, caused by operation in the tunnel, is not exceeded.
- EN 50122 applies voltage limits in two ways: 1) longitudinal voltage drop in tunnel reinforcement and 2) structure to the earth potential shifts in tunnel reinforcement. Stray current designs assume that the longitudinal 0.1 V limit is applied over individual section lengths of the stray current grid (collection system), where a length is defined as being between two traction substations or two dielectric joints should the system be segregated, accordingly. The remote measurement of the end-to-end voltage drop, which would require sense cables to be routed from each end to the nearest stray current cabinet, is not recommended as the sense cables would be susceptible to electromagnetic interference. The presence of the stray current grid allows direct measurement of the stray current flow, either in the reinforcing steel or in the traction earth cable using local sensors. The 0.1-V criterion can be converted to a maximum stray current value for each section, given the known stray current grid resistance and traction earth cable resistance. The latter value is used for performance measurement purposes.
- The tunnel reinforcement potential shift is subject to a maximum limit of +0.2 V (EN 50162:2004, Table 1) which EN 51022-2:2010 interprets as “the average value in the hour of highest traffic.” A normal industrial practice is to measure this value as a corrosion potential using an embedded sensor.
- Taken together, these two parameters (longitudinal 0.1-V limit and potential shift subject to a maximum limit of +0.2 V) will allow quantification of the stray current magnitude and direction at the measurement location and confirm whether the metro system is exporting and importing traction stray current through the tunnel walls to and from the outside environment. This will both quantify the corrosion threat to the tunnel reinforcement and the risk of stray current corrosion to external pipes and services. The tunnel-wall measurements will also allow detection of imported stray current from outside systems, such as pipeline cathodic protection systems.
- To achieve this, a network of current and tunnel corrosion sensors can be applied to locations across the metro system. Data acquisition units are then installed at each sensor and the digital output is transmitted to the stray current cabinets at each rectifier substation. The number and position of sensors are usually determined during detail design to allow the operators to locate potentially dangerous track insulation failures. The design process takes account of the traction power and stray current control designs, as well as the distribution of the different tunnel and station construction across the system and significant interfaces with external systems and services. As a minimum, current and tunnel corrosion sensors are located at each metro station (one pair per track) and in the tunnels at midpoints between stations (one pair per tunnel).

Direct Stray Current Monitoring Method Benefits

The direct measurement of stray current in the stray current grid offers a more direct correlation with rail insulation performance than is achievable from either rail-to-earth voltage measurements or longitudinal voltage drop measurements. The use of the data at the operation control center (OCC) can follow the approach defined in EN 50122-2 Annex B, with the rail-to-earth voltage measurement replaced by direct stray current measurement. Measurement of current flow will allow estimation of stray current corrosion to the stray current grid components as current flows out of the grid to return to the rail.

The inclusion of tunnel corrosion sensors will reduce the scope for external baseline and operational surveys as any stray current reaching external services will have first to traverse the tunnel wall. These measurements will give a direct measure of corrosion rates in the tunnel

TABLE 1 ***The stray current magnitude scaling for real-life conditions.***

	Calculated Values	
Rail-to-Earth Resistance (Ω km) Single Track	**Stray Current with Single Train Drawing 2,000 A 500 m from Each Substation**	**Stray Current with Single Train Drawing 4,000 A at 500 m from Each Substation**
EN 50122-2: permitted minimum: 2 Ω km	2.52 A	5.04 A
Design recommendation: 100 Ω km	50.1 mA	100.63 mA
Service operation: 40 Ω km	125.34 mA	250.21 mA

reinforcement and provide a contextual reference to the stray current grid measurements allowing key performance index (KPI) criteria and performance visualizations to be defined.

Tunnel Corrosion Monitoring

Measurement Sensors

The tunnel reinforcement to the earth potential can be measured using sensors fixed to the reinforcement cage prior to concrete pour. Each sensor can be of the same type and configuration such that it can be used to make a series of stray current and corrosion related measurements (see Table 2).

The sensors can provide sufficient components to allow the required measurements to be undertaken. A suitable minimum configuration would be a six-element sensor comprising a carbon-steel sense electrode, a carbon-steel coupon electrode, an auxiliary or counter electrode, a reference element or electrode, a reinforcement connection, and a temperature sensor. The carbon-steel electrode used for measurement can be independent of that used for measurement.

TABLE 2 *The types of sensors and monitoring methods.*

ID	Name	Method
1	Tunnel reinforcement potential	Corrosion potential measurement between reinforcement and integral reference element
2	Tunnel-wall stray current	Current flow between reinforcement and an integral carbon-steel element
3	Tunnel reinforcement corrosion rate	Corrosion rate using linear polarization or galvanostatic pulse method of the reinforcement
4	Tunnel coupon corrosion rate	Corrosion rate using linear polarization or galvanostatic pulse method of an integral carbon-steel coupon element
5	Temperature	Temperature within the tunnel-wall concrete using an appropriate sensor

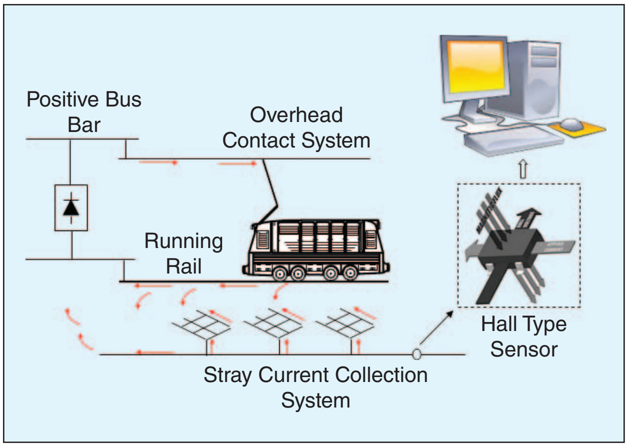

FIGURE 5 The direct stray current monitoring method.

Measurement Module

A local data measurement and acquisition unit (DAU) can be provided at each sensor location to perform the required measurements both on demand from the control system and to preconfigured schedules. The DAU is also used to convert the results into a digital format. The DAU is usually capable of bidirectional communication with its corresponding local control unit (LCU) at the rectifier substation stray current cabinet. Power for the DAU can be taken locally within the tunnel.

Stray Current Grid and RS Stray Current Cabinet Measurements

Stray Current Grid Measurement

Measurements can be made from current in the stray current grid system using a shunt resistor, installed as part of the transverse bond connection, or from currents within the traction earth cable using a suitable Hall-effect type sensor, or other suitable means (see Figure 5). In each case, the measurement sensor and equipment should be capable of withstanding over current during short-circuit fault conditions on the rail system.

RS Stray Current Cabinet Grid Measurement

The RS local measurements depend on existing measurement requirements from traction power design. These could include rail-to-earth voltage measurement and traction return current measurement.

Local Control Units

An LCU is provided at each stray current cabinet to manage communications with the tunnel and station DAU units. The LCU can have local data storage facilities. The storage capacity is defined at detail design to ensure adequate data redundancy in conjunction with OCC data management procedures.

Data Management System

Measurement Control and Configuration Software

Usually, some software is provided at the OCC to allow direct configuration of all aspects of the stray current monitoring system, including individual measurement sequences, sampling frequencies, LCU data storage, and data transfer functions. Diagnostic routines are included to allow troubleshooting of individual DAU performance. The system can be configured to allow central rail-traffic controller synchronization across the LCU/DAU network to OCC systems.

Data Storage and Management Systems

A database management system can be provided to store, archive, and analyze the outputs from the stray current monitoring system with the capability to output data in a variety of forms—from high-level diagrammatic system-health visualizations down to detailed performance-versus-time graphs at single or multiple sensor locations under user control. System alert and alarm levels shall be configurable with KPI performance tracking on a weekly and monthly basis. Such systems should be able to provide estimated location data for alert and alarm conditions.

Conclusions

This article aims to benefit stray current control designers by highlighting the relative significance of two mutually important elements that should be addressed at the design stage of dc mass-transit systems. These two elements are 1) indicative stray current calculations and assessments and 2) the specifications of the stray current monitoring system that should be subsequently installed along the route of the system.

It is worth noting at this point that the stray current calculations following simplifying assumptions, carried out at the design stage, should be interpreted with care; keeping in mind that some standard-based approaches can be generic, or in some occasions, quite conservative.

Acknowledgment

The authors sincerely acknowledge the information and practical knowledge received by their late colleague P. Aylott from Intertek. This article is a tribute to his long service in stray current control and corrosion applications across the world.

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