Stray Current Control in DC Mass Transit Systems

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***Abstract*—Stray current control is essential in direct current (DC) mass transit systems where the rail insulation is not of sufficient quality to prevent a corrosion risk to the rails, supporting and third-party infrastructure. This paper details the principles behind the need for stray current control and examines the relationship between the stray current collection system design and its efficiency. The use of floating return rails is shown to provide a reduction in stray current level in comparison to a grounded system, significantly reducing the corrosion level of the traction system running rails. An increase in conductivity of the stray current collection system or a reduction in the soil resistivity surrounding the traction system is shown to decrease the corrosion risk to the supporting and third party infrastructure.**

***Index Terms*—Corrosion, heavy rail, light rail, rail transportation, stray current, transit.**

I. Introduction

CURRENT leakage from directional coupler (DC) railway systems is an inevitable consequence of the use of the running rails as a mechanical support/guideway and as the return circuit for the traction supply current. Since the rails have a finite longitudinal, or series, resistance—around 40–80 mΩ/km or 40–80 $\mu\Omega/\mathrm{m}$ of rail—and a poor insulation from earth—typically from 2 to 100 Ω/km—a proportion of the traction current returning along them will leak to earth and flow along parallel circuits (either directly through the soil or through buried conductors) before returning onto the rail and the negative terminal of the DC rectifier. It should be noted that, in a DC system, the current loss is by direct leakage. Induced effects found in alternating current (ac) systems are less significant in terms of corrosion damage.

Given that current flow in a metallic conductor is electronic, while that through electrolytes such as the earth, concrete, etc., is ionic, it follows that there must be an electron to ion transfer as current leaves the rails to earth. Where a current leaves the rail to earth there will, therefore, be an oxidation, or electron-producing, reaction

$$Fe \rightarrow Fe^{2+} + 2e^{-}. \quad (1)$$

This reaction is visible after time as corrosion damage. For the current to return onto the rail, there must be a reduction or electron-consuming reaction. In an oxygenated environment, this will typically be

$$O_2 + 2H_2O + 4e^{-} \rightarrow 4OH^{-}. \quad (2)$$

It should be noted that the iron-reduction reaction is not thermodynamically preferred and that iron does not plate back onto the rail.

Corrosion of metallic objects will, therefore, occur from each point that current transfers from a metallic conductor, such as a reinforcement bar in concrete, to the electrolyte (i.e., the concrete). Hence, stray current leakage can cause corrosion damage to both the rails and any other surrounding metallic elements. In a few extreme cases, severe structural damage has occurred as a result of stray current leakage.

There is, therefore, a stray current control requirement to minimize the impact of the stray current on the rail system, supporting infrastructure, and third-party infrastructure. It is significant to note that stray current has not always been perceived as a problem and has been positively encouraged. Schwalm and Scandor [1] produced a paper detailing such a view that states that rails are generally not insulated from the earth so that part of the return current travels through the earth and makes use of any metallic underground path in the vicinity that provides conductivity.

This paper illustrates how the stray current magnitude varies according to the design of the power system and the running rails before, comparing the performance of stray current collection systems of different constructions and placed in different soils.

II. Impact of Running Rails and Power-System Design on Stray Current Levels

The essential elements of a transit system are the rails, power supply, and vehicles. The design and placement of these elements of the transit system dictates the stray current performance in terms of the total stray current leaving the rails. If the total stray current for a given design of a system is high, a stray current collection system may be needed to control the path through which this stray current returns to the substation negative bus. If a stray current collection system is not provided, considerable corrosion of the supporting infrastructure and of third-party infrastructure may occur.

However, as stated by Schaffer *et al.* [2], no stray current collection system will be needed if the rail insulation and power-system design themselves can keep stray current levels below a "damage-causing" value. It is, therefore, obviously desirable to eliminate the need for any stray current collection system by controlling the level of stray current being produced by the transit system. Means to reduce stray current levels below a damage-causing value may include measures such as increased power system cross-bonding, increased rail to earth resistances

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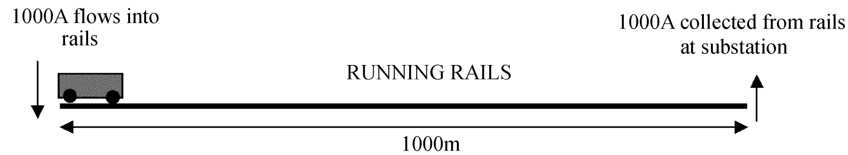

Fig. 1. Section of model to illustrate stray current production.

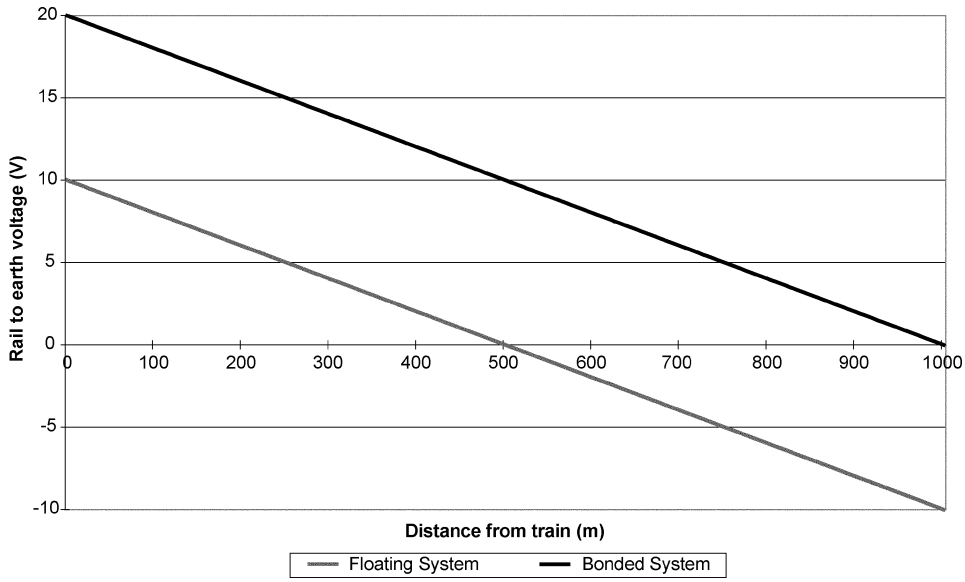

Fig. 2. Rail-to-earth voltage profiles for a floating and grounded rail system.

(by use of better coatings/insulating supports), and the encasement of the track slab by an insulating membrane.

The determination of the need for a stray current collection system is, therefore, initially based on examination of the rail-to-earth voltage profiles during the operation of the transit system (determined by the power-supply design and the electrical performance of trains themselves), the rail-to-earth insulation levels, and the resulting stray current leakage profile.

A. Impact of Floating/Grounded Running Rails on Stray Current Level

Fig. 1 shows a 1-km section of track used to illustrate the rail-to-earth voltage profile when a train draws current from a substation. This 1-km section is representative of a symmetrical 2-km section of track with a single train at the center and a substation at each end. The 1000 A that has been produced by a substation at the far end of the track is being drawn by a train placed at 0 m.

For every 1 $m\Omega/km$ of track resistance, there will be a resulting voltage drop of 1 V/km along the rail. Take a case where the resistance of a single rail is 40 $m\Omega/km$ (20 $m\Omega/km$ for the track). For 1000 A current, the resulting voltage difference between the two ends of the track will be 20 V.

This voltage will appear on the system in one of two ways. In a floating system where the running rails (and, hence, the DC negative bus) are allowed to float with respect to earth, the voltage will appear on the rails as 10 V to remote earth near the train and -10 V to remote earth near the substation.

In a grounded rail system, where the running rails are effectively bonded to earth (via a stray current collection system or any reinforced concrete/metallic structure around the track such as a tunnel) at the substation, the voltage will appear on the rails as 20 V to remote earth at the train and 0 V to remote earth at the substation. Fig. 2 shows the rail to earth voltage in a floating and grounded system.

A positive voltage in Fig. 2 represents the case where a current leaks out of the rails into the earth. For the negative voltage case, the current leaks back into the rails. The magnitude of the current leaking from the rails is determined by the voltage to remote earth at any point along the track and the resistance to remote earth of each rail. At 500 m down the track, the voltage to remote earth will be 0 V (implying no current leakage in either direction). In the floating system, stray current will, therefore, leave the rails in the region 0–500 m and then re-enter the rails in the region 500–1000 m. This is shown in Fig. 3.

In the case of a grounded rail system, where the voltage is always positive with respect to earth, stray current leaves the rails along their full length and returns to the traction system power supply at the substation earth bond (i.e., through the substation earthing system and any metallic components connected to it).

For the two forms of system described, the overall stray current level can be described using the following equations. These equations are based on the single-train case shown in Fig. 3 with a uniform rail coating. In the floating system, stray current leaves the track over the first 500 m, returning to the track over the final 500 m. It can be shown that the total stray current leaking from the system can be described as

$$I_{\text{stray}} = \frac{I r_t l^2}{8 r_c} \tag{3}$$

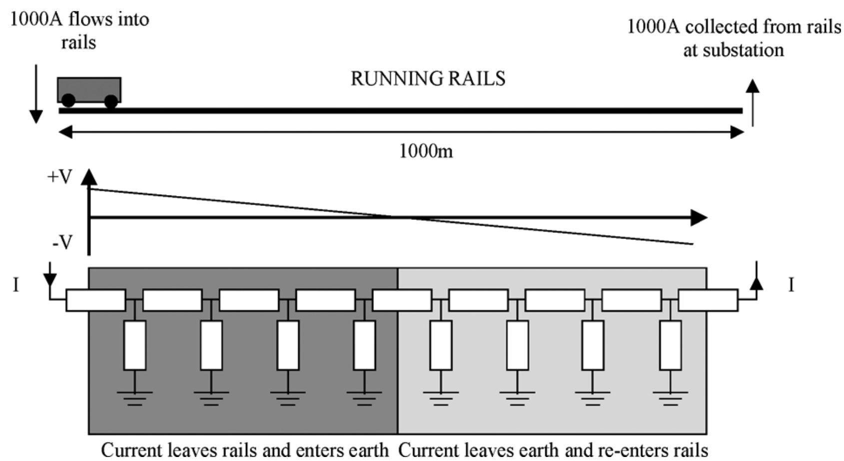

Fig. 3. Basic model of floating rail system, illustrating stray current leakage.

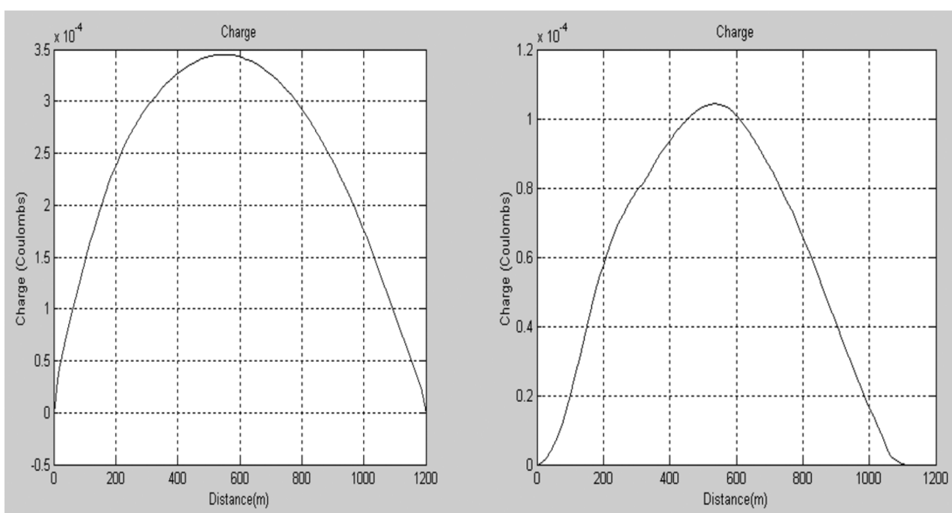

Fig. 4. Positive (corrosive) stray current charge from running rails in dynamic simulation of the (left) grounded and (right) floating system.

where I is the traction current in amps, 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 substation in kilometers, and r_c is the resistance to earth of the tracks.

For a grounded system, this equation can be rewritten as

$$I_{\text{stray}} = \frac{I r_t l^2}{2 r_c}. \tag{4}$$

The increase in stray current level by a factor of four on the grounded system arises from the doubling in the peak rail-to-earth voltage in combination with a halving of the resistance through which stray current can leak by a factor of two (due to doubling the amount of track at positive rail to earth potential). It would, therefore, seem that floating running rails are the best option if stray current is to be minimized. This conclusion is shared by Yu and Bomar. Yu [3] states that the floating rail system is the best option for the reduction of stray current levels while Bomar [4] describes a case in which extremely high levels of stray current was observed in a system where the rails were directly bonded to a ground mat at the traction substations.

With the use of dynamic simulations of rail voltages and stray currents, it is shown that the "factor of four" is generally a low estimate of the increase in stray current level from a grounded system. The model used for the dynamic simulations was implemented in MATLAB. The simulation determines the train position, velocity, current requirement, and rail voltages as a function of time [7].

Fig. 4 is based on a dynamic simulation and shows the summated positive (i.e., corrosive) stray current charge produced by a train running between two stations at a 1200-m interval. Substations are located at 0 and 1200 m, i.e., at the two end stations. Fig. 5 then shows the ratio of the grounded system to floating system summated positive stray current charge along the rail length.

While these results clearly demonstrate the advantages of a floating rail system, it must be proven that unsafe levels of track-to-earth voltages will not develop during fault conditions (such as the conductor rail coming into contact with earth). As safety is the prime concern in the design of mass transit power systems, grounded systems may occasionally be the only choice. Modern protective devices do, however, allow faults to be detected and cleared with relative ease.

An oft-proposed variation on these systems is the use of a diode-bonded approach, in which the rail is connected to the

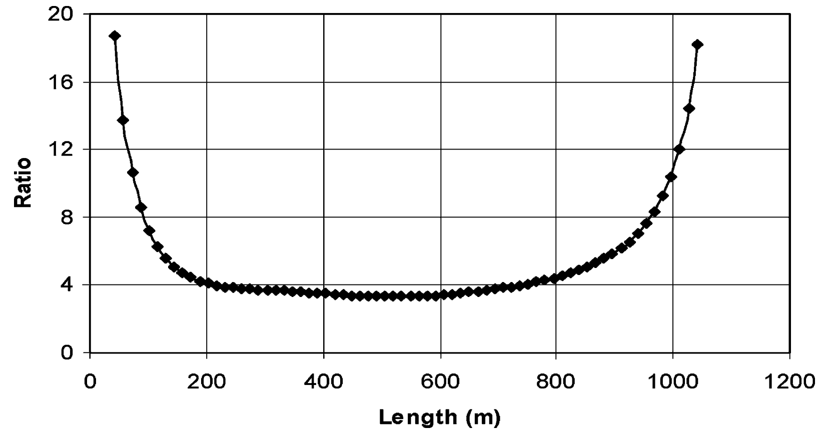

Fig. 5. Ratio of grounded to floating system summated positive stray current charge along the rail length.

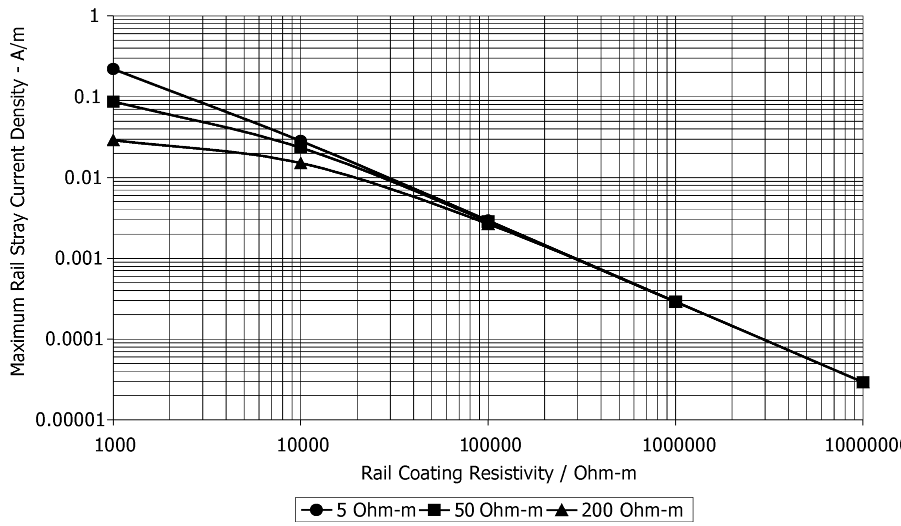

Fig. 6. Variation of maximum rail stray current density as a function of rail coating and base material resistivity.

ground mat via a diode. This diode will prevent stray currents passing directly from a ground mat to the rail. When the rail is at a negative potential with respect to earth, the system is, therefore, floating. The diode will, however, appear as a short circuit when the rail potential moves positive with respect to earth and the general effect is to increase stray current levels in comparison to a floating system [5], [8].

B. Variation of Rail Leakage Current as a Function of Rail Insulation Level and Soil Resistivity

An important parameter in (3) and (4) is the rail resistance to earth. If near-perfect insulation was placed around the rails, any level of rail voltage could be tolerated with minimal stray current effects (although it should be noted that other considerations such as touch voltages restrict the maximum rail potentials allowed in a traction system).

The rail resistance to earth usually is a function of the insulating pads upon which the running rails are mounted and the resistivity of the base material (e.g., concrete or ballast) on which the rails are laid. In normal circumstances, the resistivity of the rail insulation/the pads upon which the rail is mounted is more significant than the resistivity of the material upon which they are placed (such as concrete).

Fig. 6 shows the variation in the maximum stray current leakage density of the floating system previously described in Fig. 1 as a function of the resistivity of the base material and resistance of the insulating pads used to fix the track to the ground at regular intervals. The stray current leakage density is expressed in A/m, i.e., the stray current leaving a 1-m section of rail. The maximum stray current leakage density is found at the location of the train or substation in the case of the floating system where the rail voltage is at a peak.

In the CDEGS software [6] used to carry out this modeling, the resistance of insulating pads used in a rail system must be converted to a coating of a given resistivity that is placed uniformly along the rails. This simplifies the modeling requirements. Altering the resistivity of a 10-mm thickness coating placed around the rail varies the value of insulating pad resistance. A rail coating resistivity of 100 MΩm (the last point on the x-axis) is equivalent to an insulating pad resistance of 340 Ω/km (produced by all the insulating pads found in 1 km being placed in parallel).

Fig. 6 shows that the resistivity of the material the rail is laid on does not have an effect on the stray current leakage density until the rail coating resistivity drops significantly lower than 100 $k\Omega$m, equivalent to an insulating pad resistance of 3.4

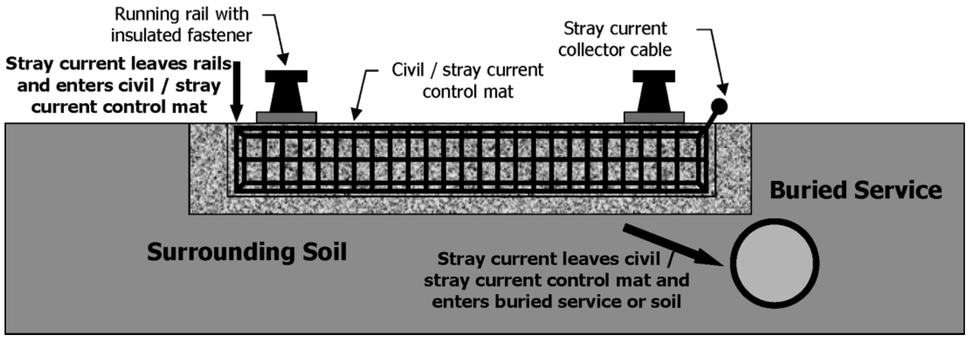

Fig. 7. Path of stray current leaving the running rails.

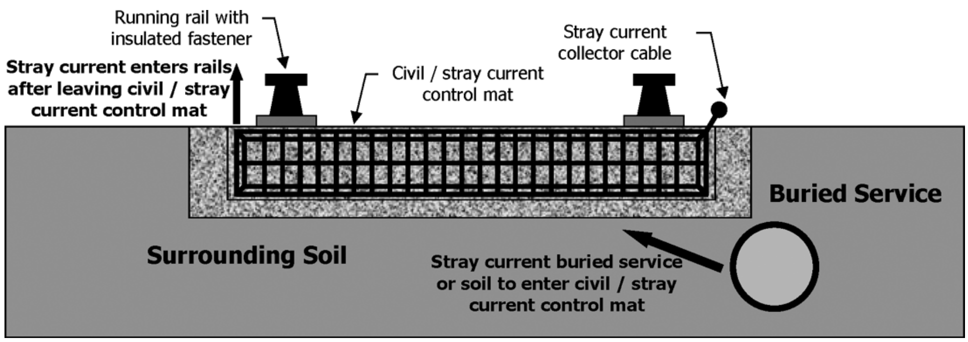

Fig. 8. Path of stray current returning to the running rails.

Ω/km. The base material resistivity would only become significant in conditions where the rail insulation was rendered ineffective (for example, for light rail systems running on streets that are gritted with salt during winter).

The key point illustrated by the graph is the illustration of the importance of the rail insulation. If the rail insulation resistance can be maximized, then the resulting stray current leaving the running rail will be minimized.

In practice, the production and operation of a transit system with a high rail-to-earth resistance is possible in the short term after construction. Regular maintenance of the insulation is required thereafter to ensure that there is no decrease in resistance and resulting risk to the transit system or third-party infrastructure. However, it may not be possible to maintain the rail-to-earth insulation of surface transit systems running on roadways, since the insulation will quickly become coated with dirt and/or salt during winter weather.

C. Impact of Stray Current on Rails, Supporting and Third-Party Infrastructure

As previously detailed, corrosion will occur at each point that current transfers from a metallic conductor, such as a reinforcement bar in concrete, to the electrolyte (i.e., the concrete). The previous analysis has shown that current leakage will occur from areas of the rail in both a floating system and a grounded system. The running rails are, therefore, the part of the rail system where corrosion must occur unless they are perfectly insulated from earth. The level of corrosion may influence the lifetime of the running rails; this should be considered at the start of any analysis.

Should the running rails be placed in an area where there are no other metallic conductors, the only corrosion risk is to the rails. However, a transit system may be placed in a tunnel made with some form of reinforced concrete or for urban transit systems close to power cables, gas mains, and similar utilities.

For a tunnel system, the primary corrosion risk is to the rails, their fixings, and the tunnel walls. The exact nature of the risk depends on the form of tunnel construction (cut/cover or bored), local soil resistivity, volume of metallic material used in the construction, and longitudinal continuity of the construction. There also is a secondary risk to structures outside the tunnel.

For a transit system placed above ground, the primary corrosion risk is again to the rails and their fixings as well as to any nearby utility cables/pipes. Again, the risk is determined by the local soil resistivity, the relative positioning of the transit system and the utility cables/pipes, and the longitudinal conductivity of the cables/pipes.

Figs. 7 and 8 illustrate the risk posed to the rails and other elements of the supporting infrastructure or third-party infrastructure due to stray current flow. Fig. 7 shows the effect of stray current leaving the rails; this case is found in the sections of rail systems where the rail potential is positive with respect to earth.

Stray current leaves the rails causing corrosion to the rails/rail fasteners themselves. If present, the stray current will then enter any civil/stray current mat found in rail systems where the rails are placed on a concrete base. The entry of the stray current to this mat of reinforcement does not cause corrosion itself, but the limited conductivity of the mat results in the further leakage of a proportion of the stray current into the surrounding soil and into any buried services (or the longitudinal conductors of any tunnel). The only corrosion risk at this time is to the mat reinforcement due to the leakage of current off the mat.

Fig. 8 shows the return of the stray current to the running rails. At risk in this case are the buried services and the civil/stray current mat, where current flows from the metallic object into the soil. Of particular significance is the fact that, in both cases described, the civil/stray current control mat has had stray current leaving the metallic reinforcement bar to enter an electrolyte causing corrosion. The same conclusion could be applied to segments of an underground tunnel constructed with reinforced concrete.

In a symmetrical system where the running rails remain floating with respect to earth, half of the system could be taken to be operating as in Fig. 7 while the other half will be operating as in Fig. 8.

In a system where the running rails are grounded to earth at the substation, the stray current leakage is generally from the rails, unless regeneration is taking place by a train. The stray current leaves the rails and will again pass into any civil/stray current mat and partly pass through any tunnel segments, buried services, or the soil before returning to the substation earth bond via the substation earthing grid or the civil/stray current control mat (usually bonded directly to the DC negative busbar in such a case). Stray current would also not leak from the civil/stray current mat to the rails. It would, instead, pass directly through the bond between the civil/stray current mat and the DC negative busbar mentioned before.

Due to the obvious corrosion risks resulting from the stray current flows detailed before, an analysis of the stray current flows within a system, and the impact on the rails, the traction system supporting infrastructure and any third-party infrastructure should be carried out. This assessment would usually identify the components that are vulnerable to stray current attack and calculate their lifetime based on the level of corrosion that they will suffer. The calculation would involve an application of Faradays law that can relate the total charge leakage from a metallic component with the amount of metal oxidized.

If the risk to any component/structure is too much to tolerate in terms of a reduction in lifetime or through safety considerations, further steps must be taken to control the level of stray current. There are a number of options, such as increases in the rail-insulation level, an increase in the operating voltage of the traction system, and reducing the substation spacing. However, a stray current collection system is often used to “catch” the stray current leaving the rails and provide a conductive path through which it can flow without a risk of damage to supporting/third-party infrastructure.

III. Stray Current Collection System

A stray current collection system can be constructed under the rails in order to “capture” the stray current and avoid damage to the segments. Such collection systems usually take the form of reinforcement in the concrete track bed of a traction system. This reinforcement is bonded along its length to provide a continuous and relatively low resistance path. The stray current leaking from the running rails is intended to flow into this collection system and be captured upon it, as opposed to flowing through the tunnel construction or other local conductors such as utility pipes/cables. For this strategy to succeed, the mat must offer a significantly lower resistance path than segment reinforcement in a tunnel, buried services, and the surrounding soil itself. In a floating system, the stray current collection system will not be bonded to the running rails.

Figs. 7 and 8 show an example stray current collection system. The reinforced concrete mat placed underneath the rails is used for both structural support and as a conductive path for a stray current. Connected to this mat is an insulated cable, generally copper, that increases the overall conductivity of the stray current collection circuit relative to the alternative stray current paths in the soil and other buried objects. Stray current control mats have generally been constructed in 100-m sections with the starts/ends of each section being electrically connected to each other and to the stray current collector cable producing a continuous stray current path. If a designer considered that stray current was likely to be a problem in a specific region of the transit system, local stray current collection systems could be used but careful attention would have to be given to the design of the terminations of the system in which severe corrosion could occur.

A. Model for the Prediction of the Stray Current Collection System Efficiency

Prediction of the stray current collection system efficiency before construction of a transit system is essential to ensure that the stray current levels will not have an adverse effect on the transit system lifetime. The restriction on the transit system lifetime is broadly based on the amount of time the system would operate far before corrosion started to render the structural elements of the system unsafe. Consideration of the effect of the stray current system on other buried services must also be taken in account.

A CDEGS [6] model of the system described is used to illustrate the impact of factors such as soil resistivity and size of the stray current control mat on the efficiency of the stray current collection system. CDEGS allows a geometrically accurate model of the system to be constructed and allows the investigation of the performance of a stray current collection system along its length. It is, however, restricted to the simulation of nondynamic situations within the transit system.

Fig. 9 shows the perspective view of a CDEGS model. A simplified model of the stray current control mat is constructed using 12 longitudinal conductors and hoops at regular intervals. This is a reduction in the number of conductors that would be present in the real reinforcement mat. This simplification is, however, necessary since the number of conductors that would be required to model a complete reinforced concrete mat would result in excessive memory and time requirements in computations. The simplified model has the same longitudinal conductivity of the real mat and tests have shown that the simplified model performs with accuracy comparable to a more complex model.

The stray current collector cable is connected directly to the stray current control mat at 100-m intervals, at which point the stray current control mat is also sectioned (as in practice for ease of construction). As with the dimensions of all conductors in the model, the size of the stray current collector cable can be altered to assess the impact it has on the system performance.

The running rails are placed above the mat, the separation of the reinforcement bar and the rails being equivalent to

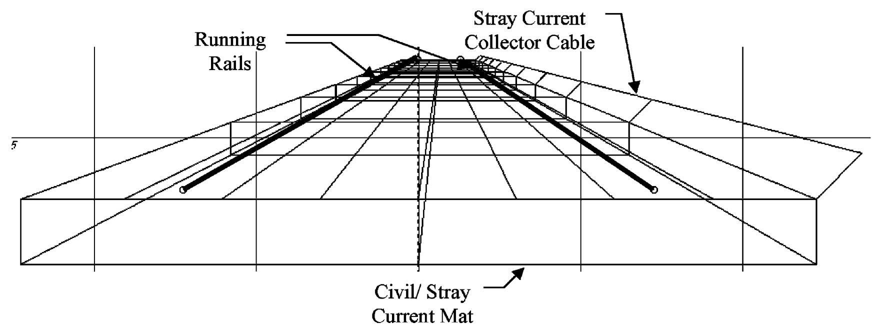

Fig. 9. CDEGS model of stray current collection system.

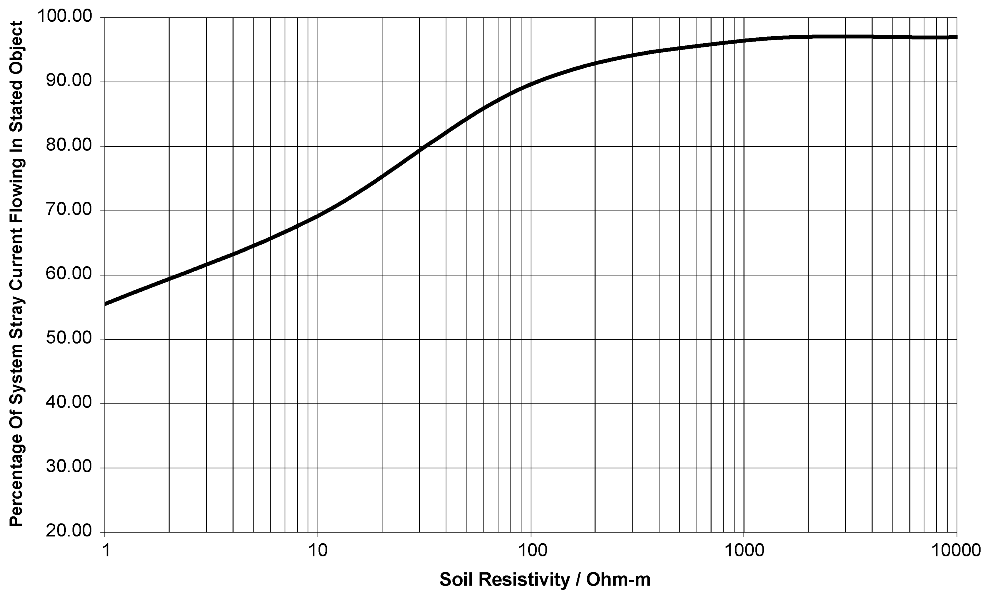

Fig. 10. Efficiency of the stray current collection system against soil resistivity.

that in a real system. The running rails are simulated by a cylindrical conductor having the same longitudinal resistance as an actual rail. The rails are also coated with a resistive coating to model the insulated pads on which the rails are placed in a real system.

The civil/stray current control mat is modeled as being placed within wet (30 Ωm) or dry (180 Ωm) concrete, while a varying soil resistivity can then in turn be placed around this concrete. Buried services, tunnel segments, and other conductive objects that may need to be considered in any particular case can also be simulated if necessary.

B. *Results of Stray Current Collection System Modeling*

1) Variation of Efficiency With Soil Resistivity: A model of a 1-km section of floating rail system is initially used to illustrate the effect of soil resistivity on the performance of a stray current collection system. The copper stray current collector cable has a cross-sectional area of 120 mm^2, the steel stray current mat has a cross-sectional area of 1600 mm^2, and the concrete resistivity is 180 Ωm. The soil resistivity is 100 Ωm.

The rail voltage profile due to the injection of 1000 A into the track is as shown in Fig. 2. The total stray current leaving the rails in the first 500-m section is 26 mA (equivalent to a track to earth resistance of 96 Ω/km). This 26 mA, 13 mA from each of the running rails, will flow into the stray current collection system. It will then either remain in the stray current collection system or will flow into the soil surrounding the reinforced concrete slab. Measurements of the current flows are taken at the 500-m point where, for this symmetrical floating rail system, no stray current is entering or leaving the rails. A plot of the efficiency (i.e., the percentage of stray current found on the stray current collection system at 500 m compared to the total stray current) of the stray current collection system against the resistivity of the soil surrounding the reinforced concrete slab is shown in Fig. 10.

As the soil resistivity increases, the percentage of the stray current retained on the stray current collection system is increased. This is due to the reduction in the conductivity of the alternative path through the soil. The ratio of the current carried by the stray current mat in comparison to the collector cable is approximately 1:1 (not shown on the graph).

While the resistivity of the soil is an important factor in the determination of the stray current collection system efficiency, it may in fact vary throughout the year and a worst case value should be taken. Factors that can be controlled are the stray current collector cable cross-sectional area and the diameter of the reinforcement bar used for the stray current control mat.

2) Variation of Efficiency With Mat/Cable Size: In the model described, the total cross-sectional area of the steel within the mat is 1600 mm^2. Adjusting this cross-sectional area to take

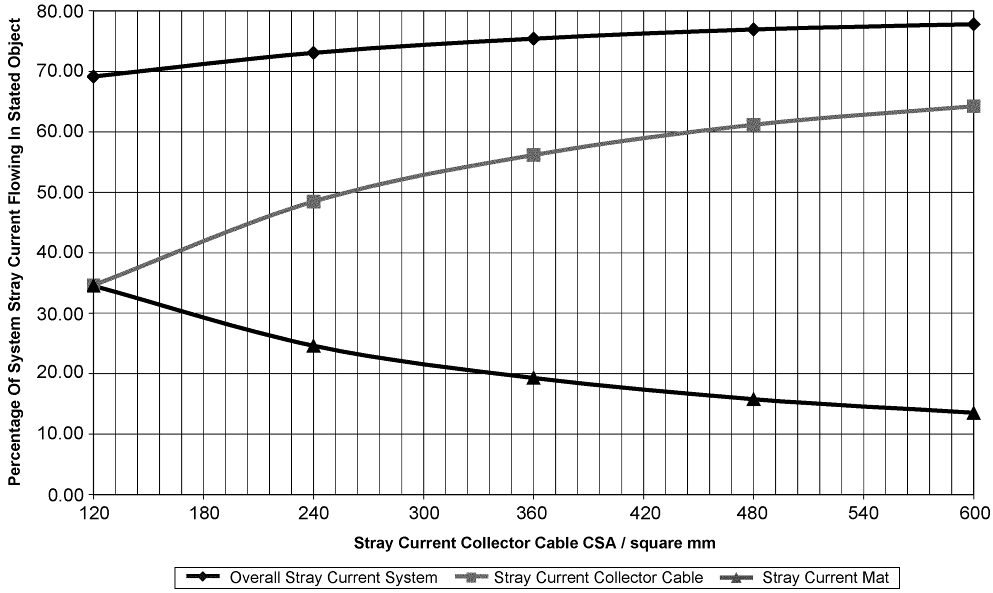

Fig. 11. Efficiency of the stray current collection system against stray current collector cable cross-sectional area (10 Ωm soil around the dry concrete base).

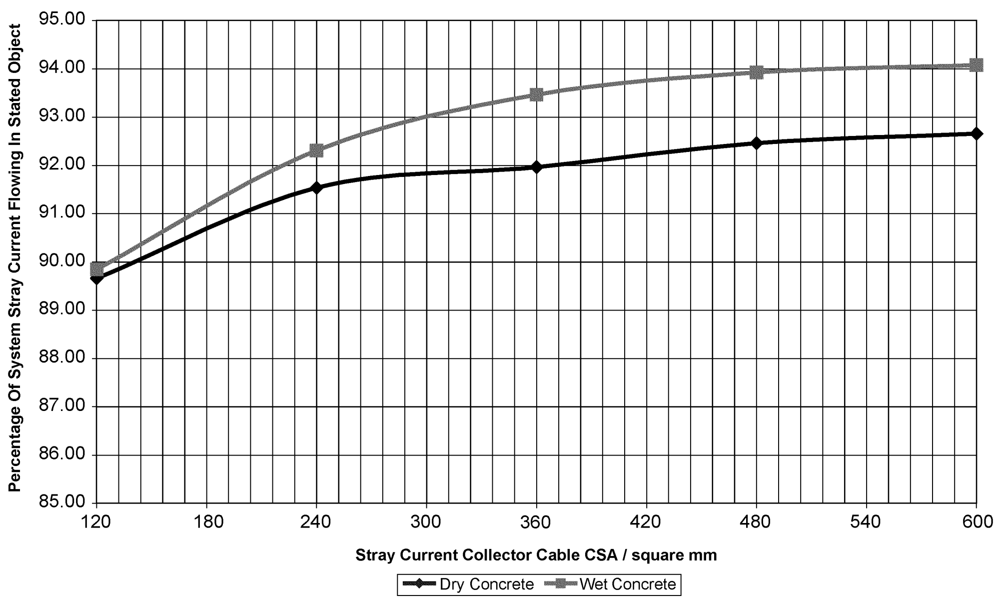

Fig. 12. Efficiency of the stray current collection system for wet and dry concrete.

into account the fact that the steel used has a resistivity 13.1 times that of copper, this would be equal to 123 mm^2 of copper. The simulations carried out for Fig. 11 show the relationship of the stray current collection system efficiency to the stray current collector cable cross-sectional area. This plot relates to a surrounding soil resistivity of 10 Ωm where the overall efficiency of the system is relatively low (69% for a 120 mm^2 collection cable as compared to 90% in 100 Ωm soil).

A 120-mm^2 collector cable results in an approximately equal current flow in both the mat and collector cable. This confirms that the 1600 mm^2 of steel within the mat is equivalent to approximately 120 mm^2 of copper. As the cross-sectional area of the stray current collector cable is increased, the percentage of the total stray current flowing through the collector cable also increases, but the current flowing through the stray current mat is decreased.

In the case where the stray current collector cable size changes from 120 mm^2 to 240 mm^2, there is an increase in the conductivity of the total stray current collection circuit by 50%. The efficiency of the stray current collection system is, however, only increased by a relatively small 3.9%. It can, therefore, be concluded that control of stray current levels using stray current collection systems can, therefore, be difficult in areas where there is a low soil resistivity or other highly conductive infrastructure.

3) Variation of Efficiency With Base Material Resistivity: The base material resistivity may change, particularly in the case of concrete placed above ground, where it may vary between wet and dry states. Fig. 12 shows the impact of changing the base material resistivity from 180 Ωm to 30 Ωm when the system is placed in 100 Ωm soil. Changing the base material resistivity does result in a small change in system efficiency, but is not significant in comparison to the effect of a changing soil resistivity.

IV. Conclusion

The total stray current produced by a DC mass transit system will adversely affect the transit system itself and third-part infrastructure by causing corrosion. The stray current produced by a DC mass transit system can be limited in a number of ways, including the reduction of substation separation, rail resistance, and operating currents and an increase in the rail resistance to earth. A system where the running rails float with respect to earth produces roughly four times less stray current in comparison to an equivalent grounded system when static simulations are carried out. Dynamic simulations show that a floating system can actually result in even higher local reductions in stray current level in comparison to a grounded system.

Reducing stray current levels is best done by careful control of factors, such as substation spacing, rail-to-earth resistance, and rail resistance. However, if after analysis the stray current level produced by a transit system is too high and may affect supporting or third-party infrastructure, a stray current collection system may have to be considered. The role of the stray current collection system is to collect the stray current leaving the rails and to conduct it along the traction system to the point where it re-enters the running rails. In this way, corrosion damage to supporting and third-party infrastructure might be avoided.

The performance of a stray current collection system is, however, highly dependant on the conductivity of the system itself and of the neighboring soil. Extremely high efficiencies can be achieved when the material surrounding the stray current collection system is highly resistive. At lower soil resistivities, the results showed the difficulty in achieving a stray current collection system with a high efficiency. In such cases, it may be more economic to consider the other ways to reduce the stray current level at source (i.e., from the rails), as previously described.

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