Stray Current Control Within DC-Powered Transit Systems

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An overview is presented on the historical aspects of stray currents created by dc-powered transit system operations and their control. The relatively recent resurgence in the interest and the construction of dc-powered transit systems has emphasized the necessity for control of stray currents. This is particularly significant for new systems being built in areas where the utilities and other facilities were not designed with consideration for the need for stray current control measures. The theoretical aspects of the reasons for stray currents and the methods available for their control are presented along with practical applications within new and old systems as part of revitalization programs. The results obtained have shown that stray current control is practical. Although certain aspects of stray current control are common within all dc-powered transit systems, the variations within the transit systems and the areas they serve require that systems be treated individually to determine the level of stray current control required and the best means of achieving this level.

The concept of detrimental corrosive effects that can result from stray earth currents emanating from dc-powered transit facilities was recognized soon after the start of operations for this type of transit system in the late 19th and early 20th centuries. This corrosive effect on metallic structures created by the dc traction currents, often referred to as electrolysis, remains to this day and has received renewed emphasis within the last two decades with the building of new dc-powered transit systems and the rebuilding of parts of older systems.

In those areas in which new systems are being constructed, the effects of stray currents become particularly important because the utility facilities have not been built to facilitate the control of stray currents. The increased costs to the utilities to address the stray current effects could be appreciable, and a case for reimbursement by the transit system could be made if significant levels of stray current effects exist. In areas in which stray currents have been experienced in the past, rebuilding of the transit system facilities provides a means for reducing these effects and thus reducing the maintenance requirements for the utility companies and others that operate underground metallic facilities. In either case, responsibility for control of the magnitudes of stray currents to reasonable levels rests with the transit system; as with many similar situations, it is accepted practice that the utility operators, or others, should not be put in distress by transit system operations without there having been a reasonable and prudent effort made to control stray currents during the design, construction, and operation of new transit facilities.

The theoretical concept of the effects of the electrolytic interchange of dc current between a metallic structure and its environment is well understood for the more common metals of construction, such as those used for utility facilities and structures, including those owned and operated by the transit system. A dc current flowing from the electrolyte to the metallic structure will provide a protective effect to that structure; it tends to reduce the corrosion rate that existed before to the introduction of the current. (*Note*: All reference to current flow polarities is in the conventional sense as opposed to the electronic flow used in scientific research.) This protective effect is the basis for cathodic protection that can be used to control corrosion of metals immersed in an electrolyte by proper engineering and consideration of the many factors involved. Certain metals, for instance, lead and aluminum, are amphoteric and can be corroded by current flow from the electrolyte to the metal if the rates are excessive. Thus, in the area in which the stray current passes from the electrolyte to the metallic structure, the structure may receive beneficial effects, especially if it is steel, cast iron, or copper. At a location on the metallic structure where the current passes from the structure to the electrolyte, corrosion will occur. The rate of the corrosion depends on the metal. For instance, one ampere of dc current passing electrolytically from the metal to the electrolyte for 1 year will result in the dissolution of approximately 20 lb of iron, 75 lb of lead, 22 lb of copper, and 6.5 lb of aluminum. The effects of this corrosion process are quite apparent on many streetcar rails embedded in roadways where current discharge has recurred over the years, resulting in the corrosive destruction of the bottom rail flange, tie plates, and spikes. This corrosion process can be even more dramatic on pressured structures, such as pipelines.

Although the mechanism of electrolysis corrosion from stray currents has not changed from the start of dc-powered transit operations in the 1890s, other aspects of the problem have changed. The power requirements for transit operations have changed, with accelerating currents (for a typical 750 V system) for heavy rail trains reaching 10,000 to 15,000 amp; the light rail vehicles (LRV) having accelerating currents of around 1,000 amp compared with 400 amp for President's Conference Committee vehicles; and the new LRV's are quite often operated in consists of up to four vehicles. The concept of the traction power substation has changed for the better with the advent of solid state, automatic controlled units; stations can be placed more appropriately throughout the system as opposed to the use of the rotary converters at a centralized location covering large areas. The introduction of continuously welded rail has reduced the problem associated with negative return continuity that occurred because of broken rail bonds and rail joints every 40 ft.

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On the utility side, there has been a tremendous change from the days of essentially a cast iron, low pressure gas system to a steel, often higher pressure system that by federal law must have a corrosion control system, which generally means being cathodically protected. The presence of stray traction or other earth currents greatly increases the testing, maintenance, and number and type of facilities required for compliance. The construction of other utilities and civil structures have also changed in concept, resulting in structures that are much more prone to failure because of relatively low levels of corrosion. The older structures could, and of course still can, withstand higher levels of transit system stray currents without catastrophic results, the newer structures cannot, in many cases, tolerate the same levels. This general concept also applies to many of the transit system structures in addition to those operated by utility companies and others.

Before the relatively recent interest (late 1960s) within the United States in the construction of new dc-powered transit systems and rebuilding some portions of some of the old facilities, relatively few areas of the country had what could be considered significant stray current effects from dc-powered transit systems. These areas were limited to those within or near cities such as Boston, Chicago, Cleveland, New Orleans, New York, Philadelphia, and Pittsburgh. The stray current problems incurred by the utilities and others within these areas have been discussed by corrosion engineers through local coordinating committees and through technical societies such as the National Association of Corrosion Engineers (NACE). With this background information, the corrosion engineers for the utilities within the areas where new transit systems were contemplated became quite alarmed and, in many cases, formed groups to present a common front relative to the possible problem of stray current control. Transit system designers and operators were put on notice that the utility operators and others would not tolerate the stray current conditions that had occurred and still existed in the older systems in many of the cities. Their alarm and concern were justified by the experience from these older systems.

Review of the stray current problems associated with the old systems revealed the following general problems:

1. Traction power substations too widely spaced, or conversely, a single substation used to cover too large an area.
2. Common traction power ties between surface streetcar lines and high-speed subway or elevated lines, and in some cases, negative ties between high-speed lines.
3. Grounding points within the system, such as at yards, maintenance facilities, and traction power substations.
4. Use of elevated and portions of subway structures as part of the negative return system and connections between abandoned streetcar rails and the negative buses of substations.
5. Inability of the transit operators to maintain continuity on operating surface streetcar rails.
6. Direct embedment of the streetcar rails into the paving, providing low resistance, electrical contact with earth.
7. Changes made within the traction power distribution system, which affects stray current conditions causing different modes of stray current effects, resulting, in some cases, in the need for more than one stray current mitigation system.

With these problems in mind and considering that sufficient transit system resources are not normally available to correct these conditions as a separate project, it is absolutely necessary that appropriate action be taken during rebuilding work within the transit system to assure that stray current control matters are properly addressed. Otherwise, it may be another 40 or 50 years before the next realistic opportunity arises and, as noted, those adversely affected by stray currents are no longer taking a passive attitude toward acceptance of the burden of stray current control when corrective actions could have been taken as part of some other work within the transit system.

The basic reasons for stray earth currents from dc-powered transit systems are essentially the same today as they were at the beginning of the 20th century; however, changes have occurred. Figure 1 shows a simplistic schematic circuit that illustrates the basic factors within the traction power system that results in the creation of stray currents. It is the general rule, with some exceptions of course, that the positive distribution circuits are so well insulated from earth that they are not a significant portion of the stray current problem. With the insulating hardware currently available, this is probably more true today than it has been in the past. The positive portion of the traction power system generally contributes insignificant amounts of stray currents compared to the basic problem associated with the negative return system and is normally not a significant factor in stray current control.

In this simplified circuit (Figure 1), there is one substation feeding one load through a positive feeder conductor with a negative feeder conductor, which in most but not all cases is the running rails. Because a current (I_T) is required to operate the vehicle and the resistance of the negative return conductors cannot be zero, a voltage (E_N) will be developed within the negative return conductors, resulting from the product of I_N and R_N (I_N will equal I_T if I_S is zero). This voltage (E_N) will result in a stray current flow (I_S) depending on the values of R_L and R_S; the stray current flow being calculated from the relationship $I_S = E_N/(R_L + R_S)$. To put some of these factors into perspective, consider the following:

R_N—four rails of 115 lb/yd weight in parallel will provide a resistance of about 0.0022 ohms/1,000 ft of two track system;

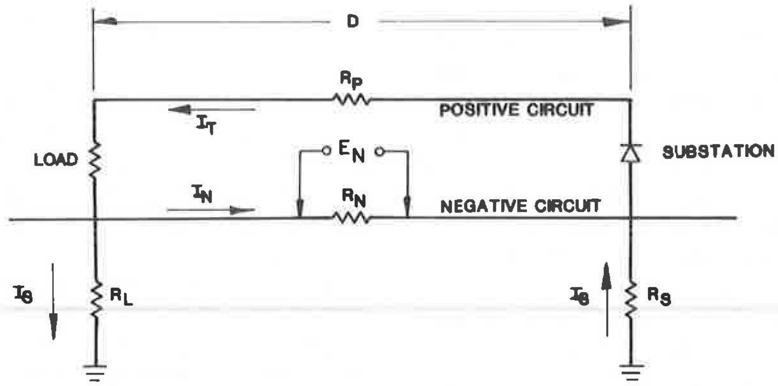
I_T—can vary, depending on system, from 1,000 to 13,000 (or more) amp;

d —will vary from 3,000 to as much as 15,000 ft on some systems.

Table 1 gives a summary of the values of E_N that will exist under the conditions described. The calculated voltages are based on perfect rail continuity.

TABLE 1 VOLTAGE DEVELOPED WITHIN THE NEGATIVE RETURN SYSTEM AS A FUNCTION OF DISTANCE AND LOAD CURRENT

		E_N – Volts, d (ft)				
		1,000	2,000	3,000	4,000	5,000
	1,000	2.2	4.4	6.6	8.8	11.0
	3,000	6.6	13.2	19.8	26.4	33.0
I_T (amp)	5,000	11.0	22.0	33.0	44.0	55.0
	8,000	17.6	35.2	52.8	70.4	88.0
	12,000	26.4	52.8	79.2	105.6	132.0



D DISTANCE BETWEEN SUBSTATION AND LOAD

R_N RESISTANCE THROUGH NEGATIVE CONDUCTORS (PRINCIPALLY RAILS)

R_P RESISTANCE THROUGH NEGATIVE CONDUCTORS (CONTACT RAILS OR OVERHEAD)

R_L NEGATIVE SYSTEM TO EARTH RESISTANCE AT LOAD END

R_S NEGATIVE SYSTEM TO EARTH RESISTANCE AT SUBSTATION END

I_T TRAIN OPERATING CURRENT

I_N CURRENT RETURNING THROUGH NEGATIVE CONDUCTORS

I_S CURRENT RETURNING THROUGH EARTH

FIGURE 1 Simplistic circuit illustrating the major components that affect the levels of stray currents generated by a dc-powered transit system.

The values of R_L and R_S (negative system to earth resistance) will govern the values of stray current (I_S) for the various values of E_N.

The values of R_L and R_S can vary over many orders of magnitude; some representative examples are as follows:

Type a: Newly constructed transit system with well-insulated track and insulating fasteners, 500 ohms/1,000 ft of track.

Type b: Timber tie and ballast construction (not insulated).
- *b1*: new, 4 ohms to several hundred ohms per 1,000 ft of track with an average in the range of 20 to 30 ohms/1,000 ft.
- *b2*: old, 0.3 to 30 ohms/1,000 ft of track (highly dependent on type of ballast, maintenance, and condition of ties).

Type c: Embedded, joint usage with automobile traffic.
- *c1*: in portland cement concrete, 0.1 to 0.2 ohms/1,000 ft of track
- *c2*: in asphaltic concrete, 1.0 to 3.0 ohms/1,000 ft of track
- *c3*: intentionally insulated, 50 to about 300 ohms/1,000 ft of track (limited data to date)

Type d: Connections to grounding systems.
- *d1*: maintenance facilities, 0.03 to 0.05 ohms.
- *d2*: diodes or solid connections at substations.
  - *d2a*: Power neutral connected, 0.03 to 0.05 ohms.
  - *d2b*: Power neutral not connected, 1.0 to 3.0 ohms.

These values should not be used as design parameters; however, they do represent a range of values the author has witnessed and can be used for preliminary estimating purposes.

Thus the possible combinations of R_L and R_S cover a very wide range. Using an illustrative value of I_T = 5,000 amp, d = 3,000 ft, E_N = 33.0 V (a relatively common occurrence within modern transit systems), the values of I_S can vary as indicated in the examples given in Table 2. This comparison illustrates the influence of negative system-to-earth resistance on the magnitudes of stray earth currents, all other factors being equal.

TABLE 2 STRAY EARTH CURRENT VARIATIONS AS A FUNCTION OF NEGATIVE SYSTEM-TO-EARTH RESISTANCE

	I_S (amp)	Percentage of Load Current
Type a throughout	0.050	0.001
Type a and b1	0.095	0.002
Type a and d2a	0.198	0.004
Type b1 throughout (at 20 ohms)	1.24	0.025
Type b1 and d1	4.95	0.10
Type c2 throughout (at 2.0 ohms)	12.4	0.25
Type c1 throughout (at 0.2 ohms)	124.0	2.5
Type c1 and d2a	309.0	6.2

The range of possible variations is, of course, quite dramatic, and of particular significance is that the maximum current represents only 6.2 percent of the load current. However, even though the percentage appears relatively small, the propensity for electrolysis damage is great because of the actual magnitudes of currents involved. As a point of comparison, some old type streetcar systems have stray current characteristics with upwards of 50 percent of the traction power station outputs returning directly through stray current mitigation bonds and recorded situations whereby operating currents for vehicles at some locations within the system become all stray current. It must be remembered that these situations were generally associated with lower operating currents than present day systems.

To further illustrate the concept of stray current accumulation and therefore the effects on utility or other structures, consider the basic condition shown in Figure 2, which illustrates the condition shown in Figure 1, except that the stray earth current pattern and therefore the creation of voltage gradients within the earth path are illustrated. Shown in Figure 2 are several factors to be emphasized:

1. The voltage (or earth) gradient will be a function of the soil resistivity, the length over which the gradient is measured, and the magnitude of the current. As a general rule, the only control is on the magnitude of current. However, if the stray current problem exists or is anticipated, some control of the electrical length of a metallic structure can be exercised by the use of insulating joints or other means. For existing structures, the cost of installing insulating joints can be very high. There is no practical means of controlling the resistivity of a large volume earth environment.

2. The maximum earth gradients per unit length are going to occur where the current levels are most concentrated; that is, in the vicinity of the track or other location of traction power interchanging with earth. For the simplistic example in Figure 2, this would occur at E_{E2} and E_{E3}. Thus the most severe effects are most likely to occur near the operating transit system. This results in the need for special consideration for the metallic structures in the immediate vicinity of the track or other low resistance ground points, or both (substation ground, yard/maintenance facility, etc.). As a general rule, if the earth gradients within the vicinity of the transit system are held to reasonable levels, the remote effects (Item 3) will also be reasonable.

3. Earth gradients will also exist at remote locations, such as E_{E1}, especially if the length (Item 1) is great. Thus an electrically continuous pipeline remote from the track but covering a long distance, such as between the load and the substation, may also be significantly affected. The major controllable factor in this case is also the level of stray currents.

The level of earth gradients, and therefore an estimate of stray current magnitudes, can be obtained on an operating system by studying the earth gradient patterns as illustrated by E_{90} to E_{270} at various locations. These gradients can be related to transit system operations by direct correlation or by studying of general patterns and characteristics over several days.

Experience shows that, in general, the most severe effects from stray currents will occur near the transit system. However, experience also shows that where conditions of high-level stray currents or transit systems, or both, exist over wide areas with continuous negative and positive buses, the remote effects of

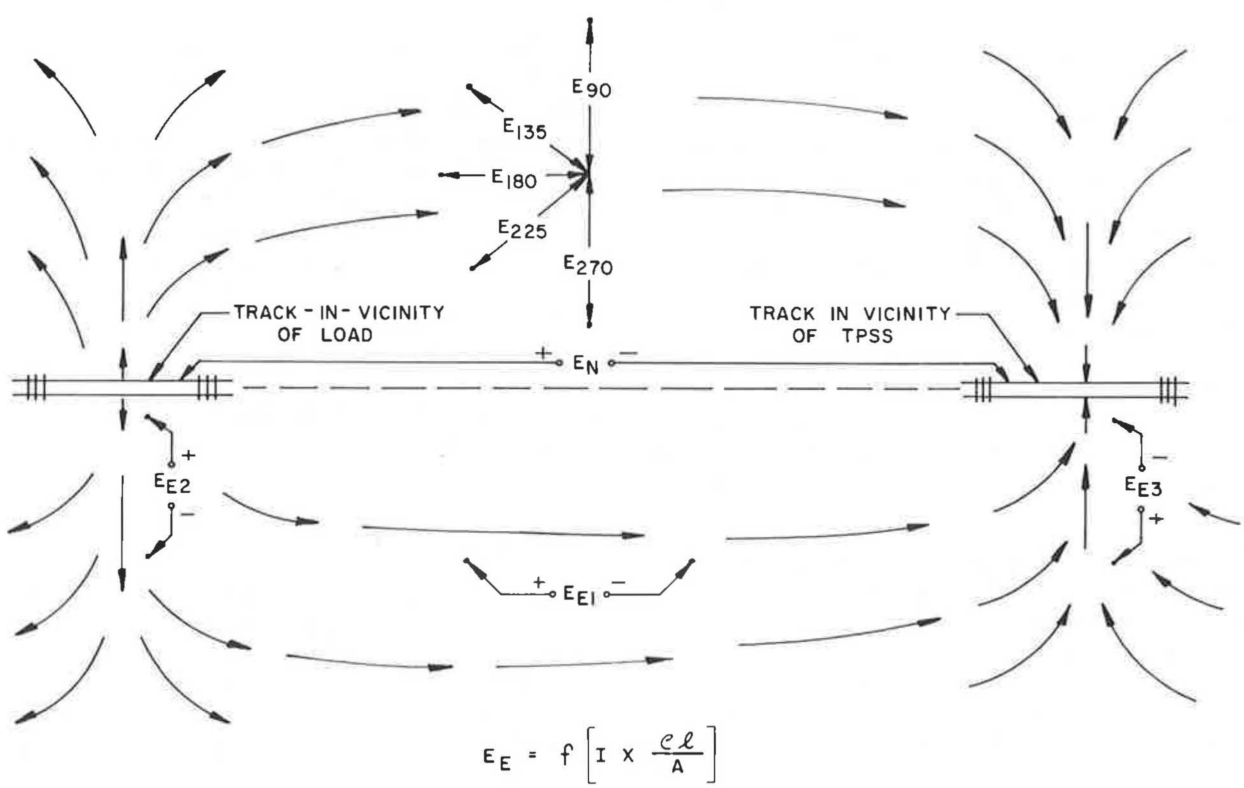


FIGURE 2 Earth gradients created by stray currents from dc-powered transit systems.

stray currents can also be significant. It is not unusual to observe these effects on long, cross-country transmission systems 20 to 30 mi from the transit system. It must also be noted that these effects are often attributable to other structures that may pass close to the transit system and, in some cases, may operate a stray current drainage facility to the transit system. However, the lower the levels of stray earth currents, the smaller will be the effects on other structures. An analysis of the various components shown in Figure 1 and their influence on the magnitudes of stray earth currents is reviewed relative to actions that can be taken to reduce these magnitudes.

1. Increase the system operating voltage. This would allow for a reduction in operating current to provide the same power to the vehicle. The practicality of this is being continuously evaluated; to date, however, the maximum voltage used in this country on heavy or light rail has been 1,000 V, with the majority of the newer systems using 750 V and many of the older systems using 600 V. (This action will not be effective if the substation spacing is correspondingly increased along with the system voltage.)
2. Decrease the distance between substations and thereby decrease the value of R_N. A dramatic change has occurred in this aspect of stray current control, because the use of self-contained solid state rectifier units with remote/automatic control provides an economic means for the use of more substations at closer distances. Nevertheless, there are practical limits to this method of improving stray current conditions.
3. Reduce the resistance within the negative return conductors. This has been accomplished in recent transit system construction by the use of heavier, continuously welded rails. However, analysis of most systems indicates that further reduction in the resistance of the negative return conductors by using parallel negative feeder cables is not justified economically because of the small incremental improvement for the expenditure required. Further significant improvements are unlikely in the future.
4. Restrict the distance in which a particular substation or group of substations can participate in load sharing within the system. This requires the introduction of power segregation points on both the positive and negative at select points throughout the system. This procedure will reduce stray current conditions, especially during light load periods. It will also restrict the energy-saving factors associated with regeneration during light load periods and must be closely studied for the particular system relative to operational constraints.
5. Increase the resistance-to-earth of the negative return conductors. The single most important factor in this respect is the increase in resistance-to-earth of the running rails and appurtenances and elimination of intentional ground connections.

Work on Item 5 to improve the negative system-to-earth resistance is the area within which improvements in stray current control will provide the most benefits in the near future. The ultimate approach to electrical isolation of the negative from earth has been used with excellent results on some types of systems where a separate insulated conductor is used for the negative (similar to construction of the positive), such as those used for trolley coaches with dual trolley wires, linear induction motor-powered-systems, and rubber-tired subways with dual contact rails. The practicality of this approach on more conventional heavy and light rail systems should not be overlooked in the analysis for future projects.

The simplistic schematic in Figure 1 does not represent an actual modeling of a transit system for stray current analysis purposes. The actual model will have numerous substations, generally all feeding common positive and negative buses, and the track-to-earth and negative conductor (track) resistances will form a distributed network similar to that shown in Figure 3 for a portion of a transit system. Also shown in Figure 3 are the track-to-earth voltage and the stray current level per unit length profiles that would occur for the situation shown, assuming uniform resistances for R_E and R_T. Using this distributed network approach, an analysis is conducted early in the system design studies, shortly after the basic traction power configuration has been decided, to determine the stray current levels that can be expected with the design factors proposed. Generally, this will include information on system operating voltage, power/current characteristics for the vehicle(s), locations of passenger stations and other points of heavy loading, and the configuration of the yard/maintenance facility. Also, at this point, the track configuration will have been established relative to type of track construction, such as areas of direct fixation fasteners, tie and ballast, grade crossings, and embedded construction along streets.

A schematic representation of the system is then prepared that will be used to analyze the stray current levels and characteristics that can be expected under various conditions such as load locations, selected substations out of service, low-resistance grounding connections at the shop or other areas, and by varying the track-to-earth resistance.

The information generated from this analysis is then used to determine the levels of stray currents that will result from various levels of track-to-earth resistances within the areas of different track construction. This information, along with information on the types of transit structures to be used, the density and type of utility structures within the area of influence of the stray currents, and the soil resistivity characteristics, provides a basis for decisions on the levels of stray currents that will be tolerable. Thus, this information allows the determination of the level of electrical isolation required for the negative conductor system and the corrosion control measures required for the fixed facilities. Variation of other factors, such as relocating or installing an additional substation, can occasionally be justified based on the results of the analysis. The significance of the track-to-earth resistance in controlling stray earth currents cannot be overemphasized. Some experience on new transit system construction has indicated the following generalized results.

DIRECT FIXATION

The proprietary and assembled fasteners on the market and in use at present will provide track-to-earth resistances in the range of 500 ohms/1,000 ft of track under relatively dry and clean conditions. This resistance quickly degrades when moisture or dirt films are allowed to develop on the exposed surfaces of the insulating materials. This is particularly prevalent in subways where the passage of each train creates a mist from any water that has accumulated. Generally, this moisture is also

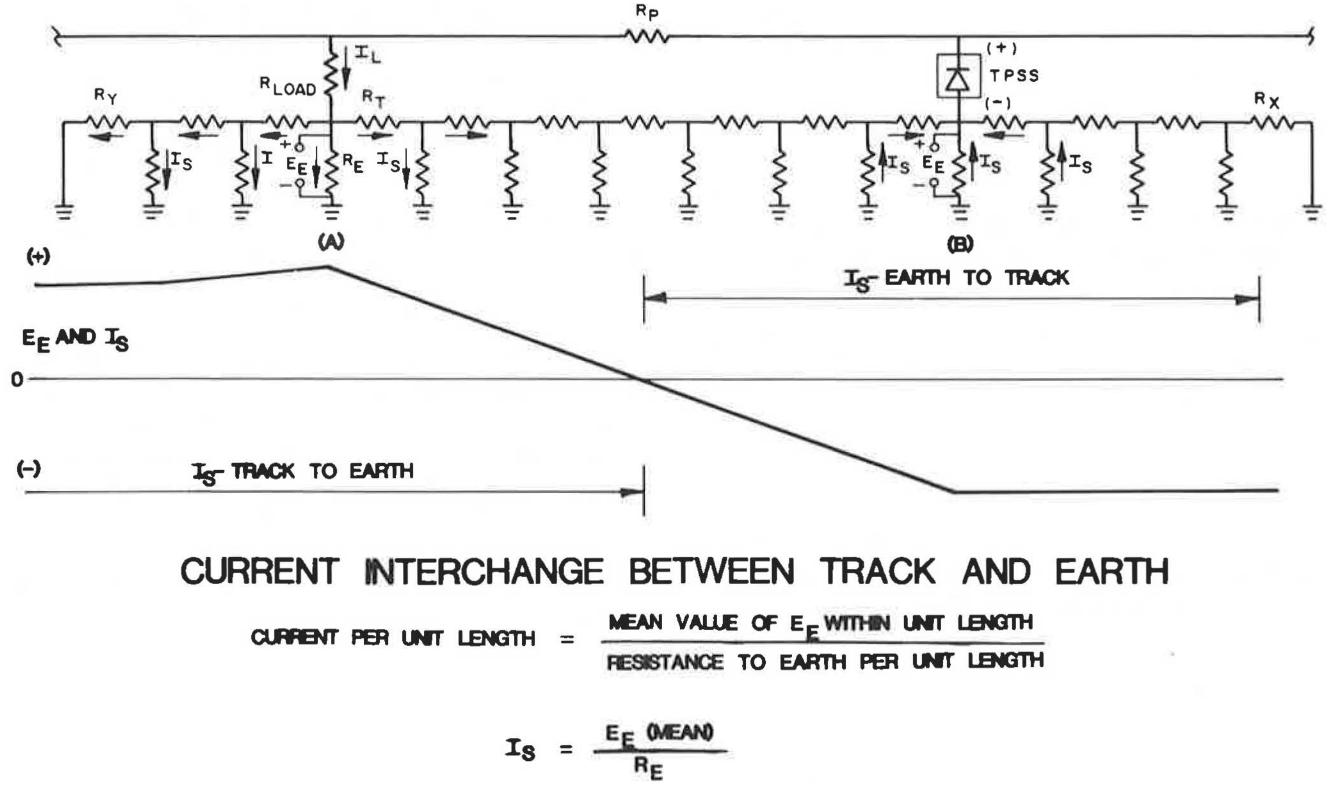


FIGURE 3 Distributed network schematic representation of transit system for stray current analysis.

very low in resistivity. This aspect of the electrical effectiveness of direct fixation fasteners must be reviewed carefully during design to ensure that proper characteristics are obtained, depending, of course, on the in-service track-to-earth resistance levels required.

TIE AND BALLAST CONSTRUCTION

Timber tie and ballast construction has shown variable results, depending on the amount of rainfall that occurs and the weather conditions before and during testing. Experience has shown such large swings in effective track-to-earth resistances and therefore stray current magnitudes that this type of construction cannot be relied on to perform at required levels, if this level is above about 10 ohms/1,000 ft of track. The only exception to this would be in areas of extremely low rainfall where the increase in stray currents may be acceptable during short periods of rainfall. Experience has also shown that ballast cleanliness and tie conditions are extremely important. The use of insulated fasteners on timber ties has not gained widespread use to date. However, one transit system under construction will be using insulated fasteners and other existing systems are considering their use. Theoretically their use should be entirely acceptable.

This author's experience on concrete tie track-to-earth resistance has been limited to the Pandrol system using the embedded shoulder, steel clip, insulating tie pad, and clip insulator. The resistance-to-earth characteristics of this system run approximately on 500 ohms/1,000 ft of track or greater under relatively dry conditions, decreasing to the 300 ohms during rain, which is excellent performance. It must be emphasized that these values are based on limited data; to date it has not been practical to obtain long-term, in-service data on specific track sections. However, experience does indicate that concrete ties with insulated fasteners can perform very well relative to requirements for track-to-earth isolation for stray current control. Review of other types of insulated fasteners for concrete ties indicates that they should perform well in this service; however, the author has no personal experience and has found no reference to such fasteners in the published literature.

EMBEDDED TRACKWORK/GRADE CROSSINGS

Achieving electrical isolation of embedded trackwork is presently the most experimental of the three major classes of trackwork construction. However, it is also quite likely the most critical for stray current corrosive effects on utility structures because of their proximity within embedded areas. There are four types of electrical isolation of embedded track:

- The rails are placed in troughs formed in poured concrete, and an insulating compound is used to electrically separate the rail from the concrete. Only limited in-service data are available within the United States; however, an arrangement of this type used in Calgary reportedly has been successful.
- Rails with timber ties are placed on well-drained ballast, with the entire track structure encapsulated in asphaltic concrete. This method has been effective when used in dry areas with utility relocation or replacement, or both, with nonmetallic materials within the transitway.
- An insulating membrane is placed on the bottom and along the sides of the concrete track slab forms before pouring

of the slab, thus encircling the slab on the bottom and sides. In-service data are not available, although several variations of this type are being built.

- Rails are installed on a continuous insulating pad on top of a concrete track slab; the top of the bottom rail flange and the top of the concrete are coated with a high-resistivity insulating coating. The entire track is then embedded in asphaltic concrete. This method was reported to have been effective in controlling stray currents immediately after the start of revenue service, although no follow-up information has been obtained.

The variations associated with electrical isolation of the embedded trackwork results from the many variations that exist in this type of track construction.

SUMMARY

Research and product development programs for the field of stray current control within the transit industry should concentrate on the following basic considerations:

1. Use of an electrically isolated negative feeder system with resistance-to-earth characteristics similar to that commonly achieved for the positive distribution circuit.
2. Methods for reducing the surface leakage effect common to direct fixation rail fasteners.
3. Methods for achieving effective, long-term electrical isolation for embedded trackwork and road crossings.
4. A practical, cost effective method for insulating rails from timber ties, including special trackwork.

The stray current control measures that have been or are being included in transit system construction have been effective. As with most relatively new concepts of this type, they have not been perfect. It is the responsibility of the transit system operators to keep others within the industry informed of the in-service results obtained on the measures used if the industry is to learn the best methods of stray current control to be employed in future construction projects.

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