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An overview of stray current control in DC railway systems

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Abstract

In DC rail transit systems, the running rails are usually used as the return conductor for traction current. This arrangement mainly focuses on economic considerations, since it does not require the installation of an additional return conductor. Low resistance between the traction return rails and the ground allows a significant part of the return current to leak into the ground. This is normally referred to as leakage current or stray current. The amount of leaking current depends on the conductance of the return tracks compared to the soil; and on the quality of the insulation between the tracks and soil. The stray currents represent serious problems for any electrified rail transit system. The corrosion problem has been a major concern to the railway and other parties involved since the early days of DC railways. The stray currents create or accelerate the electrolytic corrosion of metallic structures located in the proximity of the transit system. This causes metal pipes, cables and earthing grids laid in the ground near the tracks have a much shorter life which is high importance in regard to safety and economy. Hence, great efforts and research have been carried out to control stray current in DC electrified rail transit system. Stray current control is essential in these railway transit systems where the rail insulation is not of sufficient quality to prevent severe corrosion to the rails and third-party infrastructure. Good control of stray current is also of direct benefit to the operational and safety aspects of the DC electrified railway systems; it could reduce the rail touch voltage. This paper provides an overview of control schemes currently applied to the DC traction electrified rail transit system.

Keywords: DC electrified railways, stray current, corrosion control, earthing.
1 Introduction

Electric railways were first developed just after 1880, and now electrified-transit systems are widely used for urban and suburban transportation around the world. It is constructed to alleviate congested highways and provide efficient mass transportation. When the land and natural resources are limited and the population density is very high, the development of an electrified-transit system is important and necessary (Liu [1], Meany [2]).

1.1 Advantages and disadvantages of electrified railway systems

The main advantages and disadvantage of electrified railway systems are (Liu [1], Meany [2], Barlo [3]):

1.1.1 Energy conservation through railway electrification: Railway transport is far more energy efficient as compared to road transport. Railways are: a) Six times more energy efficient as compared to road, b) Four times more economical in land use c) Six times more cost effective vis-à-vis road in construction costs for comparable levels of traffic. Among the modes of rail transport, electric traction is the most energy efficient. This can be seen in the light of the fact that every 100 kilometers route electrified section result in saving of annual consumption of more than four million liters of diesel oil.

1.1.2 Role of electric traction in suburban transport: Electric Multiple Units (EMUs) are ideal for suburban services with high acceleration and braking features required for frequent starts and stops. Electrification has made possible the introduction of EMU services in many suburban like main line sections. These services have become extremely popular.

1.1.3 Haulage of heavier freight trains and longer passenger trains under electric traction: Electrification is making possible running of heavier freight trains then other types railway systems.

1.1.4 Benefits of clearer environment: One of the major advantages of electric traction is pollution free atmosphere not only to the travelers but also to the surrounding environment. The electric traction is proven to be less pollutant than the existing diesel mode and thus could be more eco-friendly to an area having delicate flora and fauna. The electric traction could reduce noise and air pollution and result in lesser disturbance to wild life habitant of the region.

1.1.5 Underground metallic structures corrosion: Some instances of corrosion will cause damage to piping equipment and structures, possibly shortening lifetimes. The worst cases will impact public safety and destroy the environment.
1.2 What's the Problem?

In DC rail transit systems, as shown in fig. (1), the running rails are usually used as the return conductor for traction current. This arrangement mainly focuses on economic considerations, since it does not require the installation of an additional return conductor. The rails along the railway, which lie exposed on the ground, will easily cause larger stray current. When the train operates in heavy transportation of mass rail transit systems, the current required by the train will be quite large up to several thousand amperes and the resistance of the running rail will be about several milliohms to tens of milliohms per kilometer. Therefore, a significant voltage drop (60–100V) on the running rail will be generated. This voltage drop will force parts of the current to leak from the rail and flow into the earth or steel bars in a structure. Afterwards, the current leaves the pipe or steel bar and flows through the earth, back into the negative side of the traction substation. This current is known as the stray current or the leakage current. In earlier DC rail transit systems, no special insulation was provided on the rail or ground. As a result, stray current flows through the earth, the underground pipe and a structure, without limits, to form a considerable magnitude of stray current (Barlo [3], Lundquist [4], Szelig [5]).

There are several examples where DC leakage from one railway system onto another could create significant interference problems with signaling equipment and very costly provisions will have to be made to ensure safety (Nica [6]).

2 Stray Current Corrosion

The corrosion problem has been a major concern to the railway and other parties involved since the early days of DC railways. Metal pipe, cables and earthing grids laid in the ground near train tracks have a much shorter life because of corrosion. The corrosion is caused by railway currents, called stray currents.
leaking from the train tracks and traveling through the ground. Any metals in the ground will act as a path for this current. At the location where the current leaves its metal path to return to the tracks an electrolysis reaction occurs and the metal corrodes.

![Corrosion diagram]

Figure 2: Stray current corrosion process

Where a current leaves the rail to earth there will, therefore, be an oxidation, or electron producing, reaction:

\[
\text{Fe} \rightarrow \text{Fe}^{2+} + 2e^{-} \quad (1)
\]

This reaction is visible after some time as corrosion damage. Stray currents can dramatically accelerate corrosion. Telephone cables, water mains, electricity cables and gas pipes are all affected. The problem is accentuated by the fact that often the most geographical site to lay these pipes and cables is along the train tracks (Szeliga [5], Nica [6]).

![Corrosion damage]

Figure 3: Stray current corrosion on metallic pipe

Damage by stray AC currents is far less significant than damage by DC currents. It is estimated that for metals like steel 60 Hz AC current causes less than 1% of the damage caused by the same amount of DC current (Szeliga [5]).
A recent report included a survey of the cost of transit system stray current corrosion to both transit and third-party infrastructure and concluded that the annual cost to the US economy was $500 million (Every year the US spends approximately $10 billion because of corrosion and its detrimental effects). (Meany [2], Davis [7]).

3 Stray current modeling

A simplified single traction substation (TSS) and single-train model is shown in Fig. (3).

The touch voltage and stray current of the model are:

\[ I_s = \frac{R_R I_T}{R_s + R_R + R_s} \]  \hspace{1cm} (2)

\[ V_{touch} = R_e I_t \]  \hspace{1cm} (3)

Where \( I_t \) is the train current, \( I_r \) is the running rail current, \( R_R \) is the running rail resistance, \( R_s \) is the earth resistance at the TSS, and \( R_e \) is the earth resistance as seen at the train. The problem of reducing the touch voltage and stray current in DC railways is multi-objective and conflicting. It is affected by many factors such as the earthing and bonding design, as well as the normal and failure operating conditions (Chang [8]).

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. In broad terms, design issues that impact on stray current can be placed into ten categories (Aylott [9]):

(i) Conductivity of the return circuit (i.e. the rails)
(ii) Insulation of the return circuit from earth,
(iii) Operating voltage between the track and the overhead tine,
(iv) Insulation of the overhead line,
(v) Conductivity of the overhead line.
(vi) Spacing of supply substations.
(vii) Train current demand.
(viii) Regenerative braking.
(ix) Substation and system safety earthing, and
(x) Signaling requirements.

The maximum value of stray current leaving the tramway network and finding its way into the ground is a function of two parameters. One is the voltage of the rails above true earth, and the other is the resistance of the insulation between the rails and the surrounding road structure or ballast. The actual stray current at any instant is also a function of variables such as how many trams are accelerating and decelerating, the weather, and how the track has been maintained. All of these variables were considered by the designers and a value determined for the quantity of electricity "lost" from the rails in a year. So far, all of these variables are outside the control of us and the utilities. This could be the worst case if we were to do nothing and leave all of our metallic services in situ, close to the rails (Dodds [10], Natarajan [11]).

4 Stray current control

Hence, stray current leakage can cause corrosion damage to both the rails and any other surrounding metallic elements. Therefore, there is a stray current control requirement to minimize the impact of the stray current on the rail system, supporting infrastructure, and third-party infrastructure. Therefore it is good practice to limit the level of stray currents at the source through specific stray current control methods, rather than to mitigate the effects on the transit and other underground structures.

A reduction in the source of stray current is the best strategy for electrical corrosion protection. To reduce the source of leakage current in electrified railway systems, stray current can be reduced by an existing method, such as reducing the resistance of the running rail, increasing the insulating resistance of the rail and the earth, raising the voltage level of a substation, shortening a distance between substations, adopting the fourth rail as the traction current return conductor etc (Liu [1], Natarajan [11]).

Modern stray-current control can be categorized into two parts: modification of the transit system and modification of neighboring underground structures. The two categories are accomplished by doing one or more of the following:

a) decreasing the rail-return circuit resistance;
b) increasing the resistance of the leakage path to ground;
c) increasing the resistance between ground and underground metallic structures;
d) increasing the resistance of the underground metallic structures

Items a) and b) are related to modification of the transit system while items c) and d) are related to modification of the underground structures (Chien [12]).

An effective corrosion control program requires that the negative return running rails have a high rail-to-ground resistance, which requires that the running rails be installed with special fasteners. This also means that all additional
components that may come in contact with the return rail be insulated or isolated from ground. Examples of this are track switch machines, trip stops, bumping posts, return cables, ballast, and any other device that may be attached or close to the running rail. By maintaining an effective corrosion control program the traction power circuits are assured of having a low resistance return path, which is free of stray currents (Dev Paul [13]).

4.1 The railway earthing system

The resistance of the leakage path to ground and railway earthing system has effective role on magnitude of stray current and rail touch voltage. Generally, design of the dc power system grounding needs to compromise two contradictory requirements (Thomas [14], Yu [15], and Pham [16]): 1) minimum dc stray current and 2) maximum personnel/equipment safety. Various methods employed to achieve the system grounding schemes and their limitations are discussed.

4.1.1 Solidly grounded system

The negative of each substation is grounded to the local ground grid without any intentional impedance in the grounding circuit. It should be recognized that the running rails' negative return circuit effectively becomes in parallel with the ground and, thus, a considerable part of the negative return current may seek the path of ground, increasing the threat of corrosion to underground utilities in vicinity of the tracks. Drainage bonds between underground utilities near the traction power substation and electrical bonding of underground utilities in the vicinity of the tracks is mandatory to mitigate the corrosion effect of dc currents. This method may exist only in older transit systems. The modern systems do not employ such a grounding system (Pham [16], Lee [17]).

4.1.2 Ungrounded (floating) system

The "ungrounded system", meaning that the negative return rails are not bonded to earth at the substations. The system is kept ungrounded under normal and abnormal conditions. This system provides the least stray current (four times less than an equivalent grounded system), however, it may prove to be dangerous to the general public and maintenance persons as the vehicle or running rails may be at an elevated dc voltage with respect to ground, especially during positive-to-ground fault. This method is not used in present transit systems for safety reasons, especially under abnormal fault conditions (Liu [1], Dev Paul [13], and Lee [17]).

4.1.3 Diode-grounded system

Diode act as a low resistance path to stray current which is trying to return to the negative busbar, but blocks the flow of current from the negative busbar into the earth. The diode also provides a low resistance return path for short circuits between live parts in the substation, and the earth bar. Figure (5) also shows
another feature often incorporated in systems which follow this particular design philosophy. Steel meshes underneath the track are connected to a low resistance conductor which is connected to each substation negative busbar via a diode. The steel meshes may be the reinforcing bars of a concrete track-bed or of a concrete tunnel. Sometimes the meshes are introduced exclusively for stray current control, and do not have any structural purpose. The theory is that the meshes will “intercept” any stray current, which will then flow safely along the low resistance path via the stray current conductor and related diode. Again, diodes block the flow of currents from the negative busbar to the earth.

To reduce the magnitude of the stray current, the diode-grounded system is an improvement over the solidly grounded system, but the rail potential and stray current remains problematic. Because the diode device provides a path for stray current, the magnitude of stray current can be easily and conveniently monitored, and positive-pole earth faults can be inspected. In a novel control scheme the output voltage of the traction substation is controlled such that it remains constant in the diode-grounded system, thus the magnitude of rail potential and stray current can be reduced (Liu [1], Yu [15], and Lee [17]).

The operation mechanisms of “automatic grounding switch method” and “Thyristor-grounding method” are almost similar to diode-grounded system. All these methods will allow the system to operate ungrounded for normal conditions until ground-to-negative rail potential rises to the set limit (60 V) under abnormal positive feeder-to-ground fault condition. The advantage of the thyristor scheme over the grounding diode scheme is that the thyristor unit will ground the system only when the set dangerous voltage occurs due to either train bunching load currents or due to positive-to-ground faults that develop. Under normal system operation below the set negative-to-ground overvoltage, the
system is kept ungrounded and, thus, stray leakage current is minimum (Dev Paul [13], Lockyear [18]).

4.2 Stray current collection system

As shown in Fig. (5), 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 (an insulated cable, generally copper). 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. 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. The performance of a stray current collection system is, however, highly dependent 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 (Dev Paul [13], Lockyear [18], Ian Cotton [19], Kale [20], and Lee [21]).

The arrangement of a reinforcement mat being bonded electrically back to the substation through parallel conductors has therefore a dual function (Nica [6]):

a. to prevent corrosion of the reinforcement bars themselves
b. to act as a secondary level of protection against stray currents penetrating the surrounding earth and possibly into buried services.

4.3 The fully insulated earthed system

The fully insulated earthed power supply system has rails which are insulated (with polymer insulation), from sleepers or ballast and the running rails act as negative return paths for the power. The rails are bonded to the local earth at each substation. This primary insulation of the rail forms the most important protection against potential stray currents and good maintenance procedures are necessary to keep the insulation levels high. A good form of secondary protection could be provided in the case of leakage to earth at any one point if a membrane or geo-textile was inserted under the track-bed during installation. This would of course only be practical in situations where new track is laid, either ballasted or street running sections. Retrofitting would not be a practical solution. Often such membranes are being used for civil engineering reasons (barriers) and there would be little or no additional cost by providing such level of protection (Nica [6], Dev Paul [13], and Kale [20]).
4.4 Drainage bond

As before mentioned, corrosion only occurs when current leaves the structure and enters the soil. It does not occur at the section where current enters the structure or when it leaves the structure other than to enter the soil. The previous methods prevent current entering the structure at all, drainage bonds however allow the current to enter the structure but prevent it from leaking into the soil. A drainage bond according to figure (6), is a metallic joint between the structure and rail that provides an alternative path for the stray current to return to the rail. Returning the stray current through a metallic path reduces current flow through the ground and therefore reduces the amount of corrosion at the structure/soil interface. If a low resistance metallic connection is made between the structure and the rail the potential of the structure approaches the potential of the rail. Both the structure and the soil are positive to the rail; however the lower resistance of the bond means that the structure is closer in potential to the rail than to the soil. Consequently the structure becomes negative to soil even though it is positive to the rail. Since the structure is negative to the soil, current cannot flow from the structure into the soil. The drainage bond connection to the underground structure should be located where the railway and the structure cross or where they are closest together. In addition, the location should be convenient for checking the equipment and where it does not interfere with traffic (Nica [6], Dev Paul [13], and Lockyear [18]).

![Diagram of Drainage Bond](image)

Fig. 6: Drainage bond for mitigating the corrosion effects of stray current

To mitigate the corrosion effects of stray current, a drainage bond is used. Therefore, by diverting most of the current into the bond rather than into the soil the amount of corrosion of the metal structure will be reduced.
5 Conclusions

The corrosion problem has been a major concern to DC rail transit systems and third-party infrastructure. The stray currents create or accelerate the electrolytic corrosion of metallic structures located in the proximity of the transit system. Reducing stray current levels is best done by careful control of factors, such as substation spacing, rail-to-earth resistance, and rail resistance.

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. For reducing the magnitude of stray current, the diode-grounded system is an improvement over the solidly grounded system, but the rail potential and stray current remain large. In a novel control scheme the output voltage of the traction substation is controlled such that it remains constant in the diode-grounded system, thus the magnitude of rail potential and stray current can be reduced. However, if the stray current level is too high and may affect supporting or third-party infrastructure, a stray current collection system may have to be considered. The performance of a stray current collection system is, however, highly dependent 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.

To mitigate the corrosion effects of stray current, a drainage bond is effective method for diverting and returning most of the stray current to rails. Therefore, the amount of corrosion of the metal structure will be reduced.

References


