Effects of earthing systems on stray current for corrosion and safety behaviour in practical metro systems

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Abstract: Running rails are used as the return path for the train current in most DC electrified rail transit systems. The resultant rail voltage causes stray current to return to the DC supply source via other paths, such as nearby metallic infrastructure. Stray current is the main cause of corrosion in metallic parts located in the railway proximity. This study reviews various earthing schemes including thyristor earthed, diode earthed, floating and solidly earthed and corrosion phenomenon in DC railway traction systems. Then, based on simulations, a comparative study of safety and corrosive effects of the stray current, produced by various earthing schemes is presented. The study is part of the concept designed to control the stray current at Tehran Metro Line 3. Results of the study have been validated by simulation studies using a multi-train simulation software tool and the system data from Tehran Metro Line 3. The study shows some interesting findings such as corrosion damage increases near traction substations.

1 Introduction

Owing to economic purposes most DC traction systems use running rails as the return path of the train’s current to the supply source. Consequently, the resultant voltage drop on the running rails produces stray current leaking off the rails onto earth and embedded infrastructures. The stray current produced by DC transit systems plays a major role in the corrosion of rails and buried metallic structures, which are located within proximity of the railway. In addition to the corrosion damage, leaking stray charges create interference problems with the signalling equipment of traction systems (see Fig. 1).

Underground transit systems are proposed as a solution to traffic and air pollution problems in metropolitans. Tehran with a population nearing 10 million is not an exception and a great deal of construction and extension work is being carried out on its mass rapid transit (MRT) system. Problems caused by the stray current corrosion in Tehran underground provided motivation for the authors to run a study about the effect of the various earthing schemes on stray current corrosion. As Tehran Metro Line 3 was in the design period, it could be considered as a best test-bed for comparing different schemes. Tehran Metro Line 3 is one of the new MRT rail lines, which uses a 750 V DC power supply system. It is made up of two parallel tracks, 32 stations with 26 traction sub-station. There is 523 m difference in altitude between the line end stations that are, respectively, located at the southwest and the north east of the Iranian capital. More descriptions of Tehran Metro Line 3 will be given later in this paper.

Decreasing rail resistance and increasing rail-to-earth resistance by coating and improving insulations are the preliminary measures proposed in the literature to reduce stray current. Declining running rail resistance increases the proportion of current flowing through the rail, whereas elevating track to earth resistance reduces the amount of current leaking off the rail [1]. Also rising DC source voltage to higher levels, hence lowering the train current for a constant power, is another measure for solving stray current problems [2]. Nowadays, most modern DC metro systems are designed for 750 or 1500 V DC supply voltage. London Underground is an exception that uses 630 V DC and a fourth rail as the return path. Reducing the distances between traction substations (TSS) is another measure that can be taken for controlling stray current. However, this solution increases the construction cost as the optimum placement of TSS should be carried out on the basis of peak service conditions and rectifier ratings.

Schemes adopted in the earthing of TSS include solid earthed, diode earthed, floating and thyristor earthed [3–8]. It will be shown in this paper that various earthing schemes can change stray current quantity. Depending on the flowing direction, the stray current can play a protective or corrosive role for metallic objects. The corrosion damage in underground structures is more destructive and costly than other sections of a rail line. Constraining stray current is therefore important to prevent corrosion of infrastructures in adjacency of running rails.

A possible alternative earthing scheme for Tehran Metro Line 3 has been discussed in [9]. A new earthing scheme titled ‘Reversed Diode Earthed scheme’ is presented and...
In continuation of the work [10], in this paper, a simplified model of a DC electrified traction system has been simulated for directly earthed, floating, diode-earthed and thyristor-earthed schemes. Variations of rail voltage and stray charge are illustrated for the earthing schemes and a comparison is made for validating the best earthing scheme suitable for Tehran Line 3.

Reducing rail voltage and stray current corrosion at the same time is one of the challenging problems in DC-electrified rail transit systems. Stray current is the main reason for corrosion in the metallic parts located in the proximity of the railway. Choosing an appropriate earthing scheme is an effective way to decrease corrosion intensity and provide safety for personnel. Corrosion of metallic objects occurs where the current leaves the metallic structure [11]. This paper investigates safety concerns (owing to high voltage in the rails) and corrosive effects of the stray current produced by various schemes in normal operation time. The simulation study reveals that in the vicinity of TSS the stray current causes a greater level of corrosion than at any other point along the track. Finally, the best earthing scheme is selected on the basis of simulation studies.

2 Earthing schemes

2.1 Directly earthed scheme

In a solidly earthed scheme, the DC negative path is earthed without any intentional impedance and the earth resistance is kept as low as possible. Earthing the running rails at TSS reduces the rail voltage, thereby meeting the safety requirements. The main objective of an earthing system is to provide means to guarantee the continuity of the power supply and to ensure that a person in the vicinity of the earthed installation is not exposed to a dangerous electrical shock. Thus, the apparent electrical resistance of an earthing system should be low enough. It is noticed that many stray current problems have been in the vicinity of depots or repair shops, where local standards and practice demand the use of directly earthed running rails with low earthing resistance as a protection for staff [3].

2.2 Unearthed system

A floating running rail scheme has no intentional connection to earth; thereby stray current is limited by a high rail-to-earth insulation using rail fastenings. The rail voltage fluctuation owing to the floated return path at TSS, generally increase the running rail potential when compared with earthed schemes. Increasing the rail voltage beyond the level stipulated in the relevant standards is dangerous to personnel and public lives. In addition, if a rail-to-earth connection is provided, for example, as a result of an earth fault, then a comparatively high rail voltage could sometimes be observed. Thus, over-voltage protection is required to reduce the risk of hazardous rail voltage [7].

The simulation results clearly indicate that the stray currents and rail potentials are closely related in both unearthed and earthed systems. Generally, the rail potential on the running rail in the unearthed system is higher but it would reduce considerably when the substations are earthed. There is a linear relationship between stray current and rail potential. Thus, higher rail voltage in an unearthed scheme should result in a higher amount of stray current in comparison with the solidly earthed scheme through the path. However it will be shown later in this paper why the stray current increases where earthing of running rails is implemented.

2.3 Diode-earthed scheme

Recent practical and theoretical studies have shown that diode earth strategies may result in high touch potentials and stray currents at the same time [12]. In the diode-earthed systems the connection between the earth and negative busbar in TSS is made through diodes. Diodes limit rail voltage by short circuiting the path of return rails at TSS when the voltage exceeds the diode’s threshold limit. The diode also provides a low-resistance return path for short-circuit faults between live parts in the substation, and the earth bar [12]. Stray current collection mats are located beneath the track at regular intervals and connected to stray current collection cable that is connected to each substation negative busbar via diodes.

As 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 [13, 14]. Although, making a low-resistance path by diode is for the sake of enabling faster fault clearing, the earthing diodes will also allow system leakage current to return to the substations thus intensifying stray current corrosion. The diode-earthed system only permits current to flow back from the earth and the current collection mat to the negative bus of a substation, and prevents traction current from the negative bus of a substation from flowing into either the earth or the current collection mat.

2.4 Thyristor-earthed scheme

There are many forms of rail potential control devices, while recent practices use thyristor-controlled switches [15]. This scheme uses the floating negative automatic earthing switch that consists of DC potential and current monitoring circuits and two thyristors connected to provide bidirectional control of current flow between the negative bus and earth. Thyristors are located at TSS grounding systems [7]. Fig. 2 shows the exact places at which thyristors can be located. When rail potential exceeds a predetermined voltage, the corresponding thyristor (depending on the polarity) will activate and then connect the negative bus to earth. The activated thyristor will continue to conduct until the current reduces to zero or until the polarity reverses across the thyristor.
The thyristor is a semiconductor device that can be controlled by a logical signal depending on the voltage, the current and the gate signal. The control device is activated when the voltage goes beyond its threshold value. The thyristor device turns off when the current flowing in the device becomes zero and a negative voltage appears across the anode and cathode. During this time, the system is floating and stray current is limited. Selection of the appropriate voltage level for activating the thyristor significantly influences the characteristic of this scheme. For compromising between safety and stray current, average values should be chosen. Approving low values makes the characteristics of the thyristor-earthed system similar to a directly earthed system. In contrast, choosing high values makes it more similar to the unearthed scheme. However, the thyristor-earthed system is a very suitable choice in the event of extra-high rail voltages owing to the outage of one TSS. As suggested in [7], the limit value of 60 V has been adopted for the gate signal.

3 Corrosion

Stray current deviates from its intended path to a parallel and alternative low-resistance route, such as buried metallic structures. Underground pipelines can pick up current strayed from a railway system at some point remote from the traction substation and discharge the current to the soil and then back to rails near to the substation. In electric railway systems stray currents are random, dynamic and bipolar in character [16]. Flow direction depends on the instantaneous parameters of stray current sources, including the actual momentary load of the electric traction. Stray current corrosion is a result of DC outside sources leaving a particular metallic structure. Corrosion occurs where the current leaves the structure [17]. The type of corrosion caused by railway systems is called stray current corrosion.

The problem of corrosion caused by stray currents has been the subject of an increasing number of research publications. Not only is it important from an economical point of view, but also the fact that stray currents can indirectly cause a significant ecological hazard is becoming more fully appreciated. It is indicated that electrolytic corrosion of metallic underground structures can lead to leakage of transported or stored aggressive media (oil, liquid fuels, hot water and gas). Pollution of natural environments and hazards to human life are consequences of, for example, gas explosions.

In the cathodic protection method, metallic structures are subjected to negative voltage. Similarly, if flowing of stray current through a metallic path creates negative potential on the structure, it will have the benefit of some degree of protection against corrosion. Otherwise, positive rail voltage (in anodic zones) initiates the corrosion. Therefore corrosion hazards exist in the areas where current leaves the metallic structure. The distance between anodic and cathodic zones can be as short as a few metres or as long as several kilometres depending on the source type and metallic structure position.

Several types of structure may be subjected to stray current, such as bridges and tunnels of the railway networks or structures placed in the neighbourhoods of railways [18]. The most common methods of corrosion control involve material selection, coatings, electrical insulation, electric drainage and cathodic protection [16]. Each of these measures has distinct advantages and disadvantages. All should be considered when planning a comprehensive corrosion control programme.

4 System description

Tehran Metro Line 3 is made up of two parallel tracks, the first one running from station A3-6 in the south west to
station Y3 in the north-east of the Iranian capital (uphill track) and the second one running from station Y3 to station A3-6 (downhill track). The characteristics of Line 3 are referred to as a chainage spreading from $-10.1$ to $+25.175$ km. The positions of the 32 stations with regard to the chainage are shown in Table 1. Both tracks are placed next to each other in a single tunnel where the gradients in some sections of the northern part of the rail line range between 3.5 and 5%. It can be seen from Table 1 that there is 523 m difference in altitude between the line end stations at A3-6 and Y3.

The operational data include a 2-minute headway, 25 s dwelling time for an 8-car train with exceptional overload of ten passengers per square metre during rush hours not exceeding 2 h twice a day, one in the morning and one in the afternoon. TSS supply 750 V DC to the train via contact rail. The nominal line voltage is 750 V DC with a minimum 500 V DC and a maximum 1000 V DC according to Standards [19, 20].

Using multi-train simulation (MTS) studies the traction power supply system has been designed comprising 26 TSS at the stations given in Table 1. For a uniform rating, a $2 \times 2.5$ MW rectifier-transformer unit with a 2-hour 150% capacity at each TSS will meet the power supply requirement to maintain normal revenue services with a single TSS outage. To achieve a high receptivity for regenerative braking, 13 inverters each rated at 3 MW have been considered in the simulation at A3-6, A3-4, A3-2, A3, B3-1, E3, I3, L3, P3, R3, T3, V3 and X3. It is impossible to achieve 100% receptivity as this would render the size of inverters uneconomic. There is a trade-off between the on-board braking power and inverter rating. It should be noted that the loadings on the inverters (and to a lesser extent on the rectifiers), are sensitive to the synchronisation of traffic between up and down tracks, which determines the coincidence of motoring and braking trains at stations.

An iterative approach has been used to optimise the power supply scheme. An initial baseline model is built and simulated by means of a multi-train simulator. Results are then processed and compared with TUSRC (Tehran Urban and Suburban Railway Co) requirements for the power supply scheme. If the TUSRC requirements are not met, the proposed power supply scheme is reinforced. If TUSRC requirements are met, then opportunities for reducing over-engineering are investigated. In both cases, the model is modified accordingly and the simulation work is repeated until TUSRC requirements are met and over-engineering is kept at a reasonable level, bearing in mind that the final system may have different rolling stock and operating conditions.

The requirement of minimal usage of mechanical and rheostatic brakes implies that most of the brake effort is provided by regenerative braking. This is only possible if the line is sufficiently receptive during operations. To ensure line receptivity, ENOTRAC (Engineering Organization Traction) proposes to introduce inverter devices at selected TSS to absorb the regenerated energy.

In practice, the introduced methodology is carried out in two steps:

1. The power supply scheme is assessed for peak service conditions (2-min headway) to determine the location of TSS rectifiers and their rating. The dense traffic represents the greatest constraint on the power supply scheme in terms of power demand and line voltage. The dense traffic also ensures that for each regenerating train, there is a motoring train in the vicinity that can absorb the regenerated power. Line receptivity is therefore a less of a concern.

2. The power supply scheme is then assessed under light service conditions (10-min headway). Under such conditions, it cannot be assumed that there will be a motoring train in the vicinity of a regenerating train. It is therefore important to check that the inverters can also absorb the regenerated energy in light traffic.

- **Minimum train voltage**: The minimum voltage seen by any train current collector shall not go below 500 V. This implies a sufficient number of TSS to prevent line voltage falling below 500 V.
- **Maximum train voltage**: The maximum voltage seen by any train current collector shall not exceed 1000 V. This implies that regenerative braking should be disabled at 1000 V.
- **Average speed $\geq 37$ km/h**: The average speed of a train shall exceed 37 km/h over its entire journey (from one end of the line to the other), including dwell time. This implies a line voltage high enough so that train performance is not continuously degraded.
- **Payload of ten passengers/m²**: The power supply scheme shall be robust enough, both in terms of available power and line voltage, so that train performance is not degraded.
- **Mechanical and rheostatic brake**: The modelled trains shall minimise the usage of mechanical and rheostatic braking to avoid specific problems associated with

### Table 1: Location of stations

<table>
<thead>
<tr>
<th>Chainage, km</th>
<th>Station position [centre of platform]</th>
<th>Ground level, m</th>
<th>Stations with traction substation</th>
</tr>
</thead>
<tbody>
<tr>
<td>0</td>
<td>A3-6 station</td>
<td>1086.85</td>
<td>✔</td>
</tr>
<tr>
<td>1.21</td>
<td>A3-5 station</td>
<td>1083.02</td>
<td>✔</td>
</tr>
<tr>
<td>2.67</td>
<td>A3-4 station</td>
<td>1094.85</td>
<td>✔</td>
</tr>
<tr>
<td>3.89</td>
<td>A3-3 station</td>
<td>1098.30</td>
<td>✔</td>
</tr>
<tr>
<td>5.19</td>
<td>A3-2 station</td>
<td>1100.35</td>
<td>✔</td>
</tr>
<tr>
<td>7.09</td>
<td>A3-1 station</td>
<td>1107.04</td>
<td>✔</td>
</tr>
<tr>
<td>~810.33</td>
<td>A3 station</td>
<td>1109.30</td>
<td>✔</td>
</tr>
<tr>
<td>359.67</td>
<td>B3 station</td>
<td>1111.80</td>
<td>✔</td>
</tr>
<tr>
<td>11.27</td>
<td>B3-1 station</td>
<td>1112.20</td>
<td>✔</td>
</tr>
<tr>
<td>12.512</td>
<td>C3 station</td>
<td>1114.00</td>
<td>✔</td>
</tr>
<tr>
<td>13.439</td>
<td>D3 station</td>
<td>1121.40</td>
<td>✔</td>
</tr>
<tr>
<td>14.332</td>
<td>E3 station</td>
<td>1132.50</td>
<td>✔</td>
</tr>
<tr>
<td>15.017</td>
<td>F3 station</td>
<td>1141.80</td>
<td>✔</td>
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<tr>
<td>15.755</td>
<td>G3 station</td>
<td>1155.30</td>
<td>✔</td>
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<tr>
<td>16.569</td>
<td>H3 station</td>
<td>1173.40</td>
<td>✔</td>
</tr>
<tr>
<td>17.255</td>
<td>I3 station</td>
<td>1190.00</td>
<td>✔</td>
</tr>
<tr>
<td>17.89</td>
<td>J3 station</td>
<td>1208.30</td>
<td>✔</td>
</tr>
<tr>
<td>18.492</td>
<td>K3 station</td>
<td>1227.40</td>
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<tr>
<td>19.662</td>
<td>L3 station</td>
<td>1267.00</td>
<td>✔</td>
</tr>
<tr>
<td>20.613</td>
<td>M3 station</td>
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<tr>
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<td>N3 station</td>
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<td>P3 station</td>
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<td>Q3 station</td>
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<td>✔</td>
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<tr>
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<td>R3 station</td>
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<td>✔</td>
</tr>
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<td>S3 station</td>
<td>1354.00</td>
<td>✔</td>
</tr>
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<td>28.31</td>
<td>T3 station</td>
<td>1392.50</td>
<td>✔</td>
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<td>29.63</td>
<td>U3 station</td>
<td>1427.00</td>
<td>✔</td>
</tr>
<tr>
<td>30.912</td>
<td>V3 station</td>
<td>1473.00</td>
<td>✔</td>
</tr>
<tr>
<td>32.054</td>
<td>W3 station</td>
<td>1517.50</td>
<td>✔</td>
</tr>
<tr>
<td>33.504</td>
<td>X3 station</td>
<td>1575.00</td>
<td>✔</td>
</tr>
<tr>
<td>34.415</td>
<td>Y3 station</td>
<td>1610.00</td>
<td>✔</td>
</tr>
</tbody>
</table>
operations in tunnels. Mechanical brakes shall only be used to stop at station for speeds below 5 km/h. Rheostatic brake shall only be used to prevent the line voltage from reaching 1000 V. For all other conditions, the trains shall rely on regenerative braking, which implies the line is receptive.

- **Headway of 2-min:** The power supply scheme shall be robust enough, in terms of both available power and line voltage, so that it can support a timetable with a minimum 2-min headway.
- **Rail touch potential ≤ 120 V:** This implies to compromise several conflicting design issues such as maximum spacing between TSS, earthing of running rails, sizing of running rails, bonding, etc.
- **Minimum number of TSS:** The number of TSS should be minimised to keep the total construction costs at a reasonably low level. However, the scheme must be robust enough to cope with single substation outages.

## 5 System modelling

### 5.1 Running rail circuit

For a homogeneous rail-to-earth resistance, the distributed line model can be used for a simulation of running rails. Fig. 2 shows the stray current model used for the simulation purpose. In this, the earthing box is connecting the negative bus to the earth. The connection is assumed to be an ideal line for a directly earthed scheme, an open circuit for an unearthed scheme, a diode for a diode-earthed scheme and two thyristors in opposite directions for a thyristor-earthed scheme, as shown in Fig. 2. In each section between the train and an adjacent station the rail current and rail voltage profile can be obtained from [5]

\[
i(x) = c_1e^{\gamma x} + c_2e^{-\gamma x} \quad (1)
\]

\[
v(x) = -R_g(c_1e^{\gamma x} + c_2e^{-\gamma x}) \quad (2)
\]

where \(\gamma\): propagation constant \((m^{-1}) = \sqrt{RG}\); \(R_g\): characteristic resistance of the rail conductor earth system \((\Omega^{-1}) = \sqrt{RG}/G\); \(G\) is ground conductance per metre; \(C_1\) and \(C_2\): differential equation constants which are determined by boundary conditions.

### 5.2 Multi-train simulation

MTS studies have been carried out to assess the electrical rating and location of the following power equipment: TSS rectifier devices, TSS inverter devices, DC circuit breakers, feeder cables, third rail conductor, running rail return conductors and train power consumption and position. The running rail resistance has been taken as 41 m with 15% wear (type UIC 54) for the track and the trackbed to running rail resistance has been taken as 41 m conductors and train power consumption and position. The feeder cables, third rail conductor, running rail return rectifier devices, TSS inverter devices, DC circuit breakers, rating and location of the following power equipment: TSS and thyristor-earthed systems. CCC is defined as charges leaking off the infrastructures and collection mats, entering into the running rails or negative pole of the substation [21, 22]. What have been plotted in Fig. 4 is based on the following equation

\[
CCC(x) = \int \int f_{corrosive}(x, t) \, dt
\]

\[
dt = \int T C_{corrosive}(x) \, dt \quad (3)
\]

where corrosive charge is a charge which leaves infrastructures [17]. As illustrated in Fig. 4 areas where the limit. This model assumes that the resistance of the contact rail to earth is very high and there is no coupling between the positive circuit and earth.

The train has eight cars with a nominal load of five persons per square metre. The total weight of the train is 360 tones. The MTS software includes a train performance simulator, which simulates speed, distance and power against time for a single train, and an electric network simulator, which simulates the power flow in the traction system while all trains are running. The multi-train network simulation includes the information on voltage, current and power of each TSS, as well as voltage, current and power of each train on the rails. A discrete time based simulation has been executed by MTS. The software at each time step, typically 1 s, calculates the train motoring or braking (regenerating) current depending on the train position and speed. The rectifiers loading are then calculated from the train currents. The current drawn from contact rail against time is simulated by MTS and plotted in Fig. 3 which illustrates different modes of the train movement. The gradient of the track is also demonstrated. It is obvious that in the inclined parts of the track, more energy is drawn by the train. In acceleration and deceleration modes, high values of current flow through the rail. The train consumes power in acceleration mode while regenerating power in deceleration mode. In deceleration mode, dynamic brakes are applied up to their limit and then the mechanical brakes are used if necessary. However, the implementation of the dynamic brakes within the MTS simulation was achieved through the regenerative braking mode. During dynamic braking, the traction motors run as generators and feed energy back to the power supply system. This energy is damped in on-board brake resistors or consumed by another train. In constant state, the train moves at 80 km/h. The consumed power in this state is for overcoming the air and rail friction and also AC electric system consumption (i.e. air conditioners, pumps, fans, air compressors and lighting). In this mode the current is rather low and close to 1800 A.

Because MTS software does not provide a simulation programme to analyse stray current, the results of simulation from MTS software is further processed using MATLAB programme. A discrete time based simulation with the same time step (1 s) also has been implemented in MATLAB.

## 6 Simulation results and discussion

### 6.1 Corrosive charge

Fig. 4 depicts cumulative corrosive charge (CCC) during the train movement from the first station to the end for the whole path of Line 3 for solidly earthed, unearthed, diode-earthed and thyristor-earthed systems. CCC is defined as charges leaking off the infrastructures and collection mats, entering into the running rails or negative pole of the substation [21, 22]. What have been plotted in Fig. 4 is based on the following equation

\[
CCC(x) = \int \int f_{corrosive}(x, t) \, dt
\]

\[
dt = \int T C_{corrosive}(x) \, dt \quad (3)
\]

where corrosive charge is a charge which leaves infrastructures [17]. As illustrated in Fig. 4 areas where the...
corrosive charge is higher are most likely to be corroded, like infrastructures located at kilometre 22nd of the track. Comparing the above mentioned figure with the train current in Fig. 3 discloses that around this point because of intense and repetitive regenerative breaking the rail voltage is usually negative, thereby more corrosion hazard is expected. Also, owing to the fairly far distance of the nearest inverting substation, a significant resistance has to be overcome by regenerated currents causing large potential drop. Consequently, large amount of corrosive stray current will be produced. However, this effect can be reduced owing to the existence of other trains as the regenerative current will be absorbed via other trains. Adding an inverting substation at 22.5 km can also decrease a high amount of stray current around this point.

Written numbers on Fig. 4, state the equivalent integrated corrosive charge value. Integrated cumulative charge (ICC) value gives more clear criteria for comparing the discrepancy between schemes. ICC can be explained as the following formula

\[
ICC = \int_{x \neq \text{substation premises}} CCC(x) \, dx
\]

Fig. 3 Line current when a train is moving between the first and the last station on the track

Fig. 4 Comparison of CCC for earthing schemes
As ICC is defined for comparison of corrosion level in infrastructures along with the Line 3 path, for ICC calculation, the corrosive charges in the substation premises has not taken into account. Later on in this section the level of corrosion at the substations will be compared and discussed.

Comparing these numbers makes known that the corrosion hazard in an unearthed system is about eight times that of a solidly earthed system. The second-highest rank in the corrosion hazard belongs to the thyristor-earthed system. Because, the normal operation of the thyristor-electrifying system is similar to an unearthed system except when the voltage goes beyond the threshold value, which is rare. Peak values of the corrosive charge and integration of the corrosive charge through the whole track show that corrosion damage is larger, respectively, for solidly earthed, diode-earthed, thyristor-earthed and unearthed schemes.

Diodes do not permit any occurrences of negative voltage at substations, and as a result the diode-earthed system has a very low corrosion characteristic through the rails. The CCC diagram for a diode-earthed system is approximately identical to a solidly earthed system which shows the earthing action of diodes. Regarding the diode activation threshold, those diagrams differ slightly.

DC current can induce corrosion initiation in the anodic zone only after it has circulated for a certain time, which depends on the anodic current density, the presence of chloride in the concrete and interruptions in the current. Environmental conditions are directly related to chloride pollution and the traffic directly shows interruption of the corrosive current. Therefore chloride pollution and interruption of the corrosive current are considered constant for the simulation of all different earthing schemes. In this paper only the effect of anodic current density has been taken into account. During the acceleration mode, a larger amount of current is drawn by the train. A part of this current will go back to the substation through buried infrastructures. At the anodic point, where the current leaves the structure, owing to the corrosion phenomenon, metal loss takes place. This current is usually localised and can have dramatic consequences especially on pipelines [18].

Solidly earthed schemes and activated diodes, thyristors cause a major part of corrosive current that affects the third-party structures at the proximity of TSS. This current enters the negative pole of the power supply system through the low earth resistance. Owing to high values of this returning current, corrosion damage is more common near to TSSs, rather than at other places of the track. This fact has been confirmed by observations.

Current flowing through the earthing resistance is illustrated in Figs. 5–8, respectively, for solidly earthed, unearthed, diode-earthed and thyristor-earthed systems. The results are shown for the 15th traction substation. A dashed line shows average corrosive current and the corresponding value has been written next to the line. It should be mentioned that corrosive leaking current for all systems except for an unearthed scheme is greater and about more than one thousand times in the immediacy of traction substation in comparison with other places of the track. A comparison of Fig. 4 with Figs. 5–8 confirms this point. Owing to the intensity of the current leaking off the metallic structures located close to substations, corrosion damage is enormously more dangerous in this area than other places of the rail. Therefore it is more important to compare damaged produced by various schemes at the vicinity area around the substations for the corrosion damage investigation.

It is seriously suggested to study stray current corrosion control systems like the current collection mat to achieve optimisation. It is shown in this paper that corrosion damage is severe closer to the substations. Further study will improve the above phenomena by utilising the optimum systems approach. For instance, intervals of the placement of current collection mats can be reduced considerably when they are far from earthing stations and in contrary using thicker bolts at the adjacency of the earthing grid.

![Fig. 5 Flowing current at traction substation resistance for a solidly earthed system](image-url)
6.2 Comparison

Figs. 9 and 10 compare the rail voltage for various points on the track for different earthing schemes. As illustrated, the solidly earthed scheme has the minimum values of rail voltage among all earthing systems. In contrary, the diode-earthed scheme results in highest values of rail voltage. In diode-earthed schemes, high resistance is produced by the diode when the voltage is over the threshold level. If the voltage is below the threshold, the diode acts as a short circuit. Owing to the exponential relation in different points of rail voltage, when the voltage is raised from negative to zero at substations by the diode, the potential of all points increases. In this case the diode acts like a shifter. Relatively high voltage, created owing to diode action, is hazardous and produces a higher level of stray current.

Minimising rail resistance and at the same time utilising high-resistance insulations for the trackbed reduces the effect of different earthing systems. However, choosing an appropriate type of earthing scheme in the substations is the most effective measure on rail voltage. Different rail potentials for different earthing schemes shown in Figs. 9 and 10 confirm this fact.

As shown in Figs. 9 and 10, points which are marked with a star depict the location of TSS where as a result of reaching to high values of voltage in substations, earthing thyristors have been activated. Applying the thyristor-earthed scheme results in the substation voltage to become zero and as a consequence

![Fig. 6](image1.png)  
*Fig. 6 Flowing current at traction substation resistance for an unearthed system*

![Fig. 7](image2.png)  
*Fig. 7 Flowing current at traction substation resistance for a diode-earthed system*
reduces the rail voltage of other places on the path. Comparing the rail voltage for different schemes shows how effective the thyristor-earthing scheme is on reducing rail voltage.

6.3 Violation evaluation

Fig. 11 illustrates the effect of each earthing system on rail voltage in terms of ‘Time of violation’. ‘Time of violation’ is defined as time duration when rail voltage goes over the standard value (120 V). Written numbers explain the average rate of violating over the whole path. According to the results, adopting the diode earth scheme raises the time when rail voltage goes beyond the standard value two times that of an unearthed system. Furthermore, the thyristor scheme reduces hazardous conditions about ten times that of the unearthed scheme.

The earthing scheme directly affects the rail voltage at substations and consequently other places of the rail. As shown in Fig. 11, the thyristor-earthed scheme significantly reduces the rate of hazardous voltage. Generally, rail voltage control devices like thyristors can be utilised for controlling rail voltage at distant places from substations where dangerous values of voltage could occur. If it is necessary to use voltage controlling schemes, because thyristor earthing seriously increases the rate of localise corrosion as depicted in Fig. 8, and hence measures to deducting of corrosion damage like using more thick collection mats must be taken.

![Fig. 8 Flowing current at traction substation resistance for a thyristor-earthed system](image)

![Fig. 9 Rail potential for various systems at time 2775](image)
A comparison of results shows that the diode-earthed scheme has the highest level of rail voltage. Therefore unearthed and thyristor-earthed schemes are producing higher rail voltages, respectively, after diode-earthed schemes. The solidly earthed system produces lowest rail voltage among different kinds of schemes, which is compatible with previous works.

The most hazardous stray charge originates from negative rail voltage, which leads to the corrosion of infrastructures. In this paper this corrosive part of stray current is simulated and compared for various earthing schemes. Results show that unearthed, thyristor-earthed, diode-earthed and solidly earthed schemes, respectively, are better in preventing damage in infrastructures located in the vicinity of the rail, in places distant from substations.

Near the TSS, the rate of corrosion is significantly higher in comparison with other locations of the rail. Except for unearthed systems, other schemes provide a low-resistance path for stray current to return to the power supply. This causes a great amount of charges leaking off the structures in the proximity of the TSSs. In this case solidly earthed, thyristor-earthed, diode-earthed and unearthed schemes, respectively, are more likely to inflict corrosion damage.

Dangerous rail potential hardly occurs for all investigated earthing schemes. Hence, among the investigated features of the earthing systems, corrosion damage is more significant. As shown in this paper, corrosion damage can be more costly and hazardous near the substations rather than at other places on the rail. Therefore for choosing the best scheme, owing to the small amount of rail potential hazard and corrosion damage through the rails, these features can be ignored. Hence, considering the corrosion damage near to the TSS, the unearthed scheme is the best scheme for implementing in subway systems. This work will be continued on investigating the effect of current collection mats, for example, utilising optimum placement. For instance, intervals of placement of current collection mats can be reduced considerably when they are far from earthing stations and in contrary using thicker bolts at the adjacency of earthing grids.

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