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Effects of Different Earthing Schemes on the Stray Current in Rail Transit Systems

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***Abstract* - Running rails are used as return path for DC electrified rail transit systems. The resultant rail voltage causes stray current returning to the source via other paths such as metallic infrastructures. Stray current is the main reason of corrosion in the metallic parts which are located in the proximity of the railway. Many efforts have been made for controlling and reducing stray current. This paper discusses possible solutions for reducing stray current in Tehran Metro Line 3. Floating, diode earthed and solidly earthed schemes are various schemes for controlling stray current which are investigated here. Comparison of the rail voltage and stray current level for the mentioned schemes is presented. Also the stray charge and corrosive stray charge are investigated for Line 3. Finally multi train simulation study has been used to propose the best scheme for line 3.**

***Index Terms* - DC electrified railways, diode earthed schemes, floating schemes, solidly earthed schemes, stray current.**

I. INTRODUCTION

Historically due to economic problem running rails are being used as the return path for DC electrification systems. Utilizing running rails as return path originates stray current problem. Stray current produced by the DC transit system plays an important role in corrosion of rails and buried metallic structures which are located in the proximity of the rails. The voltage drop resulted from return current passing through the running rails causes stray current leaking off the rails to earth and embedded infrastructures. This leakage charge accelerates corrosion of metallic structures. The effects of stray current not only should be considered as corrosion phenomena but also there are several examples where DC leakage from one railway system creates significant interference problems with signaling equipment and very costly provisions will have to be made to ensure safety [1].

According to one report corrosion phenomena induced by stray current for electrified rail systems in the USA causes losses of about $500 million annually [2].

There are some basic strategies like decreasing rail resistance, increasing rail to earth resistance by coating and improved insulation to reduce stray current. Declining of running rail resistance provide a better way for return current to go back to the DC source and elevating track to earth resistance, hinder current to flow into the earth. Also rising DC source voltage to higher levels in constant power is another measure for solving stray current problem [3]. Nowadays most modern DC metro systems are designed for the 750 DC supply voltage.

Another measure in maintaining train operating voltage within acceptable limits and minimizing the generation of stray currents as the vehicle moves away from the power source is to keep the substation as close to the point of maximum load as possible. This may require the use of more traction substations than otherwise would be necessary [4].

It is proven that various schemes of earthing can change stray current quantity. Solidly earthed scheme, diode earthed scheme, floating scheme and thyristor earthing scheme are different schemes used in earthing of traction substations.

Underground transit systems are posed as a solution to traffic problems in metropolitans. For this sake, a great deal of establishment and extension of Tehran subway system is being done. Tehran Metro Line 3 uses 750 VDC power supply system to provide energy source. More descriptions of Tehran Metro Line 3 will be presented in this paper.

In this paper, simplified model of DC electrified traction system has been simulated for directly earthed, floating and diode earthed schemes. Variation of rail voltage and stray charge is illustrated for the mentioned earthing schemes and comparison is made for validating the best earthing scheme suitable for Tehran Line 3.

II. MODEL DESCRIPTION

DC earthing system should satisfy two major contradictory factors: 1) minimum stray current and 2) maximum safety. For achieving these goals, decreasing rail resistance and insulating return path have already been considered. Stray current collection methods are applied to obstruct earth leakage currents. Different earthing schemes have various characteristics about safety and stray current. These characteristics are explained below [5].

A. Solidly earthed scheme

In a solidly earthed system, DC negative path is earthed without any intended impedance and the earth resistance is kept as low as possible. Earthing the running rails at traction substations reduces the rail voltage, thereby meeting the safety requirements.

B. Floating scheme

A floating running rail system has no intentional connection to earth. The rail voltage is fluctuating due to the floating of return path at traction substations. Increasing the rail voltage beyond the level stipulated in the relevant standards is dangerous to personnel and public lives. Safety is ensured by a complementary protection scheme performing a critical function. For keeping the running rails potential within the safe limits at all times usually a protective device is utilized. Typically this device is a contactor which is normally open, and closes temporarily if the potential exceeds a preset limit.

C. Diode earthed scheme

In the diode earthed systems the connection between earth and negative busbar in traction substations is made through diodes. Diodes limit rail voltage by short circuiting the path of return rails at traction substations when the voltage exceeds diode threshold limit (just in one direction). Two diodes are used, one between negative busbar and earth that acts as a low resistance path for stray current 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 [6]. Steel meshes underneath the track are connected to a low resistance conductor which is connected to each substation negative busbar via another diode.

III. SYSTEM MODELLING

For a homogeneous rail to earth resistance, distributed line model can be used for simulation of running rails. Fig. 1 shows stray current model used for simulation. In this model R_{NG} is the earth resistance in substations which is near zero for earthed scheme and infinite for floating and diode earthed schemes. It is substituted with diode when diode earthed scheme is considered As shown in Fig. 1 in each section between the train and an adjacent station the current and rail voltage profile can be obtained from [7]:

$$i(x) = c_1 e^{\gamma x} + c_2 e^{-\gamma x} \tag{1}$$

$$v(x) = -R_0 (c_1 e^{\gamma x} + c_2 e^{-\gamma x}) \tag{2}$$

where :

i	Current flows between the train and stations
v	Rail voltage profile
γ	Propagation constant $(m^{-1}) = \sqrt{RG}$
R_0	Characteristic resistance of the rail conductor earth system $(\Omega^{-1}) = \sqrt{R/G}$
R	Longitude of the rail conductor $(\Omega.m^{-1})$
G	Leakage conductance resistance of rail conductor and earth $(S.m^{-1})$
c_1, c_2	Constants decided according to specific boundary conditions.

The movement of trains on the Tehran Metro Line 3 is simulated by multi-train simulator (MTS) software. 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

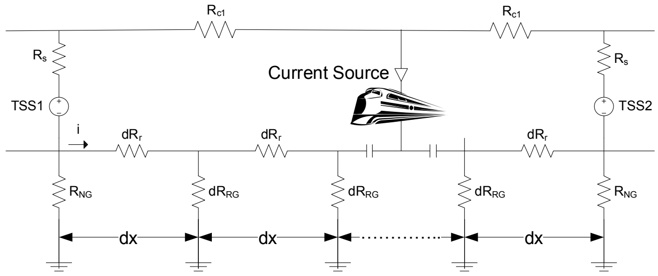

Fig. 1 Stray current model

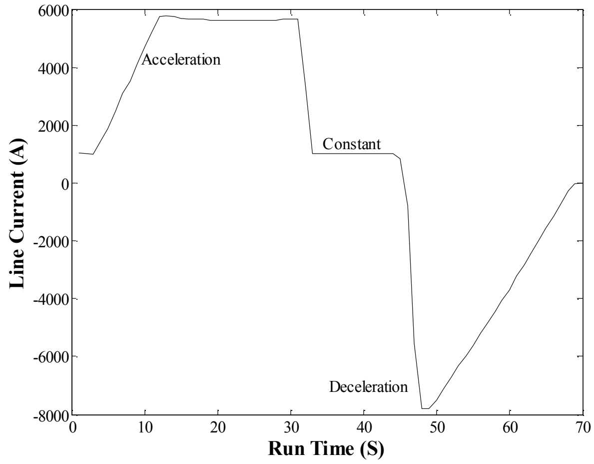

Fig. 2 Line current when train is moving between two stations

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 traction substation (TSS), as well as voltage, current and power of each train on the rails. Fig. 2 shows the current drawn by a single train on a level and without curvature path at 1 km length between two adjacent stations. The train has 8 cars with nominal load of 5 persons per square meter. The total weight of the train is 360 tones.

For simulating trains movement for Tehran Metro Line 3 by means of multi-train simulation software tool, the rail resistance has been taken as 0.07 Ω/km for one rail and the total trackbed to earth resistance has been taken as 0.02 S/km for uphill and downhill tracks. Crossbonding between running rails serves to equalize the traction return current, reduces individual running rail voltage and therefore reduces stray leakage currents. Crossbonding should be duplicated and installed at frequent intervals (typically 200 to 500 meters). So we can assume that rails make parallel electrical circuits. On the basis of this assumption equivalent rail resistance is 0.017. The value of contact rail resistance Rc is taken 0.07 Ω/km. 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.

Because MTS software does not have any simulation program to analyze stray current, the results of simulation from MTS software is more processed using codes written in

MATLAB environment. The Current drawn from contact rail versus train position is simulated by MTS and plotted in Fig. 2 which illustrates different modes of the train movement. In acceleration and deceleration modes, high values of current flow through the rail. The train consumes power in acceleration mode while regenerates power in deceleration mode. In deceleration mode, dynamic brakes are applied up to their limit and then the mechanical brakes are used if necessary. 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 is moving at 80 km/h. The consumed current is for overcoming the air and rails friction and also AC electric system losses. In this mode the current is rather low and close to 800A.

IV. System Characteristic

The proposed concept is based on an 8-car train on a straight, level and dry track under a normal loading condition and nominal voltage. The nominal line voltage is 750 V DC with a minimum 500 V DC and a maximum 1000 V DC according to EN 50163:2004. Vehicle propulsion is provided by four AC asynchronous traction motors in each motor car, supplied via IGBT converters giving a maximum speed of 80 km/h. The vehicle is equipped with both electrical (dynamic) and mechanical (friction) brakes.

Tehran subway system has both traction and auxiliary power systems. Traction power system supplies the power required by the train and the purpose of the auxiliary electric system is to convert the DC link voltage to a three-phase voltage and a battery charger voltage. The three-phase voltage supplies the train auxiliary systems, for example air conditioners, pumps, fans, air compressors and lighting. The battery charger voltage charges the battery and supplies DC loads. These loads are supplied from the batteries when the auxiliary electric systems are not in operation.

To obtain a higher quality of power supply, The Tehran Metro system is supplied from 63 kV bulk supply substation (BSS) which are themselves receive power at 63 kV from the Tehran Regional Electricity Company. The BSS steps the voltage down to 20 kV, and then the power is distributed to each station, depot and parking area. Most stations have traction substation and all stations have lighting and power substation to supply non-traction loads of stations and tunnels. Traction substation supplies 750 VDC for train via contact rail. Other power substations provide 280/220 VAC for different facilities which is used in subway system.

V. Simulation Result

A. *Rail Voltage*

Figs. 3, 4 and 5 show rail voltage for floating, diode earthed and earthed schemes respectively. Depicted times (i.e. 20, 40 & 50) are corresponding to acceleration, constant and deceleration modes. When the train is moving with constant speed, the rail voltage is independent of train moving mode and approximately equals to zero. This is due to small amount of current which train draws from the source. This results in a very low voltage drop on the rails and hence a very low stray current is produced between the trackbed and earth.

In the floating schemes, rail voltage not only depends on current but also it is relevant to earth resistance at substations and equivalent resistance of other connected tracks. These

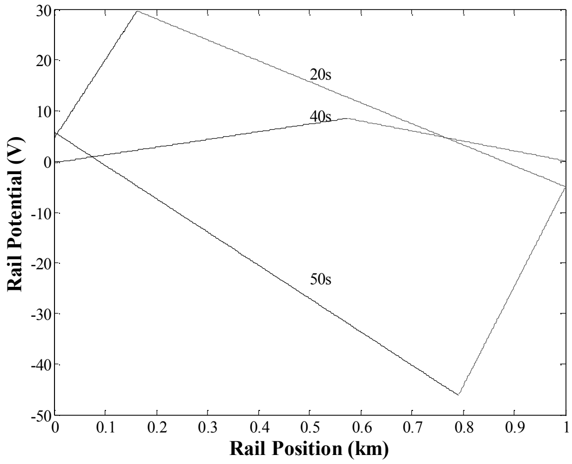

Fig. 3. Rail voltage vs. position (instances 20, 40, 50) for floating system.

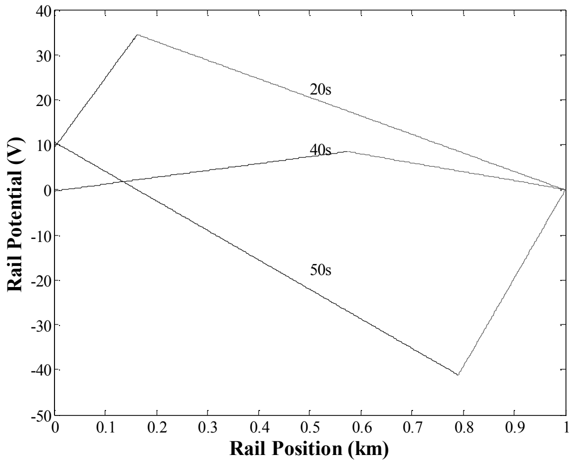

Fig. 4. Rail voltage vs. position (instances 20, 40, 50) for diode-earthed system.

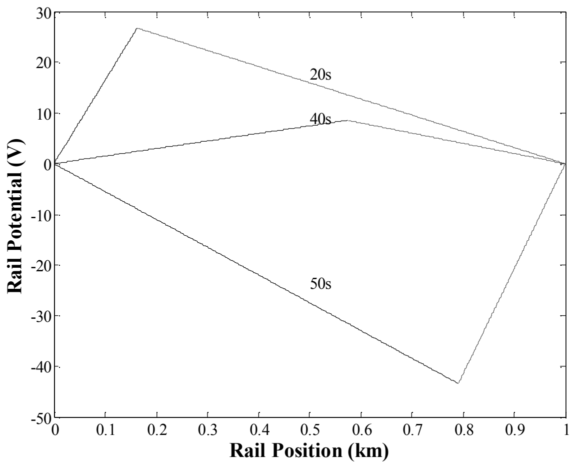

Fig. 5. Rail voltage vs. position (instances 20, 40, 50) for earthed system.

factors cause different rail voltage in comparison with the earthed scheme. Due to train to substation distance and flowing current rail, voltage could have various negative or positive values.

In diode earthed schemes, high resistance is produced by the diode when the voltage is below the threshold level. If the voltage is above the threshold, diode acts as short circuit. Because of exponential relation in different points of rail voltage, when the voltage is raised from negative to zero at substations by diode, potential of all points increases. In this case diode acts like a shifter. Comparing Figs. 4 and 5 clarifies this concept. Relatively high voltage created due to diode action is hazardous and produce higher level of stray current.

B. Accumulative Charge

Fig. 6 shows the result of dynamic simulation during train motion between two floating traction substations. The magnitude of the current leaking off the rails is determined by the voltage to remote earth at any point along the track and the resistance to remote earth of each rail. Equation below expresses the relationship between rail voltage and stray current.

$$I_S(x) = -\partial i(x) / \partial x = gV(x) \tag{3}$$

Variable g is equivalent conductance for the both rails.

Stray charge is resulted from stray current. Accumulative corrosive stray charge represents the whole charge leaking off any point of the track when train travels between two end stations. According to [8] and [9] just positive stray current (i.e. current leaks off the rail) causes corrosion. This corrosive (positive) stray charge is illustrated in Fig. 6 and 7 for floating and diode earthed schemes, respectively. Clearly, maximum stray charge takes place at the position where train is about to reach the maximum speed for both diode earthed and floating schemes. Diode earthed scheme return rail could create higher voltage than the floating scheme. As a result the produced stray charge is higher for diode earthed scheme than the floating scheme.

Solidly earthed schemes were historically used on older transit systems. They are not used today on modern transit systems mainly because they cause more problems than they solve. The only advantage of a solidly earthed scheme is that the negative return voltage is at the same voltage as the earth, thereby eliminating the hazard of having electric potential developed between station platforms and earth. Therefore, only comparison of diode earthed and floating schemes is presented here.

Fig. 8 shows the ratio of the diode earthed scheme to the floating scheme accumulated positive stray charge along the rail length, which clearly demonstrates the advantage of the floating rail system. According to Fig. 8 the floating scheme produces approximately 1.5 times less stray current in comparison with an equivalent diode earthed scheme. As mentioned above when the rail voltage at substation goes beyond the diode threshold level, the diode turns on and connects return path directly to the earth and sets rail voltage to zero. Moving up rail voltage at each substation directly affects on rail voltages at other places of rails and produces

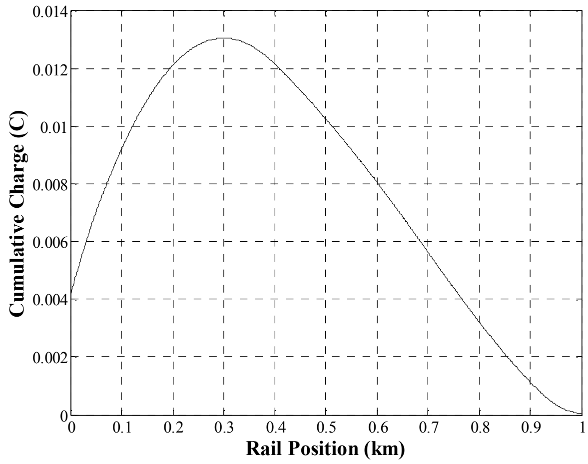

Fig. 6. Accumulated corrosive stray charge in floating system

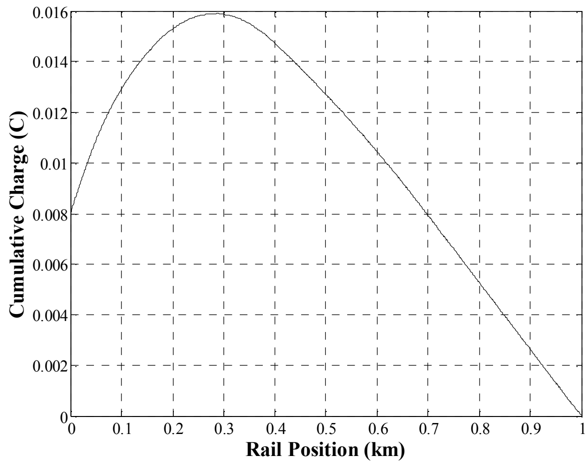

Fig. 7. Accumulated corrosive stray charge in diode earthed system.

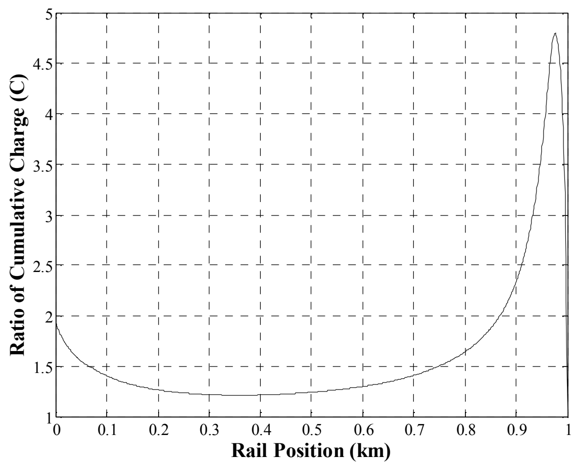

Fig. 8. Ratio of diode earthed over floating stray charge during train moving between stations

higher voltages at adjacent substations in comparison with the floating scheme. Therefore, diode earthed schemes not only produce more corrosive stray current than the floating scheme, but also safety could not be provided the same as the floating schemes.

Fig. 9 shows leaking charge surface in each instant of time along the track between two stations in floating scheme. As illustrated, highest instantaneous stray current and consequently highest values of voltage occur during acceleration and deceleration modes and also at the stations. In special cases this voltage is dangerous for personnel and passengers lives.

Changing diode direction in diode earthed scheme effectively reduces corrosive stray current. Comparing Fig. 10 and Fig. 8 clearly shows reduction in accumulative corrosive stray charge when diode direction is changed. By calculating the whole positive charge leaking off the rails for diode earthed scheme, the ratio of 1.6 is obtained. In other words, reversing diode direction scheme produces stray charge 1.6 times less than conventional diode earthed scheme. Reverse diode earthed scheme also produce positive stray charge less than the floating scheme. However, reversing diode direction should be considered when a fault takes place. It needs more study in railway transit system protection context.

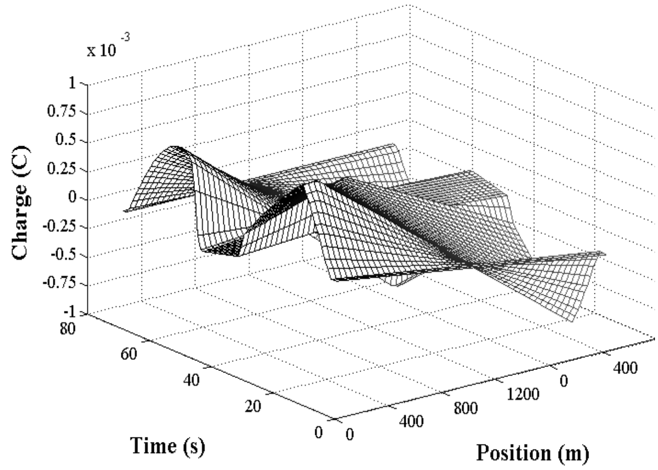

Fig. 9. Leaking charge surface of floating scheme during train moving between stations

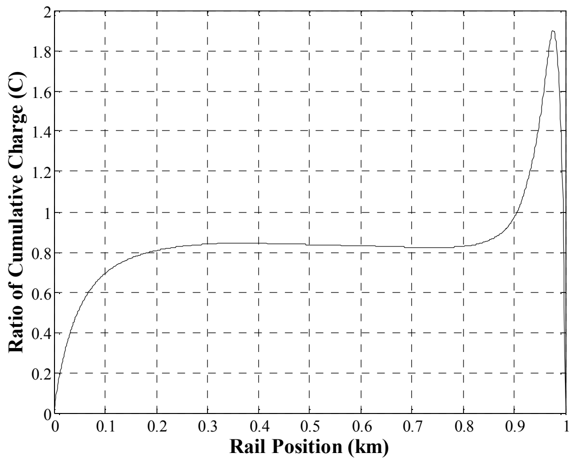

Fig. 10. Ratio of reversed diode earthed over floating stray charge during train moving between stations

VI. CONCLUSION

There is no proven optimum solution to protect against stray currents from DC railways. Available options are with their own advantages and disadvantages. However, constraints are determined in standards. In general the most important form of stray current reduction is to increase rail to earth resistance along the lines as high as possible and at the same time to minimize line resistance by cross bonding parallel tracks and cables. Also current collection mat is used as an extra provision to reduce stray current damage.

Comparisons show that the floating scheme produces approximately 1.5 times less stray current in comparison with an equivalent diode earthed scheme when dynamic simulations are carried out. When the substation voltage becomes negative, the diode turns on and connects return path directly to earth. This sets the rail voltage to zero and moves up rail voltage at each substation which is directly affects on the rail voltages anywhere else along the track. This leads to facing with higher values of voltage at adjacent substations in comparison with the floating scheme. Therefore diode earthed schemes not only produce more corrosive stray current than the floating scheme, but also deteriorates the safety.

Changing the diode direction in diode earthed scheme effectively reduces corrosive stray current. Reverse diode earthed scheme also produce positive stray charge less than the floating scheme. However, effects of reversing diode during fault condition should be studied and both safety and stray current analysis should be considered.

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