THE EFFECTS OF EARTHING STRATEGIES ON RAIL POTENTIAL AND STRAY CURRENTS IN D.C. TRANSIT RAILWAYS

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SYNOPSIS When the running rails are used as the traction current return conductor in a rail transit system, the control of rail potential and stray current is an important aspect of system design. The choice of earthing strategies within the transit system has a profound influence on rail potential and stray current control. The tasks of controlling both rail potential and stray current are conflicting, therefore a balance has to be struck between the two. This calls for a comprehensive study before a strategy is chosen. Previous research work at the University of Birmingham in collaboration with Cegelec Projects Limited [1-4] established an approach to the definition of the performance criterion for both rail potential and stray current. A computer program was also developed to simulate the performances of systems against the defined criterion. The simulator takes account all relevant system parameters that affect the power supply system. This paper describes the follow-on work, following further developments on the simulator, having taken account the latest technological advancements on rail potential control devices (RPCD). The merits of floating earth in combination with RPCDs are examined in detail. The simulation model has been validated against practical test results. Sample simulation results for a test track are presented for analysis.

1. INTRODUCTION

In most rail transit systems, with the exception of London Underground Limited, the running rails are used as the return conductor for traction currents. This arrangement has the distinctively economic advantage in that no dedicated return conductor is required. The disadvantages associated with such an arrangement are rail potential and stray current problems:

- Rail potential rise or fall may be hazardous above certain thresholds, in the forms of touch and/or step voltages.
- Stray current may cause or accelerate electrochemical corrosion to metallic structures in the vicinity of the transit system.

There are many measures that have been adopted in the attempt to mitigate the harmful effects of the two problems.

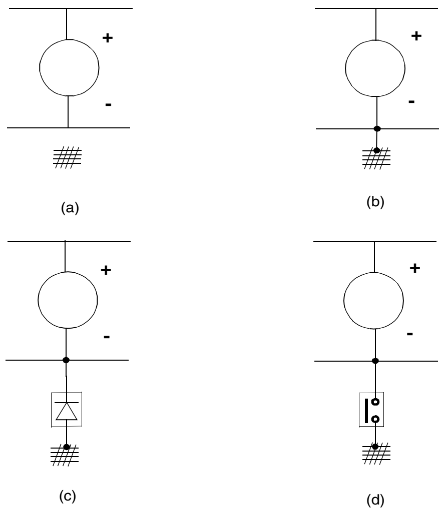

Figure 1: Schematics of Different Earthing Schemes
(a). Totally Floating Earth (b). Directly Connected Earth
(c). Diode Earth (d). Floating Earth with RPCD

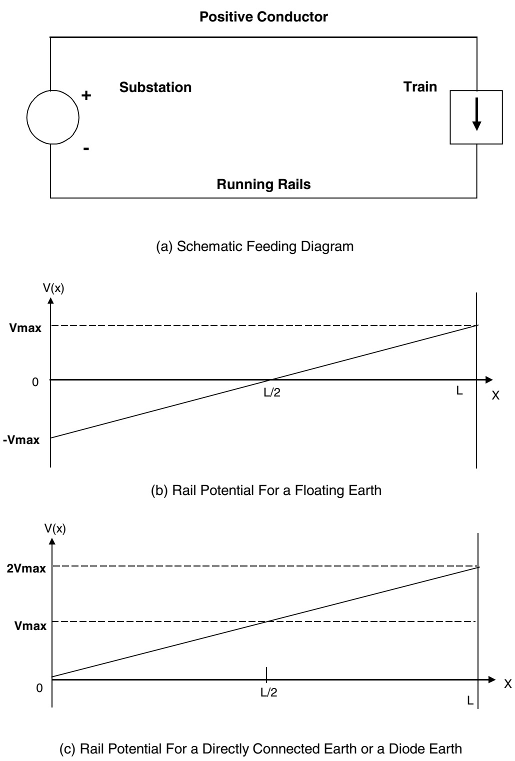

Figure 2: The Effect of Earthing Arrangement on Rail Potential

Among them the choice of the overall earthing strategy has a profound influence on the performance of the system.

Broadly the earthing strategy can be classified as follows:

- Totally floating earth (with no intentional connection between the rail and earth)
- Directly connected earth
- Diode earth
- Floating earth with RPCDs (RPCD earth)

These are illustrated in Figure 1. Figure 2(a) shows a feeding situation with one substation and one train only. It is assumed that the rail to earth resistance is homogeneous. Figure 2(b) shows the rail potential when there is no intentional earth in the system, while Figure 2(c) shows the rail potential profile when the rail is connected to the substation earth. The rail to earth leakage current density follows the rail potential profile.

2. RAIL POTENTIAL CONTROL DEVICES

The RPCDs can be in many forms, while the modern practices use thyristor controlled switches.

In the Ankara Rapid Transit System of Turkey, the device is called Floating Negative Automatic Ground Switches (or FNAGS). In the Lantau & Airport Railways of Hong Kong, it is called Over Voltage Protection Devices (or OVPD). The two devices are similar in that both are thyristor controlled, bi-directional switches. However, the design and operating details differ in certain aspects. Figure 3 shows a schematic diagram of such a device. These devices have been installed in the respective systems and tested for their functions in the integrated systems.

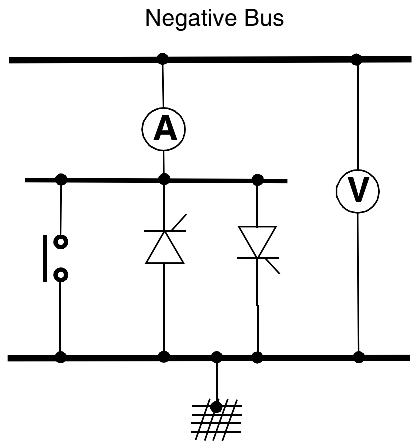

Figure 3: Schematic of a Rail Potential Control Device

Refer to Figure 3. Where a RPCD unit is installed, the voltage between the rail and the local earth is continuously monitored. The device will be activated if the measured voltage exceeds a pre-set voltage-time characteristic: the thyristor gates will be pulsed and the contactor will be instructed to close. The appropriate thyristor will conduct, depending on the polarity of the voltage across the thyristors. This will then be followed by the action of the contactor. The contactor takes longer to switch ON than the thyristor due to its inherent and intentionally built-in delays. This is desirable since the contactor rating is usually chosen to be less than the thyristors.

Once the contactor is switched ON, the voltage across the thyristors will collapse and the conducting thyristor will be switched OFF since the conduction current is transferred to the contactor.

The contactor will remain ON until the current through the RPCD falls below a pre-set current threshold <u>and</u> its ON time is longer than a pre-set minimum ON time. The thyristor will not be pulsed for the next switch ON cycle until the contactor is in the fully open position.

In some applications, the contactor does not have a required minimum ON time. The contactor will be switched OFF once the current through it falls below the pre-set current threshold.

3. SIMULATION MODEL

A computer simulation model has been developed to simulate the rail potential and stray current for d.c. transit systems. The methodologies are explained in [3,4]. Briefly the input and output of the simulation are as follows:

The basic data input starts with track profiles, including gradients, curvatures, speed limits, substation/track parallel hut locations, passenger station locations, train characteristics, train headways, electrical power network parameters including earthing data, etc. The results are given for train performance including minimum voltages, train speeds and journey times, electrical plant load cycles, etc.

To obtain results for rail potential and stray current, the distributed rail-earth circuit is represented by lumped circuit parameters. A large amount of information is made available for analysis. This includes rail potential against distance at any particular time of simulation (figures 5 & & 6) , rail potential against time at any particular chosen location (Figure 9). Similar output is made for rail to earth current (Figures 10 & 11). The following parameters are defined to assess the performance of a system in terms of rail potential and stray current.

3.1 Rail Potential Parameters

At all instants of time during the simulation (usually at 1 second's interval), the positive maximum potential and the negative maximum potential of the rails are found and their locations recorded. The overall maximums are also recorded. These give an indication of what touch voltages can be expected in the system [4].

Over the simulated period of time, the maximum positive and negative potential can be plotted against time, as shown in Figure 7.

3.2 Stray Current Parameters

Faraday's Law states that the amount of metal dissolved in a corrosive reaction is proportional to the electrical charge that causes the reaction. The performance of a transit system can therefore be measured by the gross leakage charge that is emitted from the transit system. The definitions are as follows [3].

Total Stray Current This is defined as the total current that is leaked to the earth.

$$i_{tsc}(t) = \sum_{k=1}^{N(t)} i_{re}(t,k) \quad \text{for } i_{re}(t,k)>0 \qquad (1)$$

where $i_{tsc}(t)$ is the total stray current at time t, $i_{re}(t,k)$ is the rail to earth current at electrical node k and at time t, N(t) is the total number of electrical nodes at time t. A plot of total stray current vs. time is shown in Figure 8.

Gross Leakage Charge The gross leakage charge Q_x (in Coulombs) is obtained by integrating the total stray current $i_{tsc}(t)$ against time for the simulated duration of time (t_1,t_2) (in seconds).

$$Q_x = \int_{t_1}^{t_2} i_{tsc}(t) \cdot dt \qquad (2)$$

Usually the simulated duration varies for different studies, depending on the train headways. To make a meaningful comparison, Q_x is normalised to one hour's equivalent Q_h (also in Coulombs):

$$Q_h = Q_x \cdot \frac{3600}{t_2 - t_1} \qquad (3)$$

Q_h can also be quoted in the unit of Ampere-hours.

Mean Total Stray Current Dividing the gross leakage charge by the simulated duration of time, the mean total stray current (in Amperes) during the simulated load cycle is obtained:

$$I_{tsc} = \frac{Q_x}{t_2 - t_1} \qquad (4)$$

3.3 RPCD Model

For the rail potential control devices, 3 setting parameters are modelled:

- Voltage Setting - This is the voltage threshold to switch the RPCD ON. If the measured voltage is greater than the voltage setting, the device will be switched ON.
- Current Setting - This is the current threshold to switch the RPCD OFF. If the measured current through the RPCD falls below the current setting, the RPCD will be switched OFF, provided the time setting is satisfied as well.
- Time Setting - This is the minimum required time for the RPCD to be in the ON state before it is switched OFF. If the device has conducted for a period up to the time setting, it will be switched OFF, provided the current setting is satisfied as well. Where the time setting is not required, it can be set to zero.

In practice, all three setting parameters are built with certain ranges specified by the users, so that the users have the flexibility to fine tune the settings to suit their particular systems.

The diode is modelled as an ideal switch.

4. SIMULATION RESULTS AND ANALYSIS

A test line is used to simulate the effects of earthing strategies on rail potential and stray currents. This is a double track line with a route length of 18km and 16 passenger stations. See Figure 4 for the gradient profile of the uproad track, simulated train speed, voltage and current.

The line is powered by 7 traction substations at a nominal voltage of 1500V d.c. The traction substations are located near selected passenger stations. Each train consists in 6 cars with induction motor drives and regenerative braking. A headway of 120 seconds is used.

A number of cases are studied and the results are summarised in Table 1. Graphical output plots are shown in figures 5 to 11.

For each case, it is assumed that each earth position has a resistance of 0.5 Ω and the rail to earth leakage resistivity is at 50 Ω-km . For cases A and B, it is assumed that the rails are floating freely. For cases C to E, 7 earths are in place, one at each substation. For Case F, two extra RPCD earths are added: one at Stop-2 and the other at Stop-14. For cases G to M, 16 RPCDs are installed, one at each passenger station/substation.

Table 1 - Summary of Simulated Results

Cases	Scenarios	Overall Max. Potential (V)	Overall Min. Potential (V)	Q_h (Ah)
A	totally floating earths, with 10.25 mΩ/km rail resistance	67.2	-72.0	3.3
B	totally floating earths, with 7.50 mΩ/km rail resistance	54.2	-54.4	2.5
C	Case “A” + 7 RPCD earths, settings at 60V,50A,1s	106.2	-72.0	3.4
D	Case “A” + 7 diode earths	110.3	-29.4	10.8
E	Case “A” + 7 directly connected earths	82.6	-53.5	80.6
F	Case “A” + 9 RPCD earths, settings at 60V,50A,1s	63.7	-72.3	23.5
G	Case “A” + 16 RPCD earths, settings at 50V,50A,1s	63.2	-63.3	91.6
H	Case “A” + 16 RPCD earths, settings at 60V,50A,1s	72.7	-76.5	50.5
I	Case “A” + 16 RPCD earths, settings at 60V,25A,1s	70.7	-76.5	65.8
J	Case “A” + 16 RPCD earths, settings at 60V,50A,5s	70.7	-76.5	58.8
K	Case “A” + 16 RPCD earths, settings at 70V,50A,1s	67.3	-76.9	27.4
L	Case “A” + 16 diode earths	115.0	-11.2	11.3
M	Case “A” + 16 directly connected earths	61.3	-61.5	268.2

Note Q_h = 1 hour’s equivalent Gross Leakage Charge (in Ampere-hours).

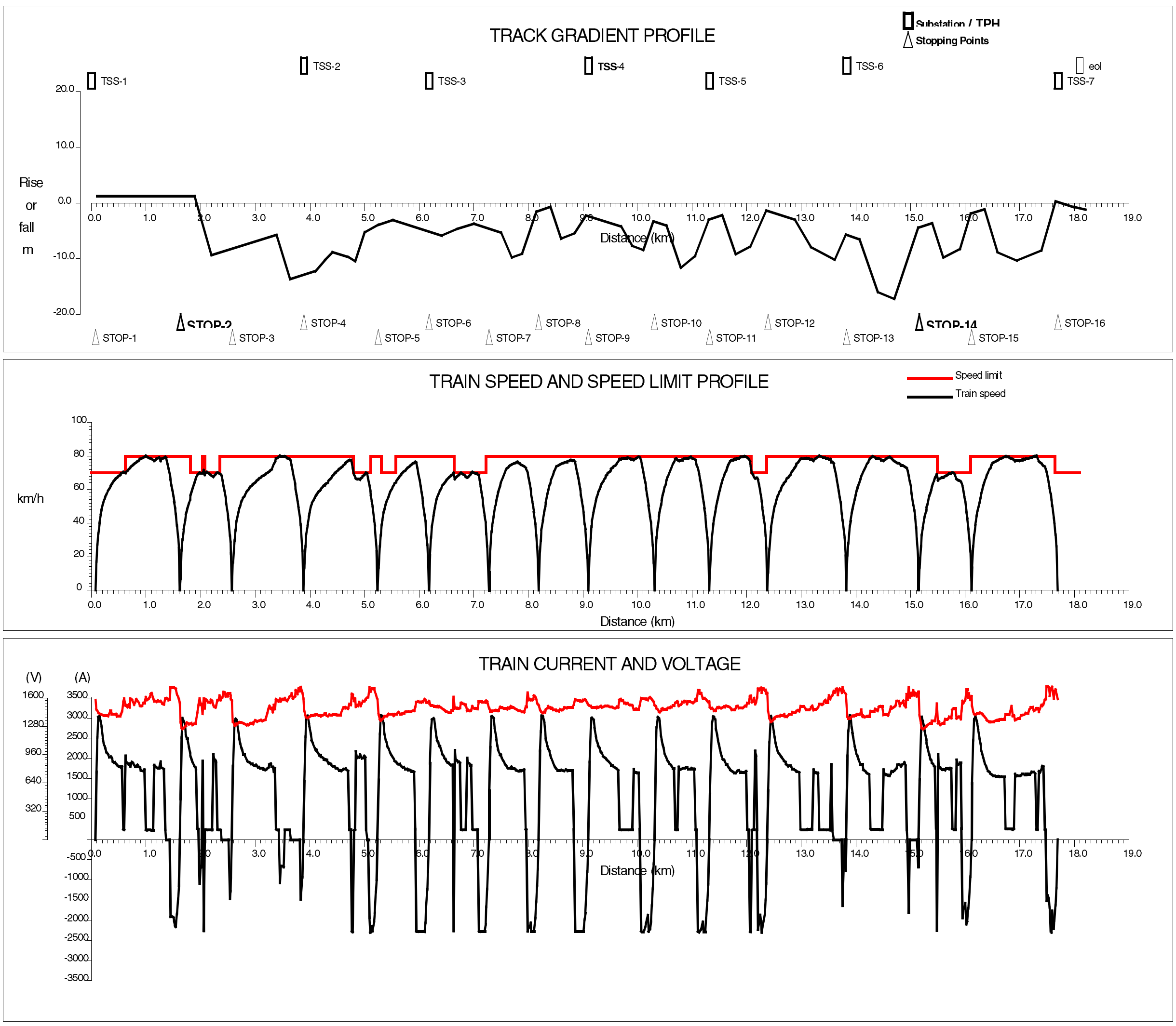

Figure 4: Test Track Simulation Results for Train Performance

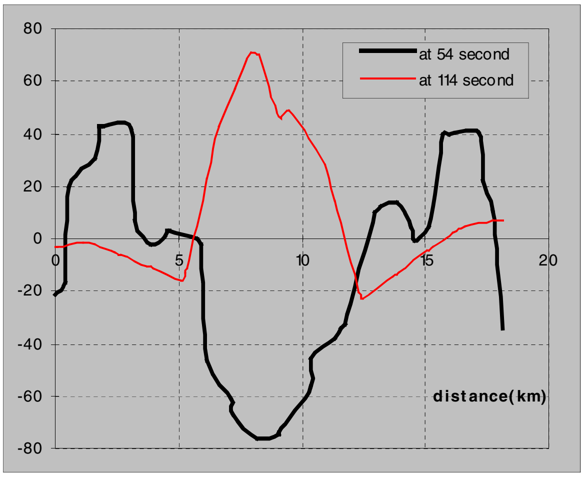

Figure 5: Rail Potential (V) Snapshots for Case J

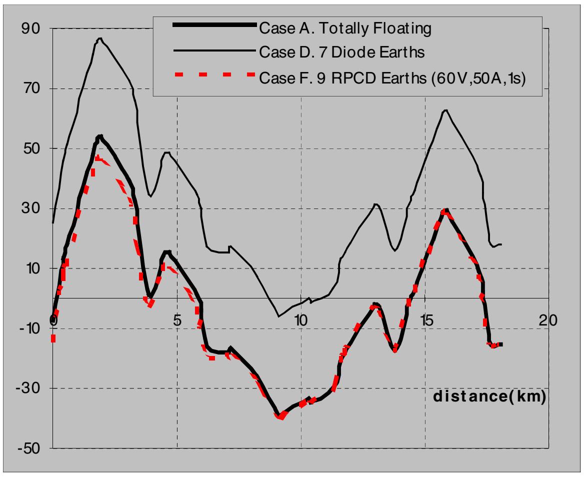

Figure 6: Rail Potential (V) Snapshots at 80 Second for Cases A, D & F

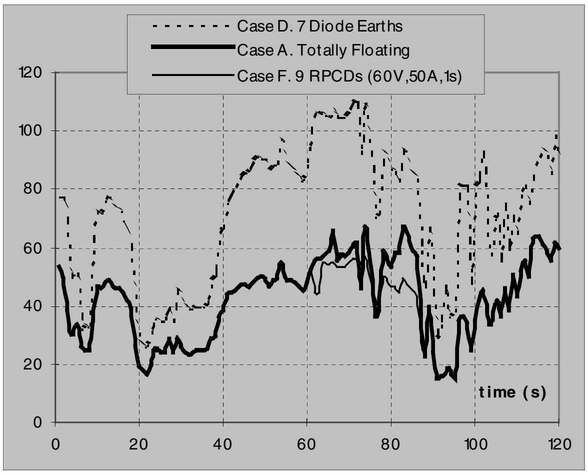

Figure 7: Maximum Rail Potential (V) vs. Time for Cases A, D & F

Figure 5 shows the rail potential snapshots at two different instants of time for Case J. This illustrates how the rail potential changes when the loading conditions have changed. The overall maximum potential occurred at 114 second and the overall minimum potential occurred at 54 second. In this particular case, the maximum and minimum occurred near passenger stop-8.

The maximum occurred when a train accelerated to leave the stop, while the minimum occurred when a train braked regeneratively to approach the stop.

Figure 6 shows the rail potential snapshots at 80 second for 3 cases (A, D & F). This illustrates how the rail potential varies when the earthing conditions are changed. Figure 7 shows the maximum rail potential vs. time for 3 cases (A, D & F). Figure 8 shows the total stray current vs. time for 3 cases (A, D & F).

Figure 9 shows the rail potential vs. time at passenger stop-2 for 2 cases (D & F). This illustrates the necessity to install rail potential control devices at such locations.

Figure 10 shows the earth to rail current at passenger stop-2 for 2 cases (H & I). This illustrates how the earth to rail current is affected by RPCD current settings.

Figure 11 shows the earth to rail current at passenger stop-2 for 2 cases (J & K). This figure, in conjunction with Figure 10, illustrates how the earth to rail current is affected by RPCD voltage settings and time settings.

Observations made from these simulated results are discussed as follows.

- **Rail Resistances** Both cases A and B have totally floating earths with different rail resistances. The simulation results indicate that the rail resistance has a fundamental role in rail potential and stray current control.

All other conditions being equal, different earthing strategies have a significant effect on rail potential and stray current control. In the cases studied, Case A is the base case. Cases C to M are based on Case A, with variations on earthing arrangement, as identified in Table 1.

- **Totally Floating Earth** The totally floating earth comes out as the best option in terms of stray current control, as shown in cases A and B. All forms of intentional earthing, such as directly connected earths, diode earths and earths with RPCDs, increase the gross leakage charge.

- **Directly Connected Earths** The directly connected earth schemes result in very high gross leakage charges, as illustrated in cases E and M.

- **Diode Earths** In the cases studied, the diode earths are not acceptable since the rail potential cannot be effectively controlled, as shown in cases D and L.

Diode earths are inflexible since the diodes are not controllable. Besides, diodes are unidirectional devices and are ineffective in reducing positive rail potential. This makes it impossible to control the rail potential at locations other than at traction substations.

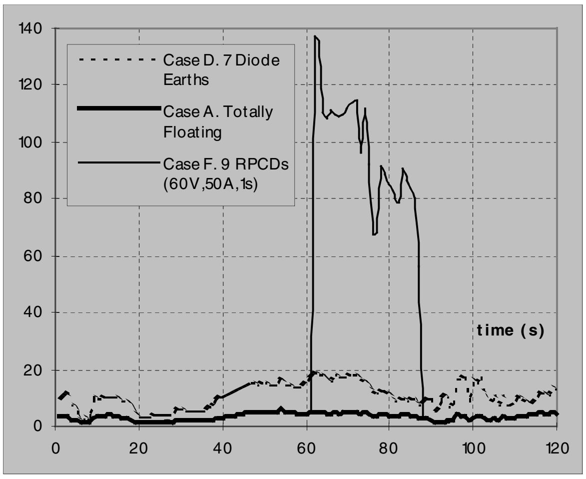

Figure 8: Total Stray Current (A) vs. Time for Cases A, D & F

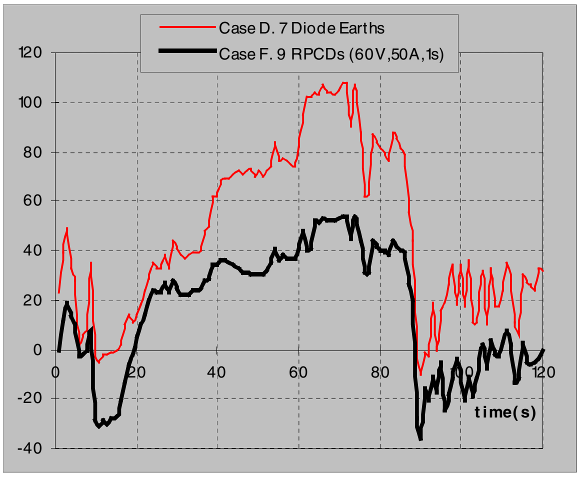

Figure 9: Rail Potential (V) vs. Time at Stop-2 for Cases D & F

- **RPCD Earths** A floating earth scheme with rail potential control devices is an effective scheme for rail potential control. The RPCDs have the flexibility to make the system totally floating by setting the voltage threshold high enough. (Case A is equivalent to 16 RPCD earths with voltage settings at 75V or higher. Case B is equivalent to 16 RPCD earths with voltage settings at 55V or higher.) The gross leakage charge depends on the three settings chosen.

  - ♦ Voltage Settings Within the RPCD schemes, a higher voltage setting reduces the occurrences of the RPCD being switched on and reduces the gross leakage charge. This is compared between cases G, H and K. Plots for cases H and K are shown in figures 10 and 11. Therefore it is recommended that the voltage settings should be made as high as is acceptable.

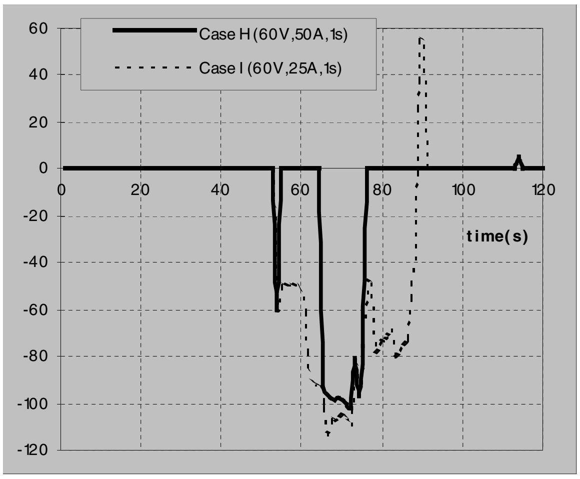

Figure 10: Earth to Rail Current (A) vs. Time at Stop-2 for Cases H & I

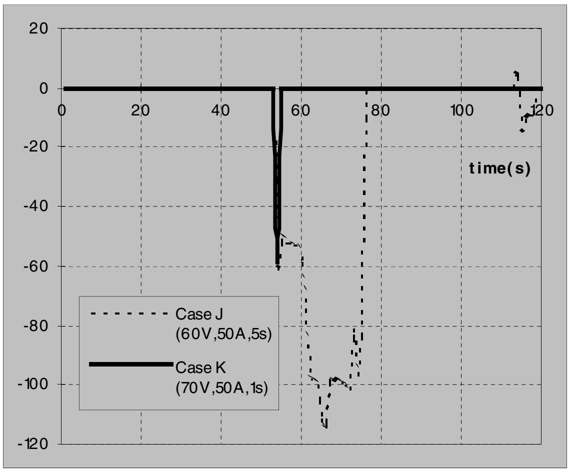

Figure 11: Earth to Rail Current (A) vs. Time at Stop-2 for Cases J & K

  - ♦ Current Settings Within the RPCD schemes, a higher current setting means that the RPCD already switched on can be switched off sooner, therefore reducing the gross leakage charge. The disadvantage of the higher current setting is the heavier duty on the contactor. This is compared between cases H and I, shown in Figure 10. The results show that it is worthwhile to have a heavier duty contactor in exchange of a lower gross leakage charge.

  - ♦ Time Settings Within the RPCD schemes, a shorter time setting means that the RPCD already switched on can be switched off sooner, which results in a lower gross leakage charge. The disadvantage of the shorter time setting is the increased frequency of RPCD switching, which results in more wear and tear for the devices. This is compared between cases H and J, shown in figures 10 and 11.

- **Passenger Stations** Since the RPCDs are bi-directional devices, they can be installed in locations other than traction substations, such as passenger stations, where high rail potential usually occurs due to train acceleration.

Case F represents two extra RPCDs at passenger stations that are located in the two longest feeding sections. The results show that the rail potential is reduced substantially compared with Case C. This means that these two extra RPCDs are adequate for the system under normal operational conditions. They may not be adequate under substation outage conditions which are not studied here. For a passenger station located within a relatively short feeding section, a RPCD installation may become a necessity if one of the substations feeding the section is out of service.

Compared with Case F, the results in Case H indicate that more installations of RPCDs increase both rail potential and gross leakage charge. However, this can be avoided if the voltage settings at the added installations are made higher, so that Case H becomes equivalent to Case F, under normal feeding arrangement. The added installations can be made active in emergency feeding conditions only.

5. CONCLUSIONS

A computer simulation model has been developed and sample simulation results are presented and analysed. The model is essential for effective system design concerning rail potential and stray current control, in addition to its normal function of assessing other aspects of system performance and designs.

The model can simulate different earthing schemes, including diode earths and floating earths with rail potential control devices. These can be used for two aspects of system design:

- The performance of the system in terms of rail potential and stray current can be assessed through simulation studies. This, together with other system performance indicators, can be used to determine the overall system configuration (e.g., system voltage level, maximum feeding section length, maximum rail resistance, etc.) and the overall system earthing strategy;
- Once the decision has been made on the overall system earthing strategy, the simulation results can be used to determine device locations and ratings. In the case of rail potential control devices, optimum settings can also be derived through simulation studies.

The simulation model has been verified against system integration test results from the Phase-I track of the Ankara Rapid Transit System in Turkey, where rail potential control devices are used. Excellent agreement has been found between simulation and test results.

The simulation results for a test track demonstrate that the floating earth scheme with rail potential control devices is the best choice.

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7. REFERENCES

[1] Yu,J.G. & Goodman,C.J. "Modelling of Railway Potential Rise and Leakage Current in DC Supplied Railway Systems", IEE Colloquium Digest No.1990/129. Presented to IEE Colloquium on Stray Current Effects of DC Railways and Tramways. London, October 1990.

[2] Yu,J.G. & Goodman,C.J. "Computer Simulation of Stray Currents in DC Supplied Rail Transit Systems and Their Corrosive Effects", Proceedings of the IMechE International Conference on Transit 2020, pp.121-127, London, October 1990.

[3] Yu,J.G. & Goodman,C.J. "Stray Current Design Parameters for DC Railways", Proceedings of the ASME/IEEE Joint Railroad Conference, pp.19-28, Atlanta, USA, March,1992.

[4] Yu,J.G. & Goodman,C.J. "Computer Analysis of Touch and Step Voltages for DC Railways", Proceedings of the Third International Conference on Computer Aided Design, Manufacture and Operation in the Railway and Other Advanced Mass Transit Systems, Washington DC, USA, August 1992.