# Dynamic Analysis of the Leakage Current Corrosion for the Non-Grounded DC Railway Systems

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***Abstract*—This paper proposes the dynamic analysis of the leakage current corrosion for the non-grounded DC railway systems. In the non-grounded DC traction system, the current leaks from the track to the earth, sometimes for positive, sometimes for negative, thus this behavior to be similar AC power supply system. It is not unlike the diode-grounded system which only permits current to leak from the track to the earth and come back from the leakage diode to the negative side of the traction power substation. The electrical corrosion by AC current is less than by DC current, essentially. The corrosion quantity is proportioned to the leakage current corrosion to integral of the time. This paper uses Kaohsiung Mass Rapid Transit (MRT) as an example to simulate multiple traction substations and multiple trains for the non-earth system DC traction system.**

***Index Terms*—leakage current, DC railway system, non-grounded system, diode-grounded system**

## I. Introduction

MRT systems generally adopt DC power supplies of 750V or 1500V. First, high-voltage AC from the public power grid is stepped down and rectified from AC to DC in order to supply power for the train via the third rail or catenary. Finally, the running rails are used as the traction-current return conductor [1], [2], and are composed of one DC power network.

In DC railway systems, the running rails are usually used as the return conductor for traction current. This arrangement mainly focuses on economic considerations, since it doesn't 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 MRT 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 on the running rail will be generated, and the voltage level could reach 60V to 100V [3], [4]. This voltage drop will force parts of the current to leak from the rail and flow into a pipe in the earth or the steel bar in a structure. Afterward, 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. The parts from which current flows out are those in which metal electrical corrosion will occur, as shown in Fig. 1.

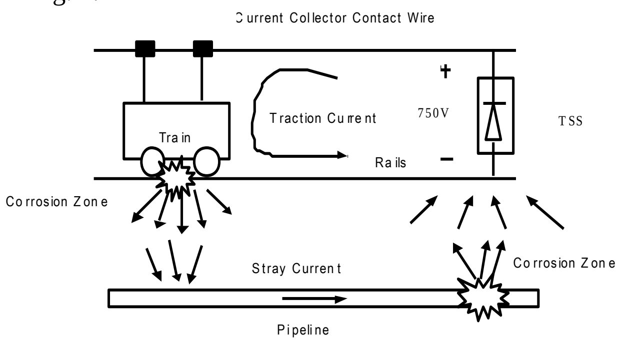


Figure 1. Leakage current model for DC railway systems.

Some leakage current exists in the MRT running rail and rail fastener, and in the MRT station, tunnel, structure facilities in a bridge, and piping. Stray current causes not only electrical corrosion to the structure and piping in MRT systems, but also to adjacent structures and underground piping, including those carrying oil, gas and water. Thus, MRT systems cause electrical corrosionas well as loss of third-party infrastructure. 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.

Leakage current corrodes underground piping in DC traction systems but seldom in AC traction systems. Since the current of each cycle of AC systems is both positive and negative, metal ions resulting from an oxidation half-cycle are deposited back in a reduction half-cycle. Although damage by AC current is less than by DC current, the resultant corrosion is usually greater for lower-frequency and less for higher-frequency currents. According to research, it is estimated that for metals like steel, lead and copper, 60Hz AC current causes less than 1% of the damage caused by equivalent DC current.

## II. Leakage Current Model

### A. Leakage Current Model for a Substation and a Train

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The grounding of DC traction systems can be classified as solidly grounded, diode-grounded and non-grounded systems. The earlier DC traction system is solidly grounded, with no specific insulation between the running rail and the earth. For reducing the magnitude of leakage current, the diode-grounded system and the non-grounded system offer improvements over the solidly grounded system.

If the running rails are sufficiently frequently bonded, they may be considered as a single return conductor. Further, if the longitudinal rail resistance and the rail-to-earth resistance are assumed, a very simple model results. Fig. 2 shows a single power supply and single-train rail circuit diagram for a substation and a train. Assuming that the train-to-substation distance is *L*, the train current is Is at point A, rail potential is *v(x)*, *r* is longitudinal rail resistance, and w is the track-to-earth resistance.

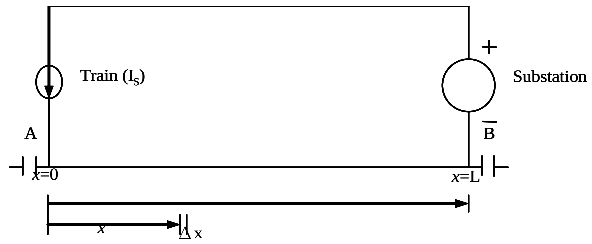


Figure 2. Leakage current model for a substation and a train.

In the non-grounded system, the initial rail current is given by i(0) = Is at point A (before leakage), and the final rail current is given by i(L) = Is at the point B (after leakage). The current and potential of the rails have the following solutions:

$$i(x)=\frac{I_S}{\sinh \alpha L}(\sinh \alpha (L-x)+\sinh \alpha x) \tag{1}$$

$$v(x)=\frac{\gamma \cdot I_S}{\sinh \alpha L}(\cosh \alpha (L-x)-\cosh \alpha x) \tag{2}$$

where:

$\alpha=\sqrt{\frac{r}{w}}$ , $\alpha$ is a propagation constant (in $m^{-1}$),

$\gamma=\sqrt{rw}$ , $\gamma$ is the characteristic resistance of the transmission line (in ohms).

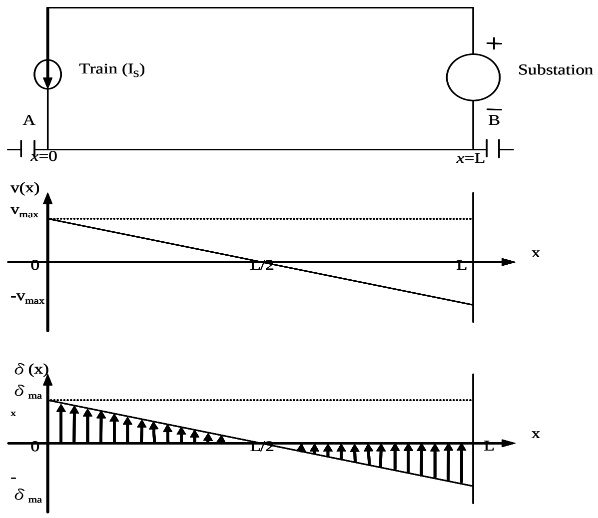


Figure 3. The rail potential and l leakage-current density for the non-grounded system.

Fig. 3 shows the rail potential and leakage-current density for the non-grounded system. In rail section *x* from 0 to *L/2*, the rail potential is positive, and the stray current leaves the rails to enter the ground. At rail location *L/2*, the rail voltage and stray-current density *δ(x)* are both zero. In the rail section *x* from *L/2* to *L*, the rail potential is negative, and the stray current leaves the ground and flows back to the rails. According to Kirchhoff's Current Law, the total current leaked to the ground is equal to the total current that flows back from the ground, as shown in (3).

$$\int_0^{L/2}\delta(x)dx=\int_{L/2}^{L}\delta(x)dx \tag{3}$$

In the above system, assume the negative side of the substation is diode-grounded, and that the diode is in the conducting state. At point B, the rail voltage is given by *v*(L) = 0, and at point A, the train current is given by *i*(0) = $I_s$. The rail potential and stray current for the diode-grounded system are obtained from these two conditions. Fig. 4 shows the profile of the rail potential and stray-current density for the diode-grounded system. The diagram shows the location of the train with maximum rail potential and maximum stray-current density. In the diode-grounded system, the maximum rail potential is about twice that in the non-grounded system. Furthermore, the diagram shows that in the diode-grounded system, all of the rails' stray current leaks, even from the rail into the ground, which is different from the non-grounded system's rails. In the non-grounded system, current leaks from the rail flowing into the ground at some rail sections, and back from the ground in others.

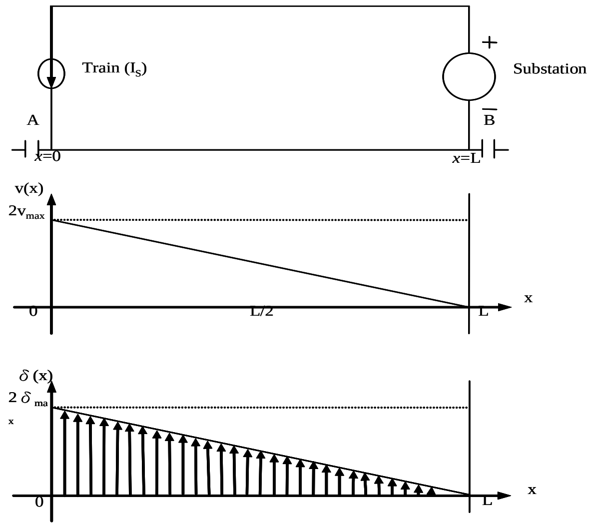


Figure 4. Profile of the rail potential and leakage-current density for the diode-grounded system.

## B. *Proposed Leakage Current l for Multiple Substations and Trains*

This paper will simulate and analyze rail potential and leakage current in MRT systems using Train Operations Model (TOM) software [5], [6] and an analytical model of leakage current; a flow chart is shown in Fig. 5. Fig. 6 is a model of leakage current simulated by computer. A substation is represented by a Thevenin equivalent voltage source, where *Vs* is the equivalent voltage of a substation, $R_s$ is the equivalent resistance of a substation, $r$ is longitudinal rail resistance, $\omega$ is the track-to-earth resistance, and $R_p$ is the resistance of the conductor rail. In order to simplify the analysis, parameters of the rail are given as follows: Resistance of the rail and resistance of the rail to the earth are uniform and constant, and are independent from time and position.

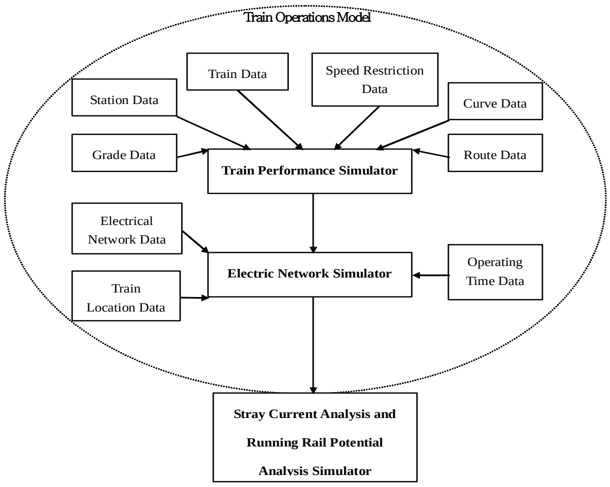


Figure 5. Flow chart for the rail potential and leakage current simulator.

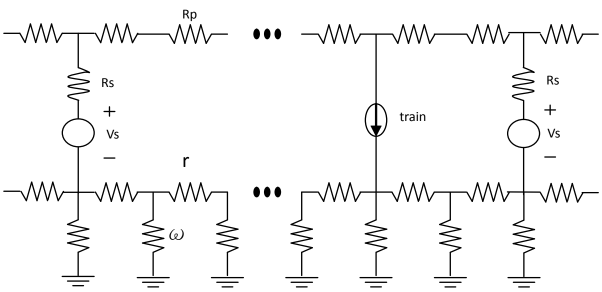


Figure 6. Model of leakage current for the non-underground systems.

## III. The Kaohsiung MRT System

### A. System Description

The Kaohsiung MRT network consists of the Orange and Red lines (Fig. 7), whose total length is 42.7km, which includes 37 stations, one main depot and two sub-depots.

The Orange Line route runs east-west across Kaohsiung City, from National Sun Yat-Sen University to Taliao. The total length of 14.4km includes 14 stations, one of which is ground-level while the remaining 13 are underground, and one main maintenance depot with an area of 55 hectares. The Orange Line includes the nine traction substations on the main line. On average, one traction substation is installed per 1.6km in every other passenger station.

The Red Line route runs north-south through Kaohsiung City, from Chiaotou to Linhai Industrial District. The total length of this line is 28.3km, of which 19.8km are underground, and 8.5km are elevated. This line has 15 underground stations, eight elevated stations and two light depots with areas of 26 and 34 hectares, respectively.


Figure 7. Kaohsiung MRT routes map.

### B. Traction Substation

Kaohsiung MRT systems adopt DC power supplies of 750V and non-earth system. A Kaohsiung MRT train consists of three or six cars, arranged as DM-T-DM or DM-T-DM-DM-T-DM, in which DM denotes a car with a driver's cab, and T denotes a trailer car. Another set of parameters is given below. Car 22m×3.1m×3.6m (length×width×height); Track gauge 1,435mm; Each train can carry a total of 1,794 people; Full load of six cars is 338.4 tons; Maximum speed 80km/h, maximum acceleration rate 1.0m/s$^2$, maximum deceleration rate -1.0m/s$^2$.

Table I shows the location of Traction Substations (TSS) and the distances between stations on the Kaohsiung MRT Orange Line. Moreover, the depot also requires the installation of TSSs that are dedicated to the depot dispatch vehicle and maintenance.

TABLE I. Locations of TSSs for the Kaohsiung MRT Orange Line

| Station | O1 | O2 | O4 | O5 | O6 | O7 | O8 | O9 | O10 | O11 | O12 | O13 | O14 | OT1 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Distance Between Stations (km) | | 1.57 | 1.29 | 0.93 | 0.87 | 0.58 | 1.08 | 0.74 | 0.66 | 0.83 | 0.71 | 0.73 | 1.11 | 2.13 |
| TSS Location | X | X | X | | X | | X | | X | | X | | X | X |

Fig. 8 shows the TSS and the third-rail structure, which uses a 24-pulse diode transformer rectifier to reduce harmonic components. Each TSS includes two transformer rectifiers, each with one primary side (delta connection) and two secondary sides (delta connection and wye connection); thus, each transformer rectifier can receive 12 pulse rectifications. Furthermore, the two transformer rectifiers are allowed to go through each primary-side delta connection; with each phase shift of ±7.5$^{o}$, these two transformer rectifiers would have phase shifts of 15$^{o}$, thus obtaining 24-pulse rectification. The section switch is installed to separate the power supplied by the third rail, and normally this switch is closed. The bypass switch is installed, and is normally open, but when the TSS malfunctions, the bypass switch is closed to maintain continuous third-rail power.

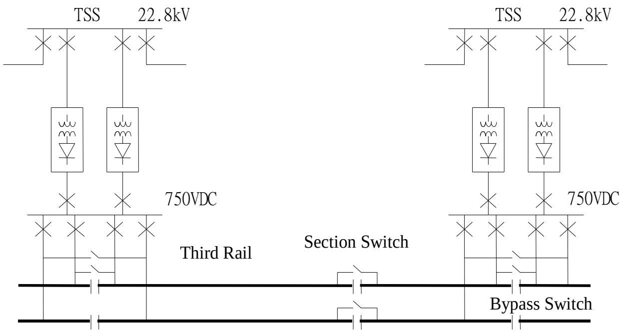


Figure 8. TSS and the third-rail structure.

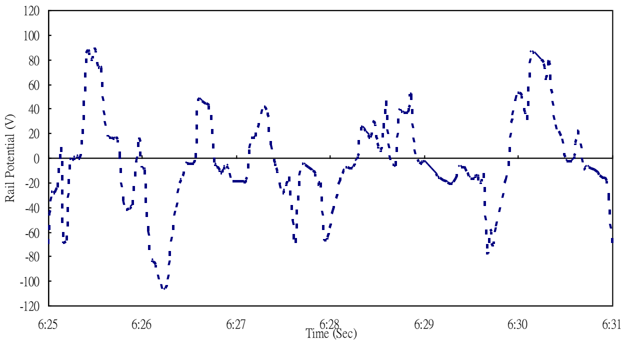


Figure 9. The rail potential of orange line station O1.

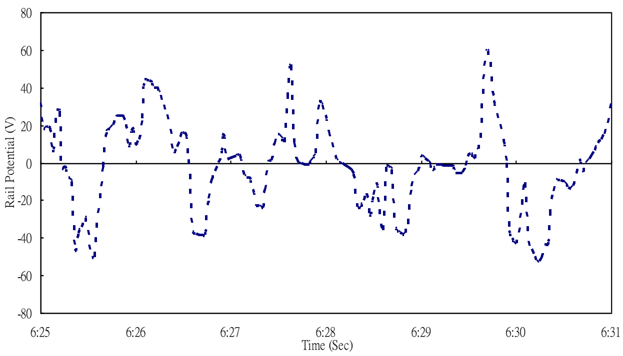


Figure 10. The rail potential of orange line station O6.

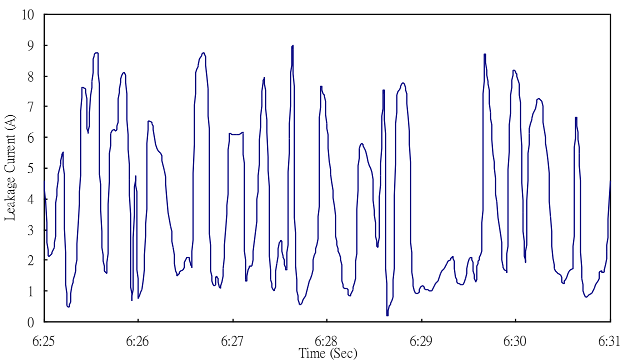


Figure 11. The profile of total leakage current versus time.

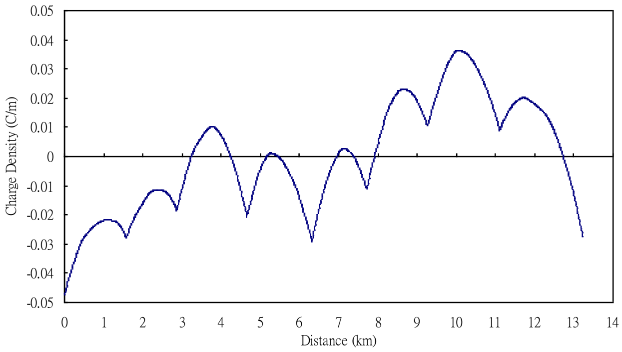


Figure 12. The amount of accumulated leakage charge versus distance.

## IV. Analysis Results

This paper uses Kaohsiung Mass Rapid Transit as an example to simulate multiple traction substations and multiple trains for the non-earth system DC traction system. Fig. 9 shows the rail potential of Orange Line O1 snapshots taken from 6:25 to 6:31 for six-minute headway. Fig. 10 is a rail potential at station O6 for the track location at 4640 meters. Fig. 11 shows the profile of total leakage current versus time, the average value of the total leakage current is about 3.71A. Fig. 12 shows the amount of accumulated leakage charge for six-minute headway (6:25~6:31).

## V. Summary

This paper uses Kaohsiung MRT as an example to simulate multiple traction substations and multiple trains for the non-grounded system DC traction system. In the non-grounded DC traction system, the current leaks from the track to the earth, sometimes for positive, sometimes for negative, thus this behavior to be similar AC power supply system.

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En-Chih Chang is the equal contribution author.

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