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Evaluation of rail potential and stray current reduction by using NEG-ETP in DC railway system

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Abstract

The NEG-ETP system that providing zero resistance closed circuit reducing the reverse path of current on the running rail is presented in this article. The NEG-ETP system is created by installing additional electronics in conventional electrical systems. Without modifying trains, tracks, or tunnels. Using MATLAB program through models for MRT purple line (North), rail potential and stray current are assessed in accordance with EN 50122 standards of all three systems, including CON-ETP, REC-ETP, and NEG-ETP. According to the simulation, the percentage reduction of the rail potential was 9.14% when the REC-ETP versus the CON-ETP system was 32.99% when the NEG-ETP system compared to the CON-ETP system and 26.25% when the NEG-ETP system versus the REC-ETP system could be seen in this negative resistance converter system, which can reduce the cost of rails and leakage currents in the DC system. It can also be applied to new rail transport.

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Keywords: Rail potential; Stray current; Negative resistance converter (NEG); DC railways; Return conductor

1. Introduction

There are two electrical systems used to drive trains, namely the direct current system (DC) and the alternating current system (AC). As for the electricity supply system to drive the electric trains, there are two systems, namely the third rail system and overhead wire system. Which the overhead wire system, there will be a structure of the current feed system above the rails, often used for long-distance train journeys. The third rail system has advantages in terms of visual pollution effects. There is no cluttering power supply structure above the railroad tracks. But there are restrictions on use and safety. This system is often used on subways or mass transit systems. In this research, the focus is on the third rail direct current system due to case studies MRT purple line (North) organized in this.

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Nomenclature

NEG-ETP	Negative resistance converter electric traction power.
CON-ETP	Conventional electric traction power.
REC-ETP	Return conductor electric traction power.
NEG	Negative resistance converter.
FEC	Feeder cable.
SW	Switch unit.
u_r	Voltage of zero-resistance loop.
u_{NEG}	Output voltage of NEG.
u_{FEC}	Voltage across FEC.
u_{SW}	Conducting voltage drop of SW.
u_{rT}	Rail potential of CON-ETP.
u_{rR}	Rail potential of REC-ETP.
u_{rN}	Rail potential of NEG-ETP.
i_{rT}	Stray current of CON-ETP.
i_{rR}	Stray current of REC-ETP.
i_{rN}	Stray current of NEG-ETP.

The traction current flows back to the power substation through the track in DC electric propulsion systems such as electric trains, trams, and mass transit systems causing the rail potential. Part of the reverse current flows to the soil through the running rail. This section is called stray current [1]. In running rails and underground metallic pipes, stray current can cause substantial electrochemical corrosion and when people enter or exit the train, the rail potential might create an electrical shock [2].

However, this paper will focus on the rail potential and stray current reduction in DC electric train system by a new method called NEG-ETP. It is a new method in which additional equipment is installed in the old system as shown in Fig. 1. Whether it is a CON-ETP and a REC-ETP. It is a method of bringing the conductors parallel to the running track [3]. Extra tracks divide the current and reduce the equivalent resistance of running rail. However, installing extension rails and modifying relevant components in an electric train system can often be costly and constraints on cable quantity and cost. If the number of cables is not enough the result of the reduction would be unclear [4]. These two systems are the ones that are currently in use. The new method uses the principle by reducing the rail current that returns on the moving rails by applying zero resistance in a closed circuit [5].

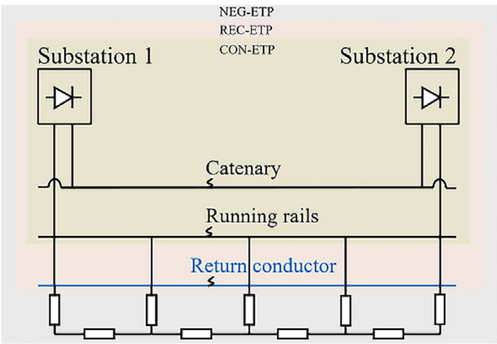

Fig. 1. Diagram of CON-ETP, REC-ETP and NEG-ETP.

The topics of this article are organized as follows: The operation principles and assessment are in-depth analysis in Section 2. Section 3 presents the model of case study. The simulation results and mitigation percentage of rail potential and conclusion are proposed in Section 4 and Section 5, respectively.

2. Operating principles and assessment

The power supply systems of electric traction substations include rail conductors or contact lines, and tracks or running rails, with CON-ETP, REC-ETP, and NEG-ETP layouts available presented in Fig. 1. and separated in Fig. 2. The classical mathematical model for double-side power supply is determined by a model for supplying power to the train, including power supply substation, trains, rail resistance and conductive unit length to make it easier to calculate as shown in Fig. 3, when I_{x1} and I_{x3} are currents flowing in and out at nodes a and c, respectively, and L_1 is the considered length of this section.

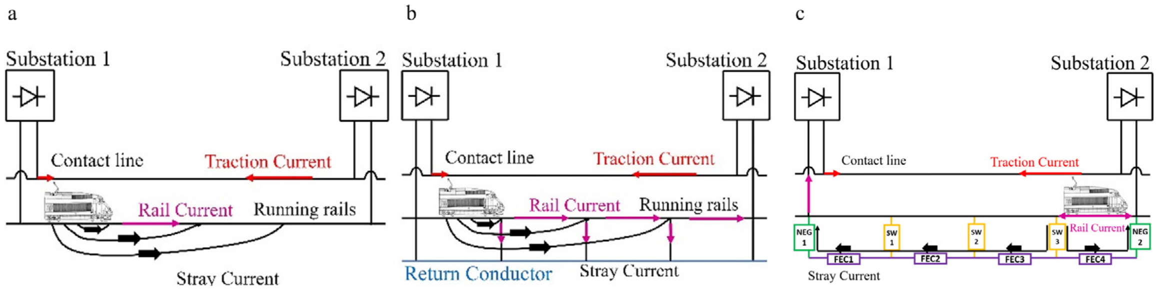

Fig. 2. Operation principles of return current to substations. (a) CON-ETP (b) REC-ETP (c) NEG-ETP.

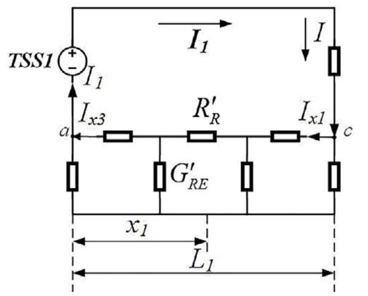

Fig. 3. Classical mathematical model for double-side power supply for calculation between considered nodes.

2.1. Conventional electric traction power system

Fig. 2(a) shows the configuration of CON-ETP as a train travelling between substation 1 and substation 2, traction current is delivered to the train via the overhead wire, which is parallel to the rails. Once the power supplies the electric traction motor on the train, the current will go to the wheel and running rail then back to substation. In addition, the stray current capably flows to the ground and returns to substation [6].

For the CON-ETP operation, the parameters A_k and B_k are obtained in terms of the summation of currents. It would be seen the mathematical model in Fig. 3. If the train moves a distance x_1 from node a to node c for a distance L_1, rail potential, u_{rT}, and stray current, i_{sT}, are computed as follows in Eq. (1) when $\alpha = \sqrt{R'_R G'_{RE}}$

$$\begin{cases} u_{rT(k)} = R_g(A_k e^{x\alpha} + B_k e^{-x\alpha}), \qquad 2 \le k \le n \\ i_{sT} = \dfrac{1}{2R_g} \displaystyle\int_0^L \sum_{k=2}^{k=n} \left| u_{rT(k)} \right| dx = \dfrac{u_{rT(k)}}{R_g} \end{cases} \tag{1}$$

According to the $x_1 = 0$ (node a) and $x_1 = L_1$ (node c). Substitution such values in Eq. (1) can be expressed in Eqs. (2) and (3), respectively.

$$I'_R(0) = A_k e^{\alpha(0)} + B_k e^{-\alpha(0)} = A_k + B_k \tag{2}$$

$$I'_T(L_1) = A_k e^{\alpha(L_1)} + B_k e^{-\alpha(L_1)} \tag{3}$$

When $I'_R(0) = I_{x3}$ and $I'_R(L_1) = I_{x1}$ $(B = I_{x3} - A)$. From the above equation, it was found that the variables A_k and B_k which can be calculated according to as follows in Eq. (4):

$$A_k e^{\alpha L_1} + (I_{x3} - A_k) e^{-\alpha L_1} = I_{x1}$$
$$A_k = \frac{I_{x1} - I_{x3} e^{-\alpha L_1}}{e^{\alpha L_1} - e^{-\alpha L_1}} \tag{4}$$

2.2. Return conductor electric traction power system

Fig. 2(b) shows the configuration of REC-ETP. The parallel rails and the return conductors are connected at the definite distance for example every 5–6 km. The rail currents mostly return to substations through the return conductors [7]. As a result, the amount of rail current leaking to the ground is decreased.

The calculation in REC-ETP can be also calculated from Eq. (1) and considered mathematical model in Fig. 3. However, the model of REC-ETP is slightly different in comparison with CON-ETP with additional nodes of the next sections.

2.3. Negative resistance converter electric traction power system

Fig. 2(c) shows the schematic diagram of NEG-ETP. NEGs, FECs, and SWs are included in the CON-ETP model. During a train running pass SWs in the closed circuit, SWs would be activated, enabling the return current to take a shorter path [8]. The output voltage of NEGs is changed to match the negative equivalent voltage of FECs and SWs that makes the voltage summation in the new closed circuit to be zero. The zero resistance is ideally obtained from the turning-on SWs to NEGs connection.

As illustrated in Fig. 4(a), the NEG is a full-bridge bipolar-switching dc–dc converter with a adaptable tuning output voltage and output resistance. A bidirectional switch, or SW includes a couple IGBTs connected in series with reverse direction illustrated in Fig. 4(b). The model of FEC is configured the parallel of the rail resistors as shown in Fig. 4(c). Therefore, the return current can flow in both direction via NEGs and SWs.

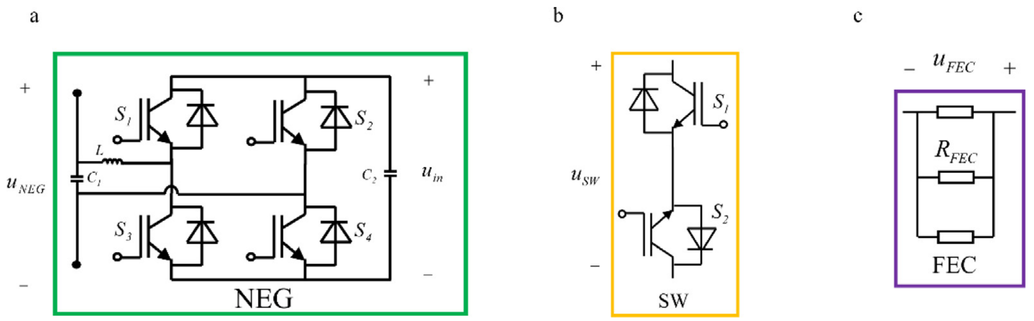

Fig. 4. Power electronic devices connected in NEG-ETP. (a) NEG. (b) SW. (c) FEC.

The mitigation of rail potential and stray current could be obtained by separated the rail to be a section with the specific length. To simplify the case study, the running rails would be separated into four sections, then the output resistances of NEGs are determined in Eqs. (5) and (6). Rail potential, u_{rN} and stray current, i_{sN} in NEG-ETP shown in Fig. 3, are expressed in Eq. (7), where parameters G_k and H_k are derived from the proof of each consideration scope given in variable by applying KVL and KCL calculation.

$$u_{NEG1} \equiv \begin{cases} -u_{FEC1} - u_{SW1}, & k = 1 \\ -\sum_{j=1}^{j=k-1} u_{FECj} - u_{SW(k-1)}, & 2 \le k \le n \end{cases}$$

$$u_{NEG2} = \begin{cases} \sum_{j=k+1}^{j=n} u_{FECj} - u_{SW(k)}, & 1 \le k \le n-1 \\ u_{FEC(n)} - u_{SW(n-1)}, & k = n \end{cases}$$

$$\text{So } R_{NEG1} = \frac{u_{NEG1}}{i_{NEG1}} \tag{5}$$

$$\text{So } R_{NEG2} = \frac{u_{NEG2}}{i_{NEG2}} \tag{6}$$

$$R_{NEG1} = \begin{cases} -R_{FECj} - R_{SW1}, & k = 1 \\ -\sum_{j=1}^{j=k-1} R_{FECj} - R_{SW(k-1)} & 2 \le k \le n \end{cases}$$

$$R_{NEG2} = \begin{cases} -\sum_{j=k+1}^{j=n} R_{FECj} - R_{SW(k)}, & 1 \le k \le n-1 \\ -R_{FEC(n)} - R_{SW(n-1)}, & k = n \end{cases}$$

$$\begin{cases} u_{rN(k)} = R_g(G_k e^{x\alpha} + H_k e^{-x\alpha}), & 1 \le k \le n \\ i_{sN} = \dfrac{1}{2R_g} \displaystyle\int_0^L \sum_{k=1}^{k=n} \left| u_{rN(k)} \right| dx = \dfrac{u_{rN(k)}}{R_g} \end{cases} \tag{7}$$

2.4. Assessment stray current for the MRT purple line

The stray current offered as a reference value for electric trains should be no more than 2.5 mA/m/track to assess stray current according to EN 50122-1 and EN 50122-2 [9,10], however the runway stray current measurement is a concern. Only the influence caused by stray current may be measured, which is essentially impossible. This will be the rail's own potential. The rail potential may be computed using EN 50122-2 determined in Eq. (8).

$$U_{RE} = 0.5 \times I_{tr} \times R_c \times \left(1 - e^{-\left(\frac{L}{Lc}\right)}\right) \tag{8}$$

where, U_{RE} is the voltage value along the length (V), I_{tr} is the mean return current circuit of the section under consideration during peak load (A), R_C is the resistance characteristics of the rails per unit length (Ω/km), L is the length of interest to consider for the route (km), L_C is the length of the track (km). Which values R_C and L_C can be obtained from Eqs. (9) and (10)

$$R_C = \sqrt{\frac{R'_R}{G'_{RE}}} \tag{9}$$

$$L_C = \frac{1}{\sqrt{R'_R \times G'_{RE}}} \tag{10}$$

where, R'_R is the rail resistance per unit length (Ω/km), G'_{RE} is the conductivity per unit length between rail and ground (S/km).

3. Model of case study

The flow chart to evaluate the rail potential is presented in Fig. 5. Firstly, the detection of train location is obtained by the train movement calculation with obtaining the train position, train speed and train power. Secondly, REC-ETP and NEG-ETP calculate the rail potential for rail-section and CON-ETP is also calculated the rail potential. If a train travels to the end of the track, then the simulation will also be end. A train simulation program is carried out in MATLAB using a model of the train in MRT purple line for determining the rail potential. It includes 16 passenger stations and 10 traction substations. The train and system information of the MRT purple line (North) are presented in Table 1. and the station location information is shown in Table 2. The train is electrified through the third rail with a rated voltage of 750 V.

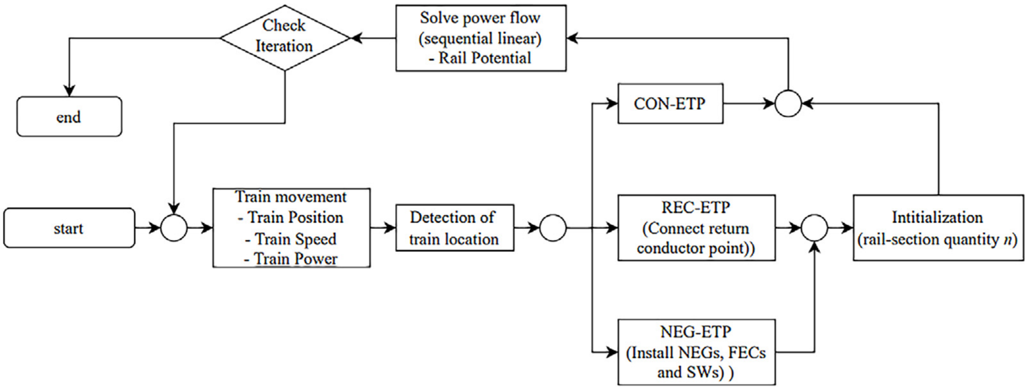

Fig. 5. Rail potential evaluation procedure: CON-ETP, REC-ETP and NEG-ETP.

Table 1. Train and system information of the MRT purple line (North) for simulation.

Specific data	Information	Value	Unit
Train parameters			
Movement feature	Max. speed	80	km/h
	Max. acceleration	1.2	m/s^2
	Max. deceleration	0.9	m/s^2
Weight	Train mass	135	ton
	Passenger mass	75	ton
Tractive effort curve	Maximum tractive effort	228.8	N
	Maximum braking effort	168.8	N
Efficiency	Motor power factor	0.86	–
Auxiliary power	Constant load	270	kW
Train resistance			
3rd Rail resistance		0.007	Ω/km
Track resistance		0.0175	Ω/km
Earth resistance		12	Ω
Rail-to-earth conductance		2	S/km
Substation parameter			
Voltage no-load		750	V
Short-circuit capacity		50	MW

4. Simulation results

4.1. Assessment stray current for the MRT purple line (North)

The stray current assessment for the MRT Purple Line (North) is calculated from (8), (9) and (10) mentioned above. It was found a rail potential of 48.97 V and a stray current of 0.0979 mA/m for a rating of 7106.413 A and compared with the simulation result of a single train movement as shown in Fig. 5, as shown in Table 3.

From Table 3, it is found that the rail potential is different. As a result of a single train simulation, there is stray current accumulated in the ground that flows back into the propulsion substation. However, both obtained rail potentials are standardized to the EN 50122-2 standard, i.e., the allowable voltage is no more than 120 V, and it is recommended that no damage to the railway up to 25 years, if stray current per unit is below 2.5 mA/m. The simulation results of CON-ETP, REC-ETP and NEG-ETP systems can be described in Figs. 6–8, respectively.

Table 2. Station location information.

Station code	Substation code	Station name	Station position (km)
PP01	TSS01	Khlong Bang Phai	0.00
PP02	TSS02	Talad Bang Yai	1.27
PP03	TSS03	Sam Yaek Bang Yai	2.83
PP04	–	Bang Phlu	4.40
PP05	TSS04	Bang Rak Yai	5.60
PP06	–	Bang Rak Noi Tha It	6.85
PP07	TSS05	Sai Ma	8.10
PP08	–	Phra Nang Klao Bridge	9.57
PP09	TSS06	Yaek Nonthaburi 1	11.20
PP10	–	Bang Krasor	12.46
PP11	TSS07	Nonthaburi Civic Center	13.36
PP12	–	Ministry of Public Health	15.15
PP13	TSS08	Yaek Tiwanon	16.35
PP14	TSS09	Wong Sawang	18.07
PP15	TSS010	Bang Son	19.36
PP16	–	Tao Poon	20.94

Table 3. Comparison of stray current assessment results during single train motion simulations with rail potential calculations obtained from grounding models according to EN 50122-2.

Assessment procedure	Rail potential (V)
Simulation result of a single train movement	76.38
Calculation of rail potential according to EN 50122-2	48.97

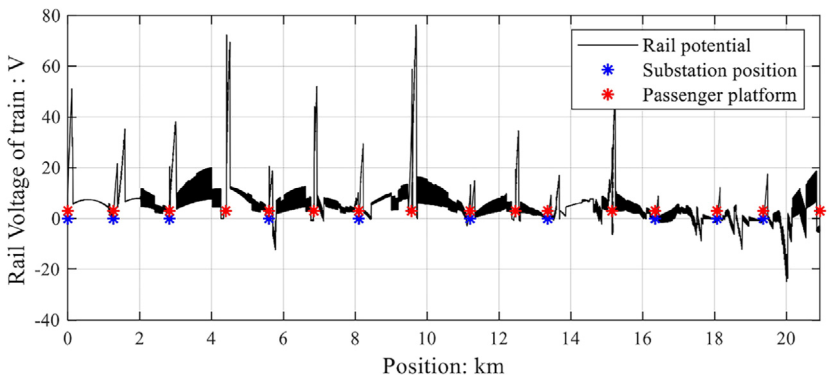

Fig. 6. Rail potential of CON-ETP.

4.2. Conventional electric traction power system

Fig. 6 shows the rail potential of the CON-ETP system. At the passenger station 8 (PP08) located between substation 5 and substation 6 (TSS05-TSS06), the maximum rail potential of 76.38 V is obtained. Considering the other peaks of rail potential, they are occurred at passenger station located between substations during the train operation in accelerating mode. The rail potential would reduce when the train running in cursing and coasting modes.

4.3. Return conductor electric traction power system

As a case study, the connected points of the return conductor and the running rail are located at of 0, 5, 10, 15, 19.36 and 20.94 km. The maximum rail potential of 69.40 V is obtained at the passenger station 10 (PP10) located halfway between substation 6 and 7 (TSS06-TSS07) as shown in Fig. 7. It is pointed out that the peak rail

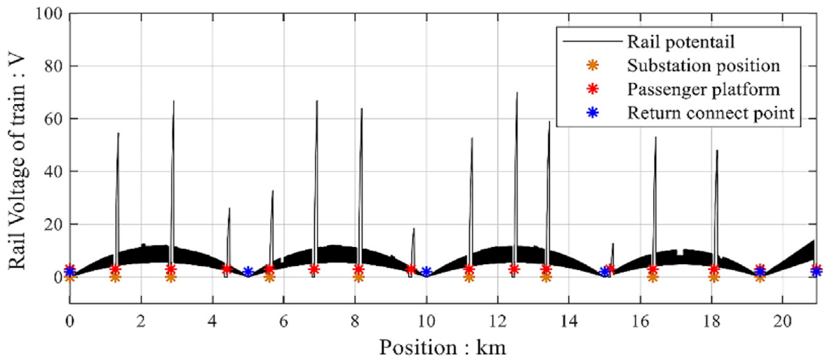

Fig. 7. Rail potential of REC-ETP.

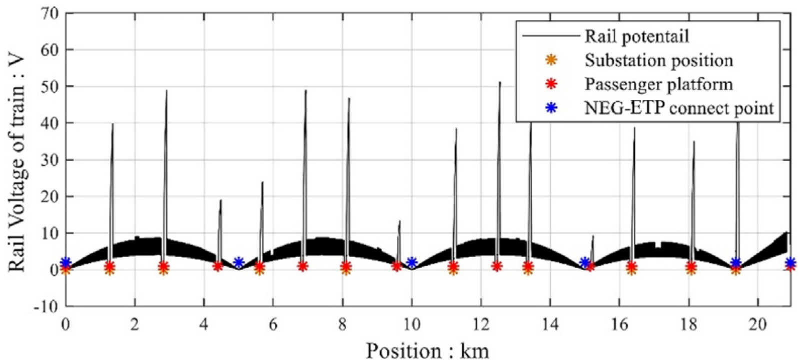

Fig. 8. Rail potential of NEG-ETP.

potential occurred at each passenger station located around middle between the connected points is higher than the passenger station located near the connected point. The maximum rail potential of REC-ETP system is lower than that of CON-ETP system of 9.14%.

4.4. Negative resistance converter electric traction power system

The connected points of the return conductor and the running rail are located at same position as the REC-ETP system. The rail potential of the NEG-ETP system is shown in Fig. 8. At passenger station 10 (PP010) located halfway between substation 6 and 7 (TSS06-TSS07), the maximum rail potential of 51.18 V is obtained. The peak rail potential occurred at each passenger station located around middle between the connected points is higher than the passenger station located near the connected point similar with the REC-ETP system, but a bit lower. The maximum rail potential of the NEG-ETP and the REC-ETP are reduced by 32.99% and 9.14% in comparison with the CON-ETP as shown in Table 4. Regarding the maximum rail potential evaluation, the NEG-ETP is lower than the REC-ETP by 26.25%.

Table 4. Percentage reduction of rail potential.

System	Rail potential (V)	Percentage decrease (%)
CON-ETP (Base case)	76.38	–
REC-ETP	69.40	9.14
NEG-ETP	51.18	32.99

5. Conclusion

In this paper, NEG-ETP is a new concept developed by installing additional power electronic equipment, there is no need to modify the original structure of the railway infrastructure, recommended in the urban rail transportation to mitigate rail potential and stray current. The configuration of NEG-ETP is separated into several rail-sections, with non-train rail-sections having zero rail current. From proposed method, this was applied to the mass rapid transit system namely MRT purple line (North), in Thailand simulated by the MATLAB/M-file. This was pointed out that rail potential and stray current would be evidently mitigated by NEG-ETP as a percentage reduction compared to CON-ETP and REC-ETP is 9.14% and 32.99% respectively.

Declaration of competing interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

No data was used for the research described in the article.

Acknowledgements

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