RESEARCH ON CATENARY ANTI-ICING (ICE-MELTING) TECHNOLOGY IN HIGH-SPEED RAILWAY

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***Abstract**:* The ice coating on the catenary of high-speed railway will severely affect the railway operation. At present, the research on the catenary ice coating problem in the electrified railway field at home and abroad is not deep enough. Combined with the characteristics of high-speed railway catenary, this paper studies the principle of ice-coating and ice-melting, demonstrate the feasibility of high-current thermal anti-icing (ice-melting) technology which would not affect its performance and can prevent ice-coating or de-icing. Furthermore, it systematically studies on various of feasible programs. It proposes the AC and DC anti-icing (ice-melting) technical scheme of high-speed railway catenary, and demonstrates the feasibility of catenary anti-icing(ice-melting)without interrupting the transportation.

1. INTRODUCTION

Current domestic and international anti-icing and de-icing technology can be divided into three categories, which are thermal melting ice, mechanical icebreaking, natural passive methods, etc. These studies mainly focus on aspects of aviation and transmission lines. With the affection of many factors such as transport mode, research on catenary ice coating problem in electrified railway field is not more.

High-speed railway catenary system has to be adequate mechanical, electrical strength and security, should also meet the catenary - pantograph system matches the dynamic performance of high-speed operation of the indicators. Thus, in studying high-speed railway catenary prevention and de-icing technology, it is necessary to achieve sustained and effective economic, easy to implement for anti-icing or ice-melting, but also to avoid or minimize the impact on performance of catenary to ensure traffic safety . To achieve the above purpose, it should give priority to high-current thermal technology for ice-melting, which including AC ice-melting scheme and catenary ice coating on-line monitoring system. To achieve these objectives, high-current thermal technology for ice-melting is most appropriate.

2. CONCLUSION

(1)The catenary structure of electrified railway is special to electrical power line. Despite the same ice-coating and ice-melting principle, differences are existed that can’t be simply applied.

(2)The ice-coating on catenary is harmful to the safety operation of high-speed railway, and it is hard to anti-icing (ice-melting). Using the high-current thermal ice-melting technology can achieve not only perfect results, but also avoid the affection to the catenary performance. The technology is safe and reliable, and greatly reduces impacts to the high-speed railway operation.

(3)The DC or AC methods both are feasible. Considering factors like difficulties of project implement, impacts of railway operation and so on, it is one of the best ice-melting program that access the limiting devices at the end of feeding arm, and providing power by the traction transformer.

(4)Based on the theoretical analysis, simulating calculation and engineering verification, we can connect the limiting devices in series in the end of feeding arm, which is monitored by catenary online monitoring system and ice-melting comprehensive monitoring devices, to achieve conditionally locomotive uninterrupted operation anti-icing (ice-melting).

These conclusions apply not only to anti-icing (ice-melting) of high-speed railway catenary, but also to the similar engineer like normal-speed railway and urban mass transit.

Considering the appliance of current anti-icing (ice-melting) technology is not yet mature, therefore recommending that: ① Speeding up the process of field test and analysing systematically to the test data, to verified the contact line anti-icing (ice-melting) theory and optimize the mathematical model; ② Summarizing the experience of field trail, optimizing the anti-icing (ice-melting) system program, to generate practical and reliable anti-icing (ice-melting) products; ③ Unified studying the prevention-treatment and safe operational management measures, which combine of high-current anti-icing (ice-melting) with mechanical ice-breaking and nature passive de-icing, to meet the demand for safe operation of electrified railway and promote widely application of catenary anti-icing (ice-melting) technology in the electrified railway.

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Abstract: **The ice coating on the catenary of high-speed railway will severely affect the railway operation. At present, the research on the catenary ice coating problem in the electrified railway field at home and abroad is not deep enough. Combined with the characteristics of high-speed railway catenary, this paper studies the principle of ice-coating and ice-melting, demonstrate the feasibility of high-current thermal anti-icing (ice-melting) technology which would not affect its performance and can prevent ice-coating or de-icing. Furthermore, it systematically studies on various of feasible programs. It proposes the AC and DC anti-icing (ice-melting) technical scheme of high-speed railway catenary, and demonstrates the feasibility of catenary anti-icing(ice-melting)without interrupting the transportation.**

Keywords- ice-melting; high-speed railway catenary; ice-coating

I. INTRODUCTION

Current domestic and international anti-icing and de-icing technology can be divided into three categories, which are thermal melting ice, mechanical icebreaking, natural passive methods, etc[1-2]. These studies mainly focus on aspects of aviation and transmission lines. With the affection of many factors such as transport mode, research on catenary ice coating problem in electrified railway field is not more.

Presently, ice-melting at abroad mainly adopts methods as mechanical de-icing, anti-frost deicing coating, high current thermal ice-melting, etc. In Frence, it commonly uses the mechanical icebreaking method of setting the deicer similar to pantograph before the real one on the lines which operation speed is lower than 200km/h, and uses the high current thermal ice-melting system on the lines which operation speed is higher than 200km/h. In German, it uses the measure of coating the anti-frost deicing agent on the wire in urban mass transit. In Janpan, it studys the contact line with electric wire in experiment way, achieving ice-melting by the heat generated by current. In China, it uses mechanical catenary ice-meting method commonly.

High-speed railway catenary system has to be adequate mechanical, electrical strength and security, should also meet the catenary - pantograph system matches the dynamic performance of high-speed operation of the indicators[3]. Thus, in studying high-speed railway catenary prevention and de-icing technology, it is necessary to achieve sustained and effective economic, easy to implement for anti-icing or ice-melting, but also to avoid or minimize the impact on performance of catenary to ensure traffic safety . To achieve the above purpose, it should give priority to high-current thermal technology for ice-melting, which including AC ice-melting scheme and catenary ice coating on-line monitoring system. To achieve these objectives, high-current thermal technology for ice-melting is most appropriate.

II. THEORETICAL RESEARCH ON CATENARY ANTI-ICING (ICE-MELTING) TECHNOLOGY IN HIGH-SPEED RAILWAY

A. Contact Wire and Catenary Wire Icecoating and Ice-melting Model

The high-speed railway catenary is a constant tension system which consists of contact line, catenary wire, hanging strings, tension compensation and the related support devices, etc. It has different characteristics from power system, maily in: the contact line is the hard copper alloy rod, smooth surface with groove, the catenary wire is copper alloy hinge line, small span, keeping in the straight status in constant high tension, the catenary wire keeps in a stable force of suspension status, and the overall system has a certain rigidity. Otherwise, in the normal operation condition, the train obtains power by sliding and contacting with contact wire using pantograph.

(1) Contact wire ice-coating

The causes of ice-coating in catenary are basically the same with the power overhead wire. The main factors include: weather conditions, topography and geography, altitude, wire itself (dimensions, stiffness, current) and so on.

Bearing a certain stiffness under the constant tension, the catenary doesn't prone to reverse in the ice-coating process, which could not formate the round ice-coating, but much easier to formate the icicles shown in Figure 1.

Figure 1. Schematic diagram of the collision between cooled water droplets and column wire

In the working state, the current is discontinuous and dramatic changing. The formation of ice in climatic conditions, the joule heat generated by current can't maintain the wire surface temperature above 0 ℃ in general, therefore, the current is not enough to melt ice. As the sliding and contacting with pantograph would break or disrupt the ice-coating process, the contact wire is hard to coat ice in the high density of train running and not too bad weather.

(2) Contact wire ice-melting model

Because the contact line is not prone to reverse, the ice-coating is much easier to form icicles, shown in Figuer 2.

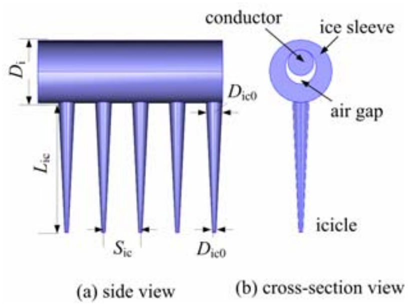


Figure 2. Icicle ice-coating wire model

In the process of ice-melting, the ice-layer which contacted with the wire melts first. After the loss through the gap, the melting water generates gap between the ice-layer and wire. According the material differences in the ice-melting process, it divides ice-melting into four areas:

θ_0 indicates environment

θ_1 indicates ice area()including icicles

θ_2 indicates gap

θ_3 indicates wire

Each region is separated by three boundary surface: Γ01, Γ12, Γ23. Ignored the solar radiation affection in the ice-melting process, joule heat generated by the current consumpts mainly in the following three areas:

a) Convective heat transfer in the ice-layer surface and radiation heat loss;

b) Latent heat absorbed by ice-melting;

c) Heating wire, ice and air gap.

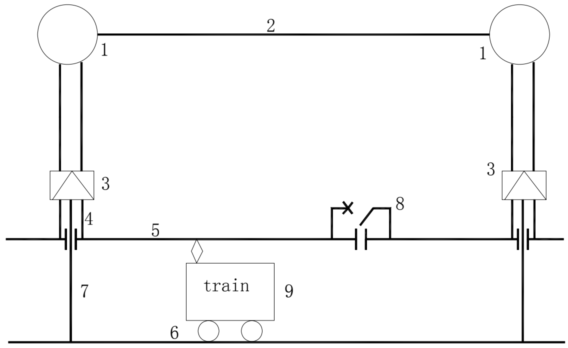
$$[I^2 r_T - h\int_{\Gamma 01}\left(T(x,y,z)-T_a\right)dS]dt = \rho_{\Theta 1} L_F dV_m + \sum_{k=1}^{3}\rho_{\Theta k} V_{\Theta k} C_{\Theta k} dT_{\Theta k}$$

Where r_T is resistivity of the wire, Ω/m; T_a is the environment temperature, °C; h is the heat exchange coefficient between the outer surface of the ice and air, W/(m^4·K); dV_m is the bulk of ice-melting, m^2; $T_{\Theta k}$ (k=1,2,3) indicates temperature distributing of Θ_k area, °C； $T_{\Gamma i,j}$ ($0 \le i,j \le 3$ & $i=j-1$) indicates temperature distributing of the interface $\Gamma_{i,j}$, °C; $\rho_{\Theta k}$ (k=1,2,3) indicates the density of Θ_k area , kg/m^3; $C_{\Theta k}$ (k=1, 2, 3) indicates the specific heat capacity of Θ_k area , J/(kg. °C)； $\lambda_{\Theta k}$ (k=1,2,3) indicates the htermal conductivity of Θ_k area, W/(m. °C).

B. Study on The Ice-melting Technology

(1) Constitute of the high-speed railway traction power supply system

The high-speed railway traction power supply system consists of traction substation and catenary, which main role is to obtain power from the power system, and sent it to the motor train units. The constitute of traction power supply system is shown in Figure 3[4].



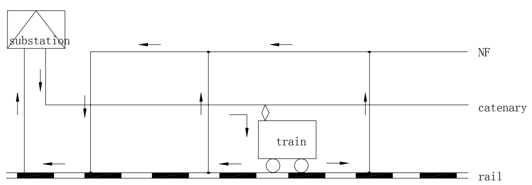
1- Area substation or power plant; 2-High voltage transmission line; 3-Traction substation; 4-Feed line; 5-Contact line; 6-Rail; 7-Return wire or boosting wire; 8-Section post; 9-motor train unit

Figure 3. High-speed railway traction power supply system of the composition map

The power supply mode of high-speed railway commonly uses direct power supply with back flow mode (Figure 4(a)) or autotranformer power supply mode (Figure 4(b)). Compared to the direct power supply with back flow mode, the autotranformer power supply mode has more complicate network. As limited space, this paper only analyses the autotranformer power supply mode.

The auto transformer power supply mode consists of contact line, catenary, rail, earth, AF line, PW line, and autotransformer. The voltage between contact line and rail is 25kV. In the catenary system, there is parallel connection between autotransformer line terminl, contact line and AF line every certain distance, besides the connection between autotransformer winding neutral point terminal and rail, which enables the 2×25kV voltage of the catenary power supply network. The current of the autotranformer power supply mode is shown in Figure 4.

(a) The direct power supply with back flow mode



(b) The autotranformer power supply mode

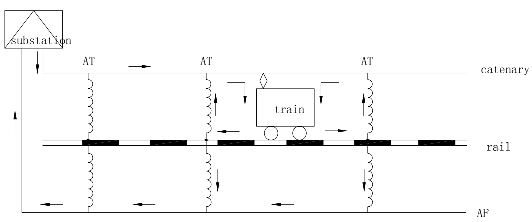


Figure 4. Diagram of the power supply mode

(2) Ice-melting simiplify circuit derivation of high-speed railway catenary

In order to analyse the ice-melting feature of high-speed railway catenary, the autotransformer (AT) traction power supply network with ice-melting equipment could deduce to the network in Figure 5[5].

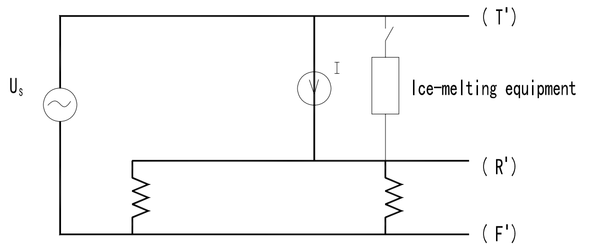


Figure 5 Simplified circuit of traction power supply system in AT mode

Assuming the train is in the second AT section, the simplified circuit in Figure 5. can be expressed as follows:

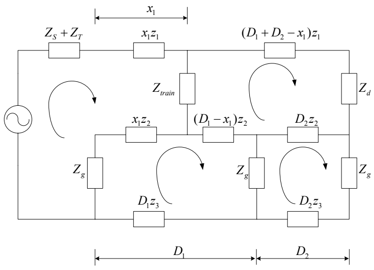


Figure 6. Catenary equivalent circuit with ice-melting equipment

According to Figure 6, the following equation can be established.

$$\begin{cases}(Z_S+Z_T+x_1z_1+Z_{train})\dot{I}_1-Z_{train}\dot{I}_2-(x_1z_2+Z_g)\dot{I}_3=27.5\text{kV}\\ -((D_1-x_1)z_2+Z_{train})\dot{I}_1+((D_1+D_2-x_1)(z_1+z_2)+Z_d+Z_{train})\dot{I}_2-(D_1-x_1)z_2\dot{I}_3-D_2z_2\dot{I}_4=0\\ ((D_1-x_1)z_2+Z_g+D_1z_3)\dot{I}_1-(D_1-x_1)z_2\dot{I}_2+(D_1z_2+2Z_g+D_1z_3)\dot{I}_3-Z_g\dot{I}_4=0\\ -Z_g\dot{I}_1-D_2z_2\dot{I}_2-Z_g\dot{I}_3+(D_2z_2+2Z_g+D_2z_3)\dot{I}_4=0\end{cases}$$

Where Zs is the system impedance; Z_T is the tranformer impedance; Z1 is the equivalent catenary impedance; Z2 is the equivalent rail (earth) loop impedance; Z3 is the equivalent negative feeder impedance; Zd is the impedance of ice-melting device.

It can get the main electrical parameters by solving formula (1) in the state of ice-melting.

(3) The feasibility analysis of high-current ice-melting of the high-speed railway catenary

In the power system, high-current ice-melting scheme is often limited to the tranformer capacity of substation and difficult to implement[2]. Compared to it, the electrified railway has much smaller need of source capacity. Table 1 lists some high-current ice-melting power capacity of overhead line and catenary in power system.

Table 1. AC ice-melting power capacity of different wire (Ta=-5℃，di=10mm，va=5m/s，t=60min)

Wire combination	Idc(A)	Iac(A)	Sdc(kVA/km)	Qac(kvar/km)	Sac(kVA/km)
LGJ-4*400	4524	4490	378	2525	2553
LGJ-2-240	1531	1526	132	601	615
LGJ-400	1131	1123	95	631	638
LGJ-240	765	763	66	301	308
JTMH120+CTMH150	833	833	92	251	267

According to the calculation result in Table 1, the DC ice-melting power capacity needs 2.76MVA and the AC ice-melting power capacity needs 8.01MVA with the 30km feeding arms. The general high-speed railway power capacity can reach 25MVA (T section capacity) in China, which is higher than the ice-melting need. Thus, it is feasible for high-current ice-melting in high-speed railway catenary.

(4) Analysis of ice-melting current distribution in high-speed railway catenary

In the high-speed railway catenary system, contact line, catenary wire, messenger wire together constitute the flow path of the traction current. To achieve the object of high-current ice-melting, the wires must meet the carrying capacity needs. While adopting DC ice-melting, current distribution between wires only associate with wire resistance, which is easy that this paper only analyse the AC ice-melting scheme.

The high-speed railway catenary loop can always simplify the contact line and catenary wire current distribution to the schematic diagram in Figure 7. As in Figure 7, the size of current distribution between the contact line and catenary wire is inversely proportional to the leakage impedance respectively[5], while the messenger wire current is very low that can be ignored[1].

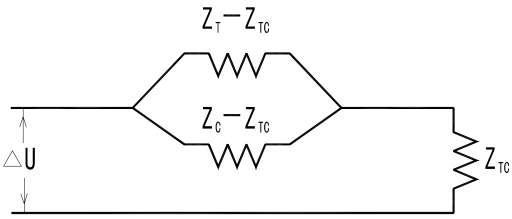


Figure 7. Current distribution diagram between contact line and catenary wire

According to the calculation of Figure 7, the current distribution diagram between contact line and catenary wire is shown in Table 2.

Table 2. Current distribution of commmon wire in High-speed railway

Chain suspension type	Current division ratio
JTMH120＋CTMH120	0.515/0.485
JTMH120＋CTMH 150	0.495/0.505
JTMH120＋CTMH 120＋LGJ240(reinforcedcore)	0.578/0.422(chain suspension/reinforcedcore)
JTMH120＋CTMH 150＋LGJ240(reinforcedcore)	0.564/0.436(chain suspension/reinforcedcore)

III. HIGH-CURRENT THERMAL ICE-MELTING PROGRAM IN HIGH-SPEED RAILWAY

According to the theoretical research on catenary wire high-current ice-melting, as long as a controlled current going through the catenary, we can achive high-current ice-melting of catenary. Basing on the differences of current standard in ice-melting loop, ice-melting includes AC and DC mode. The AC mode can also be divided into catenary-earth mode and up-down loop mode, which is based on the constitution of ice-melting loop; And the DC mode can be divided into three phase rectifier mode and single phase rectifier mode, which is based on the rectifier system.

Considering synthetically the needs of anti-icing, saving investment, compatibility with existing traction power supply system, the high-speed railway adopts “catenary-earth loop AC program”.

The high-current ice-melting program in high-speed railway is to connect the AC ice-melting equipment in series in the catenary-earth loop. The equipment consists of limiting resistor (inductor), control and protection system, catenary ice-coating online monitoring system, etc.

IV. ELECTRICAL ANALYSIS AND CALDULATION

A. Electrical Analysis

On the basis of theoritical analysis, in order to get more comprehensive traction power supply system parameters on the state of ice-melting, it can use the Matlab/Simulink software to establish the traction power supply system model under the ice-melting state, including traction substation model, AT substation model, catenary model, locomotive power model, and ice-melting equipment model, etc.

B. Power Supply System Simulating Calculation under Ice-melting State

In the theoretical analysis and modeling calculation, there are no way to consider the real-time load changes while the locomotives are operating in the feeding arm. It can be sovled by adding ice-melting parameters which is using the simulation software. Taking high-speed railway for example, after setting the ice-melting equipment in the section post, the catenary voltage and locomotive voltage simulating results are shown in Figure 8 and Figure 9, while only one train is operating on the feeding arm. From the simulating results, it can meet the need of one train operation after connecting ice-melting in series at the catenary end.

While there is one train operating on the feeding arm, the catenary current and ice-melting equipment current simulating results are shown in Figure 10 and Figure 11. The results show that the maximum current of ice-melting equipment is 838A, and the maximum power is 22.62MVA.

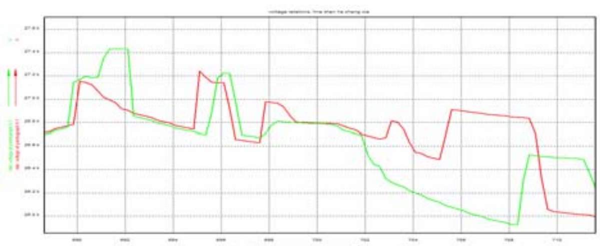


Figure 8. Voltage distribution of catenary

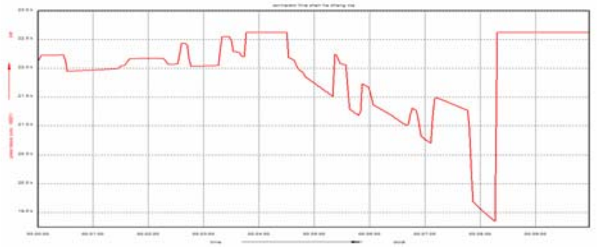


Figure 9. Voltage distribution of locomotive

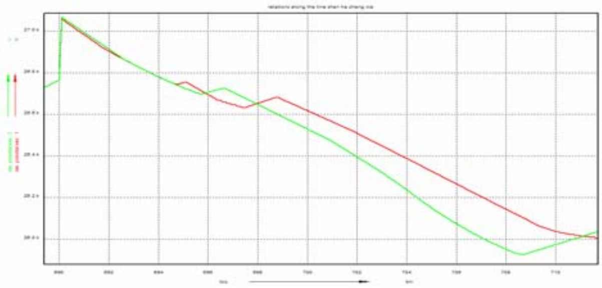


Figure 10. Ice-melting current

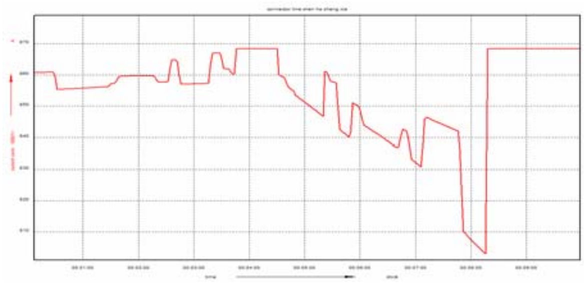


Figure 11. Ice-melting power

C. Experimentation

In order to confirm the feasibility of AC anti-icing (ice-melting), we conducted a preliminary field test in domestic electrified railway. Table 5 is the electrical parameters of traction power supply system, and Table 6 is the current through ice-melting equipment.

Table 5. Measured value and calculated value of the electrical parameters of traction power supply system

Test site	Test factor	Measured value	Calculated value
Traction substation	T line	417	387
	F line	356	387
AT substation	T line	469	426
	F line	312	349

Table 6. Measured value and calculated value of the current through ice-melting equipment

Serial number	Measured value	Calculated value
1	769	773.96
2	764	773.96
3	754	773.96
4	749	773.96
5	744	773.96

Table 5 and Table 6 show that the measured value is basically the same with the calculated value. The accordance between the measured results and theoretical calculation proof the correctness of high-speed railway anti-icing (ice-melting) program.

V. Conclusion And Recommendations

From the systematic study of the high-speed railway anti-icing (ice-melting) theory and corresponding measures, besides the accordance between the measured results and theoretical calculation, it comes to the following conclusions:

(1)The catenary structure of electrified railway is special to electrical power line. Despite the same ice-coating and ice-melting principle, differences are existed that can't be simply applied.

(2)The ice-coating on catenary is harmful to the safety operation of high-speed railway, and it is hard to anti-icing (ice-melting). Using the high-current thermal ice-melting technology can achieve not only perfect results, but also avoid the affection to the catenary performance. The technology is safe and reliable, and greatly reduces impacts to the high-speed railway operation.

(3)The DC or AC methods both are feasible. Considering factors like difficulties of project implement, impacts of railway operation and so on, it is one of the best ice-melting program that access the limiting devices at the end of feeding arm, and providing power by the traction transformer.

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These conclusions apply not only to anti-icing (ice-melting) of high-speed railway catenary, but also to the similar engineer like normal-speed railway and urban mass transit.

Considering the appliance of current anti-icing (ice-melting) technology is not yet mature, therefore recommending that: ① Speeding up the process of field test and analysing systematically to the test data, to verified the contact line anti-icing (ice-melting) theory and optimize the mathematical model; ② Summarizing the experience of field trail, optimizing the anti-icing (ice-melting) system program, to generate practical and reliable anti-icing (ice-melting) products; ③ Unified studying the prevention-treatment and safe operational management measures, which combine of high-current anti-icing (ice-melting) with mechanical ice-breaking and nature passive de-icing, to meet the demand for safe operation of electrified railway and promote widely application of catenary anti-icing (ice-melting) technology in the electrified railway.

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