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Research Article

Analysis of Electrochemical Corrosion in Traction Motor's Bearings Considering Overvoltage and Stray Current in High-Speed Trains

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ABSTRACT

The electrochemical corrosion of traction motor bearings is a critical issue in high-speed rail systems. The over-voltage caused by over-phase and on-board vacuum circuit breaker (VCB) opening and closing of the high-speed train will be spread to the traction motor through the coupling of the car body, bogie frame, etc.,. It makes the shaft end of the traction motor to the motor shell voltage rise significantly for a long time, which will cause serious electrochemical corrosion of motor bearings. In this paper, the mechanism of the electrochemical corrosion of traction motor bearings is studied. It is of great engineering significance to reduce the risk of bearing corrosion and improve the operating environment of traction motors. The principle is analyzed, and the overvoltage corrosion model of the traction motor bearing during train phase separation is established. The simulation data and the measured data are verified to show the model's reliability. It found that the change of train protective grounding mode has a great effect on the operating overvoltage propagating to the motor shaft. The findings provide insights into the damage mechanisms and influencing factors, contributing to the development of effective suppression techniques to extend the reliability and lifespan of bearings in high-speed train applications.

Keywords: Electrochemical corrosion, high-speed trains, stray current, traction motor bearings.

INTRODUCTION

The high-speed train's electrical power supply system operates through a 27.5 kV overhead contact line, with energy transfer achieved via sliding contact between the catenary and pantograph (Fig. 1). This high-voltage power is subsequently transmitted through dedicated cabling to the vehicle's traction transformer [1]. The system incorporates a dynamic grounding mechanism designed to safely return current to the rail network, a critical safety feature, especially during high-speed operation [2]. The current ultimately completes its circuit back to the traction substation through multiple parallel return paths comprising dedicated return conductors, running rails, and auxiliary grounding lines [3-5]. High-speed rail transit systems are critical for efficient and rapid urban and intercity transportation, requiring high reliability and minimal downtime to meet global passenger and freight demands. However, these systems frequently face challenges due to the high electrical and mechanical stresses imposed on their components, particularly bearings [6].

Bearings are essential for smooth mechanical performance, but they are prone to degeneration owing to electrochemical corrosion, particularly in settings with high voltage and stray electrical current [7]. Switching devices, power regulation problems, and electrical fluctuations all contribute to overvoltage in rail systems, causing unwanted electrical currents to flow through the bearings. When electrical currents pass through bearings, electrochemical processes occur that gradually wear down the material, resulting in structural damage, increased friction, and a loss of operational efficiency [8]. Electrochemical corrosion in bearings poses considerable hurdles to the maintenance and reliability of high-speed rail systems. Over time, corrosion can cause pitting, grooves, and surface wear, jeopardizing the bearings' structural integrity and mechanical performance [9]. The principal sources of this corrosion are stray electrical currents that penetrate the bearing assembly because of overvoltage. Inadequate insulation and grounding worsen the problem, causing currents to flow in unexpected directions within the bearing system [10]. This degradation not only reduces the lifespan of bearings but also increases maintenance costs, causes unexpected downtimes, and poses possible safety threats to train operations.

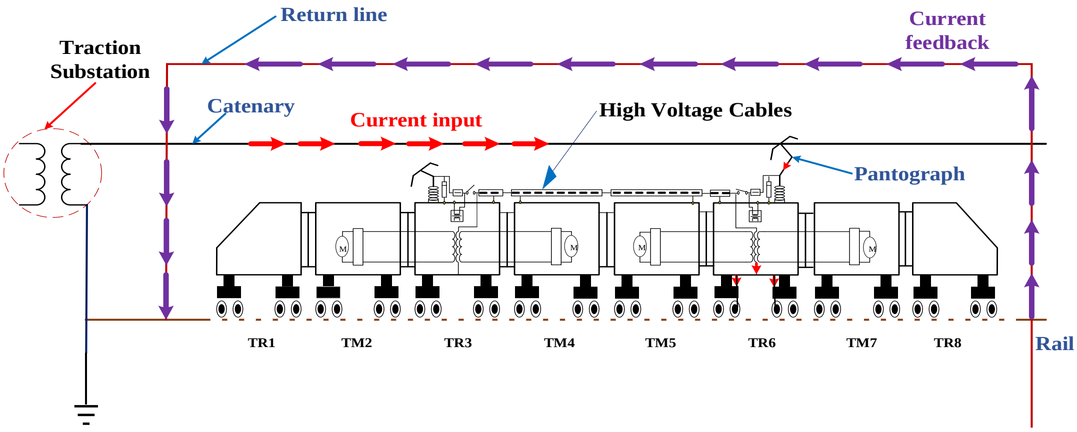

Figure 1: Operating principle of the high-speed train-power supply system.

During normal operation, traction current discharged through working grounding wheel sets may return to the train body via adjacent protective grounding wheel sets. This process generates a train body (TB) current that can subsequently leak through other protective grounding points back to the rail, establishing a circulating current path between the TB and rail. As demonstrated in [11], the trajectory of this circulating current exhibits transient fluctuations caused by dynamic variations in train-to-rail grounding impedance during motion. The 'train-rail' circumflux can lead to several adverse effects, such as long-term TB currents causing electrochemical corrosion in wheel bearings, grounding carbon brushes, and insulation joints on the rail [12], as illustrated in Fig. 2. Additionally, an elevated TB potential may interfere with or damage onboard sensors and low-voltage equipment [13]–[14]. These negative impacts can potentially compromise the safe operation of high-speed trains.

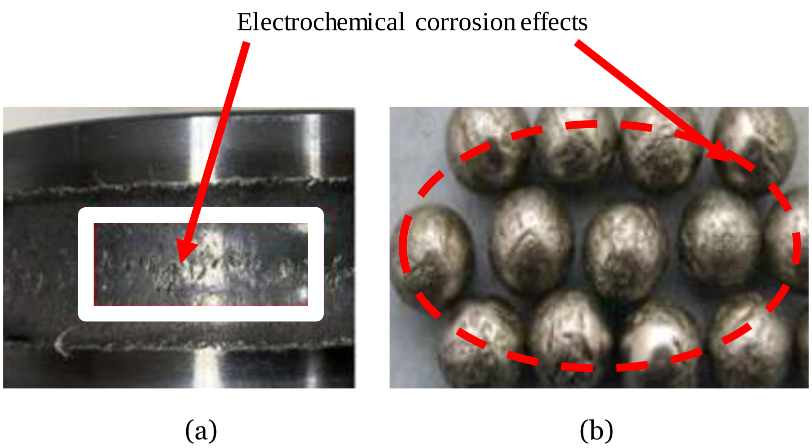

Figure 2: (a) shows the electrochemical corrosion on the inner ring of the bearing. (b) Electrochemical corrosion effects on balls.

The electrochemical corrosion of bearings due to stray currents is a major factor contributing to the premature failure of traction motor bearings in high-speed EMU trains [15]. The primary cause of bearing current is the potential difference between the inner and outer rings of the bearing, referred to as bearing voltage [16]. When this voltage

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surpasses the insulation threshold of the lubricating film, the film breaks down, leading to spark discharge and the formation of bearing currents.

However, limited research has been conducted to analyze the electrochemical corrosion mechanism of bearings, hence the need for further research. Previous research [17] systematically identified the primary causes of bearing failures in high-speed trains. The study developed two key models: First, an equivalent circuit model was created to simulate grounding coupling effects, incorporating measured impedance values from critical traction-power supply system components. Second, a complementary model analyzed the propagation pathways and frequency characteristics of grounding currents flowing through the train body.

With an emphasis on the effects of overvoltage and stray currents, this work attempts to present a thorough analysis of electrochemical corrosion in traction motor bearings of high-speed rail systems. This study aims to pinpoint important elements causing bearing deterioration by investigating the underlying mechanisms, operating conditions, and material interactions. The study also suggests efficient mitigation solutions, such as the use of corrosion-resistant materials, improved grounding techniques, and sophisticated insulating techniques. The results of this study will help create traction motor systems that are more dependable and effective, which will eventually improve the performance, safety, and longevity of high-speed rail operations.

STATIC STRUCTURAL ANALYSIS OF THE BEARING

Contact Area

Understanding the contact mechanics of bearings is crucial in high-speed train applications to assure dependability and performance. The contact area between rolling elements and raceways determines load distribution and stress concentrations, which are important in bearing design and analysis. [18] A dynamic model of high-speed train axle box bearings was developed to simulate variable-speed operating conditions. The model integrates key parameters, including contact stress and rotor mass eccentricity, enabling detailed analysis of bearing dynamic performance under real-world operational scenarios. Hertzian contact theory was employed to determine the contact geometry between bearing balls and raceways. As demonstrated in [19], this approach provides accurate calculations of ball-to-raceway contact surfaces characterized by elliptical contact areas with major a and minor b axis dimensions.

$$a = 0.02363a * \sqrt[3]{\frac{Q}{\Sigma\rho}} \quad (1)$$

$$b = 0.02363b * \sqrt[3]{\frac{Q}{\Sigma\rho}} \quad (2)$$

Q: is the maximum normal load.

$$Q = 5\frac{F_r}{Z} \quad (3)$$

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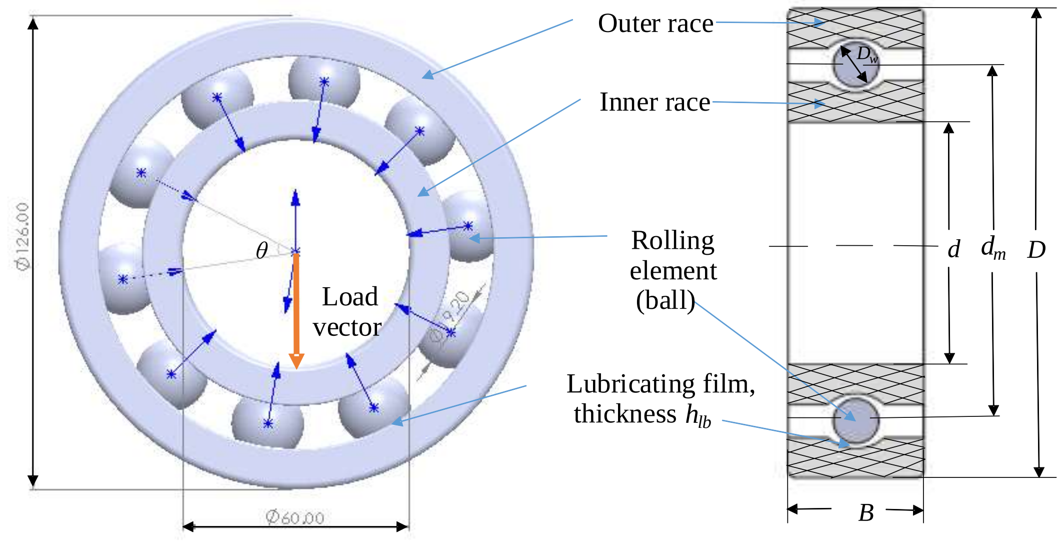

Figure 3: The traction motor bearing's geometry

The Operational Conditions and Features of the Lubrication Oil

Bearing discharge is the breaking of an oil film induced by an axial current during rotation. [20] The oil film's thickness changes with speed. The thickness of the oil film is a key consideration when evaluating bearing electrochemical corrosion. In this study, deep groove ball bearings are used, and the minimum oil film thickness between the steel ball and the raceway is evaluated using the following formula:

$$h_{ce} = 3.63\alpha^{0.49}\frac{(\eta v)^{0.68}R_x^{0.466}}{E^{0.117}Q^{0.073}}(1 - e^{-0.68K}) \tag{4}$$

The formula for determining the oil film thickness at the contact center h0 is as follows:

$$h_0 = 2.69\alpha^{0.53}\frac{(\eta v)^{0.67}R_x^{0.464}}{E^{0.117}Q^{0.073}}(1 - 0.61e^{-0.72K}) \tag{5}$$

Equations for calculating surface average velocity u and corresponding curvature radiusR_x:

$$v = \frac{\pi n}{120}d_m(1 - \gamma^2) \tag{6}$$

$$R_x = \frac{1}{2}D_w(1m\gamma) \tag{7}$$

Where D_w is the rolling element's diameter, γ is a dimensionless geometric parameter, and dm is the bearing pitch circle's diameter. The following formulae are used to determine the dimensionless geometric parameter γ and the ellipticity K:

$$\gamma = \frac{D_w \cos\alpha}{d_m} \tag{8}$$

$$K = 1.03\left(\frac{R_y}{R_x}\right)^{0.64} \tag{9}$$

Where R_y is the curvature radius equivalent in the axial plane, determined as follows:

$$R_y = \frac{R_1R_2}{R_2 - R_1} = \frac{f_jD_w}{2f_j - 1} \qquad (j = i, e) \tag{10}$$

Where R1 and R2 are the steel ball's radius and the ring groove curvature's radius, respectively, f_j is the coefficient of the groove curvature radius of the inner ring or outer ring.

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Substitute (6) and (7) into (4); under a stable state of operation of the bearings, the lubricating oil will be squeezed to form a uniform film. When the outer ring /inner ring and balls, raceway moves relatively, the minimum thickness of oil film is expressed as:

$$h_{ce} = 0.2207\alpha^{0.53}\frac{(\eta n d_m)^{0.68}D_w^{0.466}(1+\gamma)(1-\gamma)}{E^{0.117}Q^{0.073}}(1-e^{-0.68K}) \quad (11)$$

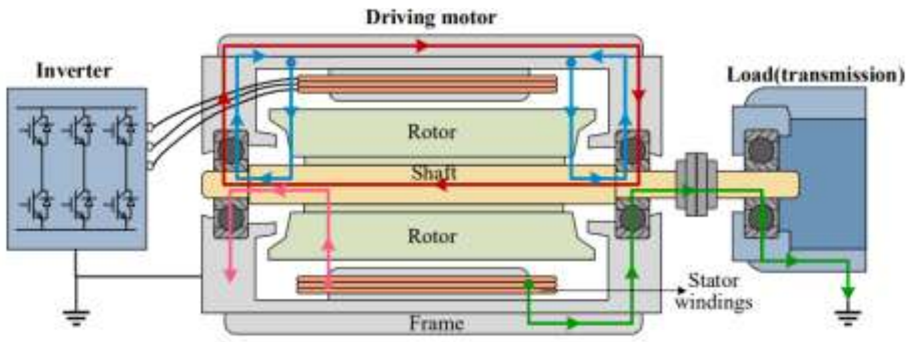
$$h_{ci} = 0.2207\alpha^{0.53}\frac{(\eta n d_m)^{0.68}D_w^{0.466}(1-\gamma)(1+\gamma)}{E^{0.117}Q^{0.073}}(1-e^{-0.68K}) \quad (12)$$

The performance and durability of traction motor bearings are impacted by operating circumstances and the qualities of the lubricating oil used. Temperature, load, speed, and climatic conditions can all have an impact on the lubricant's viscosity, thermal stability, and chemical composition, affecting the bearing's efficiency and wear properties. Additionally, the chemical makeup of the lubricant is critical in avoiding corrosion. Additives that suppress oxidation and corrosion can considerably extend bearing life, particularly under the high-speed and high-temperature conditions seen in traction motors.

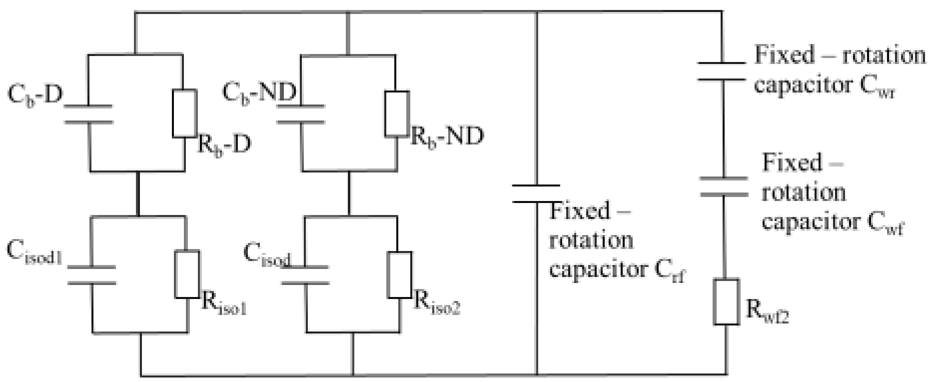
The Corrosion Evolutionary Process of Traction Motor Bearings

Bearings under long-term current erosion evolve in four stages such as normal mechanical wear, initial electrochemical corrosion, electrochemical corrosion expansion, and extensive electrochemical corrosion resulting in cracks and extremely rough balls, possibly fracturing the cage and invalidating the bearing.

The bearing currents appear within various drive systems such as Electrical-discharge machining (EDM) current, Circulating bearing current, Capacitive coupled ( ) current, and Rotor ground current as shown in figure 4.



(a)



(b)

Figure 4: representing the bearing, (a) the Stray currents flow paths, and (b) the Bearing circuit.

In a previous study [19], the common mode voltage is directly loaded between the stator windings and the motor casing.

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$$V_{bearing}^{\rightarrow} = V_{common}^{\rightarrow} \frac{C_{wr}}{C_{rf-b}+C_{wr}} \tag{13}$$

As shown above, the circuit modeling was completed based on the circuit analysis.

ANALYSIS OF THE ELECTRICAL DAMAGE MECHANISM OF THE TRACTION MOTOR BEARINGS

This chapter presents the development of a Simulink simulation model to analyze key parameters of high-speed train axles, including grounding voltage, grounding current, and bearing voltage under varying grounding configurations and conditions. To enhance model accuracy, field-measured impedance data for critical components of the traction-power supply system—such as train bodies, bogies, the catenary, and rails—are incorporated. As summarized in Table 1, the RCL high-frequency impedance analyzer is employed to measure the impedance characteristics of train bodies and grounding systems.

Table 1. Impedance parameters of the train body and grounding system.

Parameters	Values	Parameters	Values
Resistance R_c	4.45Ω	Resistance R_{link}	0.025Ω/km
Inductance L_c	35.7mH	Inductance L_{link}	0.812Mh/km
Resistance R_s	0.165Ω	Resistance of rail R_r	1.34Ω/km
Inductance L_s	10.8mH	Inductance of rail L_r	0.27mH/km

According to the literature, a rail in the ground reflux subsystem has a specific conductance and capacitance and capacitance to the ground, and the differential equation is applied to express the voltage between the rail and the ground.

$$\frac{\partial u(x,t)}{\partial x} R_{rail-ground} i(x,t) + L_{rail-ground} \frac{\partial i(x,t)}{\partial x} \tag{14}$$

$$\frac{\partial u(x,t)}{\partial t} = G_g u(x,t) + C_g \frac{\partial u(x,t)}{\partial t} \tag{15}$$

$$G_G = \frac{1}{R_g} \tag{16}$$

Where x is the distance between a given rail position and the point of origin (0). R_r and L_r denote the rail's unit resistance and unit inductance, respectively. Meanwhile, G_g and R_g correspond to the rail's conductance and resistance to the ground, while C_g signifies the rail's capacitance to the ground.

$$C_g = \frac{2\pi\varepsilon_0\varepsilon_1 l_{rail}}{\ln\left[2h/\left(r_{eq-rail}\sqrt{(2h/d)^2+1}\right)\right]} \tag{17}$$

In the train section, from top to bottom, there is a model of high-voltage equipment, a model of a carriage section, and a model of a grounding return system

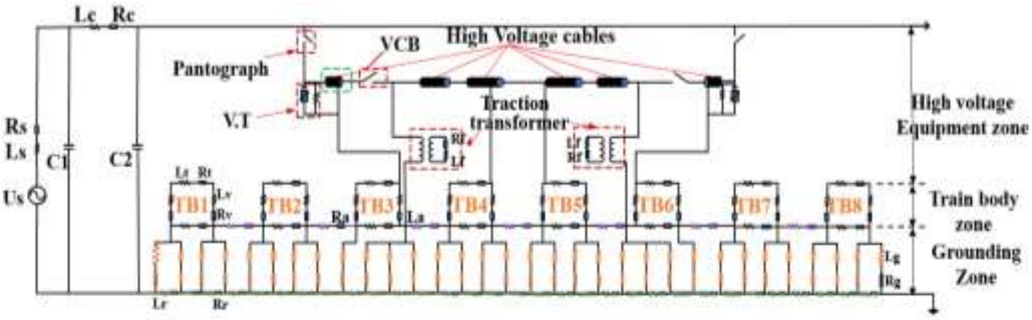

Figure 5. The traction-power supply system's simulation circuit model

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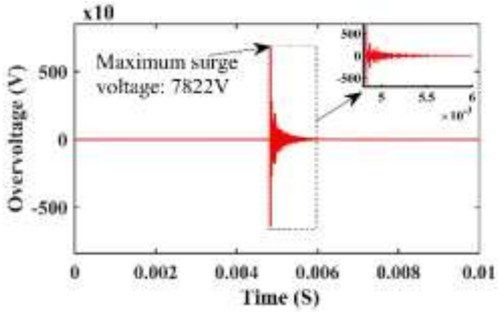
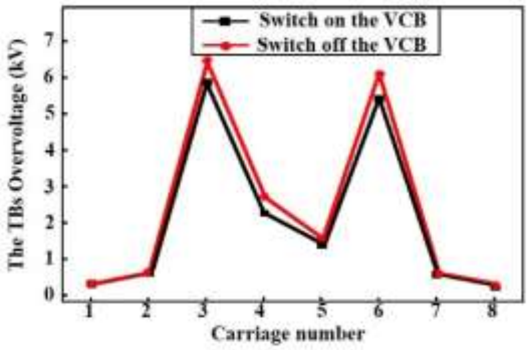
THE IMPACT ANALYSIS OF TRANSIENT OVERVOLTAGE ON BEARINGS

Evaluation of the protective grounding position's mechanism of effect on shaft voltage:

To ensure safe operation, neutral sections must separate adjacent power supply arms. When faults arise in the traction transformer, converters, or motors—causing abnormal voltage conditions—the onboard vacuum circuit breakers (VCBs) are triggered. Unlike traditional power systems with permanent grounding, each carriage's train body (TB) potential experiences transient fluctuations. These variations stem from changes in the impedance between the train and the rail and the train's dynamic movement. As shown in Fig. 5, carriages containing traction transformers and motors (TB3–TB6) feature grounding points that link the high-voltage cable shield to the roof of the train body. Electromagnetic induction between the high-voltage cable and the train body, combined with overvoltage discharge via the roof grounding points, causes a sharp increase in train body potential during VCB activation. Fig. 6 demonstrates this effect, displaying an overvoltage waveform at TB3 with a peak of 7.822 kV. The voltage decays at 50 Hz, lasting roughly two cycles.



(a)



(b)

Figure 6. The amplitude of TB overvoltage (a) when turning off the VCB at TB3, (b) at different carriages.

Therefore, these changing Capacitance parameters helped to know the main capacitance. As the Peak-to-peak shows, capacitor C1 is the main one where it has a lower peak-to-peak as well as Lower Voltage amplitude compared to C2 and C3.

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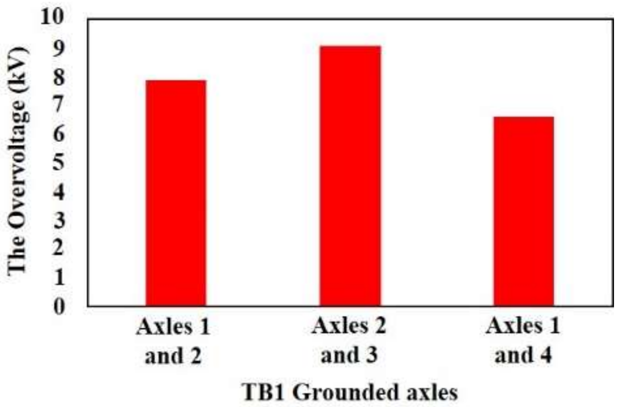
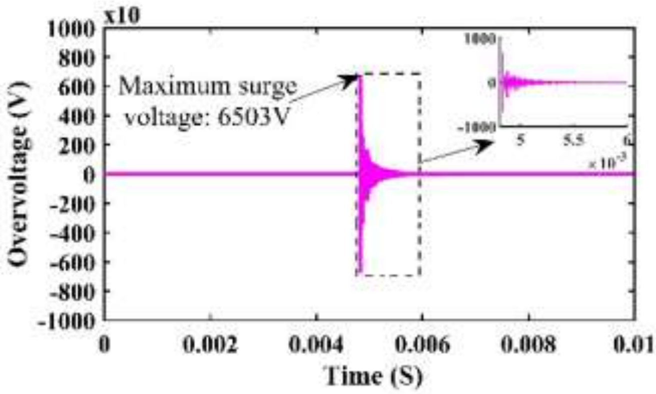


(a)



(b)

Figure 7. The Grounded Axles (a) Measured at TB3 (b) The TB3 Overvoltage amplitude of grounded Axles 1 and 4

According to the various iterations, when the first and fourth shafts are grounded, the voltage reflection at the end of the line can be decreased because the first shaft is grounded. However, when the first and second or second and third shafts are grounded, the first or fourth shaft's open circuit can result in violent end reflection and voltage superposition, which raises the amount of surge voltage coupling and ultimately damages the motor bearings. Therefore, the first and fourth grounding effects are better than the first and second or second and third grounding effects.

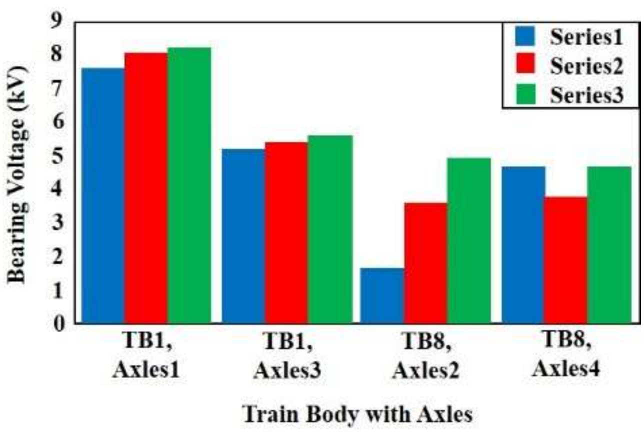


Figure 8. The overvoltage amplitude from grounding mode of the car body.

Raising the protective grounding point can also appropriately reduce the grounding current and the electrochemical corrosion of the traction motor bearings. Effective reduction of the grounding voltage's amplitude is possible when the grounding mode is switched from the two ends of the car body to the middle, resulting in a uniform grounding voltage. In addition, the electric field density distribution contour and magnetic field density distribution contour also show that increasing the number of protective grounding points can reduce the electric and magnetic field density of the axle part.

The findings emphasize the crucial role that grounding configurations play in preventing the flow of stray currents through the motor bearings, thereby reducing the risk of electrochemical degradation and ensuring the operational reliability of the bearings. with an emphasis on the role of surge arresters, grounding improvements, and filtering components in reducing overvoltage impacts.

CONCLUSION

This study examines the electrochemical corrosion of traction motor bearings in high-speed rail systems, with an emphasis on the negative impacts of overvoltage and stray currents. The study identifies major vulnerabilities in bearing design and operation by examining the interactions of electrical, chemical, and mechanical components. The findings lay the groundwork for improving bearing reliability, increasing operational efficiency, and ensuring safe rail transit operations.

(1) Understanding the Corrosion Mechanism. This study provides a complete understanding of electrochemical corrosion in rail transit bearings caused by overvoltage and stray currents. To identify early corrosion in high-speed rail, it establishes the foundation for predictive maintenance and sophisticated diagnostic systems by identifying critical elements such as surface pitting, grooves, and wear patterns.

(2) Framework for Mitigation Strategies. Using corrosion-resistant materials, improved grounding systems, and sophisticated insulation techniques, the study creates a workable framework for preventing corrosion. These suggestions offer practical engineering answers for creating robust bearing systems and improving operational effectiveness.

(3) Improving Rail System Reliability. The research enhances the safety and Reliability of high-speed rail systems by tackling corrosion issues. By extending the bearing lifespan, lowering maintenance requirements, and improving system performance, the suggested solutions help make rail operations safer and more energy-efficient. Future studies should look into the integration of improved monitoring systems as well as the use of innovative materials to reduce corrosion hazards, extend bearing lifespan, and assure reliable rail transit operation.

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