MITIGATION STRATEGIES FOR BEARING CURRENTS IN HIGH-SPEED TRAIN TRACTION MOTORS

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Abstract*:* A major reliability concern is the mitigation strategies of traction motor bearings in high-speed trains, which are caused by bearing currents induced by train operations and electrical conditions. Bearing currents occur when voltage differences overcome the insulating effect of bearing lubrication, resulting in electric discharge machining (EDM) of the bearing surfaces and premature wear. In order to preserve bearings and increase motor longevity, mitigation techniques concentrate on lowering or rerouting these currents. Important strategies include installing shaft grounding brushes to safely channel currents away from sensitive components, employing insulated bearings to prevent current passage through the bearing race, and strengthening the bonding and grounding of motor frames and related systems to provide low-impedance pathways for fault currents. For larger power motors, common-mode filters can also be used to lower common-mode voltages that can cause bearing currents. Because high-speed trains have a variety of operating conditions and motor designs, a combination of these techniques is frequently needed for effective mitigation. In high-speed rail applications, the risk of bearing damage can be considerably decreased, and traction motor reliability can be increased by understanding the electrical and mechanical interaction mechanisms in conjunction with appropriate design and maintenance procedures.

Keywords: Railway traction, insulated bearings, shaft grounding rings, conductive grease, traction motors, permanent magnet synchronous motors, high-speed rail, pulse-width modulation, inverters, mitigation strategies, electrical discharge machining.

I. INTRODUCTION

This Research into high-speed train motor bearing current mitigation strategies is motivated by the damaging effects of high-frequency currents caused by PWM inverters, which degrade bearings and shorten their lifespan[1]. The motor winding, rotor, frame, bearing rollers, and raceways act as capacitive electrodes, which form a coupling capacitance in the motor and provide a grounding path for the common-mode voltage[2]. Several attempts have been made to mitigate the negative impact brought by the TB current. As an example, a scheme was proposed to connect a resistance in series with the protective grounding ends to restrain the flow of the stray current from the protective grounding points to the rain body, as shown in Figure 1[3]. 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 [4]. Under normal operation, the bearing's lubricating grease acts as an insulator, but the oil film can break down if the shaft voltage becomes too high. When this happens, the electrical current arcs through the bearing to find a path to ground, bypassing the motor's normal grounding.

Failures brought on by bearing currents result in significant mechanical damage to electrical machines, which causes expensive maintenance and operational costs[5]. Sundaresan studied the analysis, measurement, and mitigation methods for bearing current-related bearing failures in inverter inverter-supplied motor[6]. The authors offer an in-depth overview of bearing currents, focusing on practical and simple approaches for mitigating bearing current in conventional PWM inverter drives, such as inverter output filters and insulated bearings, without considering mitigation methods that require hardware and motor modifications[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]. However, since the birth of motors, there has been the problem of bearing current. Particularly, the widespread use of PWM inverter-driven motors exacerbates the problem of bearing current [9].

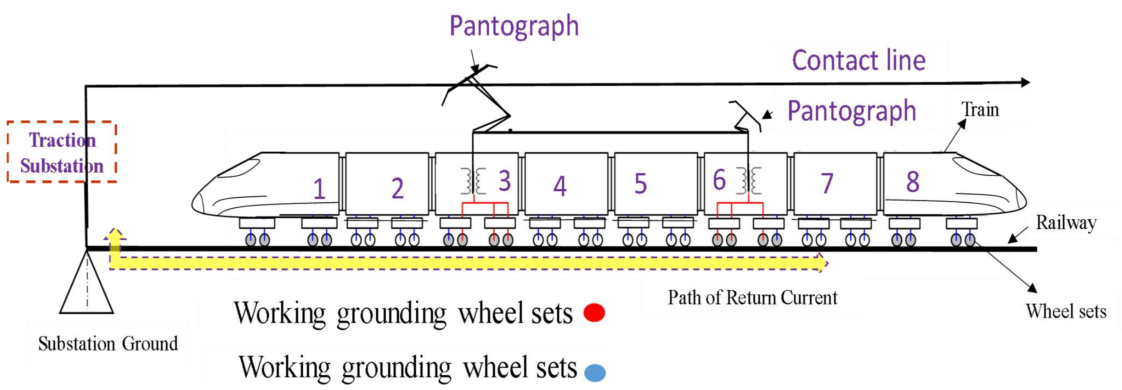


Figure 1: The structure of the 8-unit train with the grounding scheme.

[10] The diagnostic procedures are diverse. The criteria for choosing an approach depend essentially on the information that the person wishes to acquire about the system and the complexity of the system itself[11]. Generally, an AC motor is driven by a DC-to-AC converter equipped with a speed sensor; however, this speed sensor may tend to lower the system's reliability and increase the investment cost. Moreover, its implementation is difficult. To conquer this difficulty, many researchers focus on sensorless induction motor drives[12]. Under feedback conditions, various speeds and production were contrasted under internal parameter variation and external disturbances. It was reached that the staging of the model reference adaptive system (MRAS) has the upper hand over variant speed estimators [13]. The generated EMI can affect the power source grid and the elements connected to it, for instance, sensors and safety systems in electric cars [14]. Time-domain analysis extracts fault features by calculating statistical parameters such as the kurtosis, crest factor, skewness, and probability density curve [15].

II. STATIC STRUCTURAL ANALYSIS OF THE BEARING

In high-speed train applications, reliability and performance depend on an understanding of bearing contact mechanics. Stress concentrations and load distribution are determined by the contact area between rolling elements and raceways, and these factors are crucial for bearing design and analysis. An essential method in mechanical engineering and finite element analysis (FEA) is static structural analysis, which assesses how a structure, like a bearing, responds to constant (non-time-varying) loads and circumstances. Statistical analysis assumes that the structure is in a balanced state

Where forces and moments are not changing over time, in contrast to dynamic analysis, which takes into account time-dependent forces like vibrations or impacts. When this voltage surpasses the insulation threshold of the lubricating film, the film breaks down, leading to spark discharge and the formation of bearing currents [16]. 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 [17]. This approach provides accurate calculations of ball-to-raceway contact surfaces characterized by elliptical contact areas with major a and minor b axis dimensions.

$$\alpha = 0.02363\alpha * \sqrt[3]{\frac{Q}{\sum p}} \qquad (1)$$

$$b = 0.02363b * \sqrt[3]{\frac{Q}{\sum p}} \qquad (2)$$

Q is the maximum normal load

∑p is the total of the parameters that determine the distribution of contact pressure.

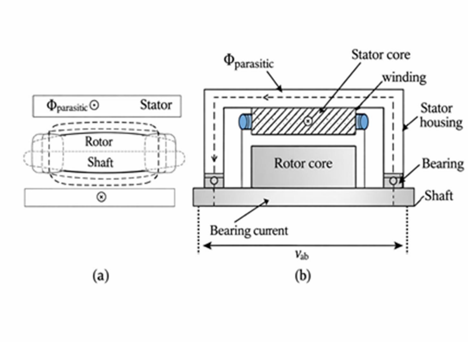
$$Q = 5Fr/Z \quad (3)$$

Fr is the bearing's total radial load.

Z is the quantity of rolling components (balls or rollers).

The nonstationary signal processing method using computed order analysis and the weak signal enhancement method using adaptive stochastic resonance both show good performances for the above problems. Inspired by these, a hybrid diagnosis strategy for motor bearings under these speed conditions is proposed. Firstly, the nonstationary fault signals of the motor bearing are transformed into stationary angular signals via computed order analysis[18]. The author Alger pointed out in the literature that bearing currents also occur in conventional AC-powered motors. The main reason for this is that errors in the motor's mechanical parameters, such as rotor eccentricity, winding asymmetry, etc., lead to asymmetric magnetic flux. As shown in Figure 2a, the asymmetric magnetic flux $P_{arasitic}$ will induce shaft voltage v_{sh} on both sides of the shaft. When the shaft voltage generated by the asymmetric magnetic flux is greater than the threshold that the system can withstand, a circulating current will be generated in the motor system. This type of current is called circulating shaft current, and its main flow path is "drive end bearing-motor shaft-non-drive end bearing-stator housing," as shown in Figure 2 b

[19]. The high-frequency LPM models are developed for many purposes in the literature. For example, to analyze the influence of the winding placement and the winding connection on the bearing currents[20], as shown in Figure 2



(a) The tangential magnetic flux
(b) Bearing current flow path.

Figure 2: The voltage induced at both ends of the shaft due to the tangential magnetic flux

The primary cause of bearing current is the potential difference between the inner and outer rings of the bearing, referred to as bearing voltage [21]. With the extensive use of pulse width modulation (PWM) inverters in electric motors, the occurrence of bearing current in the motor has become non-negligible.

III.THE OPERATIONAL CONDITIONS AND FEATURES OF THE LUBRICATION

Lubricating oil is not composed of a single component. Several key elements work together in its formulation to produce the best outcomes. The two main components are base oil and additives. Base oil makes up between 70- 90% percent of the lubricating oil's overall composition. This base oil is typically derived from crude petroleum, also known as mineral oil. The characteristics of the base oil primarily determine the viscosity, boiling point, and thermal stability of the lubricant. Because it influences how well the lubricating oil can tolerate high temperatures, high pressures, and demanding workloads, the quality of the base oil is crucial.

Lubricating oil contains additives to improve its performance in addition to the base oil. Despite being added in tiny amounts, these additives serve important purposes like.

- Preventing Oxidation: Preventing the lubricant from degrading as a result of exposure to air.
- Reducing Wear: To avoid direct friction, a protective film is formed on machine surfaces.
- Improving Thermal Stability: Making the oil more resilient to high temperatures.
- Reducing Deposit Formation: Stopping deposits from accumulating inside the engine.

These additives prolong the life of machinery and equipment while enabling lubricating oil to function under more demanding circumstances.

According to its definition, preventive maintenance can assist maintenance specialists in planning time-based tasks and specified intervals. The recommended intervals for changing lubricants (usually after 500 hours or 5000 km) will be specified in any maintenance manual. Nonetheless, a certain amount of lubricant loss may be anticipated over the system's lifetime, depending on the system. Therefore, by injecting new oil or grease (with new additives) and keeping the necessary reservoir levels, lubrication intervals can help avoid unneeded downtime.

The voltage across the contacts may increase abruptly when a VCB cuts off current, as

$$V = L\frac{di}{dt} \quad (4)$$

V is the induced voltage in volts.

L = Henry's inductance

Dt/di = rate at which current changes over time

An LC resonance circuit can be used to model the transient oscillation.

$$V(t) = Voe \;- \varsigma\omega ot\ \sin(\omega dt) \qquad (5)$$

V (t) is the voltage at time t.

V V 0 = starting voltage, or initial amplitude

$e\ -\zeta\omega\ 0\ t$ e −ζω 0 t = damping (exponential decay factor)

ζζ = damping ratio (the rate at which oscillations stop)

ω 0 ω 0 = the LC circuit's natural angular frequency.

IV. THE MITIGATION STRATEGIES EVOLUTIONARY PROCESS OF TRACTION MOTORS BEARINGS

In electric rail-trains, trains, and trams, traction motor bearings are essential parts. Extreme conditions are present in their operations: hefty loads, fast speeds. The bearing races are pitted and damaged by Electrical Discharge Machining (EDM), which is brought on by electrical stresses and stray currents. Temperature fluctuations: from chilly beginnings to hot running temperatures.
According to Figure 3, the bearing currents can be found in a variety of drive systems, including circulating bearing current,

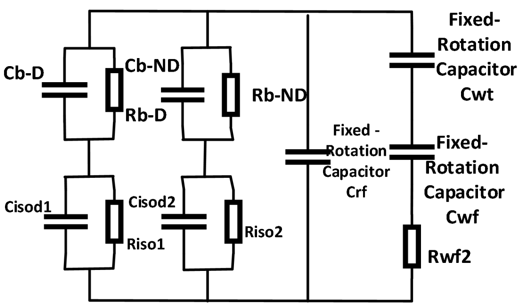


Figure 3: The bearing circuit

It will lead to corrosion damage to the bearing, shortening the motor service life and consequently causing motor failure [22]. Also pointed out that the increase in switching frequency of the inverter increases the dv/dt current amplitude, but it has a nonlinear effect on the current discharge frequency of EDM. It is surmised that the increase in switching frequency may increase the common-mode voltage amplitude and the electric field of the oil film. Measured the influence of cable shielding on EDM currents, high-frequency circulating currents, and rotor ground currents, and found that using shielded cables only affects the high-frequency circulating currents of large motors[23]. Measured the influence of cable shielding on EDM currents, high-frequency circulating currents, and rotor ground currents, and found that using shielded cables only affects the high-frequency circulating currents of large motors. Because of the long cable voltage reflection phenomena and the asymmetry of the long cable, the motor bearings may be exposed to higher voltages, increasing the risk of bearing current damage[24].

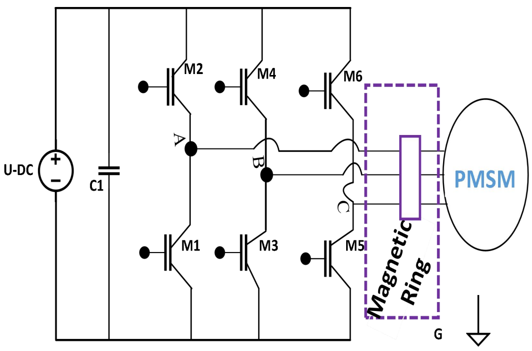
V. ANALYSIS OF THE ELECTRICAL DAMAGE MECHANISM OF THE TRACTION MOTOR BEARINGS

Concern over electrical damage to these bearings is growing, particularly in contemporary systems that are driven by inverters or variable-frequency drives (VFDs). In contrast to mechanical wear caused by load or vibration, electrical damage results from unwanted currents or voltages passing through the bearings and causing deterioration. In high-speed applications, this may result in increased noise-vibration-harshness (NVH), early failure, and safety hazards. Understanding causes, processes, effects, and evaluation techniques is necessary for this mechanism's analysis, which is frequently accomplished through modeling, simulation, and experiments.
The contact points between the outer ring, inner ring, and rolling elements were where the typical pitting and crater-like damage in this study mostly happened. Previous studies have documented comparable damage patterns, demonstrating that the electrical voltage and current used during the experiments are directly responsible for the damage seen. An electrical current flowing through the thin layer of lubricant between the rolling elements and the raceways would cause the bearing damage to start. Because the lubricant film was not thick enough to completely insulate the contact surfaces under the low-speed conditions of this study, voltage was able to accumulate across the points of contact. An electrical discharge happened when the voltage was higher than the lubricant's breakdown threshold.

VI. THE IMPACT ANALYSIS OF TRANSIENT OVERVOLTAGE ON BEARING

These transients are mostly brought on by the Insulated-Gate Bipolar Transistors (IGBTs) high-speed switching when a motor is powered by an inverter. These switches generate the AC waveform for the motor by turning on and off in nanoseconds. Ringing and voltage reflections are caused by this amazing speed, as well as the capacitance and inductance of the lengthy cable that connects the inverter to the motor.

The stator and rotor of the motor are not electrically connected. Nevertheless, the motor internals are perceived as a network of these discharges that happen repeatedly at regular intervals as the motor shaft rotates, eventually joining the pits to create a characteristic fluted pattern that resembles grooves carved into the race. This is the traditional method for identifying EDM damage. The pitting and fluting destroy the perfectly smooth bearing surfaces. Increased noise and vibration, lubricant degradation, accelerated mechanical wear, and eventually total bearing seizure and motor failure are the results of this. As shown in Figure 4(a), the high-frequency common-mode voltage that the three-phase switches bridge is Phase A: M2 (upper) and M1 (lower); Phase B: M3 (lower) and M4 (upper); and Phase C: M6



(upper) and M5 (lower).

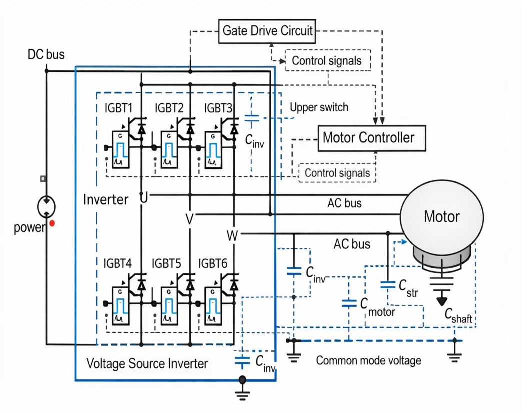
(a)

(b)

Figure 4 Schematic diagram of the motor drive system.

The DC bus and AC bus act as connection bridges between different components of the drive system. To enhance the system's electromagnetic compatibility (EMC), these buses are often shielded. The DC bus links the battery to the inverter, while the AC bus connects the inverter to the motor.

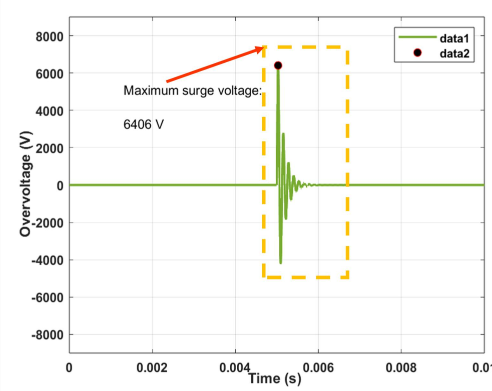
Analysis of the mechanism by which the protective



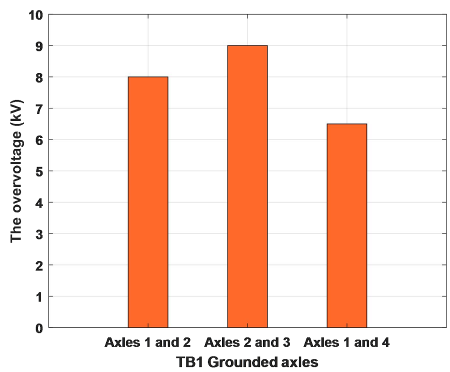
grounding position affects shaft voltage:

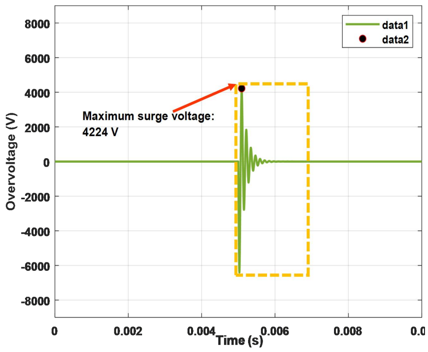
Unusual voltage conditions, caused by issues with the traction transformer, converters, or motors, trigger the activation of onboard vacuum circuit breakers (VCB). Electromagnetic induction between the high-voltage cable and the train body, and overvoltage discharge through the roof grounding points, because the train body's potential spikes during VCB activation. Figure 5 shows an overvoltage waveform at TB3, with a peak of 6.406 kV, and a mitigation technique of 4.224 KV, demonstrating this effect.

A larger VCB causes a higher surge (6406V) because of faster current interruption and higher dielectric recovery. The surge (4224V) is reduced by a smaller VCB because it produces a smoother interruption and more damping. The difference in surge voltage indicates that in systems with high-speed traction motors, transient overvoltage is significantly influenced by the size and design of VCBs. These surges need to be managed for bearing current mitigation, insulation life, and electromagnetic compatibility.



(a)Bigger VCB





(b) Smaller VCB

Figure 5: The amplitude of TB overvoltage

When turning off the strategies VCB at TB3.

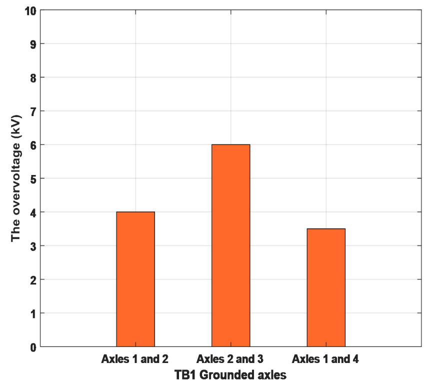
To control stray currents and voltages, grounding involves connecting particular axles to the train's electrical ground. However, incorrect setups can result in overvoltage that spreads throughout the system, as seen in Figure 6.

Since these overvoltage's can surpass the lubricating film's dielectric strength and cause spark discharges, stray currents, and electrochemical corrosion, they are essential for assessing electrical damage to traction motor bearings. Through pitting, fluting, and grease breakdown, this corrosion erodes the bearing surfaces, lowering the motor's lifespan and dependability in the end. The graphs most likely come from or resemble those found in research on electrochemical corrosion in traction motor bearings, where overvoltage transients couple to the motors via the train body, bogie, and axles (phase separations or vacuum circuit breaker (VCB) operations).

The pairs of grounded axles, namely Axles 1 and 2, Axles 2 and 3, and Axles 1 and 4, are labeled on the graphs. A distinct pattern can be seen in the red bars for each grounding configuration: the end pair (Axles 1 and 4) has the lowest overvoltage, while the middle pair (Axles 2 and 3) has the highest. This implies that while grounding the outermost axles (1 and 4) dampens voltage reflections and surges more effectively, grounding the adjacent middle axles increases them.

The scale of overvoltage in (a) and (b) differs; the former displays higher values, indicating a baseline or unmitigated scenario, while the latter displays lower values, possibly under an optimized grounding mode or under a different measurement condition. This is consistent with studies showing that changing grounding modes, like switching to middle grounding with elevated protective points or end-axle grounding, can lessen overvoltage and bearing damage.

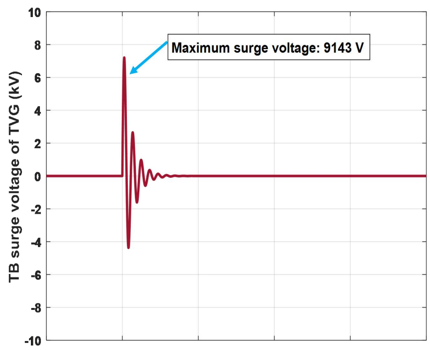
(a)



(b)

Figure 6: The Grounded Axles.

The waveforms of the TB voltage measured under the two mentioned typical conditions are presented in Figures 7(a) and 7(b), respectively. In the case of switching on the VCB, the maximum TB surge voltage reaches 9143 V. The maximum TB surge voltage is found to be 3379 V when the pantograph is raised, which appears to be much worse. For the comparison between the experimental and simulation results, the measuring points—as chosen in experiments—are selected to be the same as in the 'rail-train' coupling grounding model. Moreover, for comparison, the TB overvoltage under both conditions of raising the pantograph and switching on the VCB is captured based on the 'rail-train' coupling grounding model, as shown in Figures 7(a) and 7(b). It is found that the maximum values of the surge voltage obtained from experiments and simulations are similar.



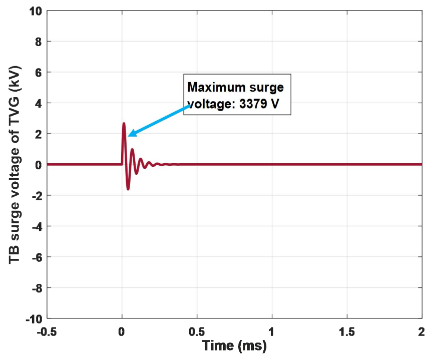
(a) The TB voltage surges when the VCB is switched on

(b) The rising pantograph's TB voltage surge.

Figure 7: The TB overvoltage's from the experiments

CONCLUSION

Common-mode voltages, high-frequency switching inverters, and inadequate grounding are the main causes of bearing current, a crucial reliability problem in high-speed train traction motors. These currents shorten the lifespan and efficiency of motors by causing electrical discharge machining (EDM), lubricant deterioration, and significant mechanical damage to bearings.



This study demonstrated that insulated bearings, common-mode filters or chokes, optimized grounding configurations, and shaft grounding techniques are all necessary for effective mitigation. Preventive maintenance and proper lubrication management are also important for reducing electrical damage and bearing wear.

While improper middle grounding increases voltage stress, grounding end axles (1 and 4) effectively reduces overvoltage amplitude, according to an analysis of transient overvoltage and grounding configurations. Additionally, the design of vacuum circuit breakers (VCBs) has a major impact on the magnitude of surges, which in turn affects insulation life and bearing safety.

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