Shaft Voltage and Current Phenomena in Turbo generators: Case Study of Post-Overhauling Bearing Anomaly at a 210 MW KWU Turbine Set

Case Study of Post-Overhauling Bearing Anomaly at a 210 MW KWU Turbine Set

Shobhan Kumar Malana, Suryabali
Sr. Manager, BHEL, Sr. Engineer, BHEL
Bharat Heavy Electricals Limited, Varanasi, India
shobhan@bhel.in, suryabali@bhel.in

Abstract— Shaft voltage and bearing currents represent critical reliability challenges for large-scale gubernators. Left unmanaged, these phenomena accelerate bearing degradation, trigger unplanned outages, and compromise machine longevity. This paper investigates the physical mechanisms of shaft voltage generation through a detailed case study of a 210 MW KWU-design turbine following a scheduled overhaul. By correlating electromagnetic, capacitive, magnetic, and electrostatic sources with field observations, this study proposes a robust framework of tiered operational thresholds. Findings indicate that voltages exceeding specific levels, when paired with leakage currents, serve as vital condition-monitoring indicators to prevent catastrophic failure The study demonstrates that voltages above certain level corelated with leakage currents can be an effective tool for condition monitoring, improving reliability and also preventing catastrophic failures. A framework of threshold zones is introduced, and future research recommendations include digital twins, AI-based predictive diagnostics, and advanced materials for grounding brushes. The findings support both immediate operational decision-making and longer-term design improvements for large synchronous machines [1,5&6].

Index Terms—shaft voltage, bearing current, electrical discharge damage, grounding brush, KWU turbine, turbogenerator reliability.

Nomenclature

EDD: Electrical Discharge Damage

EDM: Electrical Discharge Machining

SCC: Short-Circuit Condition

OCC: Open-Circuit Condition

LP / HP / LPT: Low/High Pressure, Low Pressure Turbine

IR: Insulation Resistance

EMF: Electromotive Force

FFT: Fast Fourier Transform

V: Shaft voltage (V)

I: Shaft current (A)

R: Resistance of grounding path (Ω)

List of Abbreviations

BHEL: Bharat Heavy Electricals Limited

NEMA: National Electrical Manufacturers Association

IEC: International Electrotechnical Commission

IEEE: Institute of Electrical and Electronics Engineers

I. Introduction

Turbogenerators are vital for modern electricity production, serving as the electromechanical interface between turbines and the electrical grid. Their performance and availability directly influence plant reliability and overall system stability. In large units, subtle degradation mechanisms often manifest as hidden threats, one of which is the development of shaft voltage and bearing currents [1,5&6]. These phenomena are insidious: they may remain undetected under steady-state operation, yet progressively erode bearing health until catastrophic failure occurs.

The consequences of unmanaged shaft voltage are severe. Discharge currents create microscopic craters in bearing metal, which coalesce into corrugated fluting patterns. Over time, vibration increases, oil film stability decreases, and sudden bearing seizure may occur [1,5&6]. Field reports confirm that such failures are costly, often requiring rotor removal, extensive re-metalling, and long outages.

Two operational phases are particularly critical: rolling (during machine run-up) and synchronization (when connecting to the grid). During rolling, shaft speed passes through resonance bands, amplifying induced voltages, while oil films are thin and fragile. During synchronization, sharp excitation surges and grid transients cause abrupt voltage spikes [1,5&6]. These conditions combine to create the highest risk periods for shaft current initiation.

Standards such as NEMA MG1 and IEC 60034-25 provide indicative shaft voltage limits, but these thresholds were derived mainly for small and medium rotating machines [1,5&6]. In practice, large synchronous generators (≥200 MW) experience shaft voltages well beyond these limits, underscoring the importance of developing unit-specific criteria as well as its correlation between the current discharged through the shaft grounding system which is critical to understand the machine health and determine its reliability.

This paper therefore addresses the knowledge gap by combining a mechanistic review with a detailed case study from a 210 MW KWU-design turbine. The objective is to provide an engineering framework that links physical mechanisms to real-world failure observations, defines threshold zones for monitoring, and outlines corrective and preventive strategies for long-term reliability.

II. Mechanisms of Shaft Voltage and Current

Shaft voltage is not the product of a single mechanism, but the cumulative outcome of electromagnetic, capacitive, magnetic, and electrostatic effects. Each source contributes uniquely depending on the machine design, excitation system, and operating environment [1,5&6]. The most important mechanisms are outlined below.

A. Electromagnetic Induction

Any asymmetry in the magnetic field across the rotor–stator air gap creates stray axial flux. When this flux links with the rotor shaft, Faraday’s law dictates that an electromotive force is induced. The induced voltage increases with both rotor speed and flux imbalance. Even small eccentricities in the rotor or variations in steel permeability can lead to voltages of several volts in large synchronous machines [1,5&6]. Harmonic components, particularly twice line frequency, are often observed and may resonate during acceleration. This may carry significant energy and a cause of concern.

B. Capacitive Coupling

The rotor, stator windings, and exciter system behave like a distributed capacitor. Any rapid switching in the excitation circuit—such as from thyristor or PWM-based exciters—produces steep voltage changes. These are capacitively coupled onto the shaft, producing spikes with rise times in the microsecond range. Although their energy is low, their ability to puncture thin lubricant films during low-speed rolling is significant [1,5&6].

C. Residual Magnetism and Stray Flux

Residual magnetization in rotor components, whether from prior operation or external disturbances like lightning, interacts with excitation fields to create unpredictable shaft voltages. These effects are especially pronounced during start-up and coast-down, when field interactions vary rapidly [1,5&6].

D. Electrostatic Charging from Steam Flow

Steam flow through turbine blading induces triboelectric charging on metallic surfaces. This effect is amplified under wet or contaminated steam conditions. In extreme cases, potentials of several kilovolts have been reported [1,5&6]. Without adequate grounding, such charges discharge through the bearings, producing severe electrical erosion.

E. Transition to Shaft Currents

Shaft currents occur once the shaft-to-ground potential exceeds the dielectric strength of the lubricant film. Typical breakdown voltages range between 0.5–15 V depending on oil condition and bearing geometry. Discharge paths follow shaft → bearing → housing → ground. Manifestations include electrostatic discharges (sporadic, high-frequency spikes), electrical discharge machining (repetitive arcing that creates micro-craters), and fluting (periodic erosion driven by harmonics and vibration) [1,5&6]. Discharge temperatures can exceed 2000 °C, permanently altering babbitt microstructure.

F. Critical Operating Phases

During rolling, induced voltages are amplified by resonant conditions while lubrication is weakest. During synchronization, voltage surges from excitation transients and grid mismatches create conditions for sudden discharge events [1,5&6]. Together, these mechanisms explain why shaft currents are so closely linked with start-up anomalies and synchronization failures.

II. Mathematical Modeling of Shaft Currents

1. Total Shaft Voltage Model

The total shaft-to-ground voltage is the summation of all transient and steady-state sources:

$$\boxed{V_s(t) = V_{\text{ind}}(t) + V_{\text{cap}}(t) + V_{\text{res}}(t) + V_{\text{es}}(t)}$$

are described as follows:

- ***$V_s(t)$* (Total Shaft-to-Ground Voltage):** The instantaneous potential difference between the rotor shaft and the machine ground at any given time t
- ***$V_{ind}(t)$*(Electromagnetic Induction):** Voltage induced by any magnetic asymmetry in the air gap or stray axial flux linking with the shaft. This typically manifests at 1× or 2× line frequency (50/100 Hz).
- ***$V_{cap}(t)$*(Capacitive Coupling):** High-frequency voltage spikes coupled onto the shaft through the distributed capacitance between the rotor, stator, and exciter system. This is often driven by rapid dv/dt switching in static excitation circuits.
- ***$V_{res}(t)$*(Residual Magnetism):** Voltage induced by the interaction of the rotor's residual magnetization with excitation fields, particularly significant during start-up or coast-down.
- ***$V_{es}(t)$* (Electrostatic Charging):** Potential generated by triboelectric charging due to steam flow through turbine blading. POTENTIALS can reach kilovolt-scale levels in cases of wet or contaminated steam.

When **Vs(t)** exceeds the dielectric strength of the lubricant film, it triggers shaft currents that follow a path through the bearings to the ground, leading to Electrical Discharge Machining (EDM) and pitting.

2. Equivalent Circuit and Current Flow

The shaft forms a voltage divider between the grounding path and the bearing oil film. The current diverted through the bearing (I_b) is critical:

$$\boxed{I_b(t) = \frac{V_s(t) \cdot Z_g}{Z_g + Z_b}}$$

- **Note:** If the grounding brush impedance (Z_g) increases due to wear or contamination, the current I_b through the bearing increases proportionally, leading to EDM.

3. Oil Film Breakdown and Energy

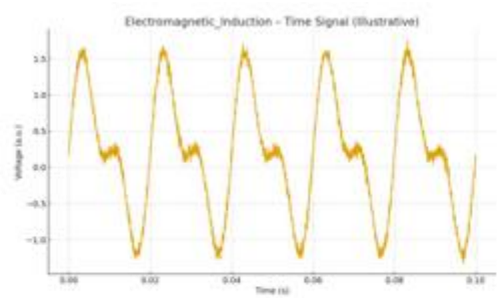
Dielectric breakdown occurs when the shaft voltage $V_s(t)$ exceeds the threshold (V_{bd}) defined by the oil film thickness (h_{oil})

$$V_s(t) > V_{\text{bd}} = \frac{E_{\text{bd}} \cdot h_{\text{oil}}}{\ln(1 + \frac{4h_{\text{oil}}}{d})}$$

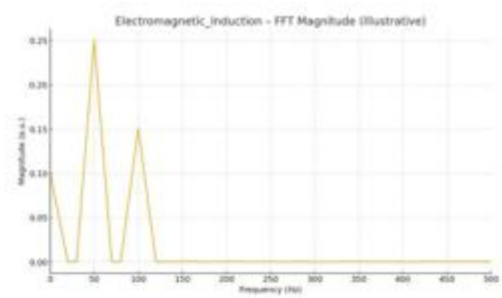
The energy released during a capacitive discharge (E_d)is:

$$E_d = \frac{1}{2} C_b [V_s(t)]^2$$

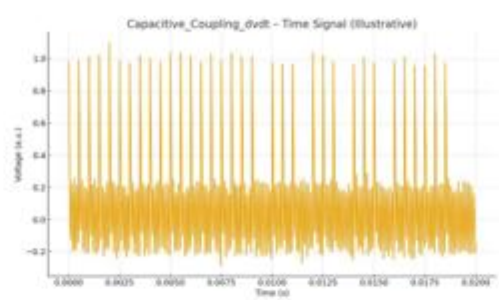
Pitting typically initiates when $E_d > 10^{-9}$ Joules.



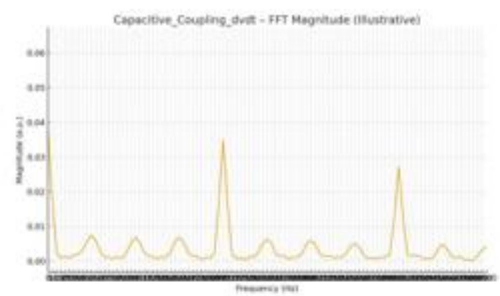
A: Electromagnetic induction — Time



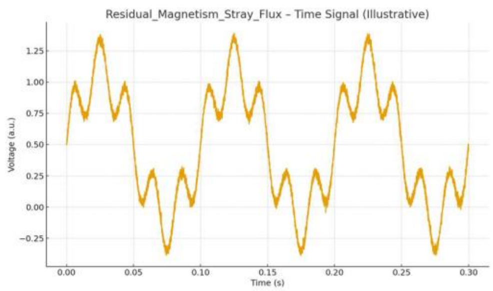
A: Electromagnetic induction — FFT (0–500 Hz, 50-Hz ticks)



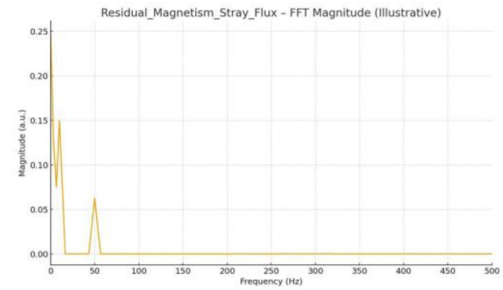
B: Capacitive coupling (dv/dt) — Time



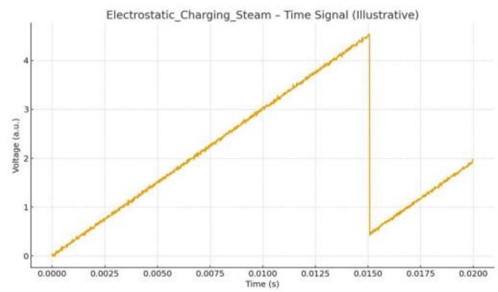
B: Capacitive coupling — FFT (0–5 kHz, 50-Hz ticks)



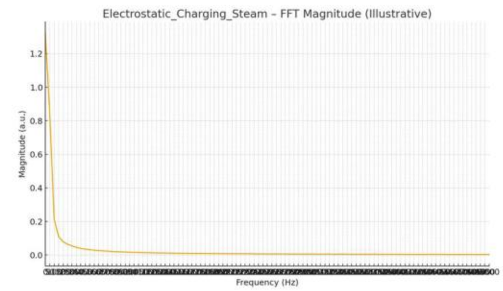
C: Residual magnetism/stray flux — Time



C: Residual magnetism/stray flux — FFT (0–500 Hz, 50-Hz ticks)



D: Electrostatic charging — Time



D: Electrostatic charging — FFT (0–5 kHz, 50-Hz ticks)

III. Case Study: Powerplant A (210 MW)

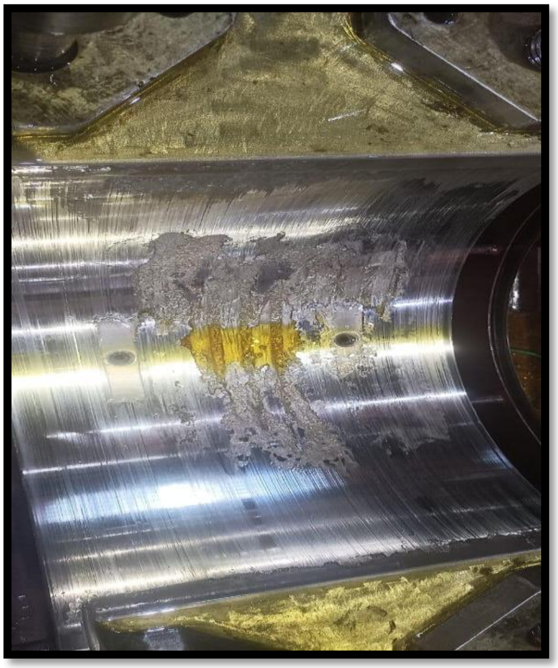
A unit of 210 MW Kwu Turbine, underwent scheduled overhaul and within 72 hours of synchronization, operators reported abnormal bearing vibrations and temperature excursions. The machine was forced to shut down, and a detailed post-shutdown inspection was initiated. This case study documents the observed defects, correlates them with shaft voltage/current measurements, and integrates findings with theoretical mechanisms [1,5&6].

A. Bearing Observations

Inspection revealed progressive damage across multiple bearings. Bearings 1 and 2 displayed moderate to severe rubbing and pitting, whereas Bearings 4 and 5 exhibited heavy white metal delamination and surface erosion. Localized discoloration and cratering patterns were consistent with electrical discharge damage (EDD). Bearing 3 showed superficial markings, suggesting uneven progression of the phenomenon [1,5&6].

B. Rotor and Casing Findings

The LP turbine rotor and blades showed no metallurgical cracks or structural failures. However, labyrinth seals exhibited rubbing marks, suggesting transient misalignment or casing distortion during operation. This rubbing was likely secondary/complementary to vibration induced by shaft voltage-related discharge currents [1,5&6].



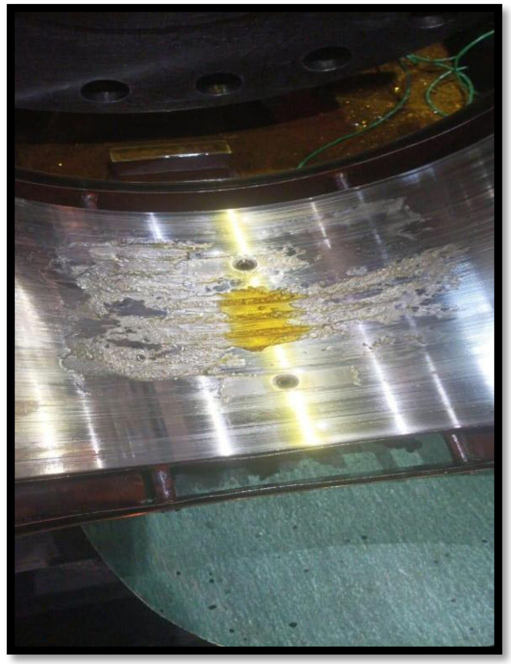


Figure 1: Severe babbitt damage on Bearing 5.

Figure 2: Babbitt wear and surface erosion on Bearing 4.

Figure 3: Electrical discharge markings at bearing torus support.

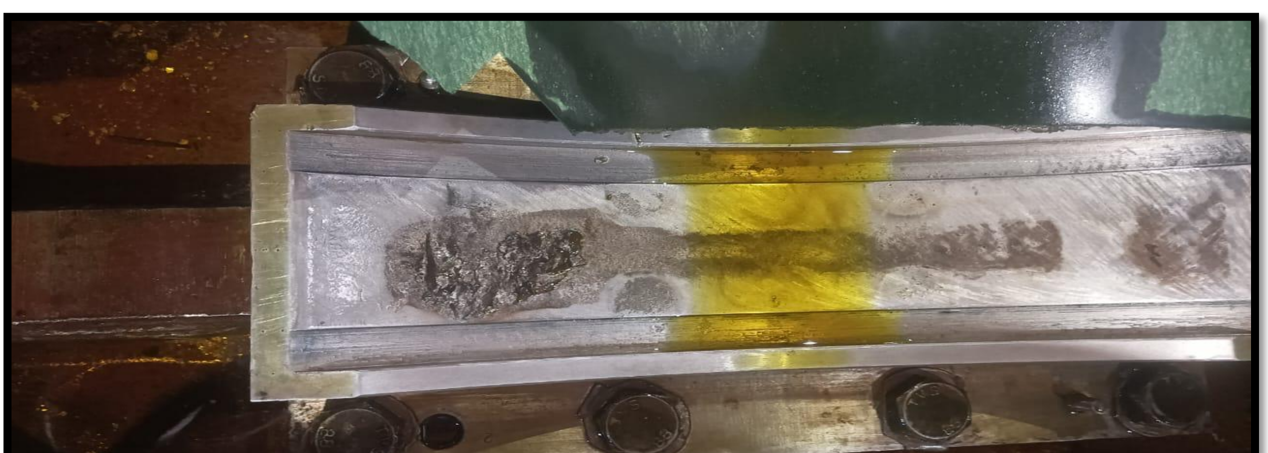


Figure 4: Bearing support showing discharge-induced wear.

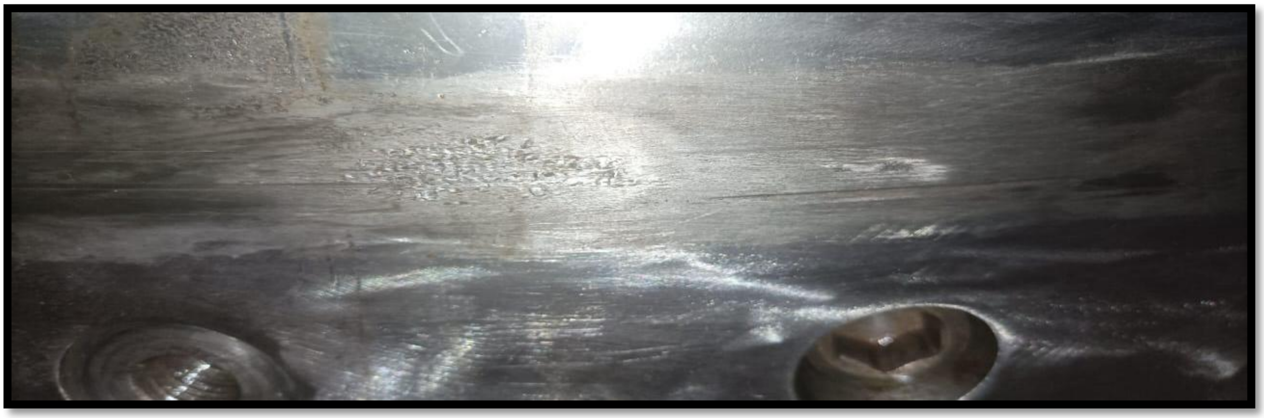


Figure 5: Bearing surface discoloration consistent with overheating and arcing.

Figure 6: Discharge evidence at torus contact surface.

C. Voltage–Current Measurements

During diagnostic testing, shaft voltage ranged between 3.6–6 V under rolling and increased further during short-circuit tests, with maximum recorded values approaching 11.2 V. Corresponding shaft currents rose proportionally, with a peak of ~976 mA under simulated 8000 A short-circuit current. Comparative analysis with similar 210 MW units (e.g., NTPC, Stateboards and other Utilities) confirmed that higher shaft voltages were strongly corelated with inadequate grounding and also due to combined effect of minor eccentric flux disturbances as the increase in leakage current corresponded with overall increase in stator current and less with voltage variation or load change.[1,5&6].

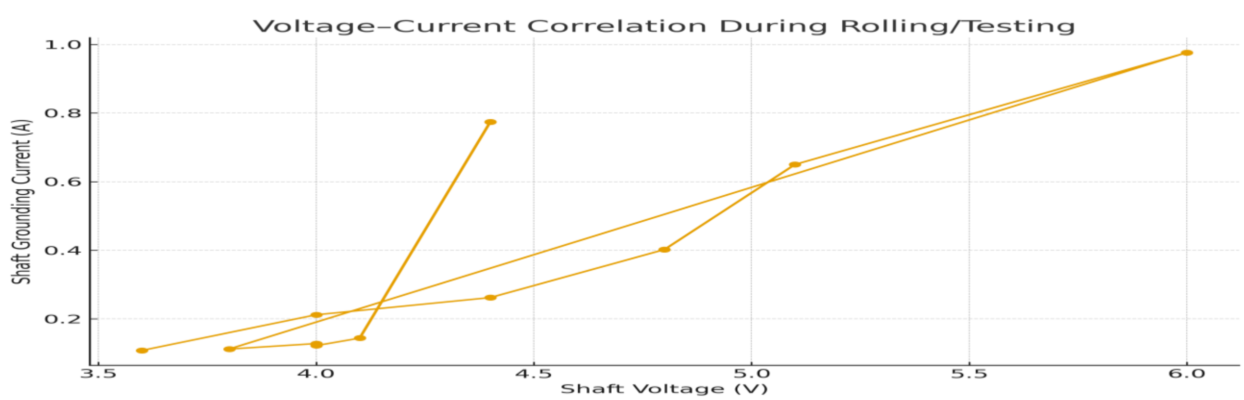


Figure 7: Shaft voltage–current correlation during rolling and test conditions at Referred **210 MW KWU-design turbine**.

The shaft voltage and current were regularly monitored and values noted in reference to machine synchronization and testing:

Sl. No.	Speed/Load/Condition	Measured Voltage	Grounding Currents w.r.t brush at turbine end	Remarks
1	Barring gear	NA		
2	3000 RPM	3.6 V	108 mA	
3	Excitation On	4 V	212 mA	
4	1000Amps	4.4 V	262 mA	SCC
5	2000 Amps	4.8 V	402 mA	SCC
6	4000 Amps	5.1 V	650 mA	SCC
7	8000 Amps	6 V	976 mA	SCC
8	1 KV	3.8 V	112 mA	OCC
9	5 KV	4 V	128 mA	OCC
10	10 KV	4V	122 mA	OCC
11	Synchronization	4.1 V	144 mA	
12	196 MW	4.4V	774 mA	

To establish context and draw comparisons, shaft-to-ground voltage and grounding current at the turbine-end grounding brush were measured on multiple units of similar rating at the same and other stations. Table 1 summarizes the steady-state values recorded near rated operating conditions of similar sets of same rating. (Names have been intentionally omitted)

Sl.No	Plant Name /Rating	Speed/Load/Condition	Measured Voltage	Grounding Currents w.r.t brush at turbine end	Remarks
1	Plant U (210 MW KWU)	120 Mw	3.8 V	89 mA	On Load
2	Plant V (210 MW KWU)	176 MW	3.9 V	93 mA	
3	Plant W (210 MW KWU)	183 MW	4.2V	102 mA	
4	Plant X (210 MW KWU)	207 MW	5.4 V	444 mA	
5	Plant Y (210 MW KWU)	198 MW	4.9 V	410 mA	

Mechanistic attribution and damage pathway

Composite origin. Correlating the measurements with known shaft-voltage mechanisms indicates a **multi-cause** origin. The **secondary driver** is consistent with **electromagnetic induction from magnetic asymmetry**, which produces axial stray-flux linkage and an EMF on the shaft (dominant **50/100 Hz** content with mild harmonic distortion). **Superimposed** on this are (i) **electrostatic charge accumulation** from steam-flow tribo-charging that releases as **impulsive discharges**, and (ii) **transient eccentricity/rubbing** during start-up/rolling that thins the oil film and distorts the waveform, raising the observed potential and effective severity.

Spectral discrimination. To isolate the excitation system as a source, the exciter and shaft-voltage waveforms were compared. The exciter showed a **pulsating DC component at 300 Hz** (6-pulse rectifier ripple), whereas the shaft-voltage spectrum **lacked a coherent 300 Hz line**, indicating that static-exciter ripple was **not** the dominant contributor under these conditions. With **stator loading**, a **low-amplitude, slowly varying AC influence** on the shaft voltage was detectable, but its magnitude remained small relative to the 50/100 Hz induction signature and impulsive events.

The major cause of damage was improper grounding that prevented the discharging through low resistance path and in turn forced the same to be mitigated through bearings causing electrical discharge, initiating EDM pitting/frosting and localized film breakdown/heat. The resulting stiction and micro-rubs increase vibration, further modulating air-gap asymmetry and promoting additional charging—a self-reinforcing loop creating a restriction in bearing free movement that resulted in heavy vibrations, these acted as a complement to rubbing caused in LP further fueling electrostatic charge and spiraling the effect to create the damage.

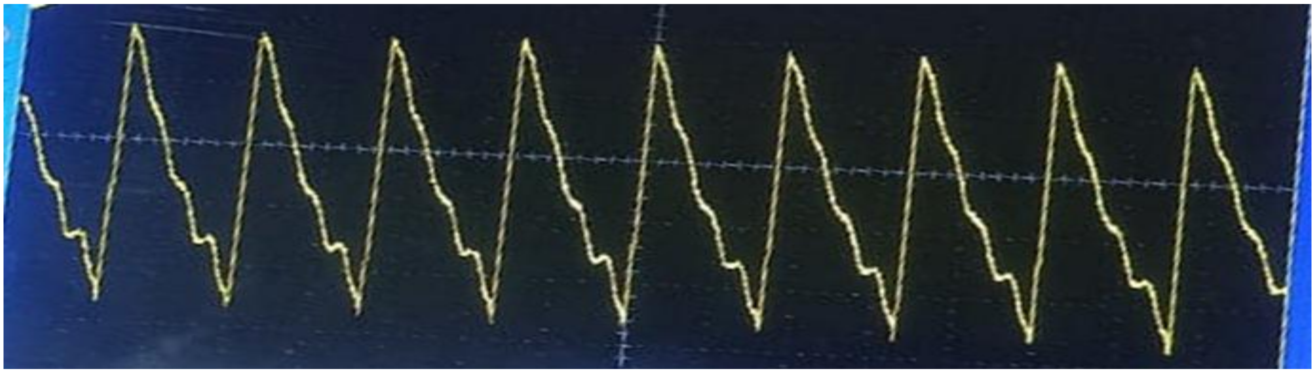


Figure 9: Pulsating Excitation Voltage 300 Hz

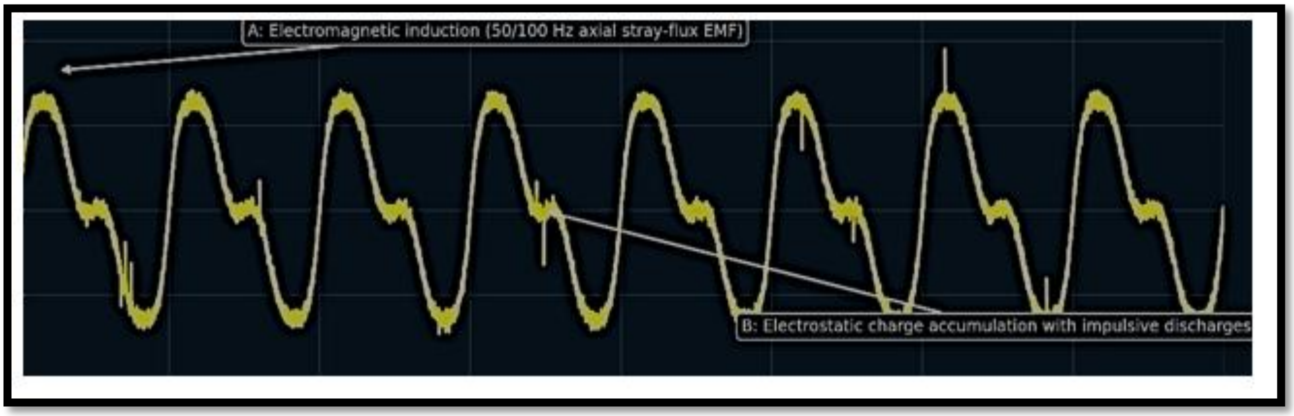


Figure 10: Developed voltage waveform

Voltage-Current Relationship in Shaft Grounding

When a shaft voltage develops between the rotor and earth, and a conductive path (like a grounding brush, bearing, or oil film) exists, a shaft current (I) flows according to Ohm's Law:

$$I = \frac{V}{R}$$

Where:

- I = Shaft current (A)
- V = Shaft voltage (V)
- R = Effective resistance of the path to ground (Ω)

Why Correlation Is Important

1. Higher voltage across a low-resistance path (e.g., lubricated bearing film) means significant current, which can cause:
   - Electrical Discharge Machining (EDM)
   - Bearing pitting
   - Coupling and shaft surface erosion
2. The current magnitude is a more direct indicator of damage potential than voltage alone.
3. By monitoring both voltage and current, one can establish critical thresholds for alarms or interlocks.

True nature of the relationship between shaft voltage and current, especially when **a shaft grounding brush is effective**:

Understanding the Inverse Behaviour

When a **shaft grounding brush** is in good condition (low resistance path to earth):

- **Voltage remains low**, because any induced charge is **quickly discharged**.
- **Current may still flow**, depending on the induced EMF and the continuity of the path.

This creates a situation where:

Effective grounding = Low Voltage + Possibly High Discharge Current

Inverse Observation in Practice

Grounding Brush Condition	Shaft Voltage (V)	Shaft Current (A)	Interpretation
Excellent	~1–5V	High (~.1–2.5 A)	Good discharge path
Worn or Dirty	~6–20 V	Low (<.05 A)	Current blocked, voltage builds up
Broken/Absent	>20 V	~0 A or erratic	Dangerous — voltage rising, no discharge

In **healthy grounding conditions**, an **inverse relationship** is established.

But this only holds **as long as the grounding path is linear and resistive**, and no high-frequency impedance effects distort the signal.

Why This Happens

- A clean brush has **low contact resistance** → shaft voltage gets clamped close to earth potential.
- A dirty or worn brush has **high contact resistance** → less current can flow → shaft voltage increases due to charge accumulation.

Practical Implication: Voltage-Critical, Current-Diagnostic

- **Shaft Voltage** is the primary danger indicator — even a low current can cause bearing damage **if voltage builds up across oil films**.
- **Shaft Current**, especially spikes or harmonics, is diagnostic — it tells **how well grounding is working**.

Measurement Correlation Curve (Conceptual)

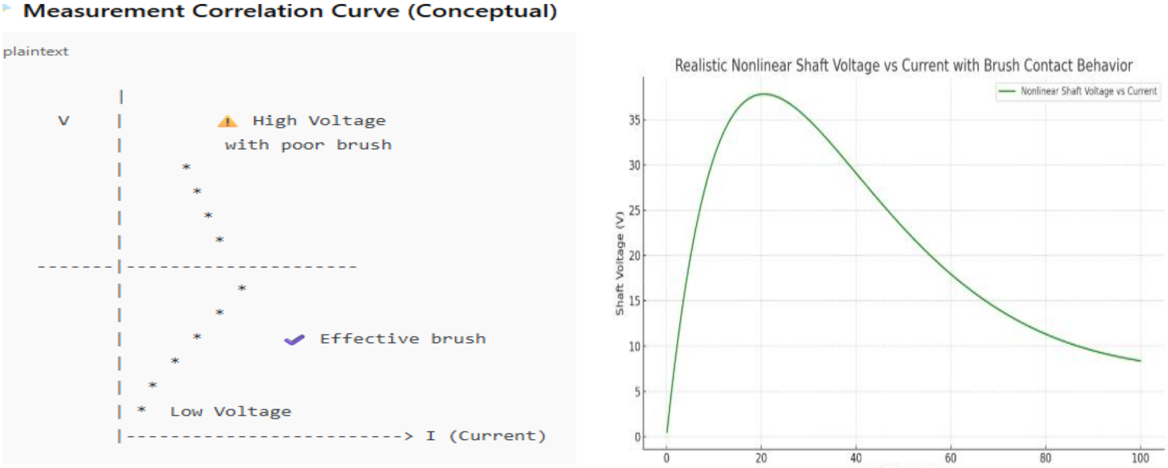


Figure 10: V~I relationship w.r.t grounding behavior

IV. Results and Recommended Thresholds

Analysis of field data, combined with literature and standard references, suggests that shaft voltage/current monitoring must be based on tiered operational zones. These thresholds not only indicate machine health but also provide guidance for corrective action and can be set for BHEL similar rating as well as other machines of similar nature and ratings. [1,5&6].

Category	**Shaft Voltage (V)**	**Shaft Current (mA)**
Preferable	< 6	< 200
Satisfactory	< 6	< 700
Observation	< 10	< 1200
Alarming	> 12	< 100
Critical	> 100	Immediate shutdown required

Table 1: Recommended operational thresholds for shaft voltage and current in large turbogenerators. Values above 12 V accompanied by low discharge current (<100 mA) are particularly alarming as they indicate brush wear or loss of grounding integrity. Shaft voltages exceeding 100 V demand immediate shutdown and inspection to prevent catastrophic bearing failure [1,5&6].

V. Standards and Industry References

International standards provide general guidance on shaft voltage and current limits, though they are primarily intended for small- and medium-sized rotating machines. The NEMA MG 1-2014 standard specifies that shaft voltages in motors should not exceed 300 mV peak, while IEC 60034-25 sets an upper limit of 500 mV for low-voltage systems [1,5&6]. These values are far below what is commonly observed in large turbogenerators, which routinely operate in the 1–10 V range during normal conditions.

**NEMA MG1 300 mV and IEC 60034-25 ~500 mV limits apply to motors (esp. LV) and do not directly govern large turbo generators

IEEE Std 115-2019 and IEEE Std 112-2017 outline procedures for synchronous and induction machine testing, but do not yet define comprehensive thresholds for shaft voltages in large thermal units. Recent literature emphasizes the need for plant-specific criteria and continuous monitoring frameworks [1,5&6].

The case study taken at Plant A reinforces this gap, as measured voltages exceeded all standard limits yet aligned with observed field experience.

VI. Corrective Measures Executed

Following the anomaly at the referred Plant A, several corrective measures were implemented to restore machine integrity:

• Bearings 4 and 5 were replaced with new bearing, followed by precision blue matching, centering and resetting of all assembly clearances as per norm.
•Labyrinth seals were re-machined to remove rubbing marks and restore clearances.
• Grounding brushes were replaced and their contact surfaces cleaned to ensure low-resistance paths.
• Electrical insulation and resistance-to-ground checks were performed to confirm integrity of the grounding system.
• LP roll checks were done and re set values with proper offsets.

Post-correction testing showed stable operation, with shaft voltages maintained below 6 V and shaft currents within the satisfactory zone of the proposed thresholds which have further stabilized post operation loading and running of machine for a period of time.

VII. Recommendations for Practice

Based on the case study and literature review, the following best practices are recommended for utilities operating large turbogenerators:

• Continuous online monitoring of shaft voltage and current, integrated with alarms for threshold breaches.
• Regular inspection and maintenance of grounding brushes to avoid contact resistance buildup.
• Establishment of baseline vibration and temperature profiles after each overhaul to detect deviations.
• Adoption of hybrid protection strategies, combining shaft grounding with insulated bearings to limit current paths and its proper maintenance and cleaning.
• Integration of shaft voltage/current monitoring into Generator Parameter Monitoring (GPM) systems for early warning.

VIII. Future Research Directions

Future work should focus on advanced techniques to predict and mitigate shaft voltage phenomena. Key research directions include:

1. Development of digital twin models capable of simulating electro-mechanical interactions and predicting shaft voltage behavior under transient conditions.
2. Application of machine learning techniques to shaft voltage/current data for predictive diagnostics.
3. Exploration of advanced grounding materials, such as nanocomposite brushes, offering low resistance and high durability.
4. Standardization of operational thresholds by IEEE and IEC specifically for large (>200 MW) turbo-generators.
5. Integration of shaft voltage/current monitoring with vibration and temperature data to create multi-sensor predictive maintenance frameworks.

IX. Conclusion

The referred **210 MW KWU-design** turbine case highlights the significant risks posed by unmanaged shaft voltage and bearing currents in large turbogenerators. Electrical discharge damage (EDD), combined with thermal and mechanical stresses, rapidly degraded multiple bearings. Through systematic inspection and diagnostic testing, the root causes were traced to deficient grounding and voltage transients during rolling and synchronization.

The study demonstrates that practical thresholds must go beyond international standards, recognizing that shaft voltages up to 10 V may occur in large machines. The proposed operational zones—preferable, satisfactory, observation, alarming, and critical—provide a structured framework for monitoring and intervention. Corrective measures at referred Plant A successfully restored unit performance, and future adoption of continuous monitoring and predictive models will further enhance reliability.

References

1. NEMA MG 1-2014, Motors & Generators, National Electrical Manufacturers Association, 2014.
2. IEC 60034-25, Rotating Electrical Machines – Part 25, IEC, 2007.
3. IEEE Std 115-2019, IEEE Guide for Test Procedures for Synchronous Machines, 2019.
4. IEEE Std 112-2017, IEEE Standard Test Procedure for Polyphase Induction Motors and Generators, 2017.
5. M. J. Prieto et al., 'Shaft Voltage and Bearing Currents in Turbomachinery: Mechanisms, Monitoring, and Mitigation,' Energies, vol. 14, no. 21, pp. 1–15, 2021.
6. Comprehensive review of shaft voltages and bearing currents, Energies, 2025[1,5&6].
7. [IEEE T-EC 1988] Ammann et al., "Shaft voltages in generators with static excitation systems—problems and solution," IEEE Trans. Energy Conversion, 3(2):409–419.
8. [IEEE T-PEL 1997] Busse/Erdman/Kerkman/Schlegel/Skibinski, "Bearing currents and their relationship to PWM drives," IEEE Trans. Power Electronics, 12(2):243–252.
9. [IEEE IAS 1997] Busse et al., "System electrical parameters and their effects on bearing currents," IEEE Trans. Industry Applications, 33(2):577–584.
10. Salazar et al., "Electrostatic enforcement of steam power plant," IEEE IAS Annual Meeting, 2013.
11. [11] Mailula et al., "A Comprehensive Review of Shaft Voltages and Bearing Currents…," Energies, 2025.
12. [ABB Library] Technical Guide No. 5 – Bearing currents in modern AC drive systems.
13. [13] Desroches, "Investigation of Hydrogenator Vulnerability Regarding Shaft Voltage and Bearing Current," IRMC 2023.
14. [EASA] "Understanding Shaft Voltage & Grounding Currents of Turbine Generators."
15. "Electrostatic Discharge on a Large Steam Turbine Generator," ORBIT Vol. 27 No. 2.
16. [Zhao et al., "Electrostatic discharge impacts on the main shaft bearings of wind turbines," Wind Energy Science, 2023.
17. Kumar and S. Roy, 'Electrical Discharge Damage in Generator Bearings: A Review and Field Case Studies,' IEEE Trans. Energy Convers., vol. 37, no. 4, pp. 3124–3135, Dec. 2022