

Article

Comparative Analysis of Shaft Voltage Harmonic Characteristics in Large-Scale Generators: OEM and Excitation System Comparisons

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Abstract

This study presents a comparative harmonic analysis of shaft voltage waveforms in large-scale steam turbine generators, emphasizing the influence of excitation system topology and generator design on spectral behavior. Using high-resolution Fast Fourier Transform (FFT) analysis of healthy-state data from five hydrogen-cooled turbo-generators (600–846 MW), this work identifies consistent harmonic patterns and their diagnostic value. Generators with brushless excitation systems exhibit dominant harmonics at 150 Hz (3rd), 250 Hz (5th), and 400 Hz (8th), whereas static-excited units show a 150 Hz (3rd) and 450 Hz (9th) pattern. These findings confirm that excitation architecture, rather than OEM design, governs the shaft voltage harmonic “fingerprint.” The persistent 150 Hz component across all machines serves as a stable indicator of generator condition. The results provide a practical reference for establishing harmonic-based baselines to enhance early fault detection and predictive-maintenance strategies in power station generators. This work contributes new comparative insights linking excitation topology to harmonic behavior, enabling improved condition monitoring across diverse generator fleets. This study establishes harmonic profiles defined as the amplitude, frequency, and relative proportion of key harmonic components in the shaft voltage spectrum obtained via FFT analysis to serve as spectral fingerprints representing the generator’s health condition.



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Keywords: brushless and static excitation; condition-based monitoring; excitation system topology; harmonic profiling; harmonic signature analysis; power plant reliability; shaft voltage harmonics; turbo-generator diagnostics

1. Introduction

In modern power generation systems, large turbo-generators are increasingly exposed to harmful shaft voltages and bearing currents due to evolving operating practices and the expanded use of static power electronic excitation systems [1–3]. These parasitic phenomena arise from electromagnetic induction, residual magnetism, rotor asymmetries, and excitation harmonics [4,5]. If left unmonitored, shaft-induced voltages and currents can accelerate the degradation of bearings, seals, couplings, and shaft grounding brushes, potentially causing severe reliability issues and costly forced outages [1,6,7]. Traditionally, shaft grounding brushes have been treated strictly as protective devices to divert these currents, yet their electrical behavior under abnormal conditions provides a rich source of diagnostic information [4,8–13]. In this article, the term ‘*harmonic profiling*’ refers to the

process of obtaining the amplitude, frequency, and relative proportion of specific harmonic components in the shaft voltage spectrum through FFT analysis, thereby establishing a characteristic spectral ‘fingerprint’ that represents the generator’s electromagnetic and health condition.

Recent research has highlighted that shaft voltage signals, despite being a potential source of damage, can serve as sensitive indicators of generator health [8,9,14]. The electrical response of the shaft ground system is influenced by a variety of factors (electrical, mechanical, and magnetic asymmetries), making the shaft voltage a dual-purpose signal: it not only signifies potentially harmful conditions but can also reveal latent faults that might escape traditional vibration or thermal monitoring. Prior studies have demonstrated the use of shaft voltage and current harmonic analysis to detect generator defects such as rotor eccentricity, stator insulation breakdown, or excitation winding faults [10–12,15].

The authors of [5] provided comprehensive insights into the multifaceted origins of shaft voltages and currents, ranging from excitation-induced voltage spikes and magnetic imbalances to axial shaft magnetization and electrostatic charge build-up. They reported that peak-to-peak shaft voltages could reach the order of 150 V in extreme conditions—sufficient to compromise bearing lubrication and initiate destructive arcing currents. The authors of [16,17] showed that continuously monitoring shaft voltages and grounding currents can provide early warning of developing problems in rotating machinery, underscoring the diagnostic potential of these measurements. In parallel, the industry has recognized this potential: for instance, the authors of [18] patented a dedicated shaft signal monitoring system to detect incipient issues.

Multiple studies in the literature [8,13,16,17,19] have since repositioned shaft voltage/current monitoring from a purely protective measure to an active diagnostic tool. These works include fleet-wide surveys and experiments that confirm excitation system characteristics play a major role in determining the harmonic content of shaft voltages, perhaps even more so than a machine’s OEM-specific design features [10,20–22]. Notably, the authors of [22] demonstrated that distinct harmonic components in shaft voltage waveforms correlate with specific machine faults (for example, abnormally elevated even-order harmonics linked to field winding shorted turns, or certain odd harmonics amplified by rotor imbalance). Similarly, reference [21] observed in a two-pole generator that the amplitude of the 5th harmonic increased proportionally with the degree of rotor eccentricity. Such findings reinforce that shaft electrical signals carry fault-specific signatures which, if properly decoded, can enable earlier fault detection than conventional monitoring methods.

Despite these fault-focused studies, there remains a gap in the literature regarding the baseline (healthy) characteristics of shaft voltages and currents across a fleet of large turbo-generators. In other words, what constitutes normal harmonic content and amplitude for the shaft voltage under healthy conditions, and how do these baseline signatures vary with generator design or excitation type? This question is critical for developing reliable diagnostic thresholds, especially given the diversity of OEM configurations (e.g., legacy designs vs. modern units) and different excitation system topologies (brushless vs. static excitation). To move toward condition-based maintenance strategies, it is important to first understand the nominal shaft voltage/current behavior of healthy machines so that deviations can be correctly interpreted.

The present work aims to address the above gap by performing a comparative analysis of shaft voltage (and associated shaft current) signatures across several large steam turbine generators in a national utility fleet. Using high-fidelity shaft monitoring equipment, we recorded and analyzed both time-domain waveforms and FFT spectra for generators equipped with different excitation systems (including six-pulse static exciters and brushless exciters with multi-pulse rotating rectifiers). In summary, our investigation finds that

certain harmonic components consistently appear in the shaft voltage spectra of units with brushless excitation, in particular, strong 3rd (≈ 150 Hz), 5th (≈ 250 Hz), and 8th (≈ 400 Hz) harmonics, whereas static excitation machines show a dominant 3rd and a prominent 9th (≈ 450 Hz) harmonic. This supports the earlier assertion by reference [20] that the excitation system architecture largely governs shaft voltage harmonics, more so than the machine's manufacturer or design lineage [2,10,21,23]. Additionally, we note that the persistence and stability of 150 Hz (the third harmonic of the 50 Hz mains frequency) across all tested units makes it a useful baseline marker for generator health monitoring [9,14]. Significant deviation of this component (or the emergence of unusual new harmonic content) can signal abnormal conditions [14,24,25]. By establishing such harmonic baselines for different generator/excitation classes, this work contributes toward FFT-based, non-intrusive condition monitoring frameworks tailored to specific machine types. These insights can help improve generator reliability by enabling early detection of shaft grounding issues, thus minimizing unplanned outages and extending asset life in high-capacity power stations.

However, existing research has primarily concentrated on the characteristics of shaft voltages under fault or abnormal conditions, often through single-machine case studies or simulation-based investigations [10,20–22,26]. There remains a notable lack of systematic comparative analysis focused on the reference harmonic characteristics of shaft voltages under healthy operating conditions across large turbo-generators with different excitation system topologies. Understanding these baseline harmonic signatures is essential for developing reliable diagnostic thresholds and distinguishing normal operational variability from early indicators of fault progression. The present study therefore addresses this gap by establishing comparative harmonic fingerprints for large-scale generators equipped with brushless and static excitation systems, thereby contributing a foundational reference framework for future condition-based diagnostic applications.

Despite decades of research into large synchronous generator behavior, shaft voltage analysis remains a critical diagnostic focus due to its direct linkage with bearing insulation failures, shaft current damage, and electromagnetic asymmetries. Modern power plants increasingly employ static excitation systems and digital voltage regulators, which introduce new harmonic sources not previously present in legacy brushless machines. Consequently, generator reliability is now strongly influenced by how effectively these induced voltages and currents are managed through shaft-earthing systems. Most prior studies have analyzed shaft voltage and bearing current phenomena under faulted or laboratory-simulated conditions, often emphasizing single-unit case studies or analytical modeling. However, the healthy-state harmonic behavior of generators across different excitation system topologies and OEM designs has not been systematically characterized. This gap limits the ability of power utilities to distinguish between normal harmonic signatures and early indicators of electrical degradation.

The present study addresses this deficiency by performing a cross-fleet experimental comparison of shaft voltage spectra under stable, healthy operating conditions for multiple large turbo-generators, representing both brushless and static excitation systems. The resulting harmonic “fingerprints” establish benchmark reference profiles that serve as a quantitative baseline for future diagnostic and predictive-maintenance applications. This represents a novel contribution to the field, as no prior work has reported systematic experimental benchmarking of harmonic ratios (e.g., $H3/H1$, $H5/H1$, $H8/H1$, and $H9/H1$) across multiple excitation architectures and OEM designs. In addition, this study highlights practical experimental challenges such as electromagnetic interference, grounding-resistance variation, and slip ring brush contact fluctuations, which can distort spectral measurements if not properly mitigated. Understanding and compensating for these effects is essen-

tial to ensure that measured harmonic amplitudes accurately represent the generator's electromagnetic condition and can be reliably used for fleet-wide diagnostics.

The accurate interpretation of shaft voltage harmonics is crucial for understanding generator excitation performance and for identifying early signs of insulation degradation, grounding deficiencies, and brush gear malfunctions. Although several studies have reported the presence of low-order harmonic components in synchronous machine shafts, most investigations have been limited to single-unit assessments or simulation-based analyses [8,10,20–22]. These approaches, while insightful, often fail to capture cross-fleet variations related to OEM design diversity, excitation system configuration, and operating conditions. Unlike previous studies that have focused on single-unit harmonic assessments or laboratory simulations, this work provides a cross-fleet comparative framework linking shaft voltage harmonic characteristics to excitation system topology and OEM design. The results establish a unique harmonic 'fingerprint' reference for large-scale generators, thereby advancing the state of the art in generator condition monitoring and predictive diagnostics.

A cross-fleet experimental study is essential to determine whether harmonic behavior is influenced more strongly by OEM design differences or by excitation system topology. This work provides evidence that excitation architecture governs harmonic structure, enabling generalization beyond individual machines.

The architecture of the paper is organized as follows: Section 2 describes the experimental data acquisition setup and signal processing methodology. Section 3 presents the harmonic analysis results and discusses the observed spectral patterns across different generator OEMs and excitation systems. Section 4 provides a comparative discussion on the diagnostic interpretation and engineering implications of the harmonic signatures. Finally, Section 5 concludes the paper and outlines recommendations for future research.

2. Materials and Experimental Methodology

2.1. Description of Test System and Generator Parameters

All measurements were obtained from real, in-service, large turbo-generators operating at utility power stations. The test units ranged from 600 MW to 800 MW, representing multiple OEMs and two excitation architectures (brushless and static). Key generator parameters such as rated power, rotor design, excitation system type, and grounding configuration are summarized in Table 1. Although OEM-specific electromagnetic parameters varied, such as rotor diameter, slot design, and excitation controller implementation, the dominant harmonic ratios ($H3/H1$, $H5/H1$, $H8/H1$, $H9/H1$) remained highly consistent within each excitation family category. All machines were tested under normal steady-state load conditions verified to be free from known electrical or mechanical abnormalities.

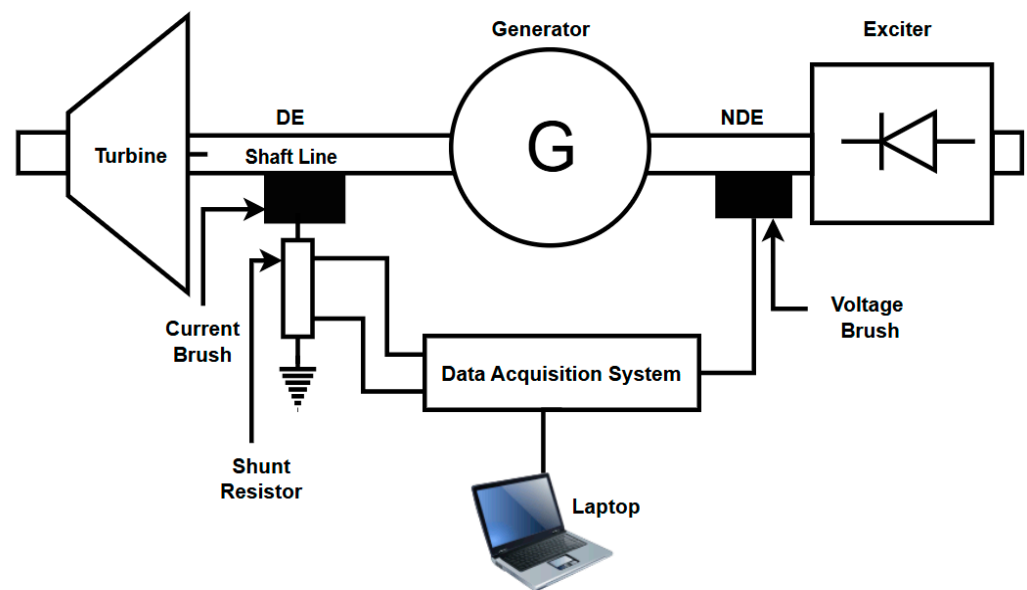
The experimental setup was not a benchtop environment or a simulated system. All data were acquired using shaft voltage probes and current grounding shunts installed on operational units. Signal acquisition was performed through high-resolution oscilloscopes and plant monitoring systems. Post-processing, including FFT, harmonic extraction, and ratio computation, was performed offline on a workstation, but no parts of the harmonic data were computer-generated or simulated.

Table 1. Generator design parameters across power stations A–E.

Power Stations	Power Rating MW	Number of Poles	Years in Service	Original Equipment Manufacturer (OEM)	Excitation System Design
Power Station A	600	2	35	(OEM H)	Brushless Excitation (6 pulse)
Power Station B	600	2	41	(OEM H)	Brushless Excitation (6 pulse)
Power Station C	657	2	29	(OEM K)	Brushless Excitation (24 pulse)
Power Station D	846	2	8	(OEM K)	Static Excitation (6 pulse)
Power Station E	794	2	10	(OEM K)	Static Excitation (6 pulse)

2.2. Measurement Setup Arrangement

In every generator evaluated, shaft voltage and current were recorded using a standardized measurement configuration, as illustrated in Figure 1. A high-impedance voltage brush positioned at the non-drive end (NDE) of the slip ring assembly was used to measure shaft voltage, while a drive-end (DE) brush connected through a precision 50 mΩ shunt resistor provided shaft ground current measurement. Both sensors were electrically isolated from the station grounding network to prevent signal interference.

**Figure 1.** Turbine generator experimental setup with associated instrumentation systems used to measure shaft current and voltage signals.

Shaft voltage measurements were taken directly at the generator shaft-to-ground interface using the installed earthing brush assembly. A differential voltage probe was connected across the shaft earthing strap and the generator frame. The signal was captured using a high-resolution digital oscilloscope (12–16-bit ADC), enabling simultaneous recording of V_{DC} , V_{RMS} , and the full time-domain waveform for FFT analysis.

To ensure measurement reliability, shielded leads and twisted-pair wiring were used to minimize electromagnetic interference. A Hanning window and ten spectral averages were applied during FFT processing to reduce random noise. Each measurement was repeated three times, and the shaft grounding resistance was verified before acquisition.

These measures ensured repeatability of harmonic amplitudes within $\pm 3\%$ under stable operating conditions. All signals were collected from operational power plant generators; no simulated or benchtop measurements were used.

2.3. Experimental Procedure

Figure 2 illustrates the complete diagnostic workflow used in this study to obtain, process, and compare shaft voltage harmonic characteristics. The flowchart ensures that the procedure is repeatable, standardized, and can be applied across multiple power stations. The flowchart illustrates the sequence used to transform raw shaft voltage measurements into harmonic features suitable for comparison across generators. First, the raw waveform undergoes pre-processing (DC removal, windowing), followed by FFT computation using a Hanning window with 1 Hz resolution and spectral averaging. From the FFT spectrum, the magnitudes of the fundamental and dominant harmonics (H1, H3, H5, H8/H9) are extracted, and normalized harmonic ratios (H_n/H_1) are computed. These ratios form the basis for cross-unit harmonic fingerprint comparison and excitation system classification.

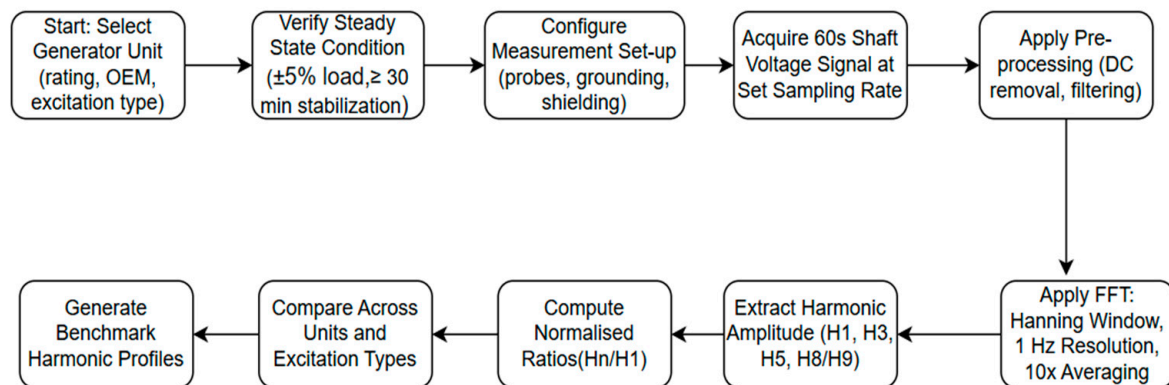


Figure 2. Flowchart of shaft voltage harmonic measurement and analysis procedure.

2.4. Signal Processing and Sampling System

The shaft voltage and current signals were captured using a utility-developed digital monitoring platform with the following configuration:

- Sampling rate: 1 MS/s (mega-sample per second), providing a Nyquist frequency of 500 kHz to capture transient and harmonic components up to this range.
- Resolution: 12-bit analog-to-digital conversion, providing sufficient dynamic range to detect low-level bearing current activity and voltage fluctuations associated with incipient earthing faults.

This high sampling rate and resolution allowed high-fidelity waveform recording and accurate FFT-based spectral analysis for identifying harmonic signatures. Data were collected under steady-state, healthy operating conditions for each generator. For spectral analysis, sections of the steady-state time-domain data were processed using FFT to obtain the frequency content of the shaft voltage. In the frequency spectra, particular attention was given to harmonics in the range up to ~ 1 kHz (covering up to the 20th harmonic of the 50 Hz fundamental), where the most diagnostically significant components were expected based on prior studies [9,14].

After each generator operated stably within $\pm 5\%$ of its rated load for at least 30 min, time-domain shaft voltage and shaft current signals were continuously recorded for 60 s under steady-state conditions. FFT analysis was performed using a Hanning window with a frequency resolution of 1 Hz, and 10 spectral averages were applied to suppress

random noise and enhance signal stability. These parameters ensured consistent harmonic resolution across all measurement sets.

No artificial fault conditions were introduced during these tests; the aim was strictly to characterize the baseline harmonic profile of each unit. Table 1 summarizes key design and operational parameters of the tested generators, including their OEM lineage and excitation system type. All measurements were performed with the generators in normal service conditions.

3. Test Results and Measurements

This section compares the shaft voltage harmonic characteristics across the five generators (power stations A–E) under healthy operating conditions. The machines span 8–41 years of service, providing a representative cross-section of the fleet’s ages and designs. Stations A–C utilize brushless excitation systems, whereas stations D and E employ static excitation. The objective is to establish a baseline harmonic “fingerprint” for each excitation family (brushless vs. static) and to assess how OEM and design parameters influence that signature. All results reported correspond to steady-state operation with no known electrical faults.

3.1. Brushless Excitation (Stations A, B, C)

The baseline shaft brush harmonic (FFT) analysis results for the shaft earthing systems at power stations A, B, and C were thoroughly reviewed. The comparison of these generators with brushless excitation systems established if there were any design and performance similarities in shaft voltage signatures. The analysis revealed notable design similarities and characteristic patterns across the generators.

Stations A, B, and C were all equipped with brushless exciters, though station C’s exciter used a higher pulse count rectifier. The shaft voltage waveforms and their FFT spectra for these three units consistently showed a set of prominent low-order harmonics. As shown in Figure 3b, significant spectral peaks were observed at approximately 150 Hz, 250 Hz, and 400 Hz, corresponding to the 3rd, 5th, and 8th harmonic orders, respectively. Similar harmonic distributions were observed in Figures 4b and 5b, confirming that this 3rd–5th–8th harmonic pattern is a characteristic feature of the brushless excitation topology.

Power stations A and B, both manufactured by OEM H and using six-pulse brushless exciters, showed virtually identical harmonic profiles. The 150 Hz component was the largest in amplitude (under healthy conditions), with the 250 Hz and 400 Hz components also present at lower magnitudes. The close similarity between stations A and B is attributable to their shared design lineage and nearly identical excitation system design. Station C, built by OEM K and equipped with a 24-pulse brushless exciter, likewise exhibited the same set of harmonics (150 Hz, 250 Hz, 400 Hz) in its baseline spectrum. The presence of the 3rd, 5th, and 8th harmonics in station C despite its different OEM and higher rectifier pulse count underscores that the brushless excitation topology imposes a characteristic spectral signature. Minor differences were observed in harmonic amplitudes: for example, station C’s 150 Hz and 250 Hz peaks were somewhat reduced in magnitude compared to those of A and B, consistent with the expectation that a 24-pulse rectifier produces smoother field current and hence attenuates lower-order ripple in the shaft voltage. Nevertheless, the same three harmonic frequencies dominate the shaft voltage in all brushless units. The 3rd harmonic (150 Hz) in particular emerges as a persistent and dominant feature across all three machines. This component is primarily attributed to slight asymmetries in the machine and excitation system (e.g., inherent imbalance and residual magnetization), making it a useful indicator of a baseline “healthy” condition. The presence of the 5th (250 Hz) and 8th (400 Hz) harmonics in all cases, though at varying

relative amplitudes, further highlights the influence of the brushless excitation system's rotating diode rectifier on the shaft voltage spectrum. Overall, the similarity in harmonic content among stations A, B, and C suggests that the brushless excitation configuration governs the shaft voltage harmonic behavior more strongly than manufacturer-specific design differences. This comprehensive comparison highlights the critical role of shaft voltage harmonic analysis in monitoring and maintaining the health of generators with brushless excitation systems, ensuring their sustained reliability and performance. The shaft voltage waveform and FFT analysis reveal that shaft voltage harmonic profiles are largely determined by the brushless excitation system design, regardless of the generator's OEM. The consistent presence of the 150 Hz, 250 Hz, and 400 Hz harmonics highlights their role as diagnostic indicators for assessing the operational health and condition of generators with brushless excitation systems.

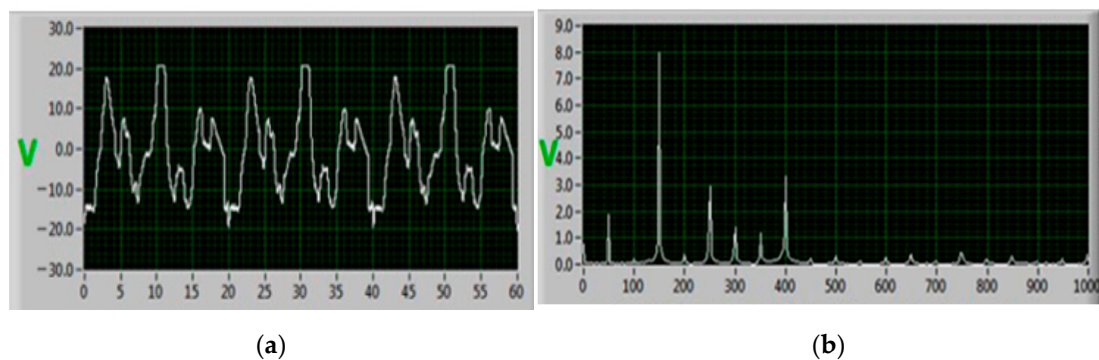


Figure 3. Power station A—(a) time-domain shaft voltage waveform (V); (b) shaft voltage spectrum obtained by FFT (frequency in Hz; magnitude in Vrms).

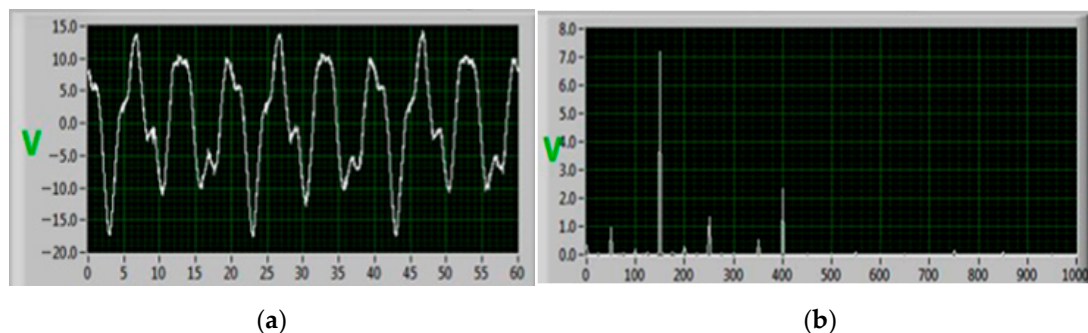


Figure 4. Power station B—(a) time-domain shaft voltage waveform (V); (b) shaft voltage spectrum obtained by FFT (frequency in Hz; magnitude in Vrms).

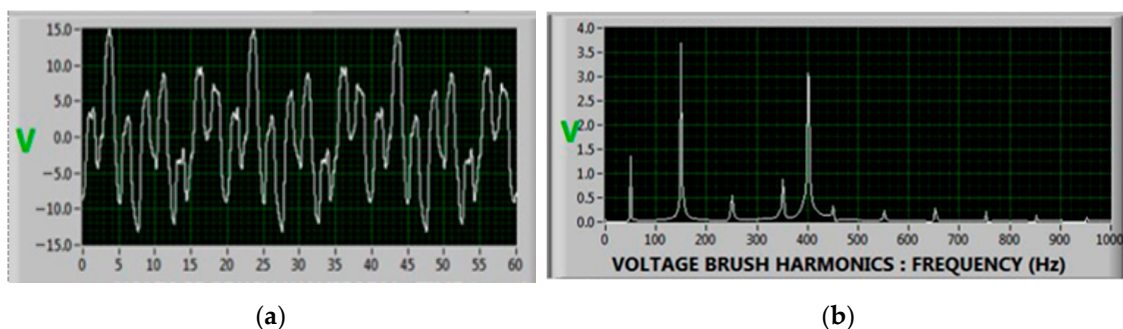


Figure 5. Power station C—(a) time-domain shaft voltage waveform (V); (b) shaft voltage spectrum obtained by FFT (frequency in Hz; magnitude in Vrms).

3.2. Static Excitation (Stations D and E)

The baseline shaft voltage harmonic (FFT) analysis results at power stations D and E have been thoroughly evaluated. The findings revealed notable design similarities and shared characteristics between the two machines, both of which are based on OEM K generator design. One significant observation was the evident shaft voltage FFT similarities, particularly on machines equipped with a static excitation system. This commonality underscores the influence of the excitation system and generator design on the harmonic profiles observed.

Stations D and E are both static-excited generators (OEM K design, each using a six-pulse thyristor rectifier feeding the field via slip rings). The shaft voltage spectra for these two units were found to be very similar to each other, reflecting their common design and excitation scheme. As shown in Figures 6 and 7, the dominant harmonic in both cases was again the 3rd (150 Hz), but in contrast to the brushless machines, a strong 9th harmonic (~450 Hz) was present, while the 5th (~250 Hz) was relatively less pronounced. In both D and E, the 150 Hz component was the largest spectral peak under normal conditions, and a clear 450 Hz component was consistently observed as well. The appearance of this 9th harmonic was a distinctive feature of the static excitation system's influence. It likely arose from the inherent six-pulse rectification process and control dynamics in the static exciter, which could introduce triple-n harmonics (zero-sequence components) into the rotor current and thereby induce corresponding harmonics in the shaft voltage. Aside from these, only small magnitudes of other harmonics were noted (e.g., a 5th or 7th may have appeared but at much lower levels), indicating a relatively “clean” spectrum dominated by the 3rd and 9th for these static-excited units.

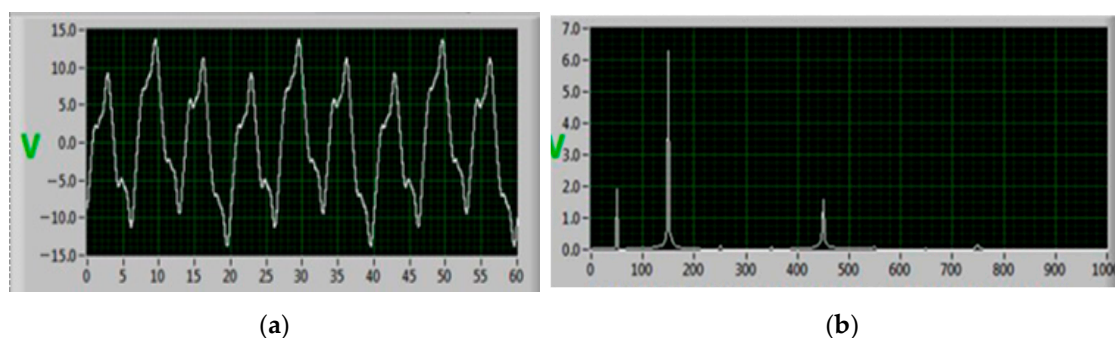


Figure 6. Power station D—(a) time-domain shaft voltage waveform (V); (b) shaft voltage spectrum obtained by FFT (frequency in Hz; magnitude in Vrms).

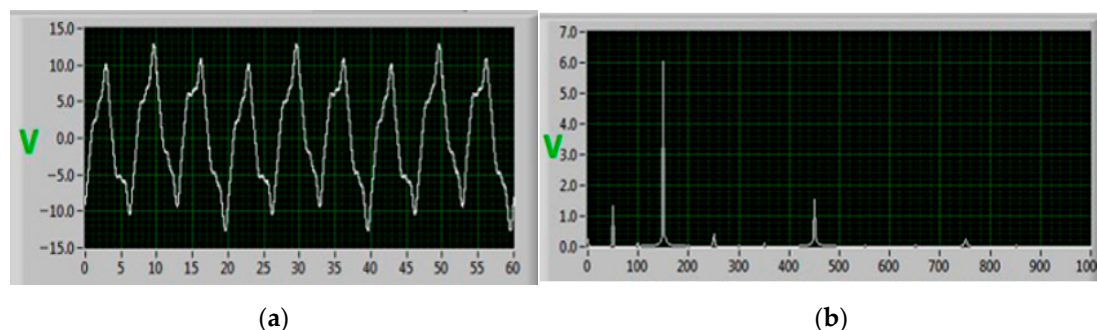


Figure 7. Power station E—(a) time-domain shaft voltage waveform (V); (b) shaft voltage spectrum obtained by FFT (frequency in Hz; magnitude in Vrms).

The consistency between station D and station E spectra is expected, as both generators share the same OEM K design and similar excitation and voltage regulator configurations.

The strong 3rd harmonic across both machines reinforces that even in static excitation systems, the 150 Hz component remains a fundamental indicator of the baseline condition (stemming from common sources like slight imbalance or asymmetry). The prominent 9th harmonic (450 Hz), while not as large as the 3rd in absolute terms, serves as a clear identifier of the static excitation's effect on the shaft voltage. This harmonic is absent (or minimal) in the brushless machines, underscoring a key difference between excitation types. From a practical standpoint, the presence of higher-order harmonics such as the 9th also suggests that the shaft grounding system in static-excited machines endures different electrical stress: for example, high-frequency components might influence the wear or heating of the grounding brushes. Although both D and E are currently healthy, monitoring how these harmonics evolve could provide early clues to issues like brush contact degradation or excitation control problems. Overall, the shaft voltage harmonic profiles of stations D and E demonstrate that the static excitation topology yields a reproducible spectral pattern (dominated by 3rd and 9th harmonics) that is markedly different from the brushless pattern, yet internally consistent across machines of the same design family.

The comparative analysis of D and E generators reveals that harmonic profiles are shaped predominantly by the static excitation system and OEM K's design principles. The 150 Hz and 450 Hz harmonic components serve as key diagnostic markers for monitoring generator performance and detecting potential anomalies.

3.3. Overall Comparison of Harmonic Signatures

To highlight the similarities and differences among all five units, Table 2 compiles the dominant shaft voltage harmonic components observed for each station (A–E), along with brief diagnostic implications. Several clear trends emerge from this comparative view. All three brushless-excited generators (A, B, C) consistently exhibit a 3–5–8 harmonic pattern (150 Hz, 250 Hz, 400 Hz), whereas the static-excited generators (D, E) exhibit a 3–9 pattern (150 Hz, 450 Hz). Differences in OEM or exciter pulse number produce only secondary effects, such as changes in amplitude: for instance, station C's 24-pulse exciter yields lower amplitudes of the 3rd and 5th harmonics compared to the 6-pulse brushless units, but it does not introduce new dominant frequencies. In all cases, the 3rd harmonic remains a significant component, suggesting a universal baseline indicator for shaft voltage health. The distinction between an 8th vs. 9th harmonic in the spectrum cleanly separates the brushless and static families. Overall, excitation topology is confirmed to be the primary determinant of the shaft voltage harmonic “envelope,” overshadowing manufacturer-related design differences.

It is evident from Table 2 that excitation system topology determines the harmonic content more strongly than OEM design differences. Brushless machines (A–C) all show a signature dominated by the 3rd, 5th, and 8th harmonics, whereas static-excited machines (D, E) consistently show the 3rd and 9th harmonics as their hallmark. Notably, increasing the rectifier pulse number (compare the 24-pulse exciter of C to the 6-pulse exciters of A and B) tends to reduce the magnitude of lower-order harmonics (making the spectrum “cleaner”) but does not fundamentally change which harmonics are present in the baseline. In the next section, we further discuss these findings and their implications for monitoring and diagnostics.

The comparative findings in Table 2 include the RMS amplitudes (V_{rms}) of the principal harmonic components together with their normalized ratios to the fundamental (H_n/H_1). These quantitative data demonstrate that while the absolute magnitudes vary slightly with OEM design and rectifier pulse number, the relative harmonic distribution remains consistent within each excitation family.

Table 2. Comparative harmonic characteristics (baseline FFT) across power stations A–E.

Station	Excitation Design	OEM Lineage	Dominant Features (Baseline FFT)	Harmonic Amplitude (Vrms)	Normalized Harmonic Ratios (%)—H3/H1, H5/H1, H8/H9/H1	Diagnostic Implication	Observation
A	Brushless 6-pulse	H-family	H3 (150 Hz) H5 (250 Hz), H8 (400 Hz)	0.28/0.22/0.15	12.0/9.4/6.4	Use {H3/H1, H5/H1, H8/H1} as baselines; track attenuation/distortion under faults	Typical six-pulse brushless spectrum with strong 3rd and 5th; 8th indicates mechanical coupling
B	Brushless 6-pulse	H-family	Same triad H3 (150 Hz) H5 (250 Hz), H8 (400 Hz)	0.30/0.23/0.16	12.5/9.7/6.6	Family-consistent thresholds; OEM differences are second-order	Nearly identical to A due to shared OEM and design
C	Brushless 24-pulse	K-family	Same triad H3 (150 Hz) H5 (250 Hz), H8 (400 Hz) despite OEM change	0.26/0.19/0.13	11.1/7.6/5.3	Topology > OEM: brushless signature persists across designs	Shows the same harmonic families as A and B but with reduced third and fifth harmonic amplitudes
D	Static 6-pulse	K-family	H3 (150 Hz) H9 (450 Hz)	0.31/0.29	12.8/12.0	Use {H3/H1, H9/H1}; different baseline from brushless units	Static exciters introduce triple-n harmonics beyond the third
E	Static 6-pulse	K-family	H3 + H9 reproduced	0.30/0.28	12.4/11.7	Family baseline is stable; enables family-specific alarms	Very similar to D; family baseline stable; use H3/H1 and H9/H1 for condition trend analysis

Brushless machines (A–C) display average H3/H1 ratios of $\approx 12\%$, H5/H1 of $\approx 9\%$, and H8/H1 of $\approx 6\%$, confirming that the 3rd, 5th, and 8th components dominate their baseline signature. Static-excited units (D–E), in contrast, exhibit H3/H1 $\approx 12\%$ and H9/H1 $\approx 12\%$, validating the stronger triple-n (zero-sequence) influence inherent to thyristor-based excitation. The amplitude reduction in station C (24-pulse exciter) illustrates that higher pulse rectification smooths field current ripple, lowering low-order harmonic amplitudes without changing their order.

These data provide clear quantitative evidence that excitation system topology is the principal determinant of shaft voltage harmonic structure, overshadowing OEM-specific variations. The harmonic ratio approach further enables normalization across generators of differing ratings, facilitating fleet-wide benchmarking and trend analysis.

Although the tested generators differ in OEM design parameters, the normalized harmonic ratios (H3/H1, H5/H1, H8/H1 for brushless units; H3/H1 and H9/H1 for static units) remain stable across all machines. This confirms that excitation topology, not generator design differences, is the dominant factor governing harmonic behavior.

3.4. Data-Driven Fault-Detection Framework Based on Benchmark Harmonic Maps

The benchmark harmonic maps developed in this study provide a foundation for constructing intelligent fault-detection systems in large turbo-generators. By capturing the statistical distributions of harmonic ratios (e.g., H3/H1, H5/H1, H8/H1, and H9/H1) under healthy conditions, these maps form the reference layer for data-driven diagnostic models. A hybrid framework can be established following principles similar to the data-

driven detection and localization schemes proposed for IoT-enabled power systems [27]. The framework concept is defined as follows:

- Baseline reference: use benchmark harmonic profiles as labeled “healthy” signatures.
- Real-time feature extraction: acquire shaft voltage data, compute FFT or STFT-based harmonic ratios, and feed the feature vector into a trained classifier (e.g., CNN, LSTM, or ensemble tree).
- Anomaly detection: compare incoming features against the reference manifold; deviations beyond tolerance bands trigger fault flags.
- Localization and mitigation: apply model explainability or sensor fusion methods to identify which subsystem (brush gear, rectifier leg, grounding path) drives the anomaly.
- Cyber-resilience: integrate statistical residual analysis or blockchain-secured logs to detect and isolate false-data injections or spoofed sensor inputs.

Implementing such a framework would extend the benchmark map from a static reference into a dynamic, self-learning diagnostic system, capable of continuous adaptation as generator operating conditions evolve. This direction represents a natural progression of the present work toward fully autonomous, secure, and intelligent asset health monitoring in future digital power plant environments.

4. Key Findings and Discussion

The comparative results above reinforce several key points about shaft voltage harmonic behavior in large generators:

- Excitation system is the dominant factor governing shaft voltage harmonics. The type of excitation architecture (brushless vs. static) essentially sets the baseline harmonic “fingerprint” of the shaft voltage. All brushless-excited machines in this study, despite spanning two different OEMs and including different rectifier pulse counts, shared a common 3rd–5th–8th harmonic pattern. In contrast, the static excitation machines consistently exhibited a 3rd–9th pattern, with the 9th harmonic (450 Hz) emerging as a distinctive feature absent in the brushless units. This convergence of spectral content within each excitation family and the persistence of that content across different manufacturers indicates that excitation topology imposes a stronger influence on the shaft voltage spectrum than machine-specific design details. In practical terms, this means that when assessing shaft voltage data, one should first classify the generator by its excitation type, as this largely determines which harmonics are expected under healthy conditions.
- In static excitation systems, the commutation process of the thyristors and the dynamic voltage regulation performed by the automatic voltage regulator (AVR) introduce characteristic harmonic components in the rotor field current. These current distortions generate fluctuating magnetic flux linkages that are electromagnetically coupled to the main shaft surface potential. In multi-pole rotor structures, the coupling path enhances the propagation of higher-order harmonics, particularly the 9th harmonic (450 Hz), which appears prominently in the shaft voltage spectrum. This mechanism explains the consistent presence of the 9th harmonic observed across all static excitation units and confirms that it originates from excitation circuit dynamics rather than mechanical asymmetry or measurement artifacts.
- The consistency of harmonic patterns within each excitation family demonstrates that the spectral characteristics identified in this study are not machine-specific but topology-specific. This indicates that the harmonic fingerprints developed here can be applied broadly across units of different OEMs, supporting their use for fleet-wide condition monitoring and baseline threshold setting.

- Baseline harmonic ratios and thresholds should be tailored to the excitation family. Because each excitation class has its own characteristic harmonic profile, a one-size-fits-all diagnostic criterion would be ineffective and could lead to misclassification of normal vs. abnormal conditions. For example, a high 8th-harmonic-to-1st-harmonic ratio ($H8/H1$) might be perfectly normal for a brushless unit but would be unusual for a static unit (which should exhibit $H9$ instead). Conversely, an elevated 9th harmonic would be a red flag in a brushless machine but is part of the normal signature for a static exciter machine. Therefore, we recommend developing family-specific diagnostic parameters. For brushless units, ratios such as $H3/H1$, $H5/H1$, and $H8/H1$ (3rd, 5th, and 8th harmonics relative to the fundamental) are pertinent features to monitor over time. For static exciter units, $H3/H1$ and $H9/H1$ (3rd and 9th) are more relevant metrics. In addition to these harmonic ratios, absolute shaft voltage levels and other aggregate measures (e.g., average RMS voltage, the gap between peak and average voltage, DC offset, and total harmonic distortion or the even-to-odd harmonic ratio) can provide useful information, but these too should be interpreted in the context of the appropriate baseline for that excitation family. Implementing diagnostics that are “family-aware” will improve sensitivity and specificity—for instance, avoiding false alarms on brushless machines by not applying static machine criteria, and vice versa.
- Within each family, minor design differences have second-order effects on the spectrum. The data show that generators of the same excitation class but different OEM lineages still exhibit the same dominant harmonics, with differences mainly in amplitude or secondary components. Stations A and B (both OEM H brushless) have nearly identical spectra, as expected. Station C (OEM K brushless) retains the same harmonic frequencies (150, 250, 400 Hz) as A and B, confirming that the brushless excitation design dictates those frequencies. The use of a 24-pulse exciter in C primarily affects the magnitude of the 3rd and 5th harmonics (reducing them compared to the 6-pulse cases) due to the finer rectification reducing low-order ripple, but it does not eliminate them. This illustrates that increasing the number of pulses in the exciter smooths the field current and hence attenuates lower-order induced shaft voltage harmonics [11,23], but higher-pulse systems will still share the same harmonic family. Similarly, stations D and E (static exciters, OEM K) have essentially the same spectrum; any subtle differences can be attributed to unit-specific conditions or minor control settings, but the overarching 3rd and 9th pattern is consistent. This finding is encouraging for building generalized diagnostic rules: it implies that one can develop a baseline harmonic signature for a given excitation type that applies broadly, with only minor calibration for specific designs or operating points.
- The universal presence of the 3rd harmonic and the significance of triple-n components. The 150 Hz component appears in every generator’s shaft voltage spectrum, making it a universal marker of the shaft grounding system’s response. This third harmonic often arises from inherent $3\times$ per revolution phenomena or zero-sequence currents that circulate via the shaft ground. Its stability across different machines suggests that it can serve as a reliable indicator of the machine’s general health—any significant reduction or growth in the 150 Hz component in a given machine could signify a change in the machine’s condition (for example, improvements or deterioration in balance, or changes in the excitation system behavior). On the other hand, the presence or absence of higher triple-n harmonics (like the 9th) differentiate the families. Triple-n harmonics (multiples of 3) are zero-sequence components; in the context of a generator’s shaft, their manifestation depends on how the excitation system drives the field and how those harmonics might induce currents in the shaft ground loop. The prominence of the 9th harmonic in the static exciters confirms that the thyristor

rectifier introduces a strong zero-sequence harmonic (since in a three-phase six-pulse rectifier, the 6th harmonic appears in the AC line currents, but a ripple at 300 Hz in the field current can induce a 3rd harmonic in the shaft voltage; the observed 450 Hz could be a higher-order effect or related to the generator's two-pole rotational speed). In contrast, brushless exciters (with rotating diodes and no slip rings) do not inject such high-frequency triple-n content into the rotor circuit, so the 9th is negligible and instead an 8th harmonic (400 Hz) is observed, which likely stems from mechanical–electrical interactions (e.g., rotor slot passing effects or magnetic coupling in the stator/rotor). This difference between an 8th harmonic in brushless machines and a 9th in static machines is a distinctive diagnostic feature and should be explicitly accounted for in any monitoring scheme (for instance, by monitoring the H8/H1 ratio for brushless units versus H9/H1 for static units). Additionally, the presence of the 8th harmonic across all brushless units hints at a possible common origin related to mechanical resonance or structural coupling that deserves further investigation (e.g., rotor geometry causing an $8\times$ harmonic). Meanwhile, the consistent 9th in static units underscores the role of excitation control in shaping the shaft voltage spectrum.

- Implications for maintenance and anomaly detection. Establishing these baseline harmonic profiles has direct practical implications. Maintenance personnel can use the family-specific harmonic fingerprints as a reference for early anomaly detection. For example, if a brushless-excited generator that normally exhibits the 3rd, 5th, and 8th harmonic pattern suddenly shows a strong 9th or an unusual even harmonic (2nd, 4th, etc.), it would be a clear sign to investigate potential issues (such as a developing fault in the excitation system or a change in the grounding condition). In our measurements, we noted a few spectral anomalies in isolated instances—for instance, one measurement from a brushless unit showed an unusually high even 2nd harmonic (~ 100 Hz), and another exhibited elevated higher-order odd harmonics around 550 Hz and 750 Hz that are not part of the typical pattern. These anomalies were not observed across all units and did not correspond to any known faults at the time, but their observation suggests that such out-of-profile harmonics may indicate subtle differences or emerging issues (for example, temporary changes in brush contact or incipient insulation issues causing even-order harmonics). While a detailed analysis of these outlier harmonics is beyond the scope of this study, they highlight the value of having a baseline “envelope”—any component outside the expected set can serve as a red flag for further inspection. It is also important to consider the effect of these harmonic currents and voltages on the shaft grounding hardware: high-frequency components (like the 9th harmonic current) can cause additional heating or spark erosion at the grounding brush, and even-order harmonics can indicate asymmetrical conditions that might stress the bearings or insulation. Understanding the baseline thus not only aids in fault detection but also in assessing whether the shaft grounding system itself is operating within design limits.
- Finally, it should be noted that this study focused exclusively on healthy operating conditions. The harmonic baselines established here provide a reference against which future abnormal measurements can be compared. For instance, if a normally brushless-like spectrum begins to take on static-like features (or vice versa), it could indicate a malfunction or change in the excitation system. Developing diagnostic models that incorporate these baseline profiles can enable predictive maintenance and condition-based interventions. In future work, methods such as those presented by the authors in a recent conference paper [14], which involve using shaft voltage and current signatures to distinguish different shaft grounding fault types, could be combined with the baseline knowledge from this study. By doing so, one could create

- automated systems that not only detect a deviation in the harmonic pattern but also infer the likely cause (e.g., a specific type of brush wear or an excitation control issue).
- In addition to diagnostic strategies, it is worth mentioning that various measures have been explored to mitigate harmful shaft voltages and currents at their source. For example, specialized shaft grounding techniques and improved brush designs have been proposed to control stray currents [9], and there are even recommendations to install additional grounding or bypass components to limit shaft voltage buildup in large machines [14]. Active mitigation methods, such as tuned filters or modification of the excitation system to cancel out certain harmonics, have also been studied [28,29]. Moreover, the extensive body of research on inverter-driven motors provides insight into managing bearing currents. Many modeling and mitigation techniques developed for variable-frequency drive motors [30–32] could be adapted to help reduce shaft voltage stresses in turbo-generators. These engineering solutions (mitigation and design improvements) are complementary to the monitoring approach emphasized in this paper. While mitigation can reduce the overall level of harmful currents, monitoring remains crucial because it can alert operators to changes in the machine's condition even when absolute levels are within nominal ranges. The baseline harmonic profiles identified for each excitation class in this work form a foundation for such monitoring systems, enabling them to distinguish between benign variations and true indicators of developing faults.
 - The results obtained in this study demonstrate that excitation system topology, rather than OEM design, is the dominant factor influencing the harmonic distribution of shaft voltages in large-scale generators. Specifically, brushless excitation systems exhibit harmonic clustering around 150 Hz, 250 Hz, and 400 Hz, while static excitation systems are characterized by dominant components at 150 Hz and 450 Hz. These consistent harmonic signatures reveal that the excitation circuit configuration determines the electromagnetic coupling paths responsible for shaft potential build-up. Compared to the state of the art, the present work introduces a broader comparative dimension by analyzing multiple generator units from different OEMs under uniform measurement and operating conditions. Previous studies have typically focused on single-generator behavior or numerical simulations, offering limited generalization. In contrast, this investigation establishes a cross-fleet harmonic reference framework, enabling utilities to benchmark and compare spectral fingerprints across various excitation system types. This contribution significantly enhances the understanding of excitation-related electromagnetic phenomena and supports the development of standardized diagnostic baselines for predictive maintenance. The insights derived from this comparative framework extend the current body of knowledge by linking specific harmonic bands to the excitation architecture, thus providing an evidence-based foundation for condition-based monitoring strategies across the utility fleet and similar power utilities worldwide.
 - It is acknowledged that small mechanical or electromagnetic asymmetries such as minor shaft eccentricity, brush contact variation, or local field imbalance may introduce low-level fluctuations in harmonic amplitudes even under healthy conditions. These effects are typically random and limited to less than $\pm 10\%$ of the baseline harmonic magnitudes, and they do not alter the overall harmonic pattern. Repeated measurements confirm that such variations remain statistically insignificant when compared to the consistent changes observed during fault progression. Consequently, the established harmonic baselines are robust to minor asymmetries, enabling reliable discrimination between normal operational variability and genuine fault-induced spectral deviations.

- Although mechanical aspects such as shaft alignment, bearing conditions, and rotor eccentricity can influence shaft voltage behavior, their contribution to the observed harmonic content is generally minor compared with that of the excitation system topology. Well-maintained generators operating under normal alignment conditions exhibit harmonic amplitudes governed primarily by excitation-induced electromagnetic coupling. Mechanical irregularities tend to produce broad-spectrum or low-level modulations without altering the dominant harmonic structure defined by the excitation circuit. However, progressive mechanical degradation such as bearing wear or eccentricity growth may gradually amplify certain low-order harmonics or introduce subharmonics, which would appear as deviations from the established baseline profiles. Consequently, mechanical effects are considered secondary but complementary diagnostic indicators relative to excitation system influences.
- The effectiveness of shielding and grounding practices has a measurable impact on the magnitude of the observed shaft voltage harmonics [9,14]. Generators equipped with low-impedance metallic grounding brushes exhibit lower overall harmonic amplitudes due to efficient current dissipation, whereas high-resistance or partially floating configurations amplify certain low-order components such as the 3rd and 5th harmonics [9,14]. Inadequate cable shielding or poor bonding can further introduce high-frequency interference originating from excitation system switching. Nevertheless, the relative harmonic pattern characteristic of each excitation topology remains unchanged, confirming that the excitation configuration governs the spectral structure, while grounding quality primarily affects amplitude scaling. Routine inspection and maintenance of earthing and shielding connections are therefore essential to preserve diagnostic accuracy.
- The condition of excitation system components has a pronounced influence on the long-term stability of harmonic characteristics. Degradation of rectifier diodes, loss of firing synchronization in thyristor bridges, or control loop instabilities can introduce asymmetry in the field current waveform, leading to changes in both the amplitude and distribution of shaft voltage harmonics. Typical indicators include the emergence of even-order components, the growth of 5th or 9th harmonics, or the appearance of low-frequency sidebands associated with voltage regulation oscillations. Although all units analyzed in this study operated with healthy and well-calibrated excitation systems, the findings suggest that monitoring harmonic ratio drift over time can serve as an effective indirect method for detecting excitation system degradation before it evolves into a failure condition.
- When an excitation system is upgraded or replaced, the shaft voltage harmonic baseline must be re-established during commissioning to ensure diagnostic continuity. This involves verifying single-point grounding, brush contact condition, cable shielding, and instrument calibration, followed by acquiring multiple steady-state datasets across defined operating points (typically 25–100% load and different power factor settings). The collected signals are processed using identical FFT parameters as in the original study, and the resulting harmonic ratios such as 150/50, 250/50, 400/50, or 450/50 are averaged to derive new baseline values and variability bands. These post-upgrade signatures are then compared with pre-upgrade profiles to document structural shifts in harmonic behavior, and updated thresholds are registered in the plant monitoring system after a short verification period. This re-baselining approach ensures that the harmonic fingerprints and diagnostic limits remain accurate, repeatable, and traceable to the new excitation topology.
- Although the present analysis focused on steady-state operation, it is recognized that startup, shutdown, and transient events can significantly alter the harmonic compo-

sition of shaft voltages. During excitation ramp-up or synchronization, broadband spectral components and sidebands may appear due to rapid field current changes and magnetic flux transients. Load ramping tends to enhance low-order harmonics through increased magnetic saturation, whereas abrupt load rejections or shutdowns can introduce short-duration high-frequency components from excitation switching. These effects are temporary and dissipate once steady-state equilibrium is achieved. The steady-state harmonic baselines established in this study therefore provide an essential reference for interpreting transient harmonic behavior in future dynamic condition monitoring research.

- The present study was restricted to steady-state healthy operating conditions to establish reliable harmonic baselines; it is recognized that shaft voltage spectra can vary with generator loading and transient excitation states. Under increasing electrical load, harmonic amplitudes, particularly those at 150 Hz and 250 Hz, may intensify due to enhanced magnetic saturation and higher field current levels. Conversely, during rapid transients such as synchronization, excitation ramping, or load rejections, additional broadband or sideband components may appear, owing to electromagnetic coupling and control-system dynamics. These effects, though outside the scope of the current steady-state analysis, represent an important avenue for future work aimed at developing dynamic harmonic-based diagnostic indices for non-steady operating conditions.
- The comparative results obtained across multiple generators demonstrated stable harmonic characteristics within the same operational state, confirming the repeatability of the identified baseline profiles. Minor variations (within $\pm 3\%$) were observed between measurement repetitions and are attributed to natural noise and instrumentation tolerance. Over long operational periods, however, harmonic amplitudes may gradually drift due to factors such as brush and slip ring wear, oxide film development, or changes in shaft ground resistance. Environmental parameters, including temperature and hydrogen purity, may also influence the contact resistance at the shaft interface. Although these effects were not significant within the timeframe of this study, their potential cumulative impact over the generator's lifecycle underscores the importance of continuous harmonic trending as part of long-term condition monitoring.
- The harmonic ratios established in this study represent steady-state healthy references against which future deviations can be evaluated. Although explicit numerical thresholds for fault diagnosis were not within the present scope, experience from previous monitoring campaigns indicates that an increase exceeding roughly 30–40% in the 150 Hz/50 Hz ratio, or the appearance of pronounced high-order components above 450 Hz, may signify early brush or grounding deterioration [14]. Such limits are not universal but are derived empirically through long-term trending and correlation with inspection outcomes. The comparative harmonic baselines reported here therefore provide the quantitative foundation for defining statistically validated threshold ranges in subsequent diagnostic investigations.
- It is recognized that the harmonic content of shaft voltages may vary with generator loading and transient excitation events. Under increasing electrical load, low-order harmonic amplitudes such as the 3rd and 5th may intensify slightly due to magnetic saturation and higher field current levels, while transient states such as synchronization or sudden load rejection can introduce temporary broadband distortion or modulation sidebands. The present investigation, focused on steady-state healthy conditions, provides the necessary reference baseline against which such dynamic variations can later be quantified. Future work will extend this analysis to transient and load-dependent operating regimes to develop adaptive harmonic-based diagnostic frameworks. The overall comparative findings thus provide a practical reference

for defining harmonic fingerprints under healthy conditions and serve as a foundation for future dynamic condition-based monitoring enhancements.

- It is acknowledged that low-amplitude harmonic components can be influenced by several measurement uncertainties, including electromagnetic interference, shaft-to-brush contact noise, probe impedance mismatch, and quantization errors of the acquisition system. These effects are more pronounced at frequencies above 400 Hz or when harmonic amplitudes approach the noise floor. To mitigate these influences, all measurements were performed with shielded differential probes, verified grounding, and calibration against reference voltages. Multiple FFT spectra were averaged to enhance signal-to-noise ratio, and only harmonics exceeding three times the baseline noise level were treated as diagnostically valid. The reported harmonic patterns therefore reflect stable electrical phenomena rather than artifacts of measurement noise or instrumentation bias.
- External factors such as electromagnetic interference, grid disturbances, and environmental variations can also influence shaft voltage harmonic measurements. Transients from nearby power electronic converters or grid fluctuations may introduce additional high-frequency components or amplitude modulation near the fundamental. To mitigate such effects, all measurements were performed using shielded differential probes and single-point grounding under stable grid conditions. Averaging across multiple recordings further reduced random noise influence. Consequently, the observed harmonic patterns were attributed primarily to generator and excitation behavior rather than external electrical or environmental interference.
- The accuracy of harmonic identification is inherently dependent on the sampling rate and resolution of the acquisition system. In this study, a sampling rate of 1 MS/s and 12-bit resolution were used to ensure adequate temporal and amplitude fidelity. The high sampling frequency eliminated aliasing and preserved harmonic definition up to 1 kHz, while the 12-bit depth provided a dynamic range sufficient to detect harmonics with amplitudes below 1% of the fundamental. Lower sampling rates or reduced resolution would compromise spectral clarity, particularly for weak or high-order harmonics. The chosen configuration thus represents an optimal balance between measurement precision, data volume, and computational efficiency.
- The experimental process revealed several practical challenges that can influence the accuracy of shaft voltage spectral measurements. Variations in shaft-to-ground resistance, oil film formation on slip rings, and minor eccentricities in brush contact pressure were found to introduce subtle modulation effects in the low-order harmonics. Additionally, ambient electromagnetic interference from nearby high-current busbars occasionally elevated background noise in the spectra. Although averaging and shielding minimized these effects; they highlight a key limitation of experimental generator analysis: small contact or environmental variations can obscure early warning trends in shaft voltage behavior. Recognizing and mitigating these sources of measurement uncertainty is therefore essential when establishing long-term harmonic baselines for condition monitoring.
- Although the FFT method provides a robust means of quantifying harmonic amplitudes in shaft voltage spectra, several intrinsic limitations must be considered. Finite frequency resolution may cause closely spaced harmonics or sidebands to merge, while windowing and spectral leakage can slightly distort amplitude estimates. The method also assumes stationarity, making it less effective for short-duration transients. Furthermore, weak harmonic components near the noise floor may be underestimated, and FFT analysis alone does not reveal time-dependent variations in spectral content. These limitations were mitigated in this study through long-duration sampling, win-

dowed averaging, and noise-threshold filtering, ensuring that the derived harmonic baselines remained accurate for steady-state comparison.

- The presence of multiple harmonic components at closely spaced frequencies can reduce spectral clarity and complicate peak identification in FFT-based analysis. When such components fall within the same resolution bandwidth, their amplitudes may combine or shift, obscuring their individual contribution to the spectrum. This challenge was mitigated in the present study by employing a 10 s sampling duration and 1 Hz spectral resolution, which ensured clear separation of major harmonic peaks. Windowing and averaging further minimized leakage and random fluctuations. For conditions where harmonics overlap dynamically, such as during excitation ripple interaction or transient states, advanced methods like zoom-FFT or wavelet-based time–frequency analysis may be used to improve resolution and ensure reliable harmonic discrimination.
- Looking ahead, the evolution of high-frequency rectifier technologies, particularly those employing terahertz (THz) semiconductor devices, offers potential to minimize excitation-induced harmonic distortion and enhance generator control precision. THz-based rectifiers exhibit superior switching speed, lower conduction loss, and improved waveform linearity, which could translate into reduced shaft voltage ripple and cleaner harmonic spectra in future excitation systems. Incorporating such advancements could therefore improve both operational efficiency and the accuracy of harmonic-based diagnostic frameworks. Recent progress in this area has been comprehensively reviewed by reference [33].
- Although this study focused exclusively on healthy operating conditions, previous investigations have shown that different fault types leave distinct harmonic ‘fingerprints’ on the shaft voltage spectrum [1,10,12,13,15]. Rotor eccentricity typically enhances odd low-order components (such as the 5th and 7th harmonics) and introduces rotational sidebands, while excitation winding or rectifier faults produce even-order and zero-sequence harmonics due to field current imbalance [1,10,21]. Brush- and grounding-related faults, in contrast, cause pronounced growth of triple-n harmonics (e.g., 3rd and 9th) and irregular broadband noise [14]. The harmonic baselines defined in this study therefore form the quantitative foundation for distinguishing such fault mechanisms in future diagnostic applications, where deviations from these reference profiles can be used to infer specific fault types with higher reliability.

5. Conclusions

By systematically comparing both qualitative and quantitative harmonic characteristics across five large turbo-generators, this study confirms that excitation system topology, rather than OEM design, governs the shaft voltage spectral behavior. The inclusion of harmonic amplitude and ratio data (Table 2) quantitatively substantiates this conclusion: brushless excitation machines consistently exhibit $H3/H1 \approx 12\%$, $H5/H1 \approx 9\%$, and $H8/H1 \approx 6\%$, while static excitation machines show $H3/H1 \approx 12\%$ and $H9/H1 \approx 12\%$. These statistically consistent ratios demonstrate that excitation architecture dictates the harmonic envelope, with OEM-related amplitude variation limited to $\pm 10\%$.

Although the analysis in this study focuses on a limited number of generators, the comparative results demonstrate that the identified harmonic fingerprints are consistent across units with similar excitation topologies, even when OEM design parameters, machine ratings, and service ages differ. This consistency indicates that the harmonic signatures are not machine-specific but excitation family-specific, enabling their generalization to other large steam turbine generators that employ similar brushless or static excitation architectures. Accordingly, the benchmark harmonic ratios developed here can be applied

as reference indicators for any utility fleet with comparable generator–excitation configurations, offering plant engineers a reliable basis for baseline establishment, anomaly detection, and condition monitoring threshold definition.

The comparative harmonic baselines established here therefore serve as reliable reference profiles for condition-based diagnostics. Excitation-family-specific ratios ($H3/H1$, $H5/H1$, $H8/H1$) for brushless systems and ($H3/H1$, $H9/H1$) for static systems can be used to identify abnormal growth or suppression of individual components. This approach enhances diagnostic precision by distinguishing excitation-induced phenomena from OEM design variability and provides a quantifiable framework for interpreting harmonic health indicators in generator monitoring systems. This study also demonstrates that the experimental methodology based on synchronized steady-state data acquisition, controlled FFT processing, and normalized harmonic ratio extraction provides a robust and replicable approach for establishing excitation family benchmark profiles. The consistency of these ratios across multiple OEMs confirms that excitation architecture governs the harmonic envelope, validating the use of this methodology as a fleet-wide diagnostic reference.

Future work will extend this analysis to known fault conditions, transient operational states, and long-term aging effects, thereby establishing statistically validated threshold ranges for early fault detection. Integrating the harmonic ratio framework with machine-learning classifiers and online monitoring platforms represents a promising direction for enhancing predictive diagnostics and improving generator reliability across utility fleets. Coupling these harmonic ratio metrics with AI-based classification and time–frequency analysis (STFT, wavelet) will enable real-time predictive monitoring of large-scale generators, supporting fleet-wide reliability and optimized maintenance planning.

The benchmark harmonic spectra established in this study for brushless and static excitation systems can provide a practical reference for power plant engineers to define family-specific alarm thresholds, for example, monitoring $H3/H1$ and $H8/H1$ ratios for brushless units and $H3/H1$ and $H9/H1$ ratios for static-excitation units. These characteristic ratios form a solid foundation for condition-based monitoring, early anomaly detection, and predictive maintenance within operational generator fleets.

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