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Simultaneous distributed acoustic and temperature sensing for early detection and localization of tracking phenomena in polymeric insulators

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ABSTRACT

Polymeric composite insulators are widely used in high-voltage transmission systems because of their excellent electrical and mechanical performance. However, prolonged electrical stress and environmental contamination progressively degrade the insulation surface through intermittent discharges, localized heating, and carbonization, eventually leading to irreversible surface tracking and dielectric failure. Existing diagnostic techniques can detect individual symptoms of degradation but are unable to continuously monitor its spatial evolution over extended transmission infrastructure. Here, we present a distributed multi-parameter fiber-optic sensing framework that simultaneously monitors the acoustic and thermal signatures of electrical surface tracking using distributed acoustic sensing (DAS) and distributed temperature sensing (DTS) implemented on a single standard single-mode optical fiber. During IEC 60587 inclined-plane testing, the proposed system continuously captured the complete degradation process from discharge inception to permanent surface tracking. 1,750 discharge events were recorded, and a Teager–Kaiser energy operator enabled reliable extraction of transient acoustic signatures under noisy operating conditions. The distributed acoustic measurements revealed a characteristic acoustic resonance near 14.8 kHz and showed strong temporal agreement with synchronous leakage-current measurements, while DTS identified localized thermal anomalies that developed concurrently with sustained discharge activity. Together, these complementary measurements provide a comprehensive view of insulation degradation by simultaneously capturing the rapid electrical discharge dynamics and the slower thermal evolution of the tracking process. The proposed sensing framework offers a scalable, non-contact approach for continuous monitoring and localization of insulation degradation in high-voltage power transmission systems.

Keywords: Condition monitoring; distributed acoustic sensing (DAS); distributed temperature sensing (DTS); fault localization; polymeric insulators; Teager–Kaiser energy operator (TKEO).

Motivation

Polymeric insulators have become indispensable components of modern high-voltage transmission systems because of their low weight, excellent hydrophobicity, high mechanical strength, and superior contamination performance compared with conventional ceramic insulators^{1,2}. Despite these advantages, prolonged exposure to electrical stress, moisture, and environmental contamination progressively degrades the insulation surface through intermittent discharge activity, dry-band formation, and carbonization, ultimately leading to irreversible surface tracking and insulator failure^{3,4}. Since these degradation processes evolve gradually before catastrophic breakdown, their early detection is essential for improving grid reliability, reducing maintenance costs, and preventing unexpected service interruptions.

Existing diagnostic techniques, including leakage-current (LC) measurements^{5,6}, infrared thermography⁷, ultraviolet imaging⁸, and ultra-high-frequency (UHF) partial-discharge (PD) detection⁹, provide valuable information regarding insulation condition. However, these techniques are inherently limited by localized sensing, susceptibility to environmental conditions or electromagnetic interference, and their inability to continuously monitor the spatial evolution of degradation over extended transmission infrastructure. Consequently, the transition from incipient surface discharge to permanent surface tracking often remains undetected until significant damage has already occurred.

To overcome these limitations, optical sensing techniques have attracted considerable interest for early fault detection in high-voltage insulation. Optical emission spectroscopy (OES) and fluorescent optical fiber sensing provide high sensitivity to incipient discharges, intrinsic immunity to electromagnetic interference, and improved detection capability compared with conventional electrical monitoring techniques^{10,11}. Fluorescent optical fiber sensors have been successfully applied to transformers, ring main units, and other high-voltage equipment^{12–14}, while recent studies have demonstrated the complementary use of fluorescent fiber sensing and optical emission spectroscopy for the early detection of tracking in polymeric insulators¹⁵.

Although these optical approaches significantly improve the detection of incipient degradation, they remain predominantly point-based sensing techniques and therefore cannot provide continuous distributed monitoring over long transmission assets. Furthermore, they cannot simultaneously localize multiple degradation events or capture the spatial evolution of both acoustic and thermal signatures. These limitations motivate the adoption of distributed fiber-optic sensing technologies.

Distributed fiber-optic sensing has emerged as a powerful technology for structural health and infrastructure monitoring by transforming standard optical fibers into continuous arrays of virtual sensors capable of measuring physical perturbations over tens of kilometres with metre-scale spatial resolution^{16,17}. Distributed acoustic sensing (DAS) measures dynamic strain from phase variations in coherent Rayleigh backscattering, whereas distributed temperature sensing (DTS) estimates temperature from the ratio of Raman anti-Stokes and Stokes backscattered signals^{16,18,24}. The widespread deployment of optical communication cables, including optical ground wire (OPGW), optical phase conductor (OPPC), and optical attached conductor (OPAC) (Fig. 1), offers a practical opportunity to exploit existing fiber infrastructure for continuous condition monitoring without installing dedicated sensing networks²⁵.

Building upon these developments, distributed fiber-optic sensing has increasingly been investigated for high-voltage power applications. DAS has been explored for distributed vibration monitoring and partial-discharge localization while benefiting from the intrinsic immunity of optical fibers to electromagnetic interference^{19,20,25}. In parallel, DTS has been employed to identify localized thermal anomalies associated with leakage currents, conductor icing, and insulation degradation in OPGW and OPPC systems^{18,21–23}. Nevertheless, these studies have generally employed DAS or DTS independently and have focused primarily on transmission-line diagnostics rather than the distributed monitoring of surface tracking and erosion in outdoor polymeric insulation.

More recently, simultaneous DAS and DTS using a single optical fiber has been demonstrated for long-range infrastructure monitoring, where the complementary acoustic and thermal measurements enabled more reliable event identification than either sensing modality alone by providing independent yet correlated information from the same sensing fiber^{26,27}. However, simultaneous distributed acoustic and distributed temperature sensing has not been applied to continuously monitor the complete evolution of electrical surface tracking and erosion in outdoor polymeric insulators. Surface tracking is inherently a coupled electro-thermo-mechanical process in which electrical discharges generate both transient acoustic waves and localized heating. Simultaneous measurement of these complementary signatures can therefore provide a more comprehensive understanding of insulation degradation while improving confidence in fault localization.

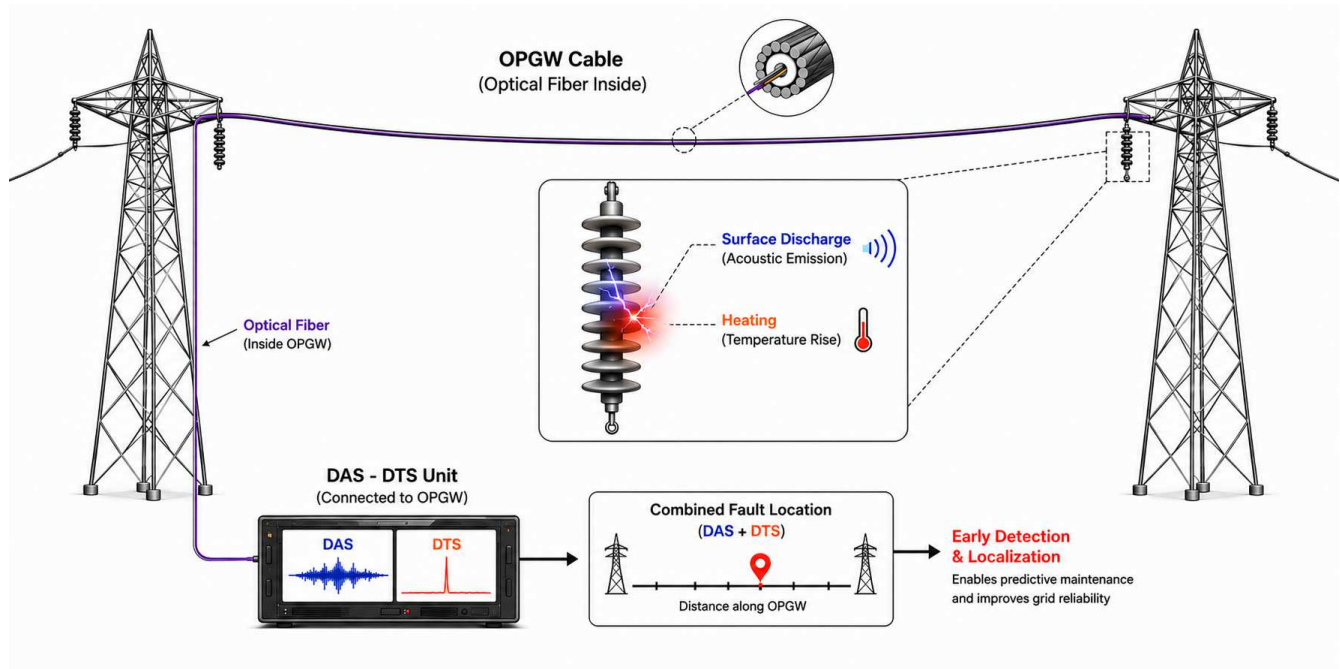


Figure 1. Conceptual illustration of the proposed DAS–DTS framework for distributed monitoring of electrical discharge tracking in polymeric insulators using telecom-grade optical fibers (OPGW, OPPC, and OPAC).

Here, we present a distributed multi-parameter fiber-optic sensing framework (Fig. 2) that combines coherent distributed acoustic sensing and Raman distributed temperature sensing using a single standard single-mode optical fiber for continuous monitoring of polymeric insulators during accelerated inclined-plane testing. A total of 1750 discharge events were recorded

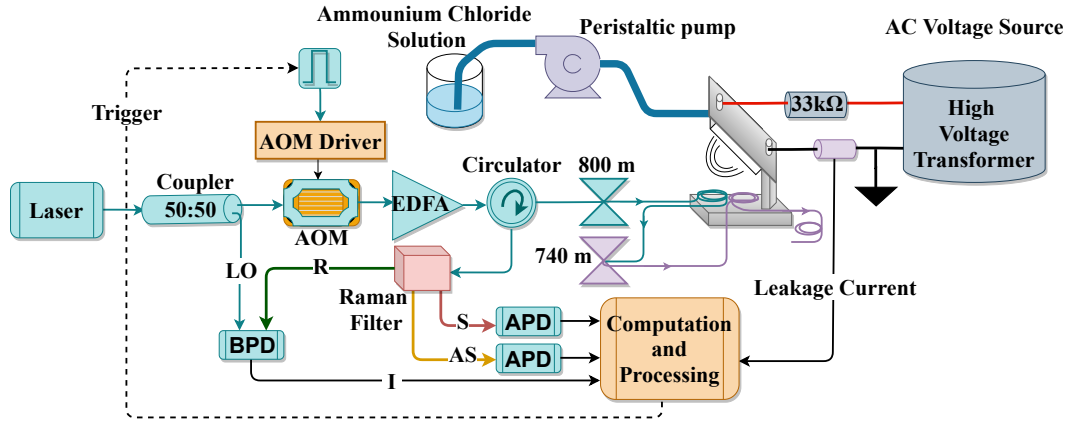


Figure 2. Experimental configuration of the integrated DAS–DTS sensing system used for simultaneous acoustic and temperature monitoring during the IEC 60587 inclined-plane tracking test.

under IEC 60587 conditions²⁸, enabling observation of the complete progression from initial surface discharge through dry-band formation and bright-spot development to permanent surface tracking. Acoustic transients were enhanced using the Teager–Kaiser energy operator (TKEO)^{29,30}, enabling reliable extraction of discharge events under noisy operating conditions. The proposed framework captures both acoustic and thermal signatures of degradation, demonstrates strong agreement with synchronous leakage-current measurements, identifies a characteristic acoustic resonance near 14.8 kHz, and enables simultaneous localization of multiple discharge sources along a single sensing fiber. These findings establish integrated DAS–DTS sensing as a scalable, non-contact, and electromagnetic-interference-immune platform for continuous monitoring of high-voltage insulation systems.

Results and Discussions

To evaluate the proposed sensing framework, polymeric insulators were subjected to inclined-plane testing in accordance with IEC 60587 (details presented in Methods section). Throughout the experiment, the evolution of insulation degradation was continuously monitored using simultaneous distributed acoustic and distributed temperature sensing through a single standard single-mode optical fiber, while synchronized leakage-current measurements were acquired as an independent electrical reference.

Evolution of surface tracking revealed by distributed acoustic sensing

The progression of surface tracking was continuously monitored using distributed acoustic sensing (DAS) during inclined-plane testing. Distinct acoustic signatures corresponding to successive stages of insulation degradation were observed, demonstrating the capability of the distributed sensing framework to resolve the spatiotemporal evolution of electrical surface activity. Fig. 3 illustrates representative DAS waterfall plots together with the corresponding acoustic phase response and synchronized leakage-current measurements for the four characteristic stages of degradation.

During the initial surface-discharge stage, intermittent localized acoustic transients appeared at the sensing position, indicating the onset of electrical discharges on the contaminated insulation surface. These events were accompanied by periodic impulsive variations in the extracted DAS phase and leakage-current pulses, confirming the occurrence of localized discharge activity without sustained degradation.

As the experiment progressed, localized evaporation of the conductive contaminant caused the formation of dry bands. This stage was characterized by a temporary reduction in acoustic and leakage current activity, resulting in regions of no activity within the DAS waterfall plots. The simultaneous suppression of both electrical and acoustic activity is consistent with the increased surface resistance associated with dry-band formation, which temporarily inhibits discharge development.

Further degradation resulted in the emergence of bright-spot activity, where localized arcing generated pronounced acoustic emissions. Strong transient features became evident in the DAS waterfall plots, accompanied by increased phase fluctuations and a gradual baseline drift in the measured phase response. The leakage-current signal simultaneously evolved into high-amplitude impulsive pulses, reflecting the increased discharge energy associated with localized arcing.

The final tracking stage was characterized by persistent high-intensity acoustic activity. The DAS phase exhibited large-amplitude, irregular fluctuations throughout the measurement period, while the leakage-current waveform transitioned into a stable high-magnitude current characteristic of a continuous conductive carbonized path. The close temporal correspondence

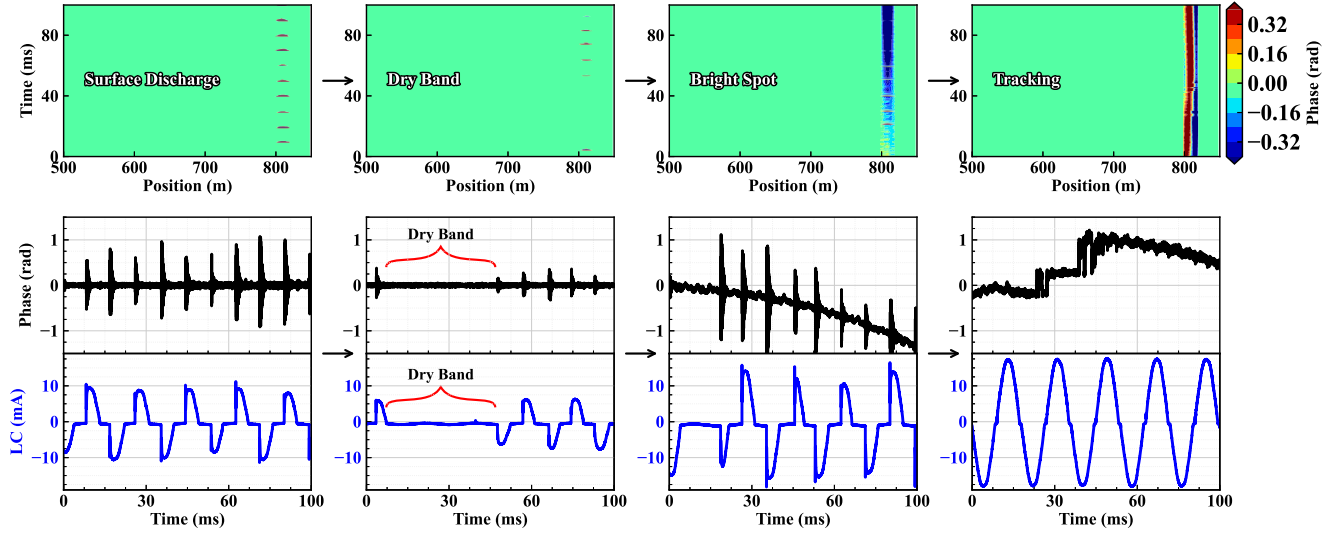


Figure 3. Stage-wise acoustic signatures during Surface Discharge → Dry Band → Bright Spot → Tracking in polymeric insulator samples.

Table 1. Criteria used to identify the different stages of insulation degradation.

Stage	Visual observation	Leakage current	DAS signature
Surface discharge	Intermittent visible surface discharges	Isolated current pulses at ≈ 20 ms intervals (50 Hz AC cycle)	Transient acoustic events at ≈ 20 ms intervals
Dry-band formation	Appearance of dry bands	Suppressed current activity for ≈ 35 – 40 ms	Suppressed acoustic activity for ≈ 35 – 40 ms
Bright-spot activity	Persistent luminous discharge at a fixed location	Repetitive high-amplitude current pulses	Sustained high-energy localized acoustic bursts
Permanent tracking	Continuous carbonized conductive track	Continuous/high conduction current until failure	Continuous large-amplitude irregular acoustic fluctuations

between the distributed acoustic measurements and the electrical reference throughout all stages demonstrates that DAS captures the complete evolution of surface tracking, from incipient discharge to irreversible insulation degradation.

These observations demonstrate that distributed acoustic sensing provides considerably more than event detection alone. The measured acoustic signatures reveal the dynamic progression of surface degradation, enabling continuous visualization of transitions between discharge regimes while simultaneously preserving their spatial location along the sensing fiber. Such capability is particularly attractive for condition monitoring of geographically distributed high-voltage assets, where early identification of evolving degradation is essential for predictive maintenance.

Enhancement of transient discharge signatures using the Teager–Kaiser energy operator

The acoustic signals acquired by the distributed acoustic sensing system contained both discharge-induced transients and low-frequency background fluctuations originating from the experimental environment. To enhance the transient discharge signatures, the DAS phase signals were processed using the Teager–Kaiser energy operator (TKEO)^{29,30}. TKEO was selected because of its low computational complexity and its effectiveness in highlighting impulsive transient events. Owing to its reliance on simple local signal operations, TKEO is particularly well suited for real-time distributed acoustic sensing applications requiring continuous processing of high-rate data streams.

Fig. 4 compares the DAS phase response before and after TKEO processing. Prior to signal enhancement, individual discharge events were partially masked by low-frequency baseline fluctuations, making the identification of weak transient events challenging. Following TKEO processing, impulsive discharge signatures became significantly more distinct, exhibiting improved temporal localization and enhanced contrast relative to the background signal.

The improved separation between transient discharge signatures and background fluctuations also facilitated subsequent

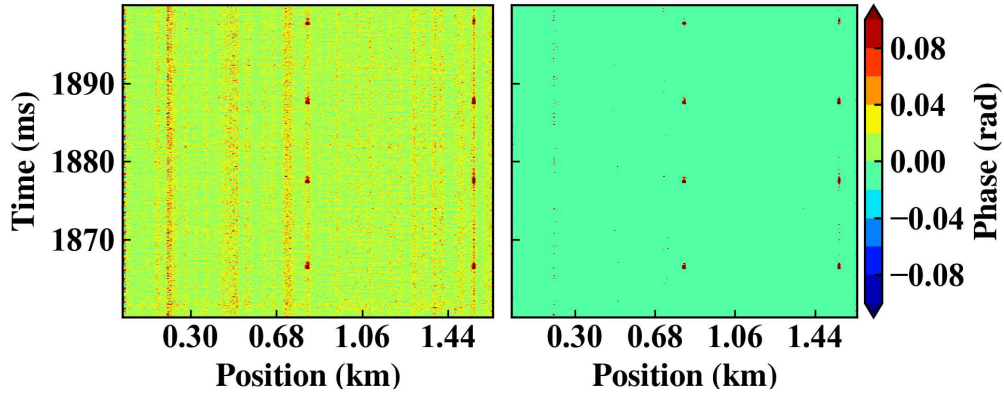


Figure 4. Spatiotemporal DAS waterfall plots illustrating the extraction of discharge transients: (left) raw phase data dominated by low-frequency environmental interference and spatial drift, and (right) the processed output after applying the Teager-Kaiser Energy Operator (TKEO)

spectral analysis and quantitative comparison with synchronous leakage-current measurements.

These results demonstrate that TKEO provides an effective preprocessing technique for distributed acoustic sensing of electrical discharge activity by improving transient detectability without requiring additional sensing hardware or modifications to the interrogation system.

The enhanced DAS waterfall plot also demonstrates the distributed sensing capability of the proposed system. Two sections of the same sensing fiber positioned adjacent to the inclined plane test specimen independently recorded the same discharge event, producing replicated transient signatures at different positions along the sensing fiber. The simultaneous observation of identical discharge events using a single interrogation unit highlights the flexibility of DAS for monitoring multiple sensing regions without additional sensing hardware

Time–frequency analysis of discharge-induced acoustic emissions

To investigate the spectral evolution of acoustic emissions during surface discharge, the enhanced DAS phase signals were analyzed in the time–frequency domain.

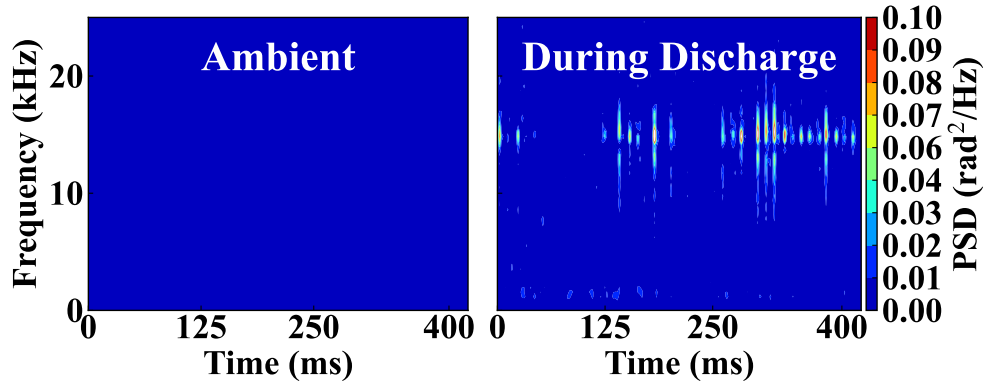


Figure 5. Comparison of the time–frequency acoustic response measured by DAS under ambient conditions (left) and during surface discharge (right).

Fig. 5 compares the time–frequency responses under ambient conditions and during surface discharge. Under ambient conditions, negligible acoustic energy was observed across the measured frequency range. In contrast, electrical discharge generated localized high-energy spectral components that evolved over time, producing distinct transient signatures absent during ambient operation.

The discharge-induced acoustic emissions were predominantly concentrated around 14.8 kHz, exhibiting substantially higher spectral energy than the surrounding frequency components. These localized spectral features appeared consistently during successive discharge events, indicating good repeatability of the acoustic response and confirming that the observed signatures originated from electrical discharge activity rather than ambient environmental noise.

The clear distinction between the ambient and discharge responses demonstrates the capability of distributed acoustic sensing to discriminate electrical discharge activity from background disturbances. Furthermore, the characteristic time–frequency signatures provide complementary information to the transient DAS phase response, enabling more reliable identification and characterization of surface discharge events.

Effect of applied voltage on the acoustic response

To investigate the influence of electrical stress on the acoustic response, the power spectral density (PSD) of the TKEO-enhanced DAS phase signal was evaluated for applied voltages ranging from 1.0 kV to 4.5 kV. Fig. 6 compares the resulting spectra obtained under identical experimental conditions. Across all voltage levels, a dominant spectral peak was consistently observed near 14.8 kHz, indicating that the discharge-induced acoustic emission possesses a characteristic frequency associated with the discharge process and the experimental configuration.

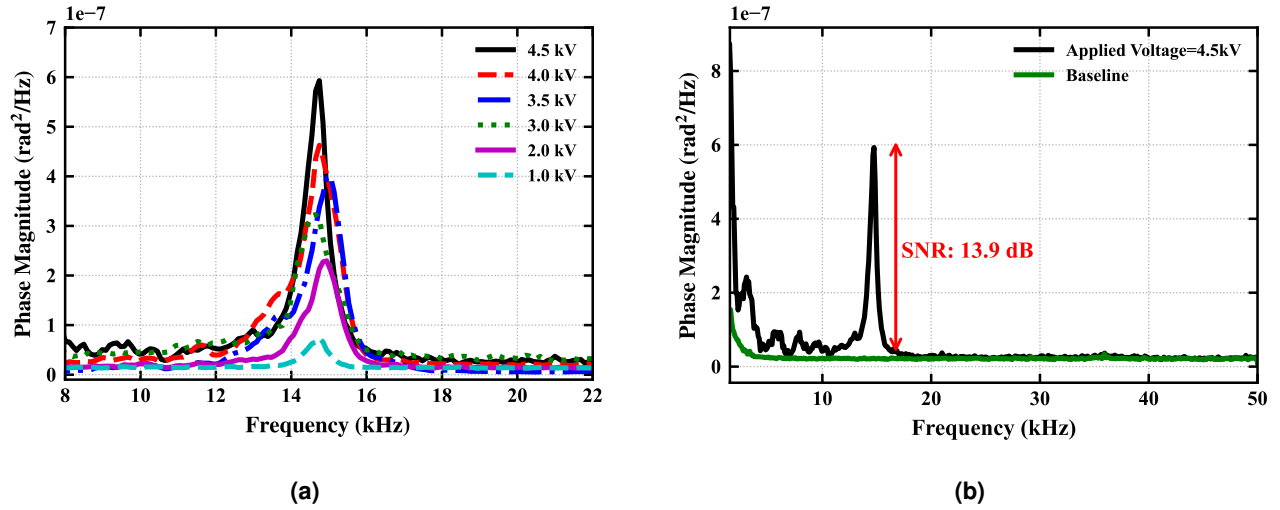


Figure 6. (a) Spectral power density of acoustic signals captured by the DAS system under varying applied voltages. (b) Spectral signal-to-noise ratio (SNR) analysis of the DAS phase signal at an applied voltage of 4.5 kV

As the applied voltage increased, the spectral magnitude at the dominant frequency increased progressively, reflecting the generation of stronger acoustic emissions under higher electrical stress. At 1.0 kV, the spectral peak was relatively weak, indicating limited discharge activity. With increasing voltage, the peak amplitude increased continuously, demonstrating a clear correlation between the applied voltage and the acoustic energy captured by the DAS system.

The background spectral noise floor remained comparatively stable across all voltage conditions, maintaining a clear separation from the dominant discharge component. The combination of an increasing spectral magnitude with a nearly invariant characteristic frequency indicates that the proposed DAS system is capable of distinguishing variations in discharge intensity while preserving a stable spectral signature. These findings suggest that the dominant resonance frequency may serve as a reliable spectral fingerprint for monitoring the evolution of surface discharge activity and insulation degradation.

To further quantify the detectability of the discharge-induced acoustic emissions, a spectral signal-to-noise ratio (SNR) analysis was performed for the 4.5 kV measurement, which exhibited the strongest acoustic response. The dominant spectral peak at approximately 14.8 kHz was compared with the average background noise floor within the 30–50 kHz frequency range. As shown in Fig. 6(b), the resulting SNR was 13.9 dB, indicating a clear separation between the discharge-induced acoustic signal and the background noise. The high SNR confirms that the proposed signal-processing framework effectively enhances the detectability of discharge events and enables reliable identification of the characteristic acoustic signature under high electrical stress.

Temporal validation of DAS measurements using synchronized leakage-current measurements

Leakage-current (LC) measurements, a conventional electrical diagnostic for surface discharge, were simultaneously acquired to provide an independent reference for validating the acoustic responses detected by the distributed acoustic sensing (DAS) system. By synchronizing the electrical and acoustic measurements, the temporal relationship between discharge initiation and the corresponding acoustic emission was directly evaluated.

Fig. 7(a) compares the differentiated leakage-current waveform with the corresponding TKEO-enhanced DAS phase response. Peak detection was performed using a local maxima detection algorithm to identify individual discharge events in

both synchronized signals. Leakage-current pulses were followed by corresponding acoustic transients in the synchronized DAS signal. The consistent agreement between the two measurements confirms that the transient acoustic responses originate from electrical discharge activity rather than random environmental disturbances.

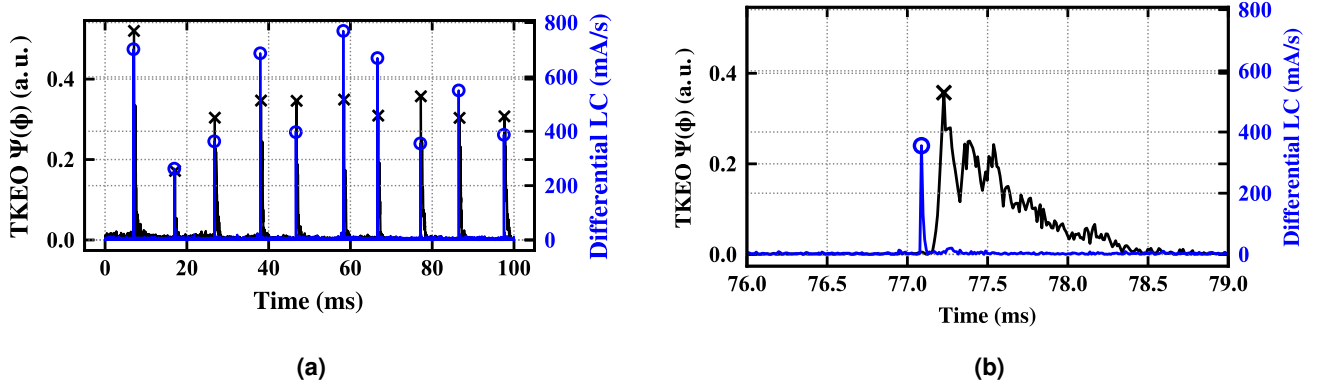


Figure 7. Experimental results: (a) Temporal correlation with differentiated LC via peak matching. (b) Delay between LC and TKEO envelope.

To further verify the physical origin of the detected acoustic signals, the discharge-to-fiber separation distance was varied while maintaining identical experimental conditions. Figure 7(b) presents the measured propagation delay between the leakage-current pulse and the corresponding DAS transient for discharge-to-fiber separation distances of 5 cm and 15 cm. The average propagation delay increased from 0.177 ± 0.029 ms at a separation distance of 5 cm to 0.471 ± 0.029 ms at 15 cm, demonstrating a clear dependence of the measured delay on the propagation distance between the discharge source and the sensing fiber.

Although the absolute propagation delay may include a constant offset introduced by the data acquisition system, synchronization circuitry, and signal-processing stages, the measured increase in delay of approximately 0.294 ms between the two experimental configurations is consistent with the additional acoustic travel time associated with the increased discharge-to-fiber separation. This behavior strongly supports the interpretation that the detected DAS transients arise predominantly from airborne acoustic waves generated by the electrical discharge.

The close temporal correspondence between the synchronized leakage-current and DAS measurements, together with the experimentally observed increase in propagation delay with increasing discharge-to-fiber separation, provides independent validation of the proposed sensing approach. These results demonstrate that distributed acoustic sensing can reliably monitor the temporal evolution of surface discharge activity while simultaneously providing the advantages of non-contact and spatially distributed sensing.

Simultaneous acoustic and thermal monitoring using DAS and DTS

Electrical insulation degradation involves both transient electrical discharge activity and gradual thermal accumulation. Distributed acoustic sensing (DAS) and distributed temperature sensing (DTS) respond to these two phenomena differently, providing complementary diagnostic information. DAS is highly sensitive to the impulsive acoustic emissions generated during individual discharge events, enabling early detection of discharge activity before significant heating develops. In contrast, DTS measures the cumulative temperature rise produced by sustained leakage current and dry-band arcing, thereby reflecting the thermal consequences of prolonged degradation.

Fig. 8 compares the DAS phase variance and the DTS temperature profile measured along the sensing fiber during the inclined plane test. A localized anomaly is observed near the 810 m sensing position, where both the acoustic activity and temperature increase significantly relative to the surrounding fiber. The DTS profile shows a localized temperature increase, while the DAS phase variance increases at the corresponding fiber position, indicating co-located thermal and acoustic activity.

By combining the rapid transient sensitivity of DAS with the distributed thermal monitoring capability of DTS, the proposed approach enables reliable localization of insulation degradation while simultaneously assessing its electrical activity and thermal severity. Such complementary measurements provide a more robust basis for condition monitoring of high-voltage insulation systems than acoustic or thermal sensing alone.

While the preceding experimental results validate the sensing performance under laboratory conditions, it is also important to compare the proposed methodology with established insulation condition-monitoring techniques. Table 2 summarizes the capabilities of the proposed DAS–DTS framework relative to conventional diagnostic approaches.

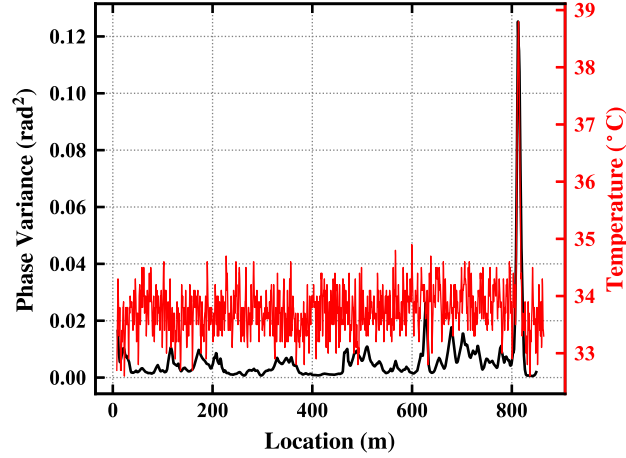


Figure 8. Spectral power density of acoustic signals captured by our DAS receiver and the corresponding temperature change at that location measured using the DTS receiver. The strong correlation between the two provides a robust detection of the electric discharge at that location.

Table 2. Comparison of the proposed DAS–DTS framework with conventional insulation condition-monitoring techniques.

Property	Visual In- spection	Leakage Current	UHF	UV/IR Imaging	Emission Spectroscopy	Fluorescent Fiber	Proposed Method (DAS– DTS)
Non-contact	Yes	No	No	Yes	Yes	Yes	Yes
Remote Monitoring	No	Partial	Yes	Yes	No	Yes	Yes
Early Tracking	No	No	Partial	Partial	Yes	Yes	Yes
EMI Immunity	Yes	No	No	Yes	Yes	Yes	Yes
Localization	No	No	Yes	Yes	No	Partial	Yes
Multiple Fault Detection	No	No	No	No	No	No	Yes
Continuous Distributed Monitoring	No	No	No	No	No	No	Yes
Multi-parameter Sensing	No	No	No	No	No	No	Yes
Measurement Type	Visual	Point	Point	Image	Point	Point	Distributed
Sensing Range	Visual range	Point only	Near sensor	Line-of- sight	Point only	Point only	Long- range (km)
Automation	No	Yes	Yes	No	No	Yes	Yes
Field Suitability	Low	High	Low	Moderate	Low	Moderate	High
Representative References	–	5,6	9	7,8	10	12–14	This work

As summarized in Table 2, conventional monitoring techniques typically provide only a single diagnostic modality, such as electrical, optical, or thermal information, and are often limited by point-based measurements, electromagnetic interference, or restricted spatial coverage. In contrast, the proposed DAS–DTS framework combines distributed acoustic and thermal sensing using a common optical fiber, enabling simultaneous localization of discharge activity, monitoring of thermal evolution, and immunity to electromagnetic interference over extended sensing distances. These complementary capabilities provide a more comprehensive assessment of insulation degradation during accelerated inclined-plane testing and demonstrate the feasibility of the proposed DAS–DTS framework for distributed monitoring of surface tracking. Although the present validation was performed under controlled laboratory conditions, the results indicate the potential of this approach for future continuous

condition monitoring of high-voltage power-system assets.

Conclusion

In this work, we present a distributed fiber-optic sensing framework for monitoring electrical surface discharge and insulation degradation using distributed acoustic sensing (DAS) and distributed temperature sensing (DTS). The DAS system successfully captured the evolution of acoustic emissions throughout the inclined plane test, enabling the identification of key degradation stages including discharge initiation, dry-band formation, bright-spot development, and continuous surface tracking. Signal enhancement using the Teager–Kaiser Energy Operator (TKEO) improved the detectability of transient discharge signatures while maintaining the low computational complexity required for real-time distributed sensing applications.

The proposed sensing methodology was further validated through spectral analysis, applied-voltage investigations, and synchronized leakage-current measurements. A characteristic acoustic component centered near 14.8 kHz was consistently observed during discharge activity, while increasing applied voltage produced progressively stronger acoustic responses, demonstrating the sensitivity of DAS to discharge severity. The close temporal agreement between DAS and conventional leakage-current measurements confirmed the reliability of the proposed approach for monitoring electrical discharge events.

The complementary integration of DAS and DTS further demonstrated the capability of distributed fiber-optic sensing to simultaneously monitor transient acoustic activity and localized thermal evolution associated with insulation degradation. Unlike conventional point-based diagnostic techniques, the proposed framework provides distributed spatial coverage, immunity to electromagnetic interference, and complementary acoustic and thermal information using a common optical fiber.

Overall, the results demonstrate that integrated distributed fiber-optic sensing offers a promising approach for comprehensive condition monitoring of high-voltage insulation systems. By combining distributed acoustic sensing with distributed temperature sensing, the proposed framework enables continuous, spatially resolved monitoring of both the electrical and thermal evolution of insulation degradation using a common optical fiber. Future work will focus on validating the proposed methodology under practical operating conditions, investigating different insulation materials and fault mechanisms, and integrating advanced machine learning and deep learning algorithms for automated event detection, classification, and prognostic assessment. Such developments could facilitate intelligent, real-time condition monitoring of large-scale power-system assets, enabling predictive maintenance and improved operational reliability.

Methods

Experimental setup

Surface discharge experiments were conducted using the inclined plane test (IPT) in accordance with IEC 60587 to investigate the degradation characteristics of high-temperature vulcanized silicone rubber (HTV-SR) under controlled laboratory conditions. The HTV-SR specimen was mounted at an inclination angle of 45° between the high-voltage and grounded electrodes. A contaminant solution consisting of ammonium chloride (NH₄Cl) and Triton X-100 as a non-ionic surfactant was continuously supplied onto the specimen surface using a peristaltic pump. The contaminant solution was maintained at a conductivity of 2.5 mS/cm with a flow rate of 0.6 mL/min to reproduce polluted service conditions. A total of 3 polymeric insulator specimens were tested. Each specimen was evaluated in 5 independent experimental runs for ≈ 6h (or until failure according to the IEC 60587 criterion). Across all experiments, a total of 1750 discharge events were recorded and analysed.

An AC voltage of up to 4.5 kV rms was applied across the specimen to initiate and sustain surface-discharge activity. During the experiment, the degradation process progressed through discharge initiation, dry-band formation, localized arcing, and eventually carbonized surface tracking.

The overall experimental arrangement is illustrated in Fig. 2. Distributed acoustic sensing (DAS) and distributed temperature sensing (DTS) measurements were acquired throughout the inclined plane test to monitor the acoustic and thermal evolution of insulation degradation. To enable direct comparison between the distributed acoustic sensing (DAS) measurements and the conventional leakage-current signal, both signals were synchronously acquired using a 14-bit, 1 GS/s data acquisition (DAQ) system equipped with four input channels and hardware triggering capability. The output of the photodetectors corresponding to the optical signals and the leakage-current sensor output were recorded simultaneously on separate channels of the DAQ. A common hardware trigger was used to initiate data acquisition, ensuring precise temporal synchronization between the optical and electrical measurements. This synchronized acquisition enabled accurate peak matching and delay estimation between the DAS and leakage-current signals during subsequent analysis.

Distributed fiber-optic sensing system

The distributed fiber-optic sensing system integrates phase-sensitive optical time-domain reflectometry (ϕ -OTDR) for distributed acoustic sensing (DAS) and Raman-based distributed temperature sensing (DTS) using a common single-mode optical fiber. A narrow-linewidth coherent laser operating at 1550.12 nm with a linewidth below 4 kHz was employed as the optical source for

both sensing modalities. The continuous-wave output from the laser was modulated into optical pulses using an acousto-optic modulator (AOM), amplified by an erbium-doped fiber amplifier (EDFA), and launched into the sensing fiber through an optical circulator. To suppress amplified spontaneous emission (ASE) noise introduced by the EDFA, a fiber Bragg grating (FBG) filter was incorporated before the sensing fiber.

The sensing fiber was positioned approximately 15 cm from the center of the inclined-plane test specimen to capture discharge-induced acoustic emissions. Initially, a 5 m coiled fiber section was placed at the 810 m sensing position. To demonstrate the distributed sensing capability, an additional coiled fiber section was subsequently introduced at 1560 m, enabling identical discharge events to be detected at two independent locations along the same sensing fiber. The total sensing fiber length was 1640 m.

As the optical pulses propagated through the sensing fiber, both Rayleigh and Raman backscattered signals were generated. The Rayleigh backscatter was used for DAS measurements, whereas the Raman Stokes and anti-Stokes components were used for DTS measurements. The backscattered signals were separated using a Raman filter. The Raman signals were detected using avalanche photodiodes (APDs), while the Rayleigh backscattered signal was coherently mixed with the local oscillator derived from the same laser source and detected using an 80 MHz balanced photodetector (BPD). The detected signals were digitized using a 14-bit, 1 GS/s data acquisition (DAQ) system.

For DAS measurements, optical pulses with a width of 100 ns and a peak power of 175 mW were launched into the sensing fiber. The pulse repetition frequency (PRF) was initially set to 100 kHz for 860 m and then set to 50 kHz, corresponding to the 1640 m sensing fiber length, to ensure complete acquisition of the Rayleigh backscattered signal without temporal overlap between successive pulses. A gauge length of 10 m was employed to provide an appropriate balance between acoustic sensitivity and spatial resolution. For DTS operation, the interrogator was configured with the same PRF of 50 kHz. The Raman backscattered signals were averaged over 10 s (approximately 5×10^5 acquisitions) to improve the signal-to-noise ratio and enhance the temperature measurement accuracy.

Signal processing and data analysis

Fig. 9 summarizes the signal-processing workflow used to extract acoustic and thermal information from the distributed fiber-optic sensing system. The acquired DAS and DTS signals were processed independently before being combined with synchronously acquired leakage-current measurements for quantitative analysis.

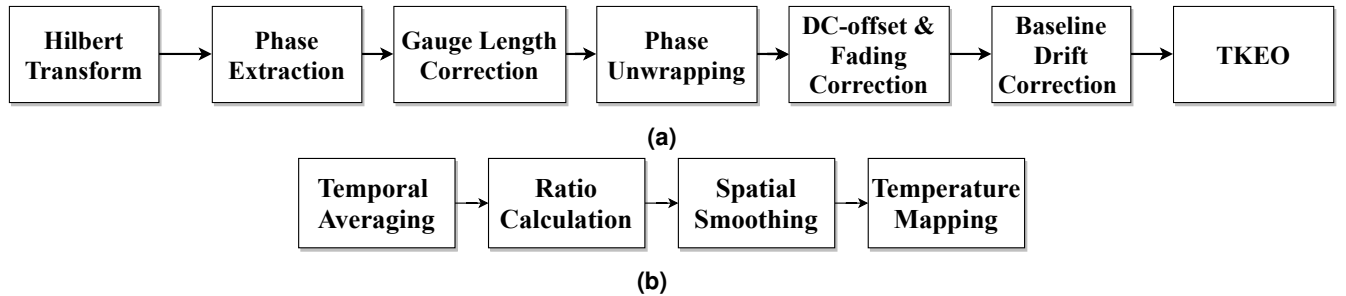


Figure 9. (a) DAS Signal Processing Flow chart (b) DTS Signal Processing Flow chart

The coherent Rayleigh backscattered signal was processed to recover the distributed phase response along the sensing fiber. The quadrature component was reconstructed using a Hilbert transform, followed by phase unwrapping and gauge-length processing to obtain dynamic phase variations induced by acoustic perturbations. Background drift and coherent fading were suppressed prior to transient enhancement.

The processed phase signal was subsequently enhanced using the Teager–Kaiser Energy Operator (TKEO), which estimates the instantaneous energy of a signal by jointly considering its amplitude and local frequency variations. Unlike conventional energy estimation techniques that rely primarily on signal amplitude, the nonlinear nature of the TKEO provides high sensitivity to short-duration impulsive events while naturally suppressing slowly varying background components. This characteristic makes it particularly suitable for detecting acoustic emissions generated by electrical surface discharges.

The discrete-time TKEO is defined as

$$\Psi[\phi(t)] = \phi^2(t) - \phi(t-1)\phi(t+1), \quad (1)$$

where $\phi(t)$ represents the recovered DAS phase signal.

During surface discharge, localized plasma formation generates impulsive acoustic waves that induce rapid phase fluctuations within the sensing fiber. In contrast, environmental disturbances such as structural vibration, thermal drift, and mechanical motion generally produce slowly varying phase changes. Since the TKEO simultaneously responds to instantaneous amplitude and frequency, discharge-induced transients produce significantly larger energy values than low-frequency background disturbances, thereby improving their detectability without requiring computationally intensive signal decomposition techniques. Furthermore, the operator relies solely on local arithmetic operations involving adjacent samples, making it computationally efficient for continuous real-time DAS applications operating at high acquisition rates.

To isolate discharge events, a statistical threshold based on three times the standard deviation of the TKEO output was employed. The 3σ threshold was selected because, for approximately Gaussian background fluctuations, values exceeding 3σ have a probability of only about 0.27% of arising from random noise. This criterion provides an effective compromise between detection sensitivity and false-positive rejection. A binary mask was generated according to

$$Mask(t) = \begin{cases} 1, & \Psi[\phi(t)] > 3\sigma \\ 0.5, & \sigma < \Psi[\phi(t)] \leq 3\sigma \\ 0, & \text{otherwise,} \end{cases} \quad (2)$$

where σ denotes the standard deviation of the TKEO output. The resulting mask was multiplied with the original phase signal to retain only high-energy transient components associated with discharge activity while suppressing low-energy background fluctuations. Since the masking operation does not introduce phase distortion or group delay, the temporal characteristics of the detected discharge events are preserved for subsequent localization and correlation analysis.

For DTS measurements, the spontaneous Raman backscattered signals were processed to obtain the distributed temperature profile along the sensing fiber. Since the Raman backscattered intensity is inherently weak, consecutive traces were averaged over a 10 s acquisition period to improve the signal-to-noise ratio prior to temperature estimation. The temperature at each position along the fiber was determined from the ratio of the anti-Stokes and Stokes Raman backscattered intensities, which exhibits an exponential dependence on temperature and provides distributed temperature measurements independent of local optical power variations. To further suppress measurement fluctuations while preserving localized thermal gradients associated with surface discharge activity, total variation denoising (TVD) was applied to the reconstructed temperature profile. The resulting distributed temperature measurements were spatially aligned with the DAS responses, enabling simultaneous characterization of the transient acoustic emissions and the gradual thermal evolution associated with insulation degradation.

Data availability

The datasets generated and analyzed during the current study are available from the corresponding author upon reasonable request.

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Author contributions

R.V.R. developed the DAS–DTS systems, performed the signal processing and data analysis, and wrote the manuscript. A.R. designed and conducted the high-voltage inclined-plane tracking experiments, performed the electrical and leakage-current measurements, and contributed to the experimental investigation. H.P.S. contributed to the implementation of the DAS–DTS systems. S.R. supervised the high-voltage experiments and provided expertise in high-voltage insulation and tracking phenomena. B.S. conceived the research idea, supervised the distributed fiber-optic sensing research, provided expertise in distributed fiber-optic sensing, and contributed to the interpretation of the results. All authors reviewed and approved the final manuscript.

Competing interests

The authors declare no competing interests.

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