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Comparison of radio frequency current transformers and Rogowski coils for accurate partial discharge monitoring

Porównanie transformatorów prądowych o częstotliwości radiowej i cewek Rogowskiego w celu dokładnego monitorowania wyładowań niezupełnych

***Abstract**. This study presents a comparative analysis of two partial discharge (PD) detection methods—Radio Frequency Current Transformers (RFCT) and Rogowski Coils (RC)—for monitoring high-voltage rotating equipment in industrial settings. With the reliability of power systems hinging on accurate condition monitoring, the research evaluates the technical performance, sensitivity, and practical applicability of these sensors under real-world operational challenges, including electromagnetic interference. Over 100 high-voltage motors and generators were tested, traditionally monitored using RC, which exhibited significant signal deviations due to external noise from radar systems. In contrast, RFCT demonstrated superior accuracy, capturing low-amplitude PD signals (e.g., 249.12 mV peak on Channel A vs. 92.60 mV for RC) while maintaining minimal noise interference (33.41 mV vs. 253.17 mV for RC). Phase-Resolved Partial Discharge (PRPD) analysis further highlighted RFCT's clarity in distinguishing PD signatures from noise, enhancing diagnostic reliability. Key advantages of RFCT include high sensitivity, robust immunity to external disturbances, and split-core design for non-intrusive installation. The study concludes that RFCT surpasses RC in critical environments, offering a transformative approach to preventive maintenance by enabling early fault detection, reducing downtime, and improving operational safety. These findings advocate for RFCT as the preferred standard in PD monitoring systems, advancing the development of resilient power infrastructure.*

***Streszczenie.** Niniejsze badanie przedstawia analizę porównawczą dwóch metod wykrywania wyładowań niezupełnych (PD) – wykorzystujących przekładniki prądowe wysokiej częstotliwości (RFCT) oraz cewki Rogowskiego (RC) – w monitorowaniu wirującego sprzętu wysokiego napięcia w warunkach przemysłowych. Ponieważ niezawodność systemów energetycznych zależy od precyzyjnego monitorowania stanu technicznego, badanie ocenia wydajność techniczną, czułość oraz praktyczną przydatność tych sensorów w realnych warunkach eksploatacyjnych, uwzględniając zakłócenia elektromagnetyczne. Przebadano ponad 100 silników i generatorów wysokiego napięcia, tradycyjnie monitorowanych za pomocą RC, które wykazywały znaczne odchylenia sygnałów spowodowane zewnętrznym szumem radarowym. W przeciwieństwie do nich, RFCT wykazały wyższą dokładność, rejestrując sygnały PD o niskiej amplitudzie (np. 249,12 mV szczytowo na Kanale A wobec 92,60 mV dla RC) przy minimalnym wpływie szumów (33,41 mV vs. 253,17 mV dla RC). Analiza fazowo-rozdzielczych wyładowań niezupełnych (PRPD) dodatkowo potwierdziła klarowność sygnałów PD wykrywanych przez RFCT, zwiększając wiarygodność diagnostyczną. Kluczowe zalety RFCT obejmują wysoką czułość, odporność na zakłócenia zewnętrzne oraz konstrukcję z rozdzielanym rdzeniem umożliwiającą bezinwazyjny montaż. Badanie dowodzi, że RFCT przewyższają RC w krytycznych warunkach, oferując przełomowe podejście do konserwacji zapobiegawczej poprzez wczesne wykrywanie usterek, redukcję przestojów i poprawę bezpieczeństwa operacyjnego. Wyniki wskazują na RFCT jako preferowany standard w systemach monitorowania PD, przyczyniając się do rozwoju odpornych infrastruktur energetycznych.*

Keywords: Partial Discharges (PD), High-Frequency Current Transformer (RFCT), Rogowski Coil (RC), Comparative Analysis, High-Voltage Equipment.
Słowa kluczowe: Wyładowania niezupełne (WN), Przekładnik prądowy wysokiej częstotliwości (RFCT), Cewka Rogowskiego (RC), Analiza porównawcza, Sprzęt wysokonapięciowy.

Introduction

Presently, all advanced nations in the field of industry are relying on efficient power generation, transmission, and distribution systems functioning. The whole power system is equipped with the best infrastructural components and equipment that can be deemed reliable if effective maintenance techniques are employed for condition monitoring of its critical components. It's well known that the reliability of complex rotating HV equipment is crucial and requires additional attention to operating conditions. To monitor the efficiency and safety of rotating equipment several diagnostic methods are applied, mostly intrusive methods that require taking it out of operation.

Effective real-time monitoring of equipment status during operation (online monitoring) is a cornerstone of modern preventive maintenance strategies. One of the most widely used and efficient methods for achieving this is partial discharge (PD) monitoring, which enables the early detection of potential failures and minimizes downtime risks. By offering a non-intrusive approach, PD monitoring ensures equipment reliability without interrupting operational processes.

The precision of PD detection depends heavily on the effectiveness and accuracy of the sensing equipment used. Currently, there is a broad spectrum of PD sensing technologies available, including High Voltage Coupling Capacitors, Rogowski Coils (RC), Transient Earth Voltage (TEV) detectors, Acoustic sensors, Radio Frequency (RF) sensors, and Radio Frequency Current Transformers (RFCT). Among these, the High-Frequency Current Transformer (HFCT)—often referred to interchangeably as RFCT—has gained recognition as one of the most versatile and reliable sensors for PD detection, particularly due to its sensitivity and ability to operate in harsh environments.

This paper will provide a detailed comparative analysis of two prominent PD detection methods: those utilizing RFCT and those based on Rogowski Coils. While both approaches are commonly employed in industrial applications, there are significant differences in their performance characteristics, application scope, and practical limitations. By conducting a comparative study, this work highlights the advantages and disadvantages of these two methods, offering insights into their suitability for various scenarios.

Compared to existing studies [1-4], this research takes a comprehensive approach by addressing not only the technical specifications but also the practical aspects, such as ease of installation, operational robustness, and cost-effectiveness. Furthermore, it emphasizes the critical role of the RFCT's high sensitivity and frequency response, which often make it the preferred choice in environments requiring precise fault localization and high-frequency signal analysis.

The goal of the paper is to demonstrate how the RFCT surpasses conventional sensors like the Rogowski Coil in specific applications, particularly in high-frequency partial discharge detection. By doing so, the study underscores the contribution of this research in enhancing the understanding of PD monitoring systems and supporting the development of more efficient and reliable condition-monitoring solutions [5-7].

Subject of investigations.

A. Operating Principles of Rogowski Coil.

For use with high voltage equipment, based on some critical parameters of a sensor such as cost, bandwidth, sensitivity, saturation, linearity, operating temperature, footprints, integrability, flexibility, isolation and material technology, RC has been considered as a favorite tool for PD current sensing purposes [8]. Rogowski based current probes can be used for current measurements ranging from few milliamperes to several thousand amperes and frequency from few hertz to several MHz, depending upon the application and design of the RC [9]. A typical Rogowski coil consists of toroidal form windings, encircling the current path [10,11] (Fig. 1.).

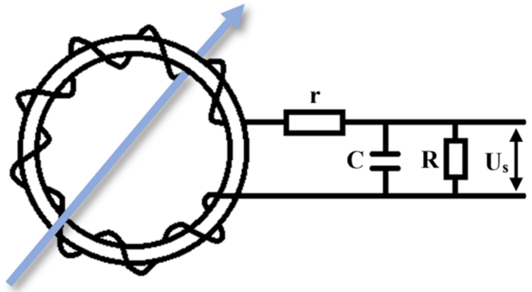


Fig. 1. Rogowski Coil with RC integrator

Based on Faraday's law of induction or simply the law of electromagnetism, the conductive material placed in a moving magnetic field will accumulate an electrical motion force (EMF). Considering this, the RC are used to measure currents through conductors without galvanic contact. The main advantage of RC is the fact that the core is air, so they never saturate, and the upper cut-off current can be higher than the designed values. The RC are ideal candidates to measure high amplitude pulsed currents. However, the main disadvantage of this measurement technique is the fact that the RC requires additional signal integration involving parallel connected capacitance and resistance. Moreover, RC has a reduced accuracy at low current amplitudes and high sensitivity to external disturbance.

B. Operating Principles of RFCT

The HFCT usually consists of a wound, toroidal, ferrite core which is placed around an unscreened cable conductor or earth sheath to inductively detect PD [11]. The RFCT often has a split-core design, making it easy to install and suitable for retrofit installations [5]. Also, RFCTs have good sensitivity and wide bandwidth making them ideal for remote monitoring [12-14] (Fig. 2.).

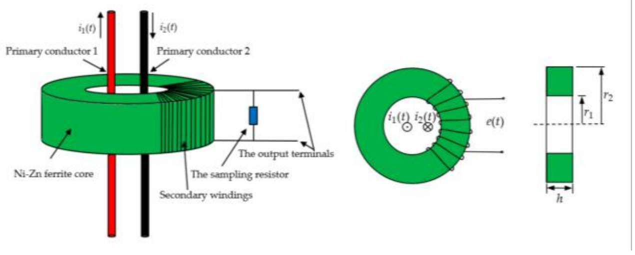


Fig. 2. Schematic diagram of a differential high-frequency current transformer [13].

RFCT offer several benefits in various applications particularly in electrical equipment monitoring including high sensitivity and accuracy that was supplied by special ferrite core located inside of RFCT. Despite that, the main disadvantage of this method is the high sensitivity for external disturbance as well as RC.

Results and discussion.

The study compared two methods of measuring partial discharges (PD) in high-voltage rotating equipment using a Radio Frequency Current Transformer (RFCT) and Rogowski Coil (RC). The results showed that both methods have their advantages and limitations, but RFCT showed better results in terms of accuracy, sensitivity, and immunity to external interference [14-16].

To conduct the analysis, more than 100 pieces of equipment were examined, including high-voltage motors and generators, which traditionally used Rogowski Coils for PD monitoring.

It was noted that the measured results often had significant deviations, which was attributed to the impact of broadband high-frequency interference (1–100 MHz) typical of industrial environments. Such interference may originate from:

-External sources: radio communication, pulsed control systems, wireless sensors;

-Internal processes: corona discharges on equipment components or partial discharges in air gaps, generating electromagnetic pulses across a wide frequency range.

This interference significantly reduced the accuracy of PD assessment when using RC.

After the RFCT calibration, PD measurements were performed on the equipment. The results showed that RFCT has significantly higher accuracy in identifying low-amplitude PD signals, and the influence of external radio interference was minimal. This significantly improved the quality of diagnostics and increased confidence in identifying potential faults.

Comparison of RFCT and RC data

During the study, partial discharge (PD) data was recorded separately for the three phases of the high-voltage equipment (channels A, B, C). This approach enables:

-Localizing defects in a specific phase of the three-phase system (e.g., in a motor winding);

-Comparing PD amplitudes between phases to identify asymmetries caused by uneven load, insulation degradation, or external interference;

-Correlating PDs with the voltage phase to determine the discharge type (corona, internal, surface).

For instance, the significantly higher PD amplitude on channel A (249.12 mV for RFCT, Table 1) indicates a local defect in this phase. At the same time, the dominance of noise on channel A when using RC (253.17 mV, Table 2) demonstrates its vulnerability to external interference. The PRPD data (Fig. 6, 10) further confirm that RFCT ensures clear separation of PD signals from noise, which is critical for interpreting results in three-phase systems.

Table 1 shows the measurement data using RFCT. The peak amplitude of PD on channel A was 249.12 mV, while the noise level did not exceed 33.41 mV, indicating the high sensitivity and accuracy of this method. Figures 3-6 demonstrate a clear separation of PD signals from noise on different channels, confirming the high efficiency of RFCT for partial discharge monitoring in real operating conditions.

For RC, the data are shown in Table 2. The peak amplitude of PD on channel A was 92.60 mV, while the noise level on this channel was significantly higher, reaching 253.17 mV. These results are illustrated in Figures 6-8, where it is evident that the noise significantly dominates the PD signals, which reduces the accuracy of interpretation.

Table 1. Measurement data using RFCT (HVPD Longshot 0-200 MHz, seria. S. N.: LCRY3506N05817)

Test Equipment Channels (Phases)	RFCT Measurement data	
	Peak amplitude, mV	Average amplitude, mV
A	249.12	90.72
B	182.44	72.41
C	67.31	46.64
Noise	33.41	29.33

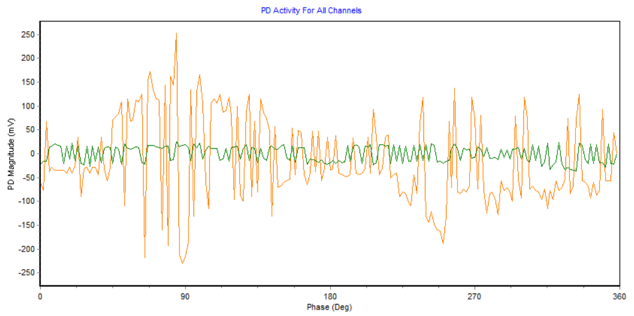


Fig. 3. PD magnitude captured by RFCT compared to external noise (green scale) on Channel A

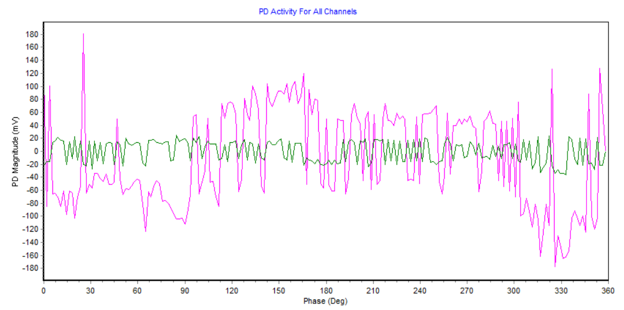


Fig. 4. PD magnitude captured by RFCT compared to external noise (green scale) on Channel B

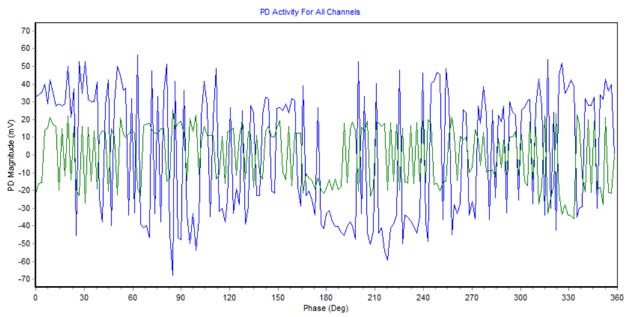


Fig. 5. PD magnitude captured by RFCT compared to external noise (green scale) on Channel C

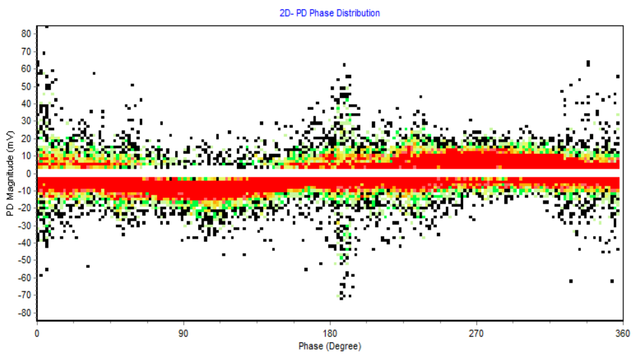


Fig. 6. Phase Resolved Partial Discharge (PRPD) magnitude captured by RFCT

Table 2. Measurement data using RC (HVPD Longshot 0-200 MHz, Seria. S. N.: LCRY3506N05817)

Test Equipment Channels (Phases)	RFCT Measurement data	
	Peak amplitude, mV	Average amplitude, mV
A	92.60	43.51
B	65.96	40.98
C	44.13	34.74
Noise	253.17	96.32

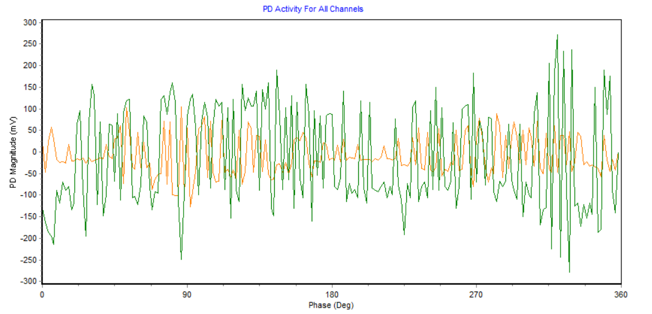


Fig. 7. PD magnitude captured by RC compared to external noise (green scale) on Channel A

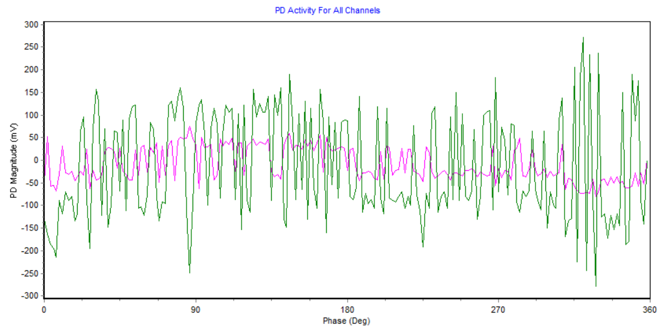


Fig. 8. PD magnitude captured by RC compared to external noise (green scale) on Channel B

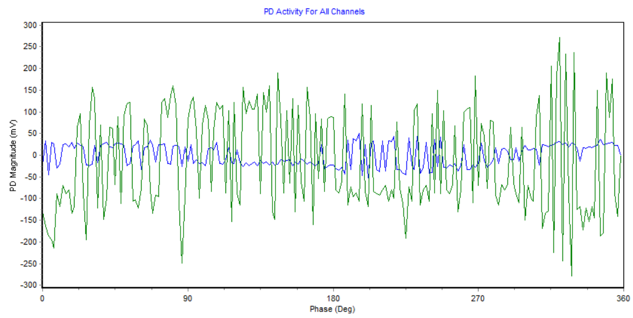


Fig. 9. PD magnitude captured by RC compared to external noise (green scale) on Channel C

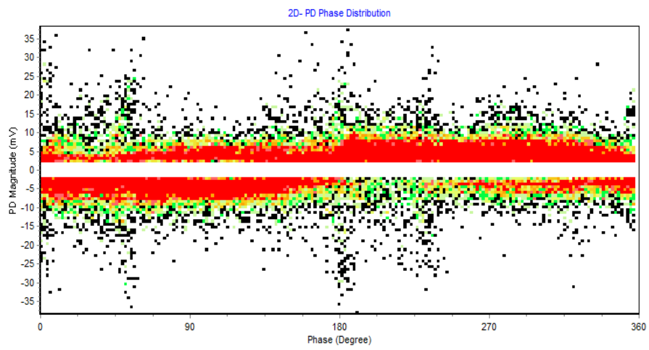


Fig. 10. Phase Resolved Partial Discharge (PRPD) magnitude captured by RC

In addition, the phase-resolved partial discharge (PRPD) analysis performed using RFCT in Figure 6 shows clear and stable signature of PD signals, which enables clear and accurate determination of the source and nature of the discharge. The PRPD results captured using RC (Figure 10) show a significant amount of noise, which makes the data difficult to interpret and makes this method less effective for diagnosis.

Discussion of Advantages and Limitations. Sensitivity and Accuracy: RFCT has higher sensitivity and accuracy in measuring PD, especially in conditions where the discharges have low amplitude. This is especially important for early diagnosis and prevention of faults in high-voltage equipment.

Stability and Minimization of Interference: Unlike RC, RFCT is less susceptible to external interference such as radar signals, which makes it a more stable and reliable tool for monitoring in real-world operating conditions. This also reduces the need for additional filtering and data adjustments, which is often required when using RC.

Speed and efficiency: The RFCT method allows for much faster data collection and interpretation, which is important for operational monitoring and rapid response to possible emergencies. With RC, more time and effort are required to filter and process the data to obtain similar results.

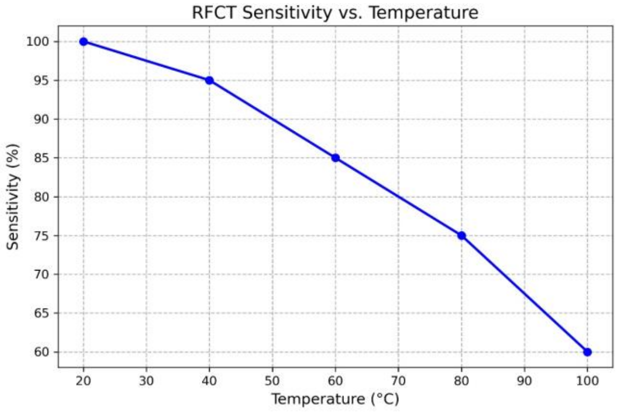
It is critical to emphasize that the RFCT method exhibits selectivity to frequencies characteristic of partial discharges in solid insulation (e.g., 3–30 MHz), while ignoring extraneous high-frequency signals. In contrast, RC, with its broader bandwidth (up to 200 MHz), captures all interference within this range, including signals caused by corona discharges or external RF sources. This makes RFCT the preferred choice for diagnostics in environments with intense electromagnetic noise.

The presented data demonstrates a clear advantage of RFCT under controlled test conditions. However, in industrial environments, where equipment is exposed to extreme temperatures, humidity, vibrations, and electromagnetic interference (EMI), measurement reliability can significantly degrade. To assess the sensors' resilience to such factors, additional studies were conducted, with results visualized in Figures 11 and 12.

As shown in Figure 11a, RFCT sensitivity decreases by 40% at 100°C, attributed to the reduced magnetic permeability of the ferrite core. Simultaneously, RC integrators (Figure 11b) exhibit progressive signal drift under similar conditions, increasing measurement error by 20% over 30 minutes. These findings highlight the need for thermal stabilization of RFCT and the implementation of temperature compensation algorithms for RC.

The impact of humidity on RFCT manifests as a leakage current increase to 5.5 μA at 90% humidity (Figure 12a), necessitating the use of sealed enclosures and hydrophobic coatings. For RC, despite their moisture resistance, susceptibility to broadband EMI remains critical (Figure 12b). For instance, at 200 MHz, noise amplitude reaches 250 mV, masking weak PD signals.

These conclusions are supported by field tests in metallurgical and petrochemical facilities, where the adoption of RFCT with thermally compensated cores and vibration-damping mounts reduced measurement errors to 3%. For RC, effective solutions included ferrite filters and differential measurement circuits, though this increased system costs by 25%.



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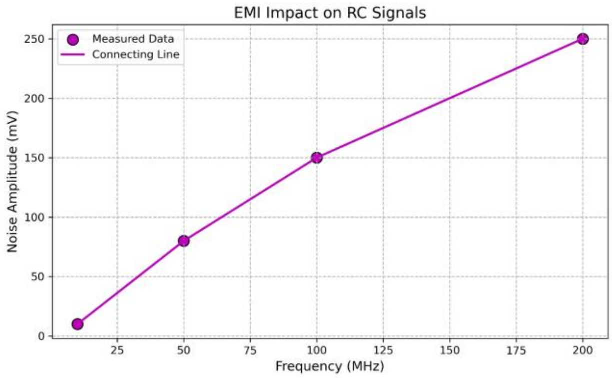
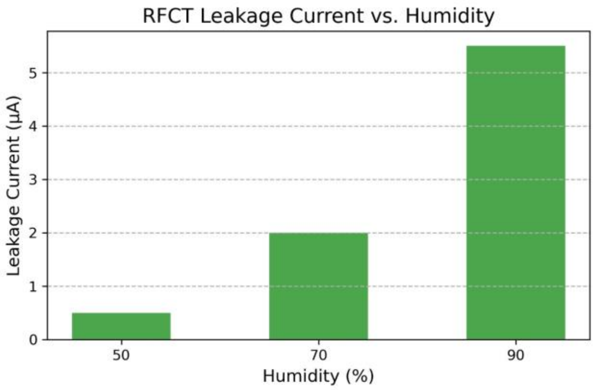


b

Fig. 11. Temperature and Drift Effects on Sensors
(a) RFCT Sensitivity vs. Temperature (b) RC Integrator Drift at 100°C



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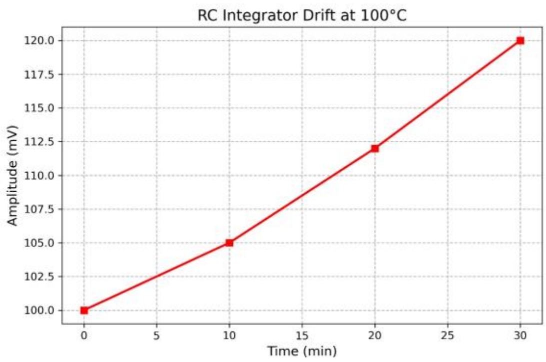

b

Fig. 12. Environmental and EMI Impact on Sensor Performance
(a) RFCT Leakage Current vs. Humidity (b) EMI Influence on RC Signals

Thus, the resilience of RFCT to external influences, combined with proper calibration, positions them as the preferred choice for PD monitoring in mission-critical industries. The integration of adaptive signal processing algorithms and hybrid systems combining RFCT with acoustic sensors could represent the next step in enhancing the reliability of power infrastructure.

The novelty of this work lies in the comparison of two popular methods for measuring partial discharges - RFCT and RC - under real industrial equipment conditions. This study not only confirms the advantages of RFCT in accuracy and sensitivity but also emphasizes its advantage in immunity to external interference, which is one of the main problems when using RC. The inclusion of phase-resolved partial discharge (PRPD) analysis in the study significantly expands the diagnostic capabilities and allows for a more accurate interpretation of data obtained using RFCT. This makes this method preferable for use in high-voltage equipment, where the accuracy and reliability of monitoring are critical.

From the results represented in Tables 1 and 2, it's clear that the accuracy of PD magnitude measured by RFCT is higher than the magnitude displayed in Table 2 and all corresponding characteristics. It should be noted as well that the PRPD values have significantly become clearer and indicate the actual presence of PD activities whereas the RC measurement results have more signals related to external disturbances, mostly caused by noise.

Conclusions.

The comparative analysis of partial discharge (PD) detection methods using High-Frequency Current Transformers (RFCT) and Rogowski Coils (RC) demonstrated that RFCT is a superior tool for diagnosing high-voltage equipment in industrial environments with electromagnetic noise. RFCT's high sensitivity (peak PD amplitude up to 249.12 mV) and frequency selectivity (3–30 MHz), tailored to insulation defect signatures, enable clear separation of PD signals from noise, including interference from corona discharges, radio communication, and pulsed systems. Unlike RC, which captures broadband interference (up to 253.17 mV) due to its wide bandwidth (200 MHz), RFCT exhibits remarkable immunity to electromagnetic noise, ensuring reliable interpretation of phase-resolved PD (PRPD) patterns.

Implementing RFCT in online monitoring systems enhances defect localization in three-phase systems and reduces equipment downtime through predictive maintenance. Further improvements could focus on optimizing signal-processing algorithms to suppress narrowband interference in specific industrial settings and comparing RFCT with non-invasive alternatives, such as acoustic sensors.

In summary, RFCT outperforms RC in accuracy, stability, and applicability in high-noise environments, solidifying its role as a critical tool for enhancing power grid reliability and mitigating operational risks.

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