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Research Article

Vibration Analysis of Transformer as an Early Diagnosis of Internal Transformer Faults: (Case Study of Transformer #3 GIS Kemang)

Yuniar Rizky[1,2], Mohammad Adhitya[1*]
[1]Department of Mechanical Engineering, Faculty of Engineering, Universitas Indonesia, Depok, Indonesia
[2]Departement of Electrical Transmission Region West of Java, PT PLN Persero, Jakarta, Indonesia
*Corresponding Author: m.adhitya@ui.ac.id

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ABSTRACT

Transformers are vital in the distribution of power. Their reliability is of utmost importance. Over time, these machines can wear down, leading to potential failures and safety issues. This study aims to identify partial discharge in Transformer #3 GIS Kemang, which has been running for almost three decades. Acoustic Emission method is considered to examine its internal state and gauge the risks of failure. This method was prompted by a troubling rise in acetylene levels from the Dissolved Gas Analysis, revealing signs of arching. High-Frequency Current Transformer and Acoustic Emission sensors were placed in high-risk locations to track PD activity during regular operations. Data were collected in real time with a PowerPD TP500A system, allowing for the classification of PD events based on pulse intervals. The findings revealed a source of partial discharge on the HV/Tubular side. The AE Sensors captured a repeating butterfly-shaped pattern of wave with intervals of 20.332 milliseconds, and the HFCT sensors picked up bursts with intervals of 0.102 milliseconds. Following the Acoustic Emission and High-Frequency Current Transformer testing, a visual inspection of the transformer's internal components was conducted and confirmed the presence of discharge marks (treeing) on the pertinax magnetic shunt, corroborating the AE sensor data that indicated signs of electrical stress that could hasten the decay of insulation. Additionally, spot marks were observed on the insulation material surrounding the high-voltage (HV) Phase T winding, further supporting the hypothesis that electrical stress contributed to insulation breakdown.

Keywords: Transformer Vibration, Partial Discharge, Acoustic Emission, High-Frequency Current Transformer, Transformer Health Index, Transformer Assessment.

INTRODUCTION

The efficient and secure transfer of electrical energy is significantly facilitated by transformers in power transmission and distribution networks. These essential components are required to function reliably under a range of operational conditions, frequently for extended periods, often spanning several decades [1]. Nevertheless, as transformers age, they encounter a variety of stressors, including electrical, mechanical, and thermal loads, which progressively compromise their insulation systems[2]. This deterioration presents considerable risks, potentially resulting in internal failures, diminished performance, and expensive interruptions for maintenance or replacement [3]. Winding failures constitute one of the most common causes of power transformer failures, representing around 40% of all incidents, based on currently available data[4].

In transformers, factors including poor design, unavoidable local flaws (such as cracks and bubbles), and deteriorating insulating materials can cause the local electric field strength to increase and the breakdown electric field strength of the materials to decrease [5]. Whereas other places with stable local field strength will maintain their insulating properties, causing partial discharge (PD), discharges will first appear in locations with low breakdown electric field strength [6], [7]. The primary method for evaluating transformer insulation status is the identification of partial discharge (PD) events. Partial discharge denotes localised electrical discharges occurring within the dielectric medium, frequently serving as a precursor to potential insulation failure. The timely detection of PD is crucial, as it allows for the remediation of problems prior to the occurrence of severe operational failures.

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Within the context of high-voltage transformers, PD is regarded as a significant marker of insulation integrity or defects, thereby constituting a central element in strategies for condition monitoring [8].

Partial Discharge analysis is typically performed within the UHF band, which spans from 300 MHz to 1 GHz. In the course of partial discharge (PD) occurring within the transformer tank, around 15% of the electrical energy from the PD pulse is converted into mechanical energy, resulting in the production of acoustic waves [9]. A notable method for detecting partial discharge (PD) is Acoustic Emission (AE), which entails measuring sound waves generated by electrical discharges within transformers [10]. Dissolved Gas Analysis (DGA) is utilised alongside AE to detect gases produced by insulation deterioration, particularly acetylene (C_2H_2), which indicates arcing and electrical stress. The presence of elevated levels of acetylene is indicative of potential internal problems, including partial discharge or arcing phenomena [11].

Numerous studies have explored the positioning of partial discharge utilizing High-Frequency Current Transformer Sensors and Acoustic Emission Sensors [12], [13]. However, a notable gap persists in the literature regarding immersed oil transformers. Currently, there are no studies that have specifically concentrated on the detection and analysis of partial discharge phenomena in this category of transformer. This oversight presents an opportunity to explore the unique challenges and characteristics associated with immersed oil transformers, which may differ significantly from those observed in cast-resin transformers. Addressing this research gap is crucial for enhancing the reliability and safety of immersed oil transformer systems.

Transformer #3 GIS Kemang, operational since 1994, has recently shown concerning indications based on dissolved gas analysis (DGA) results, specifically increased levels of acetylene. This observation suggests the potential occurrence of internal arcing and underscores the necessity for comprehensive diagnostic assessments. With 29 years of service, the transformer is at an elevated risk of insulation failure, thereby making the detection and analysis of partial discharge (PD) essential for either prolonging its operational lifespan or determining the need for replacement.

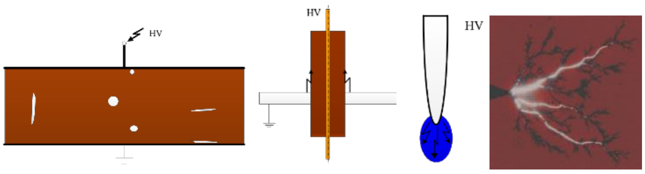
OBJECTIVES

This research aims to conduct a comprehensive assessment of the Transformer #3 GIS Kemang by identifying partial discharge (PD) by Acoustic Emission (AE) techniques. This investigation seeks to pinpoint the precise locations and severity of PD occurrences within the transformer, evaluate its overall operational condition, and formulate actionable recommendations for ongoing maintenance or potential equipment replacement. Through this endeavor, the research aims to enhance the reliability and safety of power infrastructure, with particular emphasis on aging equipment that plays a critical role in electricity transmission networks.

METHODS

A partial discharge typically occurs due to electrical stress within the insulation or along its surface. This occurs when the electric field intensity exceeds the local dielectric capacity of the insulating substance or when there is an uneven distribution of a strong electric field. This discharge manifests as pulses with durations of less than one nanosecond. When partial discharge occurs on the surface or within the insulation system, the presence of high-energy electrons or ions leads to the degradation of the insulating material through chemical decomposition. This degradation, once it reaches a certain accumulation threshold, can ultimately result in the failure of the insulation system [14].

There are five main types of partial discharge, they are: internal-discharge, surface-discharge, corona-discharge, electrical-treeing, and discharge that happens at walls [15].



(a) (b) (c) (d)

Figure 1. a) Internal PD, b) Surface PD, c) Corona Discharge, d) Electrical Treeing [15]

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In transformer predictive maintenance, established technologies like dissolved gas analysis are more frequently used than methods that rely on vibration signal assessment [16]. For vibration signal assessment, Acoustic Emission Technique is an advanced non-destructive testing method in which sound waves are transmitted to detect changes in materials. This method operates by measuring the frequency and energy released during the expansion of cracks or phase changes in the material. The energy is released due to physical changes in the solid material, which can be caused by external forces or temperature changes, such as in fluids or cracks. The detection of this energy release is used to accurately predict the location of partial releases.

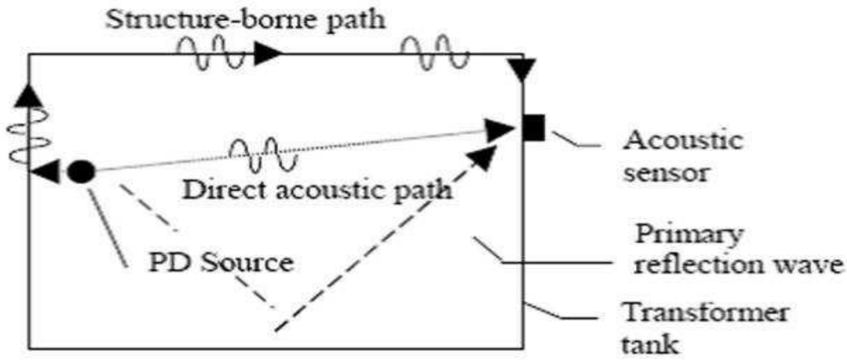


Figure 2. Schematic View for Acoustic Wave Propagation [17]

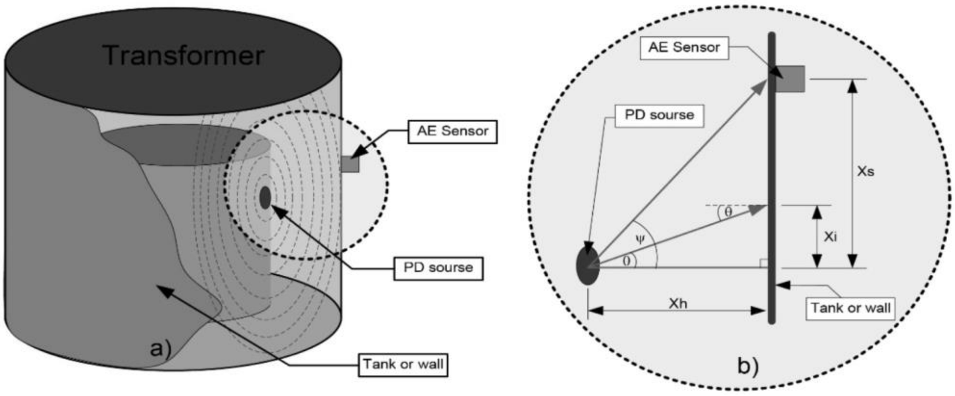


Figure 3. Relationship between AE sensor and Partial Discharge Source.
(a) Radical patterns of sound wave propagation in partial discharge (PD).
(b) numerous parameters defining the routes of PD wave propagation [13]

Figures 2 and 3 depict the spatial relationship between a partial discharge source and an acoustic emission sensor. Figure 3a illustrates the travel time of sound waves as the duration for the acoustic partial discharge signal to reach an acoustic emission sensor from its source. The transmission of the partial discharge signal is defined by symmetrical distribution, where the signal strikes the transformer casing or tank wall. The wall functions as the installation site for AE sensors and is engineered to identify PD signals. Figure 3b delineates certain factors that define PD wave propagation pathways; however, as depicted in Figure 3 and recorded in the literature [17], numerous propagation channels may be present for acoustic waves travelling to the sensor from the partial discharge source. Acoustic emission (AE) measurement approaches utilise the assessment of TOAs (time-of-arrivals) from the partial discharge source to various acoustic emission sensors for the localisation of the partial discharge source. The acoustic signal's distance between an AE sensor and a PD source is mathematically represented in Equation (1)[18]. All acoustic waves travel via the high-voltage device's interior construction before arriving at its outside.

$$distance\ (m) = velocity\ \left(\frac{m}{s}\right) \times traveltime\ (s) \tag{1}$$

Equation (3) can be utilised to compute the sound wave travel time, which is the duration of time that an acoustic PD signal travels from its discharge location to an AE sensor [17]. The total time for sound waves to reach a sensor can be calculated using Equation (2).

$$t = \sqrt{\frac{X_i^2+X_h^2}{V_{oil}}} + \frac{X_s-X_i}{V_{metal}} \tag{2}$$

$$t = \frac{X_s}{v_{metal}} \tag{3}$$

The straight path, where the sound wave only reaches the AE sensor, may have its elapsed time determined using Equation (4).

$$t = \sqrt{\frac{X_i^2+X_h^2}{V_{oil}}} + \frac{X_s-X_i}{V_{metal}} \tag{4}$$

Before hitting the wall of the transformer tank, the acoustic wave travels a significant distance XW. At a critical angle of incidence, the sound wave enters the metal tank and travels the shortest distance. Equation (5) can be used to find the crucial incident angle (α).

$$\alpha = \sin^{-1} \times \left(\frac{v_{oil}}{v_{metal}}\right) \tag{5}$$

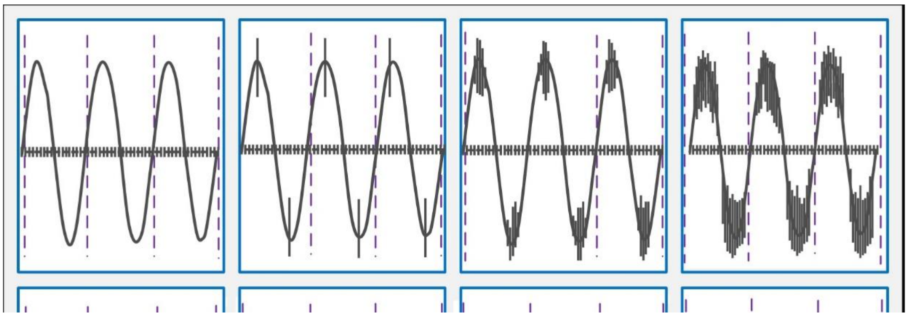
The relevant wave travel time can be computed using Equation (6).

$$t = \frac{X_s - X_W \tan\theta}{V_{metal}} \tag{6}$$

The position of the PD source can be ascertained by utilizing the sound wave's arrival time (Ti), the propagation of waves velocity (v), and the coordinates of three AE sensors (xi, yi, zi) as indicated in Equation (7) [19].

$$\begin{aligned} (x-x_{s1})^2 + (y-y_{s1})^2 + (z-z_{s1})^2 &= (v \cdot T_1)^2 \\ (x-x_{s2})^2 + (y-y_{s2})^2 + (z-z_{s2})^2 &= (v \cdot T_2)^2 \\ (x-x_{s3})^2 + (y-y_{s3})^2 + (z-z_{s3})^2 &= (v \cdot T_3)^2 \end{aligned} \tag{7}$$

Figure 4 illustrates the correlation between the signal of electrical partial discharge and the acoustic signal of partial discharge. Comparing the electrical partial discharge signal—which is derived from the transformer's actual partial discharge signal—with the auditory partial discharge signal was done. By prolonging the duration, the unipolar pulse that represents the electrical signal from the photodetector can be reduced to the millisecond level. The characteristics of the discharge determine the amplitude of the pulse at the source. High frequencies gradually decrease as the signal passes through the transformer due to the many reflections and resonance frequency of the transformer components, which change the pulse pattern. Additionally, the criteria for evaluating the severity of incomplete discharge are referred to as "Gap time," measured in milliseconds. The gap time signifies the interval between the conclusion of one burst and the commencement of the subsequent burst. If the gap period remains unestablished, it is concluded that no partial discharge exists. Analysis of the gap duration in the graph revealed that when it exceeded 7 ms, partial discharge was detected; nonetheless, the identifier categorised it as a mild partial discharge. A reduced gap time correlates with an increased rate of partial discharge, approaching a critical threshold of 3 ms, which clearly signifies impending failure. Burst intervals are essential measures for assessing the severity of Partial Discharge [20-22].



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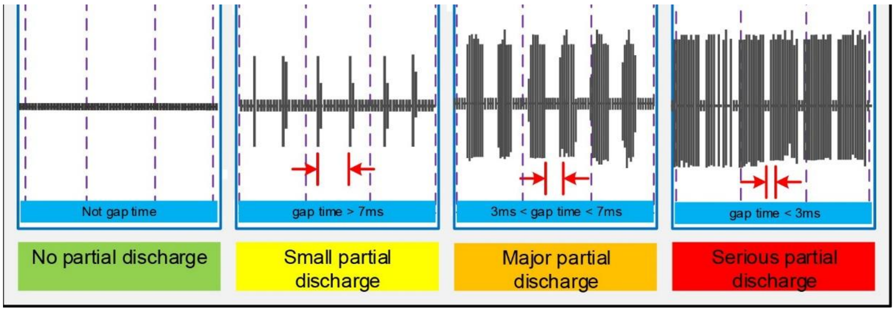

Figure 4. The parameters for assessing the severity of partial discharge; gap time [13].

Table 1 breaks down the danger level of partial discharge based on the PowerPD reference; the disparity in gap duration among levels is delineated in the data, substantiating the assessment of the differential condition level of partial discharge. This table includes recommends actions to be implemented upon the creation of the partial discharge. The minimum PD condition level was deemed acceptable in the absence of gap time, but the maximum partial discharge condition level fluctuated when the interval or gap duration was under 3 ms.

Table 1. The risk level of Partial Discharge based on the PowerPD reference [13].

Gap Time	Level of Condition	Proposed Course of Action
Absence of a partial discharge signal	Satisfactory	Maintain standard operations Annual monitoring
Gap time > 7 ms	Small Partial Discharge	Acceptable (Potentially non-harmful Partial Discharge) Biannual monitoring
3 ms < Gap time < 7 ms	Major Partial Discharge	An engineering assessment and appraisal are necessary; if the trend is upward, contemplate withdrawal from service in the near future. Monitoring every 3 months
Gap time < 3 ms	Sonous Partial Discharge	Unsatisfactory; initiate planning for removal and repair immediately. Weekly monitoring or continuous monitoring should be implemented.
Signal of Arcing	Sonous	Prerequisite for engineering evaluation and appraisal If the arc source is an essential element of the apparatus, consider its decommissioning in the imminent future.
Signal of Mechanical	Deviant	It is necessary to implement additional technologies during the engineering review and evaluation process in order to integrate the data.

This study examines the identification of partial discharge in Transformer #3 GIS Kemang, which has been operational for 29 years. The technology employs a mix of acoustic emission and high-frequency current transformer sensors to identify and also assess partial discharge within the transformer. Dissolved Gas Analysis (DGA) is used as a preliminary diagnostic instrument to verify the presence of critical gases indicative of insulation deterioration, particularly acetylene (C_2H_2), linked to internal arcing. The subsequent steps were executed as a component of the methodology:

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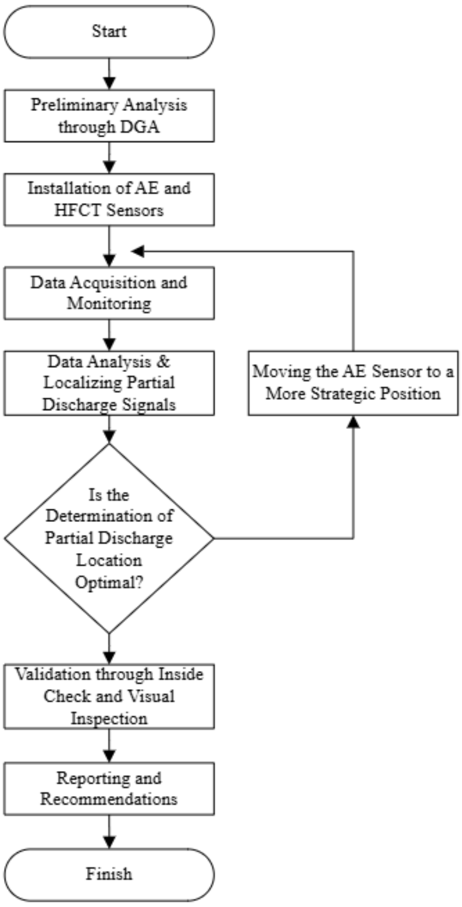

Figure 5. Methodology Flow Diagram

Preliminary Analysis through DGA

The DGA was performed prior to the acoustic emission testing to identify gas concentrations within the transformer oil. The presence of acetylene was of particular interest, as elevated levels indicate potential arcing and insulation stress. The results of this analysis informed the decision to perform a detailed PD investigation.

Installation of AE and HFCT Sensors

Acoustic emission sensors were installed on the transformer at strategic points, particularly around the high-voltage (HV) and on-load tap-changer (OLTC) sections, where the highest risk of partial discharge was suspected. In addition to AE sensors, High-Frequency Current Transformers (HFCT) were used to capture high-frequency signals indicative of PD activity [23].

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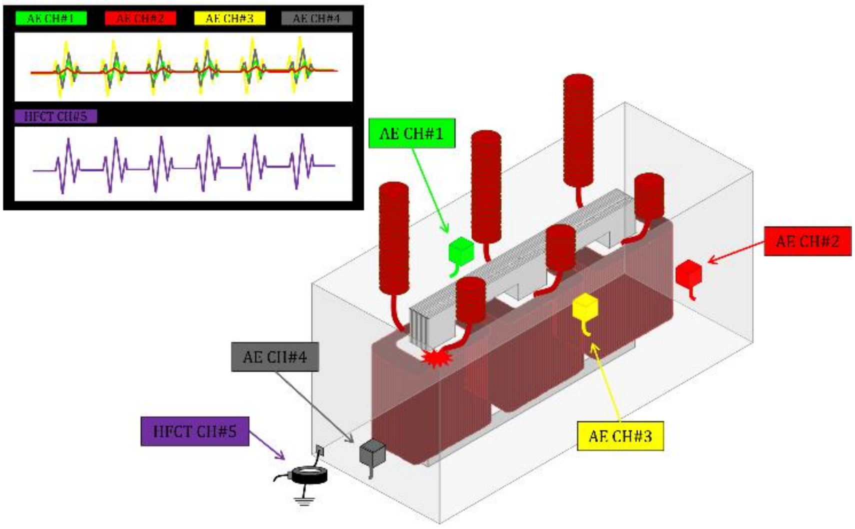
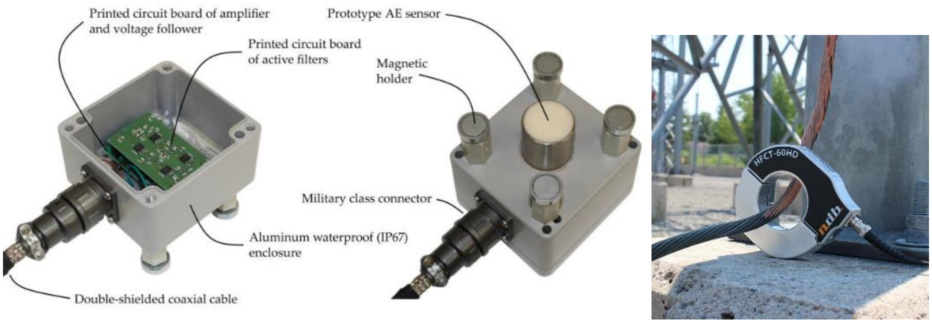


Figure 6. Schematic Representation of Experimental Setup

In order to detect ultrasonic sound waves produced by PD events inside the transformer, four AE sensors were placed. The sensors were strategically located at essential spots along the transformer's high-voltage winding, tubular, and on-load tap changer sections. HFCT Sensors: A single HFCT sensor was affixed to the ground lead to detect high-frequency signals related to partial discharge (PD) [19]. This sensor was essential for identifying burst events and measuring pulse intervals.



(a) (b)

Figure 7. a) Acoustic Emission Sensor, b) HFCT Sensor

Data Acquisition and Monitoring

The AE and HFCT sensors were connected to a PowerPD TP500A system, which is capable of real-time monitoring and data acquisition. The system recorded AE signal waveforms, time intervals between PD pulses, and the overall amplitude of PD events. Burst intervals from HFCT data were also recorded and used to classify the severity of PD activity.

Figure 8. PowerPD TP500A

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Partial Discharge Testing Procedure

The PD testing was conducted over several hours while the transformer remained in operation under normal load conditions. The testing was divided into multiple phases to cover different areas of the transformer:

- Phase 1: AE and HFCT data were collected from the HV/tubular section of the transformer.
- Phase 2: The sensors were moved to the OLTC section, where significant acoustic signals were expected due to mechanical switching components.
- Phase 3: Additional testing was conducted at specific points of interest identified during initial testing to ensure comprehensive coverage of the transformer.

Data Analysis

The data gathered from the AE and HFCT sensors were analyzed using PowerPD software. The analysis focused on identifying the specific locations of PD, the amplitude of the acoustic signals, and the frequency of the bursts. PD events were classified based on pulse interval measurements, with intervals greater than 7 milliseconds being categorized as low-level PD and intervals below 3 milliseconds classified as serious PD.

Validation through Inside Check and Visual Inspection

Following the PD testing, an inside check was performed on the transformer, focusing on areas where significant PD activity had been detected. This involved a visual inspection of the internal components, particularly the winding insulation, magnetic shunt cores, and Pertinax areas. The aim was to confirm the presence of treeing and other insulation damage indicated by the AE data.

Reporting and Recommendations

The results from the AE and HFCT analysis, combined with the findings from the inside check, were compiled to provide a detailed report on the health of Transformer #3 GIS Kemang. Based on the level and location of PD detected, recommendations were made regarding preventive maintenance, insulation repair, or transformer replacement.

RESULTS AND DISCUSSION

Dissolved Gas Analysis (DGA) Results

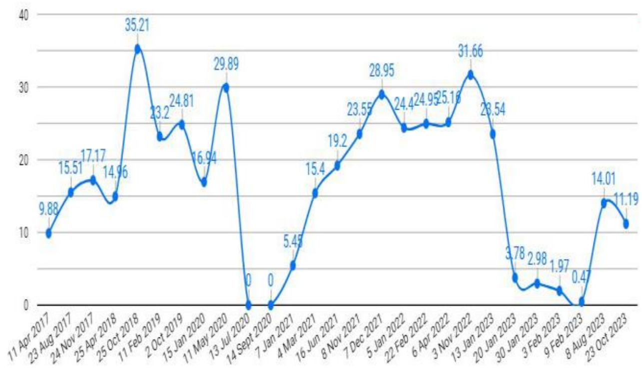

Figure 9. The Concentration of Acetylene (C_2H_2) in Bottom Maintank Transformer

The initial dissolved gas analysis (DGA) indicated an elevated concentration of acetylene (C_2H_2) in the transformer oil, particularly in the Maintank and tubular sections. Acetylene is typically produced at temperatures above 500°C and is strongly associated with electrical arcing within the transformer. The DGA results indicated that the insulation was probably under stress from arcing, necessitating more examination with Acoustic Emission sensors and strengthened by High-Frequency Current Transformer sensor.

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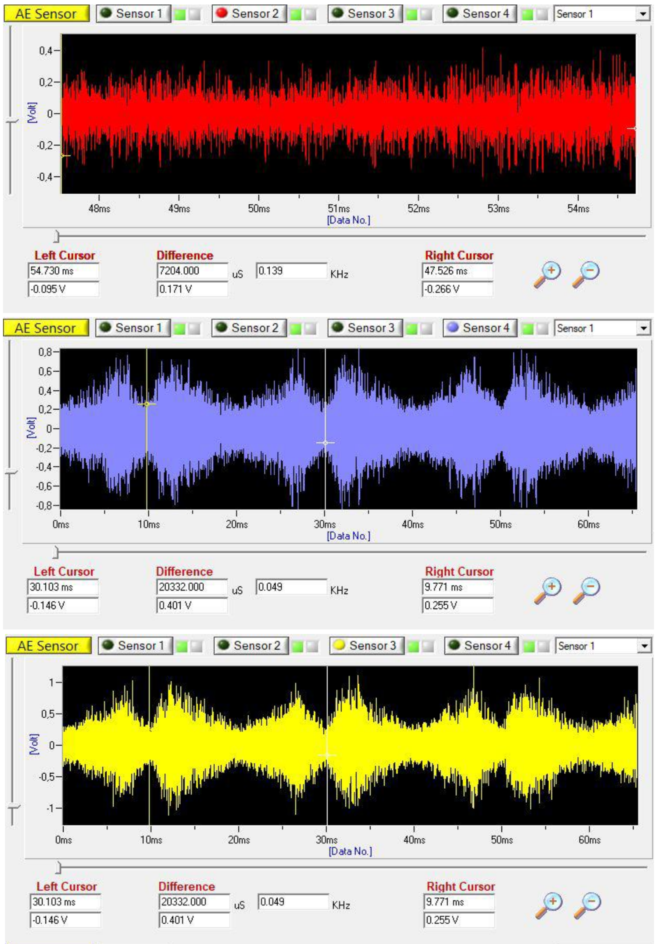
The DGA results provided a strong indication that internal electrical discharges were occurring, justifying the need for more detailed partial discharge (PD) testing.

Acoustic Emission and HFCT Testing Results

The high-frequency current transformer and acoustic emission sensors were deployed at multiple locations around the transformer. One significant PD source was identified at the high-voltage (HV)/tubular section.

Figure 10. Installation of 4 AE Sensors



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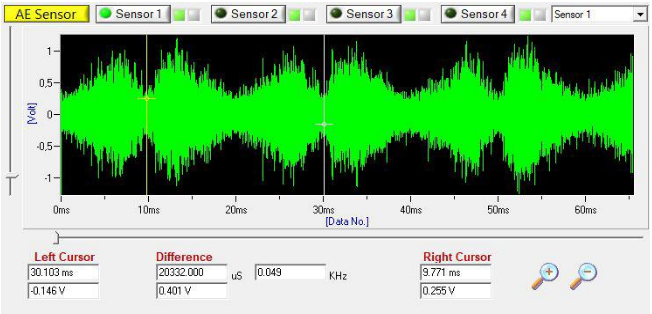


Figure 11. AE Measurements of Damaged Transformer

AE sensors positioned near the HV/tubular section detected repeated acoustic waveforms that indicated active PD. The sensors captured burst events with time intervals 20.332 milliseconds, which is consistent with high-level PD. However, the detected acoustic amplitudes were relatively high, the potential for insulation damage was significant.

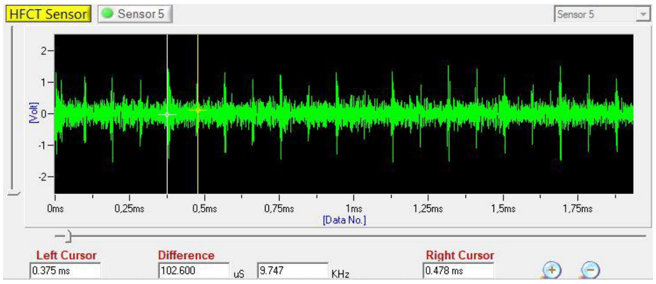
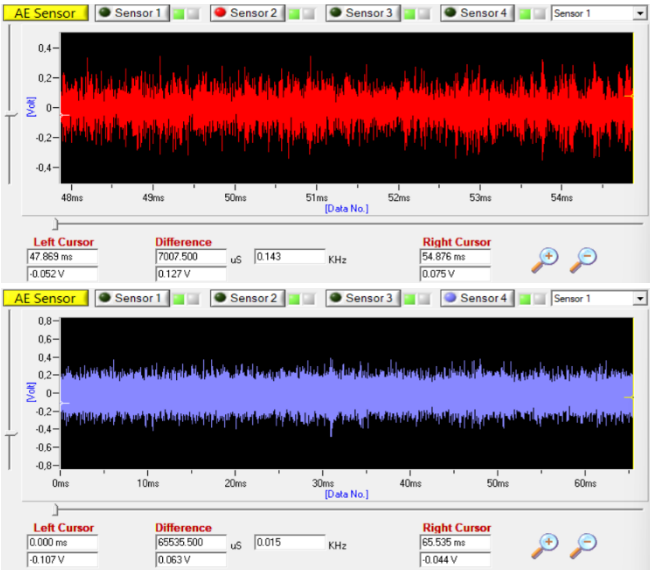


Figure 12. HFCT Measurements of Damaged Transformer

HFCT sensors confirmed the presence of high-frequency electrical signals corresponding to the burst events. The interval measurements between HFCT pulses were 0.102 milliseconds, further corroborating the AE data. As a comparison, a similar test was conducted on a healthy Transformer, Transformer #1 GIS Grogol with the same installation conditions, and the following results were obtained:



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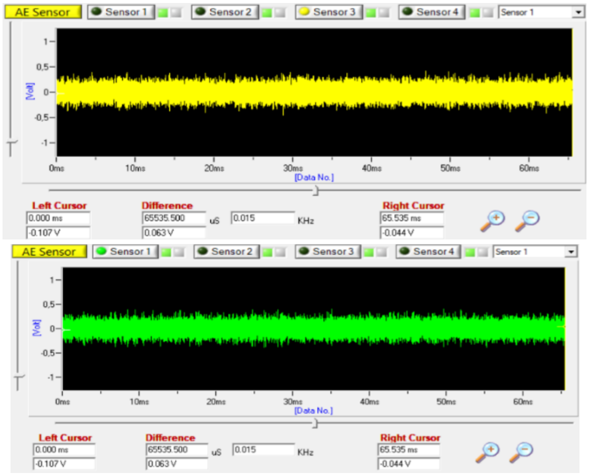

Figure 13. AE Measurements of Healthy Transformer

From the recorded waveform, a significant difference can be observed. The waveform results from the damaged transformer (Transformer #3 GIS Kemang), which are on the same scale, display a repeating butterfly-shaped pattern, whereas the healthy transformer (Transformer #1 GIS Grogol) shows no waveform formation, only a steady signal at a consistent amplitude.

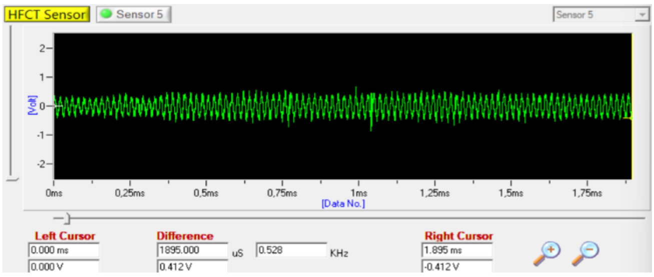

Figure 14. HFCT Measurements of Healthy Transformer

Similarly, in the HFCT sensor measurements, no burst waveforms were found in the healthy transformer, unlike those detected in the damaged transformer.

Inside Check Results

Following the AE and HFCT testing, an inside check was performed to visually inspect the internal components of the transformer.

Figure 15. Spot Marks on the insulation paper of the HV Phase T Winding

This inspection confirmed the presence of discharge marks (treeing) on the Pertinax magnetic shunt, which corroborated the AE sensor data indicating insulation degradation. The visual examination also revealed spot marks on the insulation material surrounding the winding in the HV Phase T, further supporting the hypothesis that electrical stress was causing insulation breakdown.

However, the high amplitude of the acoustic signals suggests that the risk of further insulation degradation and failure increases over time if not addressed. The inside check provided additional evidence of significant stress in the HV/tubular section and moderate stress in the OLTC, indicating that the transformer is approaching the end of its operational life without significant intervention.

Discussion

The results from both the DGA analysis and AE/HFCT testing suggest that Transformer #3 GIS Kemang is undergoing internal degradation, particularly in its insulation system. The elevated levels of acetylene in the transformer oil, combined with the detection of PD at critical points, confirm the presence of electrical arcing and partial discharge activity. The Pertinax magnetic shunt and HV windings are experiencing stress that could lead to more serious insulation breakdown if left unaddressed.

CONCLUSION

Given the age of the transformer (29 years), the detection of PD should be viewed as a warning sign that the insulation system is nearing failure.

This study examined the identification of partial discharge (PD) in Transformer #3 GIS Kemang, operational for 29 years, utilising AE and HFCT sensors. The integration of these diagnostic instruments, in combination with Dissolved Gas Analysis (DGA), provided valuable insights into the condition of the transformer insulation system and the possible risks associated with its continued operation. The subsequent conclusions can be derived from the results:

1. Elevated Acetylene Levels: The initial DGA results indicated elevated concentrations of acetylene (C_2H_2), a gas commonly associated with arcing and electrical stress. This finding provided a clear indication of internal degradation, prompting further PD investigation.
2. PD Activity Detected in HV/Tubular Sections: AE and HFCT sensors detected significant PD activity in the high-voltage (HV)/tubular section of the transformer. AE wave intervals about 20 milliseconds and HFCT measurement burst intervals about 0,102 milliseconds were measured, classifying the serious PD, though the high amplitude of acoustic signals suggested that the potential for insulation damage is considerable.
3. Treeing and Insulation Degradation: Visual inspection during the inside check confirmed the presence of discharge marks (treeing) on the Pertinax magnetic shunt and spot marks on the insulation of the HV winding in Phase T. These findings support the AE and HFCT data, confirming that insulation stress is occurring in the transformer.
4. Transformer Age and Risk of Failure: Given the transformer's age and the cumulative effects of PD over time, the insulation system is approaching the end of its reliable life. The detected PD, while currently at low to moderate levels, poses a significant risk of failure if left unaddressed. The transformer is at increased risk of major insulation breakdown, especially under continued operational stresses.

In conclusion, the combination of AE and HFCT testing has proven effective in detecting and locating PD within Transformer #3 GIS Kemang. This array of devices may identify and assess issues arising within the transformers under initial conditions for resolution. Furthermore, it can be ascertained whether the issue is attributable to partial discharge, mechanical failures, arcing, or loose components within the transformer [24]. This partial discharge diagnosis method can precisely identify and locate the partial discharge position within the transformer, facilitating prompt and effective repair. This will aid in averting the total degradation of the transformers and diminish the expenses associated with substantial repairs of compromised transformers. Online partial discharge measurement is a technique employed to avert transformer damage resulting from explosions and offers criteria for establishing transformer maintenance for enhanced safety [25,26]. Continuous monitoring and timely maintenance are crucial for preventing severe operational malfunctions, as the results of this study underscore. The findings from this analysis will assist in developing maintenance strategies and inform the decision-making process for transformer replacement.

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