

DIAGNOSTICS AND MITIGATION OF PARTIAL DISCHARGES IN POWER TRANSFORMERS

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Abstract

As the global demand for reliable and efficient electrical power continues to rise, the protection and maintenance of transformers become increasingly critical. Transformers are essential components in electrical grids, facilitating the transmission and distribution of electricity. However, they are vulnerable to various types of faults and failures, such as Partial discharges, short circuits, and insulation breakdowns. Traditional transformer protection systems often lack real-time monitoring capabilities and adaptive responses to evolving fault conditions, leading to potential outages, costly repairs, and significant disruptions in power supply. There is a pressing need for advanced transformer protection devices that offer enhanced monitoring, diagnostic, and automated response features to ensure the reliability and longevity of transformer assets and Time based maintenance changes to condition based maintenance approaches. The insulation oil temperature was monitored under various load conditions using a distributed approach and compared with traditional methods, such as single-point thermocouples and infrared thermal imaging. The test results demonstrate a strong correlation between the conventional methods and the proposed distributed RTD Temperature sensors.

INTRODUCTION

Power transformers are one of the most expensive components in any power system [1]. Reliable operation of all their components is crucial to ensure sustained power delivery [2]. One of the key components of power transformer is the insulation, which is continuously exposed to the electrical, mechanical, thermal and chemical stresses during its lifetime [3], [4]. The insulation deterioration can lead to a variety of internal faults, for instance, partial discharges, arcing, sparking, corona, and overheating. Among these, the partial discharge (PD) is a severe fault, which

in turn triggers the occurrence of more detrimental situations [5-7]. Partial discharge in a power transformer refers to a localized electrical breakdown within a small portion of the insulation material [8]. This discharge does not completely bridge the gap between conductors, and occurs due to intense electric fields within voids, cracks, or other imperfections in the insulation [9]. These discharges can progressively deteriorate insulation materials, ultimately leading to a complete breakdown [10, 11].

The early detection, accurate diagnosis, and mitigation of PDs is, therefore, essential for transformer health. Reliable and accurate condition monitoring of transformer winding insulation has been widely performed using both offline and online partial discharge (PD) measurement techniques as shown below in flow chart, all aimed at a trinomial of low cost, efficiency and rapid diagnosis[12, 13]. One of these techniques is the dissolved gas analysis, which relies on oil sampling from the transformer tank, using hydrogen as a key indicator of PD activity in the active part of a transformer[14, 15]. However, dissolved gas analysis as an indirect

measurement technique, and is ineffective in diagnosing localized PD[16]. In addition, the interpretation of dissolved gas analysis requires a slight amount of gas formation to declare a PD activity as significant [17].

There are also several practical examples where no increase in combustible gases was recorded despite a PD source being detected by electrical and acoustic methods, and confirmed by visual inspection of the transformer. As compared to this, measurements based on electrical, acoustic and electromagnetic PD pulses can be regarded as more reliable for in-depth analysis of PD activity and assessment of its severity [18-21].

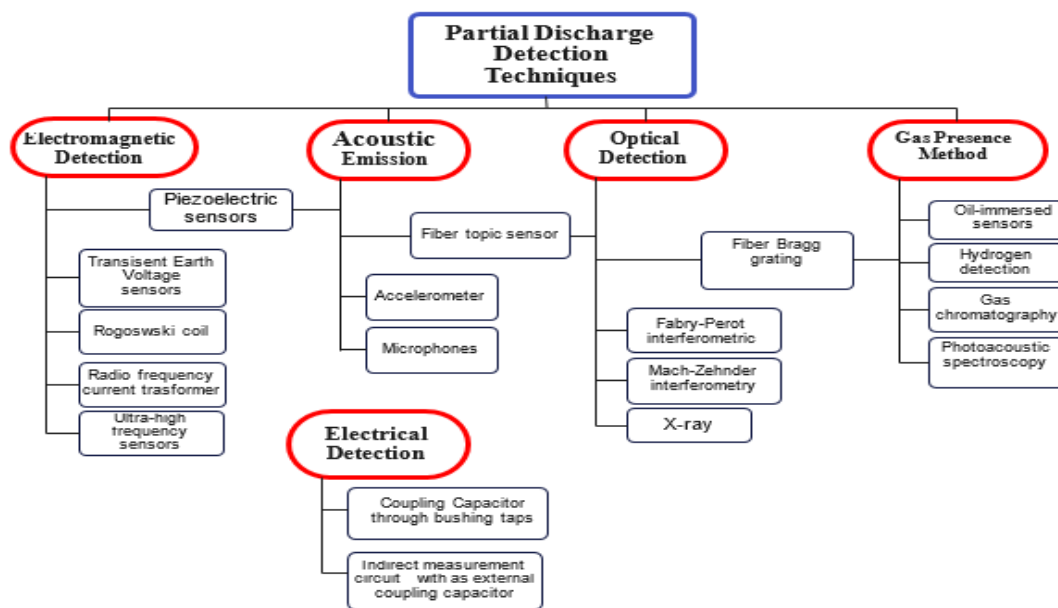


Fig. 1: Partial Discharge Detection Techniques

EXPERIMENTAL SETUP

For lab scale monitoring of PD, a setup was developed using two, 3-phase distribution transformers TF1 and TF2, of 15kVA and 10kVA rating respectively, each with voltage ratio of 11kV/400V. These distribution transformers are compact, occupy less space and can be easily accommodated and installed in the laboratory. The insulations of both HT and LT windings in these transformers is similar to that used in large

sub-station transformers manufactured by PEL and HEC. Moreover, the same grades of transformer oil were used as ambient liquid. The transformer TF1 was operated in step-up mode serving as the generation to transmission line sub-system transformer, whereas; the transformer TF2 was operated in step-down mode representing the transmission to distribution sub-system. Prior to connecting the transformers, sensors were installed at various locations in the HT winding.



Fig. 2: Transformers for laboratory setup

The middle HT winding (phase B, color code yellow as shown in Fig. 3) was selected for the purpose of installation of sensors. Four critical locations based on electrical and thermal stresses were selected for installing the sensors. These locations selected are shown in figure 2 as follows:

- Location 1: Near HT end connector

- Location 2: At the base of winding near the mounting
- Location 3: On midway of HT winding directly facing the steel tank wall
- Location 4: On the phase A of HT winding facing phase-B HT winding

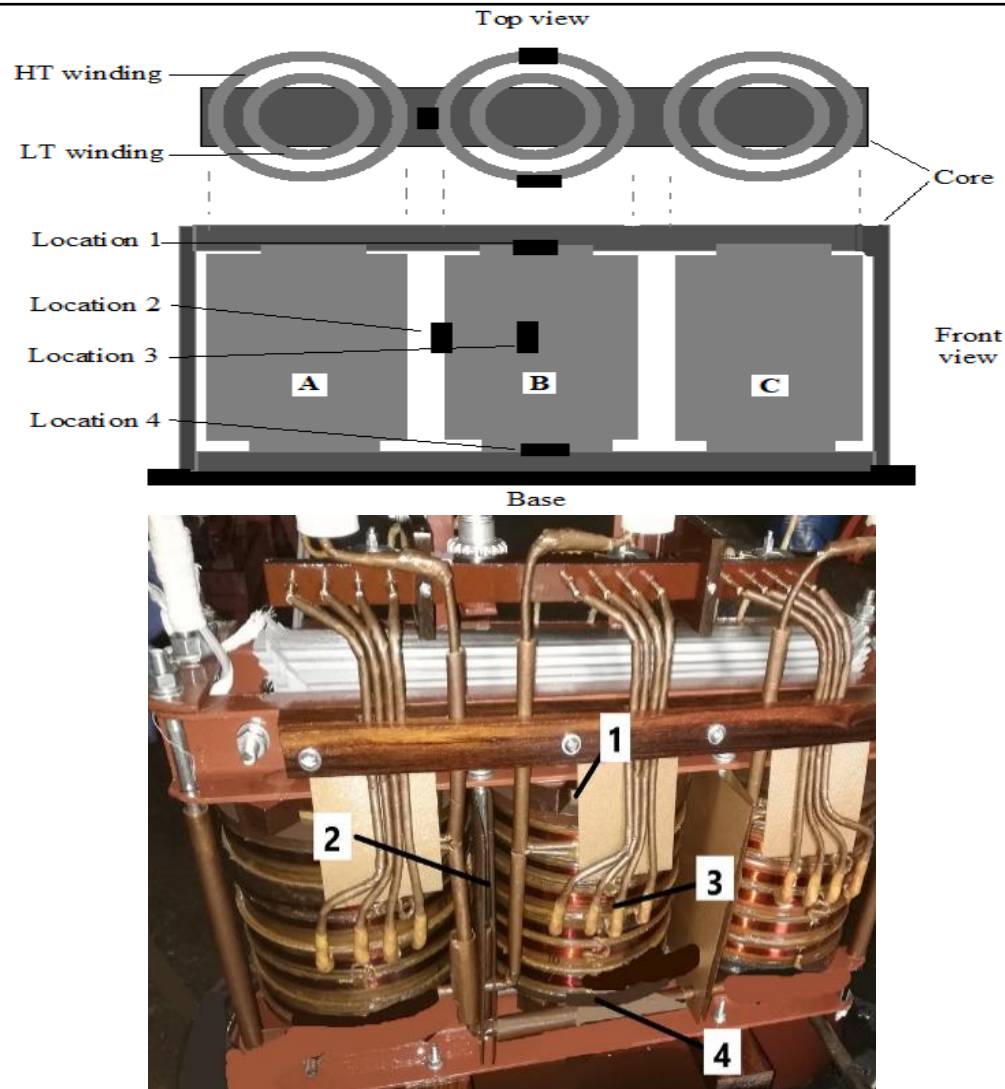


Fig. 3: Locations on transformer winding for installation of sensors

The selection of sensor locations was guided by the likelihood of hotspot formation and regions where insulation is subjected to elevated stress. Location 1 experiences the highest voltage stress, being situated near the terminal connection of the high-tension (HT) bushing. Location 2 was chosen due to its higher susceptibility to sludge deposition and sedimentation, which can impair the cooling efficiency of the winding. Moreover, the limited clearance between the HT element and the grounded steel tank base exposes this area to both thermal and electrical stress. Location 3 represents the point with the shortest distance between the

HT winding assembly and the tank wall, resulting in intensified electric field stress. Location 4 is characterized by minimal separation between two phase windings, making it another area of elevated electrical stress. Figure 3 is the photograph of the transformer winding assembly indicating locations on the middle winding (phase-B) where sensors were installed. The high-voltage (HV) bushings of the 132kV and the 11kV windings had to be disassembled for the transportation of 15KVA transformer. Upon installation at site, the bushings had to be refilled with oil. Due to the horizontal orientation bushings, the refilling was

done very carefully to avoid gas bubbles which could compromise insulation performance. To verify the integrity of the insulation and ensure proper oil filling, partial discharge (PD) measurements were conducted. The test setup followed the IEC 60270 standard [2], with PD and AC signals simultaneously decoupled at the measurement taps of all 11 kV bushings. The HT connections were made through a 10 kVA,

11kV/400 V designated as TF2 as shown in Figure 2.

RESULTS AND DISCUSSION

A study was conducted under controlled laboratory conditions on the 15KVA transformer for different load condition to evaluate the relationship between PD levels and transformer oil/winding temperatures through SEL transformer monitoring Unit. The recorded data is shown Table 1 below:

Table 1:Transformer operating conditions and observed partial discharge behavior under varying temperature and load conditions

Stage	Time (hr)	Temp (°C)	Load (A)	Condition
Stable	1–7	35–50	20–28	Normal
Early Stress	10–14	55–60	29–32	Slight PD increase
Aging Begins	16	70	34–36	Gradual PD rise
Critical Zone	20–22	80–85	35–30	Sudden to Alarming PD rise
Failure Risk	24	90	36–30	Hotspot detected

The experimental results reveal a clear progression of transformer behavior under increasing temperature and load conditions over a 24-hour period from curve below. Initially, during the first 7 hours of operation, the transformer operated under normal conditions, with temperatures ranging from 35°C to 50°C and load currents gradually increasing from 20 A to 28 A. No signs of insulation stress or partial discharge (PD)

activity were observed during this phase, indicating stable and healthy operating conditions. As the temperature rose to 55°C and then to 60°C between 10 and 14 hours, a slight increase in PD-related activity was noted. This suggests the beginning of insulation stress, likely caused by cumulative thermal loading and rising internal pressure, although the transformer was still within a manageable operating range.

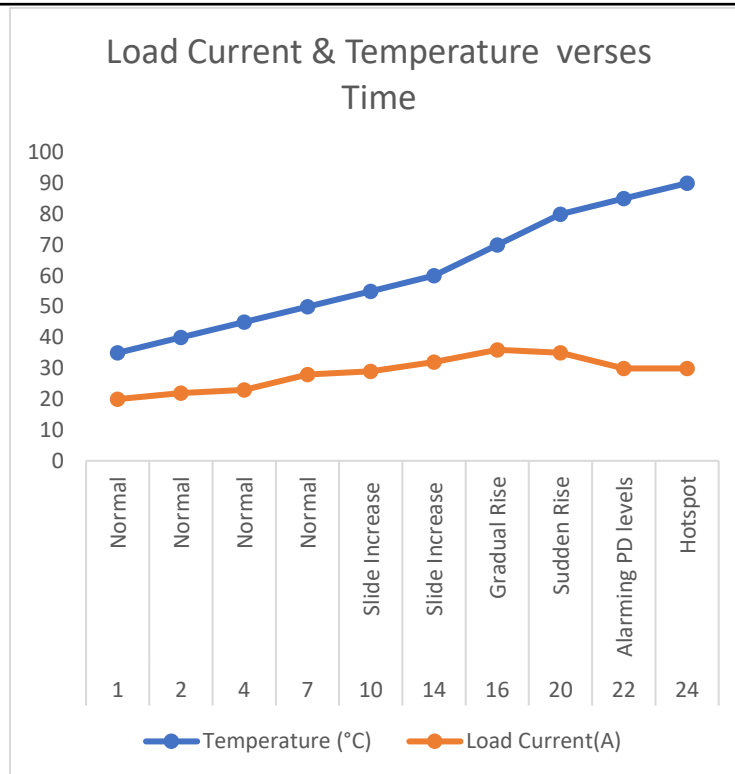


Fig. 4: Load Current & Temperature verses Time

By the 16th hour, the temperature had reached 70°C and the load current peaked at 36 A, leading to a gradual but noticeable increase in PD activity. This marks a transition point where the insulation system starts showing consistent degradation under combined electrical and thermal stress. A more severe condition was observed at 80°C during the 20th hour, when PD levels exhibited a sudden rise despite a slight reduction in load current. This non-linear jump indicates that temperature had become the dominant factor influencing insulation breakdown, overshadowing the effect of load current. At this stage, the insulation may have started to fail internally, possibly due to the formation of gas pockets or moisture-related weakening. By the 22nd hour, with the temperature rising to 85°C, PD activity reached alarming levels. Although the load current dropped to 30 A, the insulation had already been compromised, and continued heating exacerbated the damage. Finally, at 90°C and 24 hours into the experiment, a hotspot was detected, signaling a

critical fault condition. This indicates severe localized degradation, which, if left unaddressed, could lead to complete insulation failure and transformer breakdown. Overall, the results emphasize a strong correlation between temperature, PD activity, and insulation health, highlighting the importance of early detection and thermal management in preventing transformer failures. Monitoring partial discharges in Pico Coulombs against temperature using a spectrum analyzer is also offers a powerful method to assess the health of a power transformer. Temperature-induced PD rise is an early warning of insulation breakdown. Spectrum analysis further provides frequency-domain insight to characterize the type and severity of PD activity. The experimental analysis presents a progressive evaluation of PD activity in a power transformer across a temperature range from 35°C to 90°C. Initially, from 35°C to 50°C, PD levels remain relatively stable and low, rising gently from 80 pC to 100 pC. This range is considered normal for

transformer operation, indicating that the insulation system is unbroken and capable of withstanding both thermal and electrical stress within safe limits. As the temperature increases to 55°C and 60°C, PD levels begin to rise slightly, reaching 110 pC and 120 pC respectively. These increments, though still moderate, suggest the early onset of insulation stress, likely due to increased molecular activity in the oil and minor weakening of the dielectric material. At 70°C, PD levels experience a more noticeable jump to 190 pC, marking a gradual rise and indicating that the insulation system is beginning to deteriorate more significantly. This stage is critical, as it reflects a shift from stable to vulnerable conditions. When

the temperature reaches 80°C, PD levels spike to 230 pC, pointing to a sudden rise in discharge activity. This behavior is often associated with the formation of micro-voids or partial breakdowns in the insulation, indicating that thermal degradation is accelerating. By the time, the system reaches 85°C, PD levels climb sharply to 300 pC, which is classified as an alarming condition. At this point, the transformer is under severe electrical and thermal stress, and the insulation is at high risk of failure. Finally, at 90°C, PD levels peak at 400 pC, identifying a hotspot condition as shown in figure 5 below. This indicates significant internal breakdown, possibly due to localized overheating, carbonization, or moisture accumulation.

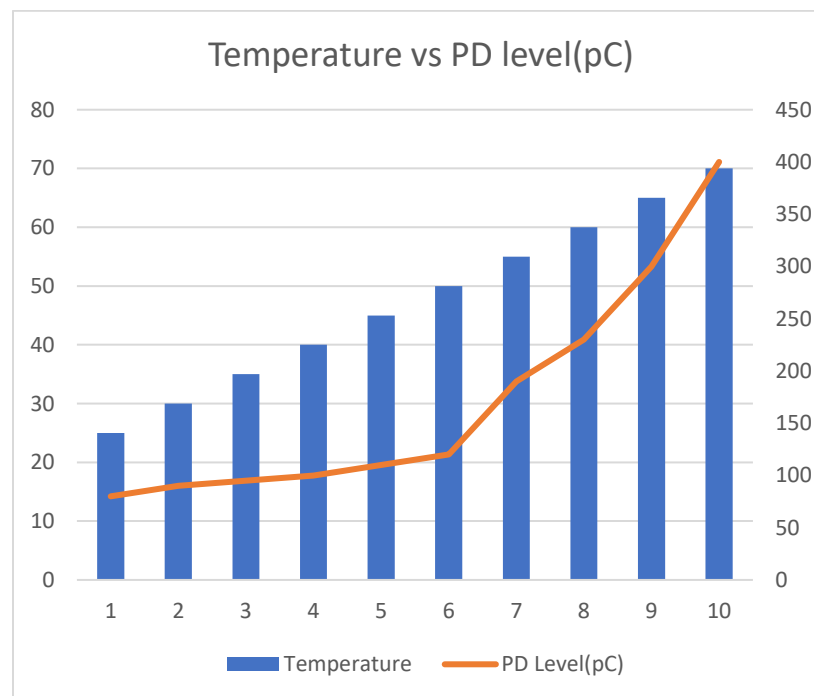


Fig. 5: Temperature vs PD level (pC)

The insulation system is now in a critical state, with a high likelihood of flashover or complete failure if corrective action is not taken. Overall, the experiment highlights a clear, non-linear relationship between temperature and PD activity,

emphasizing the importance of continuous monitoring. Early detection of rising PD levels especially beyond 60°C can enable preventive maintenance and help avoid catastrophic transformer failures as shown in Table 2.

Table 2: Variation of partial discharge level with transformer temperature and corresponding operating condition

S.No	Temperature (°C)	PD Level(pC)	Observation
1	35	80	Normal
2	40	90	Normal
3	45	95	Normal
4	50	100	Normal
5	55	110	Slide Increase
6	60	120	Slide more Increase
7	70	190	Gradual Rise
8	80	230	Sudden Rise
9	85	300	Alarming PD levels
10	90	400	Hotspot

The data reveals that PD behavior in power transformers is strongly temperature-dependent but not in a linear manner. Up to a certain threshold, PD levels remain relatively stable with temperature. Beyond that threshold identified around 70°C in this case PD activity escalates rapidly. This sharp increase could be attributed to the degradation of insulation properties, such as the breakdown of oil, the onset of cellulose decomposition, or the presence of contaminants and moisture.

This non-linear trend highlights the importance of identifying temperature thresholds that may indicate the onset of insulation failure. Exceeding such limits can accelerate the aging process and significantly increase the risk of catastrophic transformer failure.

The observed PD-temperature relationship has several practical implications:

- **Predictive Maintenance:** Continuous PD monitoring across varying temperatures helps detect abnormal insulation behavior early, allowing timely intervention.
- **Thermal Management:** Maintaining transformer temperatures below critical thresholds (e.g., 70°C) can help prolong insulation life and reduce PD activity.
- **Insulation Health Assessment:** Sudden spikes in PD at higher temperatures may indicate issues such as oil contamination, moisture ingress, or aging of paper insulation.

Based on the findings, the following steps are recommended for effective transformer health monitoring:

1. **Install Continuous Monitoring Systems:** Use online PD and temperature sensors to monitor critical points in real-time.
2. **Set Alarm Thresholds:** Define PD level alarms (e.g., >200 pC) or rate-of-change alerts to signal abnormal thermal behavior.
3. **Develop PD-Temperature Profiles:** Establish baseline trends for individual transformers to assess deviation and aging patterns.
4. **Perform Diagnostic Testing:** If high PD levels persist, conduct Dissolved Gas Analysis (DGA), moisture analysis, and other diagnostics to identify the root cause.

CONCLUSION

Correlating PD levels with temperature is a powerful diagnostic tool for power transformer condition monitoring. It enables early detection of insulation stress, supports preventive maintenance strategies, and helps extend transformer life. As demonstrated in the study, a sharp rise in PD at elevated temperatures is a warning sign that should not be ignored. By integrating PD-temperature monitoring into asset management programs, utilities can enhance reliability, avoid unplanned outages, and optimize transformer performance.

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