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# A Study on Insulation Diagnosis and Partial Discharge Interpretation for an 800kV Power Transformer in NPP

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## 1. Introduction

Every single nuclear plant has an important power transformer that delivers the power produced by a turbine to the grid system. That is why, these days, preventative maintenance for the transformer turned out to be very crucial for the system. We can occasionally see the shutdown of a nuclear power plant due to a faulty transformer. Most of electrical power supply companies are using the dissolved gas analysis for the insulation oil and partial discharge interpretation when it comes to a power transformer diagnosis. This paper shows how to detect the partial discharges generated in a power transformer and several methods to diagnose the equipment more precisely. For this purpose, the main transformer (GSU: Generator Step-up Unit) in a nuclear power plant that had been generating the acetylene gases for a while will be introduced as below.

## 2. Diagnosis of Power Transformer

### *2.1 Dissolved Gas Analysis*

All the main transformers in the power plants use insulation oil filled in them for their cooling system. By analyzing this oil to find out what type of gases are contained, which of the following defects has occurred can be distinguished. DGA is one of the methods able to determine the type of fault from the gas generated according to IEEE standard C57.104.2008: IEEE Guide for the Interpretation of Gases Generated in Oil-Immersed Transformers. [2]

*A. Key Gas Method*

IEEE key gas method becomes applicable to the transformer with developed faults where absolute values of key gases are considered.

Table 1: Key gases and their corresponding fault identification [7]

| Key Gas | Potential Fault Type |
|---|---|
| Acetylene($C_2H_2$) | Electrical Arc in Oil |
| Hydrogen($H_2$) | Corona, Partial Discharge |
| Methane($CH_4$), Etano($C_2H_6$) | Low temperature oil breakdown (thermal stress) |
| Ethylene($C_2H_4$) | High temperature oil breakdown (thermal stress) |
| Carbon Monoxide(CO) | Cellulose insulation breakdown (related to the aging process) |

*B. Dornenburg's Ratio Method*

This method utilizes the gas concentration from four ratios of gases such as Ratio1, Ratio2, Ratio3 and Ratio5 (i.e., $CH_4/H_2$, $C_2H_2/C_2H_4$, $C_2H_2/CH_4$ and $C_2H_6/C_2H_2$) which is depicted in Table 3. This methodology sets boundary limits of individual gases, if any gas exceeds the limits, then fault diagnosis limits will be employed to gas ratios to diagnose the fault type.

Table 2: Donenburg's limits for individual gases [7]

| Gas | $H_2$ | $CH_4$ | $C_2H_4$ | $C_2H_2$ | $C_2H_6$ | CO |
|---|---|---|---|---|---|---|
| Limit | 100 | 120 | 50 | 35 | 1 | 350 |

Table 3: IEEE and IEC 60599 proposed ratio to interpret fault in transformer [7]

| [Ratio1] | [Ratio2] | [Ratio3] | [Ratio4] |
|---|---|---|---|
| $CH_4/H_2$ | $C_2H_2/C_2H_4$ | $C_2H_2/CH_4$ | $C_2H_4/C_2H_6$ |
| [Ratio5] | [Ratio6] | [Ratio7] | [Ratio8] |
| $C_2H_6/C_2H_2$ | $C_2H_2/H_2$ | $O_2/N_2$ | $CO_2/CO$ |

Table 4: Donenburg's limits for fault diagnosis [3]

| Fault diagnosis | $CH_4/H_2$ | $C_2H_2/C_2H_4$ | $C_2H_2/CH_4$ | $C_2H_6/C_2H_2$ |
|---|---|---|---|---|
| Thermal decomposition | > 1.0 | < 0.75 | < 0.3 | > 0.4 |
| Corona (Low PD) | < 0.1 | - | < 0.3 | > 0.4 |
| Arcing (High PD) | 0.1 – 1.0 | > 0.75 | > 0.3 | < 0.4 |

*C. Roger's Ratio Method*

In this Roger's ratio method, mainly three gas ratios such as Ratio1, Ratio2 and Ratio4 (i.e., $CH_4/H_2$, $C_2H_2/C_2H_4$ and $C_2H_4/C_2H_6$) are used for DGA.

Table 5: Roger's ratio limits [5]

| Case | Nature of the fault | $C_2H_2/C_2H_4$ | $CH_4/H_2$ | $C_2H_4/C_2H_6$ |
|---|---|---|---|---|
| 0 | Unit Normal | < 0.1 | 0.1 – 1.0 | < 1.0 |
| 1 | Low energy density arcing | < 0.1 | < 0.1 | < 1.0 |
| 2 | High energy density arcing | 0.1 – 3.0 | 0.1 – 1.0 | > 3.0 |
| 3 | Low temperature thermal | < 0.1 | 0.1 – 1.0 | 1.0 – 3.0 |
| 4 | Thermal fault < 700℃ | < 0.1 | > 1.0 | 1.0 – 3.0 |
| 5 | Thermal fault > 700℃ | < 0.1 | > 1.0 | > 3.0 |

### *D. IEC 60599 Ratio Method*

This method is very similar to Roger's ratio method. Table 6 shows the IEC standard for interpreting fault types and gives the values for three key-gas ratios.

Table 6: DGA interpretation according to IEC ratios [3]

| Case | Nature of the fault | $C_2H_2/C_2H_4$ | $CH_4/H_2$ | $C_2H_4/C_2H_6$ |
|---|---|---|---|---|
| PD | Partial Discharge | NS | < 0.1 | < 0.2 |
| D1 | Discharges of low energy | > 1 | 0.1 – 0.5 | > 1 |
| D2 | Discharges of high energy | 0.5 – 2.5 | 0.1 - 1 | > 2 |
| T1 | Thermal fault < 300℃ | NS | > 1 | < 1 |
| T2 | Thermal fault of medium 300 to 700℃ | < 0.1 | > 1 | 1 – 4 |
| T3 | Thermal fault > 700℃ | 0.2 | > 1 | > 4 |

### *E. Duval Triangle Method*

Duval's triangle method employs graphical representation of three key gas ratios such as methane($CH_4$), ethylene($C_2H_4$) and acetylene($C_2H_2$) in order to determine the fault which is shown in Fig.1. In this method, the concentration (ppm) of the three gases are expressed as percentages of the total and plotted as a point in a triangular coordinate system which has been subdivided into six fault zones. In addition to the six individual faults, an intermediate zone 'DT' has been introduced to mixtures of electrical and thermal faults in the transformer. The fault zone in which the point is located designates the likely fault type which produced that combination of gas concentrations.

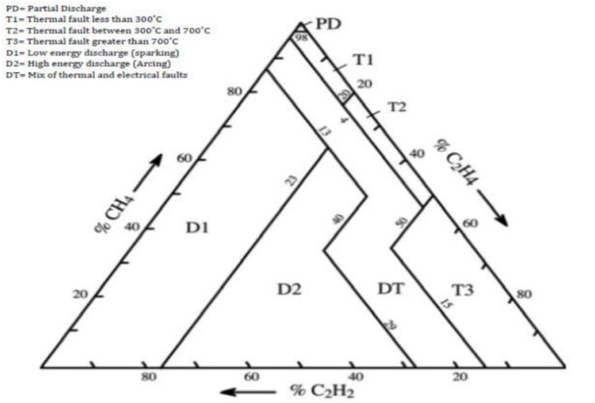


*Fig. 1. Duval triangle for dissolved gas analysis of transformer oil*

### *E. Criterion of DGA for transformer at KHNP (Table 7) [8]*

| Gas | Normal | Cautious (I) | Cautious (II) | Abnormal | Danger |
|---|---|---|---|---|---|
| $H_2$ | ≤200 | ≤400 | ≤800 | > 800 | |
| $C_2H_2$ | ≤10 | ≤20 | ≤60 | ≤120 | > 120 |
| $C_2H_4$ | ≤100 | ≤200 | ≤500 | > 500 | |
| $C_2H_6$ | ≤200 | ≤350 | ≤750 | > 750 | |
| $CH_4$ | ≤150 | ≤250 | ≤750 | > 750 | |
| $C_3H_8$ | ≤150 | ≤250 | ≤750 | > 750 | |
| CO | ≤800 | ≤1200 | > 1200 | | |
| $CO_2$ | ≤5000 | ≤7000 | > 7000 | | |
| TCG | ≤500 | ≤1000 | ≤2500 | ≤4000 | > 4000 |
| TCG Increase | | 100 ppm per month | 200 ppm per month | | 300 ppm per month |
| | | Transition analysis | | | |
| | | Every 6 months | Every 3 months | Every month | |

* *TCG: Total Combustible Gas*

### *2.2 Partial Discharge Interpretation*

In general, PD pulse currents occurred in transformers contains both the rising times approximately from 350 picoseconds up to 10 nanoseconds and pulse duration times in mere nanoseconds. If these pulses are calculated with Fourier Transform Analysis, it turns out to be various frequency bands there between kHz and MHz units. Analyzing these partial discharges of the high frequency bands is so called high frequency partial discharge analyzing method.

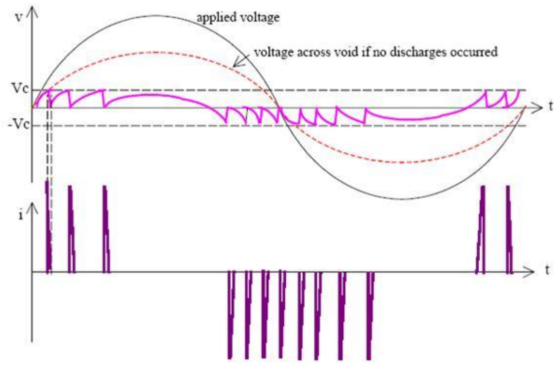


*Fig. 2. Partial Discharge Occurrence*

Partial discharge is the electrical discharge which is not completely bridging the distance between two electrodes under high voltage stress. [2] It is not easy to detect PD because it occurs periodically at the beginning. However, when it reaches beyond the critical value, that symptom proceeds itself so radically, and the number of the points are growing exponentially. Because it has a difficult problem that every preventative measurement has to be varied according to symptoms and causes which have different pattern of PD signals, somewhat professional skill is required. Nevertheless, the PD signal can be differentiated from other noises because it occurs synchronously with the phase voltage frequency. Therefore, it is very important to understand the relationship between a certain pattern of the PD and the voltage frequency.

There are four different sensors to measure the PD in the device as shown in Table 8. HFCT is the most widely used sensor in power cable diagnostics around the world. UHF sensors can detect electromagnetic waves emitted when a PD is generated. TEV sensors can detect signals that are radiated by electromagnetic radiation along metal enclosures.

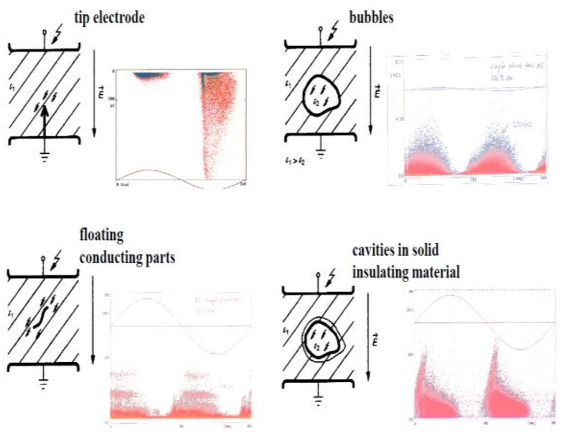


*Fig. 3. Different Types of Partial Discharge (PD) [9]*

Table 8: Different sensor for detecting PD [4]

| Type | Principle | Frequency | Sensitivity | Method |
|---|---|---|---|---|
| HFCT | VHF | 5MHz~ 100MHz | 1-30 [pC] | Connect the ground wire |
| UHF | RF | 0.5GHz~ 1500MHz | ≤ 5p [pC] | Detect aerial radiation signal |
| TEV | Transient voltage | 1MHz~ 50MHz | 1-30 [pC] | Attach magnetic tool |
| AE | Acoustic Emission | 10kHz~ 3MHz | 1-30 [pC] | Attach magnetic tool |

## 3. Application to faulted 800kV Power Transformer

Here is gas concentration as a result of dissolved gas analysis for a certain amount of time.

Table 9: Gas Concentration in the transformer [ppm]

| Date | $H_2$ | $CH_4$ | $C_2H_6$ | $C_2H_4$ | $C_2H_2$ | CO |
|---|---|---|---|---|---|---|
| Day 1 | 7.0 | 4.0 | 1.0 | 5.0 | 1.0 | 64.0 |
| Day 213 | 13.4 | 9.7 | 0.6 | 8.6 | 3.9 | 95.9 |

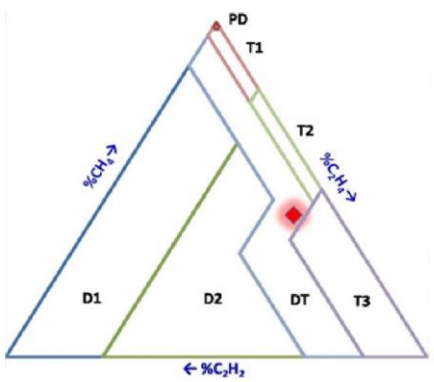


*Fig. 4. Red Plotted After Duval triangle Method.*

According to the methods mentioned previously, it is diagnosed as 'Arcing' by Dornenberg's ratio method and 'Discharge of high energy' by Roger's ratio method. Plus, Duval's triangle method result is as above in Fig 3.

In addition to DGA, PD interpretation is also applied to the same transformer. Data were collected utilizing continuous partial discharge monitor developed by UHF sensor first. It acquires PD data in the form of phase-resolved partial discharge pattern (PRPD).

*Fig. 5. UHF Sensor Attached on the Transformer [9]*

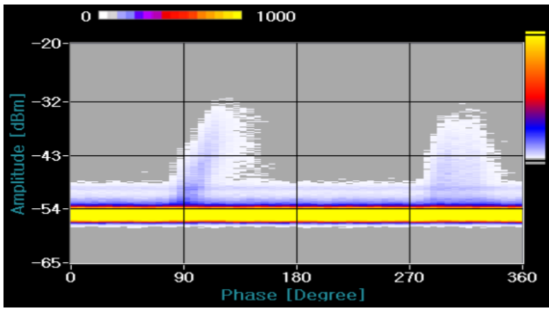


*Fig. 6. PRPD Pattern Obtained [9]*

By analyzing this from of PRPD pattern, it is supposed that some floating conducting parts perhaps cause this partial discharge. And those connected UHF sensors can be utilized to assume the location of partial discharge origin by connecting with an oscilloscope as below.

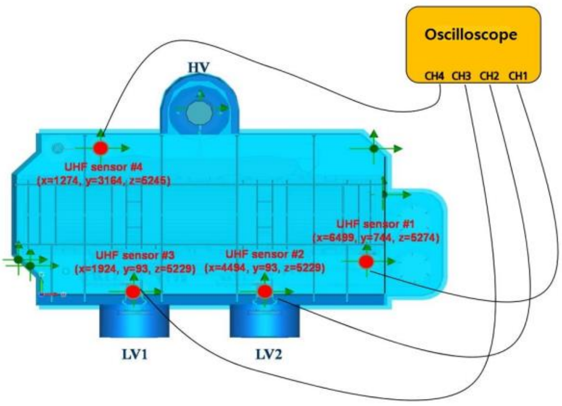


*Fig. 7. UHF Sensors Connected to a Device with Oscilloscope [9]*

These four UHF sensors simultaneously detect each signal and send them to the oscilloscope. Each signal has a different value of arrival time, and consequently tracking the location by calculating with arrival time and 3D interface is possible.

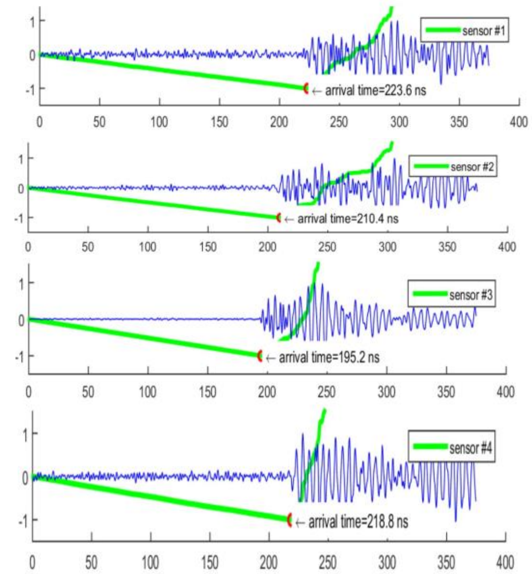


*Fig. 8. Partial Discharge Signals from Each Sensors [9]*

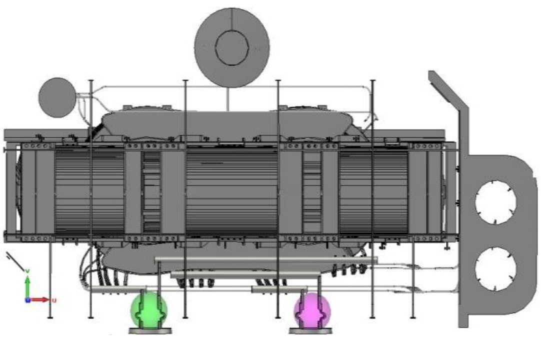

*Fig. 9. Assumed location of the faulted area in a transformer [9]*

### 3. Conclusions

This analysis has been done through two ways of diagnosis on a transformer in NPP. It is certain that performing the dissolved gas analysis has to be taken into consideration when there is an abnormal indication or when it is time to execute periodic test on it in order to figure out which type of fault that occurred inside the tank.

Even though PD signals are very often overlapped by noise pulses, which makes a PD data analysis more difficult for both human experts and for software expert systems, it is required to develop the technology of PD measurement for better effectiveness. And further work is required to standardize the procedure of PD measurement as DGA procedure in the plant so that definitive indicators of pre-fault transformers can be derived.

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