Preventing Power Transformer Failures through Electrical Incipient Fault Analysis

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Abstract: The Dissolved Gas Analysis (DGA) and partial discharge (PD) level measurement are important tools for evaluating the condition of the insulation of a transformer, which is an indicator of the health of a transformer and can help in prevention of the transformer failure. In this paper the PD level and dissolved hydrogen (H₂) and acetylene (C₂H₂) gases in oil of an artificially aged/stressed insulation system of a specially designed test cell have been analyzed and compared with the results of the experimental studies. Considering the various formulae existing in literature for the dependence of PD on applied voltage in high voltage equipment, regression analysis has been done. On analyzing the content of dissolved H₂ and C₂H₂ gases in the oil, with the PD measurements, incipient conditions of PD and low energy arcing within a transformer can be used to distinguish. This is useful for timely detection of insulation degradation.

Keywords: Dissolved gas analysis, incipient faults, low energy arcing, partial discharge, power transformer

1. Introduction

The power transformer is one of the critical units of a power system; the reliability of the system depends upon it. The health of a transformer can be indicated by the condition of its insulation system. Incipient faults develop due to degradation of the insulation in a transformer caused on account of thermal and electrical stresses which ultimately lead to breakdown of a transformer. The electrical stresses are caused due to PD and arcing. PD is associated with very low energy level but cannot be ignored as it causes pinholes in the solid insulations from where initiates the degradation of the insulation. It is difficult to identify the location of PD during physical inspection while spots where arcing has taken place can be identified. Arcing causes not only degradation in the dielectric properties of the solid and liquid insulation but also creates localized hot spots causing temperature rise. If PD process is not suppressed it can develop into arcing and failure of the transformer. Timely detection of insulation degradation would make the maintenance engineers, initiate the procedure for altering the operating conditions to prevent/slow down the destruction process and prevent total failure of a transformer.
Almost all insulation systems are made up of more than one material and also the electrical stress within a system is never uniform. The insulation system of an oil filled transformer consists of mineral oil as the liquid insulating material and paper, press board, cloth tape as solid insulating materials. The DGA methods are extensively used by utilities for incipient fault diagnosis and their classification.

The PDs are like localized electrical breakdowns which do not completely bridge the electrodes. In case of high voltage (HV) devices, the presence of PD is the commencement of the failure of its insulation material. PD is a progressive deterioration that leads ultimately to breakdown/failure of the equipment. PD prevention and detection are essential for reliable and long term operation of HV equipment.

In this paper the results used are of experimental studies conducted by P. Verma et al. [1, 2]. The results used are of the dissolved H$_2$ and C$_2$H$_2$ content (ppm) in the oil of a specially designed test cell that is aged by applying combined thermal and electrical stresses and it is analyzed for PD. The strength of the experimental work considered is the combined electrical and thermal stresses which have been simultaneously applied to a test cell. The relevant conclusions of the referred work were:

- The multiple regression of H$_2$ gas content have a significant effect of time, temperature and electrical stress and a transfer function was found.
- The multiple regression of C$_2$H$_2$ gas content could not find any transfer function.
- The H$_2$ concentration in oil is used to assess PD in the transformer

The scope of the paper is limited to the dissolved content of two key gases used for identification of partial discharge and arcing. This paper is divided in six sections. Section 2 gives the details of PD, sections 3 and 4 brief about ageing behavior of solid and liquid insulation, and DGA. Section 5 discusses the experiment, reviews and analyses the results. The conclusion is given in section 6.

2. Partial Discharge

The PD in a gas filled void of a solid or liquid insulation system can be caused due to presence of sharp edges, metallic particles, moisture in insulation, gas bubbles generation and mechanical distortion due to some fault condition, replacement of oil, sharp edges of grounded parts of tank, interface of two dielectric medium, and delamination of pressboard, etc [3, 4]. These electric pulses in the voids occur at high frequency; hence they attenuate as they propagate through the equipment. Intense PD is indicated by spitting or cracking noise. The PD can result in complete failure of the insulation system within a few days or it may take few years.

There are a large number of expressions that have been used to calculate PD for HV equipment. Using experiments, the formulas for PD that have been proposed in literature [5] are:

The linear relations:
- Skilling’s formula (1931) \( PD \propto (V-V_0) \)

The quadratic relations:
- Peek’s formula (1914) \( PD \propto (V-V_0)^2 \)
- Ryan and Henline formula (1924) \( PD \propto V(V-V_0) \)
- Peterson’s formula (1933) \( PD \propto V^2 F(V/V_0) \) where \( F \) is an experimental factor

The cubic relations:
- Forist and Menger formula (1928) \( PD \propto V^3 \)
Prinz’s formula (1940)  
\[ PD \propto V^{2}(V-V_{0}) \]
Where \( V \) is actual voltage and \( V_{0} \) is discharge inception voltage. Acoustic emission detection methods, electrical method using ultra high frequency detection are used to detect PD in electrical equipment.

2.1 Acoustic Method

Bubble form and collapse during PD, this generates acoustic singles that have a frequency of approximately 100 kHz and these signals are used to locate the source of PD. In this method the disturbance from electrical network do not interfere with its measurement however, external interferences do interfere. Wave guides are used to overcome external interferences [6].

2.2 Electrical Method

A wide frequency component is exhibited by the PD signals. When the signal propagates through the equipment and the network these high frequencies get attenuated. The detection gets hampered by electrical interference signals from surrounding equipment. To overcome this ultra high frequency field sensors are used [7].

Multiple sensor approach using different type of sensors at different locations can help to reduce external influences. Combined acoustic and electrical methods can be effective but is an expensive option.

3. Insulating System

The oil is the liquid insulation and paper and pressboard are the solid insulations within a transformer

3.1 Liquid insulation

The electrical field conduction current characteristic in a liquid insulation has three regions that are very distinct. At very low field the current is due to dissociation of ions, a saturation level is reached with intermediate field, and at high field the current generated because of field aided electron emission from cathode gets multiplied by a mechanism similar to Townsend’s type of mechanism leading to breakdown. Figure 1 gives the conduction current-electric field characteristic of liquid hydrocarbons [8].

The breakdown condition for a HV equipment is \( \gamma d = 1 \) where \( d \) is the distance \( \alpha \) is the first ionization coefficient and \( \gamma \) is the second ionization coefficient. The breakdown strength for liquid insulation is given by \( V_{bl} = Fd^{n} \), where \( V_{bl} \) is the breakdown voltage of the liquid insulation material which depend upon the nature of the voltage and the time of application, \( d \) is the gap length, \( F \) and \( n \) are constants and \( n < 1 \).

3.2 Solid Insulation

The electrical and mechanical properties of paper deteriorate when the temperature exceed 100°C [9]. The voids are present within it are filled with a medium of lower dielectric strength. Hence, the field in the void is higher than that across the dielectric and even under normal working voltages the field exceeds the breakdown strength.

The insulation between two conductors can be divided into three parts, \( C_{1} \) is the capacitance of the void, and capacitance of the dielectric in series with the void is \( C_{2} \), while the rest of the dielectric has capacitance \( C_{3} \). Figure 2 gives the details of the
insulation between two conductors and its’ electrical equivalent. If $V$ is the applied voltage and the voltage across the void is $V_l$ then

$$V_l = \frac{\varepsilon_0 E^2 d_2}{\varepsilon_{d_1} + \sum_{i=1}^{n} \frac{\varepsilon_i E^2 d_i}{d_2}}$$

where $\varepsilon_0$ and $\varepsilon_i$ are the permittivities, $d_i$ and $d_2$ are the thickness of the void and dielectric, and $d_i << d_2$.

The breakdown occurs in both the half cycles of the applied voltage and the number of discharges depends upon the applied voltage. Chemical degradation of the material occurs due to positive and negative ions being formed. The energy of the ions break the chemical bonds, this causes reduction in the thickness of insulation due to erosion of the material.

![Figure 1: Conduction Current-electric Field Characteristics of Hydrocarbon Liquids](image1)

![Figure 2: Insulation between Two Conductors and its Electrical Equivalent](image2)

### 4. Dissolved Gas Analysis

The transformer oil is a mixture of many different hydrocarbons and its decomposition process is a complex one. When the oil is subject to thermal or electrical faults first the carbon-hydrogen and carbon-carbon bonds break and active hydrogen atoms and hydrocarbon fragments are formed that recombine.

a) Thermal fault: The thermal decomposition of mineral oil produces relatively large quantity of $H_2$ and $CH_4$ and traces of $C_2H_6$ and $C_2H_4$. As thermal stress is further increased increasing quantities of $H_2$, $C_2H_6$ and traces of $C_2H_4$ are produced. The thermal decomposition of cellulose produces carbon monoxide ($CO$), carbon dioxide ($CO_2$) and water vapor. The paper degrades at lower temperature than oil. For a transformer operating at its’ nameplate CO and $CO_2$ are generated without excessive hotspots. The ratio of $CO_2/CO$ is used as an indicator of thermal decomposition of cellulose which under normal condition is $> 7$. The degradation of cellulose due to any abnormality is indicated if the magnitude of CO increases i.e the ratio $CO_2/CO$ decreases.

b) Electrical fault: Partial discharges and low level intermitted arcing produces $H_2$ with decreasing quantity of $CH_4$ and traces of $C_2H_2$. The concentration of $C_2H_2$ and $C_2H_4$ rises significantly as the intensity of discharges increases. The quantity of $C_2H_2$ becomes more pronounced if there is continuous discharge or arcing taking place. The arc occurring within an insulating system deteriorates it and can result in ultimate failure of the transformer.

The Key gas method is based on the significant gases produced for four general faults. $C_2H_4$ is the principal gas that indicates thermal fault in oil. Predominance of CO is an
indicator of thermal fault (cellulose), \( \text{H}_2 \) indicates PD while \( \text{C}_2\text{H}_2 \) is the principal gas indicating arcing [10]. \( \text{H}_2 \) is a weakly electronegative gas. \( \text{C}_2\text{H}_2 \) is a combustible gas that is highly unstable; a very hot flame is produced when it combines with oxygen.

5. Review of Experiment Results and Analysis

In a special designed test cell, combined thermal and electrical stresses were applied to composite insulation of paper and transformer mineral oil [1, 2]. The Kraft paper insulation over the conductor used was of six layers of paper having total thickness of 0.16mm; wound in half laps of a two side build-up that can withstand electrical stress (\( V_o \)) of 1.024 kV. The stress levels that were applied are given in Table 1.

<table>
<thead>
<tr>
<th>Stress level</th>
<th>Electrical Stress</th>
<th>Thermal Stress</th>
</tr>
</thead>
<tbody>
<tr>
<td>I</td>
<td>(a) 1 kV</td>
<td>120°C</td>
</tr>
<tr>
<td>II</td>
<td>(b) 1.5kV</td>
<td>140°C</td>
</tr>
<tr>
<td>III</td>
<td>(c) 2.5kV</td>
<td>160°C</td>
</tr>
</tbody>
</table>

The test cell was analyzed after 360, 720, 1080 and 1440 hrs for dissolved gas concentrations of \( \text{H}_2 \) and \( \text{C}_2\text{H}_2 \) and the PD level at voltage of 1.8, 2.7, 4.0, 5.4 and 6.2 kV were measured. Figures 3 (a-c) show, the \( \text{H}_2 \) content for the three levels of stresses [2].

![Figure 3: Concentration of \( \text{H}_2 \) (ppm) in Test Cell Oil](image-url)
Whatever is the level of thermal stress, for electrical stresses below the designed voltage withstand ability of the insulation and 1.5 times its value the H\(_2\) content increases linearly but with higher level of electrical stress the raise is exponential. However aged the transformer may be the trend of H\(_2\) increase remains same (linear) provided it is operated at its voltage rating. If the operating voltage level is higher the H\(_2\) would increase exponentially with time.

5.1 H\(_2\) and C\(_2\)H\(_2\) Content

The trend of C\(_2\)H\(_2\) content is shown in Figure 4. The content of C\(_2\)H\(_2\) increases exponentially on operating at higher voltages than that the transformer insulation is designed for. For voltage levels below the level the transformer insulation is designed for the raise may be linear or exponential due to the recombination and rearrangement of free radicals. However, the presence of C\(_2\)H\(_2\) indicates arcing.

![Figure 4: Concentration of C\(_2\)H\(_2\) (ppm) in Test Cell Oil](image)

5.2 Partial Discharge Level

The results of PD at different stress level are given in Table 2. Regression analysis was carried out taking the independent variables as \((V-V_0)\), \((V-V_0)^2\), \(V(V-V_0)\), \(V^2\), \(V^2(V-V_0)\), and \(V^3\) and PD was taken as dependent variable. For level-I of stress the index of correlation was 0.834. The best fit curve was found to be exponential \(PD = A e^{Bx}\) with \(x = (V-V_0)\). The slope is positive and less than 1, while A was found to be increasing as the
combined stress level is increased or as the transformer ages. The correlation coefficient \( R^2 \) was found to be greater than 0.9.

**Table 2:** Partial Discharge at Various Electrical and Thermal Stress Levels [1].
The figures in **bold italics** indicate PD while figure in *italics* indicate measured PD level with significant presence of \( \text{C}_2\text{H}_2 \) which indicates arcing.

<table>
<thead>
<tr>
<th>Applied voltage (kV)</th>
<th>Stress level I</th>
<th>Stress level II</th>
<th>Stress level III</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>(a)</td>
<td>(b)</td>
<td>(c)</td>
</tr>
<tr>
<td>1.8</td>
<td>0.0023</td>
<td>0.002</td>
<td>0.0059</td>
</tr>
<tr>
<td></td>
<td>0.19</td>
<td>0.179</td>
<td>0.173</td>
</tr>
<tr>
<td></td>
<td>0.921</td>
<td>5</td>
<td>11.8</td>
</tr>
<tr>
<td>2.7</td>
<td>0.0079</td>
<td>0.0254</td>
<td>0.0213</td>
</tr>
<tr>
<td></td>
<td>140</td>
<td>180</td>
<td>190</td>
</tr>
<tr>
<td></td>
<td>160</td>
<td>235</td>
<td>240</td>
</tr>
<tr>
<td>4.0</td>
<td>0.0097</td>
<td>0.0341</td>
<td>0.0358</td>
</tr>
<tr>
<td></td>
<td>280</td>
<td>543</td>
<td>700</td>
</tr>
<tr>
<td></td>
<td>330</td>
<td>550</td>
<td>581</td>
</tr>
<tr>
<td>5.4</td>
<td>0.0432</td>
<td>0.0654</td>
<td>0.0525</td>
</tr>
<tr>
<td></td>
<td>500</td>
<td>690</td>
<td>804</td>
</tr>
<tr>
<td></td>
<td>740</td>
<td>840</td>
<td>977</td>
</tr>
<tr>
<td>6.1</td>
<td>0.0992</td>
<td>0.014</td>
<td>0.158</td>
</tr>
<tr>
<td></td>
<td>670</td>
<td>810</td>
<td>960</td>
</tr>
<tr>
<td></td>
<td>830</td>
<td>890</td>
<td>989</td>
</tr>
</tbody>
</table>

For the combined stress of level II the index of correlation was 0.933 for \( (V-V_0) \). The best fit curve was found to be linear, as the stress level increases the slope increases and the intercept is always negative. The correlation coefficient \( R^2 \) was also found to be greater than 0.9. For level III of stress similar to that of level-II the best fit curve was also found to be linear, as the stress level increases the slope increases and the intercept is always negative. The index of correlation was found to be 0.974 for \( (V-V_0) \). The value of \( R^2 \) for all three stress levels was found to be very close to 1. The best fitting curves for applied voltage and corresponding PD for the three stress levels are plotted in Figure 5.
When voltages higher than that insulation of the test cell is designed for, are applied to it, the PD increases exponentially later the PD raise is linear and also the curve shifts upwards for higher applied voltages.

6. Conclusion

On carrying out regression analysis for the insulation system of a transformer, it is found that the PD is proportional to the applied voltage. At lower thermal stress level, the PD is found to increase exponentially. When the insulation system of the transformer is in good health, the field between the conducting surfaces across the dielectric is strong. On aging the degradation is taking place in the oil as per the existing theory for liquid hydrocarbons and the exponential trend is due to the conduction current in the insulation being field aided.

The PD increases linearly with increase in the thermal stress on the insulation, as the transformer ages. This linear trend is due to the presence of hydrogen ions in the oil.

For the same thermal stress and increase in electrical stress, the C\textsubscript{2}H\textsubscript{2} levels increase but no regular trend is observed, because as the intensity of discharge increases there is a significant rise in the concentration of not only C\textsubscript{2}H\textsubscript{2} but also C\textsubscript{2}H\textsubscript{4} as arcing is associated with raise in temperature.

The DGA results along with the PD measurements can be used to indicate if the incipient electrical fault in the transformer is PD or arcing stage has reached. In transformers that have been under operation for few years, initial PD leads to development of arcing after some period of operation. Traces of acetylene indicate initiation of arcing. Hence, raise in PD gives advance warning of developing arcing faults at a later stage. Detection and mitigation of incipient faults within a transformer, in the long term save cost of major repairs, prevent outages due to breakdown, followed by cost of replacements and help in maintaining continuous power supply.

For further work, online monitoring of both dissolved gases and PD measurements can give better plots which can be used to find the threshold level of gas concentrations when PD develops into arcing.

References


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