ON-LINE PARTIAL DISCHARGE DETECTION ON TRANSFORMERS

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SUMMARY

Different diagnostic techniques are currently available for on-line insulation condition assessment of power transformers. Amongst these techniques a relatively new technique for detecting partial discharges (PD) in the Ultra High Frequency range of the spectrum is also introduced. The UHF technique has been recently presented in the field of transformer diagnostics, and although it is under development it shows great potential for on-line detection, recognition and location of PD activity. Comparison of the available techniques showed that Dissolved Gas Analysis and Partial Discharge measurements are complementary. Based on this, a suggestion will be made for a condition assessment program combining the available diagnostics with PD measurements.

INTRODUCTION

Transformers are a large part of the asset cost structure of the power system. The cost of an unexpected failure can be several times the cost of the original transformer installation, when system outages, lost power sales, and possible environmental clean up costs, etc. are taken into consideration. Knowing the transformer condition is essential in order to reduce the costs associated to possible loss of production and to lower the total Life Cycle Costs which comprise of the costs for transformer retirement, refurbishment, replacement or relocation.

Transformer asset management (or Life Cycle Transformer Management), which relies mainly on risk and condition assessment study outputs, will be the main decision driver in future planning for maintenance strategy, or replacement. The risk assessment is a screening process, using statistical methods to identify and prioritize those transformers that represent the highest risk. This way normal operating equipment are filtered out from the “abnormal cases” that need further attention and thus precious resources are applied only when they are needed [1]. However this stage does not identify the actual condition or the vulnerability of the individual transformers. The next stage can be described as condition assessment, and is carried out only on the “abnormal cases” of the transformers where a more extensive diagnose of each “abnormal” case is performed. The results of this process will help the utility in the last step, the life cycle decisions.

The investigation of the transformers is performed using different diagnostic techniques for different defects in different parts of the transformer. For risk assessment, the diagnostic techniques should be inexpensive and on-line and yet sensitive and broadband in order to detect a defect in time [1]. For the condition assessment stage each possible defect should be investigated with the appropriate diagnostics’ technique, thus this stage involves a rigorous inspection and extensive testing of the transformer.

DIAGNOSTIC TECHNIQUES

The basic diagnostic tests (DGA, furan analysis, power factor, ratio, resistance, etc.) are the ones that are widely used for the risk assessment stage, in transformer service routines. The DGA (dissolved gasses in oil analysis) is probably the most established method so far, for detecting defects in transformers at an early stage [2]. Other advanced diagnostic methods, which are not usually part of routine maintenance but offer a more scientific approach, are used in the process of performing the life assessment for power transformers [2]:

- Frequency Response Analysis (FRA)
- Dielectric Response Measurement (DR)
- Partial discharge measurements (electrical and acoustic)
- Analysis of particles and metal particles in oil
- Noise and Vibration measurement, e.t.c.

Examples of some available diagnostic tools are given in Table 1 below, in order to demonstrate the value of these techniques. Dividing the transformer in 7 main parts (parts or locations where defects can be located) [3]:

1) Hard insulation (moistening, dirtying, destruction).
2) Magnetic system (core compressing, component to tank insulation damage, etc.).
3) Windings (buckling and other deformations).
4) Transformer oil condition.
5) Systems of oil cooling, treatment and protection.
6) Bushings.
7) Voltage regulators and contact system.

The sensitivity of each diagnostics tool to detect a defect in each location is indicated in Table 2. From Table 2 it can be observed that DGA and PD measurements combined cover all main cases of defects in power transformers. All dielectric defects are accompanied by the presence of PDs, thus Partial discharge measurements (electrical and acoustic) are technically able to detect dielectric defects and even identify the presence of a specific defect from the electric/acoustic patterns obtained. Most of the classical PD detection techniques had the disadvantage of being limited by external noise; the least noise-sensitive techniques are acoustic and UHF detection.

Dissolved gas analysis can be used to detect any defects caused by thermal instabilities, overheating and eventual hot spots, where PD measurement may not be sensitive enough to detect, since no PD may be present. Even when the instability...
has advanced to the formation of X-wax or carbonization of the cellulose, the ionization mechanisms may not be detectable externally. Depending on the configuration that the defect path follows, PD detection may be valuable at the later stages, however no strict guidelines can be given due to the many variables preceding thermal runaway and disruptive failure [4].

For dielectric defects, DGA will provide a reasonably good diagnostic. However, Cigré reports suggest that in the case of tracking, specifically if the tracking is in buried sections, with no gas outlet, the DGA may be less sensitive initially [4]. Partial discharge measurements however, are technically able to detect tracking discharges and even identify the presence of tracking from the electrical patterns obtained [4].

In chemical deterioration, its main mechanism is oil oxidation, which eventually will lead to paper insulation deterioration and thus partial discharges (for example surface discharges on oil-solid insulation barrier), thus making PD measurements sufficient for detection. However, DGA due to its nature (examination of oil sample) will better describe the phenomenon even at its early stages.

### PD MEASUREMENT DIAGNOSTICS

All dielectric defects are accompanied by the presence of partial discharges, thus PD measurements (electrical and acoustic) are technically able to detect dielectric defects and even identify the presence of a specific defect from the electric/acoustic patterns obtained. Most of the classical PD detection techniques had the disadvantage of being limited by external noise; the least noise-sensitive techniques are acoustic and UHF detection, especially when four UHF sensors are used.

**Acoustic**

Acoustic PD measurement, from Cigré’s experience (test bed and site experience), have been shown to have generally good sensitivity, but only when there is a clear line of sight between the discharge site and sensor location, and in addition, deep winding or core faults generally become evident only if the fault levels are significant [5]. Specifically, during site acoustic PD measurements these defects in the insulation have an acoustic frequency range (35 to 50 kHz, depending on the defect location) which overlaps the frequency range of the core noise of the transformer (40 to 60 kHz) and this can pose a problem in detection. Discharges propagating on oil-paper interface (creep discharges) are also usually difficult to detect using acoustic method [5].

**Ultra High Frequency (UHF)**

More specifically, experimental evidence suggests that the UHF method is the least susceptible to noise, with little or no effect due to insulating barriers in the insulation [5]. Furthermore UHF signals have been proven to be the most sensitive to the ageing condition of the insulation, in comparison with the other PD measurement techniques [4, 5].

**Time Domain**

In time domain, detection occurs by sensing UHF activity (not related to noise) by at least one sensor. When a signal (above a noise threshold) is detected in any

<table>
<thead>
<tr>
<th>Location</th>
<th>Method</th>
<th>Suitable for:</th>
<th>On-Line/Off-Line</th>
</tr>
</thead>
<tbody>
<tr>
<td>WINDING</td>
<td>Infrared Scan</td>
<td>Hot spots, localised overheating</td>
<td>On-Line</td>
</tr>
<tr>
<td></td>
<td>Dielectric Dissipation Factor (DDF) &amp; Capacitance</td>
<td>Moisture &amp; Contamination</td>
<td>Off-Line</td>
</tr>
<tr>
<td></td>
<td>Winding Turns Ratio</td>
<td>Faulted turns</td>
<td>Off-Line</td>
</tr>
<tr>
<td></td>
<td>DC Winding Resistance</td>
<td>Conductor damage</td>
<td>Off-Line</td>
</tr>
<tr>
<td></td>
<td>Percent Impedance/Leakage Reactance Test</td>
<td>Winding deformation</td>
<td>Off-Line</td>
</tr>
<tr>
<td></td>
<td>Partial Discharge (acoustic &amp; electrical)</td>
<td>Detect &amp; Locate defects which involve PD</td>
<td>On-Line</td>
</tr>
<tr>
<td></td>
<td>Sweep Frequency Response Analysis (Transfer Function)</td>
<td>Winding displacement, possible loose</td>
<td>Off-Line</td>
</tr>
<tr>
<td></td>
<td>Recovery Voltage Measurement (RVM)</td>
<td>winding, and core faults</td>
<td>Off-Line</td>
</tr>
<tr>
<td></td>
<td>Vibration Analysis</td>
<td>Moisture in paper and ageing of paper</td>
<td>Off-Line</td>
</tr>
<tr>
<td></td>
<td>Degree of Polymerisation (DP) Gel Permeation</td>
<td>Slack winding &amp; Mechanical distortion</td>
<td>On-Line</td>
</tr>
<tr>
<td></td>
<td>chromatography</td>
<td>faults</td>
<td></td>
</tr>
<tr>
<td>OIL</td>
<td>Dissolved Gas Analysis (DGA) &amp; gas ratio analysis</td>
<td>Detecting incipient faults</td>
<td>On-Line</td>
</tr>
<tr>
<td></td>
<td>Furin Analysis</td>
<td>Overheating and ageing of paper</td>
<td>Off-Line</td>
</tr>
<tr>
<td></td>
<td>Moisture/Water content</td>
<td>Dryness</td>
<td>Off-Line</td>
</tr>
<tr>
<td></td>
<td>Resistivity, Acid Number (or Acidity), IFT &amp; DDF</td>
<td>Ageing of oil</td>
<td>Off-Line</td>
</tr>
<tr>
<td>BUSHINGS</td>
<td>Dielectric loss angle (DLA)</td>
<td>Moisture &amp; particle contamination</td>
<td>Off-Line</td>
</tr>
<tr>
<td></td>
<td>VHF</td>
<td>Partial discharges</td>
<td>On-Line</td>
</tr>
</tbody>
</table>

Table 1: List of the available diagnostic tools and their main application for faults detection [1].
one of the sensors, the oscilloscope is triggered and the waveform is recorded at all four sensors simultaneously. The detection and recording procedure can go on for hours, days and even months if the user requires so, in order to make important conclusions based on statistical data obtained. Detection can provide a rough indication of the area where the defect is located (depending on which sensor the recorded signal has the maximum amplitude and shortest time of arrival) [6]. No exact indication of the position of the source is provided at this point however; this is a later step, which requires the use of special software: by taking into account i) the coordinates of the position of each sensor, ii) the propagation velocity iii) the path within the transformer tank and iv) the difference in time of arrival between the signals detected per each sensor, it is possible to calculate back the location of the PD with high accuracy [6, 7].

In figure 1 is shown a PD signal as it was recorded simultaneously from four sensors attached on an on-line transformer. The difference in time of arrival of the four signals (representing the same PD at the four different sensors), can help to calculate the distances of the PD from each of the sensors. The accuracy of the PD localization technique is strongly affected by the accuracy with which the time of arrival of the PD signal at each sensor, can be determined. The process of locating sources of PD activity originated by incipient defects depends on several factors such as intensity of the source, distance of the sensor(s) to the source (attenuation path), transformer construction (shields, core type, materials involved, etc.) and of course, defect type [7].

**Frequency domain** The frequency spectra (obtained using a spectrum analyzer connected to a sensor) should be used in order to gauge the possibility of a successful PD measurement and to detect on what frequencies PD activity from the transformer might be detected. From this, defect or defect frequency spectra patterns can be deduced, which can help to later recognize similar defect or fault cases. Examples of frequency spectra of two PD defects are shown in figure 2.

**Phase domain** In the Frequency domain, using the spectrum analyzer as tunable filter, effective noise suppression can be
achieved by selecting the frequency band with the highest signal-to-noise ratio, resulting in similar phase-resolved PD patterns that are obtained with a standardized measuring circuit [9]. This can be achieved by setting the centre frequency of the spectrum analyser to the selected measuring frequency, and by synchronising the sweep time option with the voltage source to obtain PD patterns correlated to the 50 or 60 Hz sine wave [9].

Once the data analysis is complete, the identification and location of the defect can be deduced as shown in figure 4.

**Pattern Recognition – Identification** Once PD activity has been detected and located, the major concern of Maintenance Engineers is to assess the severity of the defect in order to plan the corrective actions (if any) that need to be taken. A database of faults and defects should be built to simplify the work of the Maintenance Engineers; the purpose of this is to have a bank of information in which the data can be compared between sister units as this would help to facilitate identification of defects (by focusing on the discrepancies) [6]. The database should contain the most relevant information of the transformer including results of the UHF commission test performed and other diagnostic techniques’ appropriate results (such as gas in oil concentrations). It would be enhanced from site experience as more transformers are tested and different defects are identified and verified through internal inspections [6], and furthermore from laboratory tests with artificial defects. Examples of patterns obtain using the spectrum analyser in the frequency and phase domain were shown in figure 1 and figure 3 correspondingly.

**DISCUSSION**

As it was observed from Tables 1 and 2, DGA and PD measurements are complementary techniques, which can thus be combined for the condition assessment of power transformers. In the risk assessment stage DGA could constitute the tool for giving an indication of thermal and chemical defects and some dielectric ones, and PD measurement for all dielectric defects and chemical ones at later stages. In the more detailed condition assessment stage, PD measurements could be used for location of the defect and identification from the frequency spectra and phase domain patterns, which can be verified by DGA results. Further research needs to be performed on these suggestions, in order to conclude if PD and DGA can cover all possible faults and defects satisfactory. By combining the two diagnostic techniques, the condition assessment of the transformer would be performed as shown in figure 5.

A complete database of these faults and defects should also be built in parallel with this research, in order to facilitate the work of the maintenance engineers. The database should contain the most relevant information of the transformer including results of the UHF commission test performed and other diagnostic techniques’ appropriate results (such as gas in oil concentrations). It would be updated from site measurements experience as more transformers are tested, and different defects are identified and verified through internal inspections [6]. Furthermore defects can be covered from laboratory tests with artificial defects in test transformers or other experimental setups.
EXAMPLE UHF TECHNIQUE

To illustrate the UHF technique, an example is shown in figure 6. 4 UHF sensors were installed on a 500 MVA, 380 kV power transformer. A detail of the UHF sensor is shown in figure 6b.

Figure 6: UHF applied to a 500 MVA, 380 kV power transformer: a) photo of the power transformer under test, b) detail of the UHF sensor fitted to the tank of the transformer.

Figure 7 shows the results of a sensitivity check of the UHF technique by injecting 45 V pulses on sensor W4 and detecting the result on the other sensors in the frequency domain. The blue line is the response to these 45 V pulses; the pink line is the background noise level. The peaks in the graphs around 900 and 1800 MHz are coming from mobile phone network.

From experience on a 150 MVA transformer, 45 V pulses represent a discharge source of 30 pC magnitude measured using a detection circuit according to the IEC 60270 recommendations [10]. More investigation is necessary to generalize this relation between PD magnitude and artificial pulses for all kind of power transformers.

CONCLUSIONS

From the results of this paper, it can be deduced that:

1) a complete package for transformer condition assessment could be the use of PD measurements along with DGA;

2) the UHF technique for PD measurement or on-site monitoring of transformers is promising because of its immunity from external noise interference and high sensitivity to the ageing condition of the oil-paper insulation;

3) the UHF method has the capability of localization of the defect, has a simple construction (if windows are installed on tank), and has much lower price

REFERENCES


