CORRELATION OF DGA, UHF PD MEASUREMENT AND VIBRATION DATA FOR POWER TRANSFORMER MONITORING

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Abstract: Reliability of electrical energy networks depends on quality and availability of electrical equipment like power transformers. Local failures inside their insulation may lead to catastrophic breakdowns. To prevent destroying events power transformers are e.g. tested on partial discharge (PD) activity. As testing is just snapshot information about transformers condition, permanent online monitoring is more frequently used to gain operational experiences. The paper presents a monitoring case study of an aged generator step-up transformer with PD activity. Different measurement methods considering different transformer parameters are introduced. Correlation of data for information gain regarding the insulation condition assessment is discussed with the help of a recorded incident with high PD level and followed rise in gas concentration. A Hydran sensor is used to measure the actual level and the trend of dissolved gasses. The presented monitoring system uses the electromagnetic PD measurement method, also known as UHF-method. PD emitted electromagnetic waves are monitored with an oil valve sensor inside the transformer tank. Furthermore vibration monitoring is included, representing a new approach for transformer surveillance. In addition common measurements were performed for evaluation and correlation purpose, including load current, voltage, top-oil and ambient temperature of the transformer.

1 INTRODUCTION

The reliability of electrical energy networks depends on the quality and availability of primary electrical equipment such as power transformers. Localised internal insulation failures can lead to catastrophic breakdowns and incur long outage and penalty costs. To reduce such risks power transformers have to pass a range of factory tests including one for partial discharge (PD) activity before acceptance and commissioning. Once installed onsite PD testing is costly. The transformer has to be energised with e.g. induced test voltage or resonant sets. Additionally the results are often restricted by high onsite interference, e.g. corona discharge. Many users therefore rely on integrated detection methods such as dissolved gas analysis [1].

As testing provides just snapshot information about transformers' condition, permanent online monitoring is more frequently used to gain operational experiences [2, 3].

The paper presents a monitoring example of a 45 year old generator step-up transformer with the rated voltage of 110/10 kV and the rated power of 120 MVA. Due to 8 years stand still time period, operational experience is missing. A condition assessment before putting the unit back into service revealed PD activity. Because there are no common rules and threshold values for aged transformers the unit was put back into service with a permanent observation of PD activity by means of online monitoring.

Different measurement methods are performed and presented with their information gain regarding the insulation condition assessment.

The applied measuring methods are dissolved gas analyses by a Hydran sensor, PD monitoring by detection of electromagnetic waves with an UHF sensor installed at an oil-filling flange and vibration measurements by an accelerometer sensor on the tank surface. In addition, common measurements were performed for evaluation und correlation purpose, including load current, voltage, top-oil and ambient temperature of the transformer.

2 MEASUREMENT METHODS

Following the applied measurement and monitoring methods are presented.

2.1 Electrical PD measurement according IEC 60270

The conventional measurement of the apparent charge of PD according to IEC 60270 [4] and signal decoupling with a high voltage capacitor is a common measurement technology for quality assurance of high voltage (HV) equipment. According to IEC 60270 the measurement setup can be calibrated in terms of pico Coulomb (pC). The measurable so called apparent charge in pC misses a direct correlation to the charge exchange within the PD. However threshold values of the apparent charge levels for acceptance test after manufacturing of new power transformers proofed to be successful since recent years.

Conventional PD measurements on that transformer were performed with external coupling capacitors. The measurements are documented more detailed in [5]. Conclusion is that the transformer has more than one active PD source with permanent activity at nominal voltage. Therefore PD activity has to be monitored for trend analyses indicating if the failure is getting worse. Unfortunately, the electrical PD monitoring can not be performed due to missing measuring taps at the 110 kV bushings. Therefore simultaneously UHF PD measurements are performed as fingerprint measurements. Afterwards only the UHF measurement is performed as online monitoring.

2.2 UHF PD Measurements

The so called "UHF PD measuring method" (UHF: Ultra High Frequency) is based on the fact that PD are fast electrical processes radiating electromagnetic waves with frequencies up to the ultrahigh range (UHF: 300 – 3000 MHz) in the surrounding oil. Due to the moderately attenuated propagation of UHF waves inside the transformer tank, the electromagnetic wave detection is very sensitive [6].

UHF sensors [7] can be inserted into the transformer during full operation through the oil filling valve, see UHF probe in Figure 1.

Figure 1: UHF probe for power transformers

The UHF probe was developed and designed at the Institute of Power Transmission and High Voltage Technology (IEH), University of Stuttgart. It is build to be installed on a power transformers' oil valve flange. It is oil tight and actually the installation at an online power transformer is possible, because there is no galvanic contact with high voltage. As a result of shielding characteristics of the transformer tank against external electromagnetic waves, normally the UHF probe only measures internal PD. Thus a clear decision can be made concerning the PD activity of the test object.

PD-events can also be measured in reference to one phase of the transformers' feeding voltage, see examples in the following chapters. Aim is to get a phase resolved PD pattern to confirm that the measurable UHF signals correlate to PD by phase stable occurrence. The identification and characterisation of PD sources can be done similar to measurements according to IEC 60270.

A typical recorded UHF-PD-event is shown in Figure 2 and Figure 3. Figure 2 shows the fast raising signal in time domain with a signal raise time of approximately 500 ps.

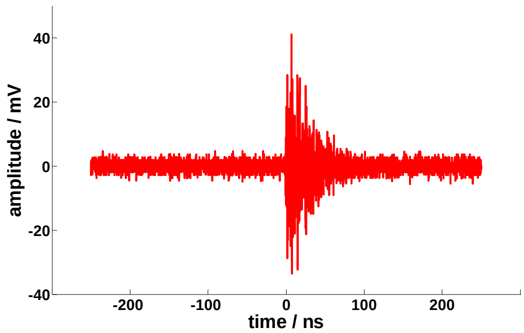

Figure 2: Typical UHF-PD-event in time domain

In Figure 3 the corresponding frequency spectra is shown. It contents broadband frequency portions up to 2.2 GHz.

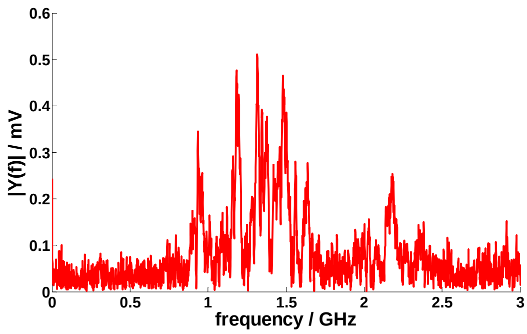

Figure 3: UHF-PD-event shown in corresponding frequency domain

2.3 Continuous gas monitoring

For the continuous measurement of the dissolved gases in the transformer oil a GE Hydran 201Ti sensor system is used. The sensor is installed at the upper right side of the tank, see Figure 4.

For sensing the gas concentration the Hydran sensor uses a fuel cell sensor. It is separated from the oil by a gas-permeable membrane. The sensor detects a mixture of 4 gases with variable selectivity: H_2 (100 %), CO (18 %), C_2H_2 (8 %), C_2H_4 (1.5 %) in the concentration range between 0 and 2000 µl/l (H_2 equivalent). The Hydran readings are stored in the sensor, backup is performed regularly.

In addition, oil samples are taken at frequent intervals and analysed in a laboratory for possible fault gases. The calculated gas concentrations form laboratory DGA are comparable to the measured Hydran values.

2.4 Vibration measurements

Vibrations are caused by voltage-dependent and load-dependent effects, which lead to oscillations in mechanical structures of power transformers.

The voltage-dependent vibration is originated by magnetostriction leading to oscillations of the core (e.g. lamination sheets). The Weiss Domains in metal align themselves along the time-varying magnetic main flux induced by applied voltage. For Weiss Domains claim a certain area in the material, their movement result in a changing length of the whole material. Expanding and tightening lamination sheets causes mechanical vibration at doubled electrical frequency [8].

At load condition, current-related effects superimpose magnetostriction. Forces of the alternating magnetic field affect current-carrying windings leading to an oscillation also with doubled electrical frequency.

Vibrations are measured at the presented transformer using one acceleration sensor, see position in Figure 4.

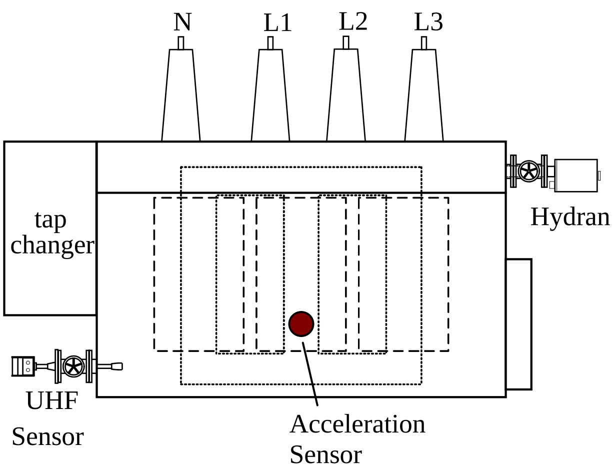

Figure 4: Transformer with installed measurement equipment

Signals are recorded with a commercial PC´s standard sound card and Matlab software. The system was installed two years ago in 2009 and is working without issues ever since. For correlation transformer's load current (RMS value) is also constantly recorded. If the transformer is online, recording is performed every 3 Minutes for a time period of 5 seconds sampling data with 44.1 kHz.

For better discrimination signals are transformed in frequency domain using Fast Fourier Transformation (FFT). For vibration measurements the trend of frequencies can be plotted over time as shown in Figure 5.

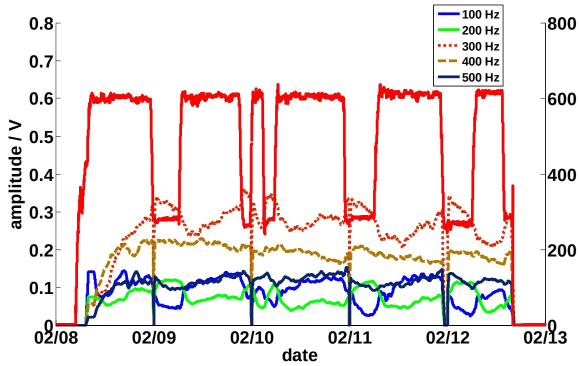

Figure 5: Vibrations at changing load current

During continuous service vibrations mainly depend on load current. Basic frequency and harmonics show different dependencies on load current which can be observed by correlating current and frequencies over time. Measurements show the long term usability of vibrations measurement outside tank wall [9].

2.5 Additional physical quantities

For evaluation and correlation purpose some common measurements are performed. Several temperatures of the transformer (i.e. top oil temperature) and ambient temperature were measured. Also voltage on primary side and load current are monitored to determine the transformer's load situation.

3 CONTINUOUS MEASUREMENT

The transformer is installed at a medium coal fired power plant as generator step-up unit. This power plant mostly runs in autumn, winter and spring for single days.

Since beginning of the monitoring process in summer 2009 the transformer was online for 80 days with overall 1325 operating hours.

3.1 Gas analysis during test run

Before the transformer is put into regular operation after an 8 year period of stand still time, 14 days of test run are performed. During this time the transformer was operating under nominal voltage without load. For this test run a Hydran sensor was mounted on the transformer, monitoring the development of dissolved gases in oil. In addition, oil samples were taken at frequent intervals and analysed in a laboratory for possible fault gases.

Figure 6 shows the measured gas concentration of the Hydran sensor during the 14-day test run. The dots represent the laboratory analysis of the dissolved gases. The dashed vertical lines clarify during which intervals the transformer was in operation (total 207 hours).

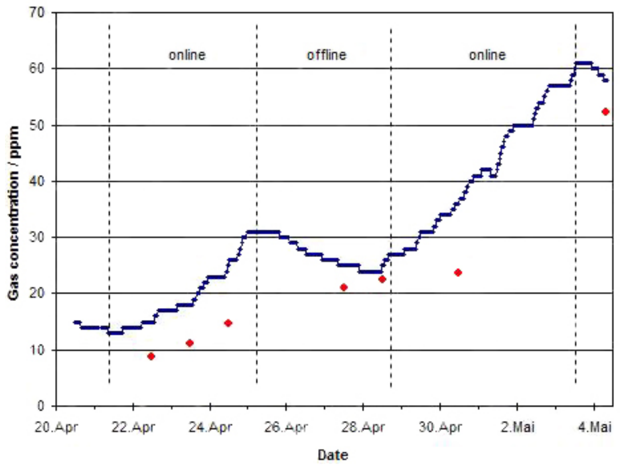

Figure 6: Transformer's gas concentration during test run

As can be seen, during the online time periods the gas concentration is increasing. Simultaneously, active PD sources were detected by UHF PD measurements. During the offline period the gas concentration is decreasing. That can be explained by the low solubility of hydrogen and thus the loss over transformer's conservator tank.

A model was generated to determine the further development of the gassing behaviour. The gas generation is presumed as a linear process. The loss of gases through the conservator tank can be assumed to be exponential as a first approximation. This leads to a differential equation for the concentration C:

$$\frac{\partial C(t)}{\partial t} = g - k \cdot C(t)\,, \qquad (1)$$

and its solution:

$$C(t) = \frac{g}{k}(1 - e^{-kt}) \qquad (2)$$

The solution function shows the expected development of dissolved gases in oil. For the determination of function variables in the first step, the loss factor k of gases was approximated by a curve fitting applied to decaying concentration curve while the transformer was offline. In the second step, the remaining unknown variable (the gas generation rate g) of the solution function is also determined by a curve fitting. Measured concentration values and fits for decay and rise are shown in Figure 7.

Using this calculation, it is possible to estimate the maximum gas concentration in the transformer oil. By a limit consideration a stationary gas level of 180 ppm is expected after 100 days, i.e. gas generation equals gas loss. However, saturation was not observed in reality, because the transformer was not available for a long term measurement.

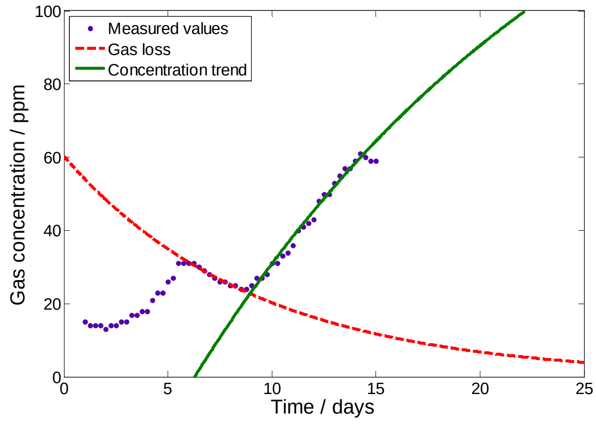

Figure 7: Fitting of measured values by trend curves

An improvement of this model can be achieved by taking into account the transformer's heating due to electrical losses as well as further boundary effects.

3.2 UHF Measurements during Service

The operation of the generator step-up transformer is monitored regarding the occurrence of PD by means of UHF measurements (LDS6 / UHF) and measurement of dissolved gas concentration in oil using a Hydran sensor.

In Figure 8 an example of phase resolved UHF PD pattern is shown measured for a time interval of one hour. UHF PD signals are measured with aprox. 35 dB amplification with a bandwidth of 9 MHz at a centre frequency of 505 MHz. For phase correlation phase L1 is used.

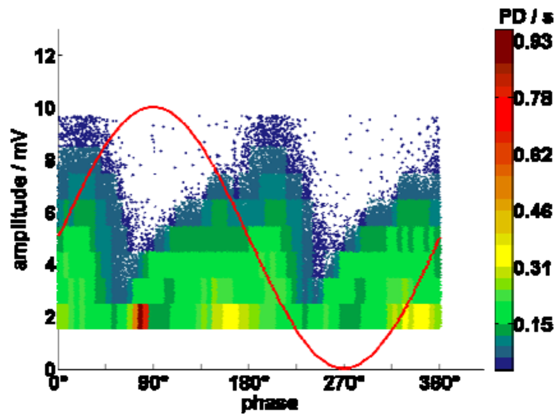

Figure 8: UHF PD Patterns (PRPD) accumulated for one hour and measured by means of an online PD monitoring system

Normally the measured patterns look like the pattern in Figure 8. But the transformer's PD activity varies. Figure 9 shows an incidence with considerably higher amplitudes. In comparison to Figure 8 the activity during the negative half cycle is missing and the strongest activity is shifted from approx. 100° to 80°. Additionally the maximum amplitude of UHF signals increases from 10 mV to more than 30 mV. Due to an overload of the measurement equipment higher amplitudes can not be detected. PD with such high amplitudes occurred for approx. four hours.

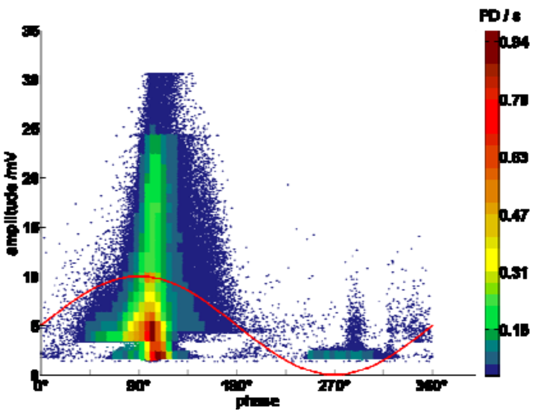

Figure 9: UHF PRPD accumulated for 210 minutes with significant higher signal amplitudes

Figure 10 shows the chronological sequence of the event. On the y-axis the correlation of PD pulses to phase L1 is plotted. The colour indexes the measured UHF amplitude in mV. The recording time of the UHF PRPD pattern in Figure 10 is the identical time period of 210 minutes as in Figure 9.

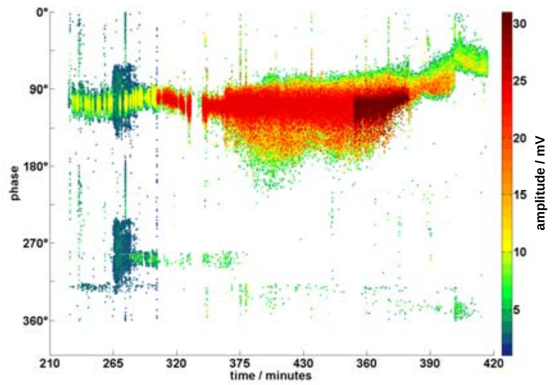

Figure 10: UHF amplitude of PD events (colour) over time, synchronised to phase L1

Correlation with gas concentration measurements shows coherence: four hours after the UHF-PD event occurred a strong increase of the gas concentration in oil from 50 to 180 ppm, see Figure 11. That gas concentration increase just occurred once. The PD event with levels up to 30 mV was also recorded only once. A dependency between both measurable effects seems to be likely but misses confirmation by more than one incidence.

In comparison, gas trends at normal operation show little variations. A physical model connecting UHF pattern and levels of gas generation has yet to be developed.

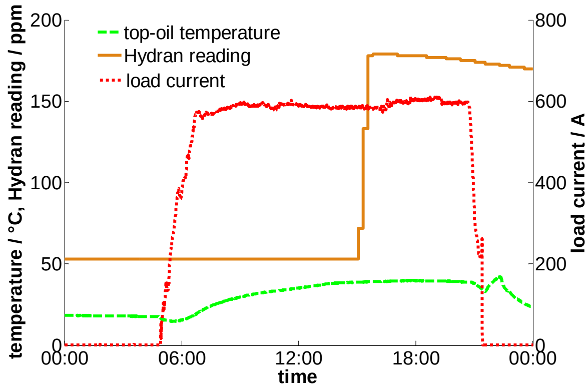

Figure 11: Development of gases (in ppm) and oil temperature against time and load current

4 CONCLUSION

This case study illustrates several monitoring approaches for permanent transformer surveillance. Considered is the UHF PD detection, gas monitoring with a Hydran sensor and vibration measurement. Since the entire setup was installed in summer 2009 and is working ever since, this contribution shows their ability for long term measurement. Given that long term vibration measurement was not performed before, proven durability is main issue for this method.

Second concern of the contribution focuses on the correlation between PD activities and delayed rising gas levels. Measurements taken at a power transformer in service demonstrate the dependency. A single significant PD event can occur within a power transformer although average activity is low. In the presented case study the event lasts for approx. 4 hours. High UHF levels indicate a high energy conversion of PD and therefore have to be considered critical for the transformer.

The presented monitoring methods are able to detect such critical issues whereas conventional measurement methods represent spot tests which will miss such PD events. Also usually seldom performed gas in oil analysis is not able to detect such events.

Further analysis of UHF monitoring is needed because the amount of measured data can dramatically expand. Effective evaluation requires automation. Also dependencies between UHF pattern and electrical PRPDs have to be investigated regarding the question if a PD identified by using electrical measurements could be monitored using UHF monitoring method.

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