EIC'07, Nashville, Tennessee, USA, (2007)

Partial Discharge Analysis to Monitor the Condition of Oils

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***Abstract* –** Partial discharges in oils are influenced by the actual dielectric properties of the liquid and especially degradation products may influence the phenomena. As a consequence of **partial discharge processes**, there may be bond scission and molecules of the dielectric may be degraded and/or split into molecules of shorter lengths that form a **gaseous phase**. This second phase can be generated in solids as well as in liquids. In solids the pressure in this gas phase will increase in accordance to the concentration of gas molecules. In liquids an increase of the concentration of molecules will lead to an extension of the gas volume until the pressure within the void corresponds to the external gas pressure. Consequently, in accordance to **Paschen's law** there will be gas discharges in this gas phase.

Analyses of the sequences of partial discharges and the corresponding pulse shapes in differently aged and/or polluted oil show characteristic differences. Possibilities to use characteristic parameters of the pulse shape of signals from PD in oil for diagnostic purposes and especially their correlation to other dielectric properties will be discussed in detail.

INTRODUCTION AND FUNDAMENTALS

Partial discharges in liquid insulations may show an effect that is characteristic for liquid insulations. This phenomenon is unique in liquids, because in contrast to solid insulations, in liquids the molecules may move easily, thus generating a **gas-filled void**, if gaseous degradation products have been generated by a preceding partial discharge.

In the presence of high electric fields in a semi-conducting or insulating material, electrons are accelerated by the electric field and gain energies much higher than the thermal energy. They become **hot electrons** that are able to transfer energy to collision partners, i.e. molecules of the material and thus a ionisation or a degradation of these molecules e.g. by bond scission may occur. The concept of **hot electrons** is well known for many years, especially for electrical treeing, the relevant degradation process in polymer insulations [1].

The **local energy input** via high energetic electrons occurs in gases (generating mobile charge carriers), in liquids and in solids. The result is not simply a heating of the insulation, but also a cleavage of bonds of single molecules. This destruction of molecules may produce ionisation and generate molecule **fragments with lower molecular weights**. Depending on their size, the state of these fragments may be the gas phase. In gases the electric strength of the newly formed gas mixture will be not very different from that of the gaseous insulation before.

The situation in **liquids** and **solids** is more complicated than in gases. If the partial discharge process generates sufficiently short molecules, a **gas filled void** will be generated in the region in which the partial discharge took place. Initially the gas pressure in this void will be very high because the phase transition of a certain amount of a liquid or a solid into the gas phase increases the pressure-volume product. Because the available volume is only the volume of the molecules in liquid or solid state there will be a high gas pressure.

In **solids** this pressure can be reduced only via diffusion of the fragments into the surrounding insulating material, a phenomenon that takes time, but that happens quicker at higher temperature, thus generating a higher growth rate of electrical trees in solids [2, 3].

In **liquids** a void with a high gas pressure inside will expand and reduce the gas pressure until the pressure inside equals the pressure outside the liquid. Thus in close vicinity of the spot at which the partial discharge took place a small region with lower electric strength is generated. This phenomenon occurs only if the energy of the discharge is sufficiently high that a sufficiently large gas filled volume is generated in which due to Paschen's law a gas discharge may occur.

Time domain PD measurements show these subsequent discharges as separate PD impulses with time differences in the range of a few **µs** [4]. Frequency domain PD measurements using band pass filters in the **kHz** range do not directly show the separate discharges. However, the output of the band pass filter is a linear superposition of the impulse responses of all incoming signals. So each subsequent discharge leads to a distortion of the shape of the response to the initial impulse [5].

PULSE SHAPE ANALYSIS

A typical oscillating signal of a partial discharge after processing is shown in **Fig. 1**. In this experiment a band pass filter with a band width of **40** to **400 kHz** was used in the measurement amplifier.

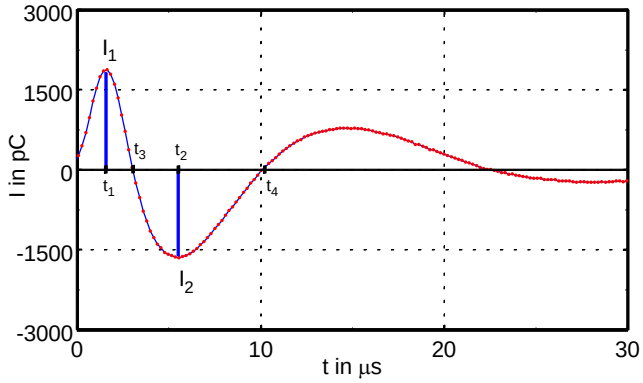

Fig. 1: Oscillating signal from the PD detecting device for a calibration pulse

Characteristic parameters to describe the shape of this signal are the peak heights $\mathbf{I_1}$ and $\mathbf{I_2}$ of the first two peaks, the corresponding times $\mathbf{t_1}$ and $\mathbf{t_2}$ and the times $\mathbf{t_3}$ and $\mathbf{t_4}$ of the zero crossings after the peaks. In addition to these single parameters the shape of a discharge signal can e.g. be characterized also by the ratio of the amplitudes $\mathbf{I_1}$ and $\mathbf{I_2}$ of the first two peaks or other combined parameters. For calibration impulses the amplitude of the second peak of the oscillating signal is typically about **80%** of the amplitude of the first peak.

The comparison of the times $\mathbf{t_1}$ and $\mathbf{t_2}$ of the maxima with the times of the zero crossings $\mathbf{t_3}$ and $\mathbf{t_4}$ of the oscillating signal is another interesting and meaningful parameter. If consecutive gas discharges occur immediately after a discharge in the oil, the zero crossing $\mathbf{t_3}$ after the first peak will occur later.

Commonly the calibration is done on the basis of the magnitude of the first peak $\mathbf{I_1}$ for a given **calibration signal** of some **pC** fed into the measurement system. Special emphasis on different shapes of the oscillating signal is usually not taken care of. Especially the ratios between the first and the second peaks are usually not used for diagnosis.

APPLIED VOLTAGE AND IMPULSE MAGNITUDES

If in a partial discharge measurement the voltage is ramped up with time, the amplitudes of the first discharges are small and increase with increasing applied voltage. Depending on the applied voltage, the actual condition of the oil and the amount of dissolved impurities, different amounts of gaseous components are formed, and a different probability for the ignition of a gas discharge exists.

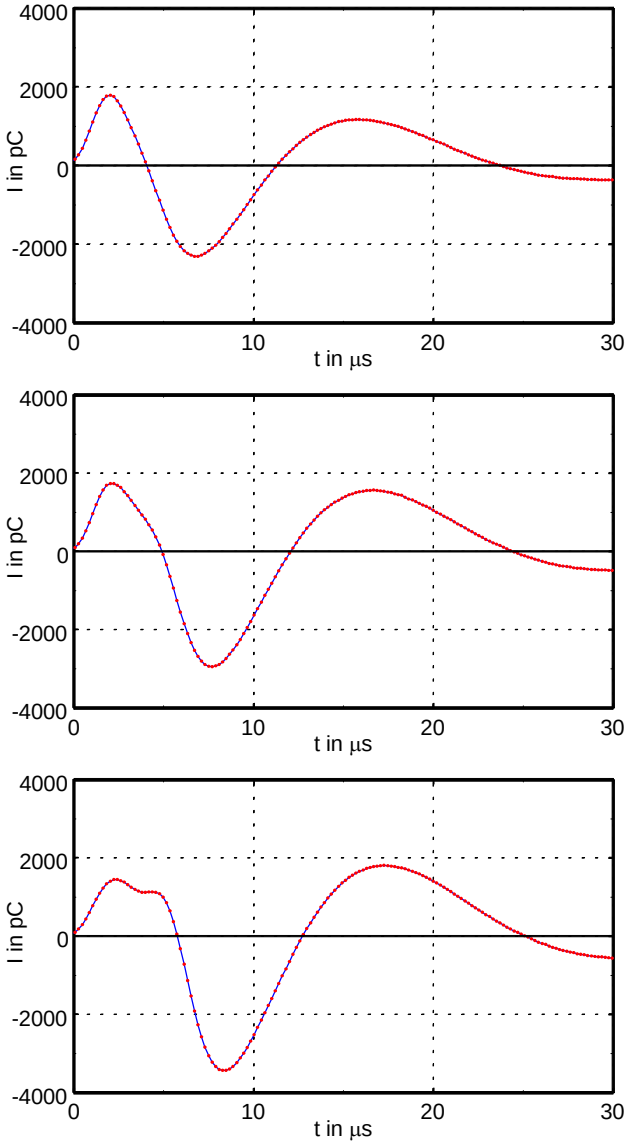

Fig. 2: Examples for different PD impulse shapes found in aged oils

Fig. 2 shows examples of different output signals from the band pass filter. The differences between the shapes of the signals – all taken from the same data set from a measurement performed with a transformer oil – are clearly visible.

EXPERIMENTAL RESULTS

It was found, that the phenomenon described leads to a change in the pulse shape. Due to consecutive gas discharges that are not monitored separately the decrease of the voltage after the first peak is slowed down and the zero crossing occurs later. In this case the magnitude of the second peak is also increased in comparison to that of the first peak.

Basic analyses of the pulse shapes performed on measurement data from transformer oils with different degrees of ageing already showed some characteristic differences. In this case mainly the amplitudes of the peaks of the signal and the times of occurrence of the peaks were taken into account [5].

Another interesting parameter is the time difference between the first and the second peak, i.e. $\mathbf{t_2 - t_1}$. This combined parameter clearly shows differences between characteristic impulse shapes. **Fig. 3** shows an example for two transformer oil samples, a new one and one with a high concentration of degradation products.

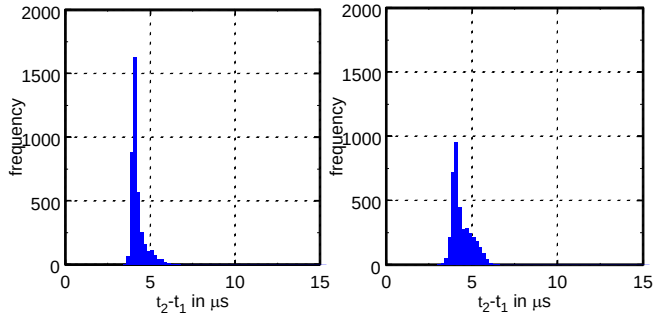

Fig 3: Time differences t_2-t_1 for a new (O7N_6) and an aged oil (O1N_18)

A more pronounced difference is visible if the partial discharge data sets are split up into those with smaller and higher amplitudes $\mathbf{I_1}$ and the frequency distributions of the parameters $\mathbf{t_1}$, $\mathbf{t_2}$ and $\mathbf{t_4}$ (see Fig. 1) are taken (see **Fig. 4**).

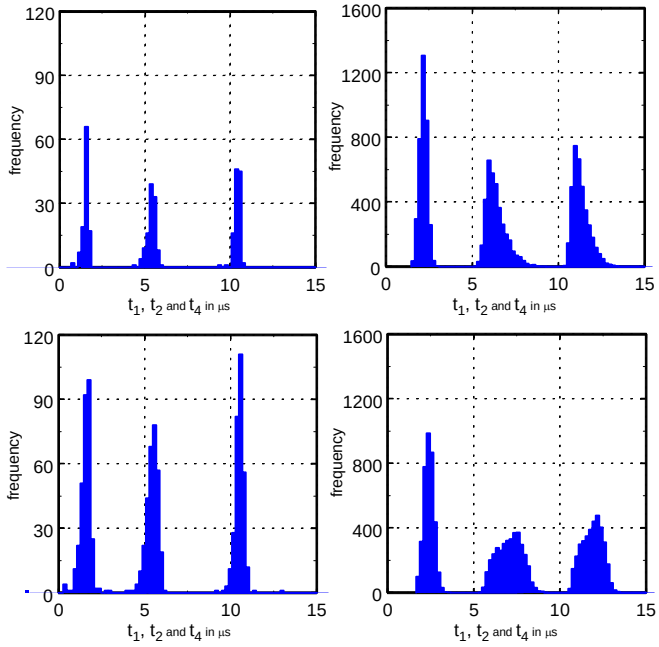

Fig 4: Time parameters $\mathbf{t_1}$, $\mathbf{t_2}$ and $\mathbf{t_4}$ for a new (O7N_7, upper graphs) and an aged oil (OBN_6) for amplitudes I_1 < 750 pC (left) and I_1 > 750 pC respectively

For partial discharges that have pulse heights $\mathbf{I_1}$ of the first peaks below **750 pC** both oils show similar distributions for all three time parameters. The only difference is the number of discharges. The new oil shows about 410 'small' discharges, while in the aged oil only 330 'small' discharges (of a total number of 4090) occur.

For discharges with higher energies (pulse heights $\mathbf{I_1}$ of the first peaks higher than **750 pC**) the distributions of the parameter $\mathbf{t_1}$ are similar, for the parameters $\mathbf{t_2}$ and $\mathbf{t_4}$ the distributions for the aged oil (OBN_6) are broader and shifted to higher values.

Another combined parameter that has proven to be very reliable and reproducible is the quotient $\mathbf{|I_2|/I_1}$ of the magnitudes of the first two peaks of the signal. Displaying this parameter in dependence on the magnitude of the first peak $\mathbf{I_1}$ leads to characteristic distributions. **Fig. 5** shows these plots for measurements on three oil samples with different concentrations of degradation products.

Clean new oil with almost no impurities or degradation products (upper graph) results in a slim distribution, with $\mathbf{|I_2|/I_1}$ ratios higher than 1 only for very high values of $\mathbf{I_1}$. Ratios $\mathbf{|I_2|/I_1}$ of more than 1.5 are very rare. For aged oils with a higher concentration of degradation products (the two lower graphs) the ratios $\mathbf{|I_2|/I_1}$ are significantly higher and they increase already at smaller amplitudes $\mathbf{I_1}$ of the first peak.

INFLUENCE OF THE EXPERIMENTAL SETUP ON THE RESULT

Especially measurements using a needle-plane geometry often lack reproducibility. This is on one hand due to the fact that there are always minor microscopic differences in the shape of the needle tips. On the other hand the PD activity and especially breakdowns lead to a certain degree of erosion of the needle tips, so that the geometry may change during the measurement or in the sequence of a series of measurements. Under these conditions it is almost impossible to perform two measurements under exactly the same conditions.

Some parameters are very sensitive to these changes in the needle geometry, other parameters – especially some parameter combinations – are not so sensitive. The peak amplitudes of the signals are very sensitive to the actual shape of the needle, while the ratios of the amplitudes $\mathbf{|I_2|/I_1}$ do not change significantly.

Fig. 6 shows the $\mathbf{|I_2|/I_1}$ values over the amplitudes $\mathbf{I_1}$ for a repetitive measurement of the new oil (see Fig. 5 upper graph) using the same needle but with approximately 20 measurements with the needle in between. For the two measurements the average impulse rates were one impulse per second for the 'new' needle (O7N_6) and one impulse per six seconds for the measurement with the 'old' needle (O7N_7). Hence the over all impulse rate decreased significantly with a 'loss of sharpness' of the needle.

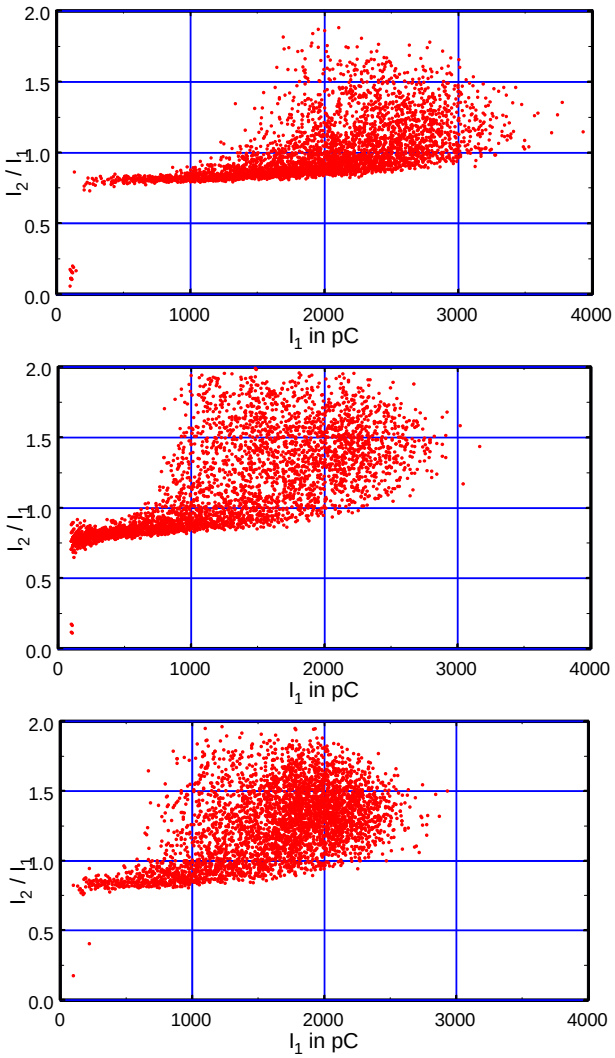

Fig. 5: $|\mathbf{I_2}|/\mathbf{I_1}$ over $\mathbf{I_1}$ for a sample of a new oil (O7N_6) and samples of two different aged oils (O1N_18, OBN_6)

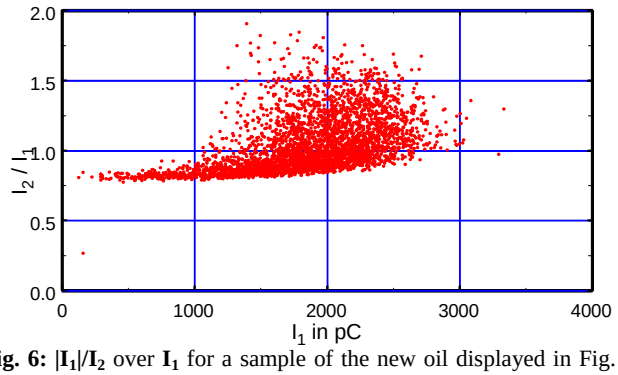

Fig. 6: $|\mathbf{I_1}|/\mathbf{I_2}$ over $\mathbf{I_1}$ for a sample of the new oil displayed in Fig. 5 but measured with an 'old' needle (O7N_7)

In addition the amplitudes $\mathbf{I_1}$ of the first peaks decreased slightly, but the plots of the ratios $|\mathbf{I_2}|/\mathbf{I_1}$ over $\mathbf{I_1}$ do not show significant differences. The maximum peak amplitudes $\mathbf{I_1}$ are a little lower with the 'old' needle (Fig. 6), but the general tendency of the plots (i.e. the shape of the distributions) is the same.

Interestingly, measurements with a sharp, 'new' needle show in most cases only positive discharges (in positive half waves), while in measurements with 'old' needles, i.e. needles that had been in use for several experiments, also small negative impulses – with pulse magnitudes of about 5 to 10% of those of the positive discharges – appear. These negative impulses occur always about 7 to 11 ms after a positive impulse in the following negative half cycle of the test voltage.

CONCLUSIONS

The analysis of the pulse shapes of the signals from partial discharge measurements in oils in an extremely non-homogeneous electrode arrangement can be used to monitor the state of degradation of oils. As a consequence of a partial discharge short fragments of liquid molecules and other degradation products lead to the formation of a **small gas filled void**. In this gas phase a few **µs** after the PD another PD may occur that leads to a change in the shape of the processed partial discharge signal. These changes can be used as a diagnostic tool to monitor ageing of the insulating liquids.

Different parameters of the pulse shape are differently sensitive on these changes. Interestingly the degree of the non-homogeneity of the needle plane arrangement influences some of the parameters of the pulse shape differently. In fact some parameters can be found which are not significantly influenced by the microscopic geometry of the electrode system and thus the diagnostic results do not dependent on the parameter 'sharpness of the needle'.

The Pulse Shape Analysis might also be performed on data from on-line PD measurements in a non-homogeneous electrode arrangement in order to monitor the condition of the oil in transformers if an adequate measuring device is placed inside the transformer.

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