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Pulse Shape Analysis of PD Signals – an efficient Tool 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 ageing processes in the liquid, oil molecules may be split into molecules of shorter lengths. The energy of a PD in the oil may heat the liquid locally and especially low molecular weight products in the oil will evaporate and form a gaseous phase within the liquid. 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 gas discharges may occur in this gas phase immediately (i.e. within µs) after a PD that generated the gas filled void. The sequence will be so quick that commonly used equipment may not be able to monitor these discharges separately. Analyses of the pulse shape of the PD signals after the band pass filter showed differences in accordance to the degree of ageing of the oils examined. Possibilities to use characteristic parameters of the pulse shape for diagnostic purposes and especially their correlation to other dielectric properties will be discussed in detail.

1. Experimental Procedure and Data Analysis

The PD behaviour of oils from transformers used in different power grids was analyzed using a needle-plane arrangement with an electrode gap of 10 mm and a needle electrode with a curvature of about 5 µm. The voltage was increased linearly with about 2.5 kV_{rms}/min up to approximately 15 kV_{rms} and then kept constant for about 7 h or until 4000 PD pulses had occurred, whichever came first. With different oils different PD rates were found. In general, the oils had comparatively low PD rates, so in some of the measurements within 7 h only 500 PD occurred. Consecutive PD measured in oils are not correlated, they appear with a statistical distribution over time.

The PD pulses are sampled after passing the 40 – 400 kHz band pass filter of the PD detector. The shape of the oscillating signals after the band pass filter can be characterized by parameters such as the amplitudes I_1, I_2 and I_3 of the first three peaks, their times of occurrence t_1, t_2 and t_3 with respect to the trigger time, the zero crossings t_4, t_5 and t_6 and the areas A_1, A_2 and A_3 under the curve between the zero crossings, i.e. under the peaks. A special software extracts the analysis parameters, including those mentioned above, and creates a matrix for further processing. Figure 1 shows an impulse response of a calibration pulse (a damped oscillating signal) with these characteristic parameters.

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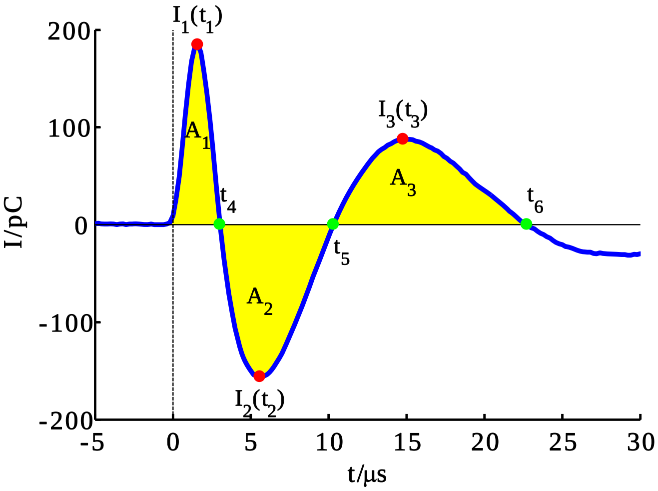

Figure 1. Parameters used for the Pulse Shape Analysis

2. Pulse Shape Analysis

The Pulse Shape Analysis is a method to analyze the shapes of the oscillating signals after the band pass filter and to use this information as a tool to characterize the underlying elementary PD behaviour. Due to the characteristics of the band pass filter, the amplitude $I_2(t_2)$ of the second peak is around 80 % of the amplitude $I_1(t_1)$ of the first peak. The amplitude $I_3(t_3)$ of the third peak is about 50 % of that of the second peak $I_2(t_2)$. The peak times usually are 2-3 µs for t_1, 6-8 µs for t_2 and about 15-18 µs for t_3.

The Pulse Shape Analysis has proven to be a useful tool to increase the amount of information that can be derived from PD measurement data. The Pulse Shape Analysis can either be used in addition to other methods like the Pulse Sequence Analysis [1], or as principal method in cases where the latter does not work, especially in insulating liquids where PD occur statistically.

In measurements of PD signals with geometrically extended specimens, distortions of the pulse shape due to the electric path to the coupling impedance may occur [2]. This phenomenon can be used to separate PD from different sources and to characterize them. ”Multiple discharges”, i.e. PD that occur simultaneously or with very short time differences in-between, may also change the pulse shape due to the fact that the output signal of the band pass filter is the superposition of all responses of the filter to the incoming PD signals that occur within a time window of a few microseconds. In this case, the shape of the impulse response can be changed significantly and the aforementioned parameters of the pulse shape are changed.

3. PD Measurements In Transformer Oils

Especially when measuring PD in dielectric liquids using a needle-plane electrode setup, high-energetic discharges can lead to the temporary formation of gas-filled voids in the surrounding of the needle electrode. Due to the significantly lower electric strength of the gas in these voids, additional discharges may occur within a few µs after the initial one [3]. As each PD causes an individual impulse response of the band pass filter, a sequence of discharges as described above will lead to a superposition of the impulse responses of all PD that occur within the given time frame.

Figure 2 shows three examples of PD signals found in transformer oils using the equipment described above. Although the amplitudes of the first peaks are not very different, the amplitudes of the second and third peaks vary significantly. Nevertheless the shape of the first half wave of the signal is changed significantly, while the following half waves seem to be changed only in their amplitude. As can be seen from the graph, the ratio of the amplitudes of the first two peaks may be a characteristic parameter.

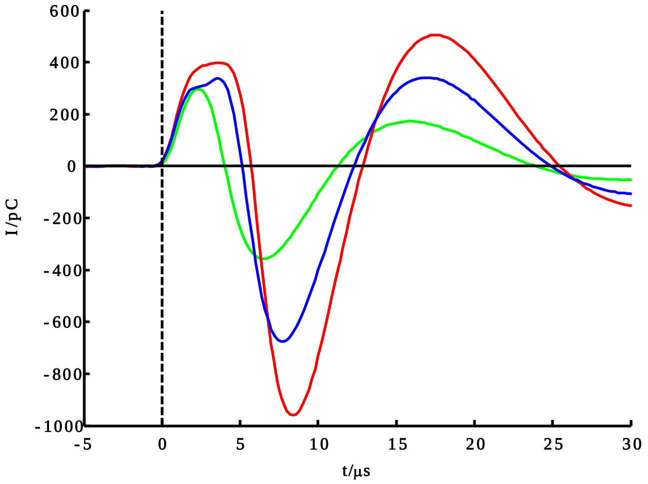

Figure 2. Examples for shapes of PD signals found in aged oils

4. Measurement Results

Previous publications [4, 5] showed that the parameters I_1, I_2, t_1 and t_2 are different for differently aged oils, but a more than qualitative description was not possible.

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].

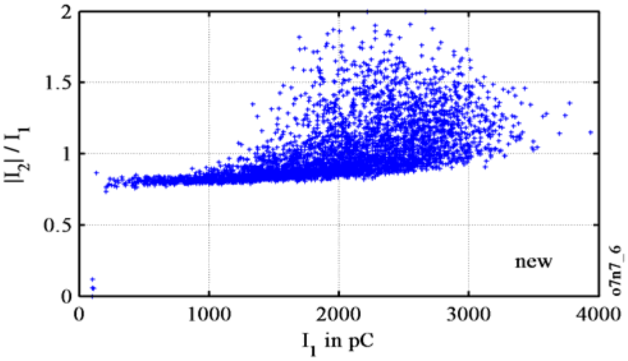

Figure 3. $|I_2|/I_1$ over I_1 for a sample of a new oil, (electrode gap 15 mm)

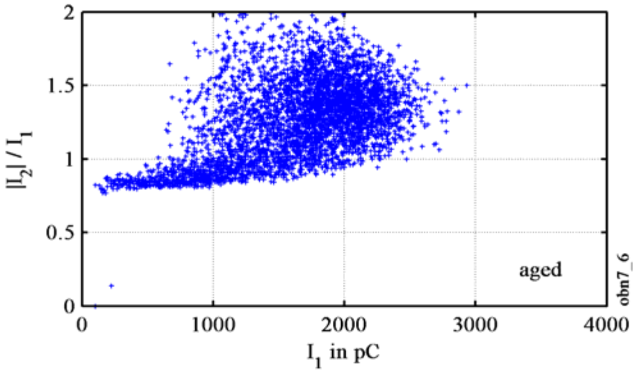

Figure 4. $|I_2|/I_1$ over I_1 for a sample of an aged oil, (electrode gap 15 mm)

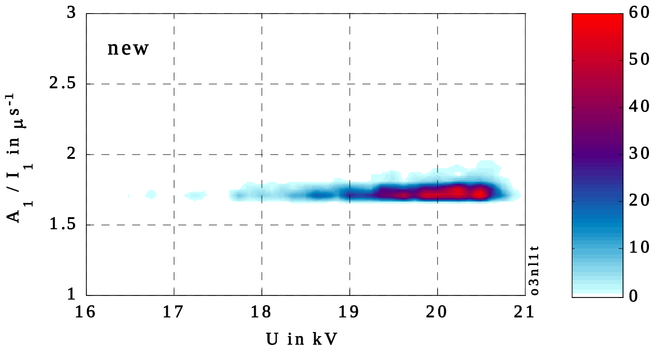

Figure 5. Distribution of the ratios A_1/I_1 of the areas under the first peaks and the amplitudes of the first peaks (in µs) over the voltage levels of occurrence U for a new oil

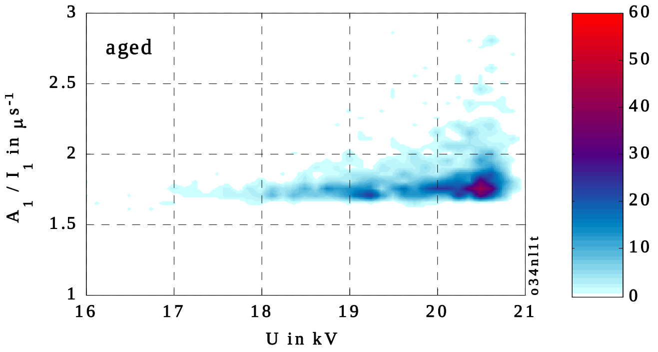

Figure 6. Distribution of the ratios A_1/I_1 of the areas under the first peaks and the amplitudes of the first peaks (in µs) over the voltage levels of occurrence U for an aged oil

The frequency distributions of the times t_2 of the second peaks of the oscillating signals usually show a distribution with a marked peak. In contrast to this the corresponding frequency distributions of severely aged oils often show distributions with two peaks (separated by more than 2 µs). Figure 3 shows corresponding results for two differently aged oils. Interestingly the frequency distribution of the times t_1 of the first peaks showed no characteristic differences.

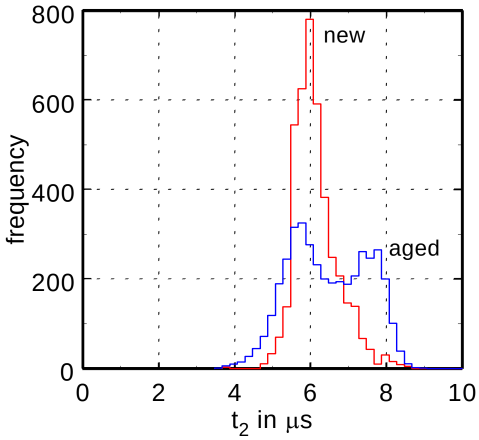

Figure 7. Frequency distributions of the parameter t_2 for different oils (O7N_4 new, and O1N_18 aged)

Another interesting parameter is the time difference between the first and the second peak, i.e. $t_2 - t_1$. This combined parameter clearly shows differences between characteristic impulse shapes. Figure 4 shows an example for two transformer oil samples, a new one and one with a high concentration of degradation products.

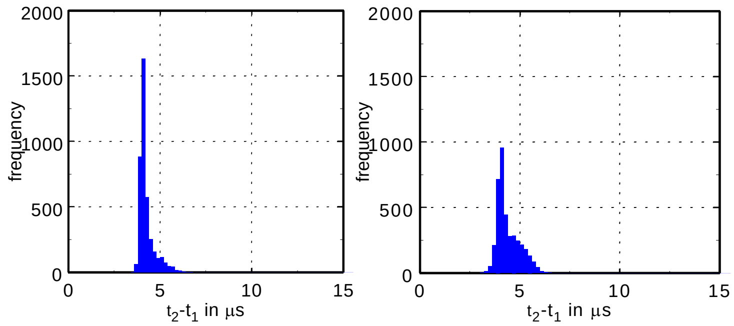

Figure 8. Time differences t_2-t_1 for a new (O7N_6) and an aged oil (O1N_18)

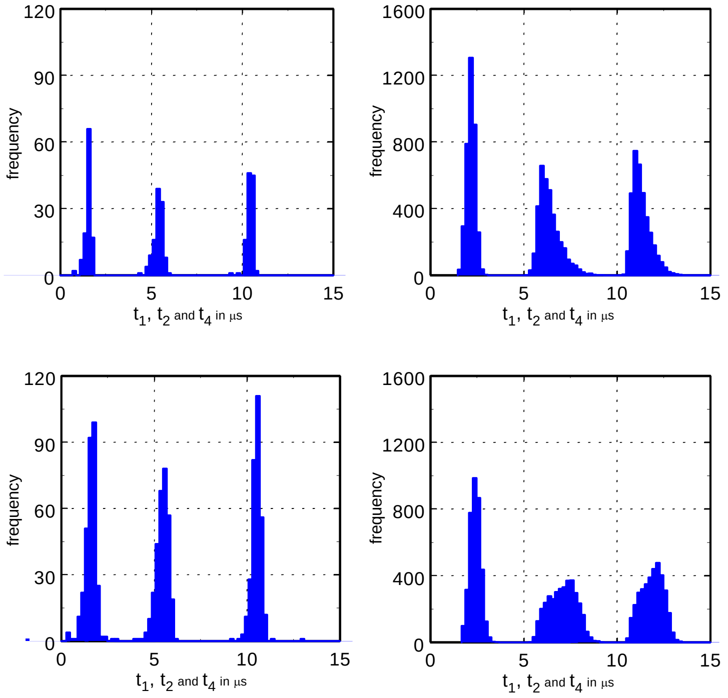

Figure 9. Time parameters t_1, t_2 and t_5 for a new (O7N_7, upper graphs) and an aged oil (OBN_6) for amplitudes $I_1 < 750$ pC (left) and $I_1 > 750$ pC respectively [read t_5 instead of t_4]

A more pronounced difference is visible if the partial discharge data sets are split up into those with smaller and higher amplitudes I_1 and the frequency distributions of the parameters t_1, t_2 and t_5 (see Figure 1) are taken (see Figure 5).

For partial discharges that have pulse heights 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 I_1 of the first peaks higher than 750 pC) the distributions of the parameter t_1 are similar, for the parameters t_2 and 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 $|I_2|/I_1$ of the magnitudes of the first two peaks of the signal. Displaying this parameter in dependence on the magnitude of the first peak I_1 leads to characteristic distributions. For calibration pulses the ration is 0.8, a factor that is characteristic for the band pass filter used.

Clean new oil with almost no impurities or degradation products (upper graph) results in a slim distribution around 0.8, with $|I_2|/I_1$ ratios higher than 1 only for very high values of I_1. Ratios $|I_2|/I_1$ or more than 1.5 are very rare. For aged oils with a higher concentration of degradation products (the two lower graphs) the ratios $|I_2|/I_1$ are significantly higher and they increase already at smaller amplitudes I_1 of the first peak.

Figure 6 and 7 show two examples for differently aged oils; the change in the ratios $|I_2|/I_1$ is obvious. More complex combinations of the basic parameters showed more details, like e.g. the ratios between the areas A_1 under the first peaks of the oscillating signals and the corresponding amplitudes I_1. For new or not significantly degraded oils the values lie usually between 2 and 3 µs, while for aged or degraded oils the ratios may increase up to about 5 µs. In the setup with an electrode gap of 10 mm this phenomenon occurs only or preferably at voltages above 20 kV. Figure 8 and 9 show the corresponding data of a new and an aged oil respectively. As could be expected from Figure 2, the shift of t_4 to higher values in the case of aged oil significantly increases the ratios A_1/I_1. The influence is more pronounced for PD at higher voltages. The corresponding ratios between A_2/I_2 are about 4.5 µs and show no significant differences between new and aged oils.

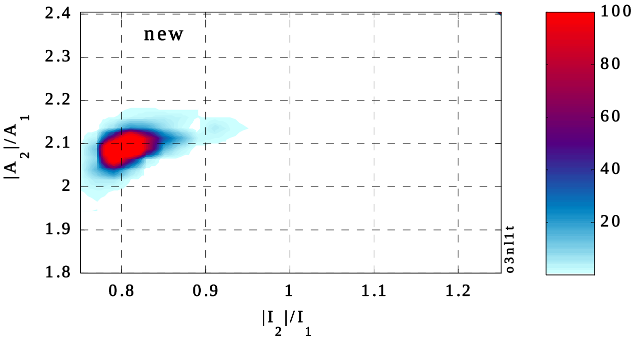

Figure 10. Distribution of the ratios $|A_2|/A_1$ of the areas under the first two peaks over the ratios $|I_2|/I_1$ of their amplitudes for a new oil

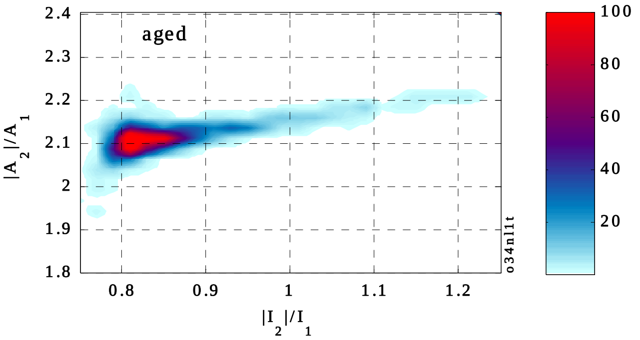

Figure 11. Distribution of the ratios $|A_2|/A_1$ of the areas under the first two peaks over the ratios $|I_2|/I_1$ of their amplitudes for an aged oil

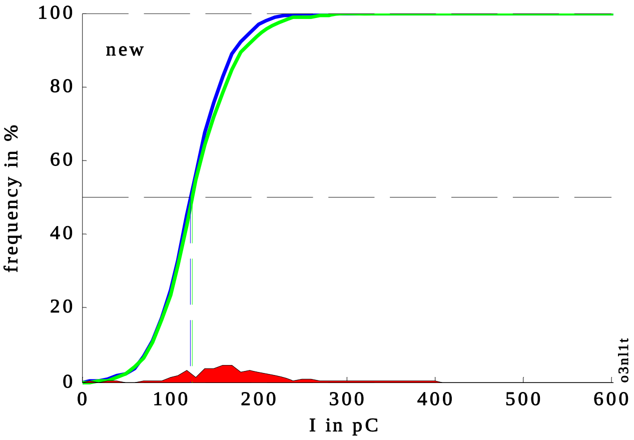

Figure 12. Cumulative frequencies for the amplitudes of the first and second peaks I_1 and I_2 and difference areas A_C for a new oil

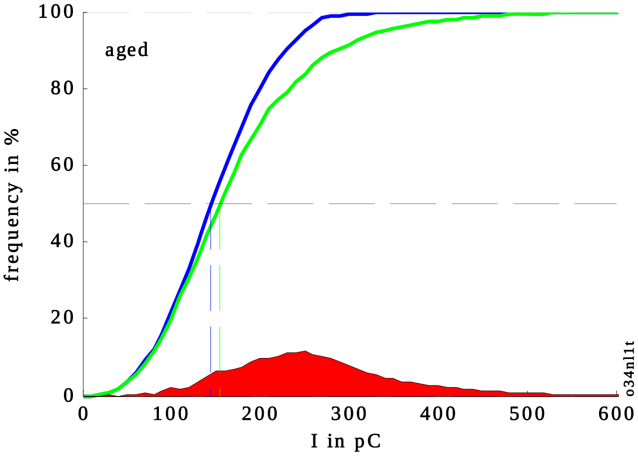

Figure 13. Cumulative frequencies for the amplitudes of the first and second peaks I_1 and I_2 and difference areas A_C for an aged oil

The correlation between the ratios of the areas A_2 and A_1 under the second and the first peaks compared to the ratios of the amplitudes I_2 and I_1 of the second and the first peaks obviously depends on the oil quality as well. An example for a new oil and an aged one with a high concentration of degradation products after a long time in service is shown in Figure. 9 and 10. For the new oil, almost all PD can be found in a very limited area with $|I_2|/I_1$ very close to 0.8 and $|A_2|/A_1$ is concentrated around 2.1. The plot for the aged oil shows more scatter and numerous PD with higher $|I_2|/I_1$ ratios and higher $|A_2|/A_1$ ratios. Nevertheless a quantitative characterization is difficult.

5. Frequency Distributions of I_1 And I_2

A new approach for a quantitative description uses the difference between the cumulative frequencies of the amplitudes of the first peaks I_1 compared to the corresponding distributions of the amplitudes of the second peaks I_2. As described above, a calibration signal would produce peak ratios of 1:0.8 for the first two peaks, so for direct comparison with I_2 the values of I_1 have to be multiplied by 0.8. This leads to almost identical distributions for such non-distorted signals as produced by calibration pulses. This holds also for partial discharges in solid dielectrics that occur during electrical treeing or for surface discharges on inorganic surfaces or with other geometrically small specimens. For new oils we also find nearly identical distributions. For aged oils with a more or less high concentration of low molecular weight degradation products the distributions are different.

Figure 12 and 13 show the cumulative frequencies of the amplitudes of the first two peaks of the oscillating signals after the band pass filter for a new and an aged oil respectively. Interestingly, differently aged oils show characteristically different distributions and difference areas A_C between the two curves, whose numerical values might be a quantitative measure for the oil degradation.

6. Standard Oil Analysis

As a standard method to characterize the degree of ageing and degradation of transformer oils the Dissolved Gas Analysis (DGA) is commonly used. In this method the concentrations of different low molecular weight degradation products such as H_2, C_2H_2, C_2H_4, C_2H_6, C_3H_6 and C_3H_8 are measured. Depending on the degradation process or the type of and intensity of partial discharges that had occurred during service, different concentrations of low molecular weight degradation products are formed. High-energetic sparks within the transformer lead to a high concentration of C_2H_2, other phenomena like e.g. local overheating lead to a high concentration of fragments without double bonds.

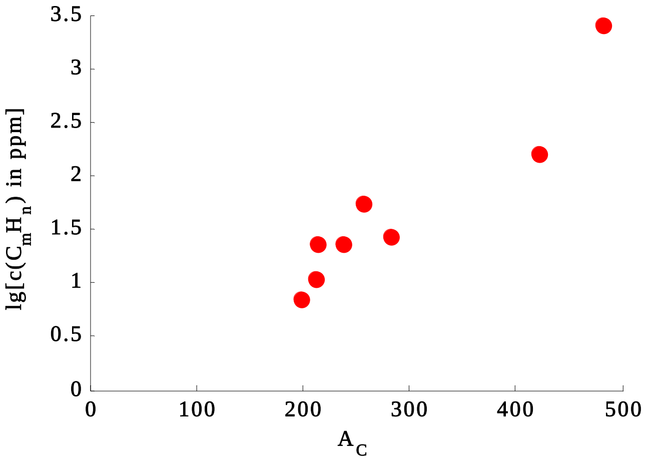

Figure 14. Correlation of the concentrations $c(C_mH_n)$ of degradation products and the difference areas A_C of the cumulative frequency distributions of I_1 and I_2 for a set of differently aged oil

To check the relevance of these molecular changes on the PD behaviour in a needle plane arrangement, oil samples were taken from power transformers in different grids and examined in the lab. The comparison of the results from the DGA with data extracted from the PD measurements shows some interesting correlations. Figure14 shows a correlation plot between the total concentrations $c(C_mH_n)$ of short molecular weight degradation products in the oils and the areas A_C between the two integral distributions of I_1 and I_2. The results found in the DGA of the oils apparently correlate with the parameter difference area A_C extracted from the PD measurements. Hence this parameter seems to be a meaningful indicator for oil ageing or degradation.

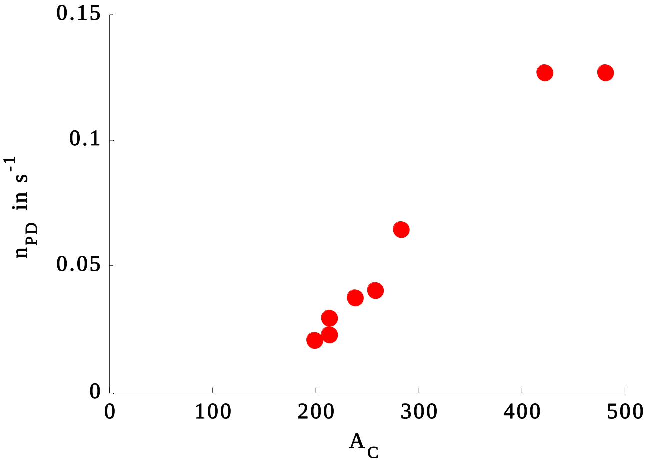

Figure 15. Correlation of PD rates n_{PD} and difference areas A_C for a set of differently aged oil samples

Figure15 shows a plot of the pulse rates n_{PD} found in the PD measurements and the areas A_C. Interestingly the discharge rates n_{PD} correlate with A_C and thus the concentration $c(C_mH_n)$ of low molecular weight degradation products in the oil. Dissolved gases from degradation phenomena during service not only change the pulse shapes of the PD pulses (due to additional discharges in gas filled voids generated by a PD), but apparently also lead to a higher pulse rates in a needle-plane measurement in the laboratory.

7. Conclusions

Using the Pulse Shape Analysis for the evaluation of PD measurements of oil samples from differently aged transformers out of different grids reveals additional information about the condition of the oil compared to other methods. Analyzing the shape of the impulse response of a 40 to 400 kHz wide-band band pass filter in detail, it is possible to monitor PD in gas filled voids that have been formed as a consequence of a preceding PD in the oil. In aged or degraded oil the probability for these gas discharges is much higher than in new oil, and thus the change of the pulse shape is an indicator of degradation products in the oil. Taking only the discharge amplitude, i.e. in this case the amplitude of the first peak of the signal, the information about the quality of the oil is lost.

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