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PD pulse burst characteristics in differently aged transformer oils under AC conditions

***Abstract**. Partial discharge (PD) detection is a technique widely used for high voltage equipment insulation condition assessment. In such applications, an understanding of PD mechanisms, characteristics and development processes is important. In this paper, PD characteristics of three typical transformer oils, aged to different degrees, are examined under AC conditions, using a needle-to-plane electrode system. The PD activity in transformer oil is confirmed as appearing in pulse burst form. Pulse burst characteristics recorded in the study show that the transferred electric charge per PD pulse burst increases with the degree of aging. This increase is accompanied by an increase in the number of discrete PD pulses and by a decrease in cavity formation time. The experimental results of cavity discharge in differently aged transformer oils are discussed and their characteristics are explained in terms of the charge exchange mechanism.*

***Streszczenie.** Przedstawiono charakterystyki wyładowania niezupełnego w trzech typowych olejach transformatorowych o rożnym stopniu starzenia przy zasilaniu napięciem przemiennym. Stwierdzono, że impulsy wyładowania zależą od stopnia starzenia. (**Charakterystyki impulsów wyładowania niezupełnego w oleju transformatorowym o różnym stopniu starzenia**)*

Keywords: partial discharges; oil insulation; pre-breakdown; PD pulse burst; power transformer.
Słowa kluczowe: wyładowanie niezupełne, transformatory mocy, izolacja olejowa.

1. Introduction

Transformers are key and widespread components of the power network. Mineral insulating oil plays a major role in power transformers, acting both as insulation and coolant. The presence of even a minor defect in the insulation structure, under normal operating voltages can create local field enhancement causing partial discharges. The defect may be a protrusion or asperity point on transformer metalwork or winding which was introduced during manufacture/maintenance. Gas cavities can be formed within the oil phase at this defect and cause partial discharge (PD) until their eventual collapse due to either dynamic instability or the diminishment of the sustaining electrical stress enhancement [1~6].

Electrically induced cavities in dielectric liquids are caused by localized injection of current pulses at a high field region where electron avalanches or streamers may develop within the liquid phase. Kattan et al [7~8] demonstrated that most of the electrical energy injected (about 90%) is converted into heat which evaporates the liquid. Pompili, R. Bartnikas et al [9-16] studied the PD pulse burst characteristics in transformer oils with different viscosities and found that PD which occurred in cavities within the liquid appeared in the form of pulse bursts that consist of a series of discrete current pulses. The time interval between discrete pulses can be as low as just a few nanoseconds and is a function of the cavity formation, growth and collapse time in liquid. The first pulse of pulse burst may exhibit a greater magnitude than the second and represents charge injection from the electrode, while subsequent pulses represent PD pulse activity within the expanding cavity.

An oil/paper structure is the typical configuration of transformer insulation and it undergoes long term aging due to gradual physical and chemical degradation subjected to electrical and thermal stress in-service. The decomposed product for insulation aging is solid, liquid and gaseous impurity species such as carbon, water, CO, CO2 and furan products, etc [17]. These impurities will alter the PD pulse burst characteristics in oil. The purpose of the study reported here was to investigate the effect of the degree of aging on the pulse burst characteristics in order to better understand the processes in terms of their effects on PD measurement and implications for insulation diagnostics in electrical plant such as power transformers.

2. Characteristics of the oil specimens

PD characteristics were examined in three differently aged transformer oils using a needle-to-plane electrode system. The first specimen was unused oil; the second was medium aged oil from an in-service 110/35kV, 20MVA transformer and the third was severely aged oil from a 220/110kV, 120MVA transformer which was close to end of life. All oil samples are Karamay 25# transformer oil and from same manufacturer. Their viscosity at 40°C was 13cSt and density at 20°C was about 850kg/m3. The physical and electrical properties of these oil samples are summarized in Table 1. The photo of samples is shown in figure 1.

Table 1 Electrical property of the oil specimens

property	Unused oil	Medium aged oil	Severely aged oil
AC breakdown voltage, kV (at 2.5mm)	42	39	30
Tan δ at 90°C, 50Hz	0.0025	0.005	0.0184
Neutralization value, mg KOH/g	0.018	0.023	0.039
Water content, ppm	21.4	24.8	32.8
Furan products, ppm	0	0.02	0.25

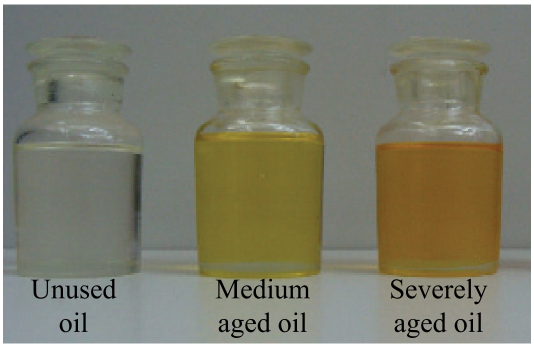

Fig. 1. Oil samples

As is shown in figure 1, with the oil aging degree increase, the color of oil is deeper and deeper.

3. Test system and procedure

The experimental setup used for the study is shown in Figure 2. A needle-to-plane electrode system was used to create a field enhancement site in order that PD was generated. The radius of needle was 40μm and the needle-to-plane gap was 30mm.

AC voltage was generated using a test transformer rated at 50Hz, 10kVA, 0-100kV. The PD pulse bursts were recorded using a 500MHz bandwidth digital oscilloscope, having a sampling rate of 2.5 Gsamples/s. The PD measurement impedance was a wideband resistor, the step response time of which was below 3 ns.

Phase resolved PD (PRPD) patterns represent each PD pulse as a point in a charge-phase diagram and are a well established tool for interpretation of PD activity. In order to study the influence of aging degree on the PRPD measurement, PRPD patterns were acquired using a PD detector that is able to record the complete PD pulse shape as well as its magnitude and phase.

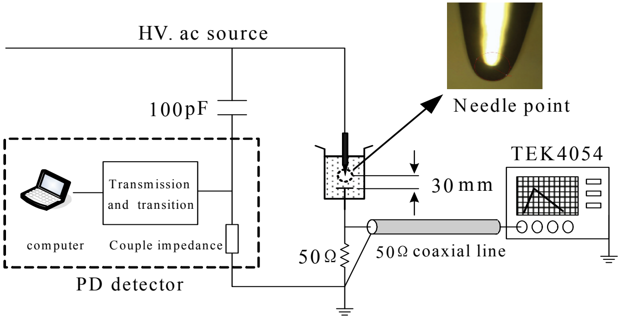

Fig. 2. Circuit of the experimental apparatus

The pulse burst parameters were measured as a function of applied voltage, with the applied voltage increased in steps of 2kVrms and maintaining a voltage constant for about 10 min before continuing to the next step. The PD inception voltage (PDIV) was determined when one or more pulse bursts first appear. The same procedure was continued above the PDIV level by recording the pulse burst activity over 10min. Subsequently, the pulse burst statistical parameters such as the average number of discrete pulses, duration of each burst, time interval between first and second discrete pulses within the PD pulse burst and the maximum amplitude within a pulse burst were computed for each voltage step. PD in oil is a stochastic phenomenon and in order to obtain a statistical law of the parameters, the numbers of PD pulse burst used to compute are above 50 in every applied voltage step.

4. Results and analusis

PD activity in a needle-to-plane oil-filled structure is concentrated around the peaks of the applied sinusoidal voltage waveform. The duration of a PD burst is much shorter than the power frequency cycle (20ms) so that the externally applied voltage can be regarded as a constant during a pulse burst [11]. The focus of study in this paper is the relatively stable negative PD pulses, since the positive PD pulses are substantially more irregular and erratic.

The PD inception voltage in all three specimens was 20kV. Figure 3 portrays some typical PD pulse burst behavior in unused oil at different voltages. The number and the maximum magnitude of discrete pulses within PD pulse bursts are seen to increase with the applied voltage. The first pulse in the PD pulse burst represents initial charge injection and is larger than the second discrete pulse caused by cavity discharge. A typical PD pulse burst waveform in severely aged oil at 30kV is shown on the same timescale in Figure 4.

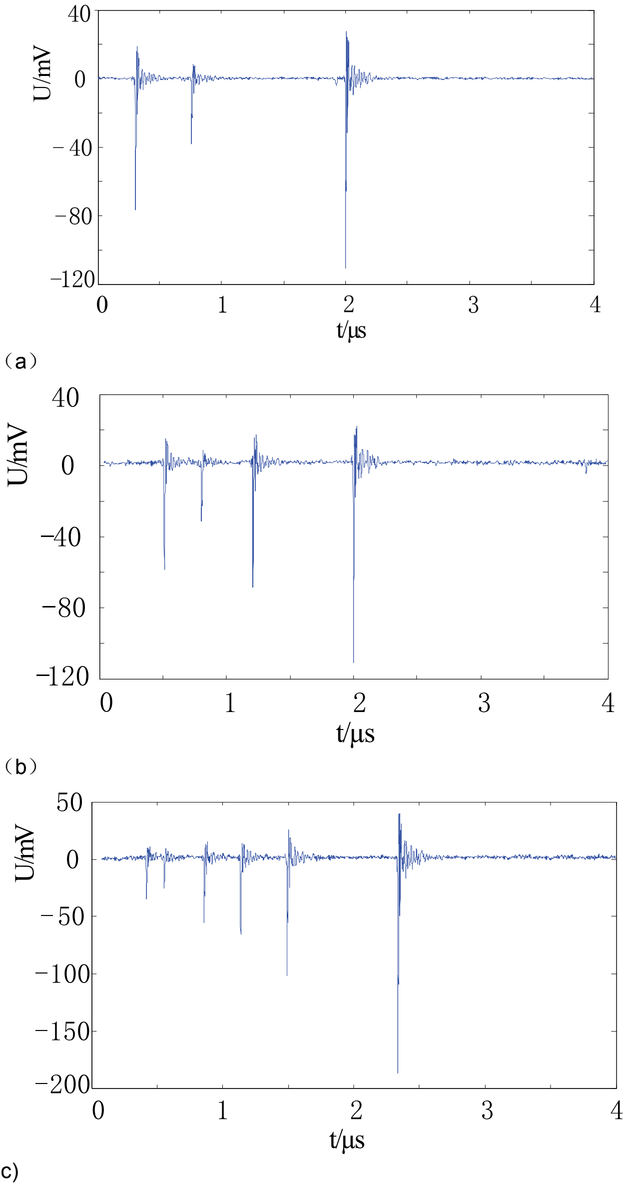

Fig. 3. PD pulse bursts in unused oil at (a) 20kV, (b) 22kV, (c) 26 kV applied voltage.

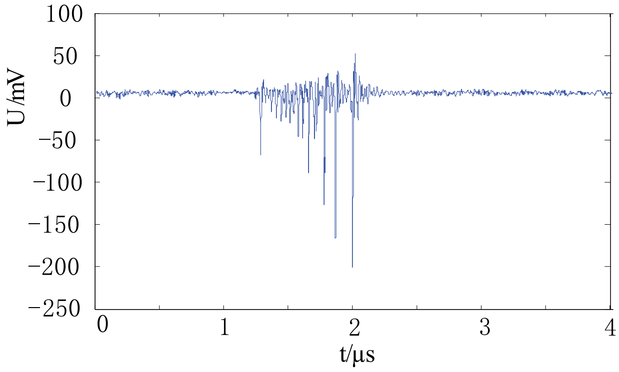

Fig. 4. Typical PD pulse burst in severely aged oil at 30kV

Differently aged oils show different characteristics with increase of the applied voltage. Figure 5 shows the characteristic variation in number of discrete pulses per PD pulse burst as a function of applied voltage. All three specimens exhibit an increase in the number of pulses but for the severely aged specimen, the increase is more pronounced than for the other two, especially with applied voltage increase.

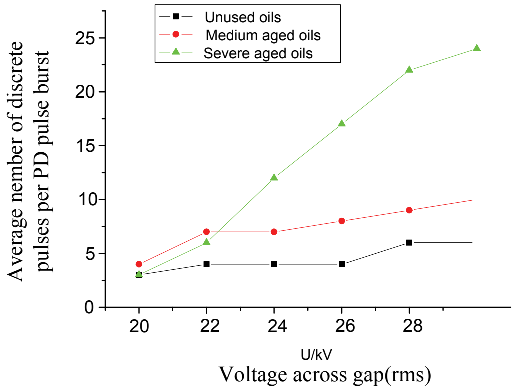

Fig. 5. Number of pulse within burst as function of applied voltage

Variation in duration time of the pulse burst is delineated in Figure 6. The duration reduces slightly with applied voltage in unused oil and medium aged oil while a sharp reduction with the increase of applied voltage is observed in severely aged oil. This phenomenon can be explained in terms of charge exchange between cavity wall and impurity species. The ions from the cavity discharge are trapped at the cavity interface by electrostatic forces but can be removed through charge exchange with impurity species in the process of cavity growth. The impurity species will diffuse to high electric field point under electric force and make the charge exchange effect more energetic.

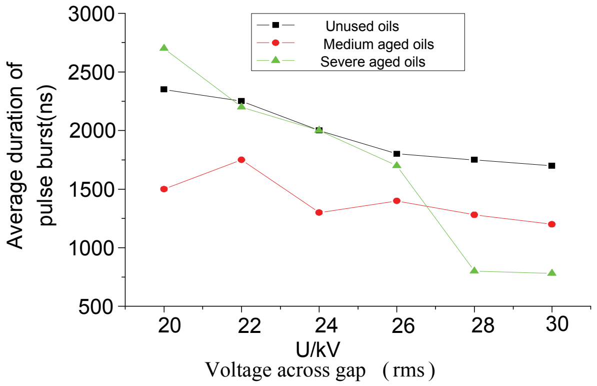

Fig. 6. Duration time of per burst as function of applied voltage

The impurity species (especially furans) show a marked increase with degree of oil aging according to Table 1. This will cause the rate of charge de-trapping from the interface between the cavity wall and liquid to increase as well. For this reason, the discharge frequency could be expected to increase with the concentration of impurity species. More frequent discharges in the cavity will contribute to its electrohydrodynamic instability and reduce its lifetime in the oil phase. Hence the duration of pulse bursts decreases with the concentration of impurity species, especially at higher applied voltages. It also can be seen from Figure 6 that the burst duration reduces by about 0.5μs between 20kV and 30kV in the unused and medium aged oil samples but by about 2μs over the same range for the severely aged oil.

The first large discrete pulse represents the initial charge injection to liquid phase, and then the time to form the cavity that supports the subsequent partial discharge process can be determined by computing the time interval between first pulse and second pulse within the pulse burst. Figure 7 portrays the variation in the time interval between the first and second pulse within the pulse burst. The cavity formation time is found to range from 70ns to 350ns. The three test specimens show the same tendency for cavity formation time to decrease with applied voltage. The formation times reported previously in the literature [9] are somewhat longer, ranging from approximately 100ns to 700ns. The one likely reason is the condition of the oil specimens. The samples in literature [9] were new transformer oils. However, the specimens in this study are aged transformer oils which contain impurities. At a given voltage, cavity formation time generally decreases with the degree of aging of the oil sample. The other likely reason is the electric field distribution in the gap, especially in the close vicinity of the needle. The electric field, besides being modified by the charge injected into the liquid at the needle tip, is a function of the electrodes configuration. The needle tip radius is different with literature [9] may lead to such different in unused oil specimen.

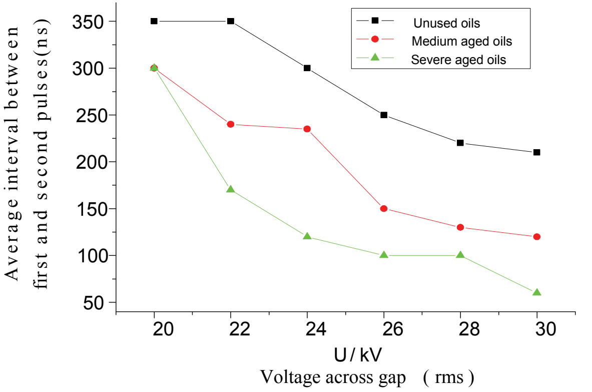

Fig. 7 Time interval between first and second discrete pulses within the PD pulse burst as a function of applied voltage

Figure 8 shows the average maximum magnitude of discrete pulses within the burst for all three specimens (The dispersion of maximum magnitude of discrete pulses within the burst is larger, so, the figure 8 and figure 9 only shows the average values of all measured dates). The maximum magnitude increases with the applied voltage in all cases and the magnitude difference is not exceptionally different as a function of ageing. However, we can estimate the approximate transfer charge per PD pulse burst using the formula $q = \int idt$. Figure 9 presents the plots of the average charge transferred per PD pulse burst as a function of the applied voltage and reveals a marked increase in the average charge transfer per burst with the applied voltage. Especially for severely aged oils, the charge transfer shows an abrupt increase when applied voltage exceeds 24kV. Comparing Figures 5 and 8 it can be seen that the difference of maximum magnitude of discrete pulse within PD pulse burst is minimal but the number of discrete pulses per PD pulse burst changes significantly across the oil samples. Charge transferred per PD pulse burst increases with oil aging.

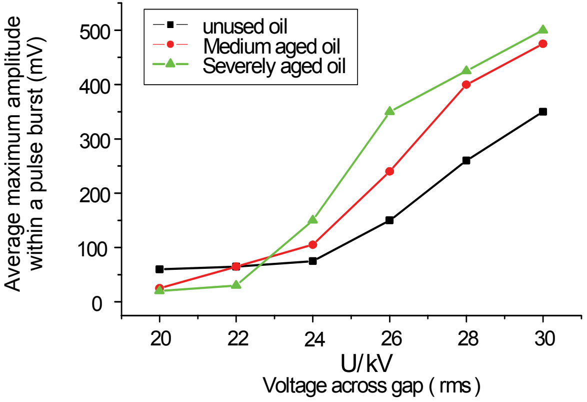

Fig. 8. The average maximum amplitude within a pulse burst as function of voltage

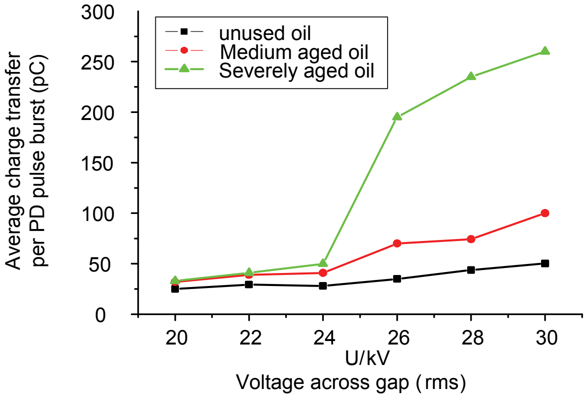

Fig. 9. Average charges transferred per PD pulse burst

In addition to the typical phenomena discussed so far, some abnormal PD bursts were also observed during testing, and some results in unused oils were more similar to those of Pompili [9] than the results presented above.

For example, a single pulse often appears in the oil, which may be due to charge injection that fails to generate a cavity and initiate cavity discharge.

In some other instances the growth of the cavity may undergo substantial fluctuation as it continues to discharge as evidenced by the irregular amplitude of the discrete pulses shown in Figure 10. The cavity may divide and create more micro-cavities in the expansion phase, resulting in this phenomenon.

The first large pulse within a PD burst usually corresponds to the charge injection in liquid phase, but in some instances a cluster of extremely small pulses appears at the beginning of the pulse burst, as shown in Figure 11. In such cases it is difficult to identify the “first” pulse. These very small pulses may represent a multi-charge injection process in which it is the total injection energy leads to cavity formation.

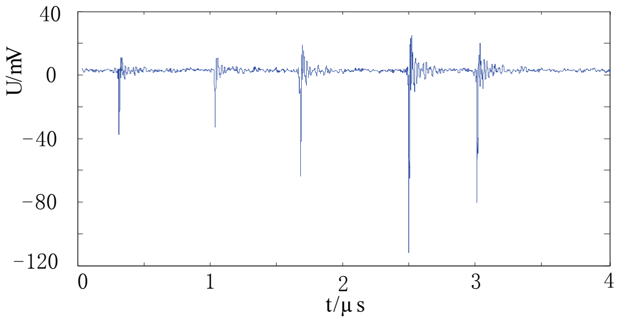

Fig. 10. PD pulse burst in unused oil at 24kV

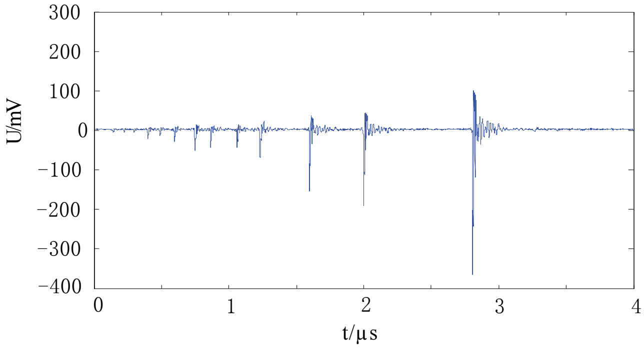

Fig. 11. PD pulse burst in unused oil at 28kV

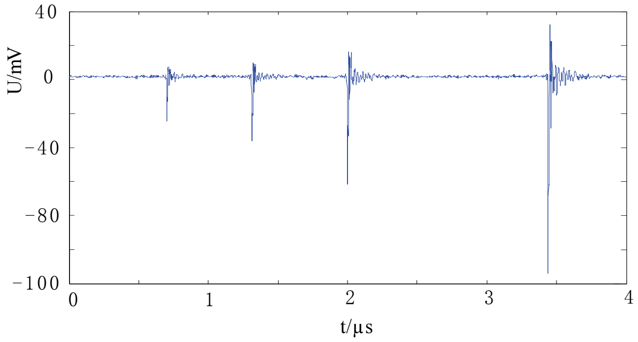

Fig. 12. PD pulse burst in unused oil at 24kV

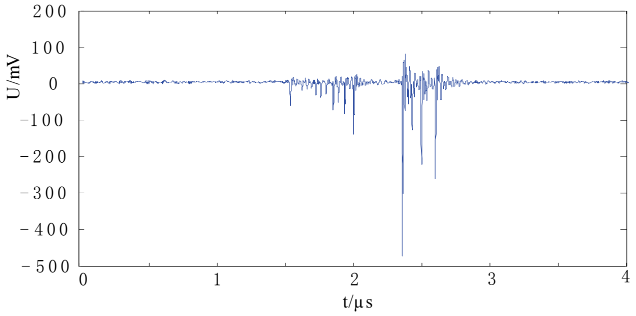

Fig 13. PD pulse burst in severely aged oils at 28kV

There exists another kind of PD pulse burst event that was regularly observed, in which a discrete PD pulse sequence is observed among the successive pulses with a monotonically ascending pulse magnitude, as shown in Figure 12. The interval time between successive pulses increases gradually without a larger initiating pulse. This may be due to cavities having been generated by previous charge injection but which could not sustain PD initially. At a later time, the phase shift of the external AC voltage may lead to re-ignition of PD in one of these “dormant” cavities.

Another instance which was observed in severely aged oil is illustrated in Figure 13. This type of pulse burst may owe to the higher concentration of impurity species in severely aged oil that result in more electrical discharge activity and shorter cavity lifetime. Impurities move to the electrode and increase the electric field aberration on a microscopic scale. Charge injection processes occur simultaneously and initiate separate cavities, thereby leading to relatively independent two-cluster PD pulse burst. This phenomenon was observed only in severely aged oils.

5. Conclusions

The PD pulse burst phenomenon in a 30mm long point-to-plane gap in differently aged transformer oils have been measured under AC conditions. For the three tested transformer oils, the cavity formation times ranged from 80ns to 350ns, compared to the average duration time of per burst of 0.7μs to 3μs. All oils tested exhibited a considerable increase in PD activity with applied voltage. The number of discrete pulses per PD pulse burst ranged from 3 to 25 and increased with the applied voltage and degree of aging. The level of average charge transferred per PD bursts was found to vary from 25pC to 250pC and have the same trend as with the number of discrete pulses per burst.

Impurity species such as moisture, furans, etc., which increase in concentration as the oil ages will tend to increase the number of discrete PD pulses per pulse burst (and hence the charge transferred per pulse burst), while reducing the duration time of pulse bursts and the cavity formation time.

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