Effect of electric field configuration on streamer and partial discharge phenomena in a hydrocarbon insulating liquid under AC stress

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Abstract
This paper concerns pre-breakdown phenomena, including streamer characteristics from a fundamental perspective and partial discharge (PD) measurements from an industrial perspective, in a hydrocarbon insulating liquid. The aim was to investigate the possible changes of the liquid’s streamer and PD characteristics and their correlations when the uniformity of the AC electric field varies. In the experiments, a plane-to-plane electrode system incorporating a needle protrusion was used in addition to a needle-to-plane electrode system. When the applied electric field became more uniform, fewer radial branches occurred and streamer propagation towards the ground electrode was enhanced. The transition from streamer propagation dominated breakdown in divergent fields to streamer initiation dominated breakdown in uniform fields was evidenced. Relationships between streamer and PD characteristics were established, which were found to be electric field dependent. PD of the same apparent charge would indicate longer streamers if the electric field is more uniform.

Keywords: streamer, partial discharge, insulating liquid, prebreakdown phenomenon

(Some figures may appear in colour only in the online journal)
the same stress level, therefore positive streamers are regarded as the main cause of breakdown under AC stress [15]. With increasing uniformity of the electric field, the probability of negative streamer induced breakdown will rise [15].

On the subject of PD studies, efforts have been made to examine the dependence of PD inception voltage (PDIV) on measurement method [17], liquid type, temperature and addition of different impurities [18–20]. At higher voltages than PDIV, efforts have been made to investigate the changes in the shape of PD current pulse, PD magnitude, pulse repetition rate, PD pattern when liquid type or liquid condition changes [19–21]. PD measurements are obligatory requirement during factory AC withstand voltage tests for high voltage equipment, e.g. power transformers, and are routine diagnostic tools for determining the insulation condition of high voltage equipment on site. Understanding of the correlation between PD characteristics and streamer physics will help interpretations of PD measurement results for industrial practices.

Investigations into PD and streamer characteristics of liquids were mostly carried out with needle-to-sphere or needle-to-plane electrode systems. A sharp point whose diameter lies between 1 and 100 μm was normally used to create a local high-field area. This allowed the experimental setup to initiate a PD or steamer without causing breakdown. However, the insulation in high voltage equipment in most cases experiences uniform or quasi-uniform electric field. Therefore, direct application of the research output obtained in divergent electric fields to condition assessment of high voltage equipment might be misleading. A plane-to-plane electrode system that incorporates an adjustable needle protrusion was used in [22]. Such an electrode system can provide electric field of various uniformities, depending on the size of the protrusion relative to the gap spacing.

In this research, PD and streamer characteristics of a hydrocarbon insulating liquid are measured simultaneously in both divergent and quasi-uniform electric fields. The paper discusses the changes in streamer shape in the transition from divergent to quasi-uniform field and the relationships between PD magnitude and streamer stopping length.

2. Experimental descriptions

2.1. Experimental setup and measurement method

Figure 1(a) presents the experimental setup for measuring PD and photographing streamers. An arrangement in compliance with the IEC 60270 was adopted for PD measurements. An AC voltage of up to 70 kV can be applied to the test cell (all the voltage levels presented in this paper are rms values). The voltage applied across the electrodes was measured using a voltage divider and was recorded using an oscilloscope (Oscilloscope 1). The PD detector used is LEMKE LDS-6, which is a computer-aided wide-band instrument. During the measurements, the applied voltage was maintained for 1 min. In addition to the PD patterns, the PD magnitudes (represented by the largest apparent charge in a PD pattern) and pulse repetition rates of the liquid at different voltages were obtained. The PDIV was determined using the method described in [23, 24] and the same apparent charge threshold, i.e. 100 pC as defined in the IEC 61294, was used. The applied voltage was increased in steps of 1 kV for the determination of PDIV. When investigating the PD characteristics at higher voltages than PDIV, the applied voltage was increased in steps of 5 kV. A 1 min resting time was given after each measurement. The PD measurements were undertaken for 3 times and at each time a new needle electrode was used. The background noise of the setup was no more than 12 pC.

In order to photograph the streamers in the liquid, the setup also includes a high speed imaging system. A 50 Ω resistor was placed between the test cell and ground to capture the current pulses of streamers. The current pulses were recorded by the Oscilloscope 1. An additional oscilloscope (Oscilloscope 2) functioned as a trigger unit for synchronising the devices. The Oscilloscope 2 was triggered by an output signal from the PD detector. The amplitude of the signal is proportional to the apparent charge of a captured PD. By altering the triggering level, PDs of large magnitudes were used for triggering the current measurement and high speed video. Shadowgraph technique was employed in the experiments to capture the 2D projections of streamers. The high speed video was operating at 20000 frames s⁻¹. At each voltage, 10 photographs of large positive streamers and the corresponding PD current waveforms were obtained.

Two electrode systems were used, including a needle-to-plane (NP) electrode system and a plane-needle-plane (PNP) electrode system, as depicted in figures 1(b) and (c). For both configurations, the gap spacing, which is the distance from the needle tip to the grounded plane electrode, was set at 40 mm. For the PNP configuration, the length of the needle protrusion was 10 mm. The diameter of the plane electrodes was 50 mm. Needle electrodes with a tip radius of 3 μm were used.

2.2. Oil sample preparation procedures

The insulating liquid used in this research is Nytro Gemini X, which is an inhibited mineral oil. It is mainly composed of
paraffinic, naphthenic and a small amount (~3%) of aromatic compounds. All the oil samples were filtered, dehydrated and degassed prior to the measurements. Average particle counts per 100ml showed that there were fewer than 1000 particles that were larger than 5 μm. Oil dehydration was performed at 85 °C, 500 Pa (5 mbar) for 48 h. This reduced the moisture content of the oil samples to around 5.5 ppm (equivalent to a relative moisture content of around 10% at 20 °C).

3. Results

3.1. PD characteristics of the liquid in divergent electric fields

Under the NP configuration, the PDIV of the liquid was 17.7 kV. Four typical PD patterns of the liquid are shown in figure 2(a). At 20 kV, which is slightly above the PDIV, 6 discharges were detected in 1 minute, lying between 45° and 135°. At higher voltages, more discharges appeared and they spread in a wider angle range. At up to 45 kV, no negative discharge was detected. The waveforms of negative PD currents typically comprised a series of discrete pulses and the apparent charge of negative PDs was less than 10 pC. This pulse burst behaviour of negative PD was reported in [25]. The charge quantity of negative PDs is so low that those discharges cannot be detected or differentiated from background noise through the present measuring system.

By increasing the applied voltage, an increase in the PD magnitude was observed, as can be seen in figure 3(a). From figure 3(b), the pulse repetition rate generally increased with voltage.

3.2. PD characteristics of the liquid in quasi-uniform electric fields

In the case a plane electrode being placed behind the needle tip, the PDIV increased to 37.4 kV. This value almost doubles the one in the case of NP configuration due to the reduction of the tip field. The profound increase in the PDIV in the
meantime resulted in a smaller margin to breakdown voltage. Under the PNP configuration, the PD characteristics of the liquid were investigated at three voltages, i.e. 40 kV, 45 kV and 50 kV. From figure 2(b), the three typical PD patterns contain fewer PDs and the PDs are smaller in magnitude in comparison with those in figure 2(a). All the PDs occurred at a phase angle between 45° and 135°. PD occurrence under the PNP configuration was more likely at crest voltages, resembling the situation where the NP configuration was used and when the applied voltage was relatively low. In the quasi-uniform fields, both the PD magnitude and pulse repetition rate increased with applied voltage, as depicted in figures 3(a) and (b).

3.3. Streamer characteristics of the liquid in divergent electric fields

As all the PDs shown in figure 2 occurred in the positive half cycle, the corresponding positive streamers were investigated. Figure 4 includes the typical photographs of positive streamers obtained at 20 kV–45 kV in divergent field conditions. At 20 kV, which is the streamer initiation stage, two small branches were observed. When the applied voltage was increased, streamer started to propagate and more radial branches and side offshoots appeared.

In this paper, the stopping length was measured as the longest possible distance from a streamer tip to the needle tip. The average stopping lengths of positive streamers in the divergent fields are plotted against applied voltage in figure 5(a). When the applied voltage increased, the positive streamer stopping length increased almost linearly at a rate of 0.6 mm kV⁻¹. When the stopping length of a streamer exceeds about half of the total gap spacing, the streamer tends to propagate continuously till triggering breakdown.

The average propagation velocity of a streamer was calculated as the ratio of stopping length to propagation duration (measured from current signal). Figure 5(a) shows the average propagation velocities of positive streamers in the liquid. In the tested voltage range, the calculated average propagation velocities lie between 1.5 mm µs⁻¹ and 2.0 mm µs⁻¹.

3.4. Streamer characteristics of the liquid in quasi-uniform electric fields

The typical photographs of positive streamers in quasi-uniform fields are also shown in figure 4. At the initiation stage, one small streamer path was observed. However, after the voltage was increased, the number of main branches did not increase. Although multiple main branches could still appear, e.g. at 45 kV, they grew towards the grounded electrode without the appearance of radial main branches. The streamers in quasi-uniform fields are clearly distinct from those in divergent fields.

Streamer stopping length increased with applied voltage linearly at a rate of 1.2 mm kV⁻¹, which is twice as high as that in divergent fields. The average propagation velocities were found to be in the same range of 1.5 mm µs⁻¹ to 2.0 mm µs⁻¹ according to figure 5(b).
4. Discussions

4.1. Change of streamer shape in different electric field conditions

At the propagation stage in divergent fields, streamers radiated outward from the high field region near the tip and elongated generally along the direction of the electric field. The motion of electrons is expected to have a similar pattern but towards the needle tip in the positive half cycle of the applied voltage. Part of the electrons are neutralised after contacting the needle tip, while the rest remain in the conductive paths. This process can lead to heating and dissociation of the oil near the tip [26]. For this reason, the paths near the needle tip normally appear to be thicker, as can be noticed from figure 4. The terminal of one branch can act as the anode tip for other branches if its net positive charge is sufficiently large. If insufficient, the extraction of negative charges would not be sustained and the branch would cease growing. A theoretical estimate of the minimum streamer tip charge for a 10 μm diameter branch is 3–4 pC [26]. Figure 5(a) evidences that all the positive streamers captured in the experiments were 2nd mode streamers [27]. The average propagation velocity is almost constant in the investigated range. This is reasonable as the streamers of higher propagation speeds, e.g. typically 10 mm μs\(^{-1}\) for 3rd mode and 100 mm μs\(^{-1}\) for 4th mode [27], are normally observed when overvoltages, i.e. voltages higher than the breakdown voltage, are applied.

In contrast, branching was largely suppressed at the high field region near the needle tip in the quasi-uniform field conditions, as shown in figure 4. Having observed a similar diameter of the streamer channels, comparing the area of streamers having a similar stopping length could qualitatively reflect the branching phenomena. The streamer area is defined as the apparent area occupied by all streamer branches in the 2D image. This area is measured by using a self-developed MATLAB program which converts the original images into binary images, then counts the pixels of the branches and finally converts the number of pixels into area. For streamers captured in both divergent fields and quasi-uniform fields, their areas are included in figure 6. Positive streamers in quasi-uniform fields generally have smaller areas or fewer branches when compared with those in divergent fields of a similar stopping length.

The effect of electric field uniformity on streamer shape under impulse stress was mentioned in [22, 28]. The qualitative analysis of streamer shape in this research provides sound evidence for the reduction of streamer branching under AC stress when electric field uniformity increases. Altering the electric field uniformity can change the streamer shape significantly.

4.2. Change of dominant breakdown factor in different electric field conditions

Comparisons of streamer propagation characteristics in different electric field conditions are shown in figure 7 for the analysis of the responsible breakdown mechanism. In figure 7, normalised applied voltage is used, which is defined as the ratio of the applied voltage to the corresponding PDIV.

From figure 7, although streamer stopping length increases with voltage in both divergent electric fields and quasi-uniform
electric fields, the rate of the increase is different. An increase in the uniformity of the electric field will facilitate streamer propagation. If the needle length is sufficiently small, the slope of the curve would be extremely large, meaning that any streamer initiated in such case would be able to bridge the 40 mm gap and induce breakdown. This supports the argument that breakdown in uniform fields is predominantly determined by streamer initiation [15]. Similarly, divergent-field condition eases streamer initiation, whereas only those streamers capable of propagating far can cause breakdown. So breakdown in divergent fields is predominantly determined by streamer propagation.

Once a positive streamer is initiated, it will prolong if the electric field is sufficiently large. The differences in the electric field distribution affect the likelihood of streamer branching in radial directions. At the initial propagation stage within the region of a few mm away from the needle tip, streamers observed in quasi-uniform fields always have one or two branches, whereas streamers observed in divergent fields already have multiple branches, as seen in figure 4. This is supported by the static field calculation results at the initiation stage depicted in figure 8. The peak values of PDIVs measured with the two electrode systems were used in COMSOL Multiphysics to perform finite element method (FEM) based field calculations. The electric field distribution is more towards radial direction in divergent fields than in quasi-uniform fields. For instance in the region circled in figure 8, blue arrows representing the divergent electric field condition have stronger radial components than green arrows representing the quasi-uniform electric field condition.

During propagation, the new branches produced carry less positive charge than the original one since splitting of charge accompanies streamer branching [26, 29]. Therefore, the new branches have a weaker ability to propagate farther. This is likely the case in divergent fields. In contrast, if a streamer does not split, it could gain more positive charge through charge amplification process [26, 29]. This results in an enhanced ability of the streamer tip to continue propagating, which is likely the case in quasi-uniform fields. This could explain how the change of breakdown mechanism is associated with streamer branching.

4.3. Correlations between streamer and partial discharge characteristics

Streamers having a longer stopping length are normally considered more dangerous, because they are more likely to cause breakdown. In standard AC withstand tests for high-voltage equipment, however, the apparent charge from PD measurement serves as a key indicator of insulation defect. This raises the question of whether the apparent charge threshold adopted can suitably reflect the presence of large streamers.

Synchronised measurements of streamer and PD allow the correlations between stopping length (shown in figure 5) and maximum apparent charge (shown in figure 3) to be established. In both divergent fields and quasi-uniform fields, the detection of a higher level of PD generally indicates a farther streamer propagation, as shown in figure 9. However, the rate of increase in stopping length with respect to apparent charge varies with the uniformity of the electric field. In this research, the rate changes from 0.42 mm per 100 pC in the divergent field to 3.2 mm per 100 pC in the quasi-uniform field. So, small apparent charge does not necessarily mean that the discharge is benign. For example, a PD of an apparent charge of 500 pC may indicate a small 3 mm-long streamer in a divergent field, or a large 15 mm-long streamer in a quasi-uniform field.

The results indicate that the common use of a simple apparent charge based criterion in the industry might not be sufficient. The evaluation of the severity of PD activity should therefore take the electric field uniformity at the PD site into consideration. For instance, knowing both the distribution of
the electric field and the PD location within a high voltage power transformer can play a crucial role in interpreting factory or on-site PD test results. Systematic PD measurements in various electric field conditions mimicking practical scenarios thus deserve more research efforts so as to generate a set of conversion coefficients to compensate the effect of field uniformity.

5. Conclusions

The streamer and PD characteristics of a hydrocarbon insulating liquid were investigated in both divergent and quasi-uniform AC fields. By varying the electric field uniformity, the shape change of positive streamers was observed. The more uniform an electric field is, the fewer branches a streamer will have. Moreover, the change from a propagation-induced breakdown in divergent fields to an initiation-induced breakdown in quasi-uniform fields was explained. The correlations established between PD apparent charge and streamer stopping length reveal that the same apparent charge could indicate different levels of streamer development in the insulation, depending on the uniformity of the electric field.

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