Positive third mode streamers in insulating oil

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***Abstract*—Third mode streamers have been studied in the mineral oil Nytro 10 XN, gas-to-liquid oil Diala S4 ZX-1 and the high viscosity white oil Primol 352, in an 80 mm point-plane gap under step impulse voltage. Third mode streamer velocities were in the range 4 – 60 km/s. The "acceleration" of the average velocity with increasing voltage is not due to third mode, and third mode existed in a wide voltage range in both Nytro 10 XN and Primol 352. The voltage where third mode becomes common is almost the same in Nytro 10 XN and Diala S4 ZX-1, indicating that the presence of aromatics may have little influence over the initiation voltage for third mode. Onset voltage for third mode was very low in Primol 352.**

Keywords—mineral oil, gas to liquid, white oil, breakdown, streamer, propagation mode

I. Introduction

The fast mode streamer of most practical importance is the fourth mode, with its velocity often in the 100 – 250 km/s range, because the high velocity means that even an overvoltage of short duration may cause a breakdown in e.g. a transformer if it triggers this mode. The third mode is in a way more of a medium velocity transition type usually in the 4 – 50 km/s range, but recently some attention has been drawn to this mode [1]. The present paper shows the third mode information from a larger streamer study. The presence of molecules with low ionization potential has been shown to have a large effect on the streamer propagation, and especially on the transition voltages for abrupt changes in the average streamer velocity [2]. In a practical mineral insulating oil, aromatic molecules have this property. Thus of the two commercial insulating oils studied, one has an aromatic content of about 6 % while the other is virtually aromatic-free. A third oil was also virtually aromatic-free, but had high viscosity.

II. Experimental

In an 80mm point-plane gap the point was a 200 µm tungsten wire point and the plane had diameter 340 mm. There was 100 liters oil in the test cell. Imaging was done with an IMACON 468 image converter camera with seven frames and one streak (in principle an image with one position axis and one time axis). Most images were "shadowgraphs" recorded with a xenon flash opposite the camera, but there were also some emitted light images (only these had streaks). In this case, a photomultiplier (PM) (Philips 56 AVP with 2 ns rise time) recorded the overall light emission. The impulse with rise time 0.55 µs and tail time to half-value 2 ms approximated a step voltage for the streamer duration and was supplied to the point electrode. A high voltage capacitor differentiated the impulse voltage signal and a passive integrator at the oscilloscope restored a scaled-down signal [3]. Current was measured at the plane electrode, with protective devices to save the oscilloscope from breakdown currents. The displacement current during the impulse rise made the current signal unusable for 5 µs after impulse start. Above about 300 kV it also triggered the protective devices, preventing current recording. The four traces on the Tektronix DPO4104 oscilloscope showed the impulse, a frame/streak timing monitor, light emission (when taking emitted light images) and current. When not using the PM, two traces on the oscilloscope were sometimes used for the current, one scaled for pulses of several amperes corresponding to channel reilluminations and the other to a continuous background current in the 1 – 100 mA range. Reilluminations are light flashes along a channel, with less than 10 ns duration of the corresponding current pulse while the light apparently has somewhat longer tail.

The insulating oils used were the mineral transformer oil Nynas Nytro 10XN with a mix of naphtenic, paraffinic and 6 % aromatic molecules, and the gas-to-liquid (GTL) Shell Diala S4 ZX-1 with virtually no aromatic content. Also used was ExxonMobil Primol 352, which is a medicinal grade white oil and not an insulating oil. It has virtually no aromatic content, and has large molecules (average 35 carbons) and high viscosity (65-75 cst at 40 ˚C vs. approx. 8cst for the others). The oils were filtered under vacuum to remove carbon particles after each breakdown, except for Primol 352 which was filtered after each ten breakdowns because the high viscosity made filtering very time-consuming.

The number of impulses applied at each voltage level was usually five. In voltage ranges where aspects of the streamer growth changed rapidly with voltage, ten impulses were applied at each level.

III. Results

Positive third mode streamers start from the positive electrode tip. They will usually transform to another mode somewhere in the gap. Below the acceleration voltage (V_a), which is the voltage where the average velocity starts to increase sharply, they transform to the slower second mode,

The project is financed by the Norwegian Research Council under the contract 228850, ABB, and Statnett SF.

This is the accepted version of a paper published in 2017 IEEE 19th International Conference on Dielectric Liquids - ICDL
DOI: 10.1109/ICDL.2017.8124601

with duration increasing with voltage. At higher voltages, they usually transform directly to the faster fourth mode, with the transformation taking place earlier (and at shorter length) the higher the voltage is.

50 % breakdown voltage (VBD) and onset voltages for third mode (denoted V3 in as in [1]) are shown in Fig. 1. In Nytro 10XN, first third mode streamer appearance was at 171 kV, 18 kV above VBD, with velocity 5 km/s, but not until 195 kV is third mode common, and at this voltage all streamers start as third mode (Fig. 1). The average velocity of third mode streamers increases to a maximum of 10 – 30 km/s in the middle of the "acceleration" voltage range, and appear to decrease with further voltage increase. This may be because they quickly transform to fourth mode, something often happening before the first frame in the framing sequence since only seven frames are available to cover the entire streamer propagation. Thus only the slower ones survive for a sufficiently long time to be measured. It is also seen in Fig. 1 that the number of third mode streamers growing past a length of 5 mm before transforming to fourth mode decreases from the middle of the "acceleration range". When the average velocity seems to level off in the logarithmic plot, fourth mode totally dominates. There is reason to believe that the only reason these streamers still usually start in the third mode is that the rising voltage of the "step" impulse is not infinitely fast. Thus the streamers initiate at a far lower voltage than the recorded peak voltage and switch to fourth mode when the voltage has become sufficiently high.

TABLE I. VOLTAGES FOR BREAKDOWN AND THIRD MODE.

Oil	50 % breakdown voltage (V_{BD}) [kV]	First appearance of third mode (V_3) [kV]
Nytro 10XN	153	171
Diala S4 ZX-1	139	205
Primol 352	169	102

V_{BD} is a little lower in Diala S4 ZX-1 than in Nytro 10XN, and V_a is much lower. Nonetheless, V_3 is slightly higher than in Nytro 10XN, and it is just below start of acceleration. The velocity range is largely the same as in Nytro 10XN, except for a few cases up to around 60 km/s. Apparently third mode start disappears as the average streamer velocity approaches "levelling off" at higher voltages. In [4] it was found that all streamers at higher voltages started as third mode. There may be two reasons for this difference, and most likely both contribute. One is that an accidental setting of a too small lens aperture caused short-exposure images typically needed for these fastest streamers to have very poor quality, so that very short third mode streamers simply cannot be seen. The other is that we used an impulse rise time of 0.55 µs while 1.2 µs was used in [4]. The slower rise probably gave third mode twice as much time to develop before switching to fourth mode.

In Primol 352 it was difficult to sort third mode from second mode at the low voltage end of the third mode existence range and from fourth mode at the high voltage end. While the average streamer velocity below acceleration is rather low, 0.5 – 1.5 km/s, there was at all those voltages a significantly faster streamer during initial growth. At the lowest voltages this was undoubtedly a fast second mode (1.7 – 3.3 km/s) judged by the shape, but there was not a very significant change in velocity at slightly higher voltages when the shape indicated that it had switched to third mode (3.7 km/s and higher). A peculiarity in this oil is that third mode apparently starts well below breakdown voltage. At the high end of third mode existence range there was little velocity difference between fast third mode and the slower of the fourth mode streamers, and here even streamer shape was not very different. Luminosity of the main channels ended up being the criterion keeping them apart with fourth mode being by far the most luminous.

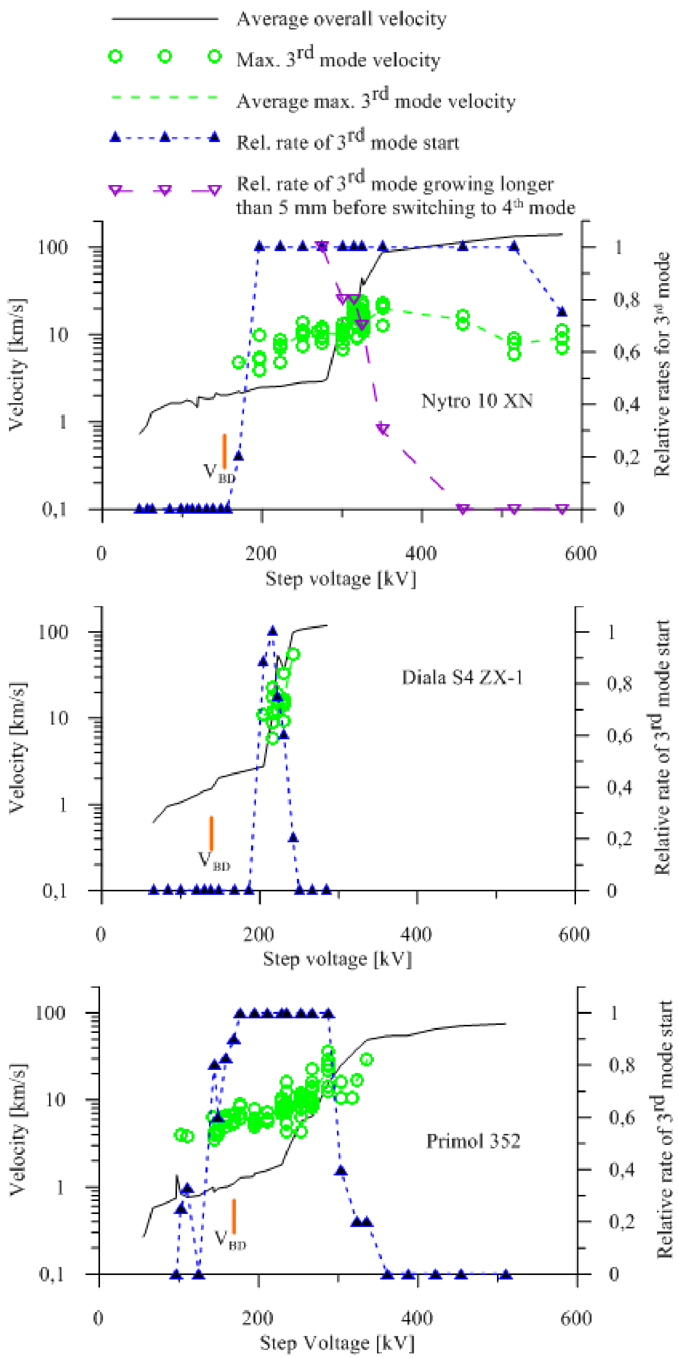


Fig. 1: Third mode velocity and probability.

This is the accepted version of a paper published in 2017 IEEE 19th International Conference on Dielectric Liquids - ICDL
DOI: 10.1109/ICDL.2017.8124601

Examples of comparatively long slow third mode streamers (5 – 9 km/s) are shown in Fig. 2. In Nytro 10 XN and Diala S4 ZX-1 they seem to be fairy similarly shaped, while there is less fine branching from the main channels in Primol 352. Faster third mode streamers (17 – 24 km/s) are shown in **Fig. 3**, and most branching is again seen in Nytro 10 XN, now with less branching in both Diala S4 ZX-1 and Primol 352.

During both second and third mode propagation, there are reilluminations, but while reilluminations are abundant in Nytro 10 XN, there are few of them during propagation in Diala S4 ZX-1 and Primol 352 (Fig. 4). Most of the reilluminaitons in the figure are in second mode, but one can see a small group of small third mode reilluminatiuons in the beginning. One can also get an impression of a small background current flowing between the reilluminations. The oscillograms belong to streamers switching from initially third mode to second mode. There is a gap in the reillumination sequence somehow associated with the mode switch as seen in the same figure, but the switch from third to second mode actually takes place before this gap as judged both from the velocity and from the shape of the streamer growth. Since the continued streamer growth in second mode is slower than the initial third mode streamers, the overall streamer shape usually still retains much of the third mode character by the start time of the reillumination gap. An example in Diala S4 ZX-1 is shown in Fig. 5. At high voltages where third mode eventually switches directly to the very fast fourth mode, typically in the

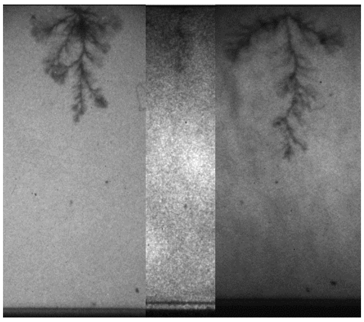


Fig. 2. Examples of long slow third mode streamers.
Left to right: Nytro 10 XN, Diala S4 ZX-1, Primol 352

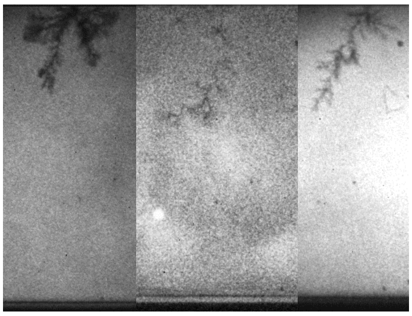
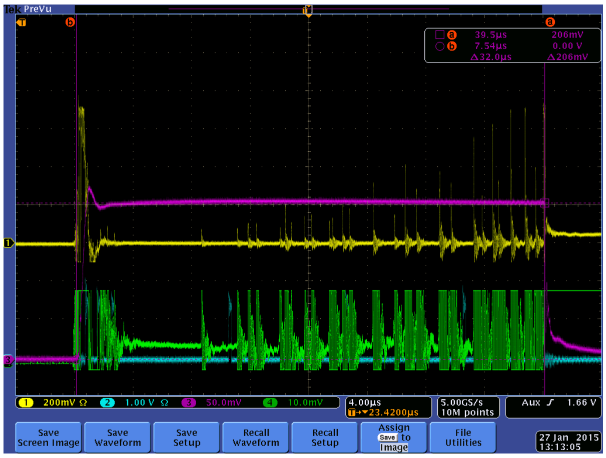
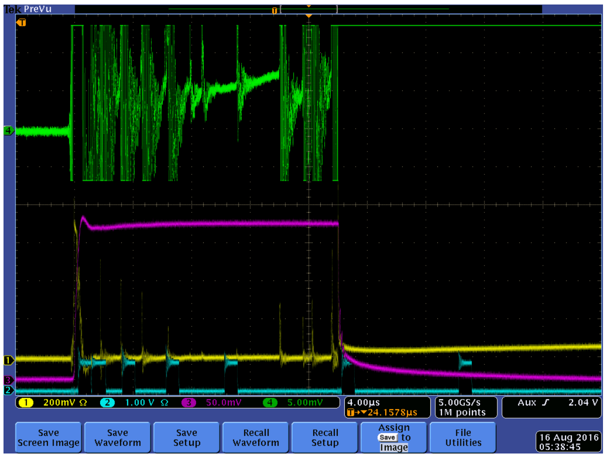


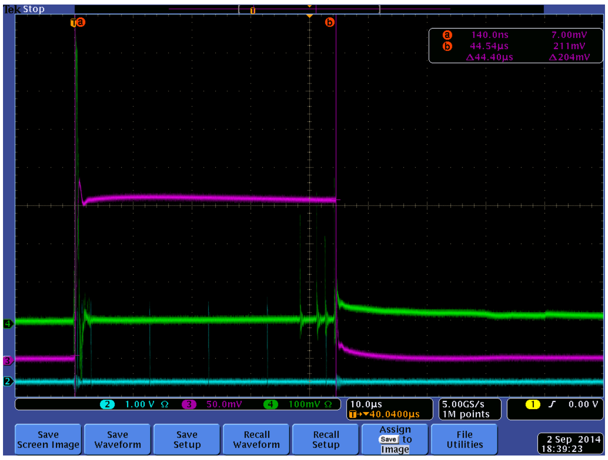
Fig. 3. Examples of long fast third mode streamers.-
Left to right: Nytro 10 XN, Diala S4 ZX-1, Primol 352



Nytro 10 XN. Yellow: 2 A/div. Green: 100 mA/div



Diala S4 ZX-1. Yellow 2 A/div. Green 50 mA/div



Primol 352: Green: 1 A/div

Fig. 4. Current pulses corresponding to reilluminations, at approx. 220 kV.
Purple: Applied voltage. Blue: Camera frame timing.

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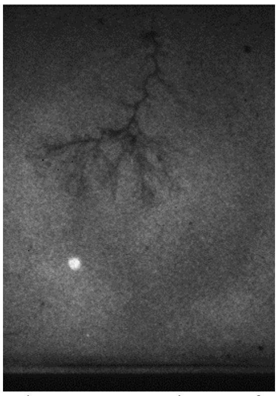

Fig. 5. Bushy second mode streamers growing out of an initial third mode streamer. Diala S4 ZX-1.

acceleration range, there are reilluminations fairly regularly during third mode propagation. As long as there is second or third mode followed by fourth mode, fourth mode with its rapid current increase takes off from what ends up as the last reillumination. An example in Primol 352 is shown in Fig. 6.

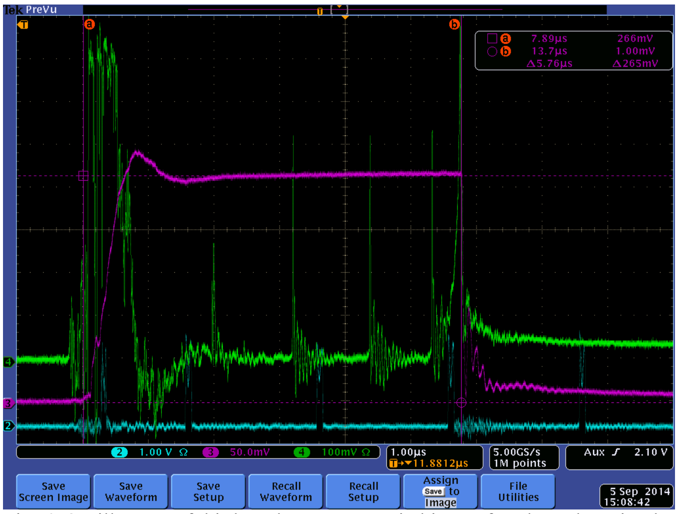

Fig. 6. Oscillogram of third mode streamer switching to fourth mode. Primol 352, 287 kV. Green: Current, 1 A/div.

IV. DISCUSSION

The "acceleration range" where the average velocity increase vs. voltage is rapid has sometimes been associated with third mode. Although it might seem partially true for Diala S4 ZX-1, it is clearly not generally true. Third mode usually appears at a much lower voltage, and in the acceleration range first second mode disappears, as also stated in [1], followed by the replacement of third mode by fourth mode.

Despite the difference in aromatic content between Nytro 10XN and Diala S4 ZX-1, third mode becomes common at rather similar voltages. Thus it is unlikely that the aromatic content has much influence over V_3.

Switching from third (or second) mode to fourth mode as a consequence of a reillumination is reasonable, since the channel is more conductive a short time after the reillumination [5].

The low V_3 of Primol 352 is interesting. It is tempting to associate it with the high viscosity, but the oil may have other differences from the two insulating oils causing this. One ought to compare with other high viscosity oils. There is also ExxonMobil Marcol 52 which is probably as chemically similar to Primol 352 as an oil can be, except for shorter molecules and a viscosity similar to the insulating oils used here. Streamer experiments have been done in that oil [2], but although all the necessary information is present, the data have not been recorded in a way which makes it straightforward to study velocities and ranges of the individual modes. Hopefully a comparison can be made at a later time.

V. CONCLUSION

The presence or absence of aromatic compounds does not seem to have any influence over the onset voltage of third mode.

There is a gap in the reillumination sequence associated with the transition from third to second mode, but the actual transition has taken place before this gap.

A third mode streamer switching to fourth mode will do so from a reillumination.

The onset voltage for third mode was very low in Primol 352. It may be, but is very uncertain, that this has something to do with the high viscosity.

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This is the accepted version of a paper published in 2017 IEEE 19th International Conference on Dielectric Liquids - ICDL
DOI: 10.1109/ICDL.2017.8124601