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Surface Flashover Breakdown Mechanisms on Liquid Immersed Dielectrics

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Flashover formation and expansion mechanisms on the surfaces of different dielectrics immersed in transformer oil have been numerically analyzed. Streamers emanating from a needle electrode tend to transform to surface flashovers, if the immersed dielectric permittivity is higher than the liquid permittivity and/or the dielectric interfacial surface cuts the path of the streamer. Perpendicular interface of the immersed dielectric impedes the breakdown by deflecting the streamer and slowing down the surface flashover. The parallel dielectric interface, however, assists the breakdown by regulating the surface flashover velocity to an approximately constant value (~ 10 km/s). [<http://dx.doi.org/10.1063/1.4705473>]

Surface flashovers are generally defined as electric discharge phenomena that develop on the interfaces between adjacent dielectrics leaving conducting traces that cause further degradation of surface dielectric strength. A surface flashover can creep along a Liquid Immersed Dielectric (LID) interface for long distances under about two orders of magnitude lower electric field intensities compared to streamers forming in the liquid-only system.^{1,2} For instance, streamers usually initiate at 1MV/cm in transformer oil², while surface flashovers on the interface of transformer oil/pressboard initiate at 10-20 kV/cm.^{1,3}

A three-carrier continuum model is utilized in two-dimensional axisymmetric geometry to describe the surface flashover formation and expansion along the LID interface. The governing equations that contain the physics to model streamer/flashover developments are based on the drift-dominated charge continuity equations for positive ion, negative ion and electron charge densities, coupled through Gauss' law². The thermal diffusion equation is also included to model temperature dynamics, predict phase conversions⁴ and model the temperature dependent mobility of different charge species⁵. The ionization function, recombination terms and all of the boundary conditions on the electrodes are set similar to a model previously used for streamers initiated from a sharp needle electrode in the oil-only system². At LID interfaces, a set of boundary conditions accounts for the surface charge density whose time derivative is equal to the difference in the normal component of current density on either side of the interface. At the same time, the surface charge density is always equal to the local jump in normal component of the displacement field across the interface. The underlying assumption for our two-phase model is that the LID has zero conductivity. In practice, the conduction through LID cannot contribute to the charge transport between electrodes in the sub-microsecond time-constants of interest in this paper, since conductivity of the LID is negligible (less than 10^{-13} s/m). The relative permittivity (ϵ_r) of the liquid is set to 2.2 that represents the transformer oil, while LIDs are examined having permittivities 2.1, 4.4 and 1.1 that represent polytetrafluoroethylene (PTFE), pressboard and Sulfur hexafluoride (SF₆) at 5-bars, respectively. As shown in Fig. 1, the LID interfacial surfaces are oriented in parallel (an axial concentric cylindrical bore in LID bulk with 0.1-mm diameter) and in perpendicular (a 10-mm thick LID disk placed 1-mm from the needle) to the primary streamer propagation direction.

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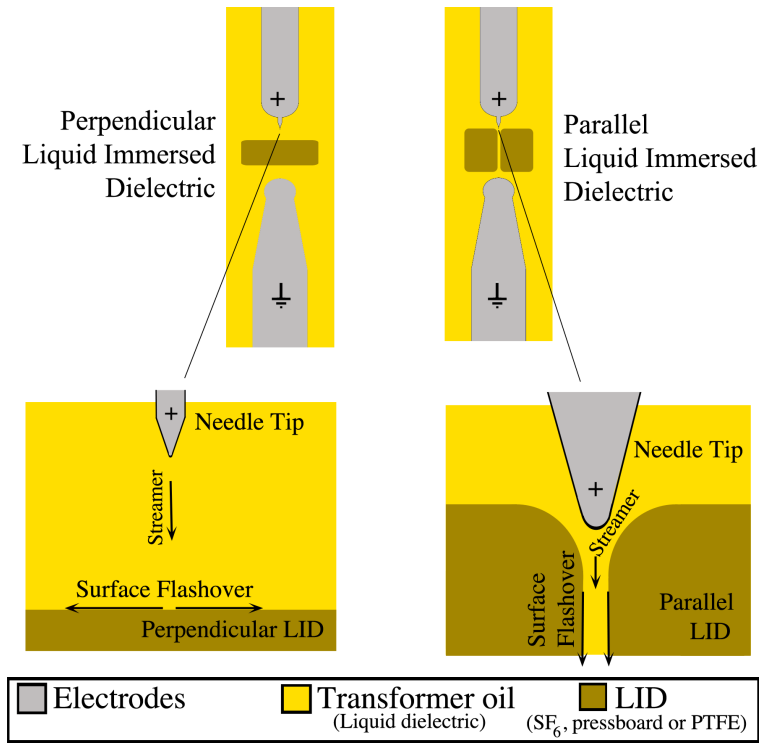


FIG. 1: Perpendicular (left) and parallel (right) liquid immersed dielectric (LID) configurations in 25 mm apart needle-sphere electrode geometries. Two bottom panels show closer views of the perpendicular (left) and parallel (right) immersed dielectrics just next to the needle electrodes. Streamers initiate from the positive needle electrode, elongate through the oil bulk and possibly settle on the LID surface as shown by arrows in the bottom panels.

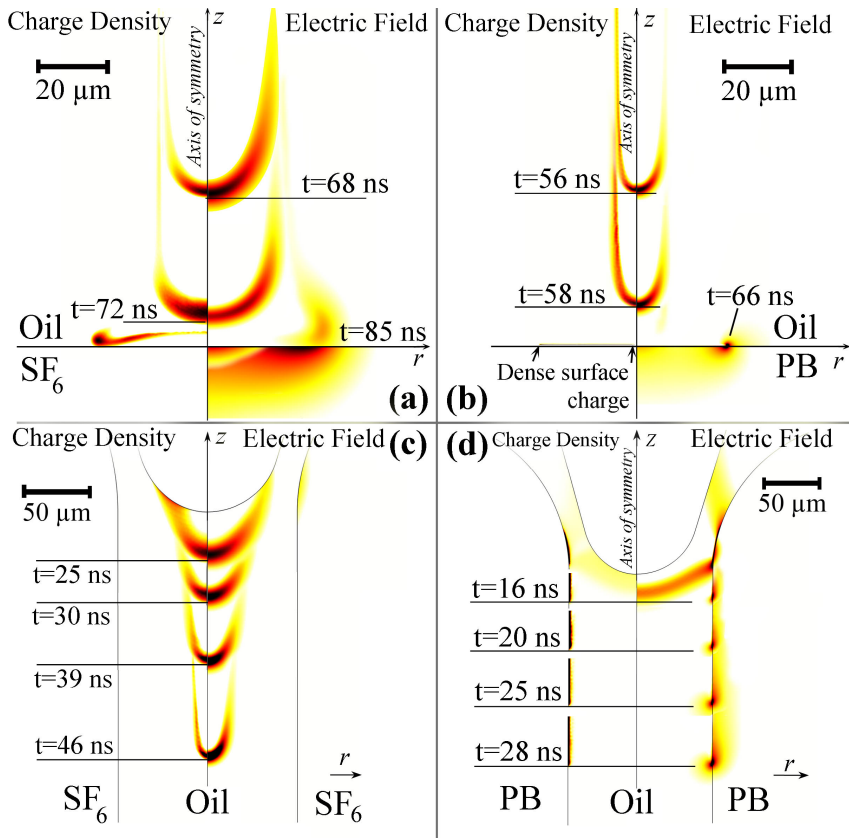


FIG. 2: Streamer/surface flashover initiation on the perpendicular [panels (a), (b)] and parallel [panels (c), (d)] LID interfaces. The streamer formed in oil emanates from a needle under an impulse voltage with 400 kV peak and 0.1 μ s rise-time hits the SF₆ surface [panels (a), (c)] and the pressboard surfaces [panels (b), (d)]. In each panel, the left hand side picture shows the normalized volume charge density (from 0.5 $|\rho_{max}|$ (the brightest color) to $|\rho_{max}|$ (the darkest color)) and the right hand side picture shows the normalized electric field magnitude (from 0.5 $|E_{max}|$ to $|E_{max}|$). Values of $|E_{max}|$ and $|\rho_{max}|$ are (a): $|E_{max}|=2.2 \times 10^8$ V/m, $|\rho_{max}|=7.71 \times 10^2$ C/m³, (b): $|E_{max}|=2.9 \times 10^8$ V/m, $|\rho_{max}|=1.85 \times 10^3$ C/m³, (c): $|E_{max}|=2.8 \times 10^8$ V/m, $|\rho_{max}|=2.31 \times 10^3$ C/m³ and (d): $|E_{max}|=3.21 \times 10^8$ V/m, $|\rho_{max}|=4.88 \times 10^3$ C/m³ respectively.

Figure 2 shows the streamer behavior as it reaches the LID interface. The LID whose permittivity is higher than transformer oil tends to attract the streamer crust to the interface (Fig. 2 (b) and (d)), while lower permittivity LID repels the streamer crust (Fig. 2 (a) and (c)). Therefore, the streamer becomes slower and thicker when approaching the perpendicular SF₆ surface and becomes faster and thinner close to the perpendicular pressboard interface compared to streamers propagating in an oil-only system.² Streamers are pulled and become surface flashovers by settling alongside the parallel pressboard interface, while a parallel SF₆ interface squeezes streamers by repelling them in the concentric parallel bore (compare panels (c) and (d) in Fig. 2). Volume charge density and surface charge density remain constantly high along the track of the surface flashover even if the flashover edge is millimeters away.

The surface flashover velocity on the parallel LID interface depends strongly on the applied voltage peak, while the shape of the flashover is not appreciably affected by the voltage peak. Instead, the flashover shape is most influenced by LID permittivity as shown in Fig. 3. The streamer is reluctant to attach to parallel LIDs whose permittivities are lower than oil, even if it propagates through an extremely narrow bore. The main difference between parallel PTFE and SF₆ interfaces is that the streamer does attach to the PTFE surface under applied voltages with peaks higher than 250 kV in a bore with diameters smaller than 0.1 mm (Fig. 3, part (b)). If the applied voltage peak is not high enough, the flashover dissociates from the PTFE surface and returns to streamer mode after initial attachment (Fig. 3, part (a)). Streamers immediately attach to the parallel pressboard surface and remain in surface flashover mode steadily keeping a similar shape over time for different applied voltage peaks (Fig. 3, part (c)).

The behavior of a streamer at the LID interface can be justified using the method of images⁶ for interfaces with different permittivities. Since a streamer carries a significant amount of free charge, the force on the streamer due to the LID interface can be assumed to be produced by the electric field from the image charge in the LID that is proportional to the permittivity difference between transformer oil and LID, $\epsilon_{LID} - \epsilon_{Oil}$. If the LID permittivity is higher than oil ($\epsilon_{LID} - \epsilon_{Oil} > 0$), then the electrical force pulls the free charge (streamer) towards the interface (attraction). On the other hand, if the LID permittivity is lower than oil ($\epsilon_{LID} - \epsilon_{Oil} < 0$), the surface (image charge) repels the free volume charge in the oil (streamer), regardless of the free charge's polarity.⁶

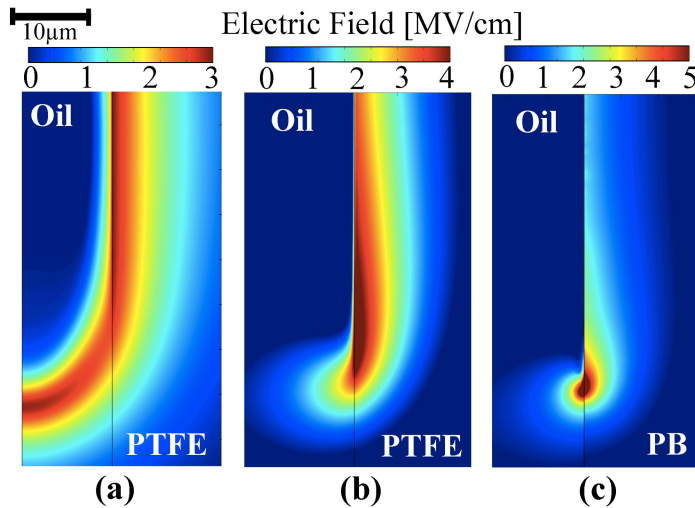


FIG. 3: Electric field distribution for flashovers expanding on the parallel LID surface under positive applied impulse voltage with (a): 200 kV peak and (b,c): 400 kV peak all with 0.1 μ s rise-time. Panels (a) and (b) show surface flashover on PTFE and panel (c) shows surface flashover on a pressboard interface. At all panels, the flashover edge is about 1 mm from the needle tip.

Figure 4 shows the electric field magnitude distribution at the perpendicular LID surface 1 mm from the needle tip under applied impulse voltage peaks of 130 kV (top), 200 kV (middle) and 400 kV (bottom) for pressboard (left panel) and SF₆ (right panel). The surface flashover is faster and thicker at higher applied voltages for different LIDs. In oil-only systems, the streamer column diameter is prominently sensitive to the applied voltage amplitude²; however, the thickness of the flashover formed at 400 kV is only about 2-3 times thicker than the 130 kV surface flashover for different LIDs as can be seen in Fig. 4. Instead, the surface flashover thickness and expansion velocity are greatly influenced by the permittivity difference across the interface such that the flashovers on the SF₆ interface are approximately 5 times thicker and 5 times slower than the flashovers that propagate on the pressboard surface formed by the same applied voltage amplitudes (Fig. 4). These are again caused by the fact that different LIDs apply different forces (due to $\epsilon_{LID} - \epsilon_{Oil}$) to the free volume and surface charge densities.

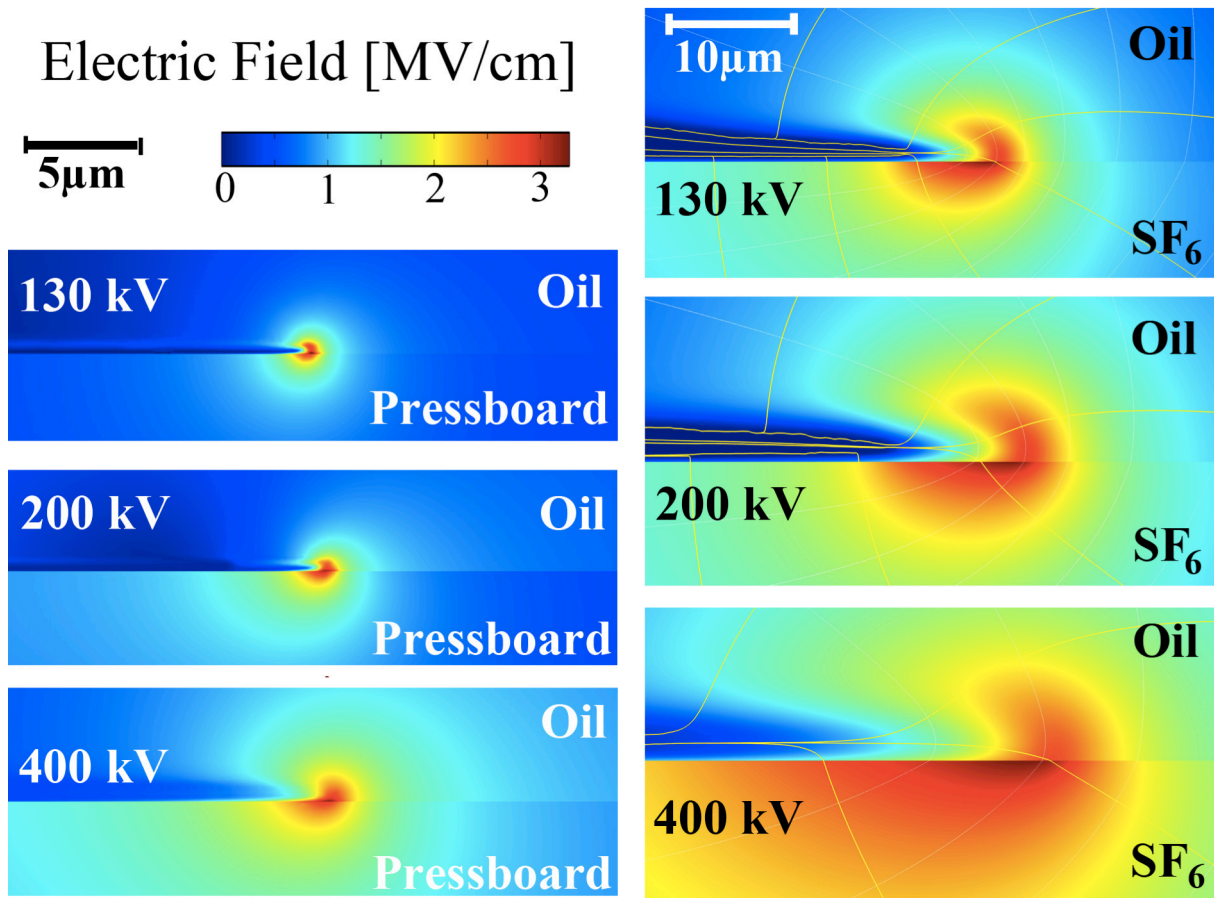


FIG. 4: Electric field distributions at the perpendicular interfacial LID surfaces 1 mm from the needle tip for applied voltages with 130 kV (top), 200 kV (middle) and 400 kV (bottom) peaks and 0.1 μ s rise-time. Left panel shows the oil-pressboard interface with size scale of 5 μ m for all three sections. Right panel shows oil-SF₆ interface with size scale of 10 μ m for all three sections. All surface flashover edges are 0.25 mm from the axis of symmetry.

At those points on the interface that the surface flashover has not reached yet, the electric field must be determined by the difference in permittivity, meaning that the electric field has to be higher at regions with lower permittivity.⁶ This is in agreement with results shown in Fig. 4, since the electric field magnitude is appreciably higher in the oil region at the pressboard interface and is higher in the LID region at SF₆ interfaces. However, at the surface flashover track (points where

the surface flashover edge has already passed), the electric field in the near field is dominated by oil volume and LID surface charge densities. The electric field generated by the surface charge superposes with the background electric field and results in a higher electric field on the perpendicular LID surface.

Figure 5 shows surface flashover trajectories on the perpendicular SF_6 and pressboard surfaces. Regardless of configuration of the LID, line integral of the electric field on any path connecting the electrodes has to be constant, equal to potential drop across the electrodes. Therefore, the higher the LID permittivity, the higher the electric field and the higher the ionization rate in the oil region. Consequently, in the presence of perpendicular pressboard, volume charge formed in the oil increases (even though the streamer is narrower, the volume charge density is still much higher) that increases the streamer velocity. On the other hand, a smaller LID permittivity lowers the electric field and ionization rate in the oil and creates less volume charge and smoother streamer heads, which result in slower streamers hitting the SF_6 surface. Furthermore, based on the method of images, LIDs with lower and higher permittivities than oil repel and attract the streamer head, respectively⁶, which is an additional cause of the difference in streamer head velocity towards different perpendicular LID interfaces. Accordingly, the higher the perpendicular LID permittivity, the greater the surface flashover velocity as shown in Fig. 5 (a) and (b). Surface flashovers on the perpendicular LID interfaces formed by higher voltages require much longer times and larger distances from the point that the streamer hits the interface (on the axis of symmetry) to slow down and eventually stop as shown in Fig.5.

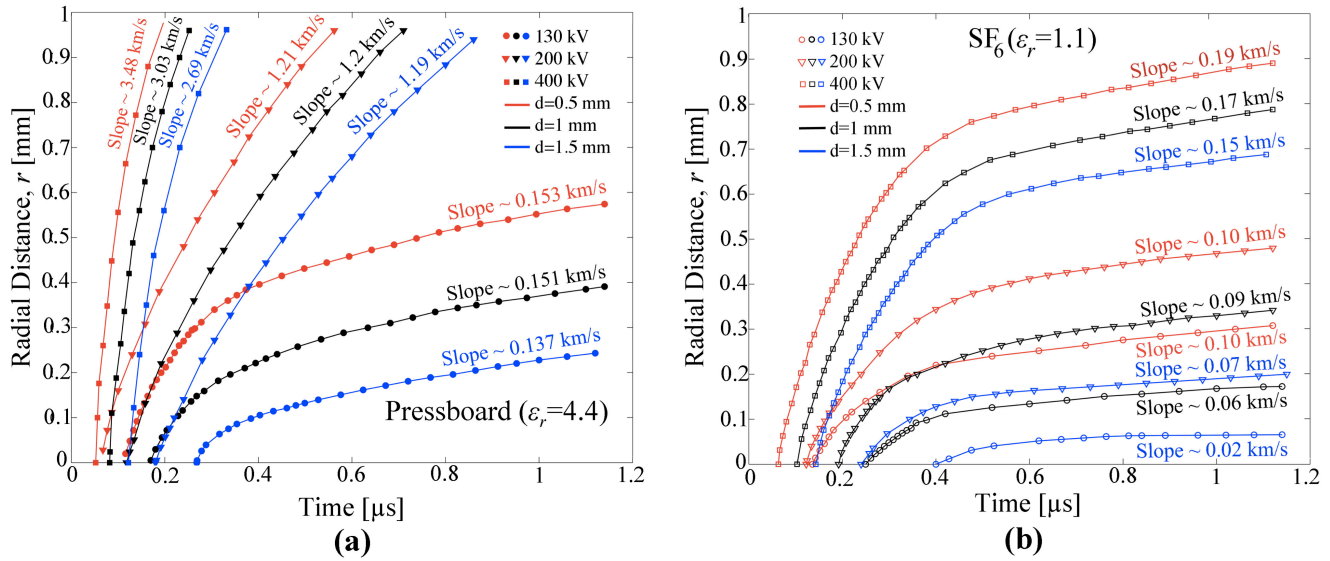


FIG. 5: Surface flashover edge trajectories on the perpendicular LID surface against time for (a): pressboard with $\epsilon_r = 4.4$ and (b): SF_6 at 5 bar with $\epsilon_r = 1.1$ (b). “d” is the distance of the perpendicular interface from the needle tip.

As shown in Fig. 6, the velocity of streamers on the parallel interface is regulated such that the surface flashover expands with approximate constant velocities along the interface regardless of the extent of the LID. In the oil-only system, however, the streamer velocity is subject to dramatic changes.² The streamers, in oil-only systems, become continuously narrower as they propagate toward the sphere electrode that results in higher local electric fields, higher charge generations and eventually higher velocities that are continuously increasing. Despite streamer mode, in the surface flashover mode, the charge density at the surface flashover edge remains almost constant as it propagates along the parallel interface, which results in an approximately constant surface flashover velocity. This is particularly true for those cases that secondary

electron emission can be ignored such as LIDs. Secondary electron emission plays an important role in surface flashover propagation on solid dielectric interfaces with gaseous dielectrics and especially vacuum.⁷

The constant velocity of the surface flashover on the parallel LID interface slightly increases as the applied voltage peak increases. The LID permittivity has small effects on the flashover velocity especially at higher voltages (>200 kV). According to Fig. 6, even if the streamer never attaches to the parallel LID interface, it still travels with approximately constant velocity within the concentric bore (constant velocity region) under the influence of the charge build up on the LID surface. In other words, if the streamer is forced to travel within a bore in the LID, whether it attaches to LID or not, the streamer velocity is regulated. The constant velocity of streamer trapped in the bore is caused by the fact that the streamer head retains its radius of curvature and the surface charge distribution pattern on the adjacent parallel LID interfaces also remains the same. The constant velocity region within the concentric parallel bore can be used as an interesting feature to design low jitter closing switches.

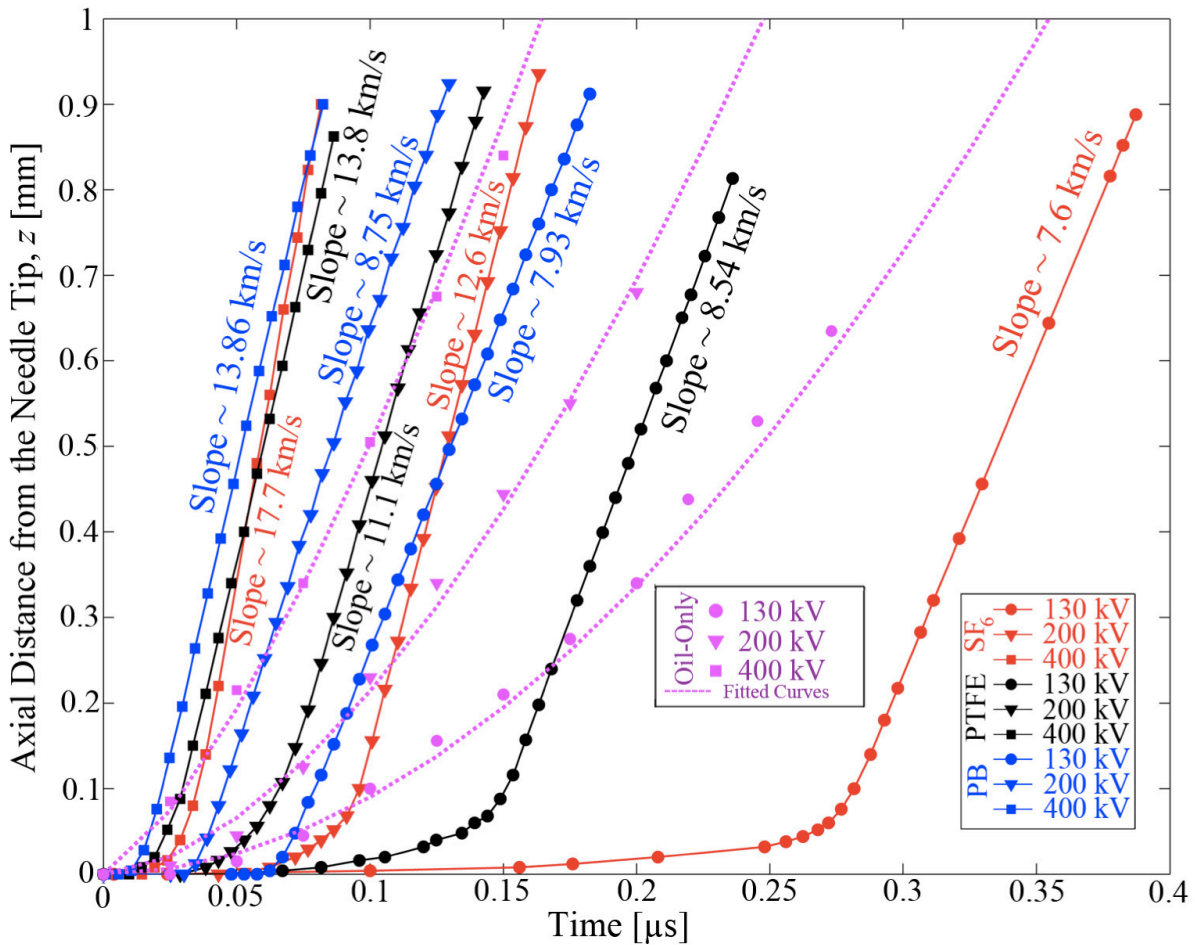


FIG. 6: Surface flashover edge trajectories on the parallel LID surface against time under applied impulse voltage with 130 kV, 200kV and 400 kV peaks and 0.1 μ s rise-time. Purple markers and dashed curves show streamer head positions in oil-only system adapted from ². Time $t=0$ corresponds to the time that streamer reaches the parallel LID interface. Purple dotted curves are fitted polynomial expressions as $1.8 \times 10^{12} t^{1.9}$, $1.7 \times 10^{11} t^{1.7}$ and $2.3 \times 10^9 t^{1.38}$ [mm] for streamers formed by 130 kV, 200 kV and 400kV, respectively in oil-only systems which are valid for $t < 1 \mu$ s.

This paper only discusses the surface flashovers formed by positive impulse voltages. The negative surface breakdown mechanisms are essentially similar to the positively formed surface discharges and can be explained based on the knowledge acquired by study of positive surface discharges. Negative surface flashovers expand almost two times slower than the positive flashovers, which is similar to the difference between positive and negative streamers propagation velocities in oil-only systems.² The modeling results can be obtained without much effort for other liquid dielectrics, such as other hydrocarbon liquids, ester and water, other LIDs or any other complicated geometry of LID interfaces.

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