Modeling a Liquid-Solid Insulation System Used in a DC Wet-Mate Connector

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***Abstract*- Subsea DC transmission and distribution system is a promising technology for powering subsea oil and gas fields with high power, long distance and ultra-deepwater depth. DC connectors as the interface between cables and electrical power component and loads in such a system play a key role. An electrodynamic model is developed in this paper to study charge transport phenomena in a DC wet-mate subsea connectors. The oil-solid insulation system of WM chamber contains the mineral oil enclosed by the solid dielectric and the electrodes covered by the solid dielectric. This complicated hybrid insulation system placed in a cylindrical electrode geometry is simulated in this paper. It is shown that the oil can be susceptible to streamer initiation and development. Moreover, it will be discussed that the free space charge carriers traveled to the interface between the oil and solid dielectric and converted to the surface charges may increase the electric field norm across the solid dielectric.**

I. Introduction

The subsea DC transmission and distribution system installed on the seabed is a promising technology for powering subsea oil and gas fields with high power of up to the 100 MW range, from a long distance of up to the 100 km range and in ultra-deepwater (UDW) depths of up to 3,000 m [1]. However, going subsea brings many challenges e.g. an increase in pressure of 10 bar/100-m depth, salt water is very corrosive and is also a conductor. Reliability is the main design criterion because the equipment should bring to the surface for maintenance that is very costly and may lead to long production outages. Hence, the system must be designed to operate without maintenance for a long period of time e.g. at least 20 years [1].

DC connectors as the interface between cables and the electrical power component and loads in such a system play a key role. Wet-mate connectors allow only the faulty module to be retrieved for repair while the other modules remain in operation. Thus, downtime for the complete subsea station reduces and the use of intervention vessels with lower-rated lifting equipment may be allowed. However due to the conductivity of salt water, the successful performance of a wet-mate connector in salt water is quite difficult to achieve. Currently there are no wet-mate DC connectors commercially available to satisfy the need for future subsea DC systems.

The insulation system as well as electrode geometry of a DC WM connector are complex and to the best of our knowledge, an electrodynamic model for this component to study the streamer development and charge transport phenomena has not been elaborated so far. Moreover, its oil-solid insulation system is further complicated with the presence of moisture and ionic contaminants.

II. Mathematical Model

The fundamental equations of the electrodynamic model include Poisson's equation and the charge continuity. Before discussing these equations, we should first formulate sink and source terms for the free charge carriers. The free charge carriers in a dielectric liquid can be either electronic or ionic in nature. Three mechanisms may lead to an increase in the free charge carrier concentration in a dielectric liquid when electrically stressed. They are: 1) Field emission, or Fowler Nordheim charge injection from the cathode [2-4], 2) Electric field dependent ionic dissociation [5-8], and 3) Electric field dependent molecular ionization [9-11].

Based on the simulation results presented in [12-14] neither Fowler-Nordheim charge injection or electric field dependent ionic dissociation play a dominant role in the initiation and growth of streamers in transformer oil. However, the simulation results generated using the full electric field dependent molecular ionization model in [13-15] indicated that the model effectively encapsulates the vast majority of the physics associated with streamer development in transformer oil. Therefore, the full electric field dependent molecular ionization model developed in [13-15] is used in this paper to study charge carriers transport in a DC wet-mate connector.

The molecular ionization process results in the generation of two free charge carriers from one neutral species where the mobility values of the two carriers differ greatly, with the electrons having a mobility value that is five orders of magnitude greater than that of the positive ions. This asymmetry in the generated carriers' mobility values means that molecular ionization leads to the formation of significant net space charge densities in electrically stressed dielectric liquids.

Charge density rate source term due to the process of molecular ionization in dielectric liquids such as transformer oil for inclusion in the positive ion and electron charge continuity equations is given by [13-16]

$$G_I\left(\left|\vec{E}^l\right|\right) = \frac{e^2 n_0 a \left|\vec{E}^l\right|}{h} \exp\left(-\frac{\pi^2 m^* a \Delta^2}{e h^2 \left|\vec{E}^l\right|}\right) \qquad (1)$$

where $e = 1.602 \times 10^{-19}\ C$ is the magnitude of electronic charge, $a = 3.0 \times 10^{-10}\ m$ is the molecular separation, $|\vec{E}^l|$ is the magnitude of the electric field in the liquid dielectric. Superscript "l" denotes that the variable exists in the liquid insulation, $h = 6.626068 \times 10^{-34}\ m^2 kg/s$ is Planck's constant, $m^* = 0.1 m_e = 9.1 \times 10^{-32}\ kg$ is the effective electron mass in the liquid, Δ is the molecular ionization potential and n_0 is the number density of ionizable molecules.

Free positive ions and electrons produced due to molecular ionization can interact with each other and the surrounding media leading to the possibility of electron/ion recombination, electron attachment to neutral species to form negative ions and ion/ion recombination. Positive/electron recombination rate, $R_{\underset{e}{+}}$, and positive/negative ion recombination rate, $R_{\pm}$, are given by [13-16]

$$R_{\underset{e}{+}} = R_{\pm} = \frac{e(\mu_+ + \mu_-)}{\epsilon_0 \epsilon_r} \tag{2}$$

where the mobility values of positive and negative ions are $\mu_+ = \mu_- = 1 \times 10^{-9}\ (\mathrm{m^2/V.s})$ [7]. $\epsilon_0 = 8.85 \times 10^{-12}\ F/m$ is the permittivity of vacuum and ϵ_r is the relative permittivity. For transformer oil with $\epsilon_r = 2.2$, $R_{\underset{e}{+}} = R_{\pm} = 1.64 \times 10^{-17}\ \mathrm{m^3/s}$ as used in [13, 14].

Electron attachment is modeled via an attachment time constant [17] with a value of $\tau_a = 200$ ns for transformer oil [13-16].

Now the full electrodynamic model for electric field dependent molecular ionization comprised of Poisson's equation and three charge continuity equations, one each for the positive and negative ions and one for the electrons is as follows:

$$-\nabla.(\epsilon_0 \epsilon_r \nabla V) = \rho_+^l + \rho_-^l + \rho_e^l, \quad \vec{E}^l = -\nabla V \tag{3}$$

$$\frac{\partial \rho_+^l}{\partial t} + \nabla.\vec{J}_+^l = G_I(|\vec{E}^l|) + \frac{\rho_+^l \rho_e^l R_{\underset{e}{+}}}{e} + \frac{\rho_+^l \rho_-^l R_{\pm}}{e}, \quad \vec{J}_+^l = \rho_+^l \mu_+ \vec{E}^l \tag{4}$$

$$\frac{\partial \rho_e^l}{\partial t} + \nabla.\vec{J}_e^l = -G_I(|\vec{E}^l|) - \frac{\rho_+^l \rho_e^l R_{\underset{e}{+}}}{e} - \frac{\rho_e^l}{\tau_a}, \quad \vec{J}_e^l = -\rho_e^l \mu_e \vec{E}^l \tag{5}$$

$$\frac{\partial \rho_-^l}{\partial t} + \nabla.\vec{J}_-^l = \frac{\rho_e^l}{\tau_a} - \frac{\rho_+^l \rho_-^l R_{\pm}}{e}, \quad \vec{J}_-^l = -\rho_-^l \mu_- \vec{E}^l \tag{6}$$

where ρ_+^l, ρ_-^l and ρ_e^l are the density of the positive ion charge, the negative ion charge and the electron charge in liquid dielectric, respectively. The negative ion and electron charge densities are both negative quantities. The sum of the right-hand sides of Equations (3)-(6) is zero showing conservation of charge requires.

Solid dielectric is modeled as a perfect insulator with zero conductivity. Therefore, the conduction current in the solid dielectric is zero, $\vec{J}^s = 0$, and the total current is only displacement current. Superscript "s" denotes that the variable exists in the solid insulation. Due to the zero conductivity of the solid insulator, all volume charges (positive ion ρ_+^l, negative ion ρ_-^l, and electron ρ_e^l) in the liquid that travel to the interface are converted to a surface charge density ρ_s. Therefore at the liquid-solid interface, an added governing equation accounts for the surface charge density ρ_s, whose time derivative is equal to the difference in normal conduction currents on either side of the interface

$$\frac{\partial \rho_s}{\partial t} = \vec{n}.(\vec{J}^l - \vec{J}^s) = \vec{n}.(\rho_+^l \mu_+ - \rho_-^l \mu_- - \rho_e^l \mu_e)\vec{E}^l \tag{7}$$

where $\vec{n}$ is the outward normal vector from the liquid side.

Based on Gauss' Law the difference in normal displacement fields on either side of the interface is equal to the surface charge density as well

$$\rho_s = \vec{n}.(\vec{D}^s - \vec{D}^l) \tag{8}$$

Equations (3)-(8) formulate the electrodynamic model developed in this paper to simulate a DC WM chamber.

III. Simulation Results

Fig. 1a shows the typical structure of a subsea connector comprising cable termination chambers and a WM chamber. Fig. 1b shows the mechanism of WM connector where there are very complicated solid-liquid insulation systems in unmated and matted positions.

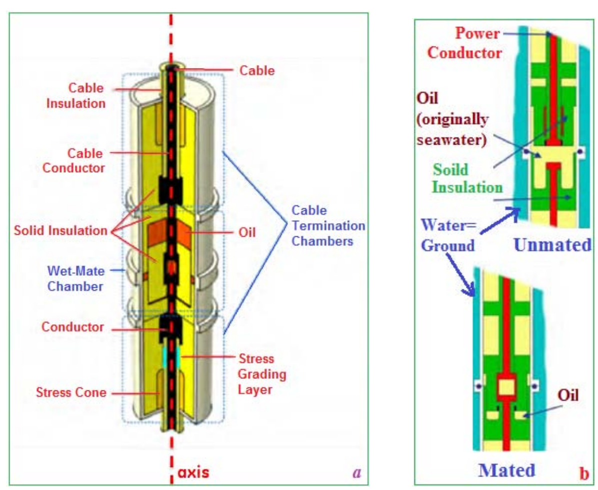

Fig. 1. a) a typical structure of a subsea connector, b) WM connector in unmated and matted positions.

For the cylindrical electrode geometry shown in Fig. 2a consisting of a inner conductor of radius a and an outer conductor whose inner radius is b and the space between the conductors filled with a dielectric of permittivity ϵ, the $\vec{E}$ field in the $a < r < b$ region is given by

$$\vec{E} = \frac{V_{ab}}{r \ln(b/a)} \quad (9)$$

This means that the $\vec{E}$ field is not constant in the dielectric and depends on r. Hence, the laboratory investigations by the simplified geometries e.g. a plate-plate electrode geometry having a uniform electric field between electrodes or even sphere-plate/needle-sphere/needle-plate electrode geometries having non-uniform electric fields which are likely different form it in a cylindrical electrode geometry cannot reproduce the $\vec{E}$ field in a WM chamber. On the other hand providing the cylindrical electrode geometry and oil-solid insulation system as a WM chamber for laboratory investigations is not a trivial task. The accurate mathematical model developed in this paper can provide a powerful tool to assess electrical insulation performance of a WM chamber.

For a 100 MW, ±100-kV HVDC submarine cable, a current of 0.5 kA flows in each conductor and hence a 350 mm^2 (r=10.555 mm) copper conductor can be considered for each conductor. Fig. 2b shows the $\vec{E}$ field in a cylindrical electrode geometry considered as an axial symmetry (2-D) geometry with $a = 10.555\, mm$, $b = 50.555\, mm$ and $L = 40\, mm$ where the transformer oil with $\epsilon_r = 2.2$ was considered between electrodes and Equations (3)-(6) implemented in COMSOL Multiphysics were used to solve the problem. Since the model is driven mainly by convection rather than diffusion, a stabilization strategy is needed to prevent numerical instabilities. It was found that using both consistent stabilization methods, streamline together with crosswind stabilization, provides the optimal stabilization strategy that leads to physically acceptable solutions with less computational loads and time.

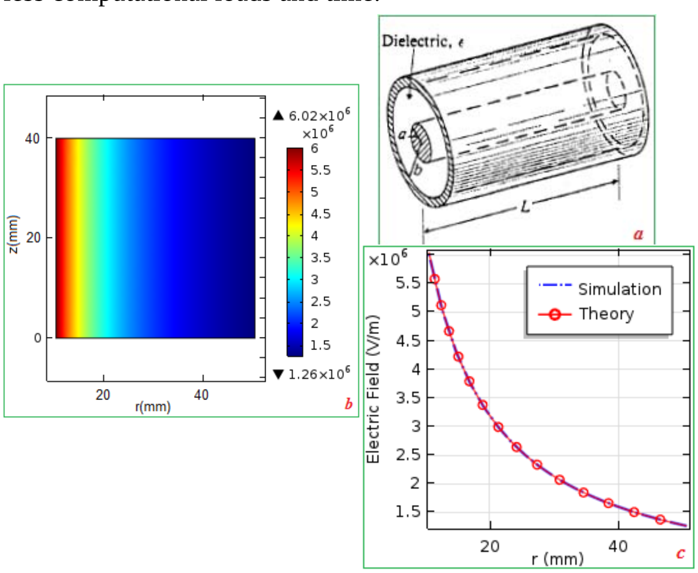

Fig. 2. a) cylindrical electrode geometry, b) the $\vec{E}$ field obtained by simulation and c) the $\vec{E}$ field resulted from simulation (across z=20 mm) and theory.

Fig. 2c shows the electric field norm across z=20 mm obtained from the model. In Fig. 2c the electric field, $\vec{E}$, resulted form Equation (9) has been shown. It can be seen in Fig. 2c that there is a good agreement between simulation and theory results. In this simple geometry the maximum $\vec{E}$ field, 6×10^6 V/m, is less than the minimum value required to initiate and grow a streamer in the transformer oil. For positive streamers, minimum field levels for streamer initiation are on the order of 1×10^8 V/m [10, 18].

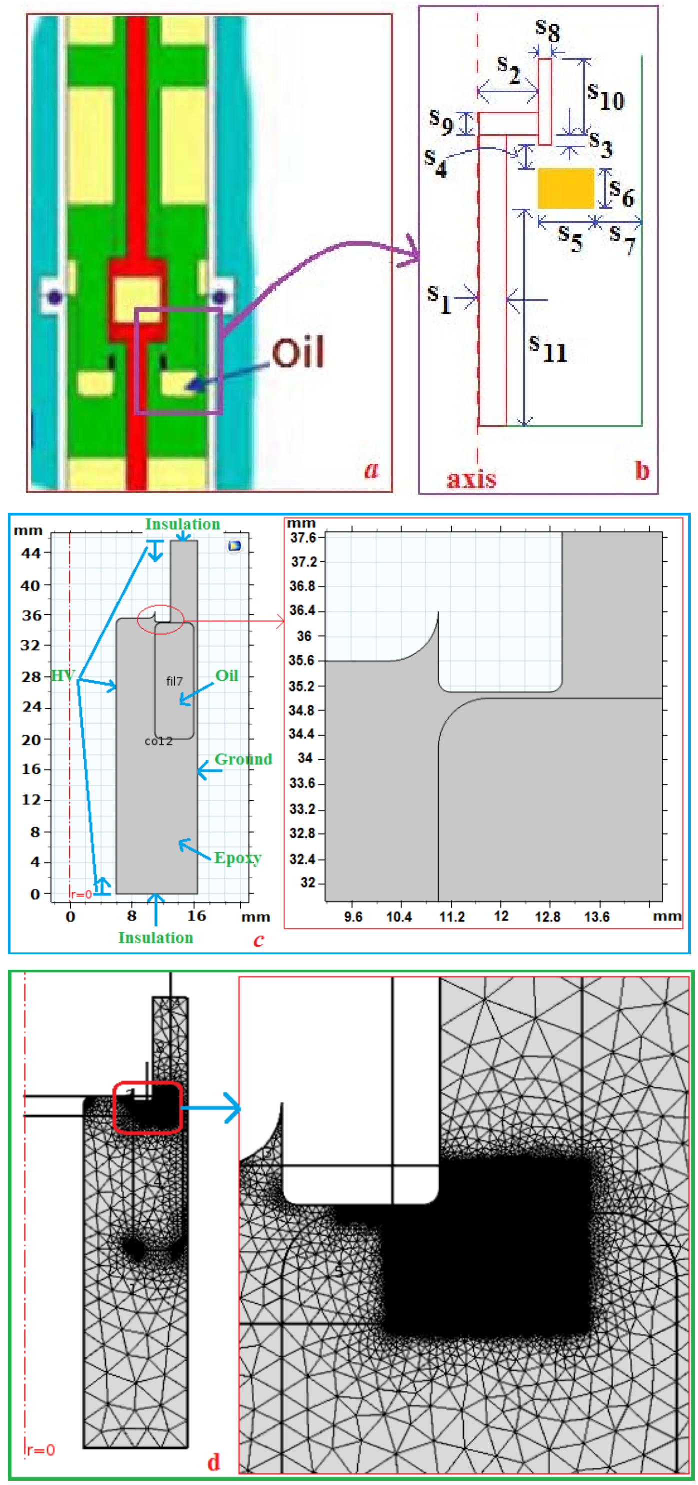

Fig. 3. The considered geometry for simulations.

Fig. 3a shows a part of the complicated geometry of WM chamber used for the simulations in COMSOL Multiphysics. Transformer oil is enclosed by solid dielectric and electrodes are covered by solid insulator. In oil-solid systems studied by mathematical models or laboratory investigations so far, high non-uniform electric fields lead to initiate and propagate streamers in the transformer oil which is in contact with the electrodes. Solid insulators added to this system are placed either as perpendicular oriented interface [19, 20] or as parallel oriented interface [21-25]. In the geometry considered in Fig. 3a for simulation, the solid dielectric covers the electrodes and thus can impede the streamers initiated from them. Here there is a key question. Will it (covering the electrodes by solid dielectric) be sufficient to prevent streamer's initiation and propagation in the transformer oil? This question is addressed in this paper.

The dimension values are considered to assess a critical compact design. Fig. 3c shows the geometry modeled in COMSOL where the sharp edges of the electrodes were replaced with the curves with appropriate radii. Fig. 3c shows the mesh structure considered for simulation. To capture the dynamic of streamers, a very dense mesh is needed across the propagation area. These areas can be indentified from preliminary simulations. Such meshing demands very large memory resources and needs long simulation run-times. Here they are areas 1 and 2 as seen in Fig. 4. A DC+ voltage was applied to HV electrode at t=0 s.

Fig 4 shows the electric field norm obtained from simulations at t=1 µs. At this time the electric field norm reaches to a maximum of 2.53×10^8 V/m around the right edge of HV electrode where the distance between HV conductor and ground electrode is minimum. It can also seen that the electric field norm in the transformer oil ($\epsilon_r = 2.2$) is higher than 1×10^8 V/m. Therefore, we can expect the initiation and propagation of the streamer in the oil as seen in Fig. 5 as the net space charge density ($\rho_v = \rho_+^l + \rho_-^l + \rho_e^l$) in the oil. The initial values (at t=0 s) of ρ_+^l, ρ_-^l and ρ_e^l were assumed to be zero.

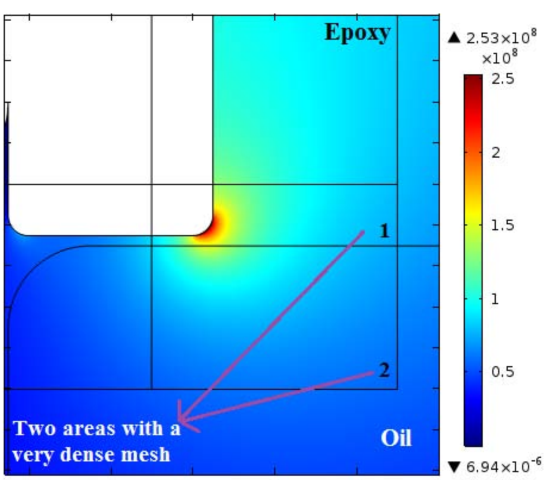

Fig. 4. The electric field norm at t=1 µs.

The electrons and the positive and negative ions are generated by electric field dependent molecular ionization mechanism used in this paper. The sign of net space charge density is positive since the mobility of the electrons is five orders of magnitude greater than it of the positive and negative ions. Therefore, the electrons travel toward HV electrode in the oil while the positive and negative ions can be considered almost motionless. The negative ions are generated due to a secondary mechanism, the attachment. This leads to a less density of the negative ions than the positive ions density in the oil.

Fig. 6 shows the net space charge density at t=0.1 µs. From Figs. 5 and 6, it can be seen that the magnitude of the net space charge density and its area increase over time showing streamer growth.

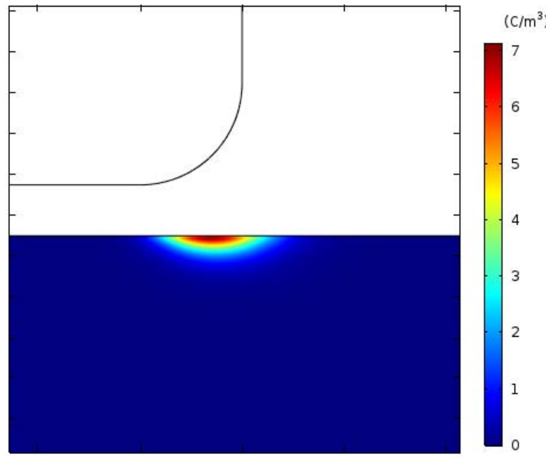

Fig. 5. The net space charge density at t=1 µs.

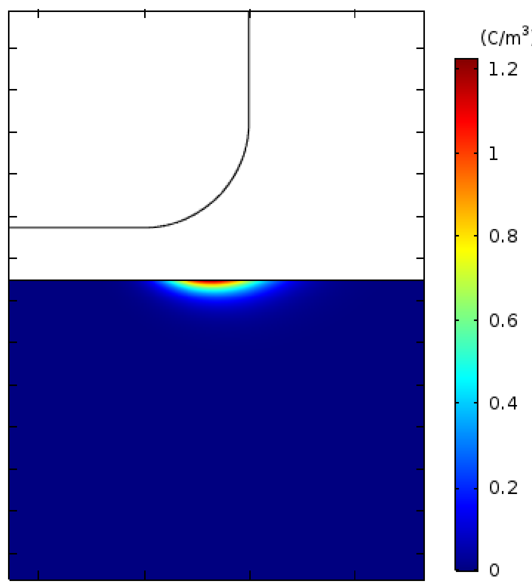

Fig. 6. The net space charge density at t=0.1 µs.

The three free charge carriers generated by the model in the oil travel toward the interface and are converted to surface charges. Fig. 7 shows the surface charge density along the path shown at t=0, 25, 50, 75 and 100 ns. At t=0 there is no space free charge carriers in the oil and thus no surface charge density. For later times it can be seen the electrons generated in the oil travel to the part of the interface close the right edge of the HV electrode where the electric field norm is maximum. The magnitude of the surface charge density increases over time showing more molecular ionization activities in the oil. This point has also been shown in Fig. 8 for t=100, 250, 500, 750 and 1000 ns.

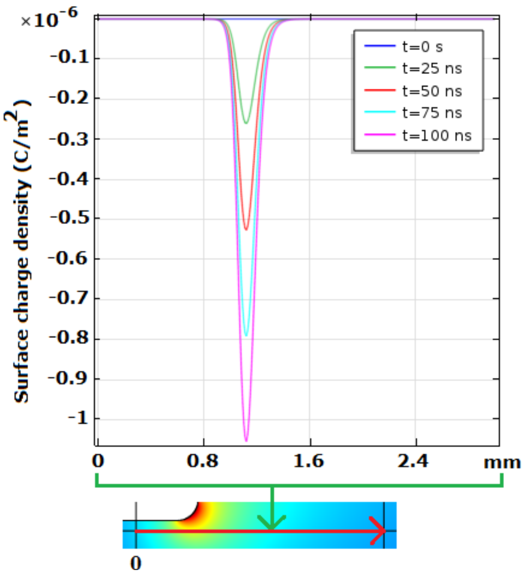

Fig. 7. The surface density along the shown path at t=0, 25, 50, 75 and 100 ns.

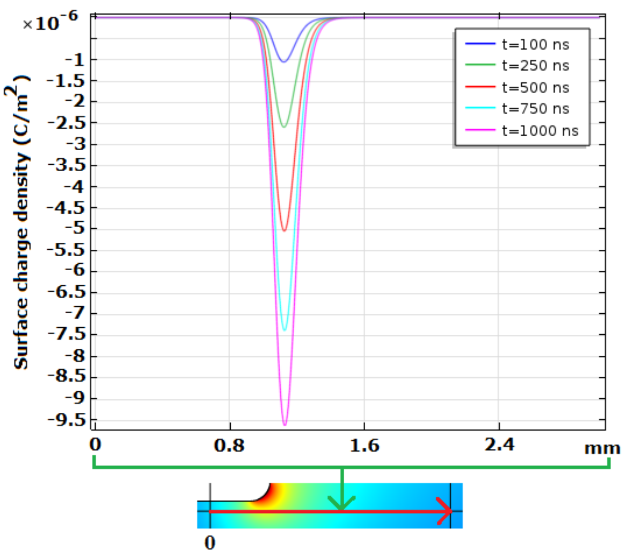

Fig. 8. The surface density along the shown path at t=100, 250, 500, 750 and 1000 ns.

It should be noted that a value of 1×10^8 V/m of the electric field norm is the minimum value to initiate streamers in transformer oil. In this case it is about this value and thus as seen in Figs. 5-9 the amplitude of space charge densities and surface charge densities are not significant to lead to notable propagation of streamers. Generally, a value of 3×10^8-5×10^8 V/m of the electric field norm in the transformer oil can cause considerable growth and propagation of the streamers [13].

On the other hand, in the clean environmental type of WM connector, seawater is enclosed in the WM chamber during connecting the two halves of the connector mechanically. Then the chamber is flushed with various processing fluids and eventually filled with dielectric oil [26]. However, it is impossible to remove all seawater molecules containing dissolved salt (sodium chloride) and other minor ionic species form chamber. Actually, there is moisture and ions during normal operation of a WM chamber [26].

Numerous experimental and theoretical researches have been devoted to study impact of water contents on transformer oils and pressboards. It is a complex issue to be addressed because it depends on other parameters e.g. temperature, age of oil, type of oil, gap distance and geometry of electrodes and thus exploring the researches with similar conditions to those in a WM connector is not a trivial task. For example it was shown in [27] that by increasing water contents from 10 ppm to 40 ppm in a new mineral oil with $\epsilon_r = 2.2$, the breakdown voltage decreased from 65 kV to 19 kV (a remarkable decrease of 70%) at 20ºC. A spherically-capped shape electrode geometry with a gap distance of 2.5 mm was used in the tests. A systematic laboratory investigation is carrying out in our center at UConn to address this issue for the WM chamber conditions.

The mentioned notable decrease of breakdown voltage leads to this key result that the minimum electric field norm required to initiate and propagate streamers in the mineral oil having some water contents should be less then 1×10^8 V/m. To the best of our knowledge, it has not been reported so far and further theoretical and experimental research is needed. Then the model parameters can be adjusted to able to simulate the initiation and propagation of streamers for this situation.

Increasing the surface charges trapped on the interface may increase the electric field norm across the solid dielectric as shown in Fig. 9 schematically. This increases the probability of punching and failure of the solid dielectric especially over time. In the case simulated in this paper, the amplitude of the surface charge density shown in Figs. 7 and 8 is too small to increase the electric field norm across the solid dielectric. However, for the oil containing seawater, with less electric field norm required to initiate and propagate streamers as discussed above, the surface charge density may be notable. Further theoretical and experimental study is undertaken in our lab to address this issue.

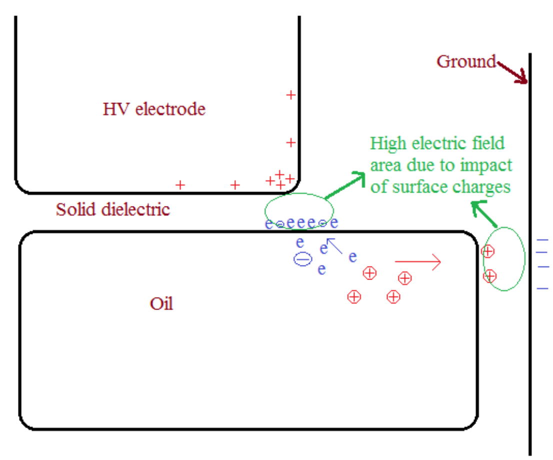

Fig. 9. The impact of the surface charges on the electric field norm across the solid dielectric.

IV. CONCLUSION

In this paper a mathematical model was developed to study the initiation and growth of the positive streamers in the clean environmental design of a WM connector. The model is based on the electric field dependent molecular ionization mechanism as the most dominant mechanism for streamer development in the mineral oil. The geometry of the WM chamber considered for simulation is a complicated oil- solid insulation system placed in the cylindrical electrode geometry where the oil is enclosed by solid dielectric after mating as well as the electrodes covered by solid dielectric. The simulation results showed that despite of covering the electrodes by the solid dielectric, the initiation and growth of streamers in the oil is possible. The transport of the generated free charge carries in the oil toward the interface between the oil and solid dielectric and converting them to surface charges may increase the electric field norm across the solid dielectric.

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