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Analysis of the Effect of Electrode Configuration on the Dielectric Behavior of Transformer Oils

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ABSTRACT

Due to the aging of transformers during their service life, the dielectric resistance of transformer oils decreases. This dangerous situation, which may cause major power outages, needs to be analyzed well in detail. Transformer oils start to deteriorate due to the high electric field between the electrodes. The sharp points on the electrodes accelerate this deterioration process. Therefore, by correctly analyzing the effect of the electrodes on the oil, information about the insulation resistance of the liquid dielectric material can be obtained. In this study, electric fields and potential difference changes of transformer oil under uniform and non-uniform electric fields are investigated. Sphere–sphere electrode configurations were used to provide uniform field, sphere–rod, and rod–rod electrode configurations for non-uniform field effect. With the increase of the non-uniform field effect, higher electric field stress occurred in the transformer oil at the same voltage level.

***Index Terms*—**Dielectric, electric field, electrode configuration, insulation performance, transformer oil.

I. INTRODUCTION

It is very important that transformers, which are frequently used in almost every part of electrical transmission and distribution systems, provide a proper service. Uninterrupted energy is one of the most important issues that need to be emphasized in order for the economic wheels of a country to turn. The uninterrupted supply of energy by transformers, which have a critical role and area of use in delivering electrical energy to users, both increases users' comfort and prevents possible financial losses.

Regardless of the voltage level, a large number of different types of insulators are used in the systems while transmitting electrical energy [1]. The fact that these insulators start to lose their dielectric properties creates a serious problem [2]. Therefore, the insulation performance of dielectric materials should be well-measured. The dielectric resistance of the liquid dielectric materials used in transformers is one of the most important parameters that determine the service life of the transformer [3,4]. Transformer oils, which are generally petroleum-based, age as a result of high electric field stress and environmental stresses [5,6]. In particular, field stress can accelerate ionization and create a completely conductive bridge between the electrodes [7,8]. Therefore, the oil will completely breakdown electrically and the transformer will be out of service.

During the evaluation of dielectric strength in insulating fluids, it is common practice to conduct various analyses, including fractal analysis. The implementation of such analytical techniques enables a meticulous examination of channel discharge within the oil, facilitating comprehensive assessments concerning the overall condition of the oil [9]. While it is customary to carry out this form of analysis under impulse voltage conditions, it is crucial to acknowledge that transformers operate under alternating current (AC) voltage [10]. Consequently, it is evident that investigations in the literature conducted under AC voltage stress encompass not only puncture resistance assessment but also measurement of partial discharges [11]. Hence, it is evident from the scholarly literature that investigations conducted under AC electric field stress yield significant evaluations pertaining to the insulation fluids of transformers [12].

Mihir Bhatt and Praghnesh Bhatt carried out a simulation by using a point-plane electrode configuration with transformer oil as the insulating medium [13]. The applied voltages were either

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direct current (DC) or AC, and the polarity of the voltage was either positive or negative. The results showed that the polarity of the voltage had a significant effect on the streamer dynamics. The streamers propagated faster and had a longer length under positive polarity compared to negative polarity. The authors attributed this to the fact that positive streamers have a higher ionization coefficient than negative streamers. Furthermore, the study revealed that the type of voltage also affects streamer dynamics. AC voltage resulted in shorter streamer lengths and slower propagation speeds than DC voltage. The authors suggested that this was due to the fact that AC voltage has a lower average value than DC voltage.

Seghir et al. carried out experiments to measure the breakdown voltage of mineral oil used as an insulating medium in transformers. The tests were conducted using a standard oil testing cell and applying voltage in accordance with IEC 60156 standard [14] The results of the experiments showed that the breakdown voltage of the oil was affected by various factors, such as the type of oil, temperature, and humidity. The authors also found that the breakdown voltage was influenced by the rate of voltage application, with higher rates leading to lower breakdown voltages. Shen et al. present a study on the effect of electric field uniformity on the positive streamer and breakdown characteristics of transformer liquids [15]. The authors carried out experiments using a needle-plate electrode configuration and varying the electrode spacing to produce different electric field uniformities. The results of the experiments showed that the breakdown voltage of the transformer liquid decreased as the electric field became more uniform. The authors also found that the presence of positive streamers was related to the non-uniformity of the electric field. Specifically, when the electric field was more uniform, there were fewer positive streamers present.

Al-rawaf and Khalaf performed a numerical analysis of electrical streamer discharge behavior in transformer oil [16]. The authors used a two-dimensional (2D) numerical model based on the continuity, momentum, and Poisson equations to simulate the behavior of streamers in transformer oil. Specifically, the authors found that positive ions in the streamer discharge were relatively more distributed than negative ions. They also observed that the highest electric field value was recorded at the streamer head. The study carried out by Sharma et al. discusses the effect of lightning impulses on transformer oils, specifically ester oils and mineral oil [17]. The authors conducted experiments to study the breakdown strength of the two types of oils when subjected to lightning impulses of different polarities. They found that ester oils had a higher breakdown strength than mineral oil when subjected to positive lightning impulses, but the difference was not significant for negative lightning impulses. Also, it is concluded that the impulse strengths of ester oil are not comparable to those of mineral oil at various electrode gap distances from 1 mm to 20 mm in nonuniform field configurations.

The breakdown strength of dielectric fluids is contingent upon the geometric attributes of their surrounding environment. Transformer windings are configured in a circular winding structure; nonetheless, the deformation of copper within these windings over time engenders the formation of sharp points and corners. This geometric characteristic gives rise to a non-uniform electric field. Consequently, a comprehensive investigation of the geometric structure within the transformer oil environment becomes imperative. In this study, electric fields and potential difference changes of transformer oil under uniform and non-uniform electric fields are investigated. Sphere-sphere electrode configurations were used to provide a uniform field, and sphererod and rodrod electrode configurations for a non-uniform field effect. With the increase of the non-uniform field effect, higher electric field stress occurred in the transformer oil at the same voltage level.

II. COMPUTATIONAL ANALYSIS

In the scope of this paper, a 2D electrostatic analysis is performed under three different electrode arrangements. In order to simulate the uniform field a sphere-sphere electrode system was used. Also, for investigating the non-uniform field effect on transformer oil, sphere-rod and rodrod electrode systems were established in the software. The dielectric strength of transformer oil was simulated by using the COMSOL Multiphysics program by implementing experimental data. Electrode arrangements in the simulation were created in a 2D environment with the same dimensions and materials. Fig. 1 shows the system with 2D geometry separately for all electrode configurations with its dimensions in millimeters. Fig. 2 shows the implementation mesh on the geometry for all electrode configurations. In addition, in Table I, the electrical and physical parameters of transformer oil is given.

The electrostatic analysis is applied to the proposed system. The electric field causing the breakdown of the liquids is analyzed by

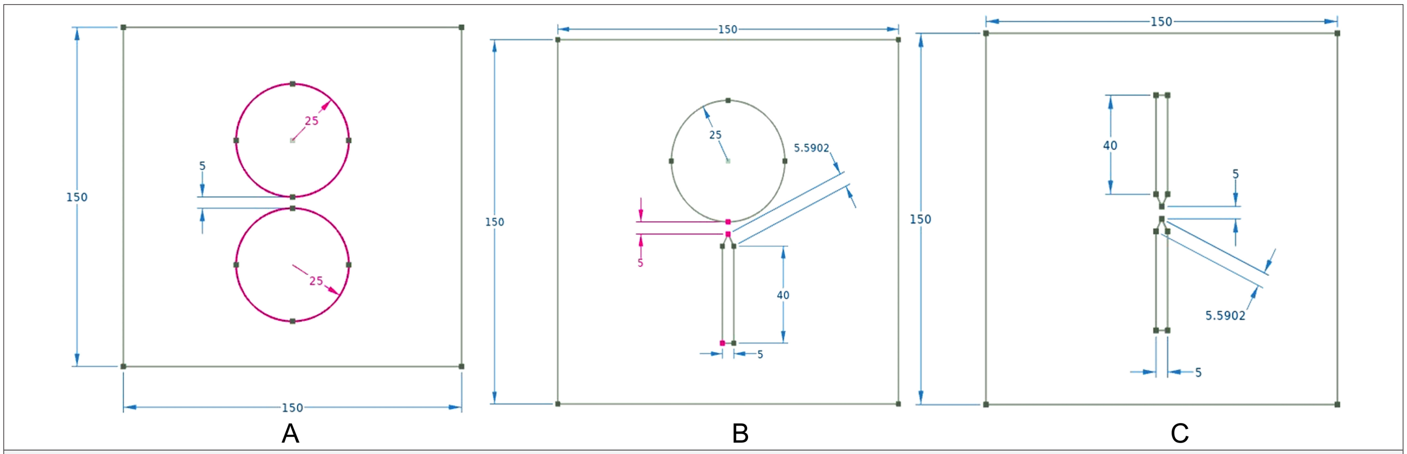

Fig. 1. Electrode configurations in 2D layout. (A) sphere–sphere electrodes, (B) sphere–rod electrodes, and (C) rod–rod electrodes.

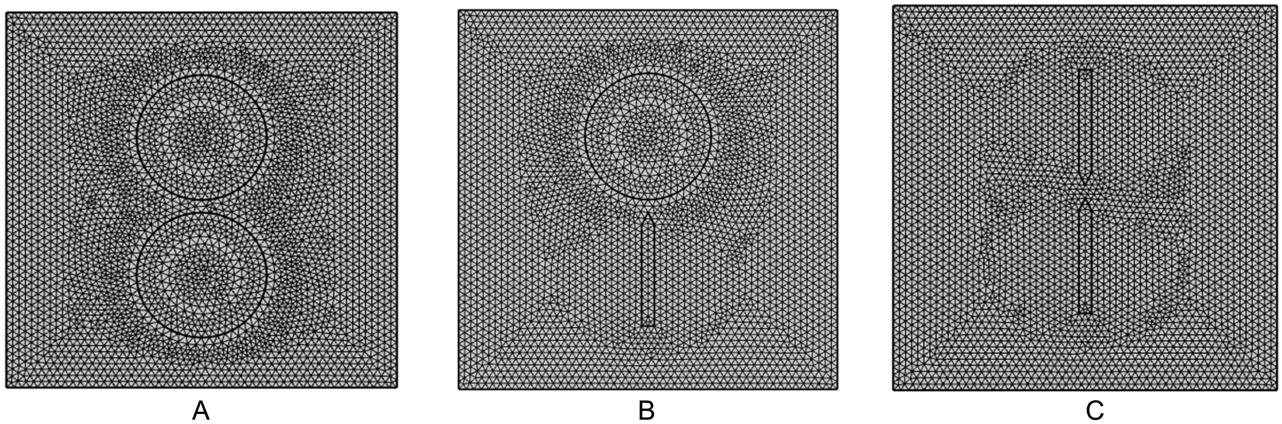

Fig. 2. Mesh implementation on the 2D layout. (A) sphere–sphere electrodes, (B) sphere–-rod electrodes, and (C) rod–rod electrodes.

TABLE I. ELECTRICAL AND PHYSICAL PARAMETERS OF TRANSFORMER OIL

Parameter/Unit	Transformer Oil
Electrical permittivity	2.2
Dielectric dissipation factor at 90°C	0.001
Viscosity at 40°C (mm^2/s)	9.5
Density at 20°C (g/cm^3)	0.87
Flash point (°C)	150
Pour point (°C)	−51
Moisture content (ppm)	6.8

applying AC voltage. The electrical potential difference in the field under static conditions is calculated as in (1) [18,19]. By writing the displacement factor, the Gauss equation is obtained by (2) [20,21].

$$E = -\nabla V \quad (1)$$

$$D = \varepsilon_0 E + P, -\nabla V.\left(\varepsilon_0 \nabla V - P\right) \quad (2)$$

where ε_0 (SI unit: F/m) is the permittivity of vacuum, ***P*** (SI unit: C/m^2) is the electric polarization vector, and ρ (SI unit: C/m^3) is a space charge density. This equation describes the electrostatic field in dielectric materials.

III. RESULTS

The analysis encompasses the examination of normalized electric field graphs and potential distribution images for transformer oil. The applied AC voltage has been set at a magnitude of 25 kV, while the distance between the electrodes has been precisely defined as 5 mm. In the laboratory condition, during an experimental investigation employing spherical electrodes, the breakdown voltage was measured as 25 kV when the ratio of the electrode distance to the sphere diameter was set to 1/10, as utilized in the simulation. This measured value was subsequently adopted as the standardized criterion across all electrode geometries within the simulation environment. It is well-established that the sphere–sphere electrode configuration, where the electric field attains the highest degree of uniformity, will exhibit the highest breakdown voltage. Consequently, applying the selected value to other electrode configurations ensures an equitable basis for comparison, thereby affirming the appropriateness of this approach. In the context of a uniform electric field, particularly in a spherical system, an electrode gap-to-diameter ratio of 10 is regarded as the optimal condition for measurements. In line with the literature and practical applications, the chosen spherical electrode possesses a diameter of 50 mm, and thus, the electrode gap for all scenarios has been adjusted to 5 mm. This distance is also implemented in the rod–rod electrode system to observe the electric field behavior of the oil under the same conditions as the spherical system. The variations in the electric potential area across different electrode systems are illustrated in Fig. 3.

As can be seen from Fig. 3, the areas where the potential difference is the highest and the lowest in the sphere–sphere electrode system are the largest. The electrical potential area is generally lower in the rod-to-rod electrode system. This is due to the fact that in the rod electrode, the highest potential is concentrated at the tip of the rod. In Fig. 3, it is clearly seen that the most uniform electric field belongs to the sphere–sphere, and the most irregular area belongs to the rod–rod electrode system. The electric field lines for all electrode systems are shown in Fig. 4.

Due to the intensification of electric field lines around the rod electrode, higher electric field stresses occur here. The arrangement in which the electric field lines are most visible is the rod–rod electrode system, where the electric field is the most non-uniform. For the sphere–rod electrode system, electric field lines are nearly the same in terms of intensity with the rod–rod electrode system. Furthermore, in Figure 4(b), the abundance of lines observed at the bulk of the rod electrode surpasses that of (a) and (c). Figure 5 depicts the electric field curves along the x-axis for all scenarios.

ctric field values are measured on the point where it is on the high-voltage electrode and the nearest point to the earth electrode. The maximum electric field value at *x* direction is observed at rod–rod electrode system with an approximately value of 500 V/cm. E_x values are nearly the same, and there is no big difference between sphere–sphere and sphere–rod electrode system. The disruptive effect of the non-uniform electric field is clearly seen in the rod–rod electrode system. As a consequence of this situation, transformer oil is weaker against electrical stress under a non-uniform electric field. Electric field curves of *y*-axis for all situations are presented in Fig. 6.

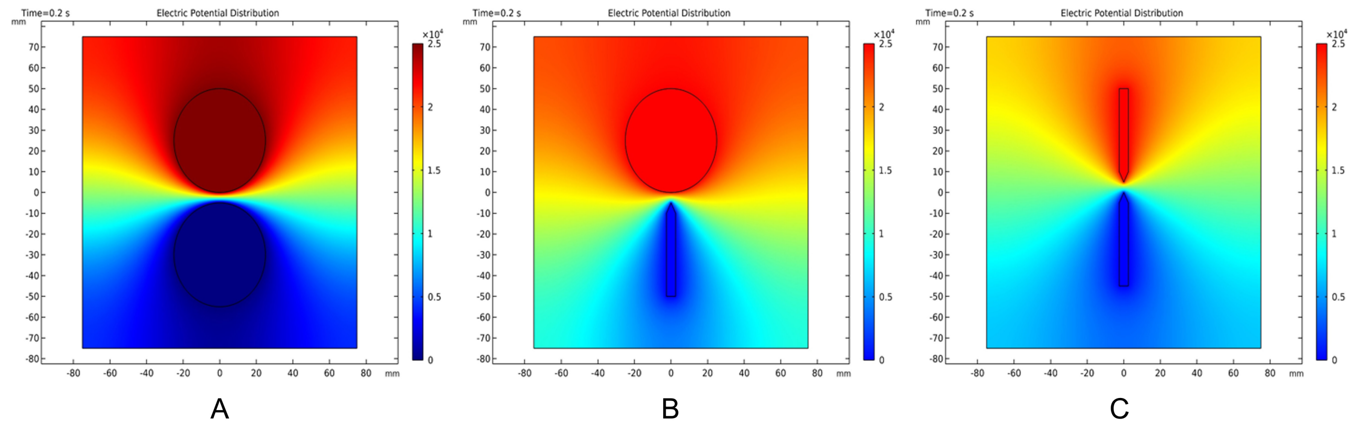

Fig. 3. Electric potential area. (A) sphere–sphere electrodes, (B) sphere–rod electrodes, and (C) rod–rod electrodes.

In the situation that at least one sphere electrode exists, the E_y value is extremely higher than E_x value. Likewise this situation, E_y is also higher than E_x in the rod–rod electrode system. At the sphere–sphere electrode configuration, E_{ymax} and E_{xmax} values are nearly 52 kV/cm and 0.36 V/cm, respectively. The difference is about 145k times for this arrangement. When it comes to sphere-rod electrode systems, E_{ymax} and E_{xmax} values are nearly 38 kV/cm and 0.25 V/cm, respectively. The difference is about 145k times for this arrangement. Under the rod–rod electrode system, E_{ymax} and E_{xmax} values are nearly 20 kV/cm and 500 V/cm, respectively. Even though the rod–rod electrode system has the worst for uniformity in an electric field, the field line concentration is more homogenous than the others. Normalized electric field curves for all situations are shown in Fig. 7. Also, to summarize, the results from Figs. 5, 6, and 7 are given in Table II.

When the data in Fig. 7 are analyzed, it can be clearly seen that the highest E_{max} value is observed at the uniform electric field under the sphere–sphere system. Although the existence of the rod electrode

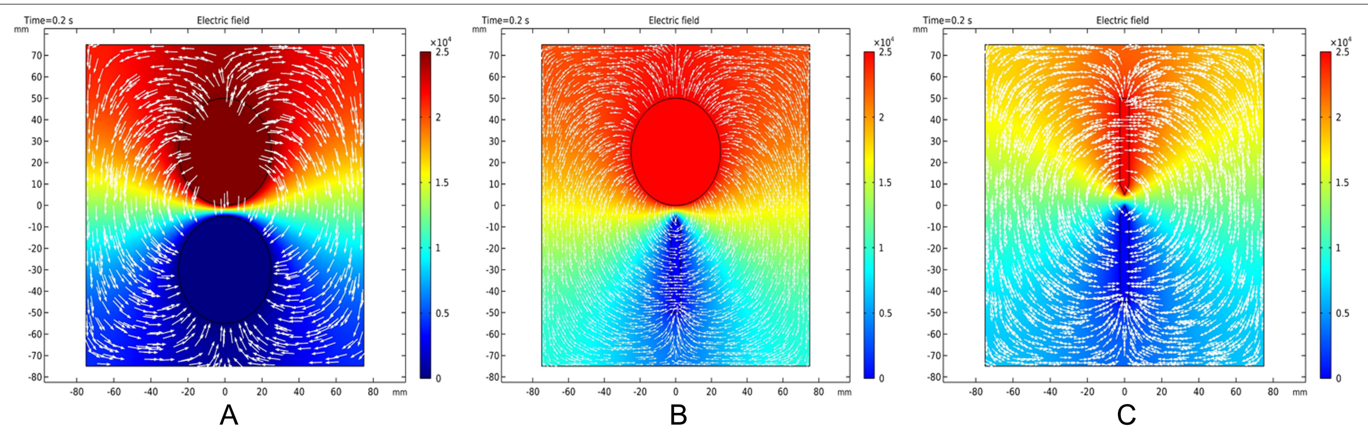

Fig. 4. Electric field lines. (A) Sphere–sphere electrodes, (B) sphere–rod electrodes, and (C) rod–rod electrodes.

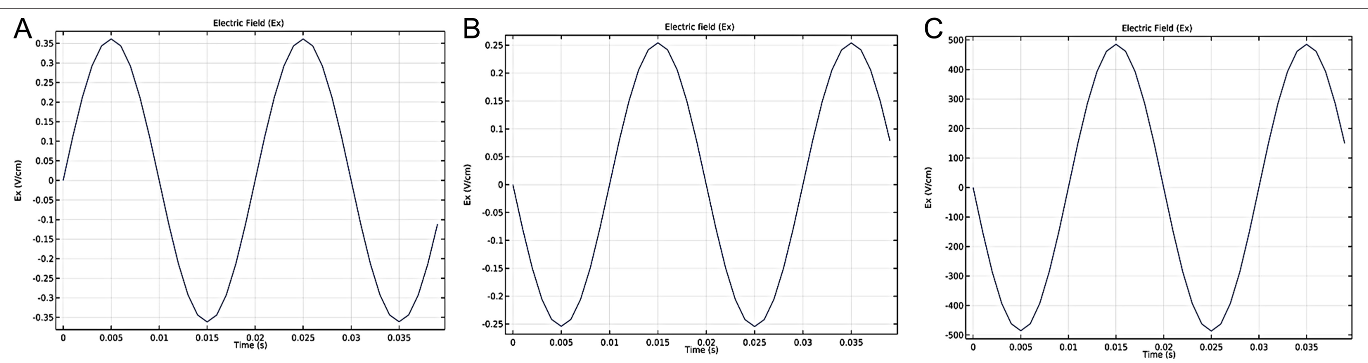

Fig. 5. Electric field curves at x direction. (A) Sphere–sphere electrodes, (B) sphere–rod electrodes, and (C) rod–rod electrodes.

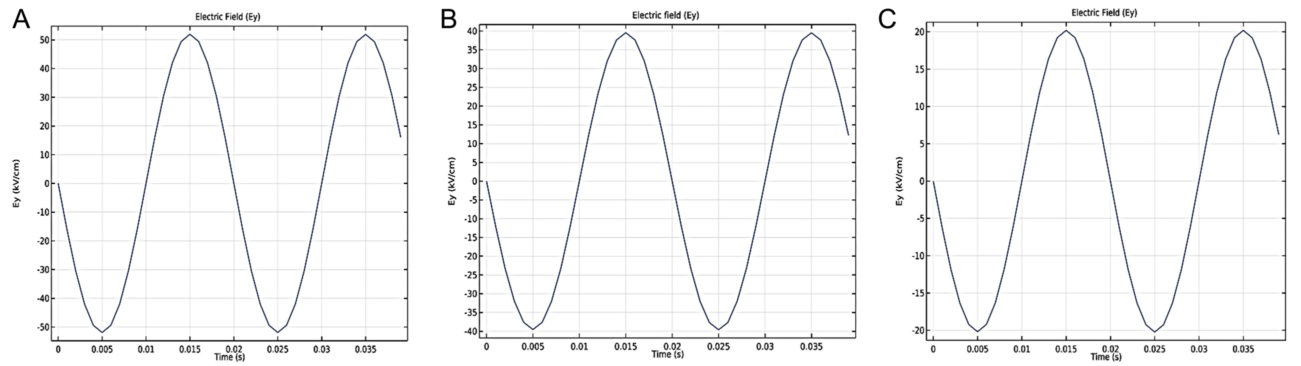

Fig. 6. Electric field curves at y direction. (A) Sphere–sphere electrodes, (B) sphere–rod electrodes, and (C) rod–rod electrodes.

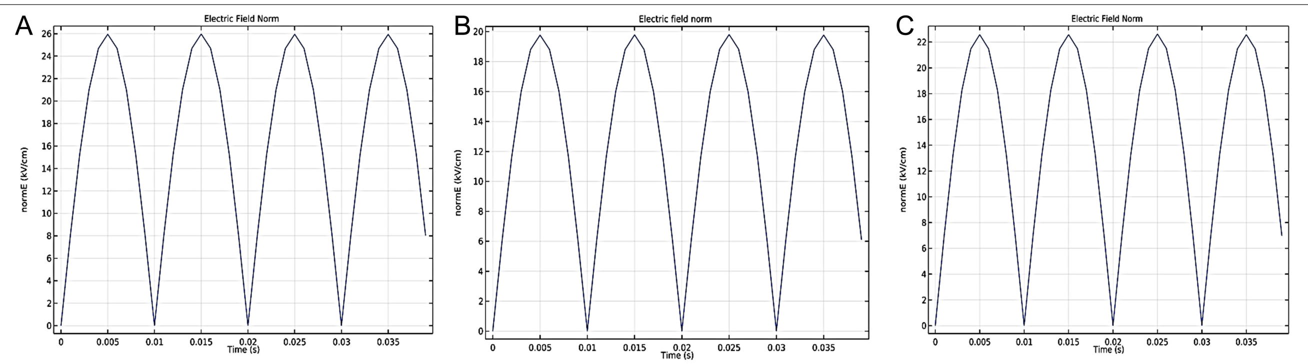

Fig. 7. Normalized electric field curves. (A) Sphere–sphere electrodes, (B) sphere–rod electrodes, and (C) rod–rod electrodes.

TABLE II. MAXIMUM ELECTRIC FIELD VALUES AT DIFFERENT ELECTRODE SYSTEMS

Electrode Geometry	E_{xmax} (V/cm)	E_{ymax} (V/cm)	Normalized E_{max} (V/cm)
Sphere–sphere	0.36	52k	26k
Sphere–rod	0.25	38k	20k
Rod–rod	500	20k	23k

decreases a bit of E_{max} value, the area of minimum electric field is the lowest. So, the discharge process tends to continue during the ionization. This process results in the aging of the transformer oils.

IV. CONCLUSIONS

In this study, a 2D geometry was utilized to simulate the impact of electric field uniformity under optimal conditions. This investigation aimed to provide a more comprehensive understanding of the electric field stress on transformer oils. The analyses were conducted using the COMSOL software, employing an AC voltage of 25 kV. Observations revealed that in the sphere–sphere electrode system, the region with the lowest electric field value, indicating the highest uniformity, possessed the largest area. However, along the y-axis, which corresponds to the vertical electric field component, the magnitude exhibited an increased value. Consistent with existing literature, the rod–rod electrode configuration in this study demonstrated higher electric field values along the x-axis, as the uniformity of the electric field decreased and became distorted. Nevertheless, with the presence of the rod electrode in the medium, the electric field component along the y-axis decreased. Therefore, while evaluating the electric field stress on transformer oils, the uniformity of the electric field remains an essential criterion, and the contribution of the vertical component should also be considered, even in scenarios where the electric field is non-uniform. Subsequent investigations aim to validate these simulation results through empirical experiments, which will lead to a more profound comprehension of the effects of electric field stress on transformer oils.

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