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Simulation of the Composite Electric Field on 170 kV Disconnector Using the Finite-Element Method

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ABSTRACT

In this study, the effects in terms of electric stress of composite voltages on a high-voltage disconnector were investigated. The main purpose of this study is to determine and evaluate the effects of the conditions that may occur in real working conditions but out of the type tests. As for the disconnector model, one phase of a center-break disconnector was considered. In order to examine the effects of composite voltages on high-voltage disconnectors, a model is defined in the Comsol Multiphysics program. Different types of voltages such as operating voltage, 50 Hz test voltage, lightning impulse voltage, and composite voltage, were applied to the 170 kV disconnector model separately. After applying a composite voltage consisting of power frequency voltage and lightning impulse voltage to the disconnector, electric potential and electric field distributions were obtained. It has been observed that the maximum electric potential and the maximum electric field strength values on the disconnector are higher when composite voltage is applied than when non-composite voltage is applied to the disconnector. It is observed that the intensity of the electric field lines increases near the contacts of the current-carrying arm and the main contacts of the disconnector.

***Index Terms*—** Composite voltage, electric field analysis, finite-element method, high-voltage disconnector, lightning impulse voltage, power frequency voltage.

I. INTRODUCTION

Electrical energy has become an extremely important need in the modern world. The need of people for this energy continues to increase day by day. Increasing electricity generation alone is not a reasonable solution to meet this need. Energy should also be transmitted and used efficiently. High-voltage systems are effectively needed for the use of electrical energy. Various devices and equipment are required to operate high-voltage systems safely. Such devices and equipment must be suitable for high-voltage systems [1, 2]. Therefore, the conditions to which the instruments and equipment will be exposed should be determined before use. It should be determined the insulating properties across open contacts of a switching device or insulation of the isolating distance or longitudinal insulation, insulation between phase to phase and insulation of phase to earth by theoretically and experimentally testing whether it can withstand the stresses to be exposed. However, these experiments may not cover every condition faced in working conditions. One of these conditions is that high-voltage disconnectors are exposed to composite voltage and how they will behave under these voltages [3, 4].

Composite voltages are obtained by combining different voltage types [5, 6]. They can occur spontaneously in nature. For example, the composite voltage may occur when a lightning strike hits a device operating under operating voltage [7, 8].

In 1990, M.R. Raghuveer, Z. Kolaczkowski, J. Weifang, and E. Kuffel studied the surface electrical strength of a plate processed under alternating current (AC) and direct current (DC) mixed voltages. In DC transmission systems, converter transformers operate under composite voltages. For this reason, it is aimed to know the surface strength of the plate under composite voltage stresses. Surface strength was found experimentally under AC, DC, lightning, and switching impulse voltages [9].

Tian et al., in 2011, carried out a studied to AC and DC electric field simulation for an 800 kV high-voltage disconnector. In this study, the ANSYS program was used to calculate the AC and DC electric field distribution. In the study, AC and DC electric field distributions were obtained

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and compared with each other. It has been mentioned that calculating the electric field in high-voltage disconnectors will benefit us in terms of structural optimization, control of corona discharge, and radio interference voltage level [3].

In 2015, Zhang et al. investigated the effect of composite AC–DC voltages on the properties of corona discharge. In this study, a series-circuit experiment platform was established to obtain the corona properties of the electrodes under AC–DC composite voltages. The effects of composite voltages and geometric dimensions on the electric field distribution were investigated. As a result of the studies, based on the electric field simulation results, it was found that the change in electric field strength is directly proportional to the corona initial voltage under composite voltages [10].

High-voltage disconnectors are opened and closed when the circuit is unloaded in high-voltage systems, so they provide the required isolation range [11-13]. In this study, a 170 kV single-phase, center-break disconnector model was considered. In center-break disconnectors, the contacts on the terminals are movable, and these contacts meet at the middle of the isolating distance of the disconnector.

Devices tested with AC, DC, or impulse voltages in laboratory conditions may be exposed to more than one voltage at the same time under real operating conditions. Especially in cases such as lightning strikes to power transmission lines or substations, during switching events in the energy system, the devices are also forced by voltages occurring in these situations, apart from the rated system voltage. In order to know in advance whether there will be any problems with the insulation status of the devices in the system in case of such events, various analyses should be carried out by combining different types of voltages in the laboratory or computer environment [5-7].

In this study, the finite-element method (FEM) was used for electric field analysis of high-voltage disconnectors under composite voltages. The three-dimensional (3D) model was created by considering the time variation of the voltage [14, 15]. With these analyses, the effects of situations occurring outside the type tests on the disconnectors in field applications were evaluated [16].

In order to examine the effects of composite voltages on the disconnectors, a model was created in Comsol Software, which is used to solve physical problems with FEM [17-19]. In order to examine the electrical field effects of the composite voltage on the disconnector, a standard lightning impulse voltage having a front time of 1.2 µs and a time-to-half-value of 50 µs and a 50 Hz AC voltage were applied separately and together. Considering the waveforms of the voltages applied to the disconnectors, the electrical potential and electric field distributions at certain times were examined. The purpose of these examinations is to determine the amplitude and location of the maximum electric field strength, which is crucial for the electrical discharge phenomena. Thus, making and operating high-voltage equipment safely and more reliably will be possible by making arrangements and taking precautions.

II. THE THREE-DIMENSIONAL ELECTRIC FIELD SIMULATION

A. Model

In this study, one phase of the center-break disconnector was used in the model. The disconnector model was drawn in 3D in SolidWorks, and then the 3D drawing was transferred to Comsol Multiphysics program for the analysis. The open and closed positions of the considered disconnector model in Comsol are shown in Fig. 1.

1) The Materials and Dimensions of Model

The dimensions of the modeled disconnector in millimeters are shown in Fig. 2. The dimensions of the model are the same as the dimensions of the 170 kV center-break disconnector used in field applications.

While modeling the high-voltage disconnector, aluminum for current paths, copper for contacts, porcelain for insulators, and steel for the base of the disconnector were selected. Also, air as a medium material was chosen in the model. The determined materials and their properties in the model are given in Table I.

2) Discretizing the Model into Finite Elements

In order to be able to solve with the FEM, a closed solution region is needed. So, the model was defined as a rectangular prism of 2 × 2.5 × 2.3 meters (width × length × height) in a closed region, as shown in Fig. 3. Although it is appropriate for these dimensions to be larger in terms of the accuracy of the analysis results, the dimensions could not be chosen larger due to the limited processing speed of the computer used for the solution.

The solution region was divided into finite elements using tetrahedral and triangle elements. All surfaces of tetrahedral elements are also triangles. For the open position model of the disconnector, the number of tetrahedral and triangle finite elements used is 805 146

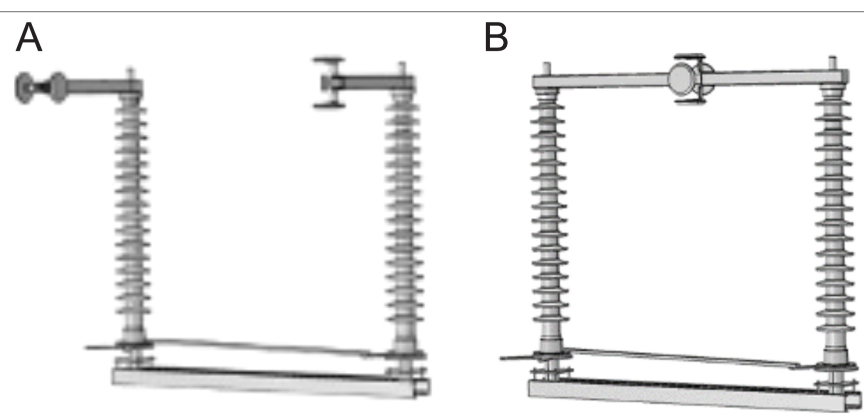

Fig. 1. Disconnector model: (a) open position and (b) closed position.

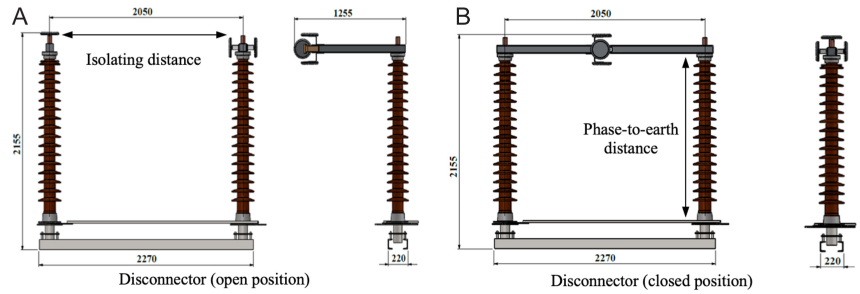

Fig. 2. Dimensions of modeled disconnector in millimeter.

and 89 278, respectively. For closed position model of the disconnector, the number of tetrahedral and triangle finite elements used is 793 602 and 88 897, respectively. For these analyses, the average quality of the element is 0.6108 and 0.6098 for the open and closed positions of the disconnector, respectively.

B. Electric Field Analysis of Disconnector

In order to understand the effects of the composite voltage on the disconnector, in the first stage, the 50 Hz AC voltage and lightning impulse voltage were applied to the disconnector separately. In this study, time-dependent models were created for analysis. The power frequency voltage was applied to the disconnector for 20 ms and the lightning impulse voltage for 50 µs. In applying power frequency voltage, 170 kV/$\sqrt{3}$ = 98.15 kV (r.m.s.) was applied. In applying the power frequency test voltage, 375 kV (r.m.s.) was applied across the isolating distance, and 325 kV (r.m.s.) was applied to phase-earth. In the application of lightning impulse voltage, 860 kV (peak) was applied across the isolating distance, and 750 kV (peak) was applied to phase-earth. Later, the composite voltage consisting of 50 Hz AC voltage and lightning impulse voltage was applied to the disconnector for 50 µs. Before applying the composite voltage, electric field investigations at AC and impulse voltages were made for the open and closed positions of the disconnector separately.

C. Analyses at Operating Voltage

The power frequency operating voltage was applied across the open contacts or the isolating distance at the open position and between phase-earth at the closed position of the disconnector. The applied operating voltage equation is given in Equation (1).

$$u(t) = 98{,}15 \cdot 10^3 \sqrt{2} \cdot sin\omega t = 138{,}8 \cdot 10^3 \cdot 2\pi ft \qquad (1)$$

Electric field simulations on the disconnector were made by applying voltage with an effective (r.m.s.) value of 98.15 kV.

TABLE I. USED MATERIALS AND THEIR PROPERTIES IN THE MODEL

Material	Relative Permittivity
Aluminum (current path)	10^5
Copper (contacts)	10^5
Steel (base of disconnector)	1
Porcelain (insulator)	6
Air (medium)	1

D. Analyses at Power Frequency Test Voltage

In case of applying power frequency test voltage to the disconnector in electric field calculations:

i. 375 kV (r.m.s.) 50 Hz AC test voltage was applied across the isolating distance at the open position of the disconnector:

$$u(t) = 375 \cdot 10^3 \sqrt{2} \cdot sin\omega t = 530{,}3 \cdot 10^3 \cdot 2\pi ft \qquad (2)$$

ii. 325 kV (r.m.s.) 50 Hz AC test voltage was applied between each contact and earth (phase-earth) at the open position of the disconnector:

$$u(t) = 325 \cdot 10^3 \sqrt{2} \cdot sin\omega t = 459{,}6 \cdot 10^3 \cdot 2\pi ft \qquad (3)$$

iii. 325 kV (r.m.s.) 50 Hz AC test voltage was applied between phase and earth at the closed position of the disconnector:

$$u(t) = 325 \cdot 10^3 \sqrt{2} \cdot sin\omega t = 459{,}6 \cdot 10^3 \cdot 2\pi ft \qquad (4)$$

In the equations (1)–(4), $\omega = 2\pi f$ is angular frequency; f is power frequency (50 Hz); and t is time.

When the 50 Hz AC test voltage analysis is examined, it is seen that the electric field values on the disconnector are the highest in the electric field examination across the isolating distance at the open position. In this case, the time-dependent variation of the electric field distribution on the surface of the contacts is shown in Fig. 4.

When the 50 Hz AC test voltage analysis was examined, it was observed that the maximum electric field value was 30 kV/cm, and it occurred on the contact surface of the voltage applied point. Otherwise, the electric field formed on the contact surface of the non-voltage point was 18 kV/cm.

E. Analyses at Lightning Impulse Voltage

The peak of the lightning impulse voltage to be applied for disconnectors is 750 kV for phase-to-earth and 860 kV for the isolating distance, according to IEC 62271-1. In this study, analyses were applied separately for positive and negative lightning impulse voltages, as specified in the standard [12]. In electric field calculations,

i. When the disconnector was open, a positive lightning impulse voltage of 860 kV was applied across the isolating distance.

$$V(t) = 860 \cdot 10^3 \left(e^{-1.4912 \cdot 10^4 t} - e^{-1.6335 \cdot 10^6 t} \right) \qquad (5)$$

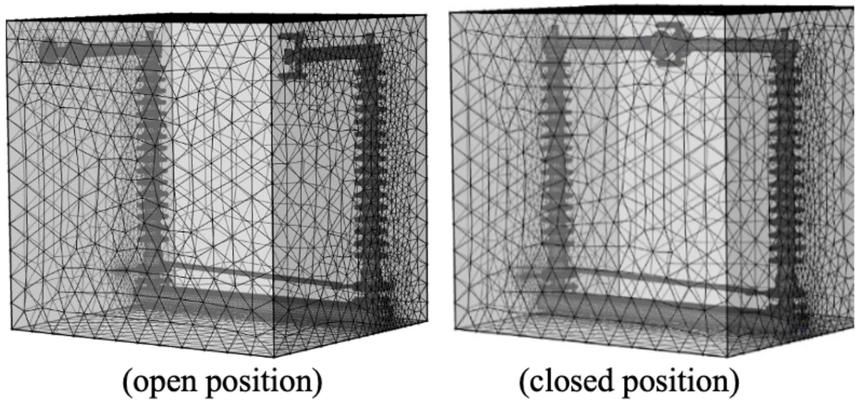

Fig. 3. Mesh models of the disconnector in Comsol.

ii. When the disconnector was open, a negative lightning impulse voltage of 860 kV was applied across the isolating distance.

$$V(t) = -860 \cdot 10^{3}\left(e^{-1.4912 \cdot 10^{4} t} - e^{-1.6335 \cdot 10^{6} t}\right) \quad (6)$$

iii. When the disconnector was open, a positive lightning impulse voltage of 750 kV was applied between phase and earth.

$$V(t) = 750 \cdot 10^{3}\left(e^{-1.4912 \cdot 10^{4} t} - e^{-1.6335 \cdot 10^{6} t}\right) \quad (7)$$

iv. When the disconnector was open, a negative lightning impulse voltage of 750 kV was applied between phase and earth.

$$V(t) = -750 \cdot 10^{3}\left(e^{-1.4912 \cdot 10^{4} t} - e^{-1.6335 \cdot 10^{6} t}\right) \quad (8)$$

v. When the disconnector was closed, a positive lightning impulse voltage of 750 kV was applied between phase-earth.

$$V(t) = 750 \cdot 10^{3}\left(e^{-1.4912 \cdot 10^{4} t} - e^{-1.6335 \cdot 10^{6} t}\right) \quad (9)$$

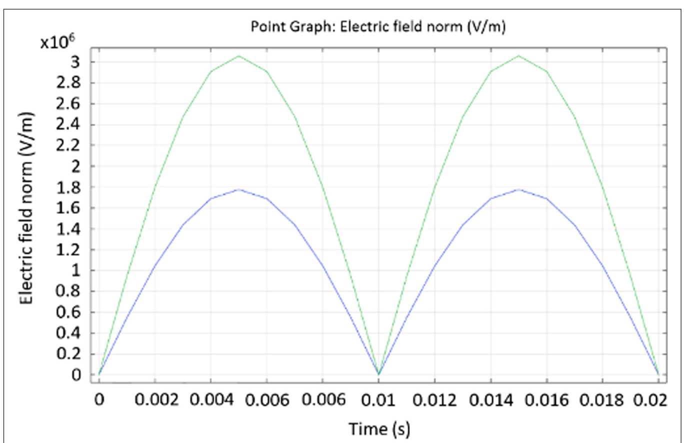

Fig. 4. Time-dependent variation of the electric field distribution on the surface of the contacts in case of open position under 50 Hz AC test voltage (green curve is for live contact; blue curve is for dead contact).

vi. When the disconnector was closed, a negative lightning impulse voltage of 750 kV was applied between phase-earth.

$$V(t) = -750 \cdot 10^{3}\left(e^{-1.4912 \cdot 10^{4} t} - e^{-1.6335 \cdot 10^{6} t}\right) \quad (10)$$

When the positive lightning impulse voltage analysis is examined, it is seen that the electric field on the disconnector is the highest in testing the isolating distance with open position. In this case, the time-dependent variation of the electric field distribution on the contact surface is shown in Fig. 5.

As a result of all these analyses, it has been observed that the maximum electric field was 54 kV/cm and occurred on the surface of high-potential contact. However, the electric field on the surface of low-potential contact was 27 kV/cm.

F. Analyses at Composite Voltage

Disconnectors can simultaneously be exposed to more than one voltage under real operating conditions. For example, the typical composite voltage can occur with lightning strikes to the electrical grid during operating voltage. If such a situation occurs, the disconnectors are forced by composite voltage.

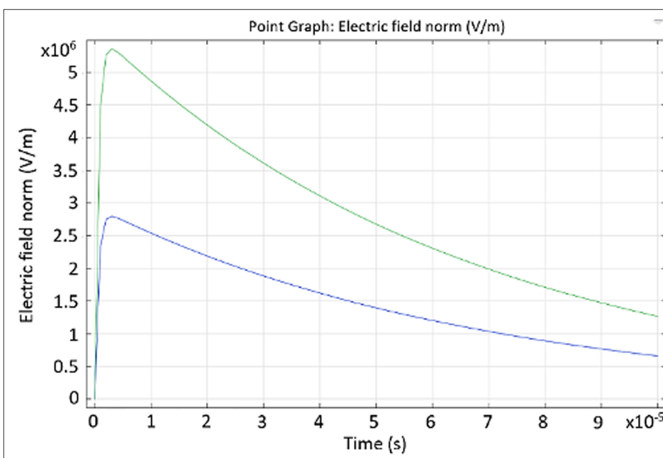

Fig. 5. Time-dependent variation of the electric field distribution on the surface of the contacts in case of open position under positive lightning impulse voltage (green curve is for live contact; blue curve is for dead contact).

1) Application of composite voltage across isolating distance with the disconnector at the open position

With this analysis applied at the open position of the disconnector, the performance of the disconnector was evaluated by superimposing 50 Hz AC operating voltage and lightning impulse voltage across the isolating distance. The composite voltage was applied across the isolating distance, obtaining the largest potential difference using Equations (11) and (12).

$$u(t) = 98{,}15 \cdot 10^3 \sqrt{2} \cdot \sin\omega t = 138.8 \cdot 10^3 \cdot 2\pi f t \quad (11)$$

$$V(t) = -860 \cdot 10^3 \left(e^{-1.49 \cdot 10^4 t} - e^{-1.63 \cdot 10^6 t}\right) \quad (12)$$

As explained in the previous sections, while the disconnector was open, a 50 Hz AC 138.8 kV peak operating voltage was applied to one terminal of the disconnector, and a 1.2/50 µs lightning impulse voltage with an 860 kV peak value was applied to the other terminal simultaneously. The base of the disconnector was earthed, as in the operating conditions. Thus, while the operating voltage was at one of the contacts at the open position of the disconnector, a lightning strike to the other contact was simulated.

In order to observe the most unfavorable situation while applying voltages, a lightning impulse voltage was applied to the disconnector when the 50 Hz AC voltage was at its maximum. The negative lightning impulse voltage was applied at the top of the positive half-wave of the 50 Hz AC operating voltage. Thus, the potential difference between the contacts was maximized, and the stress of the insulation material between contacts was aimed at reaching its maximum.

The analysis results obtained by applying the composite voltage at the open position of the disconnector were evaluated using the obtained potential and electric field distribution at 1 µs, 10 µs, and 50 µs.

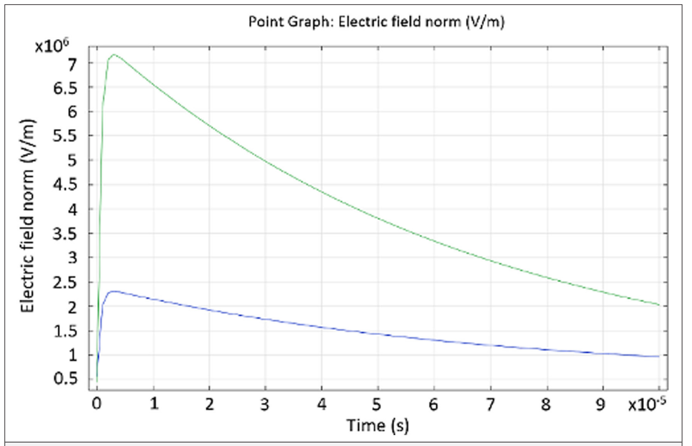

Fig. 6. Time-dependent variation of the electric field distribution on the surface of the contacts in case of open position under composite voltage (green curve is for live contact; blue curve is for dead contact).

It has been observed that the electrical potential at the end where the 50 Hz AC operating voltage was applied did not change for 50 µs with the review of the electrical potential. On the other hand, it has been observed that the electrical potential on the terminal where the lightning impulse voltage was applied changed in accordance with the waveform of the applied lightning impulse voltage. The maximum electrical potential was formed at the terminal where the lightning impulse voltage was applied. The sign of the electrical potential has changed depending on the polarity of the voltages according to time.

It has been seen that the applied voltages were proportionally distributed with the instantaneous voltage level with the review of electric field distributions. The electric field strength was highest in the current-carrying arms of the voltage-applied ends. In addition, the

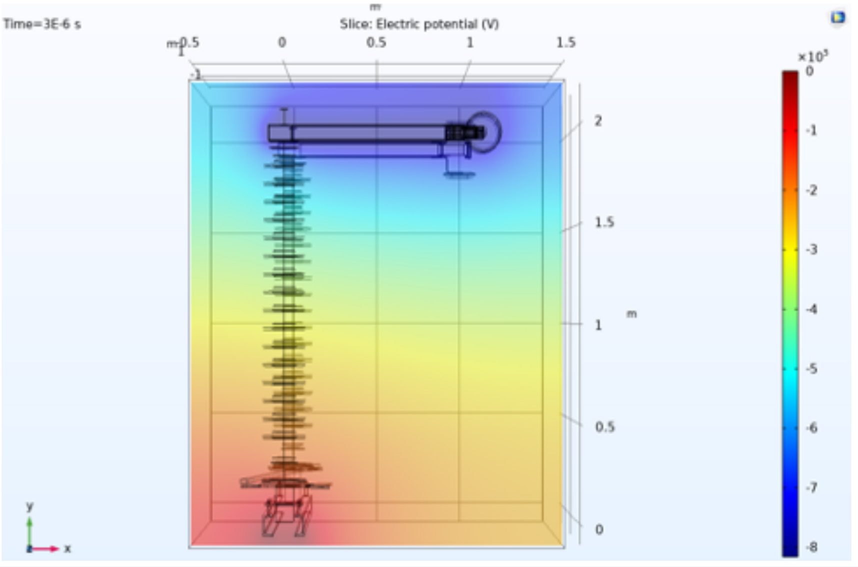

Fig. 7. Electric potential distribution on the surface of disconnector after 3 µs from applying composite voltage.

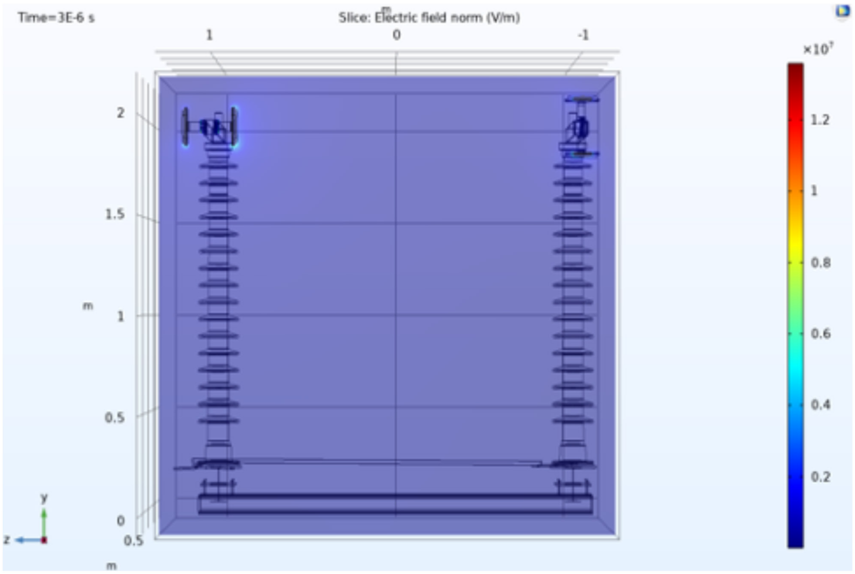

Fig. 8. Electric field distribution on the surface of disconnector after 3 μs from applying composite voltage.

highest electrical stress occurred at the contacts of the disconnector. The time-dependent variation of the electric field at the contacts of the disconnector is shown in Fig. 6.

In all these analyses, the maximum electric field strength was 72 kV/cm, and the lightning impulse voltage occurred on the contact surface of the applied tip. The maximum electric field strength on the contact surface of the tip to which the 50 Hz AC operating voltage was applied was 24 kV/cm.

In the results obtained by applying composite voltage to the disconnector in the open position, it was observed that the maximum electrical stress was at 3 μs. The distribution of electrical potential on the disconnector surface and the electric field on the disconnector contacts are shown in Fig. 7 and 8 after 3 μs from applying composite voltage, respectively.

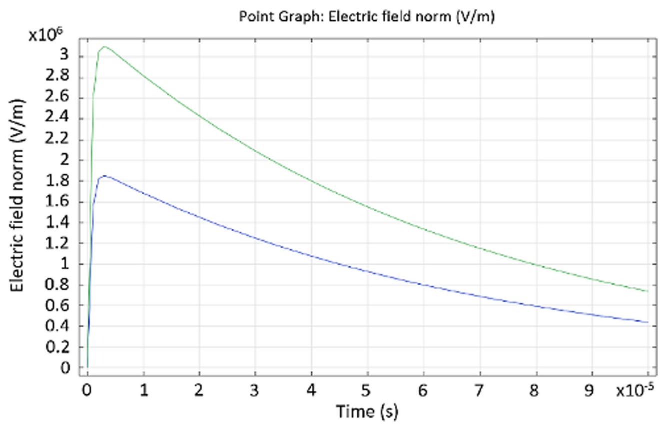

Fig. 9. Time-dependent variation of the electric field distribution on the surface of the contacts in case of closed position under composite voltage (green curve is for live contact; blue curve is for dead contact).

In applying the composite test voltage in the open position of the disconnector, the maximum electric potential of the lightning impulse voltage seen on the contact surface of the applied terminal was 810 kV. The maximum electric potential seen on the contact surface of the applied terminal of 50 Hz AC voltage was 120 kV. Then the electric field values of these same points were examined on the created model. While the electric field formed on the contact surfaces was 54 kV/cm and 27 kV/cm in the lightning impulse voltage, the electric field formed on the contact surfaces was observed to be 72 kV/cm and 24 kV/cm in the composite voltage.

2) Application of composite voltage to the between phase and earth with the disconnector at the closed position

With this test, which is applied when the disconnector is at the closed position, the performance of the phase-to-earth strength of the disconnector when lightning impulse voltage reaches the disconnector in addition to the operating voltage is evaluated.

As explained in the previous section, the composite voltage applied to the disconnector was obtained by combining the operating and lightning impulse voltages. The operating voltage and lightning impulse voltage equations are given in Equations (13) and (14), respectively.

$$u(t) = 98{,}15 \cdot 10^3 \sqrt{2} \cdot sin\omega t = 138{,}8 \cdot 10^3 \cdot 2\pi ft \tag{13}$$

$$V(t) = -750 \cdot 10^3 \left(e^{-1.49 \cdot 10^4 t} - e^{-1.63 \cdot 10^6 t} \right) \tag{14}$$

In the solution, the base of the disconnector is earthed. Thus, the lightning strike situation at the disconnector was simulated when there was operating voltage on the disconnector at the closed position.

While the voltages were being applied, the lightning impulse voltage was applied at the maximum operating voltage in order to see the most unfavorable situation. The positive lightning impulse voltage was adjusted to coincide with the positive half-wave of the operating voltage. Thus, it was aimed at maximizing the electrical stress

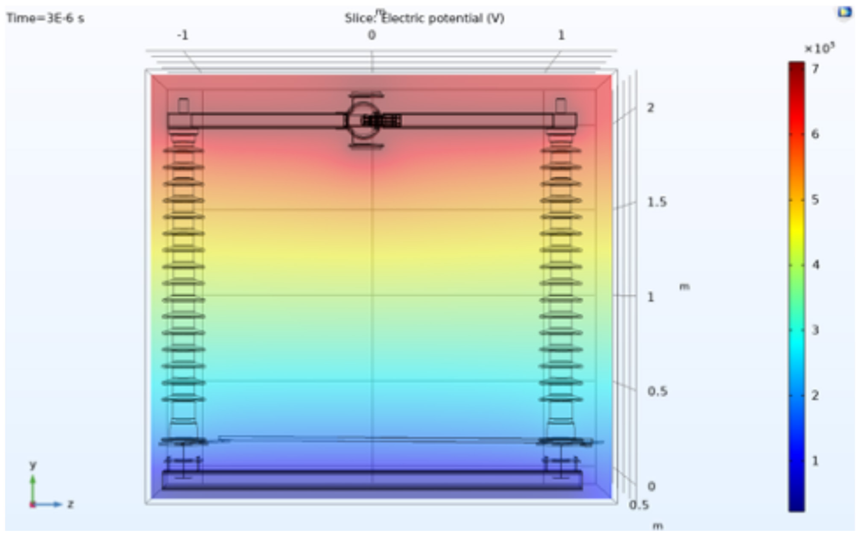

Fig. 10. Electric potential distribution on the surface of disconnector after 3 µs from applying composite voltage.

by maximizing the potential difference between the disconnector arms and the earthed base of the disconnector.

The analysis results obtained by applying the composite voltage at the closed position of the disconnector were evaluated using the obtained potential and electric field distribution at 1 µs, 10 µs, and 50 µs.

It was seen that the electric potential distribution at the applied point of the lightning impulse voltage changes in accordance with the waveform of the lightning impulse voltage with a review of electric potential. The electric potential was at its maximum at the terminal where the lightning impulse voltage was applied. The sign of the electric potential changed depending on the polarity of the half-wave of the voltages.

It has been seen that the electric field was proportionally distributed with the instantaneous voltage level with the review of electric field distributions. The electric field strength was highest on the current-carrying arms of the voltage-applied ends. In addition, the highest electrical stress occurred on the contacts of the disconnector. The time-dependent variation of the electric field at the contacts of the disconnector is shown in Fig. 9.

In all these analyses, the maximum electric field strength was 31 kV/cm and occurred at the tip surface where the lightning impulse voltage was applied. In the results obtained by applying composite voltage to the disconnector at the closed position, it was observed that the maximum electrical stress was at 3 µs. The distributions of electric potential and the electric field on the disconnector surface are shown in Fig. 10 and 11 after 3 µs from applying composite voltage, respectively.

In the lightning impulse voltage application for the closed position of the disconnector, the maximum electrical potential seen on the surface of the point where the voltage is applied was 710 kV. On the

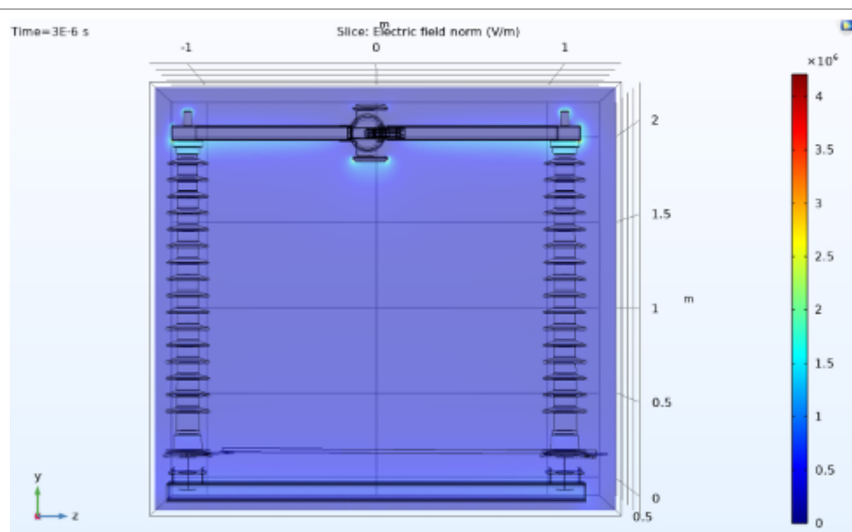

Fig. 11. Electric field distribution on the surface of disconnector after 3 µs from applying composite voltage.

other hand, it was 760 kV in the composite voltage test application for the closed position of the disconnector. Likewise, when the electric field was examined, In the lightning impulse voltage application, it was observed that the electric field formed on the terminal surfaces was 27 kV/cm and 16 kV/cm. In the composite voltage application, the electric field formed on the terminal surfaces was 31 kV/cm and 18 kV/cm.

III. CONCLUSION

In this study, 3D electric field analyses were carried out on one pole of a high-voltage disconnector, a device with no axial and rotational symmetry, taking into account the waveform and time dependence of the voltage. In the analyses, the electrical stresses on the disconnector were examined with the voltages applied across the open contacts, or the isolating distance, and between the phase and earth. These analyses were made to the disconnector at the open and closed positions. The electrical field analysis is vital to determine where and at what amplitude the maximum electric field strength occurs in terms of partial discharge or electrical breakdown in the air surrounding the disconnector.

It is seen that the composite voltage obtained by combining the lightning impulse voltage and the frequency voltage forces the disconnector more electrically, both from the stress caused by the lightning impulse voltage and the stress caused by the frequency voltage.

The analysis results obtained as a result of this study can be used by the authorities that manage the transmission systems of the countries for their own systems. Analyses can be made with parameters to be adapted according to the characteristics of their systems. Thus, the stress values suitable for the protection level aimed to be achieved in the system studied can be determined, and the test voltage magnitudes that will give the same results in laboratory experiments may be calculated in advance. Afterwards, withstand voltage values defined by standards that are above the calculated value and closest to this value can be entered into the specifications of the country. Thus, while the most difficult conditions are covered, they can be applied in practice by laboratories within the scope of type tests.

When the electrical potential and electric field on the disconnector are examined, it is observed that the most stress is experienced under composite voltage, which is a combination of lightning impulse voltage and 50 Hz AC operating voltage.

In this study, analyses were performed on a single pole of the disconnector. In future studies, it can also be done on the disconnector with its three phases. Thus, the effect of the adjacent poles (between phases) on the electric field distribution can be seen. In addition to the electric field studies, the magnetic field and thermal, mechanical, and environmental effects can be taken into account. In the analysis, ambient factors such as air temperature, pressure, humidity, pollution, frost, and wind can also be involved in the model to see the situation in real working conditions. Thus, safer and more reliable designs and structures can be created for disconnectors.

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