Electric Field Optimization Analysis for Live Opera-Tion of UHV Transmission Line

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Abstract: At present, China's economy is in a period of rapid development, and the pace of urbanization construction is constantly accelerating, followed by the soaring demand for electricity. Especially in densely populated areas where construction land is scarce, it is difficult to balance transmission capacity with the increasing demand for electricity. The problem of insufficient conveying capacity is solved well by the double-return conveying scheme of the same tower and frame. In the process of transmission line operation, it needs to be repaired and maintained, and a considerable part of the work needs to be live. Therefore, this paper studies the surface electric field changes of UHV live line workers, in order to reduce the operating risk of operators, and then make theoretical and practical contributions to ensure the safe and effective implementation of live line work and improve the operation quality and standardization degree. In this paper, SolidWorks modeling software is used to model a 500KV transmission line, and a human body model is placed in the model. The finite element simulation software COMSOL is used to calculate the surface electric field when the personnel are located at the typical position of the line, and its influencing factors are analyzed.

Keywords: 500kV double circuit transmission line; Live work; Electric field distortion; Simulation study

1. Introduction

Currently, with China's rapid economic de-velopment and the new era of socialism with Chinese characteristics, the main contradiction has shifted to the growing needs of the people for a better life versus unbalanced and inadequate development. Regardless of the aspect of social development, ensuring high-quality power is essential, making the construction of transmission networks crucial. The maintenance and overhaul of power lines play a significant role in electric power development.

During transmission line maintenance, much of the work must be performed live. Therefore, pro-tecting the operator, planning the optimal access route, and ensuring the path's electrical safety when entering the work environment are critical issues that need further study. Enhancing these aspects is vital for improving the safety and efficiency of live work [1].

In this paper, a simulation model of a 500kV double-circuit transmission line and ground struc-tures is developed using actual tower data and models. The finite element software COMSOL is employed to calculate electric field distortions ex-perienced by operators at various positions along the transmission line and to determine the optimal access path for entering the live environment. This study provides a theoretical reference for the safe live operation of 500kV double-circuit transmission lines.

2. Methodology

2.1 Calculation method of electrostatic induced voltage

When transmission lines are parallel, cross-crossing, or erected on the same pole, if one line is energized, the non-energized line will also exhibit corresponding voltage and current due to electromagnetic and electrostatic coupling effects. According to the principle of electromagnetic in-duction, when alternating current flows through a double-loop wire aligned in the same direction, an alternating magnetic field is generated around the wire. This induces a potential in alignment with that of the conductor in the adjacent line, resulting in a corresponding ground potential determined by the insulation level of that line [2]. The induced voltage depends on several factors: the strength of the magnetic field produced by the current, distance between operating and inactive wires, and their respective insulation levels relative to ground. Furthermore, based on electrostatic induction mecha-nisms—where capacitive coupling exists between active and inactive wires—the electromagnetic field created by changes in voltage along an active wire induces a corresponding potential on its inactive counterpart. Consequently, this results in specific induced voltages and currents; thus making it so that capacitive coupling from operational lines affects maintenance lines such that they exhibit potential relative to ground—a phenomenon referred to as electrostatic induction [3].

The mutual inductance coupling of transmission lines generates the inductive voltage component, while capacitive coupling results in the capacitive voltage component. Unlike conventional transmis-sion lines, the spacing between conductors in dou-ble-circuit lines on the same tower is relatively minimal, leading to a significant increase in induced voltage due to electrostatic coupling between wires [4]. The maintenance line exhibits two types of elec-trostatic induction parameters:

(1) Electrostatic induced voltage: This refers to the capacitive partial voltage produced by a normally charged line when an outage maintenance line re-mains ungrounded.

(2) Electrostatic induction current: When one side of the outage maintenance line's grounding switch is grounded, it generates an induced voltage resulting from the current flowing through this switch.

When the double circuit line operates within the same tower, cease operations on the II circuit line while maintaining normal operation of the I circuit line. If the maintenance line is not grounded at both ends, there will be no current flow; thus, the induced capacitive voltage can be calculated using formula (1):

Phases A, B, and C represent those of the I circuit, while phases a, b, and c denote those of the II circuit. C_{Aa},C_{Ba},C_{Ca} correspond to mutual capacitance and M_{Aa},M_{Ba},M_{Ca} refer to mutual inductance arising from unit length distances between phases ABC of the operating line and phase a of the maintenance line. C_0 and L signify capacitance and inductance generated by maintenance line a relative to ground per unit length; l represents distance along the line. The voltage and current values for each phase are denoted as $\hat{U}_A$、$\hat{U}_B$、$\hat{U}_C$、$\hat{U}_a$、$\hat{U}_b$、$\hat{U}_c$，$\ddot{I}_A$、$\ddot{I}_B$、$\ddot{I}_C$、$\ddot{I}_a$、$\ddot{I}_b$、$\ddot{I}_c$.

a compatibility induced voltage U_{sca} is:

$$\dot{U}_{sca} = \frac{\partial}{\gamma^2}\dot{U}_A + j\frac{M}{L}Z_C\dot{I}_A \tan\frac{\gamma l}{2} \approx \frac{C_{Aa}\dot{U}_A + C_{Ba}\dot{U}_B + C_{Ca}\dot{U}_C}{C_{0a} + C_{Aa} + C_{Ba} + C_{Ca}} \quad (1)$$

The propagation coefficient of the line in the formula:

$$\gamma = jw\sqrt{L(C_0 + C_{Aa} + C_{Ba} + CC_a)} \quad (2)$$

Equivalent capacitance:

$$\alpha = -\omega^2 l\left[C_{Aa} + \left(-\frac{1}{2} - j\frac{\sqrt{3}}{2}\right)C_{Ba} + \left(-\frac{1}{2} + j\frac{\sqrt{3}}{2}\right)C_{Ca}\right] \quad (3)$$

Wave impedance：

$$Z_C = \sqrt{L/(C_0 + C_{Aa} + C_{Ba} + C_{Ca})} \quad (4)$$

Equivalent mutual inductance:

$$M = M_{Aa} - (\frac{1}{2} + j\frac{\sqrt{3}}{2})M_{Ba} - (\frac{1}{2} - j\frac{\sqrt{3}}{2})\ M_{Ca} \quad (5)$$

According to formula (1), when the operating voltage of the line remains relatively stable, and if the capacitance parameter remains constant, the operating voltage is directly proportional to the capacitive response voltage. Conversely, if the voltage is stable and unchanged, it is inversely proportional to the capacitance. This relationship is independent of the line length and transmission power [5].

At this point, the voltage generated by elec-tromagnetic induction on the de-energized mainte-nance line will not produce any current flow, and its inductive potential value is:

$$U_{SLa} = (jwM_{Aa}\dot{I}_A + jwM_{Ba}\dot{I}_B + jwM_{Ca}\dot{I}_C)*l \tag{6}$$

According to the above formula, the inductive voltage is dependent on the line's inductance pa-rameter and is directly proportional to both the current in the running line and the line length. When the grounding switches at both ends of the line are connected to the ground, the induced voltage is primarily due to the capacitive response component. The contribution from the inductive voltage is neg-ligible and can be ignored in the calculations [6].

2.2 Electrostatic induction current, electromagnetic induction voltage calculation：

When the double-circuit line operates on the same tower, if the II circuit is deactivated while the I circuit remains in operation, and the maintenance line is grounded at one end, the inductive current value will be zero. In this case, the current I_{SCa} flowing through the ground switch is the capacitive current, or elec-trostatic induction current, and the voltage on the un-grounded side is the inductive voltage U_{SLa}.

$$\dot{I}_{sca} = -j\frac{a}{\gamma^2 Z_c}\dot{U}_A \tan(\gamma l) + \frac{M}{L}\dot{I}_A\frac{1-\cos(\gamma l)}{\cos(\gamma l)} \approx wl(C_{Aa}\dot{U}_A + C_{Ba}\dot{U}_B + C_{Ca}\dot{U}_C) \tag{7}$$

$$\dot{I}_{sca} = \frac{a}{\gamma^2}\dot{U}_A \tan(\gamma l) - j\frac{M}{L}Z_C\dot{I}_A\frac{1-\cos(\gamma l)}{\cos(\gamma l)} \approx wl(M_{Aa}\dot{I}_A + M_{Ba}\dot{I}_B + M_{Ca}\dot{I}_C) \tag{8}$$

From the above formula, the electrostatic induced current is influenced by the operating voltage, line length, and inter-line mutual capacitance, while the electromagnetic induced electromotive force is deter-mined by the inter-line mutual inductance.

This paper employs the finite element method to calculate the surface electric field distribution for live line workers. The finite element method, an approxi-mation technique, simplifies complex engineering problems into numerical problems for solution. It divides the operation area into a finite number of non-intersecting, interconnected small units, with calculations performed in each unit. Basis functions composed of unit potential variables and shape func-tions are used to superimpose and calculate field var-iables in each discrete domain, allowing the solution of differential equations to obtain an accurate numerical result [7].

2.3 change of electric field in live work

During live maintenance of the transmission line, the line remains operational, creating a high-voltage electric field in its vicinity that poses a safety risk to operators. Studying the variations in the electric field caused by maintenance personnel and the electric field strength around their bodies is crucial for ensuring their safety. Understanding these factors is essential for protecting the personal safety of maintenance workers.

During live work, maintenance personnel may come into contact with various parts of the line, cre-ating different pathways. These include contact be-tween personnel and the crossarm, the wire passing through the human body and steel tower, and the wire passing through the human body and other wires or circuits.

Before the operator enters the work area, the electric field is evenly distributed, with the electric field density decreasing as the distance from the line increases. However, once the operator is near the line, the electric field will become distorted, particularly at the interface where the air meets the human body.

The electric field distortion of the human body is divided into the following cases:

(1) Human electric field distortion on the ground When a person is on the ground, part of the electric field from the power lines interacting with the surface of the body will be distorted due to the body's shape and redirected to the ground. This distortion alters the field lines, causing a rapid increase in field strength above the body. The head, being the most prominent part, will concentrate the electric field, resulting in the highest surrounding field intensity [8]. Consequently, the field strength is lowest where the person contacts the ground and highest in the vertical direction relative to the line.

(2) Human electric field distortion between the wire and the ground

When the operator enters the work area and ap-proaches the live wire, the potential distribution on the human body differs from when they are on the ground. Positioned between the wire and the ground, the human body acts as a conductor, with the electric field en-tering through the head and exiting through the legs to the ground. This interaction causes the potential lines to bend, creating higher field strength at the head and feet, where the density of the electric field is greatest, while the rest of the body experiences a lower field strength. Consequently, when the body is situated in the electric field between the wire and the ground, the surface field strength along the body’s length, in the direction of the wire, is higher compared to other parts of the body.

(3) Human potential distortion in the process of equipotential

When the human body approaches the wire during an equipotential operation, the average field strength of the air gap between the fingertip and the wire increases. This is due to the high field strength near the wire and the electric field distortion caused by the presence of the human body. As the hand continues to move up-ward, the field strength rises rapidly. When it reaches the critical breakdown strength of air (30 kV/m), the air gap will break down, leading to discharge. Just before the discharge occurs, the electric field intensity at the fingertip is at its peak. As the body continues to approach the wire, the discharge persists until the hand fully grasps the wire, eliminating the air gap and stopping the discharge.Once the human body makes contact with the wire, its potential equalizes with the wire's potential, and the electric field is discharged through the sole of the operator's foot. At this point, the field strength on the sole of the foot is high due to the dense distribution of the electric field. Conversely, as long as the head of the human body does not exceed the wire, the field strength at the head remains low. Ad-ditionally, the electric field near the wire is reduced due to the shielding effect of the human body [9].

3. Results and discussion

3.1 Model building

In this paper, a 500 kV double-circuit transmis-sion line is used as the example for analysis. A 1:1 scale model of the operators, lines, and towers is employed, and simulation analysis is performed using COMSOL. The transmission line utilizes 4×LGJ-400 alumi-num-clad steel core aluminum stranded wire, with the towers standing at a height of 64 meters and the lowest conductor positioned 30 meters above the ground.

For the purpose of this study, which focuses on the electric field strength on the surface of workers, the model is simplified to include only the contour of a live worker. The specific dimensions of this model are illustrated in Figure 1. In the figure, the operator is depicted standing in a frontal view, with an upper body height of 60 cm and a width of 50 cm. The lower limbs and legs have a height of 80 cm and a width of 20 cm. The arms are 75 cm in length with a width of 10 cm, and the head is modeled as approximately spherical with a radius of 10 cm.

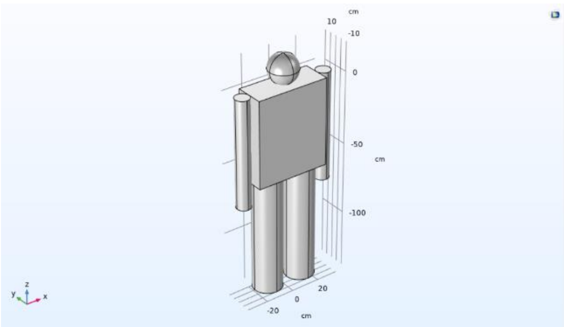

Figure.1 Human simulation model

3.2 Simulation comparison

In this paper, the live worker model is analyzed in various positions to simulate typical scenarios where individuals enter an equipotential region, with a focus on the changes in the electric field on the human sur-face. The positions considered include directly beneath the high voltage tower, on the side bars of the tower body, on the insulation arms of the three-phase transmission line, and around the wire.

When positioned directly below the tower, the live worker does not come into direct contact with the live components; this scenario is referred to as "indirect operation." When the worker ascends the tower and is situated on the cross arms or the cross bars on the tower body, both the tower and the worker are connected to the earth, thereby sharing the same potential in a ground potential working environment.

In cases where the worker is located around the wire, there is no direct contact with the charged components, and the worker is not at the ground po-tential; this scenario is termed "intermediate potential operation." When maintenance personnel come into direct contact with the wire, the personnel and the wire are electrically connected, resulting in the same po-tential for both, known as "equal potential operation" [10]-[11].

In ultra-high voltage transmission lines, live working personnel need to pass through towers and crossarms during the process of entering the electric field. Based on this ground potential live working surface simulation, personnel are selected to be located at the insulated crossarms, tower waist, and ground.

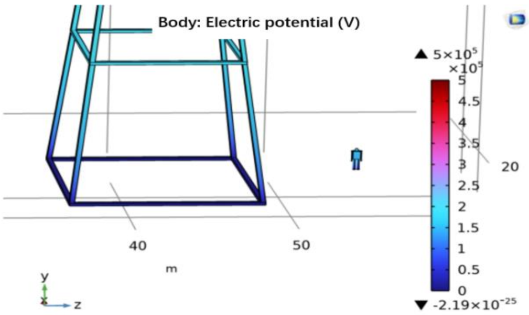

Figure.2Ground potential distribution (Potential V)

FIG. 2 illustrates the potential distribution when the electric field is still grounded as the oper-ator initially enters the field. Due to electrostatic induction, the human body experiences a transfer of electrostatic charge, altering the electric field on its surface. The figure shows that the electric potential in the upper part of the body decreases, while the field strength increases, with a marked rise in the field strength around the head .

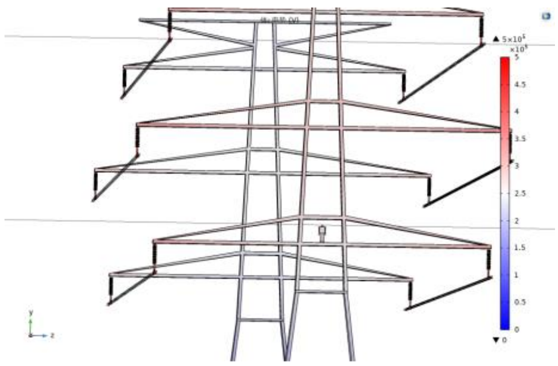

Figure.3Personnel on the tower side (potential V)

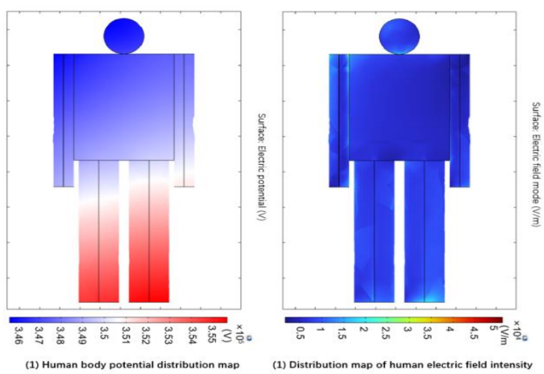

Figure.4Electric field distribution diagram (potential V, electric field mode V/m)

When the live workers reach the waist of the transmission tower, the field strength at the top of the head is small, the field strength on both sides of the neck is higher, the field strength of the body part is gradually increased from top to bottom, and the field strength of the arm part is gradually decreased from top to bottom (FIG 3, FIG 4). Because the legs of the per-sonnel are in contact with the poles, the field strength at the bottom of the legs is relatively low. The shoulders and wrists of the personnel have different degrees of electric field distortion, and the maximum field strength appears in the neck up to 17000V/m.

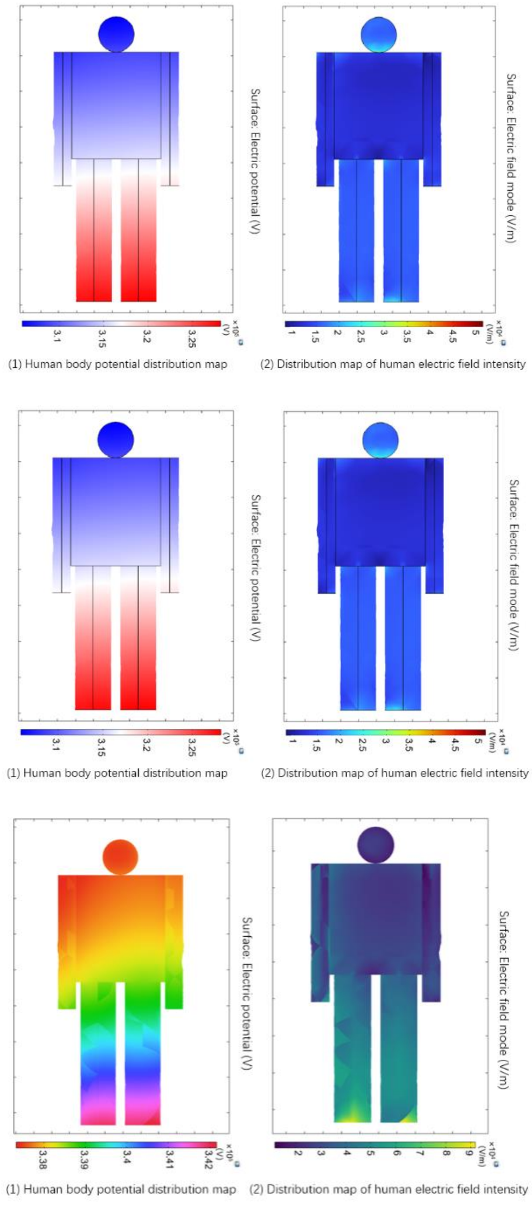

Figure. 5 Body surface electric field (potential V, electric field mode V/m) at cross arm

It is stipulated that the transmission line phases are designated as A, B, and C from top to bottom. FIG. 5 presents the simulation results of the electric field on the body surface when the operator is posi-tioned above each of the three phases, A, B, and C. The figure shows that as the operator moves from the pole and tower to the transmission line, the induced electromotive force on the body surface increases with the higher phase reached. Specifically, when the operator is in phase C, the maximum induced potential is observed at the head, whereas in phases B and A, it is observed at the foot. Regardless of the phase, the potential on the side of the body nearest to the power line is always higher than on the opposite side.

In phase C, the induced field intensity on the body surface is notably lower compared to the other phases. In phase B, the maximum electric field dis-tortion occurs at the shoulder nearest the transmis-sion line, while in phase A, it is at the neck. The greatest range of electric field distortion is observed in phases B and C, with phase A following. Any depression or protrusion of the operator's body parts increases electric field distortion, potentially com-promising safety. To mitigate this, operators should avoid extending their arms and legs and keep their torso close to minimize electric field distortion on the body surface.

Table 1 Simulation results of body surface electric field at cross arm

Job position	Minimum field strength	Maximum field strength	Distortion difference	Distortion multiple
Phase A cross arm	11kv/m	51kv/m	40kv/m	3.64
Phase B cross arm	9kv/m	50kv/m	41kv/m	4.56
Phase C cross arm	2kv/m	9kv/m	7kv/m	3.5

Intermediate potential serves as the transitional state between ground potential operation and equi-potential operation. This paper primarily investigates two scenarios for intermediate potential operation, where live workers are positioned at a horizontal distance of 3 meters from the conductor. Simulation analyses were performed for cases where workers are situated both inside and outside the conductor, yielding the following results.

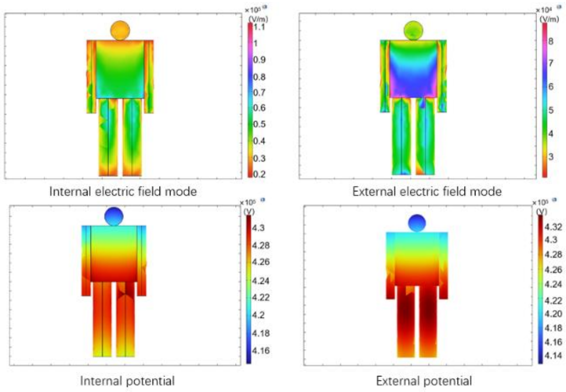

Figure.6Electric field and potential dis-tribution (potential V, electric field mode V/m) on A phase A wire

Figure 6 shows the electric field mode and potential distribution of the operators when they are located on the A-phase wire, with all personnel facing the wire. As shown in the figure, the presence of the operator causes distortion of the electric field around the wire. When the operator is located on the outside of the transmission line, the electric field modulus is larger, and the maximum electric field distortion occurs at the shoulders when they are located on both sides. When they are located on the inside, the potential on the body surface is slightly higher than that on the outside.

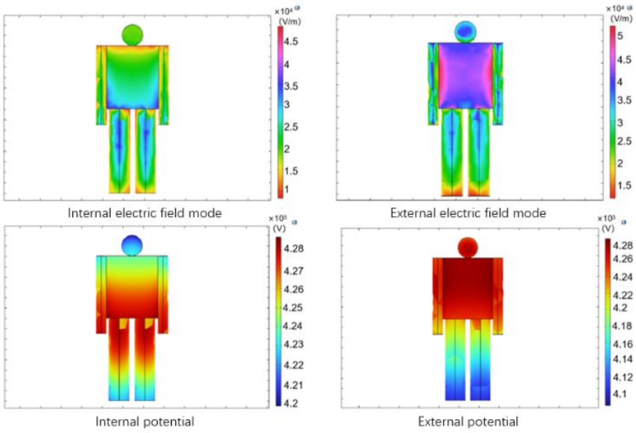

Figure.7Electric field and potential dis-tribution at B-phase wire (potential V, electric field mode V/m)

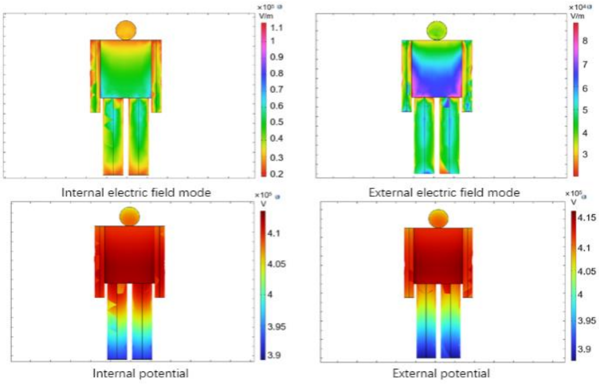

Figure.8Electric field and potential dis-tribution (potential V, electric field mode V/m) at the C-phase wire

FIG. 7 and FIG. 8 illustrate the distribution of electric field and potential when the operator is positioned in the B phase and C phase wires, re-spectively. Similar to phase A, the electric field mode value is higher on the outside than on the inside, while the electric potential is greater on the inside than on the outside. Among the three phas-es—A, B, and C—phases A and C exhibit a higher electric field mode value compared to phase B. Specifically, in phase A, the neck and shoulder ex-perience the most significant electric field distortion; in phase B, it affects the sides of the chest; and in phase C, it is most pronounced at the waist.

Table 2 Electric field simulation results of wire side surface

Job position	Minimum field strength	Maximum field strength	Distortion difference	Distortion multiple
A-phase side	18kv/m	91kv/m	73kv/m	4.10
B-phase side	14kv/m	52kv/m	38kv/m	2.72
C-phase side	21kv/m	89kv/m	68kv/m	3.24

When the operator contacts the wire, the electrical level of the body surface reaches the highest, the electric field distortion is the largest, and there is a great risk. Therefore, the model of the person standing on the wire with his arms outstretched is analyzed.

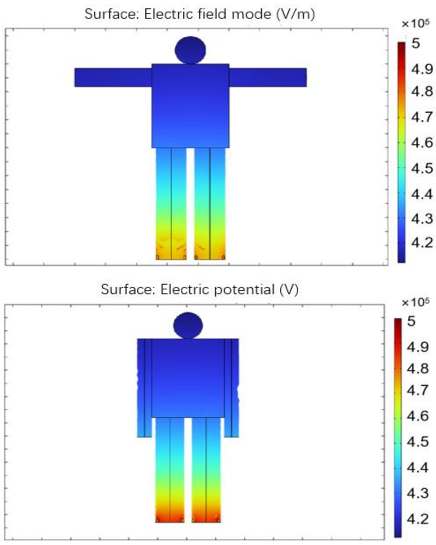

Figure.9 Surface electric field of equipotential operation (field mode V/m)

The simulation results, as illustrated in the figure, reveal that the electric field strength at the feet of operators is highest when they are working with electricity, reaching up to 490 kV/m. This represents a 400.6 kV/m increase compared to the electric field strength under normal operating con-ditions (89.4 kV/m), which is 4.5 times greater than under normal conditions, indicating severe electric field distortion. Additionally, opening the arms mitigates the distortion of the electric field at the feet, although it leads to an increase in the distortion field strength at the arms.

4. Conclusion

The surface field strength of the operators is constrained by multiple factors, and the distance from the charged body and the uneven structure of the human body surface are the biggest influencing factors. Through calculation and analysis, the following conclusions are drawn:

(1) When climbing along the transmission steel tower, the electric field strength on the side close to the live line is greater than that on the side far away from the live wire. The distribution trend of the electric field on the surface of the steel tower is similar when the operator is located at different positions on the tower body, but the specific field strength values may vary, with the shoulder and head having the highest field strength values.

(2) In any homework situation, the most severe distortion of the electric field on the body surface of the operator is the protruding and concave parts of the human body, such as the neck, shoulders, feet, etc. The protection of the protruding parts should be strengthened, and the operator should reduce the amplitude of the movement to avoid the body parts protruding too much and aggravating the electric field distortion.

(3) According to the "Technical Standards for Safety of Power Frequency Electric Fields", protective measures need to be taken by operators when working at work points where the surface field strength exceeds 20KV/m. Based on the research results of this article, live working personnel need to take electrostatic protection measures when they are not in direct contact with live objects; When entering equipotential, protective shielding clothing must be worn.

Declaration of Conflicting Interests

The author(s) declared no potential conflicts of interest with respect to the research, author-ship, and/or publication of this article.

Data Sharing Agreement

The datasets used and/or analyzed during the current study are available from the corresponding author on reasonable request.

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