Numerical Calculation and Analysis on the Surface Electric Field Characteristics of Hot-Line Robot

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ABSTRACT

Hot-Line robot (HLR) is an automatic transmission line inspection device developed in recent years. The mounting device should be contacted with the high voltage transmission line thus to realize the voltage transfer at the first operation stage of the HLR, and the HLR device which is regarded as a floating electrode might be damaged by discharge induced by the filed distortion during the voltage transfer process. The surface electric field of HLR device is optimized to improve its operation reliability, and a static-electric field finite element model of the transmission line which includes the HLR device is developed in this paper, and the dynamic surface electric filed characteristics of HLR during elevating operation process are studied by the finite elements model. Results show that influenced by the electric field which induced by high-voltage transmission line, the induced electric field can be generated on the surface of HLR during the process of elevating operation. The induced electric field distorts on the edge chamfer of HLR device which is regarded as a floating electrode. The maximum field strength position is influenced by the arrangement of the overhead wire conductor, and the edge chamfers are the key points of the electric field optimization of the HLR. The results of this study could provide theoretical basis and technical support for the optimization of HLR insulation characteristics, which is of great value to improve its operation reliability.

INTRODUCTION

Hot-Line robot (HLR) is an automatic transmission line inspection device developed in recent years, which can insure the safety of hot-line work, reduce the workload of manual hot-line work, decrease the operator's labor intensity, reduce the danger caused by strong electric field and improve the level of line operation and maintenance[1-2]. Influenced by the electric field around the high-voltage transmission lines, there will be an electric potential rise on HLR’s surface in the process of its upper and lower lines: when approaching the transmission line, a sharp change in the electric field strength may cause damage to the HLR as well as the control circuit of the elevating device [3-4]. Therefore, it is necessary to calculate and optimize the surface electric field distribution of the HLR at the product design stage to ensure the operational safety and reliability of the equipment under high voltage environment.

At present, the design research of HLR at home and abroad mainly focus on two aspects: structural function design and environmental adaptability design[8-14]. There
is little research on the safety of the initial phase (mount phase) of the HLR operation. In the process of close to the high voltage transmission line, the HLR forms a suspended electric potential by the impact of alternating electric field, the electric potential increases on surface will affect the operational reliability of the device body. There are a lot of researches on the distribution of power frequency electric field near AC overhead transmission lines. The main methods include charging simulation method, finite element method and boundary element method[5-7]. The research mainly focused on how the transmission line influence the building and the human body, but the research about the influence of the transmission line on the HLR is litter, which limits the improvement of the HLR insulation design technology. Based on the finite element theory of electrostatic field, this paper establishes the numerical model of electrostatic field of transmission line (including HLR), and based on this model, the electric potential distribution and field strength characteristics of the HLR surface under different transmission line voltage level are analyzed, and then the HLR surface insulation optimization method is put forward, the research results for the HLR insulation design can provide a theoretical basis.

MATHEMATICAL MODEL OF ELECTROSTATIC FIELD FOR HIGH VOLTAGE TRANSMISSION LINE

In order to obtain the electric field distribution of the HLR and analyze the safety of the HLR under different operating conditions, the electric field numerical modeling of the overhead line containing the HLR should be carried out first. Under normal operating condition, the electric field around the overhead line changes with time, since the change frequency of the electric field under 50Hz current is low, so that it can be considered that the electric field distribution around the overhead line subject to the law of electrostatic field. Therefore, finite element numerical model of the electric field around the transmission line is established by using the theory of electrostatic field.

HLR Physical Model

HLR is mainly composed of the robot body and the live operation compositions. Fully enclosed metal shell is used on the main electronic components of the body to achieve electromagnetic shielding; the body goes upper and lower line by using the live operation of the robot lifting mechanism. Since the automatic mounting part is made of insulating material, the HLR in the upper/lower line operation can be regarded as a floating electric potential in the electric field of the high voltage transmission line. Therefore, the finite element method (FEM) is used to calculate the electric field distribution on the surface of the equipment.

A finite element model of electrostatic field with a target about 126kV voltage HLR is established, its physical structure is shown in Figure 1, the robot body shell material is the aluminum alloy 6063-T6, shell size is 100cm (L) * 100cm (H) * 60cm (W); Automatic loading device material is the polyethylene, the arm length (D) is 0.3 m, in the process of establishing a numerical calculation model, the geometrical characteristics of the automatic mounting part of the device are ignored for the simplified calculation.
Mathematical Model of Electrostatic Field

The Maxwell equations in the electrostatic field can be expressed as:

\[ \nabla \times \mathbf{E} = 0 \]  
\[ \nabla \cdot \mathbf{D} = \rho \]  

Where \( \rho \) is the charge density, for linear media, the relationship between the electric flux density \( \mathbf{D} \) and the electric field intensity \( \mathbf{E} \) can be expressed as:

\[ \mathbf{D} = \varepsilon \mathbf{E} \]  

Where \( \varepsilon \) is the electric field strength, \( D \) is the electrical density, \( \varepsilon \) is the material dielectric constant.

As the electrostatic field is free of rotation field, the scalar potential \( \varphi \) is introduced as the auxiliary quantity to simplify the calculation. The relationship between the electric field intensity and the scalar potential is as follows:

\[ \mathbf{E} = -\nabla \varphi \]  

The scalar potential is substituted into the electrostatic field control equation, and the Poisson equation in the electrostatic field problem is obtained as:

\[ \nabla^2 \varphi = -\frac{\rho}{\varepsilon} \]  

Boundary Conditions

For the overhead transmission lines containing HLR, the boundary conditions of the surrounding electrostatic field distribution should be:

As for the three-phase high-voltage conductor of the transmission line, the boundary of the calculation domain obeys to the Dirichlet boundary:

\[ \varphi|_\Gamma = g(\Gamma) \]  

Where \( \Gamma \) is the conductor and shell surface boundary, \( g (\Gamma) \) is the voltage function, which can be constant and zero. When it is zero, it indicates that it is grounded. The boundary conditions on the interface between the surface soil and the air medium are the tangential and normal boundary conditions of the interfacial field of different media, called natural boundary conditions. The natural boundary conditions for the electric
field strength and the electrical density of the medium 1 and the medium 2 interface in the electrostatic field are

\[
\begin{align*}
E_{t1} &= E_{t2} \\
D_{n1} - D_{n2} &= \rho_s
\end{align*}
\] (7)

Where \(E_{t1}\) and \(E_{t2}\) are the tangential components of the electric field intensity on both sides of the interface, \(D_{n1}\) and \(D_{n2}\) are the normal components of the electrical density on both sides of the interface, and \(\rho_s\) is the free surface charge density at the interface of the medium. For the HLR surface, apply the floating potential boundary condition:

\[
\int_{S} \frac{\partial \phi}{\partial n} ds = Q
\] (8)

Where \(n\) is the outer normal vector of the surface \(S\) of the HLR, \(Q\) is the surface charge of the suspended conductor, and \(Q = 0\).

**ELECTROSTATIC FIELD NUMERICAL MODEL OF HLR SURFACE**

The physical model of the overhead line for the finite element numerical calculation of the electrostatic field is shown in Figure 2. The solution domain of the electrostatic field is composed of three-phase conductor, live working robot, soil, and air medium. The conductor is made of steel core aluminum hinge line LGJ-150/20. The overhead line’s height from ground is referenced to the typical 110kV overhead transmission line standard (ZM-18-type straight pole tower, tower spacing between 100m, 18 meters above the ground level, sag 1.02m), the three-phase conductor spacing is 3.5m. The lowest point (sag maximum) from the ground on the overhead line is regarded as the calculation of cross-section for two-dimensional electrostatic field modeling, and the geometrical characteristics of the HLR’s internal components are ignored.

Based on the electrostatic field finite element model of the transmission line established in this paper, electric field distribution of the surface of HLR under different operating conditions is calculated by the Ansoft. Firstly, the CAD software is used to build the solid model of overhead line and the HLR, and then import the physical model.
and set the physical parameters of the model (the relative dielectric constant of the air region is 1, the conductivity is \(2 \times 10^{-14} \text{ S} / \text{m}\), the relative permittivity of the soil is 10, the conductivity is set to \(1 \times 10^{-4} \text{ S} / \text{m}\)) through the Ansoft geometric interface. The HLR is set as a floating electrode during the calculation, the three-phase wires are respectively applied with a potential load, simultaneously applying infinite boundaries at the boundary of the solution domain. Finally, set the grid parameters and solver parameters of the model. In order to ensure the accuracy of the calculation, set the local grid control area near the surface of the HLR, near the tip the mesh size was set to 1/5 of its minimum characteristic curvature size, and the total energy tolerance is set to 1e-3.

**DISTRIBUTION OF ELECTRIC FIELD ON HLR SURFACE UNDER DIFFERENT OPERATING CONDITIONS**

The HLR rises from the ground to get to the high voltage conductors in the process of operation, when the distance between the HLR and the high voltage conductor reduced to a certain value (0.3 m), the robot arm is extended to contact with the high voltage line. The finite model of the transmission field is used to calculate the HLR’s surface electric field distribution under different operating conditions. In order to maximize the influence of the overhead line electric field on the electric field distribution of the HLR’s surface, the voltage of the corresponding phase conductor of the live operation robot is set to the maximum value.

**Surface Electric Field Distribution of the HLR on A - phase Conductor Operation**

Under A-phase conductor operating condition (A phase voltage 89.8kV, B phase voltage -44.9kV, C phase voltage -44.9kV), when the live robot is 0.3m from the overhead line, the electric field intensity near the overhead line and the surface of HLR is shown in Figure 3. Results show that the electric field around the overhead line is affected by the A-phase conductor voltage and is not evenly distributed; A-phase conductor and its vicinity electric field intensity is the largest. By the influence of the electric field of the overhead line conductor, an induced electric field is established on the surface of the HLR, and there is an electric field concentration at the edge chamfer. So the edge chamfer is the key point of the electric field optimization of the HLR; Since there is a certain distance from the line to the HLR, the maximum field strength of the HLR(4.64e5 V / m) is smaller than the that of the conductor surface(1.35e6 V / m).

![Surface Electric Field Distribution of the HLR on A-phase Conductor Operation](image)
Under A-phase conductor operating condition, the relationship between the maximum electric field strength on the surface of the HLR and the distance from the overhead line to the HLR as shown in Figure 4. Results show that with the increase of the distance, the electric field intensity of the device surface gradually decreases. When the distance increases from 0.3m to 1.8m, the maximum electric field strength decreases from 4.64e5V/m to 2.67e5V/m, for different voltage levels of the line, HLR should be located at a specific location from the overhead line to start the mechanical mount device to ensure that the surface of the electric field strength does not exceed the maximum allowable value.

**Figure 4. Relationship between maximum surface field strength of HLR and line distance under A-phase working condition.**

**Surface Electric Field Distribution of the HLR on B-phase Conductor Operation**

Under B-phase conductor operating condition (A phase voltage -44.9kV, B phase voltage 89.8kV, C phase voltage -44.9kV), when the live robot is 0.3m from the overhead line, the surface field strength near the overhead line and the HLR is shown in Figure 5. Results show that the electric field around the overhead line is affected by the B-phase conductor voltage and is not evenly distributed, the intensity of the electric field in the B-phase conductor and its vicinity is the largest; By the influence of the electric field of the overhead line conductor, an induced electric field is formed on the surface of the HLR, and there is an electric field concentration at the edge chamfer. The maximum electric field strength is lower than that under the A-phase conductor operating condition. So the edge chamfer is the key part of the electric field optimization of the HLR. Since there is a certain distance from the line to the HLR, the maximum field strength of the HLR (4.11e5V/m) is smaller than the field strength of the conductor surface (1.69e6 V/m).

**Figure 5. Surface field distributions of HLR under B-phase working condition.**

Under B-phase conductor operating conditions, the relationship between the maximum electric field strength on the surface of the HLR and the distance from the
overhead line to the HLR as shown in Figure 6. It can be seen from the figure that with the increase of the distance between the HLR and the overhead conductor, the electric field intensity of the device surface gradually decreases. When the distance between the HLR and the overhead line increases from 0.3m to 1.8m, the maximum electric field strength decreases from 4.11e5V / m to 1.27e5V / m. It can be seen from the calculation results, for different voltage levels of the line, HLR should be located at a specific location from the overhead line to start the mechanical mount device to ensure that the strength of the electric field does not exceed the maximum allowable value.

<table>
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<tr>
<th>distance (m)</th>
<th>Electric field strength (V/m)</th>
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<tr>
<td>0.3</td>
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<tr>
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<tr>
<td>0.9</td>
<td>3.00e5</td>
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<td>2.00e5</td>
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<tr>
<td>1.8</td>
<td>1.50e5</td>
</tr>
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</table>

Figure 6. Relationship between maximum surface field strength of HLR and line distance under B-phase working condition.

**Surface Electric Field Distribution of the HLR on C - phase Conductor Operation**

Under C-phase conductor operating condition (A phase voltage -44.9kV, B phase voltage -44.9kV, C phase voltage 89.8kV), when the live robot is 0.3m from the overhead line, the surface field strength near the overhead line and the HLR is shown in Figure 7. Results show that the electric field around the overhead line is affected by the C-phase conductor voltage and is not evenly distributed, the intensity of the electric field in the C-phase conductor and its vicinity is the largest. By the influence of the electric field of the overhead line conductor, an induced electric field is formed on the surface of the HLR, and there is an electric field concentration at the edge chamfer. So the edge chamfer is the key part of the electric field optimization of the HLR; Since there is a certain distance from the line to the HLR, the maximum field strength of the HLR(5.09e5V / m) is smaller than the field strength of the conductor surface(1.35e6 V/m).

![Figure 7](image_url)
Under C-phase conductor operating conditions, the relationship between the maximum electric field strength on the surface of the HLR and the distance from the overhead line to the HLR as shown in Figure 8. It can be seen from the figure that with the increase of the distance between the HLR and the overhead conductor, the electric field intensity of the device surface gradually decreases. When the distance between the HLR and the overhead line increases from 0.3m to 1.8m, the maximum electric field strength decreases from 5.09e5V/m to 2.67e5V/m. It can be seen from the calculation results, for different voltage levels of the line, HLR should be located at a specific location from the overhead line to start the mechanical mount device to ensure that the surface of the electric field strength does not exceed the maximum allowable value.

![Figure 8. Relationship between maximum surface field strength of HLR and line distance under C phase working condition.](image)

**CONCLUSIONS**

The finite element numerical model of the overhead line electric field is established and the electric field distributions of the HLR under different operating conditions are calculated. On this basis, the distributions of electric field on the surface of HLR under different operating conditions are studied. The main conclusions are as follows:

1. The electric field around the overhead line is affected by the conductor voltage, the electric field strength of the overhead wire conductor and its vicinity is the highest; By the influence of the electric field of the overhead line conductor, the HLR can be regarded as a floating electric potential, an induced electric field is formed on its surface, and an electric field distortion occurs at the edge chamfer. The maximum field strength position is influenced by the arrangement of the overhead wire conductor, and the edge chamfers are the key points of the electric field optimization of the HLR.

2. As there is a certain distance from the line to the HLR, the maximum field strength of the HLR surface is smaller than the conductor surface field strength. And in the process of the HLR approaching the high voltage wire, the maximum electric field strength of the HLR gradually increase, the increase of the electric field is related to the arrangement of the overhead wire conductor.

**REFERENCES**
