330kV Live Working Platform Design based on Minimum Approach Distances Analysis via Weighted Digraph

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Abstract. Considering the strict requirements of live working platform in compact substation, a module assembly based structure is put forward. In order to meet the demands of insulation performance, a method of calculating minimum approach distances based on graph theory is proposed, and the feasible regions of structural parameters and flow parameters are obtained, which are finally verified in experiments.

1. Introduction
Live working in the substation is conducive to reducing economic losses and casualties [1]. However, there is a lack of research on live working platform in the substation due to the strict requirements for insulation performance [2]. Relevant papers focus on the structure of the live working platform and the realization of its key functions, but seldom discuss the influence of the insulation performance on the platform design [3-4]. In this paper, minimum approach distances are taken as the constraints, and an algorithm is proposed to associate the platform design and the insulation performance based on the view of weighted digraph.

2. The Structure of the 330kV Live Working Platform
The application scenario of the discussed live working platform is the 330kV substation in Fuping, and its structure is shown in Figure 1. It mainly consists of three parts: the mobile carrier, the module assembling mechanism and the upper mobile platform. Considering that using a single long insulating support as the main body of the lifting mechanism will lead to the overall height of the live working platform exceeding demands when it travels on its own, a platform, which lifts by automatic assembly of modules, is designed to ensure the insulating distance. In view of the layout and symmetry of the whole vehicle, the number of the insulation modules are limited to three. On account of the poor wear resistance of the insulation material, the connection mechanism of the insulation modules should adopt metal material to ensure the reliability of repeated assembly. Thus, how to calculate the minimum approach distances in the live working space where multiple floating conductive objects exist is a problem to be solved.
3. Geometric Discharge Path Graph (GDPG)

3.1 Definition of the Parameters and Constraints

In the light of the floating conductors, total clearance consisting of two or more insulation clearances in series is regarded as the indicator of insulation performance. The total clearance, defined as the complex gap, is limited to no more than 3100mm when the operator in the combination gap is at the lowest 50% operating impulse discharge voltage position under the condition of 330kV [5]. For ease of description, the following symbols are defined: \( S_{LLCG} \) (phase to phase complex gap); \( S_{LLMAD} \) (phase to phase minimum approach distance); \( S_{LGCG} \) (phase to ground complex gap); \( S_{LGMAD} \) (phase to ground approach distance); \( S_{LH} \) (the minimum distance between the bare part of the human body and the charged body when entering or quitting equal potential). The constraints of the complex gaps, the minimum approach distances as well as \( S_{LH} \) are shown in Table 1.

| \( S_{LLCG} \) | \( S_{LLMAD} \) | \( S_{LGCG} \) | \( S_{LGMAD} \) | \( S_{LH} \) |
|---------------|---------------|---------------|---------------|---------------|
| 4000mm        | 3500mm        | 3100mm        | 2600mm        | 400mm         |

In order to meet the stated constraints in the whole process of the live working, a weighted digraph, namely geometric discharge path graph (GDPG), is constructed. Its vertex set \( \Lambda \) contains all the conductors in the live working space; its arc set \( \Gamma \) contains the lines linking the space conductors; and the corresponding weight set \( \Xi \) contains the minimum distances between the space conductors. Thus, the problem of solving the complex gap is equivalent to finding the shortest path of the weighted digraph. So as to create the digraph, a working plane is selected and the conductors are labelled in the graph according to the spatial location. Four subgraphs are derived from the original GDPG: phase-to-phase approach distance discharge path graph (PPD), phase-to-ground approach distance discharge path graph (PGD), phase-to-phase complex gap discharge path graph (PPG), and phase-to-ground complex gap discharge path graph (PGG). It is stipulated that when drawing the PGD and PGG, the directed arrows can only point from a conductor with a high geometric position to a conductor with a low geometric position. When drawing PPD and PPG, the directed arrow can only point from the
conductor near the high voltage operating terminal to the conductor remote from the high voltage operating terminal.

According to the system configuration of the 330kV live working platform, the conductor set is defined as \( \Lambda = \{b, h, l_p, e_p, e_{np}, c_b, m_t \} \), where \( b \) represents the insulated basket; \( h \) represents the live working operator; \( l_p \) represents the lower platform; \( e_p \) represents the high voltage electrode to be operated; \( e_{np} \) represents the high voltage electrode not to be operated; \( c_b \) represents the intelligent electric control cabinet; \( m_t \) represents the \( t \)th metallic connector from top to bottom.

For live working, the main factors affecting the minimum approach distance and the complex gap are: 1) parameters related with the substation like the diameter of the isolating circuit breaker; 2) the structural parameters of the live working platform; 3) flow parameters like parking clearance. The above parameter sets are denoted correspondingly as Env, Stru and Flow. The elements in the weight set \( Y \) could be expressed as the following:

\[
L = f(t), L \in Y, t \in Env \cup Stru \cup Flow
\]  

(1)

### 3.2 GDPG under Multiple Working Conditions

#### 3.2.1. Driving and climbing.

In the process of driving and climbing, the human body and the entire live working platform are at ground potential, so PGD is considered. That is, \( L_{e,b} \leq S_{LGMAD} \), where \( L_{e,b} \) is the distance between the high voltage electrode to be operated and insulated basket.

#### 3.2.2. Lifting.

During the lifting process, the human body and the equipotential conductors in the insulated basket are at floating potential, and PGG is considered as shown in Figure 2.

#### 3.2.3. Translation and equipotential.

During the translation of the insulated basket, the human body and the equipotential conductors in the basket are at floating potential. Thus, PPG and PGG are considered as shown in Figure 3. When the operator and the high electrode voltage to be operated are

![Figure 2. PGG of lifting process](image-url)
in equipotential, there is no floating conductor in the discharge path between the high voltage electrodes, so PPD, PGD and PGG are considered as shown in Figure 4.

![Figure 3. GDPG of translation](image)

![Figure 4. GDPG of equipotential](image)

### 4. Feasible Solution Region

#### 4.1. Structural Parameters

It could be deduced from graph $D^3$ in Figure 3 and graph $E^3$ in Figure 4 that the width of the insulated basket $W_{bask}$ should satisfy:

$$
W_{bask} \leq L_{th} - D_{ib} - S_{LLCG} \\
W_{bask} \leq L_{th} - D_{ib} - S_{LLMAD}
$$

(2)

In the formula, $L_{th}$ —— the distance between two phases; $D_{ib}$ —— the diameter of the isolating breaker. By calculation, $W_{bask}$ is designed to be 800mm.

In order to satisfy $S_{LLCG}$, the height of the insulation module $H_{im}$ as well as the height of main insulation module $H_{min}$ should satisfy:

$$
2H_{im} + H_{min} > S_{LLCG}
$$

(3)

Considering the mechanical criteria and the layout, $H_{im}$ is designed to be 1100mm, and $H_{min}$ is designed to be 1500mm. Other structural parameters are mainly designed according to the mechanical demands.

#### 4.2. Flow Parameters

The set of the flow parameter Flow is defined as the following:

$$
Flow = \{H_{human}, L_{apt}, L_{pc}, H_{lif}\}
$$

(4)

In the formula, $H_{human}$ —— vertical projection length of human body; $L_{apt}$ —— translation distance of insulated basket; $L_{pc}$ —— packing clearance; $H_{lif}$ —— lifting height.

Considering the constraints of the driving and climbing process $L_{e,b} \leq S_{LLMAD}$, the relationship between $L_{pc}$, $H_{human}$ and $L_{e,b}$ is shown in Figure 5. It could be found that $H_{human}$ has greater influence.
on $L_{p_L}$ than $L_{p_c}$. $L_{p_c}$ is chosen to be $[600,800]$ and $H_{\text{human}}$ is chosen to be $[1000,1300]$ in consideration of margin.

By solving the PGG of the lifting process in Figure 2, the relationship between $H_{\text{human}}$ and $S_{\text{LGCG}}$ is shown in Figure 6. From the figure, the minimum $S_{\text{LGCG}}$ occurs at the transition from lifting the main insulation module to lifting two modules. Since $S_{\text{LGCG}}$ should be greater than 3100mm, $H_{\text{human}}$ is further confined to $[1000,1100]$.

The minimum $S_{\text{LGCG}}$ appears at the moment when the operator enters or exits the state of equipotential during the translation and equipotential process, since the insulation distance in the vertical direction does not change during the process. By solving the PGG of Figure 3 and 4, $H_{\text{LP}}$ is limited to $[3400,3700]$.

5. Experimental Verification

Based on the feasible solution region obtained, a simplified equal-scaled experimental platform is built to measure 50% operating impulse discharge voltage $U_{S0}$, whose average measurement values are above 1300kV. The experiments are conducted in UHV Experimental Base of Beijing. For an estimation of the $U_{S0}$, it could be derived from the equation (5).

$$U_{S0} = 1080k_f \ln(0.46S_{\text{LGCG}} + 1)kV$$

In the formula, $k_f$ is a constant applicable to floating conducting objects, whose reference range is $[1.0,1.2]$. Taking $k_f = 1.2$, the calculated value of $U_{S0}$ is 1148.6kV, which is less than the experimental value. Thus, the feasible solution region is valid.

6. Conclusion

In order to establish the relationship among the insulation performance, the structural parameters and the flow parameters, a calculation method utilizing the weighted digraph is applied. The feasible solution domain of the parking distance in the task environment is $[600,800]$, the vertical projection length of human body being $[1000,1100]$ and the lifting height being $[3400,3700]$. Experiments are conducted to verify its feasibility.

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