Research on Lightning Protection Verification Based on Three-dimensional Model of Substation

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Abstract. In the past, the lightning protection design of substations was carried out by manual calculation. The joint protection of multiple lightning rods and the joint protection of lightning rods of unequal height brought a huge amount of work to the calculation, which was low in efficiency and prone to errors. At the same time, the lightning protection design based on two-dimensional drawings cannot visually display the real lightning protection situation, and cannot reflect the correctness of the lightning protection results during the blueprint review process. The review experts need to repeat calculations to demonstrate. Computer simulation and calculation of lightning protection in substations can not only greatly improve work efficiency, but also visually verify the feasibility of the design scheme through the visual display of the three-dimensional design model of the substation. This thesis mainly studies the realization method and process of lightning protection design based on 3D software, and gradually realizes 3D visualization of lightning protection area and completes lightning protection verification.

1. Introduction

1.1. Lightning protection overview

Lightning disasters in China are mainly concentrated in April-September each year, with more areas in the southeast of China as a whole. Lightning strikes in nature can be divided into two types. One is direct lightning strikes, that is, the discharge of clouds to the ground, which directly strikes on the building, causing thermal and electrodynamic effects. Strong lightning current, hot high temperature, violent shock wave, transient electromagnetic field and strong electromagnetic radiation and other comprehensive physical effects will bring great effects to buildings, power lines, people, and electronic equipment inside and outside buildings on the ground. Which can cause metal melting, fire and explosion, and cause property damage, personal injury or death. The other is lightning induced high voltage and lightning electromagnetic pulse radiation (LEMP), that is, lightning produces electromagnetic induction, lightning electromagnetic pulse radiation and electrostatic induction of thundercloud electric field around the discharge channel, which has a fairly large sensing range. Dangerous overvoltages may occur within the range of 1.5km-2km centered on lightning strikes. The research object of this thesis is direct lightning strike.

1.2. Current status of lightning protection design

At present, the commonly used measures in the design of substations against direct lightning strikes are
the installation of lightning rods. The lightning rods are grounded conductive objects whose function is to guide the attracted lightning into the ground. Lightning rods are generally set higher than the protected object. Under the action of thundercloud electric field, the strength of the tip electric field is greater than that of the air electric field, and it will cause a lightning strike when it meets the thundercloud and lightning pioneer. Under a lightning rod of a certain height, there is a lightning protection safety zone that cannot guarantee that the protected object will never be struck by direct lightning. More than two lightning rods are used in the project to expand the protection range. The combined shielding effect of the two lightning rods makes the protection range of the middle part larger than that of a single lightning rod. The other way is to use lightning protection lines, which have a smaller lightning effect and protection width than lightning rods. This way is suitable for protecting overhead lines and the lightning protection lines can be woven into lightning protection nets to protect important buildings.

The development of lightning protection design usually involves the following steps:

1. Preliminarily determine the type, position and height of the lightning rod according to the overall layout of the substation;
2. Preliminary calculate the protection range of the lightning rod, draw the protection range map, and verify whether the protected object is within the protection range based on the height requirements of the protected object;
3. According to the verification conditions of the protected objects, appropriately adjust the position, height and even the number of the lightning rods, and determine that all protected objects need to be within the scope of protection after calculation and review;
4. The number, type, location and height of lightning rods determined by electrical professionals will be provided to the general drawing and structural design personnel with the materials needed for subsequent design. The lightning protection design plan will be finalized after the designer confirms that there is no objection.

1.3. The need for research

Compared with the expression method and lightning protection calculation process of the traditional two-dimensional drawing. Using the visualization effect of the model in the three-dimensional software can greatly improve the efficiency of lightning protection design, and has significant effects in the space verification of lightning protection areas, and full-professional collaborative design.

2. Lightning protection calculation method

2.1. Roll-ball method

The roll-ball method is a calculation method for the protection range of air-termination devices recommended by the International Electrotechnical Commission (IEC), which is based on the electrical geometric model. The protection range of the lightning rod depends on the amplitude of the lightning current, fully considering the insulation level of the equipment in different areas.

The basic principle of the roll-ball method is shown in Figure 2. A sphere whose radius is the lightning current strike distance S rolls along the part that needs to be protected from direct lightning strikes. When the sphere only touches the lightning rod or the ground and does not touch the equipment H to be protected, the equipment is protected against lightning, the equipment is protected against lightning. At this time, the protection margin of the equipment is m, and the settling height of the roll-ball is X.
According to the insulation level of the protected equipment and the wave impedance of the conductor, the roll-ball method is used to calculate the maximum allowable lightning impulse current value and lightning current strike distance \( S \), and calculate the protection range through the lightning current strike distance value \( S \), the height of the lightning rod \( H_{sw} \), and the distance \( L \) between the lightning rods. The protection range of the roll-ball method is closely related to the insulation level of the protected equipment, except for the height of the lightning rod and the distance between the lightning rods.

2.2. Polygon method

At present, the "polygon method" is relatively mature in domestic power systems, that is the protection range of a single lightning rod is a polygonal cone with the lightning rod as the axis. It is characterized by intuitive design, simple calculation, and investment saving, which is suitable for buildings below 20m. The basic principle is shown in Figure 1. The protection radius \( R_x \) of the horizontal plane of the height of the protected object \( h_x \) is related to the height of the lightning rod \( h \) and the height of the protected object \( h_x \).

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**Figure 1** The principle of roll-ball method

**Figure 2** The principle of the polygon method
The height of the protective object of the polygon method is mainly related to the height of the lightning rod (h). For lightning rods of equal height, the change value of the minimum protection height is affected by the distance between the lightning rods.

3. **Lightning protection calculation process**

3.1. **Software architecture**

The lightning protection design needs to realize the software function through the data interface provided by the 3D design software, and should support both the polygon method and the roll-ball method at the same time. The specific functions of the software include: definition of lightning rod attributes (including rod height, protection height, etc.); space layout based on the three-dimensional model of the substation (including lightning rod insertion point, movement, labeling, etc.); and the software should export lightning protection calculations and calculations automatically. The architecture diagram is shown in Figure 3.

![Figure 3 The architecture of lightning protection design software](image)

3.2. **The arrangement of lightning rod**

The 3D model of civil engineering, electrical, structure, etc. can be referenced to the lightning protection design drawing file based on the collaborative design function of 3D software. Determine the location of the lightning rod according to the preliminary lightning protection design plan, add the height of the lightning rod through the lightning rod editing function, and number the lightning rod for distinction.

![Figure 4 Schematic diagram of lightning rod number](image)
The movement of the lightning rod needs to be completed in the two-dimensional view by picking the tip of the lightning rod, using the move command, selecting a new location point and pressing Enter. The main function to realize this function is shown in the following source code:

```c
// Movement of the lightning rod
Extern int MoveSpin();
{
    ads_printf("Moving the lightning rod = DQ_MoveSpin");
    ads_name entRemoveSpin;
    ads point ptPicks;
    BOOL bMark=TRUE;
    While(bMark)
    {
        Struct resbuf *pFilter;
        pFilter=ads_buildlist(RTDXF0,"INSERT",8,"F-blz",0);
        int nRes;
        nRes=Xentsl("Please select the lightning rod to be moved <Enter>:", pFilter,
                    entRemoveSpin, ptPicks);
        if(nRes!=RTNORM)
        {
            Ads_relrb(pFilter);
            return RSRSLT;
        }
        Ads_relrb(pFilter);
        ads_command(RTSTR,"_.Undo",RTSTR,"_BE",0);
        MoveSpin(entRemoveSpin);
        ads_command(RTSTR,"_.Undo",RTSTR,"_End",0);
    }
    return RSRSLT;
}
```

The lightning rods can be automatically marked separately by extracting the attribute information of the lightning rod and using coordinate matching. By reading the location attributes of the lightning rod in the general plan, two-dimensional coordinates can be obtained, and then defining a spatial coordinate system, to obtain the three-dimensional coordinates of the target point of the model to be marked. Due to the relative relationship of the positions, the coordinates of the target point relative to the plane drawing can be known, and the coordinates of the target point in the space coordinate system can be obtained through Euler angle conversion and TF conversion. At last, we can realize the annotation function of the lightning by loading the model annotation family.

3.3. Lightning protection calculation

3.3.1. The calculation process of dogleg method. D represents the distance between two lightning rods, hr is the radius of the roll-ball, when the height of the double lightning rod is less than hr, and when $D \geq \sqrt{h_1(2h_r - h_1)} + \sqrt{h_2(2h_r - h_2)}$, lightning protection calculation can be calculated according to the way of single lightning rod.

When $D < \sqrt{h_1(2h_r - h_1)} + \sqrt{h_2(2h_r - h_2)}$, the calculation method is as follows:
As the figure 5 shows, the protection range outside the ABCE area is calculated according to the calculation method of a single lightning rod. The protection range of the location of the CE line should be calculated as follows:

\[ D_2 = \frac{2h_r(h_1 - h_2) - h_1^2 + h_2^2 + D^2}{2D} \]  

(1)

\[ b_0 = \sqrt{h_1(2h_r - h_1) - D_1^2} \]  

(2)

On the AOB axis, the upper boundary line of the protection range between A and B is calculated as:

\[ h_x = h_r - \sqrt{h_r^2 - h_1(2h_r - h_1) + D_1^2 - x^2} \]  

(3)

Where \( x \) represents the distance between the calculation point F and the straight line CE. Within the protection range of the ABCE area, on the vertical plane between point C and point F with a height of \( h_x \), take \( h_x \) as the height of the imaginary lightning rod, and perform lightning protection calculations according to the method specified for a single lightning rod. Two equal height lightning rods are calculated as \( h_1 = h_2 \).

3.3.2. The calculation process of Roll-ball method. For two lightning rods of equal height, the protection range outside the two lightning rods is calculated according to the calculation method in the case of a single lightning rod; the calculation method of the lowest point height value \( h_0 \) of the protection range inside the two lightning rods is as follows:

\[ h_0 = h - \frac{D}{D'} \]  

(4)

Where, \( D \) represents the distance between two lightning rods.

The minimum width \( b_x \) on one side of the protection range on the horizontal plane of \( b_x \) height between two lightning rods is calculated as follows:

\[ b_x = h_0 - h_x, \text{ when } h_x \geq \frac{h_0}{2} \]  

(5)
For two lightning rods of non-equal height, first determine the independent protection areas of the two lightning rods respectively. Then in the joint protection area of the two lightning rods, take the point of the higher and the lower at the same height so as to obtain two lightning rods equivalent to the same height, and the higher part is calculated as a single lightning rod. The higher part shall be calculated as a single lightning rod.

4. Lightning protection design and verification based on 3D visualization

4.1. 3D visualization method based on roll-ball method

The principle that a single lightning rod adopts the 3D visualization of the roll-ball method is: It is known that the vertex of the lightning rod is pt1, the base point is pt2, the radius of the roll-ball is r, take the vertex pt1 as the center of the circle, and take r as the radius to make a circle intersection on the ground at pt3.

Taking the points pt1 and pt3 on a sphere with a radius of r as the condition, get the sphere center coordinate O of the sphere. Taking O as the center and r as the radius to make an arc that passes through pt1 and pt3, the edge of vertex pt1 and pt3, and the connection line between pt2 and pt3, two straight lines and a circular arc form a closed figure. Lastly rotating 360° with the connection line of pt1 and pt2 as the axis, and the three-dimensional lightning protection area is obtained.
The research on the three-dimensional lightning protection area composed of two lightning rods mainly focuses on the generation of the joint protection area between the two lightning rods. First, obtain the independent protection area of two lightning rods through the method of generating the protection range of a single lightning rod and determine the edge of the prism. Then calculate the position of the roll-ball according to the roll-ball method and generate a sphere, roll the sphere to obtain the solid part that intersects the prism. Finally, the remaining solid part after subtracting the prism from the sphere is the joint protection area.

4.2. 3D visualization method based on dogleg method

For a single lightning rod, the 3D visualization principle is: After determining the coordinates of the point where the vertex, base point, turning point, polyline and the reference plane intersect, connect the points into a closed polygon, and then rotate 360° around the line from the vertex to the base point to generate protection for a single lightning rod range.

For two lightning rods, if the arc between the tips of the two lightning rods is approximated as a straight line, the joint protection area can be approximated as shown in the figure below:
The height of the lowest point can be obtained through the lightning protection calculation formula of the dogleg method, and then the three-dimensional coordinate of the lowest point can be obtained according to the coordinates of the apex, base point, and turning point of the lightning rod. Combining the function with the coordinates of each point in the above figure can obtain the radian value between the pyramid surfaces, and generate the prism edge and the prism entity, and finally the effect shown in Figure 10 can be achieved after the function is processed.

Figure 10 Schematic diagram of lightning protection area

4.3. Lightning Check Based on 3D Visualization

Use three-dimensional design software to perform full professional modeling of substations, including electrical main equipment, structures, buildings, fences, etc. All majors are positioned in a unified coordinate system, so that the assembly model can be obtained by referring to the professional models.

Determine the type, position and height of the lightning rod according to the overall layout of the substation, define the base point of the lightning rod through the lightning protection design software, number the lightning rod, set the height of the protection, and finally calculate the lightning protection and generate the lightning protection range map, as shown in Figure 11.

Figure 11 Three-dimensional diagram of lightning protection range

Finally, the calculation document is output. Due to the limited space, only part of the calculation book content is extracted:

- The name of the lightning rod: #1-#2
- The height of the two lightning rods is equal and is: 25.00m
- The distance between the two lightning rods is: 40.00m
- Calculate the height influence coefficient P: h <= 30m, P=1.00
- Lightning rod protection height Hx: 14.00m
  ha=25.00-14.00=11.00m
- Calculate the protection radius on the 14.00m level of the protected object:
hx = 14.00 m, h = 25.00 m, hx >= 0.5h,
r_x = (h-hx)*P = (25.00 m-14.00 m)*1.0000 m = 11.00 m
x=Dist/ha/p=400000.00/110000.00/1.00=3.64
y=hx/h*10=14.00*25.00*10=5.60
Find the bx curve:
lenth =x-int(x)=3.64-3=0.64
Interpolation calculation temporary bx
X=5, Y=3, firstbx=0.80
X=5, Y=4, secondbx=0.68
Temporary bx=firstbx*(1.0-lenth) + secondbx * lenth=0.80*(1.0-0.64) + 0.68*0.64=0.72
Interpolation calculation temporary bx
X=6, Y=3, firstbx=0.77
X=6, Y=4, secondbx=0.64
Temporary bx=firstbx*(1.0-lenth) + secondbx * lenth=0.77*(1.0-0.64) + 0.64*0.64=0.69
b1=0.72
b2=0.69
lenth2=y-int(y)=5.60-5=0.60
b3=(1.0-lenth2)*b1+lenth2*b2=(1.0-0.60)*0.72+0.60*0.69=0.70
Calculate bx
bx=b3*ha*p=0.70*11.00*1.00=7.72 m

5. Conclusion
With the in-depth application of three-dimensional design of substations, the visualization and
digitalization of design results have become more and more significant. The lightning protection
verification based on the three-dimensional design of the substation improves the design efficiency.
Especially for the more special cases such as the combined protection of multiple lightning rods and the
combined protection of unequal height lightning rods, the three-dimensional visualization brings a more
intuitive experience to the lightning protection verification work. In order to realize the automatic
calculation, the dogleg method and the roll-ball method are used to calculate the lightning protection
using computer-made algorithms, and the effect map of the lightning protection range will be clearly
seen by visualization means.

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