Calculation of Lightning Level of Transmission Line Tower Using Graphite Grounding Device

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Keywords: Lightning protection, Graphite grounding device, ATP-EMTP, Grounding resistance, Lightning withstand level.

Abstract. In recent years, graphite grounding devices have developed rapidly and have been widely used in transmission networks. However, the main application is that they are highly corrosive to alkaline soils, and their research on conductivity and lightning resistance is insufficient. Therefore, this paper establishes the ground net model through the simulation software CDEGS, and calculates the power frequency grounding resistance of three different materials of graphite, steel and copper under different conditions and compares them. Using ATP/EMTP software, the calculation model of the lightning strike level including the tower tower, the line, the insulator flashover and the grounding resistance was established. The lightning resistance level of the transmission line tower using the graphite grounding device and the steel grounding device was calculated. Then verify the feasibility of the graphite grounding device.

Introduction

Towers play the role of supporting the conductors and ground lines of overhead transmission lines in the transmission process. Grounding device is one of the important components of tower. When tower is struck by lightning, grounding device can ensure that lightning current quickly leaks into the earth and plays a certain role in lightning protection. At present, China's traditional grounding devices are mostly made of metal materials such as steel and copper. However, the corrosion resistance of metal materials is poor, it needs to be replaced regularly, the cost is high, and it is easy to be stolen. As a form of carbon, graphite has a wide range of sources and relatively low price, and its performance in electrical and thermal conductivity is better than traditional metal materials [1]. In recent years, graphite materials have been widely used in power transmission tower grounding devices because of their high corrosion resistance[2-4]. However, their conductivity and lightning protection performance have not been fully exploited due to lack of theoretical basis [5-9]. Therefore, the use of graphite as a grounding material makes it necessary to study its electrical conductivity and lightning protection performance. In this paper, the power frequency grounding resistance of different materials under different conditions is calculated, and the influence of graphite grounding on lightning resistance level is analyzed, which shows the feasibility of graphite grounding device.

Grounding Resistance of Graphite Grounding Device

Operational experience shows that lightning strikes are the main cause of transmission line failures [10], and about 40% to 70% of line trips are caused by lightning strikes. Lightning direct strikes on transmission line poles and towers can be divided into counterstrikes and shielding strikes [11]. Among them, the lightning counterattack is closely related to the grounding resistance, and reducing the grounding resistance can improve the lightning resistance level. In the aspect of grounding device resistance reduction, the literature [12] proposed a deep well grounding technology. The literature
[13] proposed the oblique grounding pole drop resistance technology. Literature [14] proposed to reduce the grounding resistance by using blasting grounding technology.

The grounding resistance is related to factors such as soil resistivity, grounding type, and lightning current frequency, so they are compared separately. The relevant parameters of the three different grounding materials are shown in Table 1.

<table>
<thead>
<tr>
<th>Number</th>
<th>Relative resistivity</th>
<th>Relative permeability</th>
<th>radius /m</th>
<th>material</th>
<th>Resistivity /Ω·m</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>1</td>
<td>1</td>
<td>0.01</td>
<td>copper</td>
<td>1.75x10^8</td>
</tr>
<tr>
<td>2</td>
<td>110</td>
<td>636</td>
<td>0.01</td>
<td>steel</td>
<td>1.92x10^6</td>
</tr>
<tr>
<td>3</td>
<td>1857</td>
<td>1</td>
<td>0.01</td>
<td>graphite</td>
<td>3.25x10^5</td>
</tr>
<tr>
<td>4</td>
<td>1857</td>
<td>1</td>
<td>0.022</td>
<td>graphite</td>
<td>3.25x10^5</td>
</tr>
<tr>
<td>5</td>
<td>1857</td>
<td>1</td>
<td>0.028</td>
<td>graphite</td>
<td>3.25x10^5</td>
</tr>
</tbody>
</table>

### Establishment of Graphite Grounding Device Model

The model of transmission line tower grounding device is established by CDEGS software. The form of grounding device is shown in Figure 1. The depth of grounding device is 0.8 meters, the length of box edge is 10 meters, the length of quadrangular epitaxy ray is 12 meters, and the soil is uniform.

![Figure 1. Frame ray type grounding device diagram.](image)

### Grounding Resistance at Different Soil Resistivities

When soil resistivity is 10Ω·m, 50Ω·m, 100Ω·m, 200Ω·m, 400Ω·m, 600Ω·m and 800Ω·m respectively, the power frequency grounding resistance of three different materials, copper, steel and graphite, is simulated and calculated. The results are shown in Table 2.

<table>
<thead>
<tr>
<th>Soil resistivity /Ω·m</th>
<th>Require maximum resistance /Ω</th>
<th>copperΦ=10 mm</th>
<th>steelΦ=10 mm</th>
<th>graphiteΦ=10 mm</th>
<th>graphiteΦ=22 mm</th>
<th>graphiteΦ=28 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>ρ=10</td>
<td>10</td>
<td>0.27</td>
<td>0.29</td>
<td>0.41</td>
<td>0.21</td>
<td>0.21</td>
</tr>
<tr>
<td>ρ=50</td>
<td>10</td>
<td>1.36</td>
<td>1.38</td>
<td>1.65</td>
<td>1.06</td>
<td>1.04</td>
</tr>
<tr>
<td>ρ=100</td>
<td>10</td>
<td>2.72</td>
<td>2.74</td>
<td>3.05</td>
<td>2.12</td>
<td>2.07</td>
</tr>
<tr>
<td>ρ=200</td>
<td>15</td>
<td>5.43</td>
<td>5.45</td>
<td>5.79</td>
<td>4.24</td>
<td>4.14</td>
</tr>
<tr>
<td>ρ=400</td>
<td>15</td>
<td>10.85</td>
<td>10.87</td>
<td>11.23</td>
<td>8.48</td>
<td>8.28</td>
</tr>
<tr>
<td>ρ=600</td>
<td>20</td>
<td>16.28</td>
<td>16.30</td>
<td>16.66</td>
<td>12.72</td>
<td>12.41</td>
</tr>
<tr>
<td>ρ=800</td>
<td>20</td>
<td>21.70</td>
<td>21.72</td>
<td>22.08</td>
<td>16.96</td>
<td>16.55</td>
</tr>
</tbody>
</table>

According to the simulation data obtained in Table 2, the power frequency grounding resistances of the three grounding materials under different soil resistivity are compared, as shown in Fig. 2.
According to Table 2 and Figure 2, when the soil resistivity is the same and the diameter of steel, copper and graphite grounding material is 10 mm, the grounding resistance of the steel grounding device is slightly larger than that of the copper grounding device, and the difference is not significant. The grounding resistance of the graphite grounding device is the largest, because the resistance ratio of graphite is larger. According to Figure 2, when the diameter is the same, the power frequency grounding resistance of graphite, copper and steel grounding devices increases with the increase of soil resistivity. When the soil resistivity is the same, the grounding resistance decreases with the increase of graphite diameter, which reduces the influence caused by the larger resistivity of graphite grounding material itself. It can be concluded from the analysis that the power frequency grounding resistance of the graphite grounding device with a diameter of 28 mm is smaller than that of steel and copper, which is about 0.76 of the copper grounding device, which has certain advantages.

**Grounding Resistance with Different Grounding Forms**

This paper mainly considers TC5, TC10 and TC15 grounding modes. As shown in Figure 3, the grounding resistance of grounding devices with different materials is calculated and analyzed when different grounding modes are adopted.

<table>
<thead>
<tr>
<th>Grounding mode</th>
<th>H</th>
<th>L</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC5</td>
<td>15</td>
<td>8</td>
</tr>
<tr>
<td>TC10</td>
<td>15</td>
<td>20</td>
</tr>
<tr>
<td>TC15</td>
<td>15</td>
<td>28</td>
</tr>
</tbody>
</table>
When the soil resistivity is the same, 500 Ω·m, the grounding resistance values of the grounding devices with different grounding materials and different grounding types are shown in Table 4.

Table 4. Different grounding power frequency grounding resistance when ρ=500 Ω·m.

<table>
<thead>
<tr>
<th>ρ=500</th>
<th>copper</th>
<th>steel</th>
<th>graphite</th>
<th>graphite</th>
<th>graphite</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ω·m</td>
<td>Φ=10 mm</td>
<td>Φ=10 mm</td>
<td>Φ=10 mm</td>
<td>Φ=22 mm</td>
<td>Φ=28 mm</td>
</tr>
<tr>
<td>TC15</td>
<td>7.668</td>
<td>7.686</td>
<td>8.103</td>
<td>7.780</td>
<td>7.577</td>
</tr>
</tbody>
</table>

According to Table 4, the power frequency resistance histograms of different grounding forms are drawn, as shown in Figure 4.

![Figure 4. Different frequency grounding power frequency grounding resistance.](image)

It can be seen from Fig. 4 that the power frequency grounding resistance of the three grounding devices of copper, steel and graphite decreases with the increase of the area of the grounding grid.

TC5, TC10 and TC15 are grounded by round steel with diameter of 10 mm in practical engineering. The grounding resistance of steel with diameter of 10 mm and graphite grounding material with diameter of 28 mm under three grounding modes is analyzed and compared, as shown in Table 5.

Table 5. Three grounding types of grounding resistance.

<table>
<thead>
<tr>
<th>Grounding mode</th>
<th>Soil resistivity /Ω·m</th>
<th>Steel Φ=10 mm</th>
<th>Graphite Φ=28 mm</th>
<th>Maximum power frequency grounding resistance /Ω</th>
</tr>
</thead>
<tbody>
<tr>
<td>TC5</td>
<td>500</td>
<td>13.17</td>
<td>12.48</td>
<td>15</td>
</tr>
<tr>
<td>TC10</td>
<td>1000</td>
<td>18.55</td>
<td>17.59</td>
<td>20</td>
</tr>
<tr>
<td>TC15</td>
<td>1500</td>
<td>23.16</td>
<td>22.03</td>
<td>25</td>
</tr>
</tbody>
</table>

It can be seen that the power frequency grounding resistance of graphite grounding device is less than the maximum power frequency grounding resistance, which meets the requirements, and the grounding resistance of graphite grounding device with diameter of 28 mm is smaller than that of steel grounding device with diameter of 10 mm.

**Grounding Resistance at Different Frequencies**

Because of the wide frequency range of lightning current, the grounding resistance of grounding device may be affected when the frequency changes in a wide range. This section mainly calculates the soil resistivity of 500 Ω·m, the grounding resistance of different material grounding devices varies with frequency under TC5 grounding mode. The grounding resistance of three kinds of grounding materials at different frequencies is shown in Fig. 5.
Figure 5. Grounding resistance of three grounding materials at different frequencies.

It can be obtained that the grounding resistance of the three materials becomes larger as the frequency increases. When the diameter is the same, the grounding resistance of the steel is larger than that of the other two materials. When the frequency is the same, the larger the diameter of the graphite grounding device, the smaller the grounding resistance. As the frequency increases, the grounding resistance of the graphite grounding device rises less than steel and copper grounding devices.

**Tower Graphite Grounding Device Lightning Resistance Level**

**Lightning Level Calculation Model**

**Lightning Current Model.** In this paper, the Heidler model [15] is used, and the waveform is 2.6/50 μs. Its waveform is shown in Figure 6.

![Lightning Current Waveform](image)

**Figure 6. Lightning current waveform.**

**Tower Model.** In this paper, the multi-wave impedance tower model of Japanese scholar Hara is used. When the lightning wave propagates along the tower, the height of the tower and the size of the tower are the main factors affecting the inductance and capacitance. The multi-wave impedance model considers the influence of these factors, and takes different wave impedances for different parts of the tower [16], and divides the tower wave impedance into three parts: the main body, the pillar and the crossarm.

The main part of each floor of the tower:

\[
Z_{Tk} = 60 \left( \ln \frac{2 \sqrt{2} h_k}{r_{ek}} - 2 \right)
\]  

(1)

In the formula \( r_{ai} = 2^{1/3} \left( r_{b1}^{1/3} R_{b1}^{2/3} \right) \left( r_{b2}^{1/3} R_{b2}^{2/3} \right)^{1/4} \), \( k = 1, 2, 3, 4 \)

Where \( r_{ek} \) is the radius of the vertical struts of the tower;
\( r_b \) is the pillar radius of the bottom of the tower; \( R_{r_2} \) is the distance between the main pillars of the tower; \( R_B \) is the distance between the bottom pillars.

Wave impedance of each strut:

\[
Z_{LK} = 9Z_{TK}
\]

Cross-wave impedance:

\[
Z_{Ak} = 60\ln\frac{2h_k}{r_{Ak}}
\]

In the formula \( h_k \) is the height of the main body of the tower; \( r_{Ak} \) is the equivalent radius, taking 1/4 of the length of the joint between the cross arm and the main material.

In this paper, the 220kV SZ1C6 tower is used for simulation. The structure of the tower is shown in Figure 7. The calculated wave impedance of each part of the tower is shown in Table 6. The simulation model of the tower established in ATP-EMTP is shown in Fig. 8.

<table>
<thead>
<tr>
<th></th>
<th>k</th>
<th>1</th>
<th>2</th>
<th>3</th>
<th>4</th>
</tr>
</thead>
<tbody>
<tr>
<td>main body ( Z_{TK} )/(Ω)</td>
<td>140.42</td>
<td>129.16</td>
<td>107.33</td>
<td>91.19</td>
<td></td>
</tr>
<tr>
<td>pillar ( Z_{LK} )/(Ω)</td>
<td>1263.74</td>
<td>1162.43</td>
<td>965.99</td>
<td>820.73</td>
<td></td>
</tr>
<tr>
<td>Cross arm ( Z_{Ak} )/(Ω)</td>
<td>476.24</td>
<td>463.78</td>
<td>412.95</td>
<td>396.53</td>
<td></td>
</tr>
</tbody>
</table>

![Figure 7. Tower structure.](image1)

![Figure 8. ATP-EMTP Tower Simulation Model.](image2)

**Transmission Line Model.** The transmission line uses the JMARTI model. The reflected wave generated by the lightning from the top of the tower to the end of the two lines will affect the lightning overvoltage. In order to eliminate the influence, a long line of the same characteristic can be respectively set on both sides of the lightning striking tower. The line consists of six phase conductors and two ground conductors. The phase conductor type is 2*LGJ-240/40, the inner diameter is 1.083cm, and the outer diameter is 2.166cm. The wires are split and arranged vertically, and the splitting pitch is 40cm. The ground wire model is GJ-50 and the outer diameter is 0.9cm. The specific parameters of the line are shown in Figure 9.
**Insulator Flashover Model.** In this paper, the definition method is used to judge whether the insulator flashes. The insulator flashover model in ATP-EMTP is shown in Fig. 10.

The insulator flashover model is composed of a controllable switch and a MODELS module. According to the definition method, the insulator does not flash under normal conditions, and the controllable switch is set to the off state at this time. Only when the voltage across the insulator string is higher than U50% of the insulator, the insulator flashes, the controllable switch is set to the closed state, and the insulator string is turned on. The lightning impulse flashover voltage is set to 1200 kV during simulation.

**Grounding Resistance Model.** The grounding device is shown in Figure 1. The grounding material is steel and graphite, respectively. The rectangular grounding grid is 12.5 m long and 9.5 m wide, and the four-angle ray is extended by 32 m. The grounding device has a buried depth of 0.8 m. The grounding resistance of the graphite grounding device is 12.80 Ω, and the grounding resistance of the round steel grounding device is 13.58 Ω.

**Lightning Resistance Level Simulation of Counterattack**

The simulation model is shown in Figure 11.
The output of TACS module represents the state of the insulator. When the output is 0, the insulator does not flashover, and continues to increase the amplitude of lightning current. When the output is 1, the insulator flashover occurs. At this time, the lightning current value is defined as the lightning resistance level of the line, indicating the critical value of the insulator flashover.

When using round steel grounding device, lightning strikes transmission line towers to make insulators flashover, the voltage at both ends of insulators is shown in Fig. 12. The simulation results show that the lightning resistance level of round steel grounding device is 103.353kA. When using graphite grounding device, lightning strikes transmission line towers to make insulators flashover, the voltage at both ends of insulators is shown in Fig. 13. The simulation results show that the lightning resistance level of graphite grounding device is 108.275kA. The lightning resistance level of the line with graphite grounding device is higher than that of the line with steel grounding device.

Figure 12. Voltage at both ends of insulator flashover using round steel grounding device.
Figure 13. Voltage at both ends of insulator flashover using graphite grounding device.

Conclusion

In this paper, the model of transmission line tower and its grounding device is established, the power frequency grounding resistance of grounding device is simulated and analyzed, and the lightning resistance level of lightning struck tower with different material grounding device is simulated and calculated. The conclusions are as follows:

(1) Grounding resistance of grounding devices with different materials increases with the increase of soil resistivity. When the diameter is the same, the grounding resistance of graphite is larger than that of copper and steel grounding devices because of its high resistivity. When the diameter increases to 28 mm, the grounding resistance is smaller than that of 10 mm copper and steel.

(2) Grounding resistance of grounding devices with different materials increases with the increase of frequency. In terms of rising trend, graphite grounding devices are slightly smaller than round steel and copper grounding devices when the frequency is greater than 10 kHz.

(3) When the grounding device is box-ray type, the lightning resistance level of 220 kV transmission line lightning tower is obtained by simulation calculation. The lightning resistance level of graphite grounding device with diameter of 28 mm is 108.275 kA, and that of steel grounding device with diameter of 10 mm is 103.353 kA. It can verify that the lightning protection performance of graphite grounding device meets the requirements.

References


