Study on Influence of Viaduct on Electric Field Distribution around High Speed Railway under Lightning Environment

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ABSTRACT

Lightning damage is one of the key factors that affect secure and stable operation of high-speed railway. Research on the variation law of electric field intensity around high-speed railway under the effect of lightning downward leader is of great value to explain lightning-striking mechanism of high-speed railway. In this paper, a three-dimensional lightning simulation model for high-speed railway is established based on leader progression model, and the influence of different viaduct heights and materials on the electric field distribution around high-speed railway is simulated and analyzed. It is found that the electric field intensity of viaduct catenary system with rebar mesh material is greater than that with concrete material, besides, the height increment of viaduct would strengthen the electric field intensity of the catenary system. Therefore, the requirement on lightning protection designation and construction of high-speed railway in viaduct section should be higher than that in roadbed section.

Keywords: High-speed railway, viaduct, downward leader, material, height, electric field distribution.

INTRODUCTION

In recent years, high-speed railway has developed rapidly in China. According to statistics, up to June 2015, the mileage of high-speed railway in China has reached 17000 km [1]. The safety and reliable operation of the high-speed railway is related to national property and the personal safety of people. Lightning is a major factor that affects the safe operation of high-speed railway, in 2011, the "7.23" Ningbo Wenzhou Railway line is a major railway traffic accident, which is mainly caused by lightning according to official reports [2]. Therefore, it is of great practical significance to study the lightning striking characteristics of high-speed railway. This paper mainly studies the high-speed railway in the viaduct section because viaduct structure is widely used in the construction process of high-speed railway in China. Literature [3] concluded that number of lightning-strikes of high-speed railway...
catenary and 220 kV electric power system overhead line are equal. Some scholars have studied the influence of the erection method of lightning protection facilities on lightning protection, literature [4-5] pointed out that elevating PW line, setting lightning conductor of catenary system or improving installation method of lightning protector can improve the lightning withstand level of the line, literature [6] discussed the setting of grounding mode on the basis of the above research. However, the influence of the viaduct structure on the electric field near the high-speed railway needs further study. In this paper, the influence of different viaduct heights and materials on the electric field distribution near high-speed railway are studied.

MODEL ESTABLISHMENT

Viaduct Model

The power supply system of high-speed railway in China is mainly composed of catenary power supply and viaduct structure. The contact wire, catenary wire, AF Wire (Feeder wire) and PW (Protection wire) are set as Figure 1 according to AT power supply mode.

![Figure 1. Presentation of Viaduct.](image1)

![Figure 2. Diagram of High-speed Railway with Viaduct in CAD.](image2)

The working voltage of AF and T are alternating current with a value of 27.5KV but backward for each other, and the PW working voltage is approximately 0 kV. The material of the contact wire and the catenary wire are set as copper alloy, and the material of AF wire and
PW wire are set as steel, which are the same as literature [7]. The viaduct structure is mainly composed of bridge pier and box girder, which are both reliably grounded by grounding reinforcement. The lightning current leaks to the ground through grounding reinforcement in case of lightning strikes. The whole structure of viaduct is connected to the ground, thus its voltage is approximately equal to that of the ground. It is known from EGM (Electrical Geometric Model) that catenary wire can effectively shield the contact wire because catenary wire is near the top of the contact wire [8,9]. Figure 2 is the three-dimensional model of catenary system with viaduct of high-speed railway.

**Setting of Simulation Parameter**

In the process of ANSOFT simulation, the solution domain is set to 110% of the model size. Set the ground potential to be zero potential. The parameter criteria in the model is illustrated in Table 1.

<table>
<thead>
<tr>
<th>Material</th>
<th>Relative permittivity</th>
<th>Conductivity (S/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>vacuum</td>
<td>1.0006</td>
<td>0</td>
</tr>
<tr>
<td>Copper</td>
<td>1</td>
<td>5.8×10^7</td>
</tr>
<tr>
<td>Steel</td>
<td>1</td>
<td>2×10^6</td>
</tr>
<tr>
<td>concrete</td>
<td>2.7</td>
<td>7×10^-3</td>
</tr>
</tbody>
</table>

**Lightning Downward Leader Model**

The expression of the relation between the total charge \( Q_r \) produced by a single thundercloud discharge to the ground and the amplitude of the lightning current is calculated by equation (1) [10]:

\[
Q_r = 76 \cdot I^{0.68} \times 10^{-3}
\]

(1)

It is worth consideration that when setting the excitation charge source in ANSOFT simulation, large amount of calculation that the ANSOFT software cannot meet and the proportion of the field is uneven, which makes the calculation difficult to carry out if the cloud height is set to the actual height of 2500 m, therefore, it is also need to further optimize the thundercloud charge leader model. As shown in Figure 3, the downward leader is
equivalent to two cylindrical charges that are $Q_1$ and $Q_0$ in this paper.

In this paper, the charge density of main lightning channel is expressed by the most common linear distribution form. When the charge in lightning channel propagates to the ground in downward leader way to $H_C$ far from the ground, the charge density is linearly reduced to zero. When the height of downward leader head is $h_0$, the charge density is set as $\tau = \tau_m$, of which $\tau_m$ is the maximum charge density. The total amount of charge $Q_r$ can be expressed as:

$$Q_r = \frac{\tau_m(H_C - h_0)}{2} + Q_0 \quad (2)$$

In equation (2), $Q_0$ is the charge in the hemisphere of downward leader, and its calculation formula can be expressed by equation (3)

$$Q_0 = \frac{2 \cdot r_0 \cdot Q_r}{3 \cdot (H_C - h_0)} \quad (3)$$

In equation (3), $r_0$ (taken as 5 m in this paper) is the head radius of the leader charge, combined with equation (1) and (2), the charge density can be expressed by equation (4) when the leader height is $H$.

$$\tau = (H_C - h) \frac{2 \cdot (Q_r - Q_0)}{(H_C - h_0)^2} \quad (4)$$

In the process of the leader with negative thundercloud charge propagates to the ground in cascade form from the lower surface of the thundercloud, the linear distributed charge in the downward leader charge channel and the head charge both have an effect on the electric field distribution of the viaduct and the catenary system on the ground. In this paper, the volume charge of the full length of the lightning channel is optimized to be a cylindrical charge $Q$, at the high of 400 m, which is calculated as follows:

$R_v$, the induced electric field at 0 m produced by the charge in the downward channel from 400 m to 2500 m can be calculated by equation (5):

$$E(0) = \int_{h_v}^{H_v} \frac{\tau(h)}{4 \pi \epsilon_0 r^2} dh \quad (5)$$

The optimized cylindrical charge which could be considered as a point charge because of the research space is far enough, so the induced electric field can also be calculated by equation (6).

$$E(0) = \frac{Q_1}{4 \pi \epsilon_0 r^2} \quad (6)$$

Therefore, $Q$ can be obtained by equation (5) and (6).
ELECTRIC FIELD DISTRIBUTION UNDER DIFFERENT INFLUENCE FACTORS

Electric Field Distribution with fixed Viaduct Height and Material

This section, the viaduct material is set as reinforced concrete structure, the viaduct height is 12 m and lightning current is 0.5 kA. Then the excitation source is set up in the ANSOFT software according to the method introduced in chapter 1.2. The electric field intensity around high-speed railway is analyzed and the multiple field intensity distribution clouds in different sections that are top plane of the pillar, center of the bridge and the section plane along the bridge are observed respectively, as shown in Figure 3.

![Electric Field Distribution Cloudscape on Different Sections.](image)

Figure 3. Electric Field Distribution Cloudscape on Different Sections.
Electric Field Distribution under Various Materials

In this section, the viaduct material is set as concrete structure, reinforced concrete structure and steel structure respectively. The simulation results are listed in Table 2. All the simulations of this part are under the condition that viaduct height is 12 m, the inception position of downward leader is at 400 m above viaduct and the lightning current is 0.5 kA.

<table>
<thead>
<tr>
<th>Materials of viaduct</th>
<th>Left AF ($10^3$ kV/m)</th>
<th>Right AF ($10^3$ kV/m)</th>
<th>Left catenary ($10^3$ kV)</th>
<th>Right catenary ($10^3$ kV/m)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Steel_1008</td>
<td>2.3129</td>
<td>2.3239</td>
<td>1.43665</td>
<td>1.447493</td>
</tr>
<tr>
<td>Reinforced concrete</td>
<td>2.2075</td>
<td>2.2196</td>
<td>1.3118</td>
<td>1.3200</td>
</tr>
<tr>
<td>Concrete</td>
<td>2.1872</td>
<td>2.1883</td>
<td>1.2800</td>
<td>1.2780</td>
</tr>
</tbody>
</table>

The maximum field intensity of AF wire and catenary wire on condition that viaduct material is steel or reinforced concrete is greater than the condition that viaduct material is concrete. The primary reason is that massive metal material in the viaduct contributes the box girder and the soil around the catenary to produce more induction charges than the viaduct without metal material, which leads to an increase in space electric field intensity near the catenary system.

Electric Field Distribution under Various Heights of Viaduct

The influence of various viaduct heights on electric field intensity around viaduct is studied in this section based on only changing the height-of-viaduct parameter into 0 m, 5 m, 12 m, 20 m respectively. Figure 2 presents the simulation results.

As is evident in Figure 2, the maximum electric field of AF wire and catenary wire are both increasingly changing with increment of viaduct height, this is because increment of viaduct height will enhance the distortion degree of space electric field intensity between the lightning downward leader and the viaduct catenary system. Especially, when the viaduct height reaches about 20 m, the curves tend to be stable, this is because the distortion degree of the space electric field intensity is close to saturation when the height of the viaduct
reaches 20 m. Therefore, the maximum surface field intensity of the wires would still increase, but the increase is small.

CONCLUSION

This paper presents and discusses the influence of viaduct on the electric field intensity around high-speed railway under lightning environment from two impact factors that are viaduct material and viaduct height. The results show that rebar mesh material in the viaduct would enhance the electric field intensity around catenary system; besides, the degree of distortion of space electric field is strengthened with increment of viaduct height, which would enhance the electric field intensity around the catenary system.

REFERENCES