Optimization design of electric field potential for high-speed EMU high voltage box

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Abstract. Establish the three-dimensional model of high-voltage box and its internal main electrical equipment of EMU. Under the lightning overvoltage condition, through modeling and analyzing the electric field potential distribution of high-voltage components of EMU, understand the insulation weak links of high-voltage components, optimize the insulation gap of high-voltage components, local structure of components and system layout, and systematically master the layout design of high-voltage equipment of EMU method. The research results show that under the lightning overvoltage condition, the areas with higher electric field strength are mainly concentrated in the inlet port of the cable and the outlet port of the circuit breaker, the maximum electric field intensity is concentrated near the electrode of the electromagnetic voltage transformer, and the maximum field strength in the high voltage box is 21.5 kv/cm, which meets the air breakdown standard, has certain safety margin and meets the insulation requirements.

Keywords: EMU, high voltage, lightning, electric field, potential.

1. Introduction.
High voltage system on the roof of high-speed train is the core of train energy supply, and its electrical safety is directly related to the safe and stable operation of high-speed train. With the improvement of EMU operation speed, the over-voltage impact of EMU occurs frequently, which results in insulation breakdown and insulation aging acceleration of on-board electrical equipment, resulting in a sharp decline in insulation performance [2-3]. As the high-voltage system is located outside the roof, the high-voltage insulation parts are easy to be eroded by wind, sand, salt fog and other erosion, which further reduces the insulation performance of high-voltage system components, resulting in insulator flashover along the surface, short-circuit of catenary to vehicle body, tripping of isolating switch of traction substation, and even posing a threat to the safety of passengers [4-5]. The insulation flashover faults of high-voltage components on the roof of high-speed trains have occurred many times on typical high-speed railway lines such as Beijing Tianjin line and Zhengzhou-Xi'an line, resulting in many trains being delayed or even stopped.

To this end, the high-voltage system of EMU is placed in the high-voltage box from the roof outdoor, so as to reduce the impact of the environment on the high-voltage system, which is gradually paid attention by major engine manufacturers [6-7]. However, due to the limited space of the high-voltage box, it is necessary to integrate the voltage transformer, current transformer, circuit breaker,
disconnector, lightning arrester and other high-voltage equipment in the limited space, which puts forward higher requirements for the insulation design of the high-voltage equipment in the high-voltage box. Otherwise, the strong electric field will easily cause the discharge of the high-voltage end to the ground and the high-voltage end to the low-voltage end, which will accelerate the aging of the high-voltage components cause insulation breakdown.

Through the establishment of three-dimensional model of high-voltage box and its internal main electrical equipment of EMU, this paper analyzes the internal electric field potential distribution of high-voltage box when subjected to lightning strike, and understands the insulation weak link of high-voltage components, which provides important theoretical basis for the design and normal operation of high-voltage box.

2. Theoretical analysis.

2.1. layout of high pressure box.

The three-dimensional layout of the high-voltage equipment box of EMU is shown in Figure 1. It can be seen from the figure that the main electrical components in the high-voltage box mainly include the inlet port, outlet port, voltage transformer, main circuit breaker, lightning arrester, high-voltage disconnector, cable, etc. Figure 1 also shows the incoming and outgoing lines in the high-voltage box. After receiving current from the catenary, the pantograph enters the high-voltage box through high-voltage cable and is divided into two circuits, one of which passes through the current transformer and then the vacuum circuit breaker. At the same time, the resistance voltage transformer and electromagnetic voltage transformer are used to monitor the network voltage, and the current transformer monitors the network current; the other is connected to the isolating switch and interconnected with other motor cars through cables. Under normal working conditions, the working voltage of high-voltage equipment in high-voltage box is 25kV single-phase alternating current.

![Fig. 1 Structure diagram of high voltage box of EMU (top view)](image)

1-incoming port; 2-voltage transformer; 3-main circuit breaker; 4-appear port 1; 5-arrester; 6 - high voltage disconnector; 7 - presence of port 2

2.2. Standard lightning current.

Standard lightning current waveforms are specified in standard SAE ARP 5412, and current components a and D are suitable for assessing indirect effects. In contrast, a has higher amplitude and action integral, so the influence of current component A is greater, so the current component A is selected as the experimental waveform. In the standard, the current waveform a is required to reach a peak value of 90% within 3 μs and a peak value within 6.9 μs (±20%) [8-10]. The time to half value should be 69 μs (±
30%). A few negative flashback parameters were combined with the a current waveform. At low altitude, the environment represented by this kind of pulse appears most frequently. In our experiment, the scaled waveform is used to reach the peak value within 6.9 μs (± 20%). The time to half value should be 69 μs (± 30%). In order to facilitate quantitative analysis and engineering calculation, the lightning current waveform is equivalent to a double exponential waveform. The standard waveform is shown in Figure 2, and its mathematical expression is as follows:

\[ I(t) = I_0(e^{-αt} - e^{-βt}) \]  

Where \( I_0 \) is 218810a, \( α \) is 11354s\(^{-1}\) and \( β \) is 647265s\(^{-1}\).

Fig. 2 Lightning current waveform

Corresponding to the standard lightning wave; the lower limit of lightning full wave impulse withstand voltage of roof insulator in TB / T 3077-2003 is 170 kV, and 180 kV voltage is selected as the voltage under lightning overvoltage condition.

2.3. Analysis of electric field potential safety criterion.

In order to improve the safety performance of the high-voltage components in the high-voltage box, it is necessary to make the high-voltage components in the high-voltage box operate safely and stably under normal conditions and some extreme conditions. In the design, the initial field strength of corona discharge is mainly referred to, and the lightning overvoltage condition is taken as the terminal condition.

According to the structural layout of high-voltage box, the electric field environment of high-voltage system is very complex. The inhomogeneous coefficient \( f \) of electric field is usually used to judge slightly uneven electric field and extremely uneven electric field, uniform electric field \( F = 1 \); slightly uneven electric field \( 1 < f < 2 \); extremely uneven electric field \( F > 4 \). However, because \( f > 1 \), the average field strength in the gap is smaller than that in the uniform field gap. Therefore, the breakdown voltage of the slightly inhomogeneous field gap is lower than that of the uniform field gap at the same gap distance. The self sustained discharge condition is the starting condition of corona discharge. The corona inception voltage under the extremely uneven electric field is slightly lower than the breakdown electric field of air, and the stable corona cannot be allowed in the insulation system, so the corona inception voltage becomes the basis of insulation design. Under the condition of extremely uneven electric field, the gap discharge first refers to corona discharge, because the corona inception voltage of the gap is slightly lower than the breakdown voltage UB. When the gap D approaches infinity, i.e. the air gap distance is not considered, the initial breakdown field strength of air is 24.22 kV / cm. When the gap distance is in the range of 1 ~ 10 cm, the breakdown strength \( E_B \) is about 30 kV / cm.
3. **Simulation analysis.**

The upper surface of busbar connecting arrester, outlet port 1 and disconnector is selected as horizontal reference plane, vertical reference plane a of incoming port, vertical reference plane B of outlet port and vertical reference plane C of outlet port II are selected as vertical reference plane. The schematic diagram of reference plane selection is shown in Fig. 3.

![Fig. 3 Internal reference plan of high pressure box](image)

The distribution of field intensity in the high voltage box is analyzed under the lightning over-voltage condition. Under the lightning over-voltage condition, the excitation parameter is set to 170 kV. The overall electric field potential distribution of the high voltage box is shown in the figure.

![Fig. 4 Overall potential distribution of high voltage box](image)

![Fig. 5 Electric field distribution of high voltage box](image)
According to the figure, in the case of lightning overvoltage, the area with higher electric field strength is still mainly concentrated in the inlet port of bushing and the outlet port of circuit breaker, and the maximum electric field intensity is concentrated at the inlet port. This area is mainly the insulation between the cable core and the high-voltage box shell, and its main insulation is high-voltage cable insulation, which can fully meet the needs of electrical safety.

In addition, in the case of lightning overvoltage, the electric field distribution near the two busbars between the main circuit breaker and the high-voltage disconnector in the high-voltage box is investigated. The field strength near the busbar is shown in Fig. 7. The maximum values are 23.4 kV/cm and 24.5 kV/cm respectively.

According to the simulation diagram of the high-voltage box, when the connecting busbar between the main circuit breaker and the disconnector is subjected to lightning overvoltage, its field strength is that it is far away from the corona, and the safety margin is small. In order to improve the electrical safety in the high-voltage box, the local analysis model of the high-voltage components of the connection bus bar is established.

In order to improve the distribution of electric field strength near the bus bar, the connection bus bar between the main circuit breaker and the disconnector is optimized, and the local field strength distribution is studied by simulation analysis, so as to provide reference for the next optimization, and then the electric field distribution of its weak links is further analyzed. Because the simulation analysis object only involves the bus bar and high voltage box, the electric field distribution results are different from the overall results. The problem to be explained through optimization is to take optimization measures to reduce the electric field distribution nearby.

Figure 8 shows the peak value of lightning strike voltage. After solving the simulation model potential and electric field by finite element analysis software, the overall distribution of electric field near the bus bar is obtained. It can be concluded from the figure that the maximum electric field strength is 23.4 kV/cm. In order to avoid the local electric field distortion caused by it, and to reserve sufficient safety margin, it is suggested to fillet the bus bar to avoid air corona discharge due to the nearby electric field distortion when it is subjected to overvoltage. The right angle side of the bus bar shall be filleted with 1 mm, 2 mm and 3 mm fillet respectively. The simulation results show that the maximum field strength decreases to 23.1, 22.6 and 22.0 kV/cm respectively, but the optimization effect is limited.
Further, the shape of the bus bar is changed from rectangle to round cake, and then it is stretched and rounded. On this basis, the field strength distribution is simulated and analyzed, as shown in Fig. 9. It can be seen from the figure that the maximum electric field strength of the bus bar after similar round cake treatment is 19.1kV/cm. Therefore, it can be seen that fillet treatment can improve the distribution of electric field around the busbar and optimize the surrounding electric field environment, increase the electrical safety margin, improve the electrical safety performance.

4. Summary
In this paper, through the establishment of three-dimensional model of high-voltage box and its internal main electrical equipment of EMU, the electric field and potential of voltage transformer, main circuit breaker, lightning arrester, high-voltage disconnector and other main electrical components and their connecting metal parts in the high-voltage box subjected to lightning stroke are simulated and analyzed to understand the weak insulation links of high-voltage components. That is, the bus bar between the main circuit breaker and the disconnector is optimized, which provides an important theoretical basis for the design of the high voltage box and its normal operation.

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