Simulation Analysis of Vehicle Body Overvoltage Caused by EMU Operating Main Circuit Breaker based on 3D Vehicle Body Modeling

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Abstract: At present, China's high-speed railway is in the process of rapid development, followed by the safety of emu has attracted increasing attention. In the course of emu running, the main circuit breaker will be frequently operated in the process of excessive phase, lifting bow and so on, thus causing transient overvoltage. However, the shielding layer of the high-voltage cable is connected to the vehicle body, which will make the over-voltage coupling to the vehicle body, forming the over-voltage of the vehicle body and endangering the driving safety. In this paper, based on the three-dimensional vehicle body model and based on the analysis of the overvoltage generation principle of the vehicle body, the electromagnetic interference coupling path is obtained. Considering the actual working conditions of the standard emu, the interference signal caused by the disconnection of VCB is taken as the interference source to analyze the over-voltage distribution of the vehicle body caused by the disconnection of VCB. The actual three-dimensional model of the vehicle body and the high-voltage cable is built and embedded into the circuit module, which breaks the traditional equivalent method of equating the vehicle body with the four-side impedance, and the over-voltage characteristics of the vehicle body at a specific position can be obtained. The simulation results show that the generated overvoltage is about 2.9kv, the oscillation time is about 25us, and the frequency spectrum is mainly 1.62MHz, which conforms to the basic characteristics of overvoltage.

1 INTRODUCTION

Nowadays, the safe operation of high-speed emu is facing more and more challenges from the external environment. The safe operation of emu has also attracted wide attention from scholars. Frequent operation of the main circuit breaker in the process of over phase, lifting bow and short circuit fault of high-speed emu will cause transient overvoltage, which will not only accelerate the insulation aging of the high voltage components on the roof or even break down the insulation, but also affect the normal operation of the on-board electronic equipment, damage the emu train operation safety.

The domestic and foreign scholars' research on the operation overvoltage of circuit breakers mainly focuses on the power system with different voltage levels. The research on the operation overvoltage of high-speed emu circuit breakers generated by the operation of on-board circuit breakers in the process of over phase, bow lifting and short circuit fault is still relatively rare. Wan Yusu built the whole traction power supply circuit of "traction substation -- catenary network -- high-speed emu", introduced the mechanism of operating overvoltage during the operation of the circuit breaker, and finally simulated the over-voltage waveform of the vehicle body caused by the operation of the circuit breaker (Wan Yusu, 2017). Satoru Hatsukade of the Japan railway technology research institute has analyzed the causes of overvoltage on the vehicle body, arguing that excessive overvoltage on the vehicle body will cause the failure and damage of on-board equipment, especially on-board electronic equipment (HATSUKADE S, MAEDA, 2005). Ding Yong analyzed the characteristics of operating overvoltage of on-board vacuum circuit breakers in high-speed emu, and built a simulation model based on the electrical structure of a certain emu. Finally, the consistency of simulation results and test results was compared (DING Yong, 2017). Yan Jiabin analyzed the electromagnetic interference problem of the

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speed sensor and believed that the surge overvoltage of the vehicle body would be coupled to the core wire through the parasitic capacitance between the shield layer and the core wire, thus causing interference to the speed signal transmitted in the core wire of the speed sensor (Yan Jiabin, Zhu Feng, Li Jun, Sha Miao, 2015).

Most of the predecessors used the circuit to model the over-voltage simulation model of the vehicle body, equating the high-voltage cable with the distributed parameter model and the vehicle body with a four-side impedance. However, the interference of the vehicle body at a specific point cannot be accurately reflected.

Based on the analysis of the overvoltage generation principle of the vehicle body, the electromagnetic interference coupling path is obtained. Considering the actual working conditions of the emu, the three-dimensional model of the vehicle body was established based on the wiring conditions of the high-voltage cable, and the interference signal caused by the breaking of VCB was used as the interference source to analyze the over-voltage distribution of the vehicle body caused by this interference source. The actual car body model is adopted and the 3d model is embedded in the circuit module, which breaks the traditional equivalent method of equating the car body with the four-side impedance, and the over-voltage characteristics of the car body at a specific position can be obtained. The analysis and prediction of the over-voltage performance of the emus are realized to ensure the safety of the emus.

2 BASIC PRINCIPLE AND SIMULATION MODEL BUILDING

2.1 Principle of Generating Overvoltage of Vehicle Body by Disconnecting VCB Operation

Before the circuit breaker operates in normal working condition, the traction motor is no longer working, that is, the traction transformer is in no-load state. Therefore, the process of disconnecting the circuit breaker is similar to a common operation of removing no-load transformer in the power system. To cut off the no-load transformer is to cut off the small current of an inductive load, the current value is very small, at this time the circuit breaker's arc extinguishing ability will play to the extreme, so that the no-load current is truncated before 0, which is the so-called blocking phenomenon, at this time will produce a very high overvoltage. While the shielding layer of the high-voltage cable is connected to the car body, the over-voltage will be coupled to the shielding layer of the high-voltage cable through the core wire, and then transferred to the car body, causing the over-voltage on the car body. (Luigi Battistelli, et.al, 2011)

As shown in figure 1, this is the overvoltage equivalent circuit schematic diagram of high-speed emu operating circuit breaker. The circuit breaker is equivalent with switch K1, where US is the traction substation supply voltage. Catenary is equivalent in terms of centralized parameters. The resistance and inductance of catenary conductor are RS respectively, LS represents. The excitation inductance of the traction transformer is Lm, and CT is the equivalent distributed capacitance of the high-voltage cable core to the vehicle body. In general, CT value is very small.

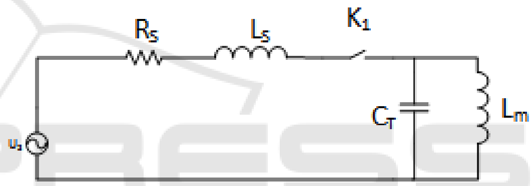

Figure 1: Operation circuit breaker overvoltage equivalent circuit diagram.

When switch K_1 is opened, assuming the current value is I_m before the zero crossing of L_m, then the voltage value at both ends of the equivalent capacitor C_T is U_m. After the current is truncated, the LC circuit will have high-frequency oscillation. Self-oscillation frequency is $\omega_0 = \frac{1}{\sqrt{L_m C_T}}$.

Since the C_T value is small, when all the magnetic field energy is converted into electric field energy instantaneously, the capacitor C_T will have a large overvoltage. The circuit equation is as follows:

$$C_T \frac{du}{dt} + \frac{1}{L_m} \int u dt = 0$$
$$\frac{\mathrm{d}^2 u^2}{dt^2} + \frac{1}{L_m C_T} u = 0 \quad (1)$$

The initial condition is $i(0) = I_0,\ u(0) = -U_0$, by solving the above equation:

$$u = -I_0 \sqrt{\frac{L_m}{C_T}} \sin \omega_0 t - U_0 \cos \omega_0 t \qquad (2)$$

The maximum over-voltage amplitude at both ends of the equivalent capacitance to earth is:

$$U = \sqrt{U_0^{\,2} + I_0^{\,2} \frac{L_m}{C_T}} = U_m \sqrt{\cos^2 \varphi + \frac{f_0^{\,2}}{f^2} \sin^2 \varphi} \qquad (3)$$

According to the above equation, the maximum overvoltage at both ends of the equivalent capacitance to earth is related to the closure phase Angle and the high-frequency oscillation frequency. When the phase Angle is 0° and 180°, the minimum over-voltage amplitude of the circuit breaker when it is opened is Um; When the phase Angle is 90° and 270°, the amplitude is the largest, and the maximum operating overvoltage is Um f0 /f. Among them, the high-frequency oscillation frequency f0 is related to the electrical parameters of traction transformer and high-voltage cable. (David D. Shipp, et.al, 2012)

2.2 Model Building

The model can be modeled from six modules including traction substation, catenary, high-voltage system, vehicle body, high-voltage cable and connection model. After the circuit model modeling is completed, the high-voltage cable and vehicle body can be connected to the circuit to complete the construction of the overall model.

(1) Traction substation

Traction substation, as a connection between the power system and the traction network of electrified railway, functions to convert the power supplied by the power system into the power suitable for electric traction and its power supply mode, among which the core equipment is the traction transformer in the substation. In practical calculation, the traction substation can be equivalent to a power supply with internal impedance, as shown in figure 2.The size of each parameter is:

$$U_s = 38.89 \sin 100\pi; \quad R_s = 0.165\Omega; \quad L_s = 10.8\text{mH}; \qquad (4)$$

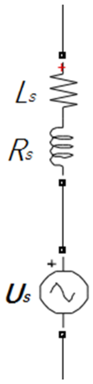

Figure 2: equivalent model of traction substation.

(2) Catenary

As the train's special working condition usually occurs in the bullet train station or station, which is far from the traction substation, the length of the taking-power arm is 25km.According to the typical parameters of the traction network, set the catenary wire resistance value is 4.45 Ω, inductance value is 35.7 mH, the capacitance between rail is 0.1342 u F, rail backflow resistance value is 1.0125 Ω, reflux inductance value is 3.24 mH, equivalent model is shown in figure 3.

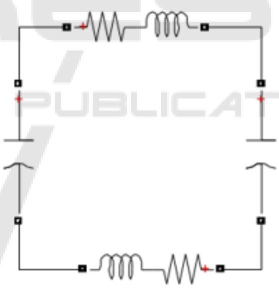

Figure 3: Equivalent model of traction network.

(3) Grounding module

In this model, each vehicle's protective grounding circuit is equivalent to two protective grounding circuits at the front and rear of the vehicle. The impedance between each connection point is calculated by the unit resistance and the unit inductance of the rail. The overall equivalent circuit diagram is shown in figure 4. The circuit in the black box represents 3 cars' protective grounding, while the circuit in the red box represents 3 cars' working grounding. The parameter values are arranged as shown in table 1.

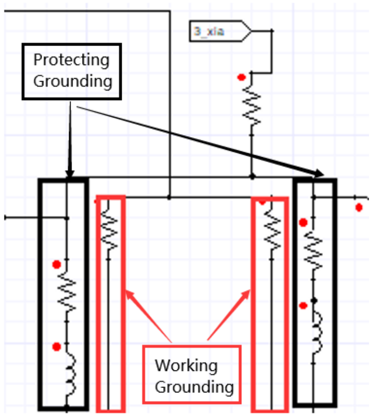

Figure 4: Schematic diagram of ground circuit.

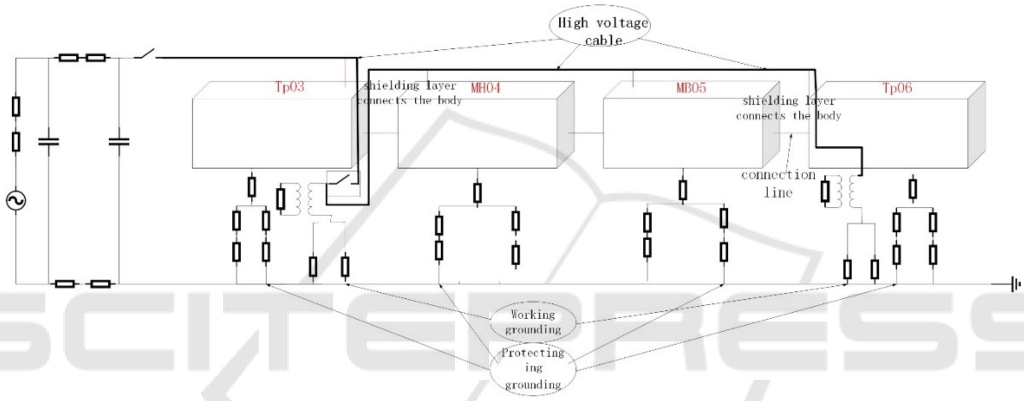

Figure 5: Schematic diagram of the model.

Table 1: Grounding parameter values.

Parameters to describe	Parameter value
Protective ground resistance	0.11Ω
Protective ground inductance	8.6uH
Working ground resistance	6.5mΩ

Based on the above judgment, the overvoltage model of vehicle body was established. As the high-voltage cables are distributed in 3-6 vehicles, the simulation diagram of 3-6 vehicles is presented as follows.

This model uses Q3D and Simplorer under ANSYS platform to conduct solid modeling of the high-voltage cable and vehicle body model, obtain the distribution parameters between each part, then import them into Simplorer for circuit connection, and preliminarily obtain the over-voltage simulation results.

2.3 Three-dimensional Modeling of Vehicle Body ad High-Voltage Cable

The simplified model of the car body ignores the parts that have little influence on the overvoltage, such as the seat, inner assembly and small parts. In order to obtain the impedance parameters of each car body, ports are set on the roof and bottom of each car to represent the current inflow and outflow, respectively. The schematic diagram of the model is shown in figure 6.

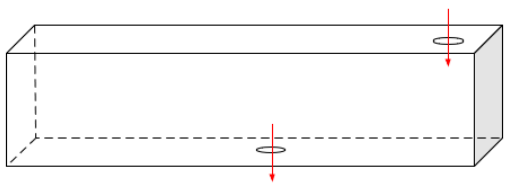

Figure 6: Vehicle body setting.

The inner and outer conductors are drawn according to the actual size of the high-voltage cable and the actual wiring condition, and the influence of the medium layer is ignored. The specific model is shown in figure 7 and figure 8.The inner and outer conductors are set as current paths respectively.

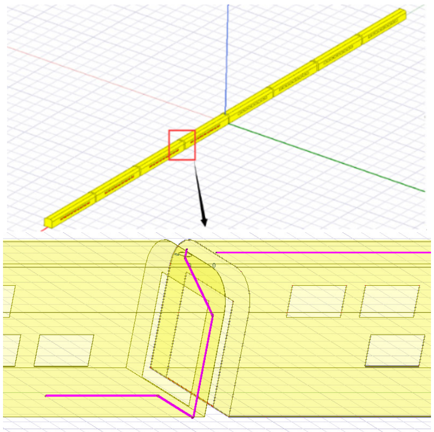

Figure 7: Distribution of high-voltage cables.

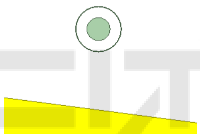

Figure 8: Section of high pressure cable.

After the simulation in Q3D software is completed, the distributed parameter results of the model can be obtained by taking three vehicles as an example, as shown in the figure below.

After encapsulating the Q3D model, import it into circuit simulation software Simplorer, as shown in figure 10. This module has taken into account the influence of distribution parameters. Each port on the module, namely the port set in Q3D, can be connected to the circuit through the port.

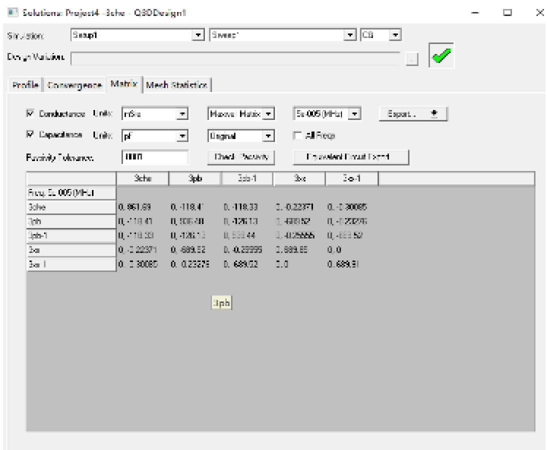

Figure 9: Distribution parameter matrix.

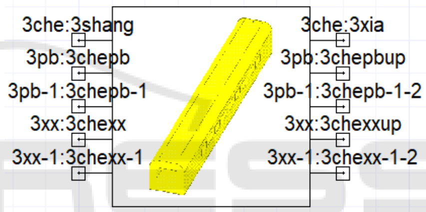

Figure 10: Q3D packaging module.

2.4 Overall Model Building

According to the above mentioned traction substation, catenary, high-voltage system, vehicle body and grounding system model, connect the high-voltage cable to the vehicle body circuit.

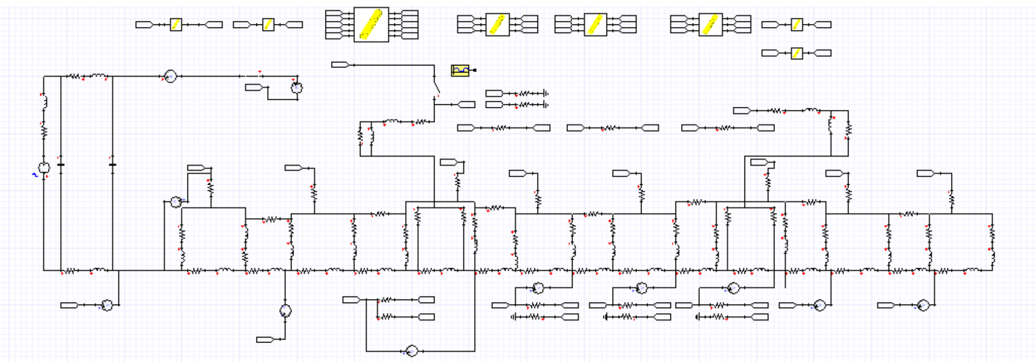

Figure 11: Overall simulation model.

Details are as follows: the body port diagram is shown in figure 12. The bottom of each car is grounded through the grounding impedance, and the workshop connection wire is connected through the resistance.

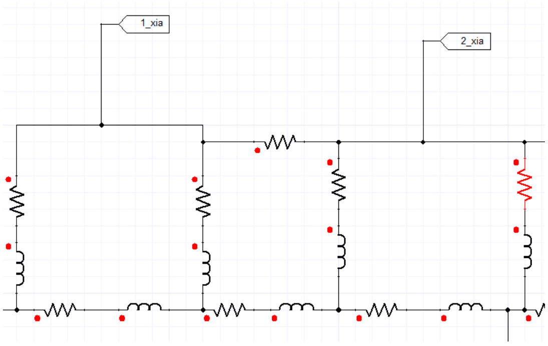

Figure 12: Vehicle body port connection diagram.

3 ANALYSIS OF SIMULATION RESULTS

The simulation setting is VCB shutdown at 5ms. The simulation results of overvoltage of 3 vehicles are shown in figure 14. The generated overvoltage is around 2.9kv, the oscillation time is around 25us, and the main spectrum is 1.62MHz.The basic characteristics of vehicle body overvoltage are: the amplitude is between 3kV and 5kV; he oscillation time is tens of microseconds. The main frequency distribution is 1MHz-2MHz. (Wan Yusu, 2017)
Through the establishment of vehicle body and cable entity model, import circuit software to replace part of the structure of the existing overvoltage circuit model, after the simulation, the overvoltage time domain waveform and frequency domain waveform are obtained, and the analysis of the waveform conforms to the characteristics of the typical overvoltage waveform, which can demonstrate the correctness of the model.

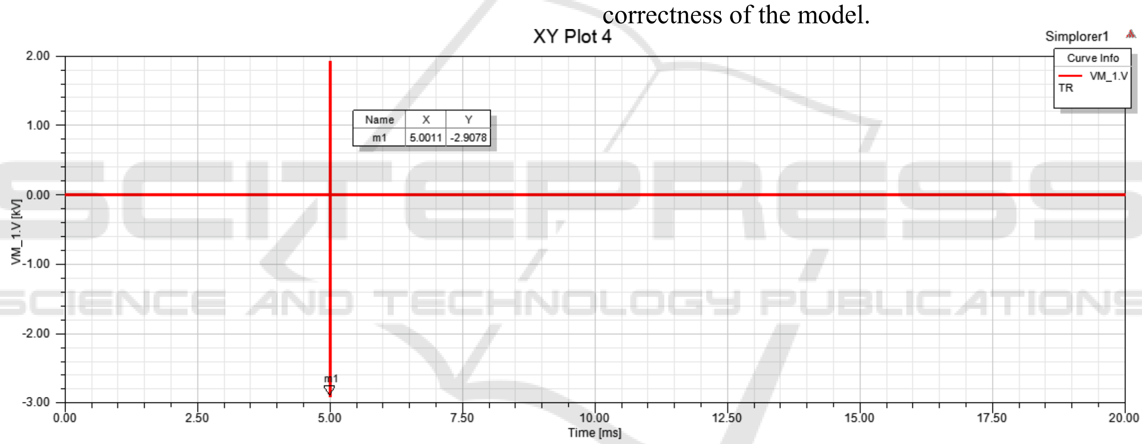

Figure 13: Vehicle body overvoltage waveform.

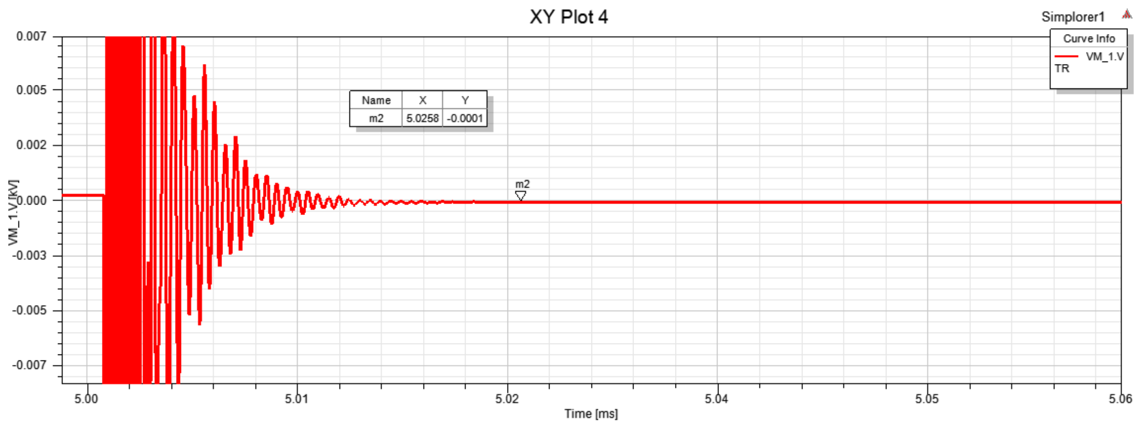

Figure 14: Duration of overvoltage of vehicle body.

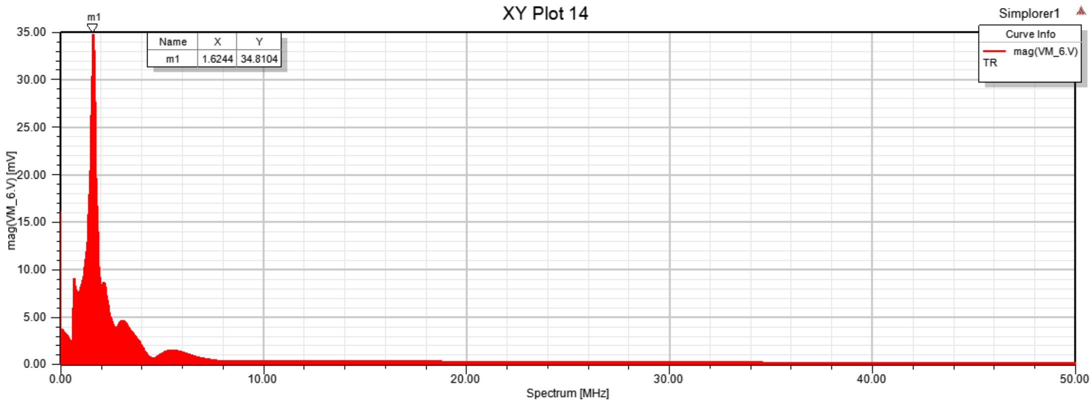

Figure 15. Spectrum of overvoltage of vehicle body.

4 SUMMARY

Based on the three-dimensional vehicle body model, this paper carried out the simulation modeling analysis on the over-voltage of the vehicle body caused by the main circuit breaker operated by standard emu. The traditional equivalent method of equating the body with the four-side impedance is broken, and the over-voltage performance of the body of emu is analyzed and predicted.

Based on the modeling method proposed in this paper, the obtained vehicle body overvoltage is around 2.9kv, the oscillation time is around 25us, and the spectrum is mainly 1.62mhz, which conforms to the basic characteristics of overvoltage. Therefore, the simulation modeling method proposed in this paper can simulate and analyze the overvoltage of the vehicle body caused by the operation of the main circuit breaker, and realize the analysis and prediction of the overvoltage performance of the emu body, so as to guarantee the safety of electromagnetic compatibility of the emu.

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