

Analysis of Lightning Interference and Protection Methods on Secondary Cables in Substation

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Abstract—When a substation is struck by lightning, it will cause the ground potential to rise, which will further cause serious interference to the secondary cable. This article is based on the grounding grid established in the testing ground. The grounding copper bar is laid in the cable trench to connect with the grounding grid. At different grounding grid points, use a lightning current impulse generator to apply high current. At the same time, the grounding grid model is established by using the ATP-EMTP software. Through the combination of test and simulation, the influence of different lightning inflow locations on the protection effect of grounding copper bar is studied, and combined with the connection method of the grounding copper bar and the grounding grid, the protective effect of the grounding copper bar on the secondary cable under the impact of lightning current was analyzed. The research results showed that the laying of grounding copper bars can reduce the influence of interference voltage on the secondary cables under certain circumstances, but when there are multiple connection points between the grounding copper bar and the grounding grid, the current injection position is different, which will affect the voltage between the cable core and the shielding layer. At the same time, it will also affect the ground potential rise of cable grounding point in different degrees.

1. INTRODUCTION

The huge potential difference in the grounding network will produce an unbalanced current on the cable shield of the two-end grounded control cable when lightning strikes; operation shocks; and grounding short-circuit faults occur in the power system. In addition, the magnetic field generated by this current will produce an alternating voltage on the cable core. In serious cases, it will burn the cable [1–5].

In fact, laying grounded copper bar in outdoor cable ditches can effectively reduce the voltage at both ends of the secondary cable shield and avoid disoperation or refusal of secondary equipment [6–9]. However, there are many disputes about the connection mode between the grounding copper bar and the main grounding grid in the cable trench. Reference [10] thinks that the grounding copper bar and the main grounding grid should be connected every 15 to 20 m in the distal end of the main cable ditch and in the main cable ditch and close to the local terminal box. However, Reference [11] thinks that the grounding copper bar at the terminal box is connected to the main grounding grid, and the grounding copper bar is not connected to the main grounding grid except the terminal box. Otherwise, the increase of the ground potential of the primary system will affect the flow direction of voltage and current on the grounding copper bar, and further affect the induced current on the secondary cable shield when the primary equipment grounding fault occurs near there. Moreover, it can affect the anti-interference effect of the secondary cable shield. There are differences in the setting of the cable trench grounding

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copper bar in the existing data. In addition, there are no clear provisions on some details, which is also the ambiguity of the substation design, construction and acceptance specifications.

It is of great significance to control the potential difference between the secondary cable shield and the connection point of the grounding grid, and reduce the voltage between the cable core wire and the cable shield when the lightning current is injected into the main grounding grid [12, 13]. When lightning strikes, the unequal potential of the ground grid is more obvious, and there is a large potential difference between the two ends of the cable shield. Adding a grounding copper bar is a very effective measure to solve this problem [13]. When the topological connection structure between the grounding copper bar and the main grounding grid is different, the influence of lightning current on the secondary cable will be very different. As a consequence, it is necessary to study the influence of the connection mode between the grounding copper bar and the main grounding grid on the safety performance of the secondary. A simplified model of substation main grounding grid is established based on ATP-EMTP software, and the interference voltage of secondary cable caused by lightning current injected into main grounding grid is calculated by simulation and test. The influence factors of interference voltage such as the grounding mode of secondary cable and the connection mode between grounding copper bar and main grounding grid are studied. In addition, the protective effect of grounding copper bar on secondary cable is analyzed.

2. SIMULATION CALCULATION MODEL

A $100\text{ m} \times 100\text{ m}$ grounding grid is built, as shown in Figure 1. The grounding body of the grounding grid of the substation adopts galvanized flat steel, and the conductor radius is 0.02 m . In addition, the buried depth of the grounding body laid horizontally is 1.0 m , and the soil resistivity is $100\ \Omega \cdot \text{m}$. The grid size of grounding grid is 10 m both from x -axis direction and y -axis direction, that is, the grounding grid is $100\text{ m} \times 100\text{ m}$.

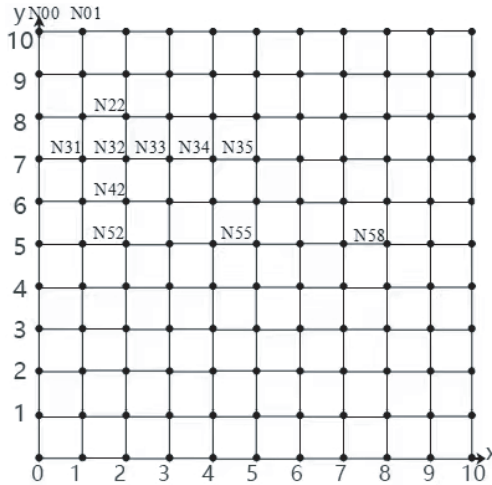


Figure 1. $100\text{ m} \times 100\text{ m}$ grounding grid structure diagram.

Shielded cable is often used in the secondary system of substation. As a consequence, two types of shielded cable models are established in this paper, which are copper tape shielded control cable (model KVVP2, single shielded cable) and copper tape shielded steel tape armored control cable (model KVVP2-22, double shielded cable).

According to the model shown in Figure 1 and the cable model shown in Figure 2, two models of secondary cables have been established in Figure 3, one corresponding to single-shielded cables and the other corresponding to double-shielded cables.

The disturbance signal produces interference signal in the cable's core through capacitance or inductive coupling, and the differential mode interference signal between the cables' cores will be relatively small. The main interference signal is the common mode interference signal, when a short

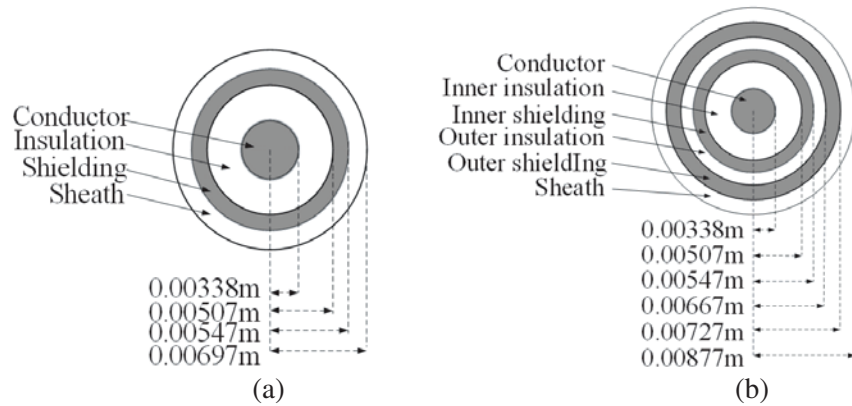


Figure 2. Cable model cross section. (a) Single shielded cable. (b) Double shielded cable.

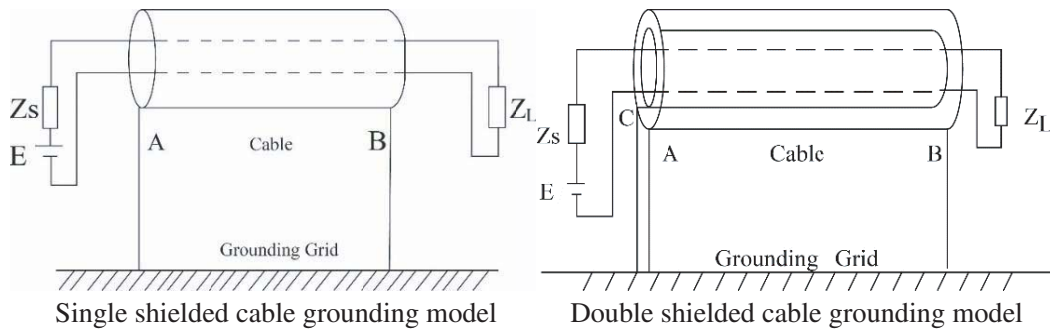


Figure 3. Secondary cable grounding model.

circuit fault or lightning strike occurs in the substation. As a consequence, the potential difference that threatens the safety in the station is mainly reflected in the potential difference between the cable’s core and the shielding layer, and the potential difference between the end of the cable’s core and the connection site of the equipment. In addition, the former will break down the cable if the former is too high. It will break down the device if the latter is too high. As a consequence, this paper focuses on the analysis of the voltage between the core and the shield of the secondary cable.

3. CALCULATION OF THE VOLTAGE BETWEEN THE CABLE AND THE SHIELDING LAYER

According to [13], it is pointed out that two-end grounded single shielded cable is often used in substation. In addition, two-end grounded single shielded cable can make cable shield have stronger anti-interference ability. However, two-end grounded single-shielded cable may not be able to meet the requirements of anti-interference for places with strong interference. As a consequence, double-shielded cable should be selected. Double-shielded cable should be grounded at both ends of the outer shield and one-end of the inner shield.

Moreover, this paper takes the two-end grounded shield of a single shielded cable as an example to study the effect of ground potential rise on the coupling disturbance of the secondary cable, effect of external electric field, which produces induced current in the cable shield. The induced current density decreases gradually from outside to inside due to the skin effect. It generates a certain interference current on the inner surface of the cable core when the cable shield is thinner or the shielding material penetrates deeply, that is, the current of the cable shield interferes with the internal core of the cable. The current of the cable shield produces the axial electric field distribution inside the shielding layer, and the axial electric field of the inner surface produces the potential difference between the cable core

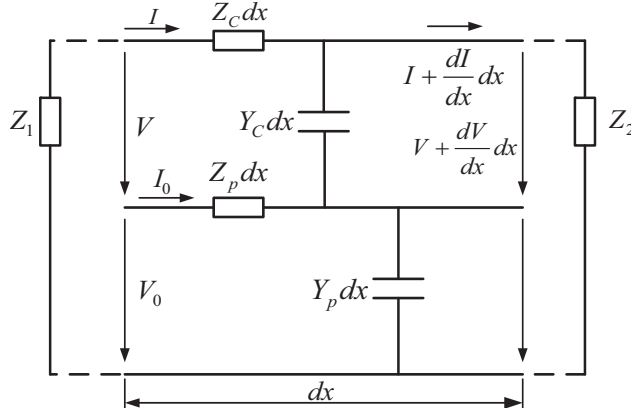


Figure 4. Equivalent circuit model inside the cable.

wire and the shielding layer. Figure 4 shows the internal equivalent circuit model of the cable, where Z_p is the loop impedance of the outer skin of the cable, and Y_p is the capacitive reactance of the outer skin to the ground. Besides, Y_c is the capacitive reactance between the core wire and the outer skin, and Z_c cable core wire is self-impedance. Besides, Z_T is the transfer impedance, and Y_T is the transfer admittance. Z_1 and Z_2 are the series impedances between the core wire and the grounding grid, which is between zero and infinity.

The current of the cable shield forms two loops through the internal core wire and conductive earth. Moreover, the difference equations of the internal and external loops are expressed as follows:

$$\begin{aligned} \frac{d}{dx} \begin{bmatrix} V \\ V_0 \end{bmatrix} &= \begin{bmatrix} -Z_C & Z_T \\ Z_T & -Z_P \end{bmatrix} \begin{bmatrix} I \\ I_0 \end{bmatrix} \\ \frac{d}{dx} \begin{bmatrix} I \\ I_0 \end{bmatrix} &= \begin{bmatrix} -Y_C & Y_T \\ 0 & -Y_P \end{bmatrix} \begin{bmatrix} V \\ V_0 \end{bmatrix} \end{aligned}$$

In the matrix, V and I are the voltage and current of the inner core and shield circuit, respectively. In addition, V and I are the voltage and current between the shield and the earth circuit, respectively. The loop voltage and current are represented by the earth as the reference point in order to meet the requirements of solving the line equation, and the following matrix equations are obtained:

$$\begin{aligned} \frac{d}{dx} \begin{bmatrix} V_C \\ V_P \end{bmatrix} &= \begin{bmatrix} -Z_C + 2Z_T & Z_T - Z_P \\ Z_T - Z_P & -Z_P \end{bmatrix} \begin{bmatrix} I_C \\ I_P \end{bmatrix} \\ \frac{d}{dx} \begin{bmatrix} I_C \\ I_P \end{bmatrix} &= \begin{bmatrix} -Y_C & Y_C - Y_T \\ Y_C & -Y_C + Y_T - Y_P \end{bmatrix} \begin{bmatrix} V_C \\ V_P \end{bmatrix} \end{aligned}$$

In the formula, V_c is the voltage of the cable core wire to ground; V_p is the voltage of the shielding layer to ground; I_c is the current flowing through the core wire; I_p is the current of the shielding layer.

In order to study the influence of different ground potential rises on the interference voltage of secondary cable under lightning impulse current is studied. In addition, the lightning current with the amplitude of 10 kA and waveform of 2.6/50 μ s is selected as the ground current. Besides, the initial injection point of lightning current is set at N34 point. The two ends of the cable are connected to the main grounding grid at N52 and N58, respectively.

4. ANALYSIS OF THE PROTECTIVE EFFECT OF GROUNDING COPPER BAR

First of all, a model is established according to Figure 3 to calculate the voltage between the cable core and cable shield when the cable length is 60 meters; the single shielded cable shield is grounded at both ends; the outer shield layer of the double shielded cable is grounded at both ends; and the inner shield layer is grounded at one end. Sort out the collected voltage data, and finally the analyzed result is shown in Figure 5.

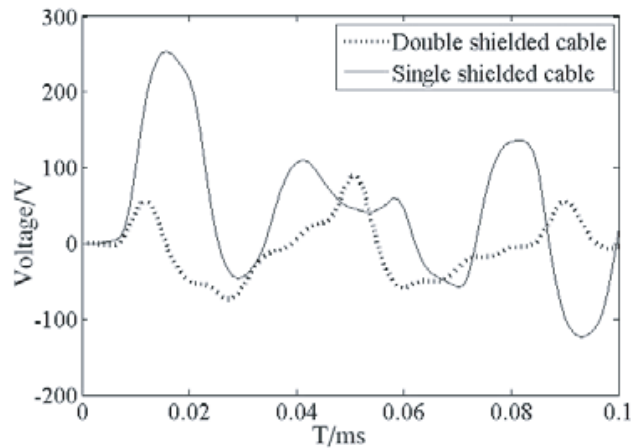


Figure 5. Voltage between the cable core and the shielding layer under different cable grounding methods.

It can be seen from Figure 5 that the voltage between the core and the shield in the double-shielded cable grounding method is smaller than that in the single-shielded cable grounding method. This further shows that the double-shielded cable has a better anti-interference effect than the single-shielded cable. In the following calculations in this article, two cable grounding methods will be selected: the two-end grounded shield of single-shielded cable, the two-end grounded outer shield and the one-end grounded inner shield of double-shielded cable.

4.1. The Effect of the Presence or Absence of Grounded Copper Bars

A grounding copper bar is added to the original model and laid in parallel with the secondary cable in the cable ditch at N52 and N58 at both ends of the cable in order to compare the different effects of copper bars with and without grounding on cable interference voltage. In addition, we connect the grounded copper bar to the main grounding grid. Keeping other parameters unchanged, only the size of the grounding copper bar is changed; the previous calculation is repeated; some data of the interference voltage changing with the size of the grounding copper bar are obtained. Results of the analysis are shown in Figure 6.

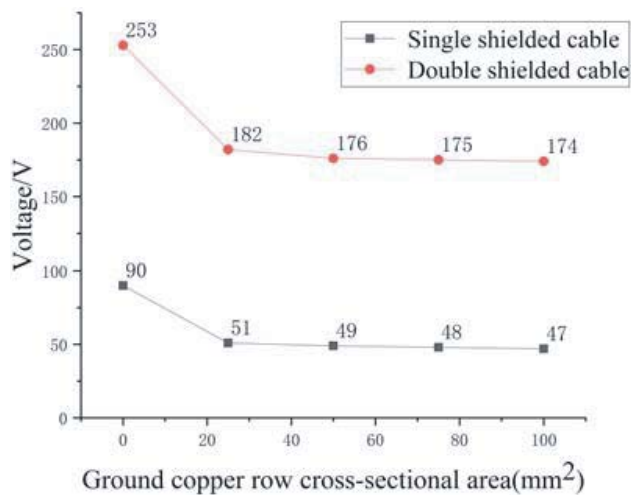


Figure 6. Voltage between the cable core wire and the shielding layer with or without grounding copper bar.

As can be seen from Figure 6, when the cross-sectional area of the ungrounded copper bar is 0, the addition of the grounded copper bar obviously reduces the interference voltage between the cable core and the cable shield. The interference voltage between the single shielded cable core and the shield of single shielded cable with a grounded copper bar is about 70% of that the ungrounded copper bar, and the interference voltage between the double shielded cable core and the cable shield with a grounded copper bar is about 50% of that the ungrounded copper bar. The fault current mainly flows through the copper bar, which reduces the current flowing through the shield and reduces the interference to the voltage of the cable core because the impedance of the copper bar is much smaller than that of the shield. It can be seen that the use of a grounded copper bar can effectively protect the double-ended grounded secondary cable. In the meanwhile, the size of the grounded copper bar will also affect its shunt effect. In addition, the voltage between the core wire and the shield becomes smaller and smaller with the increase of the cross-sectional area of the grounded copper bar. As a consequence, this paper chooses the grounded copper bar with the cross-sectional area of 100 mm².

4.2. The Effect of the Connection between the Grounding Copper Bar and the Main Grounding Grid

The first end of the cable grounding point is fixed to N52 point, and the second end is fixed to N58 point due to the limited size of the main grounding grid model set by the simulation. 2, 3, 4, and 7 connection points are set up respectively in order to reflect the function of the grounding copper bar more effectively. The specific connection mode is shown in Figure 7.

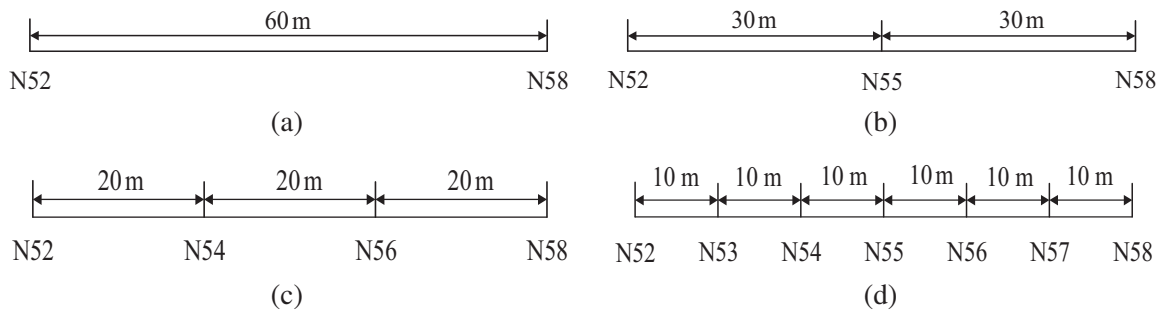


Figure 7. Connection method of ground copper bar and main grounding grid. (a) 2 connection points. (b) 3 connection points. (c) 4 connection points. (d) 7 connection points.

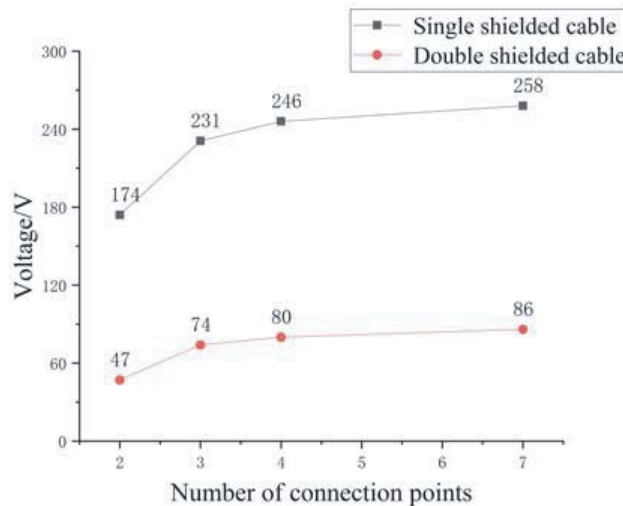


Figure 8. Voltage change curve between core wire and shielding layer of cable.

Inject current at point N34. As the connection point between the grounding copper bar and the main grounding grid increases, the voltage between the cable core and cable shield is shown in Figure 8.

According to previous literature conclusions, adding grounding copper bars connected to two points of the main grounding grid can reduce the voltage between the cable core and cable shield. However, it can be seen from Figure 8 that the voltages between cable core and shield of single-shielded cable and double-shielded cable increase with the increase of the connection point between the grounding copper bar and main grounding grid. In addition, it can be seen that the number and position of the connection points between the grounding copper bar and main grounding grid will directly affect the protective effect of the grounding copper bar on the secondary cable.

4.3. Influence of Current Injection Point Position on the Effect of Grounding Copper Bar

According to the model of the main grounding grid in Figure 1, N35 is the midpoint of the two ends of the cable. In addition, the influence of the injection current position on the cable interference voltage is the same when the injection current is symmetrical with respect to N35. As a consequence, this paper analyzes the lightning current of N31, N32, N33, N34 and N35 single point injection on the left side of N35. The curves of the voltages between the cable core and cable shield of the single-shielded cable and double-shielded cable with the connection point between the grounding copper bar and the main grounding grid are obtained, as shown in Figures 9(a)–(b).

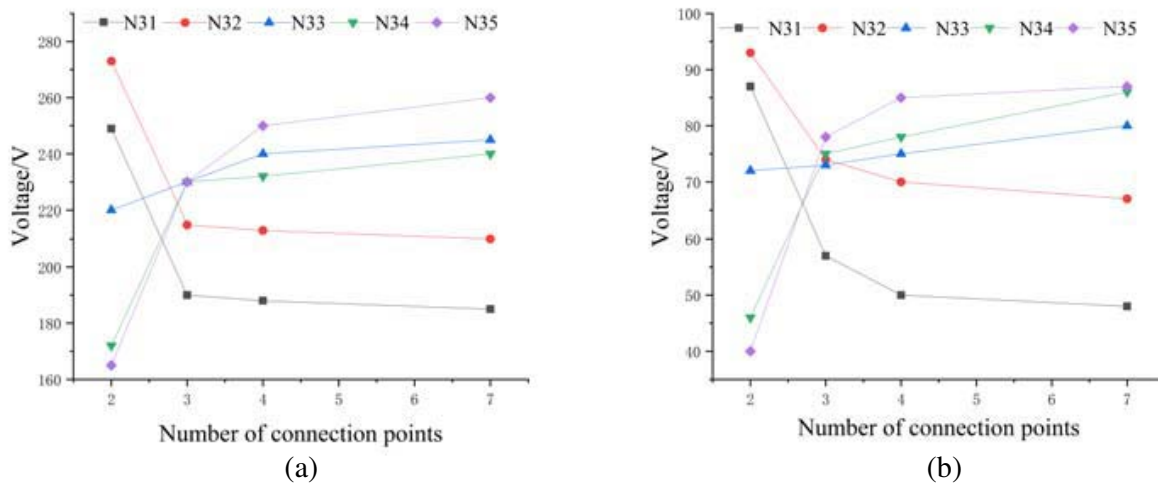


Figure 9. Variation curve of the voltage between the cable core and the shielding layer with the number of connection points when current is injected in the x -axis direction. (a) Single shielded cable. (b) Double shielded cable.

It can be seen from Figures 9(a)–(b) that the voltage variation between the core and the shielding layer of single-shielded cable and double-shielded cable is consistent. N52 is the first termination of the cable, and the main grounding grid nodes N31 and N32 are injected current in the horizontal direction of N52, respectively. The voltage between the cable core and cable shield tends to decrease with the increase of the connection point between the grounding copper bar and main grounding grid. The voltage between the cable core and shielding layer increases with the injection current of the N33–N35 nodes in the horizontal directions of N52 and N58 with the increase of the connection point between the grounding copper bar and main grounding grid. When the current is injected into the N35 on the symmetry axis of the cable at both ends, the voltage between the cable core wire and the shielding layer gradually becomes the maximum with the increase of the connection point. In other words, it does the greatest harm to the cable.

Actually, there are many connection points between the grounding copper bar and main grounding grid in the substation, and the locations of the connections are various. According to the calculation results of this model, it can still explain the related problems.

Adjust the impulse generator to generate $8/20\ \mu\text{s}$ impulse current. When the impulse generator charging voltage is 20 kV, the impulse current waveform and impulse voltage waveform at 1 point are shown in Figures 12 and 13.

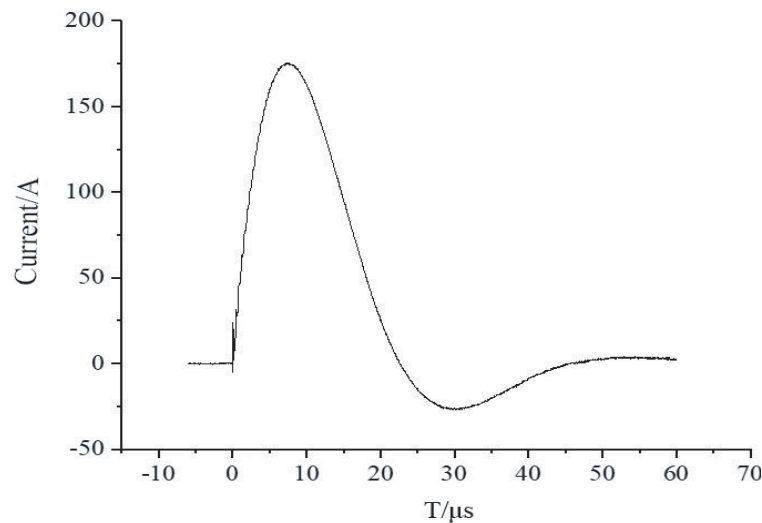


Figure 12. Current waveform at 1 point.

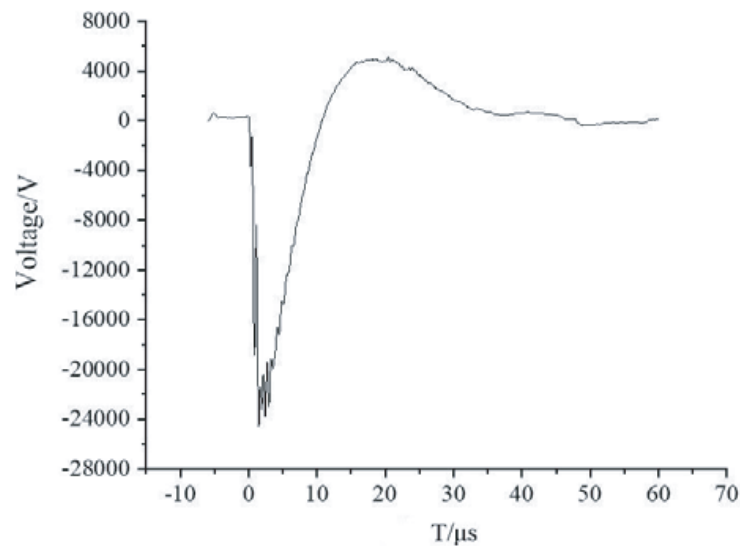


Figure 13. Voltage waveform at 1 point.

The grounding modes of the two cables are shown in Tables 1 and 2.

The impulse current injection points are arranged at 1 and 2 points in Figure 10, respectively. In addition, the impulse generator is adjusted to generate $8/20\ \mu\text{s}$ impulse current. According to the grounding modes of the two cables in Table 1 and Table 2, when the charging voltage of the impulse generator is 20 kV, the voltage waveform curve between the secondary cable core and the shielding layer measured by the oscilloscope at point A is shown in Figure 14.

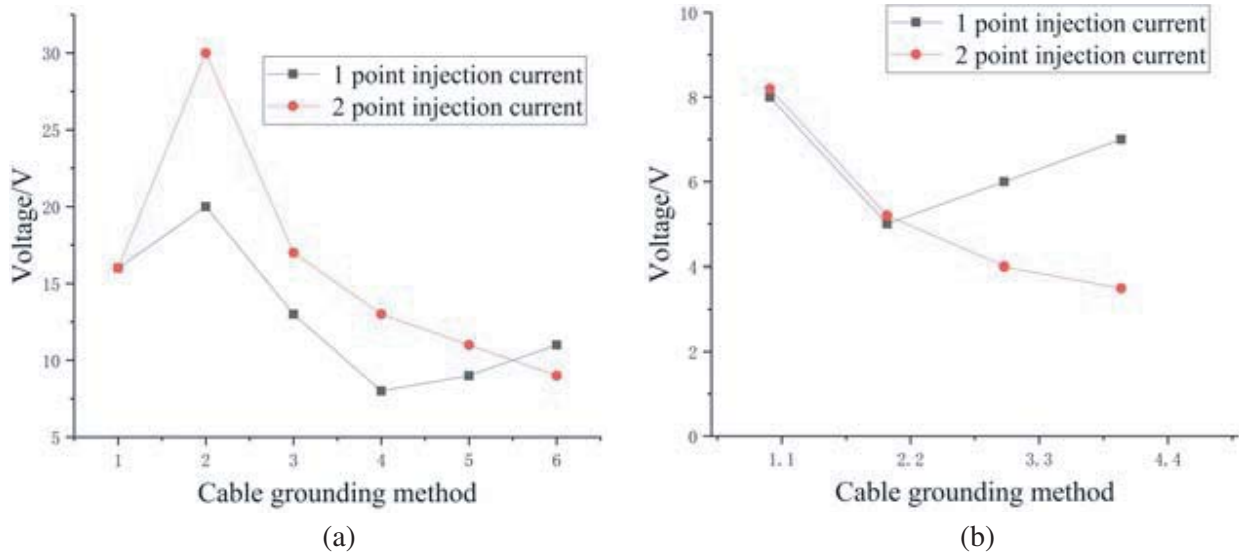
It can be seen from Figure 14 that the variation of core-skin voltage of single-shielded cable and double-shielded cable with the grounded copper bar is consistent with the conclusion obtained in simulation. The measured results further show that the voltage between the cable's core and the shielding layer increases with the increase of the number of connection points between the grounding copper bar and main grounding grid in the side of the y -axis composition plane where the two grounding

Table 1. Summary table of grounding methods for single shielded cables.

Number	Cable grounding method	Copper bar and main grounding grid connection method
1	Point B of the shielding layer is grounded; point A is not grounded	No copper bar
2	Point A of the shielding layer is grounded; point B is not grounded	No copper bar
3	Both points of the shielding layer A and B are grounded	No copper bar
4		2 connection points
5		3 connection points
6		5 connection points

Table 2. Summary of grounding methods for double shielded cables.

Number	Cable grounding method	Copper bar and main grounding grid connection method
1	Both points A and B of the outer shielding layer are grounded, point A of the inner shielding layer is grounded, and point B is not grounded	No copper bar
2		2 connection points
3		3 connection points
4		5 connection points

**Figure 14.** Cable interference voltage change curve when current is injected at different points. (a) Single shielded cable. (b) Double shielded cable.

points of the cable are located. In the outside of the plane formed by the y -axis where the two grounding points of the cable are located, the voltage between the cable core and shielding layer tends to decrease with the increase of the number of connection points between the grounding copper bar and main grounding grid.

6. CONCLUSIONS

The influence of laying grounding copper bar on secondary cable is analyzed through simulation and measurement. The main conclusions are as follows:

- 1) The anti-interference effect of the cable is the best, when the shielding layer of the single shielded cable is grounded at both ends. Besides, the outer shield of the double shielded cable is grounded at both ends, and the inner shield is grounded at one end.
- 2) Laying a two-end grounded copper bar for the cable in parallel, the voltage between the cable core and shielding layer is significantly reduced.
- 3) If the injected current is located outside the plane of the y -axis where the two grounding points of the cable are located, the voltage between the cable core and shielding layer can be reduced by increasing the number of connection points between the grounding copper bar and main grounding grid. If the injected current is located in the inner side of the plane, increasing the number of connection points between the grounding copper bar and main grounding grid will be less effective in reducing interference.

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