

# Study on the Calculation Method of Interference Voltage of Shielded Cable under the Condition of Lightning Strike in Smart Substation Grounding Grid

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**Abstract.** When lightning strikes the substation grounding grid, there will be a great transient ground potential difference between the two grounding points of the shielded cable with two terminal grounding. It will be coupled to the cable core line and affects the normal operation of second order system devices and even jeopardize the safe operation of the whole system. Therefore, it is of great significance to study the lightning characteristics of the relevant components when lightning strikes the grounding grid of smart substations. This paper mainly studies the calculation method of interference voltage generated by shielding cables when lightning strikes the grounding grid of smart substations. Firstly the equivalent circuit and the multi-conductor transmission model of the cable are established. Then, using the frequency domain method in the multi-conductor transmission line and combining the fast Fourier transform technique, the steps of calculating the interference voltage and current produced in the two cable are given. Finally, in order to test the validity of the proposed calculation method, the lightning impulse grounding test is carried out on the test grounding network. The test results show that the method is effective.

## 1. Introduction

The impact of lightning on Smart Substation mainly includes three aspects. First, lightning strikes the substation lightning rod, causing the potential difference on the grounding network, thus affecting the normal operation of the intelligent components. Second, the lightning strikes the transmission line of the substation, and the lightning penetrated wave passes through a device, transformer and connecting cable to enter the intelligent component. Thirdly, lightning strikes the grounding body near the smart substation, and affects the intelligent components through space electromagnetic induction.

After the lightning rod is struck by lightning, the lightning current is introduced into the grounding grid through the lightning rod. As the spectrum of the lightning current is wide, when the lightning current is injected into the grounding grid of the substation, the high grounding impedance of the grounding network will lead to the uneven distribution of the ground potential rise in the grounding network.

When the lightning current is injected into the grounding grid, the ground potential of the current injection is up to the highest, and the rise of the ground potential rapidly decreases with the increase of the distance from the current injection site. Therefore, when lightning strikes the substation grounding grid, there will be a great transient ground potential difference between the two grounding points of



the shielded cable with two terminal grounding. The voltage difference between the ground potential will also produce a large transient current in the shielding and grounding circuits, and will be coupled to the cable core line through the transfer impedance of the shielded cable to produce the disturbance voltage and current at the port of second order system devices. In severe cases, it will affect the normal operation of second order system devices and even jeopardize the safe operation of the whole system. Therefore, it is of great significance to study the lightning characteristics of the relevant components when lightning strikes the grounding grid of smart substations.

This paper mainly studies the calculation method of interference voltage generated by shielding cables when lightning strikes the grounding grid of smart substations. Firstly the equivalent circuit between the two grounding points at the two ends of the shielded cable and the multi-conductor transmission model of the cable are established. Then, using the frequency domain method in the multi conductor transmission line and combining the fast Fourier transform technique, the steps of calculating the interference voltage and current produced in the two cable are given. Finally, in order to test the validity of the proposed measurement method, calculation model and calculation method, the lightning impulse grounding test is carried out on the test grounding network. The effectiveness of the proposed method is verified by the comparison calculation and test results.

## 2. Multi-conductor transmission line model of shielded cable

Figure 1 shows the connection diagram of the secondary side equipment cables between the main control room in the substation and the protection chamber in the switch field, in which  $E$ ,  $Z_S$  and  $Z_L$  are voltage sources, voltage source internal impedance and load impedance, respectively.

When the grounding fault occurs in the power system or the grounding grid is struck by the substation, there will be transient ground potential difference between B and A. This potential difference will generate current in the shielding layer of a double end grounded cable, and generate interference voltages on the core line of the cable, causing electromagnetic interference to the secondary side equipment connected to these cables.

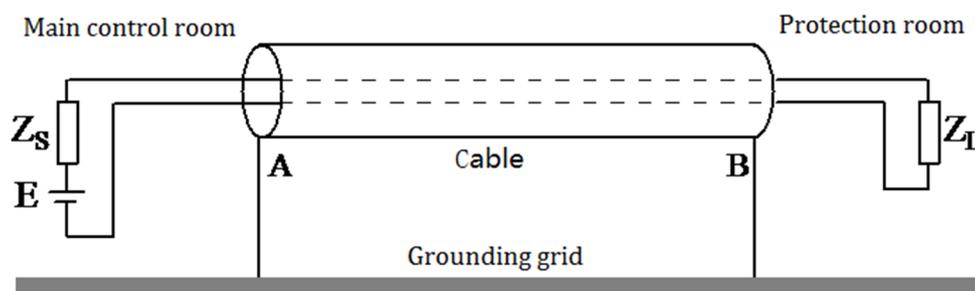


Figure 1. Cable connection diagram

In order to study the electromagnetic interference, a multi-conductor transmission line model of cable is established as shown in Fig. 2.

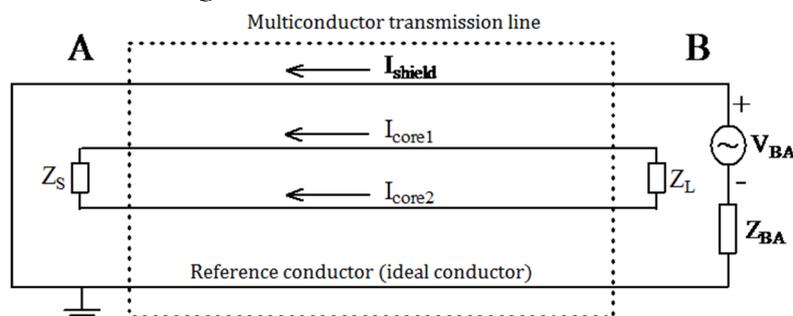


Figure 2. Multi conductor transmission line model of cable

In Fig2,  $V_{BA}$ , when the grounding grid of the substation is struck by lightning, is the phasor of the ground potential difference between two ground points of the shielding layer of the cable, which can

be obtained from the performance analysis of the grounding grid.  $Z_{BA}$  is the equivalent impedance of the grounding grid between two ends of the cable shielding layer.

### 3. Calculation of cable interference voltage when lightning strikes substation grounding grid

Supposing a cable with shielded layer has an  $N$  core, and the voltage phasor between the core line and shielding layer is  $V_1, \dots, V_N$ , the voltage phasor between shielding layer and external reference conductor is  $V_{N+1}$ , and the phasor of loop current in the circuit consisting of core wire and shielding layer is  $I_1, \dots, I_N$ , the phasor of the loop current in the loop composed of shielding layer and external reference conductor is  $I_{N+1}$ . This is a multi-conductor transmission line problem, which is excited by the potential difference at both ends of the cable. Therefore, the relationship between the voltage phasor and the phasor of the current can be written as follows:

$$-\begin{bmatrix} \frac{dV_1}{dx} \\ \vdots \\ \frac{dV_N}{dx} \\ \frac{dV_{N+1}}{dx} \end{bmatrix} = \begin{bmatrix} Z_{11} & \cdots & Z_{1N} & -Z_t \\ \vdots & \ddots & \vdots & \vdots \\ Z_{N1} & \cdots & Z_{NN} & -Z_t \\ -Z_t & \cdots & -Z_t & Z_{(N+1)(N+1)} \end{bmatrix} \begin{bmatrix} I_1 \\ \vdots \\ I_N \\ I_{N+1} \end{bmatrix} \quad (1)$$

$$-\begin{bmatrix} \frac{dI_1}{dx} \\ \vdots \\ \frac{dI_N}{dx} \\ \frac{dI_{N+1}}{dx} \end{bmatrix} = \begin{bmatrix} Y_{11} & \cdots & Y_{1N} & Y_t \\ \vdots & \ddots & \vdots & \vdots \\ Y_{N1} & \cdots & Y_{NN} & Y_t \\ Y_t & \cdots & Y_t & Y_{(N+1)(N+1)} \end{bmatrix} \begin{bmatrix} V_1 \\ \vdots \\ V_N \\ V_{N+1} \end{bmatrix} \quad (2)$$

Here,  $X$  is the transmission direction of voltage phasor and current phasor;  $Z_t$  is the transfer impedance of shielding layer to the core;  $Z_{kk} = j\omega L_{kk} + Z_{ki} + Z_{(N+1)i}$  ( $k=1,2,\dots,N$ ), is the self-impedance of the  $K$  root core line, in which  $L_{kk}$  is the self-inductance of the  $K$  root core line in the cable,  $Z_{ki}$  is the internal impedance of the  $K$  root core, and  $Z_{(N+1)i}$  is the internal impedance of the cable shielding layer.  $Z_{km} = j\omega L_{km} + Z_{(N+1)i}$  ( $k, m=1,2,\dots,N, k \neq m$ ), is the mutual impedance between the  $K$  root core line and the  $M$  root core line, in which  $L_{km}$  is the mutual inductance between the  $K$  root core line and the  $M$  root core line.  $Z_{(N+1)(N+1)} = j\omega L_{(N+1)(N+1)} + Z_{(N+1)i} + Z_{REF}$ , is the impedance of shielding layer to external reference conductor, in which  $L_{(N+1)(N+1)}$  is the shielding layer's self-inductance to the external reference conductor, and  $Z_{REF}$  is the internal impedance of the external reference conductor.  $Y_{ij} = j\omega C_{ij}$  ( $i, j=1,2,\dots,N$ ),  $C_{kk}$  ( $k=1,2,\dots,N$ ) is the self-capacitance of the  $K$  core wire with shielding layer as the reference conductor,  $C_{km}$  ( $k, m=1,2,\dots,N, k \neq m$ ) is the mutual capacitance between the  $K$  core and the  $M$  core.  $Y_{(N+1)(N+1)} = j\omega C_{(N+1)(N+1)}$ , and  $C_{(N+1)(N+1)}$  are the capacitance between the shielding layer and the external reference conductor.  $Y_t$  is the transfer admittance of the shielding layer to the core line.

If the external reference conductor is the reference conductor of the whole system, the voltage phasor between the core wire and the external reference conductor is  $V_{core1}, \dots, V_{coreN}$ , the current phasor in the core line is  $I_{core1}, \dots, I_{coreN}$ , the voltage phasor between shielding layer and external reference conductor is  $V_{shield}$ , and the current phasor of shielding layer is  $I_{shield}$ . The relationship between these phasors and the voltage and current phasor in equation (1) and equation (2) is:

$$\left. \begin{aligned} V_{core1} &= V_1 + V_{N+1} \\ &\vdots \\ V_{coreN} &= V_N + V_{N+1} \\ V_{shield} &= V_{N+1} \end{aligned} \right\} \quad (3)$$

$$\left. \begin{aligned} I_{core1} &= I_1 \\ &\vdots \\ I_{coreN} &= I_N \\ I_{shield} &= I_{N+1} - \sum_{i=1}^N I_i \end{aligned} \right\} \quad (4)$$

So, equation 1 and equation 2 can be written as:

$$-\begin{bmatrix} \frac{dV_{core1}}{dx} \\ \vdots \\ \frac{dV_{coreN}}{dx} \\ \frac{dV_{shield}}{dx} \end{bmatrix} = \begin{bmatrix} Z'_{11} & \cdots & Z'_{1N} & Z'_{1(N+1)} \\ \vdots & \ddots & \vdots & \vdots \\ Z'_{N1} & \cdots & Z'_{NN} & Z'_{N(N+1)} \\ Z'_{(N+1)1} & \cdots & Z'_{(N+1)N} & Z'_{(N+1)(N+1)} \end{bmatrix} \begin{bmatrix} I_{core1} \\ \vdots \\ I_{coreN} \\ I_{shield} \end{bmatrix} \quad (5)$$

$$-\begin{bmatrix} \frac{dI_{core1}}{dx} \\ \vdots \\ \frac{dI_{coreN}}{dx} \\ \frac{dI_{shield}}{dx} \end{bmatrix} = \begin{bmatrix} Y_{11} & \cdots & Y_{1N} & Y'_{1(N+1)} \\ \vdots & \ddots & \vdots & \vdots \\ Y_{N1} & \cdots & Y_{NN} & Y'_{N(N+1)} \\ Y'_{(N+1)1} & \cdots & Y'_{(N+1)N} & Y'_{(N+1)(N+1)} \end{bmatrix} \begin{bmatrix} V_{core1} \\ \vdots \\ V_{coreN} \\ V_{shield} \end{bmatrix} \quad (6)$$

In here,

$$Z'_{ij} = Z_{ij} + Z_{(N+1)(N+1)} - 2Z_t, i, j = 1, 2, \dots, N \quad (7)$$

$$Z'_{k(N+1)} = Z'_{(N+1)k} = Z_{(N+1)(N+1)} - Z_t, k = 1, 2, \dots, N \quad (8)$$

$$Z'_{(N+1)(N+1)} = Z_{(N+1)(N+1)} \quad (9)$$

$$Y'_{(N+1)k} = Y_t - \sum_{i=1}^N Y_{ik}, k = 1, 2, \dots, N \quad (10)$$

$$Y'_{k(N+1)} = Y_t - \sum_{i=1}^N Y_{ki}, k = 1, 2, \dots, N \quad (11)$$

$$Y'_{(N+1)(N+1)} = Y_{(N+1)(N+1)} - 2N \cdot Y_t + \sum_{i=1}^N \sum_{j=1}^N Y_{ij} \quad (12)$$

With the end conditions, the equation (5) and (6) can be solved by using the multi-conductor transmission line frequency domain method.

#### 4. Experimental test

In order to verify the effectiveness of the above methods, the experimental circuit shown in Fig. 3 is established.

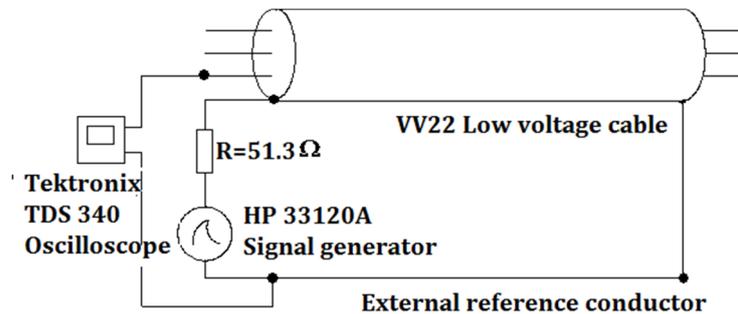


Figure 3. Experimental wiring diagram

The cable in Figure 3 is KVVP2-22A-1kV cable, and the length of the test is 10m long. The pulse voltage waveform shown in Fig. 4 is applied between the cable shielding layer and the external reference conductor by means of the HP 33120A signal generator and the resistance of 51.3 ohms. The Tektronix TDS 340 oscilloscope is used to measure the voltage waveforms of the cable core and cable shield to the external reference conductor, and the measurement results are shown in the solid line curve shown in Figure 5.

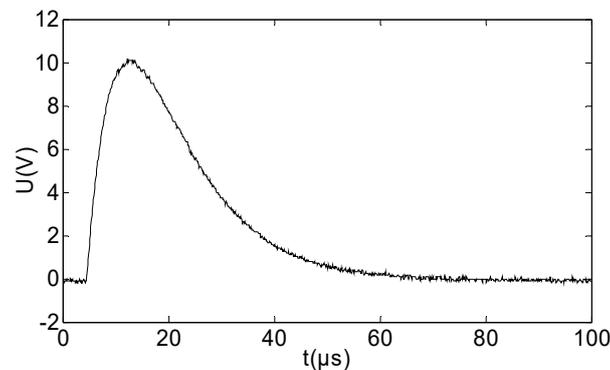
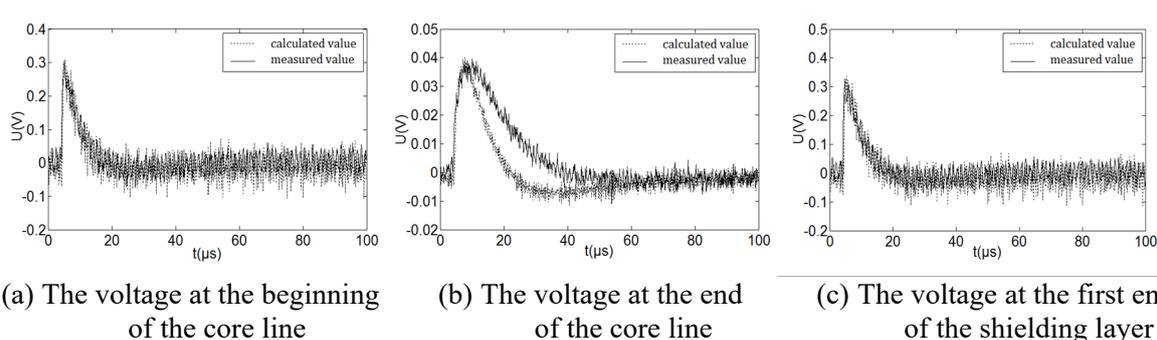


Figure 4. Pulse voltage waveform generated by signal generator



(a) The voltage at the beginning of the core line

(b) The voltage at the end of the core line

(c) The voltage at the first end of the shielding layer

Figure 5. The voltage on the cable core line and the shielding layer

In the calculation, the pulse voltage waveform generated by the signal generator is first transformed by fast Fourier transform to obtain the spectrum of the voltage waveform. Then, the voltage response spectrum of cable core and shielding layer is calculated by the above method. Finally, the fast Fourier inverse transform is used to get the transient voltage waveforms of the cable core and shielding layer, as shown in the dashed curve of Figure 5.

It can be seen from Fig. 5 that the calculation results are basically consistent with the measurement results, which shows that the calculation method is effective.

## 5. Conclusion

This paper studies the calculation method of the interference voltage of the cable when the grounding grid of the substation is directly subjected to lightning stroke. Firstly the equivalent circuit between the two grounding points at the two ends of the shielded cable and the multi-conductor transmission model of the cable are established. Then, using the frequency domain method in the multi conductor transmission line and combining the fast Fourier transform technique, the steps of calculating the interference voltage and current produced in the two cable are given. Finally, in order to test the validity of the proposed measurement method, calculation model and calculation method, the lightning impulse grounding test is carried out on the test grounding network. The effectiveness of the proposed method is verified by the comparison calculation and test results.

## References

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