Evaluation principle and method of horizontal grounding electrode based on time-varying impedance

Xiaobin Cao1 | Ming Wei1 | Manxiang Wang1 | Jiacai Liu1 | Ruifang Li1 | Lin Yang2

1 School of Electrical Engineering, Southwest Jiaotong University, Chengdu 610031, China
2 The Sichuan Electric Power Research Institute, State Grid Sichuan Electric Power Company, Chengdu 610023, China

Correspondence
Ruifang Li, Department of Electrical Engineering, Southwest Jiaotong University, Chengdu, China. Email: lrf_lirf@swjtu.cn

Abstract
The length of the horizontal grounding electrode is usually extended to decrease the impulse grounding resistance. In this paper, the mechanism for influencing the effective length is revealed by studying the dispersal process of a horizontal electrode and a method for determining the length is proposed. Firstly, the impulse current and the response voltage are measured at different positions. The results are used to analyse the time-varying characteristics of the impedance in the dispersal process, the mechanism and the factors influencing the effective length. Furthermore, the current propagation process is divided into a wave head process and a wave tail process. The variation rule and influencing factors of the transient impedance are determined. The wave head impedance acts as a dynamic process from the injection impedance to the wave tail impedance, and the injection impedance is not affected by the length of the grounding electrode. The wave tail impedance is constant and is equal to the DC steady-state impedance. It is proposed that the effective length is caused by two different dispersal processes and it is obtained when the tail impedance is equal to the impulse grounding resistance. These results are highly significant for optimizing the grounding device.

1 | INTRODUCTION

The grounding device of a transmission line is basic equipment used to maintain the safety and reliability of the power system. It can provide a diffusion channel for lightning current when lightning strikes a tower [1]. In China, the electric power industry will maintain a rapid growth in the next 15–20 years, and the realization of the national Interconnection Strategy of West to East power transmission and North-South mutual supply requires the construction of a large number of EHV/UHV transmission systems, in which the tower grounding device is mainly in the form of single conductor or type with long conductor [2]. The main measure to reduce the grounding resistance of the tower grounding device in the areas with high soil resistivity is to increase the length of horizontal grounding electrode, which can be increased to several hundred metres in some parts of China.

Increasing the length of the horizontal electrode can effectively decrease the power frequency grounding resistance. However, this approach may not be as effective for the impulse grounding resistance as impulses have characteristics that are largely different to power frequency characteristics. In [3], it was suggested that only part of the grounding device is effective and the utilization ratio of electrodes is related to the soil resistivity when the impulse current flows into the soil through the long electrode. References [4] and [5] defined the effective length as the length that the grounding impedance of the horizontal grounding electrode is affected. In other words, if the length of the horizontal grounding electrode is longer than the effective length, the impulse grounding resistance will not decrease. The effects of the external ray length of the tower device on the overall dispersion distribution was studied in [6]. Their research showed that the external ray electrode of the grounding device also has an effective length. In order to discover the mechanism of the effective length under an impulse current, accurate analysis of the dispersal regulation of the impulse current in grounding devices is required.

Existing research on the dispersal regulation of impulse currents in a grounding electrode is mainly based on simulation calculations and experiments. Several different methods, such

This is an open access article under the terms of the Creative Commons Attribution License, which permits use, distribution and reproduction in any medium, provided the original work is properly cited.
© 2021 The Authors. *IET Science, Measurement & Technology* published by John Wiley & Sons Ltd on behalf of The Institution of Engineering and Technology
as transmission line theory, simplified circuit analysis and electromagnetic field theory, have been used to obtain the grounding impulse parameters by simulation calculations [7–14]. It is easy to adjust the parameters that affect the grounding performance and to obtain an empirical formula that can be used as a reference in grounding design simulations. However, the numerical simulation method is based on some assumptions, and it is difficult to accurately and objectively describe the physical process of dispersion of the impulse current. Experimental testing is the most direct method and has been used in several studies to obtain an understanding of impulse current dispersal regulation around grounding devices [15–20]. The relationship between the impulse grounding resistance and the length of the grounding electrode was studied in [20]. The test site had a very large area and parameters such as soil resistivity are difficult to change, so very limited conclusions could be obtained. Additionally, in order to better reflect the time-varying characteristics of wave propagation in a grounding electrode, the transient impedance was analysed and impulse dispersal regulation was studied in [18] and [19].

Although an empirical formula for calculating the effective length has been summarized in the existing research, few scholars have yet to explain the effective length from a dispersal process. In this paper, using the experimental results of a horizontal electrode, the time-varying regulation of the impedance and the impulse dispersal process are analysed, in order to explain the mechanism and the factors influencing the effective length and study its discriminant method. The results are highly significant for rational selection of resistance reduction methods and optimization of grounding devices.

2 | IMPULSE EXPERIMENTS OF HORIZONTAL LONG ELECTRODES

2.1 | Experimental configuration

In order to study the time-varying characteristics of the impedance and the relationship between the length of the horizontal grounding electrode and the impulse grounding resistance, impulse experiments were performed. For these experiments, the material of the conductor is round steel. The electrode resistivity was 19.2 × 10⁻⁷ Ω·m and the relative magnetic permeability was 636. The electrode diameters were 4 mm and their buried depth was 0.5 m in earth with 215 Ω·m resistivity. The length of the horizontal grounding electrode was varied for different experiments and the following values were used: 100, 90, 80, 70, 60, 50, 40, 30, 20, and 10 m.

The experimental measurement circuit is shown in Figure 1. In this experiment, an impulse current was injected into the head end of the horizontal grounding electrode by an impulse generator. A 1 Ω non-inductive sampling resistor was used to measure the impulse current at the injection point and the current I was obtained using the equation $I = U/R$. The oscilloscope used for this experiment was Tektronix 2024C. Its first channel was used to measure the impulse voltage $U$ and its second channel was used to measure the voltage of the 1 Ω sampling resistor.

FIGURE 1 Experimental circuit

There were also two other measurement positions on the horizontal grounding electrode. The purpose for selecting multiple measurement points in the experiments is to study the propagation process of waves in horizontal grounding electrodes and to explore the cause for the effective length. The second measurement point was used to measure the current waveforms and the voltage waveforms. The current waveforms were obtained using a current sensor. In the experiment, the initial length of the grounding electrode is 100 m, so we choose the middle point (50 m) as the second measuring point. In each subsequent measurement, we cut 10 m from the end of conductor to change the length. For the sake of comparability between data, we did not move the position of the 50 m measuring point when the length of the grounding electrode greater than 50 m. However, during the measurement of 60, 70, 80, 90 and 100 m grounding electrodes, it is found that the voltage difference between the second measuring point and the terminal measuring point of these grounding electrodes is very small, and the wave head voltage measured at the above two positions is different from that of the injection point. Therefore, for the grounding electrode with length less than or equal to 50 m, the position (10 m) closer to the current injection point is selected to measure to study the process of voltage wave head deformation. The final measurement point was at the end of the grounding electrode and was used to measure the voltage waveforms at the end of the grounding electrode.

In addition, the grounding resistances of the each of the different lengths of grounding electrodes were measured using a grounding resistance tester. Since the output waveform of the grounding resistance tester is a square wave with a low frequency, the measured grounding resistances can be considered to be DC steady-state impedances.

For this experiment, the grounding resistance was measured using the classical fall-of-potential test method. In order to minimize the influence of the lead mutual inductance, the voltage auxiliary electrode (P) was positioned perpendicular to the current auxiliary electrode (C), and both auxiliary electrodes were located 50 m apart from the horizontal grounding electrode.

The amplitude of the current generated by the impulse generator in this experiment is small, so spark discharge will not happen during the measurement process, which eliminates the potential for the spark discharge phenomenon to influence the
experimental results. It is useful to explore the effect of length on the impulse characteristics of the grounding electrode.

2.2 Experimental results of grounding electrodes with different lengths

Since changing the grounding electrode lengths will affect the output waveform of the power supply, an external circuit should be added to provide the adjustments necessary to obtain a standard lightning impulse waveform. However, since this external circuit will interfere with the measurement results, we have not added an external adjustment circuit in our experiments. Therefore, the actual output waveform is not a standard lightning impulse waveform.

The research focuses on the impulse dispersal process of the horizontal grounding electrode and the generation mechanism of the effective length. Therefore, a low-power impulse generator with the same output state was selected, and the current waveform was not output based on the standard. The measured current waveforms which were injected into the grounding electrodes of different length are shown in Figure 2. The peak value of these current waves is $I_m = 8 \text{ A}$, with a zero-to-peak time of $T_1 = 16 \mu\text{s}$ and a half-width of $T_2 = 800 \mu\text{s}$. The impulse current injected into the 90 m-length electrode is different and has the following parameters: peak value $I_m = 6.5 \text{ A}$, zero-to-peak time $T_1 = 12 \mu\text{s}$ and half-width $T_2 = 1000 \mu\text{s}$.

The impulse voltage response waveforms at the injection point of the grounding electrodes of different lengths are shown in Figure 3. The figure shows that the change in the grounding electrode with length can be divided into three stages. When the length of the grounding electrode is less than 30 m, the amplitude of the impulse voltage response decreases as the length increases for the entire time period. When the length of the grounding electrode is between 30–40 m, the rising edge is almost identical for all of the impulse voltage waves but the peak value of the impulse voltage response still decreases as the length increases. In both of these cases, the length of the horizontal grounding electrode is closely related to the peak value of the impulse voltage response. However, when the length of the grounding electrode is greater than 40 m, the peak value of the impulse voltage response no longer decreases as the length increases and the wave head time is almost coincident for grounding electrodes of different lengths.

In contrast, the amplitude of the wave tail of the impulse voltage always decreases as the length of the grounding electrode increases. This phenomenon indicates that the physical processes of the wave head and the wave tail are different and the effect of length on two processes is different.

3 ANALYSIS OF THE IMPULSE DISPERSAL PROCESS OF THE HORIZONTAL GROUNDING ELECTRODES

3.1 Distribution characteristics of GPR and current

When the impulse current flows through the horizontal grounding electrode, electromagnetic fields in the surrounding soil will synchronously increase. The wave process should be considered when the voltage and current are diffusing. An experiment using a 50 m-length horizontal grounding electrode was taken as an example to study the impulse current and voltage distributions and the results are shown in Figure 4.

Figure 4 shows that the impulse current is continuously reduced as it propagates along the grounding electrode. However, the voltages at different measurement points are different in the wave head and they tend towards the same value at the wave tail, which further illustrates that the impulse current dispersal process is divided into two physical processes: a wave head process and a wave tail process.

The wave head process is the current wave that propagates from the electrode head to its end, as shown in Figure 5(a,b). At the time of the impulse current injection, the horizontal grounding electrode has the largest current density at the
current injection point, and the region of current scattering to the ground is very small (Figure 5(a)). As the impulse current flows from the head to the end along the ground electrode, the active length in the ground electrode and the region of scattering both increase (Figure 5(b)).

As the impulse current flows into the soil along the entire length of the electrode, the wave tail process takes over (Figure 5(c)). In this process, each part of the grounding electrode has a response voltage that is basically equal and gradually decays to zero.

Experiments on grounding electrodes of different lengths (20, 40, 60 and 80 m), show that these two physical processes always exist despite differences in length of the grounding electrode. The measurement results are shown in Figure 6. The waveform of the impulse response voltage of each grounding electrode has both of the above processes, and the wave tail of the three measurement points is consistent with the description above.

3.2 | Time-varying regularity of the impedance

From these experiments and analysis, we can conclude that the impulse dispersal process of a horizontal electrode changes from an electromagnetic transient process to a steady-state process. Therefore, the grounding impedance should also change from a transient wave impedance to a steady-state impedance, which will be confirmed in this section by analysing the transient characteristics of impedance.

The impulse grounding resistance $R_{ch}$ can usually be defined as follows:

$$R_{ch} = \frac{V_{\text{max}}}{I_{\text{max}}} \quad (1)$$

where $V_{\text{max}}$ is the peak value of the impulse voltage wave and $I_{\text{max}}$ is the peak value of the impulse current wave.

Since the impulse impedance of the grounding electrode has transient characteristics, $R_{ch}$ cannot accurately describe the impulse dispersal physical process. Therefore, a transient impedance $Z(t)$ is created to explain the change in the grounding resistance of the horizontal grounding electrode during the impulse dispersion, as follows:

$$Z(t) = \frac{V(t)}{I(t)} \quad (2)$$

where $V(t)$ is the real-time voltage of the measurement point of the voltage auxiliary electrode and $I(t)$ is the real-time current of the injected point.

The transient impedance is shown in Figure 7 for different lengths. This figure shows that the impedance is similar for
different lengths at the time of the impulse current injection into the head of the grounding electrode. As the measurements may be influenced by measurement errors and noise, all of the transient impedance values at the initial stage can be considered to be equal, and defined as the injection impedance.

As time increases, the transient impedance $Z(t)$ changes rapidly before approaching a stable value. The specific value is defined as the wave tail impedance. In the wave tail stage of the impulse current dispersion, the grounding electrodes with different length diffuse to the soil through the whole conductor, and the wave tail impedance is closely related to the length of the grounding electrode. Therefore, the transient impedance of the grounding electrode will gradually approach the wave tail impedance from the injection impedance.

The DC grounding resistance $R$ of each grounding electrode was measured using a ground resistance tester and the results are shown in Table 1. These results show that the wave tail impedance is extremely close to the DC grounding resistance, with an error of less than 5%.

It can be seen from Table 1 that the wave tail impedance of the grounding electrodes is different. The wave tail impedance of 40, 70, 100 m grounding electrode is greater than the injection impedance, while the wave tail impedance of 10 m grounding electrode is less than the injection impedance. Therefore, the impedance of 10 m electrode unlike the other electrodes increases with increment in the time.

Figure 8 shows the impulse response voltage and transient impedance of the 10-m long grounding electrode and 100-m long grounding electrode. The time point when the difference between the transient impedance and the tail impedance is less than 5% is marked in Figure 8 and can be regarded as the cut-off point between the two physical processes, defined as the cut-off time $t_1$.

The figure also shows that the injection impedance of the 10-m grounding electrode is smaller than the wave tail impedance and the injection impedance of the 100-m grounding electrode is larger than the wave tail impedance. Therefore, this paper defines the critical length of the grounding electrode as the length when the injection impedance and the tail impedance are equal. This critical length can be obtained by combining Figures 3 and 7. When the critical length is reached, the amplitudes
The two physical processes of transient impedance and impulse response voltage. (a) 10-m grounding electrode. (b) 100-m grounding electrode.

The rising edges of the voltage response are equal and the transient impedances of the wave head processes of the grounding electrodes of different lengths are almost the same. The only difference is the time taken to enter the wave tail process, as it takes longer to enter the wave tail process for electrodes of longer lengths. When the ground electrode reaches a certain length, the peak value of its impulse response voltage will be mainly caused by the wave head process.

3.3 Factors affecting the transient impedance

The soil resistivity, the electrode length and the waveform of the injected current all have a strong influence on the impulse characteristics of the horizontal grounding electrode.

3.3.1 Waveform of injected current

In this experiment, the effect of the wave front time on the transient impedance of the grounding electrode was studied.

Figure 9 shows the transient impedance for different types of impulse current, with a 16/800 $\mu$s and a 12/1000 $\mu$s exponential waveform.

Figure 9 shows that the injection impedance is greater with an injected current wave front time of 12 $\mu$s than with an injected current wave front time of 16 $\mu$s. Therefore, the injection impedance is related to the impulse current waveform and shorter wave front times will correspond with larger injection impedance values. This also shows that the inductance effect of the grounding electrode plays a major role in its impulse characteristics at the initial time point of current injection. The wave tail impedance of the grounding electrode under both current waveforms is almost identical, which indicates that the wave tail impedance of the grounding electrode is not affected by the impulse current waveform without spark discharge.

3.3.2 Length of the electrode and soil resistivity

The length of the horizontal grounding electrode also has an important effect on the impulse characteristics. As shown in Figure 10, for the same impulse current, the injection impedance is not affected by the length of the grounding electrode and is equal to approximately 20 $\Omega$. However, the wave tail impedance is inversely related to the length of the grounding electrode. Therefore, the length does not affect the wave head process i.e. the propagation process of the wave along the longitudinal direction of the grounding electrode. The critical length of the grounding electrode is between 20 and 30 m.

When the impulse dispersal process enters the wave tail stage, it can be regarded as a DC steady-state process of capacitor discharge. The wave tail impedance of the grounding electrode can be obtained by calculating the DC steady state resistance using the following calculation formula [7]:

$$R = \frac{1}{G}$$

(3)
Under the impulse current, the wave head process and the wave tail process are affected differently by changes in length. When the length of the grounding electrode is less than or equal to the critical length, the peak value of the impulse voltage is determined by the wave tail process, and the wave head processes are different for different lengths of grounding electrodes. When the grounding electrode is longer than the critical length but shorter than the effective length, the amplitudes of the rising edges of the voltage response are equal, but the peak value of the impulse voltage is still determined by the wave tail process. When the length of the grounding electrode is greater than or equal to the effective length, the peak value of the impulse voltage is determined by the wave head process and the impulse grounding resistance will not change with length. By combining the results with the voltage response shown in Figure 3, we can see that when the grounding electrode is 30 m or longer, the amplitude of the wave head voltage remains the same as the length of the grounding electrode further increases and the wave tail voltage gradually decreases as the length increases. Further increasing the length at this time will only reduce the voltage of the wave tail time until the potential rise due to the wave head process is greater than the potential rise due to the wave tail process. This does not affect the peak value of the wave head time and the grounding electrode can be seen to have reached its effective length.

At present, the research on the mathematical expressions of the effective length is mainly based on empirical fitting formula. Reference [4] proposed the formula for calculating the effective length as given in Equation (5).

\[ l_{\text{eff}} = 1.4\sqrt{\rho T} \]  

(5)

where \( \rho \) is the soil resistivity in ohmmeters, and \( T \) is the wavefront time for the injected current in microseconds.

Reference [19] proposed the formula for calculating the effective length as given in Equations (6)–(8).

\[ l_{\text{eff}} = \frac{1 - \beta}{\alpha} \]  

(6)

\[ \alpha = 0.025 + e^{-0.82/\rho T^{0.257}} \]  

(7)

\[ \beta = 0.17 + e^{-0.22/\rho T^{0.555}} \]  

(8)

where \( \rho \) is the soil resistivity in ohmmeters, and \( T \) is the wavefront time for the injected current in microseconds.

Under the experimental conditions of this paper, the effective length of horizontal grounding electrode calculated by Equations (5) and (6) are 82.11 and 31.56 m, respectively. It can be seen that there are great differences in the calculation of effective length by different calculation formulas. Therefore, the above empirical formula is often used as a reference for the design of grounding electrode before installation. For the reform of existing grounding device and its impulse performance evaluation, it is necessary to provide a new method based on experiments. Using the definition of impulse

### 4 Effective Length of Extended Grounding Electrodes

#### 4.1 Cause and discriminant method of the effective length

Since the impulse dispersal process of the grounding electrode is different from the power frequency dispersal process, there is a difference in the impulse characteristics and the power frequency characteristics.
TABLE 2 Impulse grounding resistance of grounding electrodes of different lengths

| L (m) | Injection impedance (Ω) | Impulse grounding resistance (Ω) | Wave tail impedance (Ω) | Voltage leads current (µs) |
|-------|-------------------------|---------------------------------|-------------------------|---------------------------|
| 100   | 19.6                    | 11.76                           | 5.9                     | 6                         |
| 80    | 21.8                    | 11.76                           | 6.8                     | 6                         |
| 70    | 20.1                    | 11.47                           | 6.9                     | 6                         |
| 60    | 22.6                    | 11.27                           | 8.0                     | 6                         |
| 50    | 17.7                    | 11.56                           | 8.8                     | 6                         |
| 40    | 19.0                    | 11.7                           | 11.9                    | 6                         |
| 30    | 16.7                    | 14.61                           | 16.3                    | 0                         |
| 20    | 15.5                    | 20.38                           | 26.2                    | −4                        |
| 10    | 21.5                    | 32.8                           | 35.6                    | −7                        |

grounding resistance in [21], Table 2 shows the test results the impulse grounding resistance for electrodes of different lengths.

It can be seen from Table 2 that the impulse grounding resistance does not decrease once the length reaches 40 m. Therefore, the effective length of the horizontal grounding electrode is 40 m for the experimental soil environment. The impulse grounding resistance is less than the wave tail impedance before the ground electrode reaches the effective length. This may explain why the ground capacitance participates in the diffusion of the high-frequency currents. As a result, the ground impedance exhibits significant capacitive characteristics and the impulse grounding resistance is smaller than the wave tail impedance. When the grounding electrode reaches the effective length, the impulse grounding resistance is greater than the wave tail impedance due to the inductance effect of the grounding electrode. Therefore, it can be determined whether a grounding electrode has reached its effective length by comparing the magnitude of the impulse grounding resistance and the wave tail impedance.

Additionally, it can be seen intuitively from Figure 3 that there are differences in the response waveform of the impulse voltage before and after reaching the effective length. After the effective length is reached, the impulse voltage waveform exhibits a steep pulse, since the impulse voltage decay speed due to the two processes is different once the effective length has been reached. The wave head is mainly driven by the electromagnetic transient process and its voltage decays faster than the voltage decay after reaching the steady state phase. Therefore, if the surge voltage response waveform has a steep pulse, it can be determined that the effective length has been reached. When the wave head of the impulse voltage generates a steep pulse and the peak value of the wave head is greater than the wave tail voltage amplitude, the grounding electrode has reached the effective length.

4.2 Factors affecting the effective length

By analysing the reasons for the effective length, the factors that affect the impulse dispersal process can be obtained that will influence the effective length of the grounding electrode. From the previous analysis, it can be seen that the wave head process is mainly affected by the soil characteristics and the injection current waveform, regardless of the length of the grounding electrode, whereas the wave tail process is closely related to the length of the electrode and the soil resistivity.

The influence of the injected impulse current waveform on the impulse voltage response mainly affects the wave head process. The initial impedance increases as the wave head time decreases, while the wave tail impedance of the wave tail is not affected by the injection current. The shorter the head time of the injected impulse current, the shorter the effective length of the grounding electrode. The soil resistivity mainly affects the wave tail process, and the soil resistivity is positively correlated with the wave tail impedance. Therefore, an increase in the soil resistivity will correspond with an increase in the effective length of the grounding electrode. Since the spark discharge facilitates the process of current flowing into the soil, the effective length will be reduced if a large impulse current causes the spark discharge.

In [5], it was seen that when the amplitude of the impulse current was large enough, it did not lower the peak value of the grounding voltage, which is similar to the effective length characteristics. This is because the soil ionization due to the spark discharge increases the conductance to ground and reduces the amplitude of the impulse voltage. When the spark discharge phenomenon reduces the wave tail voltage below that of the wave head voltage, the peak value of the voltage is mainly due to the electromagnetic transient process. At this time, increasing the amplitude of the injected current can only reduce the steady state impedance at the wave tail time and has minimal effect on the peak value of the voltage response. The results verify the two dispersal processes.

4.3 Application of tower grounding electrodes

Impulse tests were performed on two tower grounding devices using a fall-of-potential test method. During the test, the grounding device was disconnected from the tower, and two auxiliary electrodes arranged at 180 degree angles were positioned 50 m away from the tower grounding device. The measurement points and the shape of the tower grounding device are shown in Figure 11.

The test results obtained are shown in Figure 12 and Table 3. The two graphs in Figure 12 show that the transient impedances of both tower devices tend towards a stable value,
TABLE 3 Impedance of tower grounding electrode

| Tower | Injection impedance (Ω) | Impulse grounding resistance (Ω) | Wave tail impedance (Ω) |
|-------|-------------------------|-------------------------------|------------------------|
| Tower 1 | 19.00                   | 1.77                          | 1.21                   |
| Tower 2 | 4.54                    | 4.72                          | 4.76                   |

**FIGURE 12** Impulse response and transient impedance of the tower grounding device. (a) Tower 1. (b) Tower 2

i.e. the impulse dispersion will eventually enter the wave tail process. The injection impedance of the grounding electrode of tower 1 is greater than its wave tail impedance. Therefore, the wave head process has a greater influence on the impulse characteristics of the grounding electrode. Its impulse voltage waveform has a steep pulse at the wave head and the peak value of the wave head is greater than the wave tail amplitude. By comparing the impulse grounding resistance and the wave tail impedance, it can be verified that the tower grounding electrode has reached its effective length. At this time, increasing the length of the ground electrode will only reduce the wave tail voltage and does not reduce the impulse grounding resistance. The transient impedance of tower 2 shows little variance over time and its impulse grounding resistance is less than the wave tail impedance. Therefore, the grounding electrode has not reached its effective length and extending the length of the grounding electrode can effectively reduce the impulse grounding resistance. It is also proved that the method proposed in this paper can be effectively applied to the grounding device with single or multiple long conductors through the actual tower test.

For the complex grounding with large number of conductors, the wave head process is still an electromagnetic transient process and will not be affected by the conductor far away from the injection point. When the dispersal process enters the wave tail stage, at this time, all the conductors of the whole grounding grid participate in the dispersion to the ground. Due to the difference of different conductors participating in the wave head process and wave tail process, there is still an effective dispersion area in the grounding electrode. Reference [22] has carried on the simulation research to the grounding grid containing a large number of conductors. The areas of the grounding grids are different from $5 \times 5 \text{m}^2$ to $40 \times 40 \text{m}^2$. The results show that there is an effective area of a grounding grid when it is excited by impulse currents.

5 | CONCLUSION

The impulse experimental results of a horizontal grounding electrode have been used to analyse the impulse dispersal process and the effective length of the grounding electrode. The results are summarized as follows.

1. The impulse dispersal process of a horizontal electrode has been studied experimentally. By comparing the voltage and current waveforms at different positions of the electrode, it has been confirmed that the impulse process is divided into two physical processes: the wave head process and the wave tail process. The wave head process is the propagation process of the impulse current from the electrode's head to its tail and the wave tail process is the process of the impulse current flowing into the soil along the entire length of the electrode. The dispersal process and effective length of the horizontal grounding electrode are closely related.

2. The experimental results have been studied to investigate the variation pattern of the transient impedance with electrode length. It has been found that for the same injected current waveforms, grounding electrodes of different lengths have the same injection impedance. In the wave head
process, there is a transition of the transient impedance from an injection impedance to a wave tail impedance. In the wave tail process, the wave tail impedance is equal to the DC steady state impedance. The grounding electrode reaches its critical length when the wave tail impedance is equal to the injection impedance.

3. The impedance has been analysed in order to propose a method to determine if an actual tower grounding electrode has reached its effective length. When the measured wave tail impedance was equal to the impulse grounding resistance, the length of the grounding electrode was equal to the effective length. At this time, further increasing the length of the ground electrode will no longer reduce the peak value of the impulse voltage. Finally, application of this method has been demonstrated using an actual tower grounding electrode.

ACKNOWLEDGMENT

This work was supported by the National Nature Science Foundation of China under Grant 51777175.

REFERENCES

1. Liu, Y., Theethayi, N., Thottappillil, R.: Investigating the validity of existing definitions and empirical equations of effective length/area of grounding wire/grid for transient studies. J. Electrostat. 65(5), 329–335 (2007)[CrossRef]
2. He, J., et al.: Laboratory investigation of impulse characteristics of transmission tower grounding devices. IEEE Trans. Power Del. 18(3), 994–1001 (2003)
3. Mazzetti, C., Veca, G.M.: Impulse behavior of grounded electrodes. IEEE Trans. Power App. Syst. PAS-102(9), 3148–3156 (1983)
4. Gupta, B.P., Thapar, B.: Impulse characteristics of grounding electrodes. J. Inst. Eng. (India) 4(64), 178–182 (1981)
5. He, J., et al.: Effective length of counterpoise wire under lightning current. IEEE Trans. Power Del. 20(2), 1585–1591 (2005)
6. Cao, X., et al.: Current divergence validity of 500kV tower grounding device under lightning stroke. High Voltage Eng. 43(5), 1596–1601 (2017)
7. Sunde, E.D.: Surge characteristics of a buried bare wire. AIEE Trans. 59, 987–991 (1940)
8. Dawalibi, F., Xiong, W., Ma, J.: Transient performance of substation structures and associated grounding systems. IEEE Trans. Ind. Appl. 31(3), 520–527 (1995)
9. Zhu, J., Jiao, D.: A theoretically rigorous full-wave finite-element based solution of Maxwell's equations from DC to high frequencies. IEEE Trans. Adv. Packag. 33(4), 1043–1050 (2010)
10. Mentre, F.E., Grecz, L.: EMTP-based model for grounding system analysis. IEEE Trans. Power Del. 9(4), 1838–1849 (1994)
11. Geri, A.: Behaviour of grounding systems excited by high impulse currents: The model and its validation. IEEE Trans. Power Del. 14(3), 1008–1017 (1999)
12. Xiong, W., Dawalibi, F.: Transient performance of substation grounding systems subjected to lightning and similar surge currents. IEEE Trans. Power Del. 9(3), 1412–1420 (1994)
13. Sheshyekani, K., et al.: Analysis of transmission lines with arrester termination, considering the frequency-dependence of grounding systems. IEEE Trans. Electromagn. Compat. 51(4), 986–994 (2009)
14. Grecz, L.D., et al.: Evaluation of high-frequency circuit models for horizontal and vertical grounding electrodes. IEEE Trans. Power Del. 33(6), 3065–3074 (2018)
15. Wang, J., Liew, A.C., Darveniza, M.: Extension of dynamic model of impulse behavior of concentrated grounds at high currents. IEEE Trans. Power Del. 20(3), 2160–2165 (2005)
16. He, J., et al.: Laboratory investigation of impulse characteristics of transmission tower grounding devices. IEEE Trans. Power Del. 18(3), 994–1001 (2003)
17. Olsen, R.G., Grecz, L.: Analysis of high-frequency grounds: Comparison of theory and experiment. IEEE Trans. Ind. Appl. 51(6), 4889–4899 (2015)
18. Choi, J., Lee, B.: An analysis on the Frequency-dependent grounding impedance based on the ground current dissipation of counterpoises in the two-layered soils. J. Electrostat. 70(2), 184–191 (2012)
19. Grecz, L.: Impulse efficiency of ground electrodes. IEEE Trans. Power Del. 24(1), 441–451 (2009)
20. Motoyama, H.: Electromagnetic transient response of buried bare wire and ground grid. IEEE Trans. Power Del. 22(3), 1673–1679 (2007)
21. IEEE Guide for Safety in AC Substation Grounding. IEEE Standard, Vol. 80. IEEE Standards Association, Piscataway, NJ (2013)
22. Zeng, R., et al.: Lightning impulse performances of grounding grids for substations considering soil ionization. IEEE Trans. Power Del. 23(2), 667–675 (2008)

How to cite this article: Cao X, Wei M, Wang M, Liu J, Li R, Lin Y. Evaluation principle and method of horizontal grounding electrode based on time-varying impedance. IET Sci Meas Technol. 2021;15:174–183. https://doi.org/10.1049/smt2.12019