Characteristics of Two Ground Grid Potentials After a Triggered Lightning Stroke

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ABSTRACT

It has been determined that the discharge of lightning current to ground through grounding grid results in high potential at the grounding grid and other nearby grounding grids, which is very destructive. In the present paper, based on artificially triggered lightning technology, the characteristics of the ground potential rise (GPR), the transient effect at the active grid under the transient impulse of lightning current was analyzed. The impulse grounding resistance is found to decrease for large input currents. On the other hand, for small input currents, it usually increases. In addition, the characteristics of the transfer potential of the passive grid which is located 40 m from the active grid were analyzed. It was shown that the peak value of the transfer potential at the passive grid was approximately 5.1% of the peak value of the ground potential at the active grid during the return stroke. The achievements made in this study may contribute toward the optimization of the simulation model.

INDEX TERMS

Artificially triggered lightning, lightning current, grounding grid, ground potential rise (GPR), impulse grounding resistance, transfer potential.

I. INTRODUCTION

A grounding grid is critical throughout the entire lightning protection system. In the case of a lightning stroke, a grounding grid can allow lightning current to be quickly discharged to the ground, and thus reduce the damage caused by strong lightning current. At the same time, the discharge of lightning current will result in a rapid ground potential rise (GPR, usually hundreds or even thousands of kV) in the active grid. Such a high potential will easily damage the connected electrical equipment. A high potential will also be generated at the passive grid within a certain distance from the active grid, due to the transfer potential or lightning current dispersion, which also easily damages the electrical equipment connecting to it.

Some researchers have carried out studies on the GPR, transient effect of grounding grid and interactions between multiple grids by means of in-lab high-voltage tests [1], numerical modeling, etc. [2]. High-voltage impulse tests can be repeated to analyze the impact of different parameters on the transient characteristics of grounding grid under the effect of lightning impulse current, by changing parameters such as pulse peak current, grounding grid size, soil resistivity and injection point of lightning current on the grounding grid. In numerical modeling, different algorithms and analysis methods are applied to simulate the actual working conditions. Various parameters such as grounding grid parameters and soil parameters in models are adjusted, which continuously improve the model, and in turn yield more accurate simulation results. Previous studies have found that the GPR of the grounding grid was mainly affected by factors such as injected current (intensity, wave head time), characteristics of grounding grid (material, size, current injection location) and soil characteristics (soil resistivity) [3]–[5].

Due to the uncertainty of natural lightning, it is difficult to study the GPR of grounding grid caused by lightning in the natural environment. Therefore, the use of artificially triggered lightning is a good method currently available by which to conduct research in this area [6]–[9]. Unlike natural lightning, classical artificially triggered lightning does not contain the first return stroke. Consequently, the GPR of
grounding grid caused by the first return stroke cannot be studied. However, it is feasible to carry out research on the GPR caused by the subsequent return strokes, based on artificially triggered lightning, since artificially triggered lightning is very similar to natural lightning in terms of the subsequent return stroke processes [10]. Schoene et al. [11] observed the shunt of lightning current at different locations of an overhead distribution line caused by ground potential counterattack when the lightning current entered the ground at a distance of 11 m from the tower during the direct lightning strike test on the overhead distribution line. Chen et al. [12] carried out tests of lightning protection for automatic weather stations based on artificially triggered lightning, and found that the ground potential counterattack caused by the superposition of long continuous lightning current and multiple return strokes may damage the surge protective devices (SPD) with the rated flow rate connected to the grounding grid 5 m away. Guo et al. [13] also carried out research on the interaction between two grounding grids based on triggered lightning. They obtained the waveforms of GPR at the passive grounding grid in the case of common ground and analyzed its characteristics. In this last study, due to the interference of strong lightning electromagnetic pulses on the measurement equipment during the occurrence of close-range lightning, the GPR waveforms of the main grounding grid were not measured.

In the present paper, based on the artificially triggered lightning tests, the waveforms of the triggered lightning current, GPR at the active grid A and transfer potential at the passive grid B are obtained. In addition, the characteristics of the GPR, the transient effect of the grounding grid, as well as the characteristics of the transfer potential at the passive grounding grid are analyzed.

II. TEST SETUP

The experiment described in this paper was performed at Guangdong Comprehensive Observation Experiments on Lightning Discharge (GCOELD) in the summer of 2017. As shown by the configuration adopted in the experiment, two isolated grounding grids were deployed, which are located 40 m apart. Grounding grid A (the active grid which was injected with lightning currents, with the specifications of 10 m × 10 m and four grids (5 m × 5 m)) and grounding grid B (the passive grid, was a single grid with the scale of 5 m × 5 m) were composed of horizontal and vertical grounding electrodes, which was connected by galvanized flat steel (40 mm × 4 mm) buried at 0.8 m under the ground. The vertical grounding electrodes were made of galvanized angle steel with a length of 2.5 m and specifications of 40 mm × 40 mm × 4 mm, which were evenly laid around the grounding grid with 5 m intervals. Most areas of the test site (including grounding grid B) were covered by wet clay, and the measured soil resistivity was 314.8 Ω·m. The area where grounding grid A was located was the launching area of the rockets for lightning triggering. In this area (10 m × 10 m), the surface was covered by 5 cm thick concrete layer and sand soil was at a depth of 1 m below the surface.

The measured values of grounding resistance at the power frequency were 15.8 Ω for grounding grid A and 21.6 Ω for grounding grid B.

In order to accurately measure the ground potential of the grounding grid A or B, the grounding of 10 kV voltage grade insulated cables was used as the zero-potential reference point. The buried depth of the insulated cables was 0.8 m, and the zero-potential reference point was grounded with angled steel, with a length of 2.5 m and dimensions of 40 mm × 40 mm × 4 mm. The distances between the zero-potential point and grounding grid were 63 m for grounding grid A and 60 m for grounding grid B, as shown in Fig. 1.

Next, the triggered lightning current was injected into the center of grounding grid A, and directly measured at the bottom of the lightning channel via a coaxial shunt with noninductive resistance of 1 mΩ and bandwidth from DC to 20 MHz. The current signal was transmitted via optical fiber, and recorded with a sampling rate of 100 M/s by a data acquisition system. The voltages of grounding grid
A were divided by a voltage divider with a division ratio of 587, then attenuated by a 100-fold attenuator. The case for voltages of grounding grid B were the same as that of grounding grid A, but with a division ratio of 200. Finally, the reduced voltage signals of grounding grids A and B were respectively recorded with a sampling rate of 10 M/s using two data acquisition systems. In this paper, in order to reduce electromagnetic interference (EMI), the HBM high-voltage isolation system, whose system protection effect is known to be stable and reliable, was used. In addition, the coaxial cable and all equipotential bonding lines involved in the experiment had followed the standard of shortening.

### III. OBSERVATION RESULTS AND ANALYSIS

In this paper, the lightning flash analyzed in this study was from a successful triggered lightning using the rocket-and-wire technique on July 8, 2017 at 18:49:42 (local time), hereinafter referred to as lightning flash T1849. Lightning flash T1849 contains four return strokes (hereinafter referred to as RS1-RS4). The corresponding lightning current waveforms, GPR waveforms and transition potential waveforms of grounding grid B are measured by the data acquisition systems described in the previous section.

#### A. CHARACTERISTICS OF THE LIGHTNING CURRENT WAVEFORM

Fig. 2 (a) shows the full lightning current waveform for the entire process of lightning flash T1849, and Fig. 2 (b) presents the corresponding expanded waveforms. As shown in Fig. 2 (a) and 2 (b), both RS1 and RS2 contain obvious M components in the later period of the return stroke. After RS1, there is a long continuous current process, which lasts about 30 ms and is superimposed by an M component. RS3 and RS4 only contain return strokes. The current amplitude of the four return strokes is between $-9.23 \text{kA}$ and $-25.84 \text{kA}$, with an arithmetic mean value of $-15.30 \text{kA}$. The half-peak width of the four return strokes ranges from 3.45 to 8.55 $\mu$s, with an arithmetic mean value of 5.58 $\mu$s, which is comparable to the statistical results obtained by Zheng et al. [14]. The 10-90% current rise time ranges from 0.09 to 0.41 $\mu$s, with a mean value of 0.24 $\mu$s. The charge transfer of RS2 is 2.14 C, which is larger than any other return strokes. Note that RS2 has the largest current amplitude, and contains an obvious M component. The average charge transfer of the four return strokes is 0.99 C, and the detailed characteristic parameters of these strokes are listed in Table 1.

#### B. CHARACTERISTICS OF THE GPR AT GROUNDING GRID A

For T1849, the triggered lightning current flows into the ground through grounding grid A, and results in the grid’s ground potential rise (GPR) immediately. The grounding potential of the four return strokes and corresponding lightning current waveforms are shown in Fig. 3, while the detailed characteristic parameters of the grounding potential waveforms are listed in Table 2. It can be seen that the voltage peak value on grounding grid A ranges from $-200.69$ to $-353.49$ kV, with an arithmetic mean value of $-254.69$ kV, and the half-peak width ranges from 5.19 to 12.16 $\mu$s, with an arithmetic mean of 9.94 $\mu$s. The 10-90% rise time ranges from 1.0 to 1.65 $\mu$s, with an arithmetic mean of 1.24 $\mu$s. It can be seen from Fig. 3 that there is a significant difference between the waveforms of the GPR and lightning currents at the grounding grid. It is worth to note that the half-peak width of the former is significantly

![FIGURE 2. (a) Triggered lightning currents waveform for the entire process of flash T1849; (b) The corresponding expanded waveforms of return strokes RS1–RS4.](image)

![TABLE 1. Parameters of triggered lightning strikes and associated currents (T1849).](table)
larger (1.8 times) than that of the latter, and the decrease in the amplitude of the GPR is significantly slower than that of the triggered lightning currents, which is similar to the results of the residential building current shunt test carried out by Rakov et al. [15]. These are mainly due to the influence of the inductance effect. A changing magnetic field will be generated when non-constant current flows through the grounding electrodes, and this changing magnetic field acts on the grounding electrodes to decelerate the current release, which causes the half-peak width of the corresponding GPR waveforms to increase in size. The 10-90% risetime of the GPR is also larger (6.5 times) than the corresponding risetime of the triggered lightning currents.

As shown in Fig. 3, both RS1 and RS2 contain M components superimposed in the later period of the return stroke. In addition, the GPR waveforms present similar corresponding pulses, yet the return strokes do not exhibit this characteristic. This phenomenon is mainly due to the increase in the change rate of lightning current in the return strokes. At this time, under the influence of the inductance effect of the grounding electrodes, the half-peak width of the GPR is significantly greater than that of the corresponding lightning currents, while the M components superimposed at the tail of the return-stroke current is dominant by a low-frequency signal. The grounding electrodes are less significantly affected by the transient effect, thus the pulsation of the M component waveforms is very similar to that of the corresponding GPR. The above analysis shows that the ground potential of the grounding grid is affected by lightning current injected into the grounding grid in addition to the influence of the conductor inductance (current change rate) [16]. This change in the GPR waveform is ultimately determined by the characteristics of the current injected into the grounding grid and the impulse characteristics of the grounding grid.

Among the four return strokes, the peak current of RS2 is $-25.84$ kA, which is the largest, and the corresponding voltage peak value of grounding grid A is also the largest (approximately $-353.49$ kV). Although the peak current of RS4 ($-9.23$ kA) is the smallest, the corresponding voltage peak value ($-202.29$ kV) is slightly larger than that ($-200.69$ kV) of RS3 (the relevant current peak value is $-10.96$ kA). In other words, the smallest lightning current peak produced by RS4, but the smallest ground potential produced by RS3. According to the research results of Zeng et al. [17], for the same injection current, the shorter the risetime is (i.e. the gradient increases), the higher the corresponding ground potential becomes. This is due to the fact that the larger gradient of the waveform is, the higher frequency of the injected current will be. When the lightning current is injected into the grounding grid, then the induction effect of the grounding grid will be strengthened, which leads to an increase of the impulse grounding resistance. Considering the situation in this paper, although the current peak values of RS3 and RS4 are very close to one another, the 10-90% rise time of RS4 is about 37.5% that of RS3, and the relevant gradient of RS4 is about 2.3 times of that of RS3. Compared with the case of RS3, the induction effect of grounding grid A is strengthened for RS4, and the impulse grounding resistance becomes larger. Finally, the ground potential of RS4 is slightly larger than that of RS3.

### C. IMPULSE GROUNDING RESISTANCE AT GROUNDING GRID A

The impulse grounding resistance can be evaluated using the peak values of the lightning current and the corresponding ground potential of grounding grid A. It is clear that there...
are some differences among the four impulse grounding resistances. The larger the current is, the smaller the corresponding impulse grounding resistance will be. The impulse grounding resistances of the four return strokes are 17.3 Ω, 13.7 Ω, 18.3 Ω and 21.9 Ω, respectively, with a mean value of 17.8 Ω. It is worth noting that only the impulse grounding resistance of RS2 is smaller than the power frequency grounding resistance (i.e. 15.8 Ω), and the others are larger than the power frequency grounding resistance.

D. CHARACTERISTICS OF THE TRANSFER POTENTIAL AT GROUNDING GRID B

The triggered lightning current dispersion through the grounding grid and surrounding soil can generate current field and transfer potential on the connected or isolated conductors in the vicinity of the grounding grid. The magnitude of the transfer potential is related to the current density generated by the current field and soil characteristics [18]. In this paper, grounding grid B is located to the northeast of grounding grid A, and the distance between the two grounding grids is about 40 m. Fig. 4 presents the transfer potential of grounding grid B and the corresponding lightning current, and the detailed characteristic parameters are listed in Table 3.

An obvious difference exists between the peak values of the two grounding grids by comparing their respective voltage waveform characteristics. For the four return strokes, the ratios of the voltage peak values of grid B to that of grid A are 5.1%, 6.7%, 4.6% and 4.2%, respectively. This indicates that, although the lightning current releases a large amount of energy through grounding grid A, the residual energy can still cause GPR about tens of kV on grid B, which is located at a distance of 40 m from grid A.

As illustrated in Fig. 4 and Table 3, the 10-90% voltage rise time of grounding grid B ranges from 0.20 μs to 0.74 μs, with a mean value of 0.54 μs, which is close to that of the triggered lightning current (0.24 μs), and the mean value is shorter than that of grid A (about 43.5% of grid A). It is worth noting that the voltage of grid B drops rapidly after the peak point, and the drop process lasts for several microseconds. Then, the voltage forms a reverse sub-peak (as shown in Fig. 4), after which it slowly returns to zero. The voltage peak values of the four return strokes range from −8.54 to −23.79 kV, with an arithmetic mean value of −13.75 kV. The sub-peak values are −4.04, −8.30, −2.81 and −2.99 kV, respectively about 29.9%, 34.9%, 30.5% and 35.0% of the corresponding peak values. The half-peak width of the transfer potential waveform of grid B is relatively shorter, ranging from 1.31 to 1.69 μs, with an arithmetic mean value of 1.54 μs. It is clearly smaller than that of the triggering lightning current (about 27.6% of the lightning current). This is related to the rapid change process of the voltage peak, as shown in Fig. 4. However, the half-peak width of the potential waveform of grid A is 1.8 times of that of the lightning current. The time it takes to gradually return to zero after the sub-peak point for the voltage of grid B is close to that needed after the peak point for the lightning current.

In general, multiple grounding systems are connected to each other following standards. This will result in the low frequency part of the current, which flows into the active grid, and then impact on the other grounding systems. As a result, the GPR risetime on the active grid will be significantly lower. In this case, the GPR risetime on the active grid will be shorter than the independent grid [19].

IV. DISCUSSIONS

The ground potential at the grounding point caused by the return stroke is very high. In this study, the ground potential of grid A reaches −353.49 kV, as a result of the triggered lightning current with a peak value of −25.8 kA. In addition, a large majority part of the natural lightning current peak is larger than that of the triggered lightning, and the ground potential rise (GPR) may reach thousands of kV.

The transient response of the grounding grid has received significant attention [20], [21]. The results of some research indicate that the lightning current dispersion through grounding grids and surrounding soil is a complex electromagnetic transient process, accompanied by soil ionization, inductance effect, and so on. Soil ionization is the spark discharge of soil around the grounding grid, which is similar to air breakdown, when the electric field exceeds the critical breakdown field strength of soil due to lightning current dispersion in soil. The spark discharge process may reduce the resistivity of soil surrounding the grounding grid, thus causing the lightning current dispersion to occur more easily. This can be regarded as an expansion of the grounding grid to a certain extent, and results in a decrease of the impulse grounding resistance. However, the influence of the inductance effect is the exact opposite. Due to the high frequency of the lightning currents, the inductance effect of the grounding grid will become very significant, and this effect can prevent the current from flowing to the far end of the grounding grid, which in turn results in an increase of the impulse grounding resistance. The higher the frequency of the injected lightning current is, the more significant the inductance effect will be. From the results of previous research, the capacitive behavior of grounding system is dominant in soils with high resistivity and short electrode length. While in the soils with low soil resistivity and long electrode length, the inductive effect is dominant. Because the frequency of lightning current is relatively low and the soil resistivity in the test site is small, this paper does
not consider the influence of capacitance effect. However, the changes of impact grounding resistance is mainly considered to be affected by soil ionization and inductive effect. It can be concluded that the impulse grounding resistance is determined by the combination of soil ionization and inductive effect. For larger lightning currents, such as $-25.84$ kA for RS2, the soil ionization effect makes the impact grounding resistance to be smaller. This causes the impulse grounding resistance (13.7 $\Omega$) to be less than the power frequency grounding resistance (about 86.5% thereof). On the contrary, when the lightning current is relatively small, such as RS1, RS3 and RS4 (ranging from $-9.23$ to $-15.18$ kA), this renders the corresponding impulse grounding resistance larger than the power frequency grounding resistance. For the four return strokes, the impulse grounding resistance will gradually increase as the lightning current decreases. This also indicates that, although both the soil ionization and inductive effect become weak, the inductance effect remains dominant, as the current decreases. Therefore, the impulse grounding resistance of RS4 (21.9 $\Omega$) is much greater than that of RS3, and it is also greater than the power frequency grounding resistance (about 1.4 times the power frequency resistance).

The soil ionization of RS4 is weak, due to the relatively small current, and its current gradient is larger than that of RS3, which indicates that the inductance effect of the grounding grid of RS4 is stronger than that of RS3. The impulse grounding resistance is related to the soil resistivity, grounding grid size, current peak position, wave front time, and other factors [22]–[24]. It’s worth noting that the GPR on the active ground grid is measured in the center of the ground grid. According to Visacro et al. [22], the GPR on the ground grid will be higher at the angle due to the influence of current transmission effect. In this paper, the analysis of the impulse grounding resistance for grounding grid A is performed only from the perspective of soil ionization or inductance effect, which results in changes to the impulse grounding resistance.

The transfer potential of grounding grid B caused by the return strokes to grid A can reach tens of kV, and the voltage peak is about 5% of the corresponding voltage peak of grid A. The waveforms of GPR for grid A are different from those of the transfer potential for grid B, which agree with those simulated in reference [25]. The reason for this is related to factors such as the soil resistivity around grid B, size of the grid, and location of the test point of the transfer potential. The half-peak width of the transfer potential for grounding grid B is also significantly smaller than that of the triggered lightning current and ground potential of grid A, and the harm caused by the GPR of grid B is much less significant than that caused by grid A. Therefore, the protection measures of the two grids must be treated differently.

V. CONCLUSION

In this experiment, the ground potential of grid A reaches $-353.49$ kV, as a result of the lightning current with a peak value of $-25.84$ kA.

Both the soil ionization and inductive effect play important roles in the impulse grounding resistance when the triggered lightning current is injected into grounding grid A. Under the condition of low soil resistivity at the test site, the impulse grounding resistance is about 86.5% of the power frequency resistance for larger currents, such as $-25.84$ kA, and 1.4 times of the power frequency resistance for smaller currents, such as $-9.23$ kA.

The transfer potential of grounding grid B caused by the return strokes to grid A can reach tens of kV, and the voltage peak is about 5.1% of the corresponding voltage peak of grid A.

The half-peak width of the GPR waveforms at grounding grid A is significantly larger than that of the corresponding lightning currents (about 1.8 times the latter), while the half-peak width of the transfer potential at grounding grid B is significantly smaller than that of the corresponding lightning currents (about 27.6% of the latter).
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