Impact of Lightning Protection Grounding System on the Ground Surface Potential of Substations

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Abstract. Grounding device is an indispensable facility for lightning protection of buildings. Nowadays, SGCC (State Grid Corporation of China) is promoting steel structure substations, which are made of metal as a whole including the roof. There are now several grounding approaches when the roof was struck by a lightning flash, including external grounding, nearby grounding, separate grounding and common grounding. This paper took a metal structure substation in Nanjing as an example and calculated its ground potential in case of different grounding system. We came to such conclusions: 1) For substations of separate grounding system, the ground potential after a lightning strike could reach as high as 743.5kV and 230kV with a single earthing electrode and multiple electrodes respectively. 1000μs after the strike, the ground potential is 91.57 kV, which is still a significant threat to humans and equipment inside. 2) Nearby grounding and external grounding are both common grounding system. The peak of ground potential after a lightning strike is 101.4kV and 109kV respectively, much lower than that of separate grounding system. They also have similar waveform and peak time. 3) 3500μs after the lightning strike, the ground potential all over the grid is around 36V. 4) Separate grounding is not a sound choice of grounding system for steel structure substations. From the perspective of cost and discharging capacity, nearby grounding is the most reasonable scheme for a steel structure substation.

1. Introduction

Grounding device is an indispensable facility for lightning protection of buildings. Grounding network of power system has the function of lightning protection in addition to its system operation. Taking the substation as an example, the equipment in the substation are connected to the grounding network underground through the lead wire. Grounding network serves as a public potential reference ground. Meanwhile, in case of a lightning strike or short-circuit fault, it could also discharge the fault current quickly, reducing the ground potential, and thereby protect the staff and electrical equipment inside. Therefore, the design of grounding network, grounding parameters as well as grounding performance deserves highlight of relevant researchers and operation of substations [1-3]. At present, grounding impedance of grounding networks has been discussed widely by scholars. But ground potential rise and potential difference within the grounding network are often neglected, which is a real problem caused by formation of grounding networks. Lightning strikes impose significant impact on the time...
characteristics of the potential. As a result, the issue of evaluating the safety performance of large grounding networks scientifically has also attracted more researchers’ attention [4,5].

Lightning is one of major threats of power system because of its high voltage, intense current, transiency and uncertainty. Theoretical and experimental analysis of the characteristics of lightning waves, the process of lightning intrusion into the power system is necessary for effective lightning protection [6-8]. With application of new materials and improving environmental awareness, SGCC (State Grid Corporation of China) is now promoting design and construction of steel substations, which are made of metal as a whole including the roof. This raises new issues about their lightning characteristics and lightning protection [9, 10]. There are now several grounding means of a metal substation when its roof was struck by a lightning flash, which includes external grounding, nearby grounding, separate grounding and common grounding. In the first type of grounding system, the down lead is wrapped with insulating material. It is then connected with the grounding grid conductor on the outer edge of the grounding grid. In the nearby grounding system, the downlead is directly connected with the nearest grounding grid conductor. The grounding system above are both common grounding, which means lightning protection grounding and substation structure share the grounding system. As for separate grounding, the lightning protection device is completely insulated from the substation structure. In this case, the metal roof is insulated from the steel structure wall, and the lightning protection downlead is wrapped with insulating materials and separately set with grounding electrode. Through modeling and simulation, this paper analyzed the variation characteristics and surface potential distribution caused by lightning strike on the roof with the four grounding modes mentioned above separately to find out the most appropriate grounding mode. This work provides a reference for the design and safety performance evaluation of lightning protection and grounding mode of metal structure substations.

2. Modeling Establishment

2.1. Modeling of the Substation and Grounding System

Figure 1 shows the calculation model of a steel structure substation under construction in Nanjing. The grounding grid of the substation has a span of 5.5m-6m, total length of about 84.5m, width of about 43.5m and underground depth of 0.8m. Due to the edge effect of lightning current, we set the metal roof lightning point at the edge of the building. The downlead is connected to the grounding grid at 12 points. The grounding grid and the downlead is made of 40×4mm² copper coated steel. Resistivity of grounding conductor was set as \( \rho=1.78\times10^{-7}\Omega m \) and relative permeability was set as \( \mu=200 \). Earth resistivity of the substation was set as 100 \( \Omega m \).

![Figure 1. substation and grounding system model.](image-url)
2.2. Lightning Current Model

According to GB50057-2010 Code for design of lightning protection of buildings, the substation was considered as a Class II lightning protection building. So this paper adopts the standard lightning wave with specifications of 10/350μs and 100kA. Its waveform is expressed by double exponential function as follow.

\[ I(t) = I_m k(e^{-\alpha t} - e^{-\beta t}) \]

In the equation above, lightning current peak \( I_m = 100 \text{kA} \), waveform correction coefficient \( k = 1.051 \), wavefront attenuation coefficient \( \alpha = 2.127 \times 10^3 \text{s}^{-1} \), wave tail attenuation coefficient \( \beta = 2.461 \times 10^5 \text{s}^{-1} \). Sampling time, sampling frequency and time domain truncation window width were set as 0.6104s, 1.638MHz and 2500us separately. The time domain waveform is shown in figure 2, and the corresponding spectrum is shown in figure 3. We can see that the lightning current is mainly distributed in the frequency band of 0-10kHz, much within 0-1kHz. The current distribution at each frequency point doesn’t change dramatically. On the other hand, within the spectrum of 1-10kHz, the current distribution decreases rapidly with increase of frequency.

3. Simulation and Calculation

3.1. Ground Potential of Nearby Grounding and External Grounding System

Many steel structure substations have lightning downleads connected to the grounding grid of the substation structure. But grounding modes are not the same. For some substations, the downlead is wrapped with insulating material and connected to the outer edge of the grounding grid. Except for the grounding point, the downlead is insulated with the substation. This approach is considered as external grounding. In another approach, the downlead is directly conducts lightning current to the nearest grounding grid conductor, which is called nearby grounding. We carried out simulation calculation by using CDEGS (a commonly accepted grounding performance analysis package) to analyze characteristics of surface potential distribution when the substation roof was struck by a strike. The lightning-struck point on the metal roof was assumed as A (17.25m, 29.1m, 8.4m). In case of external grounding and nearby grounding, the distribution characteristics of surface potential at the point \((x=0-85m, y=0-40m)\) at different time are shown in figure 4 (a-Surface potential in case of external grounding, \(t=5.495\mu s\); b-Surface potential in case of nearby grounding, \(t=7.326\mu s\); c-Surface potential in case of external grounding, \(t=15.873\mu s\); d-Surface potential in case of nearby grounding, \(t=15.873\mu s\).
As is shown in figure 4(a) and figure 4(b), in the external grounding system the grounding potential reached its peak at 101.4kV 7.326μs after a lightning strike on the roof. In the nearby grounding system, the corresponding value was 109kV and 5.495μs. It is also seen that before the surface potential reaches its peak, the surface potential of nearby grounding rises faster than that of external grounding, and the distribution of the former system is steeper. The rise of surface potential is slightly slow and the distribution is relatively moderate in the external grounding system. Figure 4(c) and figure 4(d) shows the grounding potential 15.873μs after a lightning strike, when the two system has similar potential distribution. Besides, it is the connecting point of the downlead and ground grid where the potential reaches its peak.

3.2. Ground Potential of Separate Grounding and Common Grounding System

3.2.1. Separate Grounding with Multiple Earthing Points. The external grounding and nearby grounding discussed in 3.1 are both common grounding system. In this chapter, we take single grounding into consideration. That is to say, downlead grounding electrode is insulated with the substation structure. The lightning-struck point on the metal roof was assumed as B (44.6m, 29.1m, 8.4m). The distribution characteristics of surface potential at the point(x=0-85m, y=0-40m) at different time in different grounding system are shown in figure 5 (a-Surface potential in case of separate grounding with multiple points, t=15.873μs; b-Surface potential in case of common grounding, t=15.873μs; c-Surface potential in case of separate grounding with multiple points, t=200.855μs; d-Surface potential in case of common grounding, t=200.855μs).
We can safely come to the conclusion as follows by contrast of the grounding potential.

- The peak of the grounding potential in separate grounding system reaches as 230kV, higher than that in common grounding system. The peak comes at $t=7.937\mu s$, later than in the latter system.
- The grounding potential has a peak value at all grounding points in single grounding system and the surface potential distribution is extremely uneven. In case of common grounding system, the grounding potential fluctuates moderately without multiple peaks.
- Separate grounding has poor discharge capacity and the potential peak lasts for a longer period. The lightning current could be discharged much more quickly in common grounding system.

3.2.2. Separate Grounding with a Single Earthing Point. In this case, we assume that there is only one downlead connected to the grounding grid. Hypothetical conditions are the same with 3.2.1. The distribution characteristics of surface potential are shown in figure 6. (a-$t=15.875\mu s$; b-$t=1000\mu s$).

**Figure 5.** Surface potential at the point $(x=0.85m, y=0.40m)$ at different time in separate grounding system and common grounding system.

**Figure 6.** Surface potential at the point $(x=0.85m, y=0.40m)$ at different time in separate grounding with a single earthing point.
As is shown in figure 6, the surface potential has a peak at the grounding electrode. 15.875μs after the lightning strike the peak is as high as 743.5kV. It is 91.57 kV 1000μs later, which is also dangerous to human and device safety. So we can see a worst discharge capacity in this system.

4. Impact Time of Lightning Current

In order to study how long lightning current would impact on the grounding potential, we take nearby grounding with multiple earthing points as an example to simulate the grounding potential distribution. The lightning-struck point on the metal roof was assumed as B, which was the same as discussion in 3.2. As is seen from Fig.8, 3500μs after the lightning strike on the roof the grounding potential all over the grid is around 36V, which is safe to humans and equipment inside. So we can say that in common grounding system, including both nearby grounding and external grounding, the lightning impact on the substation would be within several microseconds due to discharge via the grounding grid.

5. Conclusions

We took a metal structure substation in Nanjing as an example and analyzed its ground potential in case of different grounding system by simulation and calculation. Nearby grounding, external grounding, separate grounding and common grounding are taken into consideration. We came to conclusions as follows.

- When the lightning downlead is insulated from steel structure and grounding grid of the substation, the grounding potential could reach as high as 743.5kV and 230kV with a single earthing electrode and multiple electrodes respectively. 1000μs after a lightning strike on the roof the ground potential is 91.57 kV, which is still a significant threat to humans and equipment inside. So discharging capacity of this grounding system is much worse than common grounding. It is not a sound choice of grounding system for steel structure substations.

- Nearby grounding and external grounding are both common grounding system. In the former system, the downlead is directly conducts lightning current to the nearest grounding grid conductor. In the latter one, the downlead is wrapped with insulating material and connected to the outer edge of the grounding grid. Except for the grounding point, the downlead is insulated with the substation. The peak of ground potential is 101.4kV for external grounding and 109kV for nearby grounding. Waveform and peak time of the two kinds of system are similar to each other. So they have similar discharging capacity. From the perspective of cost and environmental protection, nearby grounding is a more reasonable scheme.

- 3500μs after the lightning strike on the roof the grounding potential all over the grid is around 36V, which is safe to humans and equipment inside. So we can say that in common grounding system, the lightning impact on the substation would be within several microseconds due to discharge via the grounding grid.

- The point of the downlead connecting to the grounding grid tends to have the highest potential when the roof of the metal substation is struck by lightning current. So it is recommended to keep the equipment inside away from this earthing electrode as far as possible.
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