Study on the Difference of Lightning Impact on Intelligent Substation and Conventional Substation

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Abstract. Compared with conventional substations, smart substations use a large number of sensors, which leads to the impact of lightning on smart substations is significantly different from that of conventional substations. Firstly, this paper analyses the impact of lightning strike on intelligent substation from four aspects, which is obviously different from the impact of lightning strike on conventional substation. According to different situations, the mechanism of its generation is analyzed and elaborated, and the corresponding calculation methods and solving steps are given. This paper has a strong theoretical guidance for lightning analysis of intelligent substation.

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.

Compared with conventional substations, smart substations have a large number of sensors. Intelligent units are directly placed next to primary equipment in switchyard area. This leads to four main differences between the impact of lightning on smart components or secondary equipment in smart substations and the impact of lightning on secondary equipment in conventional substations.

(1) The potential difference interference produced by metal structures such as lightning rods will mainly exist in power cables due to the extensive use of optical cables connecting intelligent components and main control rooms in smart substations. However, due to the reduction of a large number of cable shielding layers which can share current, the current flowing through the shielding layer of power cable will increase, which may lead to the increase of interference voltage at power ports of secondary equipment or smart components.

(2) Although optical cables are widely used in smart substations, they are mainly used to connect smart components and secondary devices, and cable is still widely used in connection between primary devices and smart components. These cables are characterized by short cables, various sensors and different grounding modes at both ends of equipment cables manufactured by different manufacturers, which leads to new ways of introducing interference.
(3) Because there is no intelligent component near primary equipment in conventional substation, the influence of low-amplitude lightning on secondary equipment in conventional substation can usually be ignored when low-amplitude lightning bypasses lightning rod and strikes directly into metal structure in substation. However, in smart substation, when the lightning enters the earth through metal structure, if there are intelligent components near the channel, its impact needs to be studied.

(4) When the lightning overvoltage causes the arrester to operate, the lightning current will enter the earth through the arrester. In conventional substations, the interference voltage of the cable ports connected with secondary equipment will not exceed the prescribed limit because the arrester is usually installed far away from the main control room or the protection room. This has been verified by previous work of the project team. Because there are intelligent components in the switchyard of smart substation, some of them may be close to the arrester, so the current entering the ground may affect them.

2. Analysis of lightning impact on four different substations
For smart substation, the above four lightning influence modes are different from those of conventional substation. In this paper, they are called less cable effect, short cable effect, low amplitude lightning effect and lightning arrester ground current effect. Next, this paper elaborates on the analysis and calculation methods of these effects.

2.1. Analysis of calculation method under the influence of less cable
As mentioned above, the potential difference interference caused by lightning rods and other metal structures will mainly exist in power cables due to the extensive use of optical cables connecting intelligent components and main control rooms in smart substations. However, the absence of a large number of cable shielding layers which can share current increases the overcurrent of power cable shielding layer, which may lead to the increase of power port interference voltage of secondary equipment or smart components.

In order to compare the influence of different number of cables on the voltage of cable ports, we modify the calculation method of interference voltage in conventional substations, and give the main calculation steps as follows:

(1) Fast Fourier transform is used to calculate the spectral density of lightning current. According to the characteristics of its frequency spectrum, appropriate frequency points are selected.

(2) The method of moments is used to calculate the ground potential rise distribution of the grounding grid corresponding to the unit injection current at a given calculated frequency point in the presence of cables. Among them, the cable is directly simulated by metal conductors connected to the grounding grid at both ends, whose radius equals the radius of the cable shielding layer, and the cable is divided into segments according to one tenth of the highest frequency of lightning current.

(3) The current of each section of cable shield layer corresponding to each calculated frequency point is multiplied by the spectral density of lightning current, and the current distribution of cable shield layer caused by lightning strike on grounding grid of substation is obtained by fast Fourier inverse transformation.

(4) The calculated current of each section of the shielded cable is used as the excitation source, and the calculation model of the multi-conductor transmission line of the shielded cable is established. The core current and the port interference voltage of the shielded cable are calculated by the transmission line theory.

2.2. Analysis of calculation method under the influence of short cable
From the previous analysis, it can be seen that there are still a large number of cables connecting sensors and intelligent components in the primary equipment of smart substation. These cables are characterized by short cables, various sensors, and inconsistent grounding modes at both ends of equipment cables manufactured by different manufacturers. This will inevitably increase the complexity of lightning interference in intelligent substation components.

Because of the difference of the structure between GIS (gas insulated switchgear) substation and AIS (air insulated switchgear) substation, the position of cable connecting sensors and intelligent
components is also different. In a GIS substation, sensors may be placed in GIL (gas insulated transmission line) pipelines, and cables are placed directly inside the pipelines. After the cable is introduced from the pipeline, it will be placed in the metal bellows until the intelligent components connected with it. In AIS substation, sensors are connected to cables. Because there is no GIL pipeline, cables are placed directly in metal bellows or connected directly to intelligent components. Therefore, because of the existence of GIL pipeline in GIS substation, the influence of lightning is lower than that of AIS substation. But their calculation methods are essentially the same.

Here, we give the main calculation steps as follows: (1) Fast Fourier transform is used to calculate the spectral density of lightning current. According to the characteristics of its frequency spectrum, appropriate frequency points are selected. (2) The method of moments is used to calculate the ground potential rise distribution of the grounding grid corresponding to the unit injection current at a given calculated frequency point. (3) The ground potential rise of the grounding grid corresponding to each calculated frequency point is multiplied by the spectral density of lightning current, and the transient ground potential rise distribution caused by lightning striking the grounding grid of substation is obtained by fast Fourier inverse transformation. (4) The transient ground potential difference between the two grounding points of shielded cable on the grounding network is used as the excitation source, and the calculation model of multi-conductor transmission line of shielded cable is established. The shielding layer current and core line interference voltage of shielded cable are calculated by using transmission line theory.

The multi-conductor transmission line model of shielded cable is shown in Figure 1. R1 and R2 represent the internal resistance of sensors and smart components respectively, while Rs and RL represent the grounding impedance of metal hoses at sensors and smart components respectively.

![Diagram of calculation model for cables placed in metal hoses](image)

**Figure 1. Schematic diagram of calculation model for cables placed in metal hoses**

For lightning intrusion wave, because the cable connecting sensor and intelligent component is very short, the longest is not more than 5m, even considering that the frequency of lightning subsequent return stroke is not more than 5MHz and the wavelength is 60m, the cable length is far less than the wavelength, so the cable can be directly regarded as a lumped parameter in calculation. In fact, this assumption is also applicable to the case of lightning striking grounding grid, so the transfer impedance calculation can be directly applied without considering the influence of wave process.

### 2.3. Analysis and calculation of low amplitude lightning

There are two types of lightning strikes on the grounding grid of intelligent substation, one is lightning rod directly striking substation, and the other is lightning striking the metal structure of substation by bypassing lightning rod. The former is high-amplitude lightning with high lightning intensity, but the lightning rod is usually far away from intelligent devices or connecting cables, so its impact on equipment may not be large. The latter is generally low amplitude lightning, although the lightning intensity is small, but if the lightning strike point is near the smart components, its impact may not be small. The analysis of this problem needs to determine the maximum intensity of the current generated
by lightning striking the metal structure close to the smart component by bypassing the lightning rod. Here, we should use EGM (electrical geometry model) to analyze this problem.

Objectively speaking, the discharge path of thunderclouds on the ground is arbitrary and almost no regularity can be found, but from the statistical point of view, it can be approximated that the discharge path of thunderclouds is vertical downward. During the downward pilot of lightning discharge, the surface field strength of objects on the ground is increasing. When the surface field intensity of a target on the ground reaches the starting field intensity of the upward leader of lightning, the ground object begins to produce the upward leader of lightning.

The main methods for calculating the protection range of lightning rods are folding line method and rolling ball method. Considering that the broken line method is often used in the design of substations in China, the following contents also adopt the broken line method to determine the protection range of lightning rods. The method of calculating the protection range of a single lightning rod by using the broken line method is given in GB50064-2014, as shown in Figure 2.

![Figure 2. Protection range of single lightning arrester](image)

According to the theory of EGM, the protection range of lightning rod is affected by the magnitude of lightning current. When the lightning current is large, the striking distance is long. When the striking distance is larger than the distance between the lightning cloud and an object, the thundercloud leader will discharge the object, regardless of whether the object is a flasher or not. When the lightning current is small and the strike distance is short, the thundercloud will enter the lightning rod protection area. Therefore, the electrical geometry model establishes the relationship between striking distance and lightning current.

According to the electrical geometry model, the hitting point of the pilot discharge channel which develops from thundercloud to ground is uncertain before it reaches the critical breakdown distance of the target. When it reaches the range of striking distance of an object at the earliest time, it will discharge to that object. Many scholars have proposed different representation methods for choosing strike distance.

Golde first establishes a correlation between striking distance and lightning current, which makes lightning shielding technology embark on the research road of combining geometric model with electrical parameters. In Golde's research, the downward leader of lightning has the same breakdown strength for earth, linear and tower objects. For negative lightning flashes, the average field strength is 500kV/m, and for positive lightning flashes, the average field strength is 300kV/m. The stroke distance formula in this model is as follows:

\[ r = 3.3I^{0.78} \]

Among them, I is the amplitude of lightning current, kA; r is the strike distance, m.

Young and other researchers first proposed the calculation technology of EGM, believing that when the field intensity of the target surface reaches the critical breakdown strength, the target object will be struck by lightning. In the calculation, the critical average breakdown field strength of lightning to ground is 600kV/m, which is larger than the critical average breakdown field strength of
lightning arrester and conductor in transmission line. When the height of transmission line varies from 10 to 50 m, the critical average breakdown field strength is about 600kV/m~550kV/m.

The formula of striking distance proposed by them is as follows:

$$r = \frac{12000}{462 - h} I^{0.32}$$  \hspace{1cm} (2)

Among them, \(h > 17.5m\) is the average height of transmission line to ground, m.

The Zhu’s model combines lightning observation and simulation test to study the main factors affecting the probability distribution of discharge hitting point, and to some extent, the dispersion of discharge is considered, so the physical background is clearer. When calculating the breakdown distance, the critical average breakdown field strength to the ground is selected as 1, and the breakdown distance formula to the conductor is as follows:

$$r = 7.54 I^{0.6932}$$  \hspace{1cm} (3)

Eriksson improved the EGM model to some extent. He proposed that the strike distance is not only related to the magnitude of lightning current, but also to the height of the building. The strike distance formula can be expressed as follows:

$$r = 0.67 h^{0.66} I^{0.74}$$  \hspace{1cm} (4)

Among them, \(h\) is the height of the building, m.

The distance formula recommended by IEEE is:

$$r = 8 I^{0.65}$$  \hspace{1cm} (5)

In practice, according to the formula of stroke distance given by IEEE and the protection range \(r_x\) of lightning rod determined above, it can be considered that if the current is lower than the calculated value of formula (6), lightning will be directly struck on other metal structures by bypassing lightning rod.

$$I = (r_x / 8)^{10.65}$$  \hspace{1cm} (6)

On this basis, the lightning current intensity that may hit the metal structure can be obtained, and then the interference voltage of the ports of intelligent components near the metal structure can be calculated.

2.4. Analysis the influence of lightning arrester ground current
Considering the effect of the grounding current of arrester on the port voltage of the short cable connecting the sensor and the smart component, the calculation method is essentially the same as the previous calculation method, but the place of the current entering is changed. Therefore, the calculation method described above can still be used.

3. Conclusion
Compared with conventional substations, smart substations use a large number of sensors, which results in four differences between the impact of lightning on smart components or secondary equipment in smart substations and the impact of lightning on secondary equipment in conventional substations. They are called less cable effect, short cable effect, low amplitude lightning effect and lightning arrester ground current effect in this paper. In view of the two situations of less cable and short cable, this paper gives the corresponding calculation method and steps based on the analysis of its generating mechanism. Under the influence of low amplitude lightning, the corresponding calculation formula is given. In short, this paper has a strong theoretical guidance for the lightning analysis of intelligent substation.

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