Simulation Research on Lightning Protection Effect of Distribution Line Lightning Protection Measures

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Abstract. Due to the low insulation level of distribution lines, the electromagnetic transient characteristics of lightning strikes are quite different from those of high-voltage transmission lines; the lightning protection measures used in high-voltage lines cannot be well applied to distribution lines. In order to further understand the various lightning protection measures and the effect of lightning protection measures on the improvement of the lightning resistance level of distribution lines, this paper evaluates the working principles, characteristics, lightning protection effects and existing deficiencies of various lightning protection measures used in distribution lines. And using ATP-EMTP software to analyze several kinds of lightning protection measures commonly used in 10kV distribution lines, it has certain reference value for the selection of lightning protection measures of 10kV distribution lines.

1. Introduction
The lightning trip accident of the distribution line seriously threatens the safe and reliable operation of the distribution network. Statistics [1] show that lightning accidents in the distribution network account for 70% to 80% of all lightning accidents in the distribution system. At present, there has been a lot of research on the simulation of lightning protection in distribution networks and the practical application of lightning protection devices. For example, Liu Jian, etc. calculated the lightning protection performance of lightning arresters and analyzed the lightning protection effects of lightning arresters in different configurations; Wang Yu, et al. established a calculation model of lightning overvoltage for distribution lines using ATP-EMTP, and analyzed the influence of lightning arrester installation density on lightning overvoltage; Podporkin [3] developed a multi-gap arc extinguishing device. The device has studied the power frequency freewheeling extinguishing effect of the multi-chamber gap through a number of experiments, and analyzed the protective effect of its induced overvoltage. This article compares the lightning protection features of the distribution network and the main network, introduces the lightning protection measures used in the distribution network, and uses the ATP-EMTP software to set up lightning protection wires, reduce grounding resistance, the lightning resistance level of the line is simulated and calculated.
2. Mechanism of overhead lines lightning overvoltage

2.1. Lightning counter overvoltage
Lightning counter-strike overvoltage mainly includes lightning strikes at the top of the tower and lightning strike at the center of the lightning protection wire span. However, the line design has avoided the lightning strike at the center of the lightning protection wire span causing line insulation flashover. In this section, the article only analysis the lightning strikes at the top of the tower mechanism.

![Figure 1. Schematic diagram of counterattack](image)

When lightning current acts on the top of the tower and causes insulation flashover, it is mainly divided into two processes: the potential rise of the tower and the breakdown of the insulator. When the insulator is not broken down, most of the lightning current is discharged into the earth through the tower, and a small part of the lightning current flows away through the lightning conductor. According to the principle of spatial electromagnetic coupling, the lightning current passing through the lightning conductor will couple a current traveling wave on the phase conductor. At this time, the lightning current has not yet entered the phase conductor. Due to the effect of the tower, lightning conductor wave impedance and the tower grounding resistance, the lightning current will cause the potential of the top of the tower and the cross arm to rise when the lightning current is discharged. When the potential difference between the cross arm and the wire is greater than the lightning impulse flashover voltage of the insulator At this time, the insulator will flashover, and the lightning current will be directly injected into the phase conductor, causing the potential on the phase conductor to rise sharply.

2.2. Lightning bypass voltage
The bypass overvoltage is the overvoltage generated when the lightning development channel bypasses the protection range of the lightning conductor and directly hits the phase conductor.

![Figure 2. Schematic diagram of shielding](image)
Bypass hit is mainly divided into two processes: wire potential rise and insulator breakdown. When the insulator is not broken down, the lightning current is directly injected into the wire, causing the potential on the wire to rise rapidly. At this time, the potential on the tower side is zero. When the voltage on both ends of the insulator is higher than the lightning impulse flashover voltage of the insulator, the insulator breaks down and the lightning current flows into the earth through the tower.

2.3. Inductive lightning overvoltage
The formation of induced lightning overvoltage is mainly divided into two processes: the leading development process and the main discharge process. In the pilot development process, due to the large amount of electric charge under the thundercloud, an equal amount of negative charge will be induced on the overhead line. Due to the action of the electric field, the charge on the line will be restrained. When the pilot develops to a certain level and exceeds the breakdown field strength of the air, the lightning enters the main discharge stage, the positive and negative charges in the lightning strike channel are quickly neutralized, the space field strength drops rapidly, and the charge on the wire loses its restraint, and the main discharge channel travels along the wire to both sides, an overvoltage is formed on the wire. This voltage is called the electrostatic component of the induced overvoltage.

At the same time, after the main discharge occurs, the rapidly changing current in the main discharge channel will form a magnetic field that changes with the current in the space. The magnetic field forms an induced voltage on the wire. This voltage is called the electromagnetic component of the induced overvoltage.

![Figure 3. Schematic diagram of induced overvoltage formation (a)Leading discharge level (b)Main discharge level](image)

The magnetic field lines of the magnetic field cross the wire transversely, and the coupling with the wire is small, and the contribution of the electromagnetic component to the induced overvoltage is small.

3. Common lightning protection measures for power distribution lines
The lightning protection measures commonly used in power distribution lines are mainly divided into "blocking type" and "draining type" [5]. The idea of "blocking" lightning protection measures is to improve the lightning resistance level of the line, or to prevent lightning strikes from equipment that needs protection. The idea of "draining" lightning protection measures is to transfer the flashover from the equipment that needs protection to other places. Various lightning protection measures also have their own advantages and disadvantages.

3.1. "Blocking" lightning protection measures

3.1.1. Erection of lightning protection lines. As one of the most commonly used lightning protection measures, the erection of lightning protection wires mainly has the following three functions: ① Reduce
the induced voltage on the phase conductor. Prevent the lightning from directly hitting the phase conductor. When erecting the lightning protection line, it is necessary to maintain a good electrical connection between the lightning protection line and the tower. However, the erection of the lightning protection wire also increases the probability of the tower being struck by lightning. When installing the lightning protection wire, attention should be paid to the adaptation of the tower's lightning resistance level to reduce the occurrence of flashover accidents.

3.1.2. Install lightning arrester. There are many types of lightning arresters. Currently, the most commonly used lightning arresters are gapless arresters, external series gap arresters and insulator-type arresters.

The earliest lightning arrester used in the line was a gapless arrester. It was installed on a 138kV line by AEP and GE in the United States in 1982. The gapless arrester is directly connected in parallel with the insulator and bears the effect of power frequency voltage for a long time. When it is not struck by lightning, ZnO The resistance valve plate is also aging.

In order to prevent the resistance valve from aging due to long-term power frequency voltage, technicians have developed a lightning arrester with a series gap. One end of the series gap is connected to the wire and the other end is connected to the arrester body. Under normal conditions, the arrester body does not withstand voltage. When the line is struck by lightning, the air gap breaks down, the lightning current is discharged through the arrester, and the voltage at both ends of the insulator is limited to a relatively low level to prevent flashover.

In recent years, due to the short length of the insulators used in the 10kV distribution network, and the arrester needs to be connected in parallel with the insulator, additional arrester brackets need to be installed. In order to reduce the complexity of installation, China Southern Power Grid integrated the functions of insulators with series gaps and insulators to form an insulator-type arrester. Figure 4 is the physical diagram and principle block diagram of the insulator-type arrester.

![Figure 4. The physical diagram and principle block diagram of the insulator-type arrester (a) Picture of insulator type arrester (b) Block diagram of insulator type arrester](image)
In the actual operation of 110kV and above lines, the installation of lightning arresters can effectively reduce the number of lightning trips. However, in 35kV and below lines, due to the poor current capacity of the arresters, there are still vicious accidents of lightning arrester explosions caused by lightning strikes. In addition, the cost of installing lightning arresters is relatively high, and lightning arresters cannot be installed in a large area.

3.1.3. **Insulation of distribution wires.** Insulated wires can be used in 35kV and below overhead lines to improve the lightning resistance level of the line. The thickness of the insulation layer of 10kV insulated wires is 2.5mm, and its impact insulation strength is 93.8kV, which is comparable to P-15 pin insulators (insulation strength is 175kV). After mating, the impact insulation strength is 225kV [6], which is enough to withstand direct lightning strikes of lower intensity. At the same time, the use of insulated wires in urban areas can prevent wind, icing or bird interference from causing wire swings and even collisions to cause interphase or ground short circuits. In the event of a disconnection, the risk of casualties is greatly reduced due to the existence of the insulating layer.

The insulating layer has the function of increasing the insulation strength of the wire and at the same time has the function of fixing the arc channel. When the line is struck by lightning and flashover occurs, the arc channel will be fixed between the broken part of the insulated wire and the tower. Most of the heat energy of the arc acts on the wire, causing the wire to fuse quickly.

3.1.4. **Lengthen insulators or use insulated tower heads or cross arms.** Lengthening insulators or using insulating tower heads and cross arms is essentially to improve the insulation level of the line. Figure 5 shows the application of insulating tower head and cross arm in actual engineering. The insulating tower head and cross arm in the picture can be regarded as longer pillar insulators. At this time, the distance between phase conductors can be increased to the original 3-5 Times, the arc building rate decreases, and the probability of interphase flashover decreases accordingly.

![Figure 5. Insulation tower head and cross arm](image)

3.2. "**Grooming**" lightning protection measures

3.2.1. **Parallel gap.** The principle of the parallel gap is to connect the insulator string in parallel to protect the gap [7], that is, a pair of metal electrodes are connected in parallel at both ends of the insulator string, as shown in Figure 6. When the line is struck by lightning, since the dry arc length of the parallel gap is shorter than the insulator, the parallel gap will flashover before the insulator, and then the power frequency current will be injected into the arc channel to form a power frequency freewheeling. The parallel gap can guide the power frequency arc from the surface of the insulator to both sides of the parallel gap, thereby preventing the insulator from being damaged by the arc burning, and finally an automatic reclosing device is used to cut the power frequency arc. Compared with the traditional lightning protection device, the parallel gap has the following advantages:

1. Improve the success rate of system reclosing
2. Reduce line lightning accident rate
3. Protect the insulator from damage
4. Simple structure, reducing maintenance cost
On the other hand, the use of parallel gaps has the following two disadvantages:

1. The length of the insulator is shorted by the parallel gap, and the lightning resistance level of the line is lower than before installation.

2. The parallel gap needs to cooperate with the automatic reclosing device to extinguish the arc, which increases the trip rate of the line.

3.2.2. Reduce the grounding resistance of the tower. The function of reducing the grounding resistance of the tower is equivalent to dredging the passage for lightning current to flow into the earth. In the distribution network, the poles and towers are grounded naturally. To reduce the grounding resistance, the artificial grounding body is usually installed. When the grounding resistance of the artificial grounding body still cannot meet the requirements, the earth replacement and the use of resistance reducing agents are used. However, these two methods are difficult and expensive, and the resistance compliance rate after implementation is low.

4. Simulation research on lightning protection effect of lightning protection measures for distribution lines

4.1. Establishment of simulation model
The simulation research in this paper chooses ATP-EMTP as the simulation software, and the research object is 10kV overhead lines. The tower model chooses the typical \(\but\) -shaped tower in DLT 1674-2016 Guide [10]. The tower and the corresponding hit inductance model are shown in Figure 7. The ground resistance of the tower is set to 30Ω.

![Figure 7. Towers and simulation models selected in the simulation](image)
The lightning current model is selected as the Heidler model, and the waveform is 2.6/50μs. Wire model selection software J. Marti frequency change model. The insulator is selected as a P-15 pin insulator, and the insulator flashover model is simulated by a voltage-controlled switch. The lightning impulse flashover voltage of the insulator is 175kV.

4.2. Analysis of Lightning Strike Characteristics of Lines Without Lightning Protection Devices

When no lightning protection device is installed, when 1.6kA lightning current acts on the top of the #5 pole tower, due to the characteristics of the 10kV pole tower, it is equivalent to lightning directly acting on the phase conductor. The relevant electric quantity waveform is shown in Figure 8.

![Figure 8](image)

**Figure 8.** The relevant waveforms on the tower when 1.6kA lightning current hits the top of #5 tower

From the analysis of the simulation results, it can be seen that when the 1.6kA lightning current hits the top of the #5 tower, the B-phase insulator breaks down, and the lightning current discharges to the ground through the arc channel and the tower, and part of the lightning current propagates to both sides through the wire. It may cause breakdown of the insulators near the tower.

![Figure 9](image)

**Figure 9.** The relevant waveforms of the 24kA lightning current hitting the top of the #5 tower
Continue to increase the lightning current. When the lightning current increases to 24kA, the A and B phase insulators flashover. The relevant electric quantity waveform is shown in Figure 13.

From the simulation results, it can be found that the B-phase insulator of the #5 tower breaks down first, and then the A-phase insulator breaks down. The flashover time of the two-phase insulators is very close, and the line is short-circuited.

4.3. The lightning resistance level of the line after the lightning protection line is installed

When a lightning protection line is erected across the entire line, and a 1.6kA lightning current is used to strike the top of the #5 pole tower, the corresponding waveform is shown in Figure 9. From the simulation results, it can be found that after the lightning protection wire is installed, the voltage on the insulators of each phase is reduced by 87.5% compared with the time when the lightning protection wire is not installed. Breakdown occurred.

![Figure 10. The relevant waveforms of the 1.6kA lightning current directly hitting the top of the #5 tower](image)

From the analysis in this section, it can be seen that after the lightning line is erected across the line, the lightning strike mode when the top of the tower is struck by lightning is counterattack, and the lightning protection level of the line is greatly improved after the line is erected.

4.4. Lightning withstand level of the line after reducing the grounding resistance

In this section, the grounding resistance of the towers of the two configurations of the full-line erection arrester and the full-line installation arrester are adjusted. The grounding resistance is adjusted to 15Ω and 10Ω and simulated respectively. The final lightning resistance level of the line is shown in Table 1.

| Ground resistance | 30Ω | 15Ω | 10Ω |
|-------------------|-----|-----|-----|
| Erection of lightning protection lines | 12.1kA | 16.5kA | 18.2kA |
| Install lightning arrester | 27.1kA | 29.6kA | 30.3kA |

From the simulation results, it can be found that reducing the grounding resistance of the tower has a greater impact on the lightning resistance level of only the lightning protection line. The grounding
resistance is reduced from 30Ω to 10Ω, and the line lightning resistance level is increased by 6.1kA, an increase of 50.4%. Reducing the grounding resistance of the tower has little effect on the lightning resistance level of the line with only the arrester installed. When the ground resistance is reduced from 30Ω to 10Ω, the line lightning resistance level only increases by 3.2kA, an increase of only 11.9%.

5. Conclusion and Outlook
In this paper, the following conclusions are obtained through simulation research:

(1) Both the erection of lightning protection wires and the installation of lightning arresters can improve the lightning resistance level of the line, and the installation of lightning arresters can improve the lightning resistance level more significantly.

(2) Reducing the grounding resistance can effectively improve the lightning resistance level of the lightning protection line, and the installation of the lightning arrester line is less sensitive to changes in ground resistance.

(3) The line with unbalanced insulation can effectively improve the lightning resistance level of two-phase flashover, and the lightning resistance level of single-phase flashover is the same as that of normal insulation configuration.

Acknowledgements
This work was financially supported by the key technology research and application practice of big data situation awareness on digital urban distribution networks. (Item number: GZHKJXM20180068).

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