The Simulation Analysis of Factors Affecting Lightning Withstand Level of the Distribution Lines in Oilfield

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Abstract. Simulation analysis is an important method to study the lightning withstand level of distribution lines and conduct the design of line lightning protection. In the process of simulation, the components of the overhead line and the selection of the specific model of lightning current should be taken into account. All the work can be used to get the simulation results which are more consistent with the actual results. Based on investigating the parameters of oil field lines, insulators and earth resistances, a lightning protection simulation model for typical distribution lines in oil field is built by using ATP-EMTP electromagnetic transient analysis program. By simulation analysis, the influence of line insulation level, earth resistance, layout parameters of arresters and lightning conductor on the lightning withstand level are studied. The results provide a scientific basis for the proposing of the comprehensive lightning protection measures of the distribution lines in oil field.

Keywords: Distribution line; Lightning withstand level; Simulation analysis; Line arrester; Insulation level.

1. Introduction
Due to the need of production, most of the distribution lines of oilfield are located in the suburbs, with open geographical environment. And because of many points, wide area, scattered load of the line and the lack of corresponding lightning protection facilities, the lightning strike rate of distribution lines is relatively high. And the distribution line is often attacked by lightning disaster, resulting in the damage of transformer, line insulator and motor. The statistical results show that the lightning accidents of oilfield are mostly occurred in 6~35kV distribution lines.

In the lightning protection design of distribution lines, various factors should be considered comprehensively according to the operation of the lines. And the lightning protection measures suitable for the lines should be taken to protect the lines. At present, the commonly used lightning protection measures include reasonable selection of the laying path of the line, erection of the lightning line, reduction of the ground resistance of the line tower, installation of the lightning arrester, and improvement of the overall insulation level of the line, etc. The above methods are commonly used in line lightning protection design, and they are also the main factors affecting the line lightning resistance level. Therefore, it is of great significance to analyze the influence factors of line lightning protection level reasonably and put forward the lightning protection technology and scheme suitable for the characteristics of oilfield power grid line.

In this paper, 6-35kV distribution line is taken as the search object, and ATP-EMTP program is used to establish the line simulation model. According to the simulation model, the influence of line insulation level, grounding resistance, arrester parameters, the presence or absence of lightning wires and other factors on the line lightning resistance level is analyzed.
2. Establish of Line Simulation Model

2.1. Lightning model
A variety of power models, such as DC power supply, single-side slope power supply, Heildler power supply, TACS control power supply are provided by ATP_EMTP program. In this paper, the heidler power supply model is selected for the lightning model. The wave head time is set to 2.6\(\mu\)s, and the half peak time is set to 50\(\mu\)s, as shown in Figure.1.

![Lightning current waveform simulated by heidler power model.](image)

2.2. Tower model
The lumped parameter model and wave impedance model are often used to simulate line tower in ATP-EMTP program. The 6-35kV line studied in this paper belongs to medium voltage network, and the height of the line tower is relatively low, most of them are cement towers with a height of 10~20m. Therefore, the centralized parameter model can be used for the simulation calculation of the line tower. According the National Code DT/L 620, the tower inductance is 0.42\(\mu\)H/m and 0.84\(\mu\)H/m respectively for the cement tower with stay wire and the cement tower without stay wire in the simulation analysis.

2.3. Line model
Among the ATP-EMTP program, the overhead line model generally selects LCC components to simulate the transmission line. Five circuit models are provided in LCC: Bergeron, PI, JMarti, Semlyen and Noda. In the calculation process of Semlyen model, convergence calculation is involved, the calculation accuracy is low and the stability is poor. The Noda line model with frequency varying parameters is more rigorous, but the calculation time is longer, the memory space required is larger, and the stability is higher than that of Semlyn model. JMarti model is the most widely used transmission line model, which can be used for both steady-state and transient calculation, and the stability is also the highest of the three frequency varying line models. Therefore, JMarti models is selected as the circuit model for simulation analysis and calculation. When the voltage applied to the valve plate is lower than a certain critical value, the valve plate is equivalent to the resistance of very high resistance value.

2.4. Insulator string model
According to the flashover characteristics of the insulator, the insulator can be equivalent to a voltage control switch in the ATP-EMTP. Suitable parameters can be set for the voltage control switch. When the voltage at both ends of the voltage control switch reaches 50% of the impulse breakdown voltage of the insulator, the opening is on, indicating the flashover discharge of the insulator. The flashover voltage of a certain type and a certain number of insulator strings can be regarded as a fixed value. In the ATP-EMTP program, there is a voltage control switch to simulate the insulator string. When the voltage at both ends of the voltage control switch exceeds the set fixed value, the switch is closed to simulate the flashover and breakdown of the insulator string.

2.5. Arrester model
Under the action of steep wave current, the MOA valve plate is equivalent to a nonlinear resistor with very high resistance value in parallel with the capacitor. When the voltage applied to the valve plate is
lower than a certain critical value, the valve plate is equivalent to the resistance of very high resistance value. That is its slope is almost infinite in the normal voltage range. However, the slope of the valve is almost zero at the high voltage.

\[ i = p \left( \frac{u}{u_{ref}} \right)^q \]

(1)

Where, \( p \), \( q \) and \( u_{ref} \) are constants; \( u_{ref} \) is the reference voltage, which is usually taken as 2times or close to 2 times of the rated voltage; the typical value of \( q \) is 20–30.

According to the characteristics of MOA in this paper, non-linear resistance elements are selected to simulate MOA in ATP-EMTP program. This element can manually input the volt ampere characteristics parameters of the arrester which need to be simulated and analyzed.

3. Simulation Analysis of Influence Factors of Lightning Resistance Level of Distribution Lines

For the medium voltage distribution network with voltage level of 6–35kV, the line can operate continuously with fault, when only one phase insulator flashover occurs in the line. Therefore, in the simulation calculation, it is can be judged as a trip accident, when it is observed that there are two or three phase insulator strings flashover at the same time. The maximum lightning current flashover of only one phase insulator string is the lightning resistance level of the line. The simulation circuit is shown in Figure 2. The parameters of the original line are set as insulation level 230kV and grounding resistance 10Ω.

![Figure 2. Simulation circuit diagram of oil field line.](image)

3.1. Influence of line insulation level on lightning resistance level of lines

The insulation level of the line is changed, and the other parameters in the model are kept unchanged. The influence of different line insulation level on line lightning resistance level is calculated. The calculation results are shown in Figure 3 and Table 1.

| Insulation level/kV | 190 | 210 | 230 | 250 | 270 | 310 | 350 |
|--------------------|-----|-----|-----|-----|-----|-----|-----|
| Lightning strike tower top | 18.58 | 18.70 | 19.01 | 20.67 | 22.32 | 25.63 | 28.94 |
| Lightning strike central span | 1.44 | 1.72 | 1.89 | 2.05 | 2.20 | 2.55 | 3.06 |

It can be seen in the figure that in the progress of the insulation level from 190kV to 350kV, the lightning resistance level of the lines increase gradually. The lightning resistance level of lightning tower increases greatly, and that of lightning line increases slowly.

![Figure 3. The influence of line insulation on the lightning withstand level.](image)

3.2. Influence of ground resistance on lightning resistance level of lines
Change the grounding resistance of the line, keep other parameters in the model unchanged, and simulate the impact on the lightning resistance level of the line with different grounding resistance. The results are shown in Table 2 and Figure 4. It can be seen from the figure and table that when the pole grounding resistance is reduced from 10Ω to 2Ω, the lightning resistance level of the line is gradually improved when lightning strikes the tower, with an average increase of 0.625 kV/Ω. And the lightning resistance level of the lightning strike line remains unchanged.

**Table 2.** The influence of earth resistance on the lightning withstand level (kA).

| Grounding resistance/Ω | 10  | 8   | 6   | 5   | 4   | 3   | 2   |
|------------------------|-----|-----|-----|-----|-----|-----|-----|
| Lightning strike tower top | 19.01 | 20.22 | 21.46 | 22.09 | 22.74 | 23.37 | 24.01 |
| Lightning strike central span | 1.89  | 1.89 | 1.89 | 1.89 | 1.89 | 1.89 | 1.89 |

**Figure 4.** The influence of earth resistance on the lightning withstand level.

### 3.3. Influence of lightning arrester on the lightning resistance level of lines

#### 3.3.1. Group one
The influence of the installation density of the arrester on the lightning resistance level of the line is studied with the 5# tower (equipped with arrester) as the center.

- **Model 1:** Three phase installation of arrester for tower 5#.
- **Model 2:** Three phase installation of arrester for tower 1, tower 5 and tower 9 (every three poles).
- **Model 3:** Three phase installation of arrester for tower 2, tower 5 and tower 8 (every two poles).
- **Model 4:** Three phase installation of arrester for tower 1, tower 3, tower 7 and tower 9 (every one pole).
- **Model 5:** Three phase installation of arrester for tower 1 to tower 9 (every one pole).

**Figure 5.** The simulation results of different installation modes of lightning arresters.

It is found that the lightning resistance level of other towers remains the same except for the installation pole. The lightning resistance level of the installation pole is greatly improved after the installation of lightning arrester. The lightning current of 25kA is taken as an example in simulation calculation. When lightning strikes the tower 5, observe the propagation of lightning current on the
line under the condition of installation mode 1 to mode 5 of lightning arrester, and record the extreme voltage at both ends of insulator of tower 1 to tower 9. As shown in Figure 5, the following conclusions can be drawn.

- When the lightning points is the same as the lightning current, the voltage aptitude at both ends of the insulator string will decrease in the direction of lightning current propagation after installing the arrester.
- During the installation of arrester, no matter which installation method is selected, the extreme value of voltage at both ends of insulator at the lightning stroke point remains unchanged. And there is a certain degree of voltage drop at both ends of tower insulator equipped with lightning arrester.
- For oil field distribution network, the insulation lever of the line is generally higher than 170kV. Considering the economic cost, mode 2 can meet the requirements of lightning protection. That is, the installation density of arrester can be selected as three-phase installation of arrester every three poles.

3.3.2. Group two
Select tower 1 (equipped with lightning arrester) as lightning strike point, and taking the lightning current of 25kA as an example, the influence of the installation density of arrester on the lightning withstand level of the line is further analyzed. The following installation methods are selected:

Mode1: Three phase lightning arrester is installed on the tower 1.
Mode2: Three phase lightning arrester is installed on the tower 1 and tower 9 (every seven poles).
Mode3: Three phase lightning arrester is installed on the tower 1 and tower 9 (every six poles).
Mode4: Three phase lightning arrester is installed on the tower 1 and tower 7 (every five poles).
Mode5: Three phase lightning arrester is installed on the tower 1 and tower 6 (every four poles).
Mode6: Three phase lightning arrester is installed on the tower 1, tower 5 and tower 9 (every three poles).
Mode7: Three phase lightning arrester is installed on the tower 1, tower 4 and tower 7 (every two poles).
Mode8: Three phase lightning arrester is installed on the tower 1, tower 3, tower 5, tower 7 and tower 9 (every one pole).
Mode9: Three phase lightning arrester is installed on the tower 1 to tower 9 (every pole).

![Figure 6. The simulation results of different installation modes of lightning arrester.](image)

From the results of Figure 6, we can get the following conclusions:

- Under the condition that the lightning strike point is the same as the lightning current, the voltage at both ends of the insulator string will decrease after the installation of the arrester. The amplitude of both ends of the tower insulator with arrester installed on the first base of the lightning tower decreases greatly.
- The arrester can only reduce the voltage at both ends of the tower insulator in the direction of lightning current propagation, but has no effect on the voltage at both ends of the tower insulator string in the opposite direction.
- The closer the tower is to the lightning point, the greater the voltage value at both ends of the insulator. The installation density of the tower has no effect on the voltage at both ends of the insulator string.

3.3.3. Group three
Select tower 5 as lightning strike point, and taking the lightning current of 25kA as an example, the influence of the installation density of arrester on the lightning withstand level of the line is further analyzed. The following installation methods are selected:
Mode1: Three phase lightning arrester is installed on the tower 1.
Mode2: Three phase lightning arrester is installed on the tower 1 and tower 9 (every seven poles).
Mode3: Three phase lightning arrester is installed on the tower 1 and tower 8 (every six poles).
Mode4: Three phase lightning arrester is installed on the tower 1 and tower 7 (every five poles).
Mode5: Three phase lightning arrester is installed on the tower 1 and tower 6 (every four poles).
Mode6: Three phase lightning arrester is installed on the tower 1, tower 5 and tower 9 (every three poles).
Mode7: Three phase lightning arrester is installed on the tower 1, tower 4 and tower 7 (every two poles).
Mode8: Three phase lightning arrester is installed on the tower 1, tower 3, tower 5, tower 7 and tower 9 (every one pole).
Mode9: Three phase lightning arrester is installed on the tower 1 to tower 9 (every pole).

![Figure 7. The simulation results of different installation modes of lightning arresters.](image)

From the results of figure 7, we can get the following conclusions:

- The arrester only protects the mounting rod. When the lightning arrester is installed at tower 5, the insulator of tower 5 will not flashover. When the lightning arrester is installed in the adjacent tower, the tower 5 will still flashover.
- The arrester can only reduce the voltage at both ends of the tower insulator in the direction of lightning current propagation, but has no effect on the voltage at both ends of the tower insulator string in the opposite direction. The tower between the installation poles of arrester is easy to be damaged by lightning.

In conclusion, the main conclusions from the simulation analysis of the above three groups of arresters are as follows:

- The installation of lightning arrester can improve the lightning resistance level of the line, but it can only protect the installation pole from lightning.
- The surge arrester can reduce the voltage amplitude at both ends of the tower insulation in the direction of lightning current propagation to a certain extent, but it has no effect on the voltage at both ends of the tower insulator in the opposite direction.
- When lightning strikes the installation pole of arrester, the voltage of insulator string in the middle of the two arrester installation poles in high, and the probability of insulator flashover is high.

### 3.4. Influence of lightning conductor on lightning resistance level of lines

It is assumed that when lightning current is 1.85kA, there will be no flashover of tower 3 insulator with lightning conductor and will flashover of tower 4 insulator without lightning conductor. The lightning resistance level of sections with and without lightning conductor is shown in Table 3. When the line insulation level is 230kV, the lightning resistance level of the line with lightning conductor is slightly higher than that of the line without lightning conductor. And the protection effect of the lightning conductor is not obvious.
### Table 3. The lightning withstand level /kV.

|                  | Lightning strike tower top | Lightning strike line |
|------------------|----------------------------|-----------------------|
| With Lightning Conductor | 22.39                      | 1.85                  |
| Without Lightning Conductor | 19.01                      | 1.80                  |

### 3.5. Composite tower

There is no grounding device in composite tower, but the lightning current is discharged to the ground by external grounding down lead. In ATP-EMTP program, the tower is simulated by multi wave impedance according to its structure. The inductance values of composite tower grounding down lead and cement tower are different, which are 0.6382μH/m and 0.84μH/m. Reset the line parameters in the simulation software, and the simulation results are shown in Table 4. After the composite material is used, the lightning resistance level of the tower top is increased by 24.42%.

### Table 4. The simulation results of lightning withstand level.

| Lightning protection level /kA | Lightning strike tower top | Lightning strike central spa |
|--------------------------------|-----------------------------|-----------------------------|
| Cement pole                    | 11.34                       | 1.89                        |
| Composite tower                | 14.11                       | 1.89                        |

### 4. Conclusion

When lightning strikes the tower, the lightning resistance level of the line increases with the increase of the line insulation level, and increases with the decrease of the grounding resistance value. The installation of lightning arrester can improve the lightning resistance level of the line, but it can only protect the installation pole from lightning. The installation of arrester can reduce the voltage amplitude at both ends of the tower insulator in the direction of lightning current propagation to a certain extent, but it has no effect of the voltage at both ends of the tower insulator in the opposite direction. When lightning strikes the installation pole of arrester, the voltage of insulator string in the middle of the two arrester installation poles is high, and the probability of insulator flashover is high. In consideration of economy and protection effect, it is suggested that three-phase arresters should be installed every three towers in the distribution line of oil field. The measures of using composite tower and placing down lead are put forward. The kind of tower has the advantages of high mechanical strength, good insulation and strong corrosion resistance. The simulation results show that this tower can effectively improve the lightning resistance level of the tower top.

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