Faults analysis of lightning stroke-caused flashover in 220 kV double-circuit transmission lines on the same tower

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Abstract. In this paper, four-phase simultaneous lightning stroke-caused faults have been analysed, which occurred in double-circuit transmission lines on the same tower. According to the fault patrol circumstance, lightning information data, fault recording information, ATP-EMTP transient simulation analysis, it can be determined that the four-phase flashover faults were caused by backflashover. The specific process was: lightning stroke top or ground line of 75# tower. The lightning current was shunted by the ground wire and the tower, and was injected into the earth through the grounding device, cause high electric potential to rise on the top of 75# tower, and backflashover overvoltage formed across the insulators of phase B and phase C, leading to insulators flashover and simultaneous trip-out.

1. Introduction

With the rapid development of social economy, double-circuit transmission lines on the same tower have played a huge role in land resources and investments saving [1-2]. Compared with single-circuit, multi-circuit lines have high tower height, but the shielding performance of lightning protection is poor. When the lightning stroke tower is high, the potential on the top of the tower is relatively high, the probability of the wire being struck by lightning is large, the line backflashover withstand level is low, and there are problem of lightning tripping occurs on double-circuit lines at the same time [3-5].

The protection of backflashover mainly depends on improving the line insulation level and reducing the tower grounding withstand to improve the lightning withstand level, while the protection of shielding failure lightning mainly depends on improving the line protection angle and other methods to reduce the probability of lightning stroke [6-7]. Existing research on the protection of lightning overvoltage on transmission lines mostly use empirical data, electrical geometric model methods and other research methods to try to eliminate the threat of lightning overvoltage to overhead transmission lines in design stage [8-10]. However, a large amount of operating experience shows that even in the process of design stage, many comprehensive lightning protection methods have been considered [11-13]. Due to data, methods, models, and actual conditions of the commissioning line, there are still many discrepancies compared with actual lines. There is an error between the trip rate of lightning strikes and the theoretical value, and various lightning overvoltage accidents occur from time to time [14-16].
Practice has shown that lightning strike has become the primary problem in the operation of transmission lines, especially the lightning strikes on multi-circuit lines on the same tower will cause more damage than single-circuit lines. Therefore, it is of great significance to study lightning withstand performance and its measures towards simultaneous trip-out.

2. Basic situation of the fault
At 04:18 on July 21, 2019, a 220 kV double-circuit line on the same tower had a simultaneous trip fault, a failure occurred that is, the B and C phases indirectly failed, resulting in a two-wire three-phase trip, and the reclosing did not operate. Reclosing only put into when single-phase trip occurs on the line.

On-site inspection found that there were discharge marks on the upper and lower ends of the jumper composite insulator string and the equalizing ring in the B and C phases of the 75# tower double-circuit line, as shown in Figure 1.

![Figure 1. Discharge trace of composite insulator jumper string.](image)

![Figure 2. Single line model of fault tower.](image)

3. Line fault section information
The altitude of the double-circuit line is between 70 and 410 meters. The terrain ratio is 10% for flat land, 20% for hills, 70% for mountainous areas, and the ground lightning density level is C2 (multi-lightning area). During the fault period, and there was strong thunderstorm near the line passages, accompanied by strong lightning activity and heavy precipitation in the short time. The fault tower is located in the mountain, and the parameters and sections of the relevant tower are shown in Table 1 and Figure 2.

From the circumstances in the field, there is no traffic condition for large mechanical vehicles in this area, and the possibility of mechanical breakage is small; below the tower are low tree, which is far away from the line, and thus the possibility of tree to line discharge is also small; the grounding resistance of fault tower is about 9.8 Ω, meets operational requirements (grounding type is XJD-C, designed value is 20 Ω).
Table 1. Basic parameters of fault tower.

| Parameters          | Value                          |
|---------------------|--------------------------------|
| Fault tower         | 75#                            |
| Tower model         | 2F2-SJC1-30                    |
| Fault phase         | B, C                           |
| Hugo (m)            | 30                             |
| Full height (m)     | 47.4                           |
| Insulator type      | FSP-220/0.8-3 (Fixed jumper composite insulator) |
| Altitude (m)        | 303                            |
| Grounding designed value (Ω) | 20                   |

Figure 3. Recorded data of protection.
4. Cause analysis

4.1. Lightning information data query analysis

The lightning information system data shows that there are 36 lightning stroke near the line 1 min before and after the line fault trip time, and the 13th lightning strike is located near the line. The maximum lightning current is -167.8 kA, and the lightning strike point is roughly 716 m distance from line, close to the ranging data of substation protection. The calculation and analysis performed below take this lightning information data as reference.

4.2. Fault recording

The fault recording chart shows that the lightning strike causes the double-circuit lines B and C to flash at the same time. The phase of the power-frequency voltage A phase is about 180° at the moment of failure, and the B and C phase currents fluctuate significantly during the fault, and there is a zero-sequence component, as shown in Figure 3.

The lightning stroke voltage of each phase is affected by the tower wave impedance and the wire power frequency potential. Among them, the B-phase position of the double line is the highest (the line arrangement of the L1 line is B, C, A from top to bottom; the line arrangement of the L2 line is B, A, C from top to bottom respectively), the tower wave impedance is large, so the backflashover overvoltage is higher, and flashover comes relatively easier; the insulation gap is different between cross arm potential and the wire power frequency potential. Voltage value of phase B is positive polarity, phase C is close to zero, and the phase A is negative polarity. Under the negative lightning current, affected by the power frequency voltage, the B and C of the two circuits have a higher overvoltage than phase A, which is more likely to cause flashover.

5. ATP-EMTP transient simulation model

According to the electrical geometric model theory, the maximum shielding failure lightning current of 220 kV line is generally 20~30 kA. The lightning current amplitude of this fault far exceeds the maximum shielding current, and the lightning protection line and the earth are completely shielded from the formation of the wire. Therefore, backflashover withstand level of 75# tower is calculated based on multi-wave impedance model and leading progression flashover model.

Among them, the phase sequence arrangement of the double-circuit conductor is shown in Figure 4. Lightning current adopts 2.6/50μs negative surge current source, since the lightning overvoltage is fast wavefront electromagnetic transient process, even if the process time Δt is taken as 100 μs, the phase voltage variation does not exceed 3.14% of the amplitude, which can ignore the phase voltage change during the lightning strike; the multi-wave impedance of the tower adopts a 4-layer model (N=4) according to the SJC1 tower type, as shown in Figure 5. The calculation results of the parameters are shown in Table 2; the grounding resistance of 75# tower adopts actual measured value of 9.8 Ω; the distance of the dry-arc distance of the insulator string is 2 m (the length of the structure minus the short of the metal member and the equalizing ring).

![Figure 4. Phase sequence arrangement of transmission line.](image-url)
Figure 5. Typical tower form and its multi-wave impedance model.

Table 2. Wave impedance parameter of tower material.

| Principal material/Ω | Diagonal material/Ω | Pole arm/Ω |
|----------------------|--------------------|-----------|
| $Z_{T1}$ 184.5 | $Z_{L1}$ 1660.6 | $Z_{A1}$ 328.1 |
| $Z_{T2}$ 163.9 | $Z_{L2}$ 1475.0 | $Z_{A2}$ 303.0 |
| $Z_{T3}$ 140.5 | $Z_{L3}$ 1264.4 | $Z_{A3}$ 276.2 |
| $Z_{T4}$ 91.6 | $Z_{L4}$ 824.5 | $Z_{A4}$ 248.7 |

According to the withstand level model of backflashover lightning, considering the influence of the 220 kV line power frequency voltage in lightning transients, each division point (phase angle) is calculated one by one according to the 60° interval in a 360° phase of a power frequency cycle. The backflashover withstand level and the corresponding flashover phase include the lightning withstand level and flashover of single-phase, two-phase, three-phase and four-phase of the tower, as shown in Table 3. Wherein, the phase angle is based on the cosine expression of the A-phase voltage; the number of flashover phase represents the loop of double-circuit transmission line, and "-" indicates that the flashover does not exist under this phase condition.

Table 3. Calculation results of double-circuit transmission lines withstand level.

| Power frequency phase / ° | Single phase flashover | Two-phase flashover | Three-phase flashover | Four-phase flashover |
|--------------------------|-----------------------|---------------------|----------------------|---------------------|
|                          | Lightning withstand level / kA | Flashover phase | Lightning withstand level / kA | Flashover phase | Lightning withstand level / kA | Flashover phase | Lightning withstand level / kA | Flashover phase |
| 0                        | 85                    | A2                  | -                    | -                   | 108  | A1, B1, B2, A2 |
| 60                       | -                     | -                   | 88                   | B1, B2              | 108  | B1, B2, A2   | 126  | A1, B1, B2, A2 |
| 120                      | -                     | -                   | 79                   | B1, B2              | -    | -            | 142  | B1, C1, A2, B2 |
| 180                      | -                     | -                   | 88                   | B1, B2              | 108  | B1, C1, B2  | 125  | B1, C1, B2, C2 |
| 240                      | 85                    | C1                  | 102                  | C1, C2              | -    | -            | 108  | B1, C1, B2, C2 |
| 300                      | -                     | -                   | 95                   | C1, A2              | -    | -            | 117  | B1, C1, A2, B2 |

According to the formula: insulation gap overvoltage = | cross-arm potential - wire power frequency potential |. It is easy to see, if the power frequency voltage is ignored, it is undoubtedly that the B1, B2 phase in the highest position is the most likely to backflashover, but in fact each lightning overvoltage of the phase is not only affected by the tower wave impedance, but also affected by the
wire power frequency potential (power frequency phase angle), and the flashover phase has a "competitive" relationship. From the above, we can see:

a) When the phase angle condition is determined, the lightning-fastening level of flashover from single phase to two-phase, three-phase, and four is gradually increased, which means that a larger lightning current is required to cause more flashover at the same time.

b) Although the power frequency voltage is not the primary cause of the direct insulation flashover, it largely determines which phase or order of line flashes. Multi-phase flashover occurs in the double-circuit line, mostly occur in the same phase; under certain phase angle condition, single-phase or three-phase simultaneous flashover does not occur due to symmetry.

c) Under different phase angle conditions, the 75# tower backflashover level and flashover phase change, since B1 and B2 are completely symmetrical, the probability of flashover when the even number is the same is more than the flash when the odd number is the same; in general, the more balanced the power frequency phase angle (power frequency potential) and the tower wave impedance condition is, the easier it is to simultaneously flash and the lower the lightning protection level will be. The more unbalanced, the higher lightning withstand level is.

d) For the four-phase flashover, the average value of the four-phase backflashover withstand value is about 121 kA; under the 120° phase angle condition, the B-phase power frequency potential is at the positive maximum value, and. The position of B1 and B2 is the highest, the wave impedance is the largest, and the power frequency voltage and the wave impedance are most favorable for backflashover of B1 and B2. In the same way, under the condition of 0° and 240° phase angle, the wave impedance condition is more favorable for flashover of B-phase, and the power frequency voltage is more favorable for flashover of phase A and C. Occurrence probability of flashover is also the closest, and the four-phase flashover withstand level is the smallest; typical waveform of four-phase backflashover is shown in Figure 6.

![Figure 6. Typical waveform of four-phase backflashover.](image)

Simulation results of ATP-EMTP model in consistent with actual faults: the 75# tower backflashover withstand level is affected by the power frequency phase angle of the lightning stroke. The amplitude of the negative lightning current (167.8 kA) exceeds four-phase backflashover withstand level (121 kA), and the phase angle of lightning strike time is about 180°, which coincide to the fault condition.

6. Conclusions

In summary, it is determined that the double-circuit flashover fault is caused by backflashover. The detailed process was: lightning stroke top of the 75# tower or the ground line, and the lightning current was shunted by the ground line and the tower body, injected into the earth through the grounding device, which lead to the potential rise in the top of 75# tower. Finally, backflashover overvoltage was formed at the end of two-phase insulators, cause simultaneous trip-out.
Follow-up can conduct lightning damage assessment of line passage, implement lightning protection, rectification according to the assessment, installing line arresters to improve the lightning withstand level. In addition, the erection of the grounding wire below the tower is a practical modification measure, which can significantly improve the lightning withstand level, and it is recommended to be used in severely lightning sections.

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