Research of reclosing failure of transmission lines caused by multiple lightning strikes

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Abstract: Lightning faults of transmission lines are usually instantaneous faults, and most of them can automatically reclose successfully, but reclosing failure will also occur sometimes. The present paper analyses a reclosing failure of a 500kV transmission line after lightning strike. In this paper, the lightning monitoring system is used to monitor power frequency fault current and lightning transient traveling wave current, and the fault location, the cause identification and the reasons for the reclosing failure are obtained based on the monitoring data. The results show that there are several successive lightning strikes near the fault point of transmission line during the switch to closing period, which makes the fault frequency continuous current unable to return to zero, so the insulation cannot be recovered, which ultimately leads to reclosing failure.

1 Introduction
Thundercloud discharge to the earth is generally accompanied by multiple lightning strikes[1-2]. During the initial stage of thundercloud discharge, downward leader and upward leader between thundercloud and the earth meet together and a discharge channel forms, and then a strong discharge occurs, this process is called main discharge[3-4]. In the vicinity of the main discharge area there are often a number of dense charge centers, when the main discharge occurs, multiple charge centers will meet along the initial discharge channel and then multiple lightning strikes occur[5]. Most of the lightning strike faults are instantaneous faults. When the fault occurs, most of the operating mechanisms in the substation can automatically reclose the fault line and resume power supply within a short time, but in some extreme cases, for example, when a line is struck continuously for a short period of time, it is easy to happen reclosing failure and power supply cannot be restored[6-9].

Lightning fault reclosing failure is relatively rare, and related research are seldom reported at home and abroad. Based on a reclosing failure of a 500kV transmission line after lightning strike, the paper analyzed the precise location of the lightning strike point, the reason identification function and then found out the reason of the failure of the reclosing, which may provide some reference for the reason analysis of similar complex faults.

2. Working principle of lightning monitoring system
As shown in Fig 1, lightning monitoring system is composed of workstation, data center and monitoring terminals. Monitoring terminals are distributed on the conductor of transmission lines, monitoring power frequency current and high frequency transient current in real time, sending such
data to data center by the way of GPRS. Data center is used to collate and analyze the data and output the diagnostic results.

![Figure 1. Structure diagram of the system](image1)

The main components of monitoring terminal include high-frequency current sensor, conditioning circuit, acquisition and high-speed processing circuit, battery, GPS clock module and wireless transmitting module. The monitoring terminal shell is a cylindrical aluminum alloy metal container with all the electronic components installed inside it. In actual operation, the terminal shell and the wire are in equipotential connection, which can effectively protect the internal functional modules from the interference of high pressure and electromagnetic environment. The sensor adopts the self integral Roche coil, which has the advantages of good high frequency response, good linearity, wide measurement band and strong anti-interference ability[10-12]. The principle of measuring current by Roche coil is shown in Fig 2.

![Figure 2. Principle of rogowski coil current measurement](image2)

In Fig 2, \(i_2(t)\) is the current value on the wire. The output of the sensor is a voltage signal, and also the acquisition of the monitoring terminal. The value of the output of the sensor can be obtained as formula (1):

\[
    e(t) = -M \frac{di_1(t)}{dt} = L_0 \frac{di_2(t)}{dt} + (R_0 + r)i_2(t)
\]

In formula (1), \(M\) represents the mutual inductance between the coil and the tested conductor. \(L_0\) and \(R_0\) are the self inductance and internal resistance of the coil respectively. \(C_0\) and \(R\) are the distribution capacitance and the sampling resistance of the coil respectively, and \(i_2(t)\) is the current of the sampling resistor[13-14]. When frequency of measured current is very high, \(wL_0\)\(>>\)\(R_0 + r\), it can be deduced that

\[
    e(t) = i_2(t)r \approx \frac{Mr}{L_0}i_1(t)
\]

By formula (2), the output of the sensor is approximately proportional to the current of the conductor. Acquisite output of the sensor, and lightning current waveform can be obtained.

3. Lightning strike Fault monitoring and diagnosis

3.1. Monitoring terminals installation
August 19, 2016 22:59:41, a 500kV line of China Southern Power Grid lightning trip occurred, and reclosed unsuccessful. As shown in Fig. 3, the total length of the line is 141km. Lightning monitoring terminals are installed at # 1 tower, # 73 tower, # 136 tower, # 209 tower, # 253 tower and # 302 tower of the line respectively, and # 1 tower, as well as # 302 tower are located at both ends of the substation exit.

![Figure 3. Schematic diagram of the installation of monitoring terminals](image)

3.2. Trip process record

When flashover occurs, power frequency current will change suddenly at a point of time, which is the time of fault. At 2016-8-19 22:59:41, the monitoring terminal of A phase of the #209 tower monitors the mutation of line frequency current, and the waveform of frequency current is shown in Fig 4.

![Figure 4. Power frequency split current waveform](image)

Fig 4 shows that in 22:59:41 sec. 471 ms, power frequency current of the monitored line suddenly increases, with the amplitude over 5000A, far exceeding the normal operation current of the line, and it changes to 0 after maintaining two cycles, concluding that the line has a fault and trip.

Fig 5 is a frequency current waveform recorded by the A phase monitoring terminal of #1 tower at 22:59:42 time. The amplitude of the front 290ms is 0, while it increases suddenly at 292ms, and then goes back to zero after two cycles. Besides, the time interval between the waveform and the fault reclosing waveform of Fig 4 is 811ms, which is consistent with the characteristics of the reclosing process of the transmission line, so it can be concluded that Fig 5 is frequency current waveform of reclosing, and reclosing is unsuccessful.

![Figure 5. Power frequency waveform of the circuit breaker Reclosing](image)

3.3. Fault location
The fault interval positioning is realized by the power frequency current, what’s more, fault point can be accurately located by the traveling wave current of the fault interval.

![Figure 6](image)

**Figure 6.** Power frequency switching current waveform of different point

From Fig. 6, when the fault occurs, the polarity of short circuit power frequency current of #209 tower and #253 tower is the opposite, which indicates that the short-circuit fault point is between #209 tower and #253 tower.

Two fault points are found by traveling wave positioning, as is described as follows.

1. The first fault point
   Traveling waves current monitored of #209 tower and #253 tower at the time of failure are as shown in Fig.7.

![Figure 7](image)

**Figure 7.** Fault traveling wave

In Fig 7, the time difference between the fault point current traveling wave from the fault point to the #209 tower and the #253 tower is 8 microseconds, and the distance between the two tower is 20.3 kilometers. Through the double end traveling wave positioning method, the fault point distance can be calculated that it is near the #233 tower, which is about 9 km away from #253 tower.

2. The second fault point
   The reclosing of the circuit breaker also produces high frequency traveling wave, which can be applied to locate the second fault point. Reclosing traveling wave is as shown in Fig.8.

![Figure 8](image)

**Figure 8.** Reclosing traveling wave

Fig.9 shows a schematic diagram of the reflection process of the reclosing traveling wave. The reclosing traveling wave is produced when the circuit breaker of substation B recloses, and is recorded by the monitoring terminal after the fault point, such as the first main pulse 1 in Fig 8. On the other
hand, reflection occurs when traveling wave arrives at the fault point or substation, when traveling wave is reflected at the fault point, it will undergo second reflection after passing through the substation B. After two times reflection, the wave will be refracted through the fault point and monitored by the monitoring terminal, which is corresponding to the reflected pulse 2 in Fig.8. From Fig.8 and Fig.9, we can calculate the second fault point is near the #236 tower by single end traveling wave location method.

![Location sketch map by reclosing traveling wave](image)

**Figure 9.** Location sketch map by reclosing traveling wave

### 3.4. Analysis of the cause of failure

According to Fig.7, the amplitude of traveling wave reaches thousands of amperes, and the wave tail time is within 40 microseconds, which is consistent with the characteristics of lightning fault traveling wave, and there is no reverse polarity pulse in the front part of the main wave, which is initially judged as shielding failure.

### 3.5. Patrolling result

The power supply department inspected #233 and the nearby area. Results show that there were lightning flashover traces of #233 tower A phase and #236 pole tower A phase insulator, which are shown in Fig 10. Combined with the weather conditions at the time of failure, it is basically determined that lightning flashover occurred in #233 and #236 towers.

![Flashover traces](image)

(a)Flashover trace of A phase insulators in #233 tower (b) Flashover trace of A phase insulators in #236 tower

**Figure 10.** Location sketch map by reclosing traveling wave

### 4. Failure analysis of reclosing

A lightning trip fault occurred in the A phase of this line has at 22:59:41.471 ms, and then circuit breaker disconnected at 22:59:41.516ms, reclosed unsuccessful at 22:59:42.327ms. The break from the circuit breaker disconnecting and reclosing is about 811 milliseconds, during which the insulation can be recovered in normal conditions.

According to the monitoring data of lightning monitoring system and lightning location system, there are 8 lightning strikes near the #233 tower of the transmission line from closing to reclosing of the circuit breaker, all of which are around the A phase conductor, as shown in Tab 1. $I_L$ is the amplitude of lightning current.

**Table 1.** Lightning stroke process record
Fig. 11 is the power frequency current waveform recorded 300ms before the reclosing failure recorded by the lightning monitoring system. In Fig. 11 (a), $t=300$ms is the reclosing time, and power frequency current increases sharply, while the spike near 130ms is subjected to the lightning time. Fig. 11 (b) is the part of Fig. 11 for $t=0$-120ms. From Fig. 11 (b), it can be seen that the current on the line before reclosing is not 0, and presents a certain periodicity.

![Figure 11. Current waveform before reclosing](image)

In order to eliminate the high frequency component in the waveform in fig. 11(b), the filter cut-off frequency 200Hz is set up, and the waveform after filtering is shown in Fig. 12.

![Figure 12. Current waveform after filtering](image)

It can be seen from Fig. 12 that the waveform has obvious periodicity, and its period is about 20ms. It is deduced that the secondary supply current has not disappeared before reclosing, and its effective value is about 10~20A. Due to the coupling capacitance and coupling inductance between line to line and line to earth, the capacitive coupling(inductive) current will not be interrupted immediately after the fault line tripping. It will form a continuous flow at the fault point arc passage, which is called the secondary supply current. When secondary supply current doesn’t completely disappear, the arc channel will be in a free state with good conductivity. Under normal circumstances, the secondary supply current will soon disappear, enabling the line to restore good insulation.

From the monitoring results, during the trip to reclosure, 8 lightning strikes near the fault point make it difficult to extinguish the supply arc of the fault point, and the line can not restore the insulation, so the reclosing fails.

According to the above analysis, it is inferred that the reasons of the failure of the lightning reclosing of this line are described as follows:

1) When lightning fault occurs, the circuit breaker is sluice, and secondary supply current exists in the
fault point;
2) during the closing to reclosing of the breaker, 8 lightning strikes stroke near the fault point, which leads to the failure of the short-circuit point secondary supply current to be completely extinguished and the insulation can not be recovered.
3) after the automatic reclosing, the fault still exists because of the continuous arc burning in the short circuit point, so reclosing failed.

5. Conclusion
1) The fault between #209 and #253 tower is judged by power frequency current. Then two fault points are calculated by traveling wave location method, which correspond to #233 and #236 respectively, which is consistent with the actual inspection results, indicating that the fault diagnosis results are correct.
2) The amplitude of traveling wave reaches thousands of amperes, and the wave tail time is within 40 microseconds, which is consistent with the characteristics of lightning fault traveling wave, and there is no reverse polarity pulse in the front part of the main wave, so the failure is shielding failure;
3) During the closing to reclosing of the breaker, 8 lightning strikes stroke near the fault point, which leads to the failure of the short-circuit point secondary supply current to be completely extinguished and the insulation can not be recovered, resulting in reclosing failure.

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