Analysis on Lightning Strike Breaking Defects of 500kV Yangdong Line II Optical Cable

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Abstract. The 500kV Yangdong Line II starts at Shanxi Yangcheng Power Plant and ends at Shandong Dongming Switch Station. It was completed and put into operation in May 2000, with a total length of 246.465 km. In this paper, through the field investigation and weather operation statistics, as well as the metal micro-analysis of the broken strand OPGW sample, it is concluded that the root cause of the broken strand is that the continuous current discharge process of the lightning channel can keep the arc root for a long time, which may cause ablation on the surface and even the inside of the single stranded wire. This paper also put forward measures to prevent such failures.

Key Words: OPGW Optical Cable, Lightning Strike, Broken Strand, Arc Root.

1. Preface
Optical fiber composite overhead ground wire (OPGW) is a new structure ground wire used for high-voltage power transmission system communication lines. On one hand, it has the functions of ordinary overhead ground wire and communication optical cable, and on the other hand, it can play a role on lightning protection and carrying short-circuit current. Due to the harsh outdoor environment, the 500kV line OPGW has been repeatedly damaged by lightning in recent years. Strong lightning strikes the OPGW surface. When the lightning heat energy rapidly erupts, the positive and negative electrodes produce strong spark discharge, which burns the wire metal and melts it, and the OPGW is under tension. In severe cases, loose strands or direct strand breaks will occur. The loose strands of OPGW will cause an indirect grounding short circuit of the wire, and the disconnection will cause damage to the fiber core of the optical cable, interruption of the communication optical path, and cause a grid outage accident.

2. Introduction
On a certain day in 2020, line inspectors discovered that the optical cable in stall 332#-333# had broken strands during inspection of the 500kV Yangdong Line II. Confirmed by the drone on March 15th, there are 3 broken stocks, located at 170 m, 220 m and 260 m from the large side of 332#. They are 2 strands broken (distributed), 8 strands broken (6 strands spread out) and 4 strands broken (2 strands spread out) respectively, the most broken strands exceed 17% of the cross-sectional area of the optical cable, and some loose strands may sag. If the line vibrates due to bad weather, the optical cable may break. If the loose strands continue to deteriorate, they may discharge the wires at any time and
trip, which constitutes a critical defect. The optical cable uses the 651FT12 central aluminum tube composite optical cable of British BICC company, 8-core, design model OPGW-80-8B1, completed and put into operation in May 2000.

![Figure 1. Schematic diagram of the central aluminum tube type composite optical cable structure](image)

Line operation and maintenance personnel reported the situation immediately and applied for temporary line shutdown. At 10:26 on March 16th, with the permission by the provincial power dispatch and the provincial communication dispatch, the emergency repair personnel began to climb the tower to eliminate the shortage. The method of eliminating the shortage was to lower the optical cable at 332# to the position of the upper phase conductor, the personnel exited, repositioned the loose strands and used emery to reinforce them. At 15:26, the emergency response was over, the application was terminated, and the line resumed at 20:14.

3. Equipment overview
The 500kV Yangdong Line II is the asset of the Global Energy Internet Company. It starts at Shanxi Yangcheng Power Plant and ends at Shandong Dongming Switch Station. It was completed and put into operation in May 2000. The line has a total length of 246.465 km and has a total of 569 bases of iron towers, of which 1# ~ 11#, 59# ~ 527#, 529# ~ 530# are on the same tower as the 500kV Yangdong Line III, and Yangdong Line II is located on the left side facing the pole, Yangdong Line III is on the right.

332#-333# is located in a certain city in Henan Province. The terrain is plain, about 70 meters above sea level, and the surface vegetation is winter wheat. There is no external damage such as stone explosion nearby. This area is a level B1 thunderstorm-less area, and the density of CG lightning is between 0.78-2.0 times/(km²·a). The list of poles in this section is as follows:

| Running pole number | Tower model | Calling height (m) | Overall height (m) | Gear distance (m) |
|---------------------|-------------|--------------------|--------------------|------------------|
| 331+1               | SJC1        | 21                 | 50.5               | 265              |
| 332                 | SZT1        | 36                 | 59.5               | 208              |
| 333                 | SZT1        | 36                 | 59.5               | 453              |
| 334                 | SZT1        | 36                 | 59.5               | 411              |
| 335                 | SJ1         | 27                 | 56.5               | 403              |

Table 1. List of poles and towers of 500kV Yangdong II line lightning strike section
The 332#-333# section wire uses 4xLGI-300/40 steel core aluminum stranded wire, the split spacing is 450mm, the left side of the lightning protection wire uses OPGW-80-8B optical cable (651FT12), grounded by ground, and the right side uses LXGJ-80 ground wire, sectional insulated, grounded at one point. The manufacturer of OPGW-80-8B optical cable is British BICC company, its parameters are shown in the following table:

**Table 2.** 500kV Yangdong Line II OPGW Optical Cable Parameters

| Model  | Number of cores | Cable diameter (mm) | Allowable short-circuit current capacity (kA²·s) | Tensile strength (kN) | DC resistance (Ω/km) | Thermal expansion coefficient (1/°C) | Modulus of elasticity (N/mm²) | Unit weight (kg/km) | Minimum bending radius (mm) |
|--------|-----------------|---------------------|-------------------------------------------------|-----------------------|----------------------|-------------------------------------|-----------------------------|---------------------|---------------------------|
| OPGW-80 | 8               | 12.91               | 51                                              | 92.623                | 0.6545               | 13.4×10⁻⁶                         | 140078                     | 564                 | 258                       |

4. **Defects and deficiencies**

There are 3 damages in the 332#-333# optical cable, none of which damages the internal protective aluminum tube and optical fiber unit, which as follows:

**Table 3.** The scattered strands of the OPGW cable of 500kV Yangdong II line lightning strike

| Serial number | Location         | Broken stock | Loose stocks | Remarks                                                      |
|---------------|------------------|--------------|--------------|--------------------------------------------------------------|
| #1            | 332# Large side 170 meters | 2 shares     | 2 shares     | It was found that 5 shares were actually broken during repair |
| #2            | 332# Large side 220 meters | 8 shares     | 6 shares     |                                                               |
| #3            | 332# Large side 260 meters | 4 shares     | 2 shares     | It was found that 6 strands were actually broken during repair |
Figure 3. #1 332# 170 meters from the large side, 5 strands are broken, 2 strands are scattered

Figure 4. #1 emery protection line repaired and strengthened overall view

Figure 5. #2 332# 220 meters from the large side, 8 strands are broken, 6 strands are scattered
5. **Reason analysis**

5.1. **Fracture analysis.** Among the fractures, #3 is the most typical. The fractured aluminum strands are all the outer layers. Although the inner layer is damaged, the strands are not broken, and there are arc burning marks near the fracture. The figure shows 10 decapitations, divided into two groups A and B. Group A fully displays 6 decapitations, and group B B1-B3 only displays one decapitation. The broken ends of A4, A5, B4, and B5 are concave or round, which are completely melted. The broken ends on the other two sides are relatively sharp and may be partially melted or broken by force during the melting process. From the analysis of the fracture morphology, the optical cable encountered a large current from outside to inside, and it melted due to the thermal effect of the current, and the current falling point between the ends of A4, A5, B4, and B5.
5.2. Theoretical analysis of lightning.

Regarding the calculation of the number of lightning strikes per 100 km per year, IEEE 1243 and IEEE 1410 recommend the following formulas:

\[ N = N_G \left[ \frac{(28h^{0.6} + b)}{10} \right] \]

where:
- \( N \) is the number of lightning strikes per 100 km per year.
- \( N_G \) is the density of lightning strikes on the ground (the number of lightning strikes per square km per year in the area where the line is located).
- \( h \) is the average height of the ground wire or OPGW to the ground, m.
- \( b \) is the distance between lightning protection lines, m.

Take Yangdong Line 332#-333# as the center, extend 0.5kM to the large and small side each, and query the lightning positioning system in 2019 within 5 km of the line, a total of 60 times.

Yangdong line II 332#-333# is located in the B1 mine-reduced area, and the flash density is 0.78-2.0 times/(km²·a), \( h = 59 \) m, \( b = 20 \) m, and \( N \) is between 26.78 and 68.67. The left side of this place is the optical cable, and the right side is the ground wire. The actual number of lightning strikes on the optical cable is 13.39~34.34 times/(100 km·year).

According to DL/T 620-1997, the probability of lightning current amplitude exceeding \( I \) in general areas can be calculated using the following formula:

\[ \log P = - \frac{I}{88} \]

where:
- \( P \) is the probability of lightning current amplitude exceedance.
I—lightning current amplitude, kA

The probability of I exceeding -30kA is 45.61%, and the expected value of lightning strikes above -30kA on the optical cable near Yangdong line II 332#-333# is 6.10-15.66 times/(100 km per year)

5.3. Statistics of lightning strikes. Query the lightning positioning system. In 2019, there were 15 thunderfalls within the range of 332#-333# before and after 332#-333#, concentrated in 4 periods of April 24, June 5, and August 7, 2019 -06-05 16:38:37.998 and 2019-08-01 16:07:13.709 The two lightning strikes are the closest to the disconnection point, and the lightning currents are -29.6kA and -34.1kA respectively.

Table 4. Lightning monitoring situation of 500kV Yangdong line II OPGW optical cable lightning strike area

| Serial number | Time                      | Longitude | Latitude | Current (kA) | Hit back                        | Distance (m) | Nearest tower |
|---------------|---------------------------|-----------|----------|--------------|---------------------------------|--------------|--------------|
| 1             | 2019-04-24 22:04:09.572   | 114.0839  | 35.4842  | -18.1        | Subsequent second counterattack | 2,284        | 331 ~ 332    |
| 2             | 2019-04-24 22:04:09.769   | 114.0822  | 35.4782  | -30.7        | Follow-up 4th counterattack     | 1,653        | 331 ~ 332    |
| 3             | 2019-04-24 22:04:09.830   | 114.0832  | 35.4868  | -33.6        | Subsequent 5th counterattack    | 2,521        | 331 ~ 332    |
| 4             | 2019-04-24 22:04:09.887   | 114.0824  | 35.4843  | -31.4        | Follow-up 6th counterattack     | 2,262        | 331 ~ 332    |
| 5             | 2019-06-05 16:38:37.998   | 114.0850  | 35.4595  | -29.6        | Main discharge (including 1 subsequent return stroke) | 127          | 332 ~ 333    |
| 6             | 2019-06-05 16:38:38.036   | 114.0847  | 35.4472  | -28.6        | Subsequent first counterattack  | 1,343        | 332 ~ 333    |
| 7             | 2019-08-01 15:34:17.273   | 114.0820  | 35.4323  | -4.4         | Single return                   | 2,856        | 332 ~ 333    |
| 8             | 2019-08-01 15:35:35.174   | 114.0769  | 35.4490  | -6.6         | Subsequent second counterattack | 1,311        | 331 ~ 332    |
| 9             | 2019-08-01 15:39:01.198   | 114.0747  | 35.4449  | -7.7         | Single return                   | 1,749        | 331 ~ 332    |
| 10            | 2019-08-01 15:40:22.020   | 114.0761  | 35.4351  | -8.2         | Single return                   | 2,696        | 331 ~ 332    |
| 11            | 2019-08-01 15:48:42.981   | 114.0754  | 35.4226  | -5.1         | Single return                   | 3,933        | 331 ~ 332    |
| 12            | 2019-08-01 15:50:20.286   | 114.0805  | 35.4444  | -6.0         | Single return                   | 1,698        | 332 ~ 333    |
| 13            | 2019-08-01 15:52:47.634   | 114.0943  | 35.5067  | -7.9         | Single return                   | 4,675        | 332 ~ 333    |
| 14            | 2019-08-01 16:07:13.709   | 114.0856  | 35.4574  | -34.1        | Single return                   | 331          | 332 ~ 333    |
| 15            | 2019-08-07 14:42:08.944   | 114.0788  | 35.4382  | -5.8         | Main discharge (including 1 subsequent return stroke) | 2,341        | 332 ~ 333    |
Figure 10. Thunder distribution on June 5, 2019

Figure 11. Thunder distribution on August 1, 2019

Figure 12. Thunder distribution on August 7, 2019
5.4. *Mechanism of strand breakage of optical cable by lightning.* The lightning discharge includes two basic current forms in nature: pulse impulse current and long-term continuous current. The peak value of the pulse impulse current is large (about tens to hundreds of kiloamps), but the duration is short (about a few hundred microseconds). Falling lightning can reach very high temperatures, sometimes even exceeding the melting point of the metal. However, the thermal conductivity of metals is limited. In a very short time (less than 1ms) when the lightning pulse impulses the current, the heat cannot penetrate deep into the metal material. Therefore, the melting spot area of molten metal caused by pulse impulse current is large (usually a few centimeters in width). However, the depth of the melting spot is relatively shallow (approximately a few tenths of a millimeter), which is manifested as the surface melting of the metal wire.

The long-term continuous current is approximately DC current. Although the amplitude is low (about a few hundred amperes), but the duration is long (about a few milliseconds to a few tenths of a second). The heat will penetrate deep into the metal material and cause the deep metal to melt. Therefore, unlike the melting spot of metal caused by the pulse impulse current, the area of the melting spot of the long-term continuous current is small (usually 1cm~2cm in width), and the depth of the melting spot is very deep.

The plasma arc is a self-sustained discharge phenomenon. In the atmospheric gap, it will cause electric field breakdown to form an arc when the potential gradient reaches 30kV/cm.

The arc root may generate high temperature during lightning discharge. The continuous current discharge process of the lightning channel can keep the arc root for a long time, which may cause ablation on the surface of the single stranded wire. After the arc is formed, a very low voltage (about 15~30V) can maintain the arc to burn stably. There is a strong nonlinear relationship between the resistance of a stable arc and the current. The conductivity of the arc increases sharply with the increase of the current, and the cross-sectional area of the arc also increases with the increase of the current. With the increase of continuous current discharge, the degree and number of strand breakage of OPGW single-stranded wire increase. In severe cases, the optical fiber in the inner steel pipe may be damaged.

Both the theory and experiments have shown that although the pulse current of lightning instantaneously acts on OPGW is very large, the duration is very short. Therefore, the heat capacity of lightning current, i.e., I^2t, is small, and it can not cause damage to OPGW. After the arc is formed, a small current maintained by a very low voltage and a long arc root is fatal to the OPGW strands. If the volumetric heat capacity of the material is not enough or the melting point is low, the outer strands will be corroded or melt.

The strands of OPGW that are struck by lightning include two cases generally: fuse directly and damaged (pulled or vibrated).

The ability to withstand lightning strikes of OPGW is mainly determined by the instantaneous high temperature resistance of each single wire in the outer layer, and does not completely depend on the heat capacity of the entire cable. If the outer single wire is thin with a low melting point and the lightning strike contact area is small, the instant high temperature generated by the arc root of a lightning strike may erode or melt the outer single wire, even if the capacity of OPGW is large.

5.5. *Comprehensive analysis.* There are burn marks on each fracture in the site. The fracture of the broken strand is sharp, concave or round, without a neat section or cup-cone section. The optical cable has been in operation since 2000. Therefore, the possibility of strand breakage of the optical cable caused by the construction, ice and strong wind can be ruled out.

The line is plain farmland and there are no traces of rocks exploded. Therefore, the possibility of rocks breaking the optical cable can be ruled out.

The optical cable here uses the central aluminum tube 8-core 651FT12 optical cable provided by British BICC. Due to the early age and incomplete data, it is judged by the fact that the outer diameter is 12.91mm and there are 2 layers of stranded wires outside the central aluminum tube. The diameter is small (less than 3mm) and the allowable short-circuit current capacity is only 51kA2•s.
According to the 6.4.3 of the DL/T 1378-2014 "Optical Cable Composite Overhead Ground Wire (OPGW) Lightning Protection and Grounding Technical Guidelines": the outer strands of 220kV and above OPGW should be selected from aluminum clad steel wire with a monofilament diameter of 3.0mm and above.

To sum up, the main reason for the strand breakage of the optical cable is the instantaneous high temperature generated by the arc root formed by lightning in summer thunderstorms. The bottom cause of the strand breakage of the optical cable is that the diameter of the optical cable monofilament is small, because the lightning protection effect is poor caused by the earlier design and construction.

After the strands of the optical cable are broken by lightning, it is difficult to find because of the high height (about 60 m) and the unobvious appearance (2-3 square centimeters). In the long-term operation process, some monofilaments appear loose strands affected by the external working conditions such as breeze vibration, strong wind, ice coating, and the shrinkage deformation of the optical cable monofilament after the tension is released, which are obviously different from the conventional section and can be found by ground inspectors.

6. Suggestions for troubleshooting
After the defect occurred, the line operation and maintenance personnel investigated the optical cables in operation in the province and found four 500 kV lines: Song-zheng line II, Ma-Song line II, Mu-ma line II and Wo-xian line II, in which the optical cable may be broken or scattered by lightning since the lightning protection design standard is low.

In the next step, the following work will be carried out:

During the power outage of Yangdong Line II, the fiber optic cable in the broken strand section is replaced, and the entire line of this type of fiber optic cable section is checked. For the early lines with low lightning resistance level, the UAV is used to carry out the fiber optic cable broken strand inspection to detect and solve issues.

Pay attention to the early lines with insufficient lightning resistance, report the technical improvement plan, replace them in batches and phases, and improve the lightning resistance level. Before replacement, drones are used to check the condition of the early line optical cables after the thunderstorm season.

Through the analysis of the mechanism of OPGW being struck by lightning, it is possible to reduce the probability of OPGW being struck by lightning by reducing the oncoming pilot probability of the optical cable. In the frequent interval of lightning strikes, the lightning protection wires of the tower are grounded step by step to reduce the probability of arcing on the outer surface of the OPGW.

4. In order to improve the lightning resistance of the line, the following measures are taken to replace the OPGW:
   a) The outer strand material uses aluminum-clad steel wire or zinc-sleeved steel stranded wire. Due to the high melting point of steel, it is not easy to be eroded under arc high temperature. The tensile strength of steel is high. Therefore, it is hard to stretch and break under normal tension even if a certain degree of erosion is formed.
   b) Use outer strands with a larger diameter to reduce the probability of strand breakage by increasing the cross-sectional area of the strands. The diameter of aluminum-clad steel wire in lightning-prone areas should be greater than or equal to 2.5mm.
   c) Air gaps should be designed between the outer monofilament, the inner monofilament and the optical unit to avoid high-temperature heat transfer to the optical unit as much as possible to prevent optical fiber damage and communication interruption.

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