Study of OPGW Performance against Lightning Strikes in UHV Transmission Lines

Xie Shu-Hong and Yang Ri-Sheng
Zhongtian Technology Group Co., Ltd.
Shanghai, PR China
+86-21-64666595 · xiesh@chinaztt.com, yangrs@chinaztt.com

Abstract

This paper investigates the ability to withstand lightning strikes by OPGW cables used in the ultra-high-voltage (UHV) power transmission lines. With the same annual average thunderstorm days, the amount of the electric charge transferred at 1000 kV is almost an order of magnitude higher than that at 500 kV. It has been found that the best way to improve OPGW performance against lightning strikes is to use an all aluminum-clad steel wire stranded structure, and to increase the diameter of the outer layer wires as much as possible. Three types of OPGW cables with different structures have been designed and fabricated for UHV transmission lines. The lightning tests with both 200 and 250 Coulombs (C) charge transfers are carried out on three types of samples. After all tests, there are almost no attenuation increases for the single-mode fiber at 1550nm wavelength. The lighting strikes to the OPGW have no visible influence on the optical performance. No wires were found to be broken after five 200C lightning shots for two types of OPGW cable. One of these two types of OPGW cables has been operated in the 1000 kV power lines successfully.

Keywords: Cables; power transmission line; aluminum clad steel wires; lightning strike; lightning test; thunderstorm day; OPGW; UHV; charge transfer

1. Introduction

In recent years, demand for electricity in China has increased rapidly. In order to satisfy this demand, the State Grid Corporation of China has decided to speed up the building of the national power network with ultra-high voltage (UHV) transmission lines, which are composed of 1000 kV AD and ±800 kV DC. The optical fiber composite overhead ground wire (OPGW) cables for 500 kV or lower have been investigated intensively**.** However, until now, little research into the application of OPGW cables in UHV power transmission lines has been conducted – even less so into the OPGW cables' ability to withstand lightening strikes.

Compared to conventional 500 kV power lines, UHV lines have higher towers and longer distances between their ground wires, so the lightning strike trip-out rate in UVH lines is much higher than that in 500 kV lines [1]. Therefore, it is necessary to set higher performance requirements for OPGW cables used in UHV lines to resist lightning strikes. Firstly, this paper describes the relationship between annual average thunderstorm days and electric charge transfers. Then, we will study ways to improve the performance of OPGW against lightning strikes. Finally, the OPGW cables used for China's first 1000 kV power transmission line over 640km in length will be designed and fabricated. The lightning simulation tests will be carried out on three types of OPGW samples.

2. Calculation of Charge Transfer

The OPGW may be damaged in areas where it is likely to have heavy lightning strikes. Compared to conventional 500 kV power lines, UHV lines have higher towers and longer distances between their ground wires, so the lightning strike trip-out rate in UHV lines is much higher than that in 500 kV lines. For example, the lightning strike trip-out rates are 0.7/100km·year in 1150 kV lines in the former Soviet Union and 0.9/100km·year in 1000 kV lines in Japan, respectively. However, this value is only 0.14/100km·year for 500 kV lines [1]. Lightning damage is strongly dependent on the charge transfer during the strike.

In regions with UHV lines, average thunderstorm days per year may be used to describe lightning strike activity. A more detailed depiction of lightning activity may be obtained from lightning ground flash density γ, which describes the number of flashes per square kilometers per day.

The ground flash density γ can be estimated by [2]:

$$\gamma=0.023\cdot T^{0.3}\ [\text{flashes/km}^2/\text{day}] \quad (1)$$

Where T is average thunderstorm days per year in five years. The statistical data shows that the annual average thunderstorm days in five years are about 50 days in areas where the UHV lines are installed.

From equation (1), we can get:

$$\gamma=0.023\cdot 50^{0.3}=0.074\ [\text{flashes/km}^2/\text{day}] \quad (2)$$

The flash collection rate *N*, in open ground (no significant trees or building nearby), is estimated by Eriksson's equation [3], as shown in equation (3):

$$N= \gamma \cdot T\cdot (28\cdot h^{0.6} + w)/10\ [\text{flashes/100 km/year}] \quad (3)$$

Where h is the height of tower or pole, w is the space width between the ground wires.

In the 1000 kV transmission lines in China, the average tower height is 74 meters, and the space width between two ground wires is about 24 meters. The flash collection rate N_2 in a 100 kilometer lines per year is given by:

$$N_2=146\ [\text{flashes/100 km/year}] \quad (4)$$

The flash collection rate N_o in the OPGW cable of 100 kilometer per year is given by:

$$N_o=N_2/2=73[\text{flashes/100 km/year}] \quad (5)$$

The charge transfer can be calculated from the probability of lightning strike. According to lightning frequency by flash counters, the probability of negative lightning strike F_- is 95%, and the positive lightning strike F_+ is approximately 5%. We are mainly concerned about the negative lightning strike on the transmission line. The probability of negative lightning strike on the unit length of transmission line such as 100km in 5 years is estimated according to the equation (6) [2]:

$$P_- = 100/(Y \cdot N_o \cdot L \cdot F_-) \qquad (6)$$

Where Y is the statistic year of ground lightning, it is usually 5 years. N_o is the flash collection rate (flashes/100 km/year), L is the length of transmission line. F_- is the probability of negative lightning strike.

The probability of negative lightning strike to the OPGW cables of 100 km in five years is given by:

$$P_- = 100/(5 \cdot 73 \cdot 100 \cdot 0.95) = 0.00288 \qquad (7)$$

The charge transfer Q_- to the OPGW cable spanning 100km in 5 years is calculated from the equation (8) [4]:

$$Q_- = 7 \cdot (P_-^{-1} - 1)^{1/1.7} = 7 \cdot (0.00288^{-1} - 1)^{1/1.7} \approx -220 \text{ Coulombs} \qquad (8)$$

This means that in five year period for a UHV transmission line section of 100km length a maximum charge transfer can reach a value of -220 Coulombs.

The tolerance of the charge transfer is ±10%.

The charge transfers of both 200C and 250C can be used as consideration of the design parameters of the OPGW cables used in the UHV transmission lines. In the lightning test for optical aerial cables along the UHV power lines these charge transfer values will be suggested.

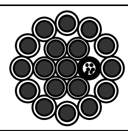
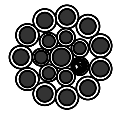
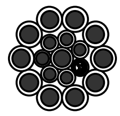
3. OPGW Cables for UHV Lines

Compared to conventional 500 kV power lines, the lightning strike trip-out rate in UVH lines is much higher than that in 500 kV lines. Therefore, it is necessary for us to set higher performance requirements for resisting lightning strikes by OPGW cables used in UHV lines.

Our investigations indicate that the aluminum clad steel wires have better performance against lightning strikes than aluminum alloy wires of the same diameters. The resistance to lightening strikes of wires with bigger diameters is better than that of smaller ones if their conductivity is the same. It has been found that the best way to improve OPGW performance against lightning strikes is to use all aluminum-clad steel wires with stranded structure, and to increase diameter of outer layer wires [5]-[6].

Three types of OPGW for China's first 1000 kV power transmission line of over 640km in length have been designed and fabricated, as shown in Table 1.

Table 1. Three types of OPGW Structure for UHV lines

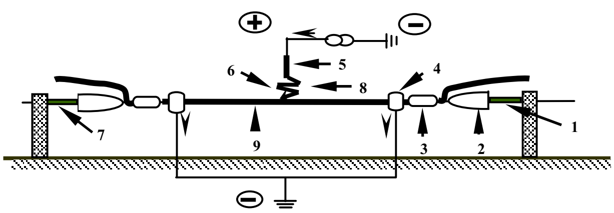
Code	OPGW-I	OPGW-II	OPGW-III
Type	OPGW-24B1 173［198；150］	OPGW-24B1 176［202；156］	OPGW-24B1 184［211；159］
Fiber No.	24 G.652D	24 G.652D	24 G.652D
Structure	1/3.5 mm (20.3AC) +5/3.5 mm (20.3AC) +12/3.5 mm (20.3AC) 1/3.4 mm (SUS)	1/4.0 mm (20.3AC) +6/3.0 mm (20.3AC) +11/3.75 mm (20.3AC) 1/3.0 mm (SUS)	1/3.9 mm (40AC) +6/2.9 mm (30AC) +10/4.1 mm (14AC) 1/2.8 mm (SUS)
Cross sectional area	173.18 mm^2	176.47 mm^2	183.60 mm^2
Diameter	17.5 mm	17.5 mm	17.9 mm
RTS	197.9 kN	201.5 kN	211.0 kN
$I^2t(kA^2s)$	150.3	156	159.4
Structure drawing			

In order to check their performance against lightning strikes, the lightning simulation tests with 200C and 250C discharge energy are carried out on three types of OPGW samples.

4. Lightning Test on the OPGW

4.1 Lightning Test arrangement

The test shall be set-up in accordance with IEC 60794-1-2 [7] and DL/T 832-2003 [8]. A typical test arrangement which can be used for the lightning test is shown in Figure 1.



1.Turnbuckle, 2.Insulator, 3.Anchoring clamps, 4.Earthing connectors, 5.Electrode, 6.Metal fuse for ignition, 7.Tension meter, 8. Gap between electrode and cable surface, 9.Test sample

Figure 1. Lightning test arrangement

The samples shall be subjected to a simulated lightning strike, which cause melting effects. The test shall be carried out with a continuing current component, which is described as “C” component in [3]. The relationships of the current, the duration and the charge transfer are shown in Table 2.

Table 2. Test parameters

	Class 0	Class 1	Class 2	Class 3
Current(A)	100	200	300	400
Duration(s)	0.5	0.5	0.5	0.5
Charge transfer(C)	50	100	150	200

The test parameters are chosen between class 0 and class 3 according to Table 2 or can be agreed upon by the purchaser and the manufacturer, depending on the construction characteristics. The applied tensile load on the OPGW sample shall be 15% to 25% of the RTS (rated tensile stress).

The initial temperature of the cable should be about 23°C ± 5°C. The test shall be repeated 5 times under the same conditions on different samples.

On completion of the test, the following criteria shall be considered.

a) A permanent increase in optical attenuation greater than 1 dB at 1550nm for single mode fibers shall constitute failure.

b) For OPGW, if any wires are found to be broken, then the residual strength of the OPGW shall be calculated for the remaining unbroken wires. If the calculated residual strength is less than 75% of the original declared RTS, then this shall constitute a failure.

Compared with the standard transmission line, the UHV transmission lines have higher voltage, longer transmission distance, larger conveying capacity, higher tower and wider area power network. It is necessary for us to set a bigger charge transfer, a higher tensile load and tighter acceptance criteria.

In the lightning test of OPGW cable used in the UHV lines, the charge transference to the cable shall increase to 200C or 250C, and the applied tensile load shall be 16% of the cable RTS [9].

On completion of the test, the following tighter acceptance criteria shall be considered.

a) A permanent increase in optical attenuation greater than 1 dB at 1550nm for single mode fibers shall constitute failure.

b) For OPGW, if any wires are found to be broken, then this shall constitute a failure.

We can see that requirements of the lightning test for the UHV lines are much higher than that of the standard test.

4.2 Lightning Test Results

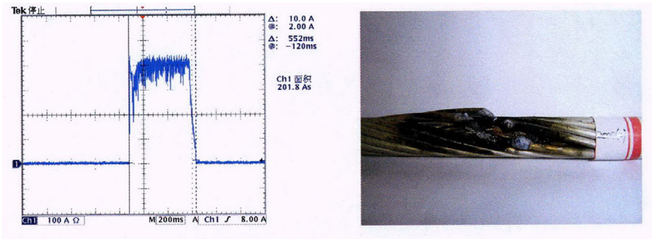
The lightning tests at both 200C and 250C are carried out on three types of OPGW samples.

The test results of OPGW-I are shown in Table 3, Figures 2 and 3.

.

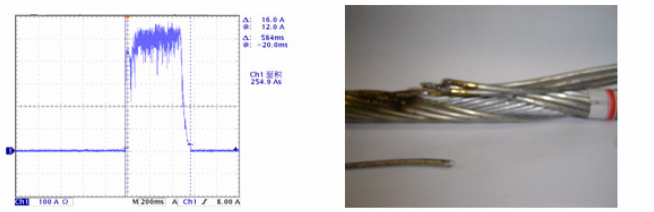
Table 3. Lightning test results of OPGW-I

Charge transfer /C	200C			250C		
Test No.	Charge transfer /C	Broken wires of out layer /wire	Attenuation increase /dB	Transfer charge /C	Broken wires of out layer /wire	Attenuation increase /dB
1st	196.3	0	0.00	254.9	3	0.00
2nd	201.8	2	0.00	254.0	1	0.00
3rd	202.2	1	0.00	254.1	2	0.00
4th	200.5	1	0.00	254.4	1	0.00
5th	202.1	1	0.00	254.0	1	0.00



(a) (b)

Figure 2. Waveform (a) and sample (b) of OPGW-I after the second 200C lightning shot (two wires were broken)



(a) (b)

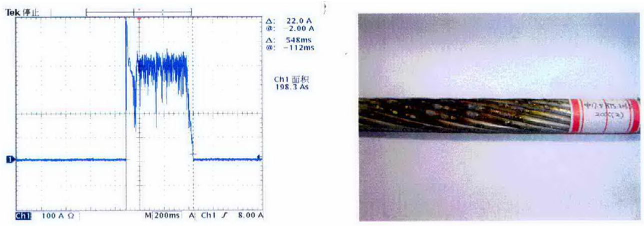
Figure 3. Waveform (a) and sample (b) of OPGW-I after the first 250C lightning shot (three wires were broken)

From Table 3, Figures 2 and 3 we can see that after the second 200C lightning shot, two wires of OPGW-I were broken. However, at 250C, three wires of OPGW-I have been broken just after the first lightning shot.

Table 4, Figure 4 and Figure 5 show the lightning test results of OPGW-II

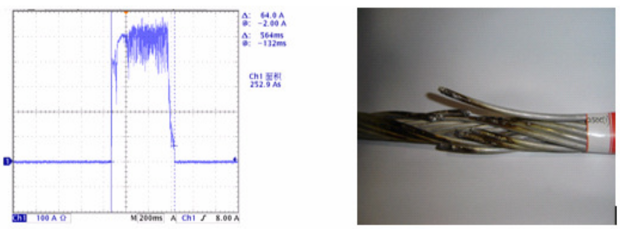
Table 4. Lightning test results of OPGW-II

Charge transfer /C	200C			250C		
Test No.	Charge transfer /C	Broken wires of out layer /wire	Attenuation increase /dB	Charge transfer /C	Broken wires of out layer /wire	Attenuation increase /dB
1st	196.1	0	0.00	252.9	4	0.00
2nd	198.3	0	0.00	252.4	0	0.00
3rd	193.7	0	0.00	254.8	0	0.00
4th	195.6	0	0.00	252.3	1	0.00
5th	197.8	0	0.00	254.8	1	0.00



(a) (b)

Figure 4. Waveform (a) and sample (b) of OPGW-II after the second 200C lightning shot (no wires were broken)



(a) (b)

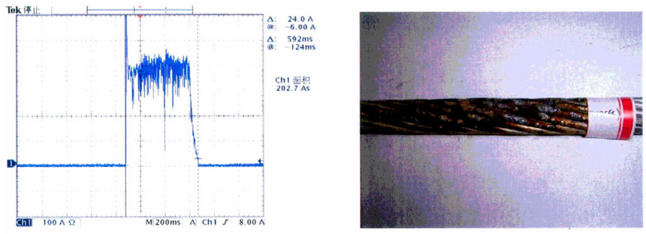
Figure 5. Waveform (a) and sample (b) of OPGW-II after the first 250C lightning shot (four wires were broken)

After five 200C lightning shots, no wires of OPGW-II were found to be broken. However, at 250C, four wires of OPGW-II have been broken just after the first lightning shot.

Table 5, Figure 6 and Figure 7 show the lightning test results of OPGW-III

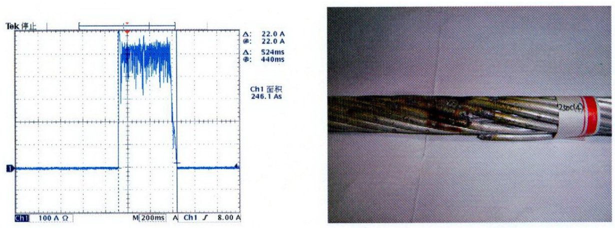
Table 5. Lightning test results of OPGW-III

Charge transfer/C	200C			250C		
Test No.	Charge transfer /C	Broken wires of out layer /wire	Attenuation increase /dB	Charge transfer /C	Broken wires of out layer /wire	Attenuation increase /dB
1st	196.8	0	0.00	246.1	0	0.00
2nd	195.5	0	0.00	246.9	0	0.00
3rd	196.1	0	0.00	242.7	0	0.00
4th	202.7	0	0.00	246.1	1	0.00
5th	194.0	0	0.00	243.0	2	0.00



(a) (b)

Figure 6. Waveform (a) and sample (b) of OPGW-III after the fourth 200C lightning shot (no wires were broken)



(a) (b)

Figure 7. Waveform (a) and sample (b) of OPGW-III after the fourth 250C lightning shot (one wire was broken)

After five 200C lightning shots, no wires of OPGW-III were found to be broken. However, at 250C, one wire of OPGW-III was broken after the fourth lightning shot.

5. Discussion and Conclusions

The lightning tests with charge transfers of both 200C and 250C are carried out on three types of OPGW samples, which were designed and fabricated for UHV lines. From the test results, we have the following conclusions:

After all tests at both 200C and 250C, there are almost no attenuation increases for the single mode fibers at 1550nm wavelength. The lighting strikes to the OPGW have no obvious influence on the optical performance.

During the tests with charge transfer of 200C, the wires of OPGW-I were broken many times. However, no wires were found to be broken for both OPGW-II and OPGW-III. This means that both OPGW-II and OPGW-III can be used in the UHV transmission lines for the areas where a maximum charge transfer of 200C may occur. Compared with OPGW-III, the OPGW-II has smaller diameter, lighter weight, and better structure. The OPGW-II cables (OPGW-24B1-176 [202; 156]) have already been used in almost all the UHV transmission line projects in China.

All three types of OPGW were found to have broken wires during the lightning tests at charge transfer of 250C. This indicates that it is very difficult to satisfy the requirement for a 250C charge transfer for our current OPGW structure designs with outer diameter range from Φ17.5 to 17.9mm, the outer layer single wire's diameter range from Φ3.5 to 4.1mm and AS wire's conductivity of 14%IACS.

Compared with OPGW-II, the diameters and conductivities of outer layer single wires in OPGW-III are increased from 3.75 to 4.1mm and decreased from 20% to 14% IACS, respectively. However, we cannot see a significant improvement of performance against lightning for OPGW-III. It seems that for the same OPGW diameter, we cannot improve the lightning performance visibly by only increasing the outer layer wire's diameter and decreasing their conductivity. The damage to the OPGW-II and -III for charge transfers at 250C seems to be more strongly dependent on the cable diameter than on the wire diameter.

Lighting resistance of OPGW not only depends on the material, the conductivity and the diameter of out layer wires, but also on the OPGW diameter, the applied tension load, stranding technique, OPGW structure composition, tower and pole height, and annual thunderstorm day, etc.

Lightning is a major cause of faults on UHV transmission lines. These faults may cause momentary or permanent interruptions on the transmission lines. It is necessary to set a bigger charge transfer (200C by using 400A during 0.50 seconds), a higher applied tension load (16%RTS) and tighter acceptance criteria, that is, no wires should be broken after five 200C lightning shots, for OPGW cables used in UHV lines. The test results of OPGW-II and OPGW-III confirm that these requirements are realistic and reasonable. The lightning test results in this paper are helpful to the coming international standard for the lightning test on OPGW cables for the UHV transmission lines.

Since January 16, 2009, the OPGW-II cables have been operated in China's first 1000 kV power transmission line of over 640km successfully.

6. Acknowledgments

The authors wish to thank the staff of Zhongtian Technology Group Co., Ltd. for their support. Thanks also to the staff of Electric Power Special Optical Cable and Optical Communication System Laboratory of China Electric Power Research Institute (CEPRI) for conducting the lightning tests.

Special thanks go to the IWCS staff for making this template available for this year's publication.

7. References

[1] Z.Y. Liu, "Ultra-High Voltage Power Network," *China Economy Press*, Beijing, (2005).

[2] R.B. Anderson, el al., "Lightning and Thunderstorm Parameters," *IEE Conference Publication, 236, Lightning and Power Systems*, London, 57–61 (June 1984).

[3] Eriksson, "The Incidence of Lightning Strikes to Power Lines," *IEEE Transactions on Power Delivery,* vol. PWRD-2, no. 2, 859–870 (July 1987).

[4] S.H. Xie, et al., "The Digital Analysis on OPGW Characteristics of Lightning Strike Resistance," Telecom. for Electric Power System, 26(8), 5-9 (2005)

[5] S.H. Xie and H.Q. Li, "Research of design and choice of OPGW in UHV transmission line," *Beijing International Conference of UHV Power Transmission Lines*, 549-554 (2006).

[6] L.R.S. Casals, et al. "Does Lightning Damage Depend on OPGW Technology?" *The 53rd International Wire & Cable Symposium*, 554-559 (2004).

[7] IEC 60794-1-2, Optical Fiber Cables-Part 1-2: "Generic Specification-Basic Optical Cable Test Procedures," (2003).

[8] DL/T 832-2003, "Optical Fiber Composite Overhead Ground Wire (OPGW)," (2003).

[9] L.Y. Qi, et al., "The Study of Lightning Test Standard of OPGW in Ultra High Voltage Grid," *Electric Power Construction*, Beijing, 30(7), 13-16 (July 2009)

Authors

Xie Shu-Hong
26/F, Baoding Building
No. 550, Xujiahui Road
Shanghai 200025
P.R. China

Mr. Xie Shu-Hong was born in 1970, in Sichuan Province, China. He graduated from the Metallic Material Department of the North-East University in 1994, and received a MBA degree in Finance and Economics from Shanghai University in 2003. He is the Chief Engineer of Zhongtian Technology Group Co., Ltd. He is a committee member of the National Bare Wire Standardization Technology Committee (SAC/TC 422), and was awarded the title of the seventh professional and technical top-notch Talent in Nantong City, Jiangsu Province. He has participated in several national and province level keynote projects like the Three Gorges Project, Ultra-High Voltage Project and Jiangsu Province Scientific Research Achievement Transformation Special Funds, etc. He was awarded the first prize of Mechanical Industrial Technology Advancement, second prize of Shanghai Technical Advancement. He holds ten patents. He has published more than thirty papers in national key journals about the overhead transmission line and OPGW/OPPC.

Yang Ri-Sheng
26/F, Baoding Building
No. 550, Xujiahui Road
Shanghai 200025
P.R. China

Dr. Yang Ri-Sheng graduated from the Physics Department of Tsinghua University, Beijing, in 1968. He received the M. Sc. degree from the Chengdu Institute of Radio Engineering, Chengdu, in 1981 and Ph.D. degree (Dr.-Ing.) from the Technical University of Braunschweig, Germany, in 1988, both in electrical engineering. Since 1984 he has been involved in various projects associated with optical fiber development and production. He is now a Representative of the President of Zhongtian Technology Group Co. Ltd. He has published over 40 papers in the field of fiber optics and holds six patents. Dr. Yang is a member of the SPIE.