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Melting and Breaking of 80 mm^2 OPGWs by DC Arc Discharge Simulating Lightning Strike

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***Abstract*— Metal strands of OPGWs (composite fiber-optic ground wires) are sometimes melted and broken by high-energy lightning strikes. DC arc tests simulating lightning strikes have thus been performed to obtain their melting and breaking characteristics. In this paper, to clarify the characteristics of thin OPGWs, experiments and calculations on the melting and breaking of 80 mm^2 OPGWs were performed for different strand types (23AC, 30AC). The calculated dependence of the flowing electric charge required for three strands to break on the strand type shows good agreement with the experimental values obtained in DC arc tests simulating a lightning strike.**

***Keywords*— arc discharges; ground wires; lightning; optical fiber cables; power transmission lines; strand type**

I. INTRODUCTION

Metal strands of OPGWs (composite fiber-optic ground wires) are sometimes melted and broken when struck by high-energy lightning, even if the strands are aluminum-clad steel. To clarify the melting and breaking characteristics of conventional and newly-developed OPGW strands, DC arc tests have been performed and test conditions that appropriately simulate high-energy lightning strikes have also been investigated [1-5]. The authors have developed a method of calculating the melting characteristics of OPGW strands due to DC arcs [6].

It is important to clarify the melting and breaking characteristics of OPGW strands with a small cross section (e.g., 60 – 80 mm^2) as thin OPGWs have been melted and broken by lightning strikes in actual transmission lines [3][7]. There are different types of OPGW strands, such as 23AC, 30AC and 40AC, where AC denotes aluminum-clad steel, while "23", "30" and "40" indicate that the electric conductivity of the AC strand is 23%, 30% and 40% of that of a copper strand with an equivalent cross section, respectively.

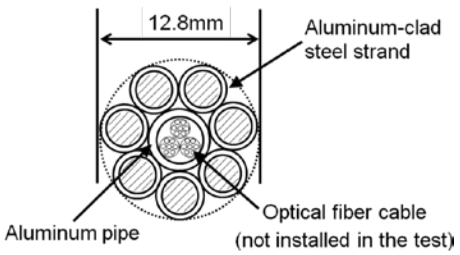


Figure 1. Structure of OPGW used in the tests.
(80 mm^2, 23AC 7/3.9)

In this paper, the melting and breaking characteristics of 80 mm^2 OPGWs, in which the strand type is 23AC or 30AC, were obtained by performing DC arc tests and calculations.

II. DC ARC TESTS

A. OPGW Specifications

Fig. 1 shows the structure of the 80 mm^2 OPGWs used in the tests. Optical fiber cables were not installed in the OPGWs in the tests. The strand type was 23AC. In [5], tests were performed on 80 mm^2 OPGWs, in which the strand type was 30AC. In this paper, the dependence of the melting and breaking characteristics of 80 mm^2 OPGWs on the strand type (23AC, 30AC) were investigated. Table I summarizes the specifications of the two types of OPGW focused on in this paper. The OPGWs in which the strands were 23AC and 30AC are denoted as OP23 and OP30, respectively. The specifications of the two OPGWs were approximately the same except for the type of strand.

TABLE I. SPECIFICATIONS OF TWO TYPES OF 80 MM^2 OPGW

Denotation in this paper		OP23	OP30
OPGWs	Cross-sectional area (mm^2)	83.65	79.38
	Overall diameter (mm)	12.8	12.6
Strands	Type	23AC	30AC
	diameter (mm)	3.9	3.8
	Number	7	7

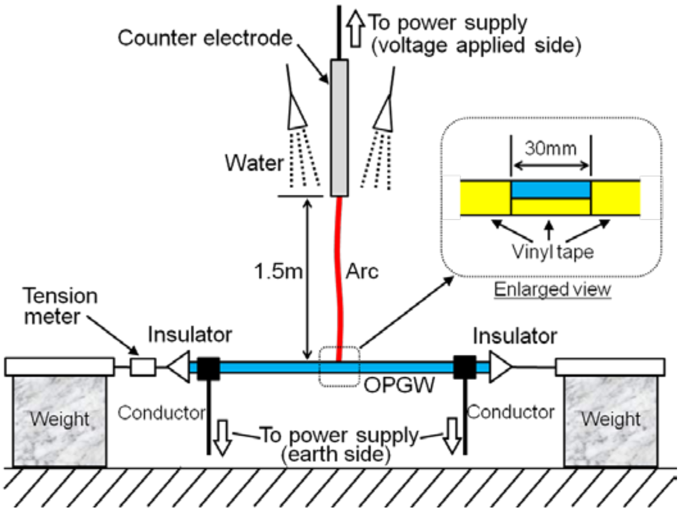


Figure 2. Setup used for DC arc tests.

TABLE II. TEST CONDITIONS

Items	Conditions
OPGW tested	OP23 (see Fig.1 and Table I)
Test voltage	DC 10 kV
Peak value of test current	DC 24 kA
Arcing duration	20 – 30 ms
Flowing electric charge	400 – 600 C
Polarity of arc	Negative
Gap length	1.5 m
Counter electrode	Iron rod of 20 mm diameter
Arc ignition method	By fusing of a copper wire of 0.2 mm diameter
Water spray	3.8 mm/min
Initial tension of OPGW	9.7 kN

B. Test Methods and Conditions

Fig. 2 shows the setup used for DC arc tests which were carried out in the air. An OPGW with a length of 5 m was stretched at both ends with a tensile force of 9.7 kN, almost equivalent to that applied when stringing in actual transmission lines. A thin copper wire with a diameter of 0.2 mm was stretched between the OPGW and a counter electrode so that current flowed to vaporize the copper wire and generate an arc. The counter electrode of iron bar with a diameter of 20 mm was set above the OPGW with a gap length of 1.5 m so that an arc jet spouting from the counter electrode had little effect on the behavior of an arc near the OPGW. However, the arc root on an OPGW tends to be too mobile to melt the strands owing to the electromagnetic force induced by the current flowing through it. Accordingly, conductors were connected to both ends of the OPGW to symmetrically divert the arc current to the earth side so that the arc root could not easily move. Furthermore, to prevent the arc from moving by forming a new arc root, whereby the arc column would be brought into contact with the OPGW, vinyl tape as insulation was wound onto both sides and the lower half of the arc-producing (exposed) part of length 30 mm as shown in the enlarged view of Fig. 2. It is likely to be raining when an OPGW is struck by lightning, and the number of arc-melted strands has been found to be greater when water is present than under dry conditions [8]. Therefore, a spray of tap water (3.8 mm/min) was used to simulate rainfall.

The test current was supplied by full-wave rectifying 3-phase AC using silicon diodes. The AC was generated using a short-circuit generator (15 kV, 2500 MVA) and a transformer. The DC output can be changed between 120 kV / 10 kA and 16 kV / 60 kA by changing the AC voltage and the combination of diodes. The arc current in DC arc tests, meanwhile, exhibits a waveform in which a ripple component is superimposed on a constant value because the arc current is obtained by full-wave rectification. The peak value of the test current was approximately 24 kA, and the time-averaged value estimated from the arcing duration and the flowing electric charge was 19.4 kA. The polarity of the current was negative, i.e., the polarity of the OPGW was positive. Table II summarizes the test conditions. These conditions were the same as those in [5].

C. Test Results

Fig. 3 shows the dependence of the number of strands breaking on the flowing electric charge. The filled circles represent the test results for OP23 obtained in this study. To investigate the effect of the strand type, the test results for OP30 [5] were added as open circles in Fig. 3. In the case of OP23, the flowing electric charge Q required for three strands to break (Q_{B3}) was 583 C. On the other hand, in the case of OP30, Q_{B3} was 467 C. Fig. 4 shows photographs of OPGW before and after tests on OP23. As shown in Fig. 4(b), no strand was broken when Q was 491 C, which was higher than 467 C (Q_{B3} for OP30). These results show that the strands of

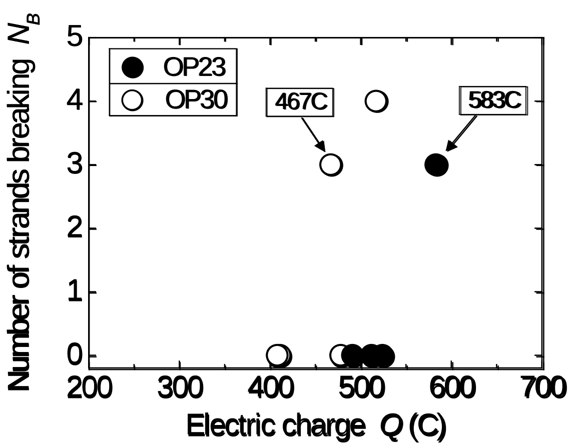
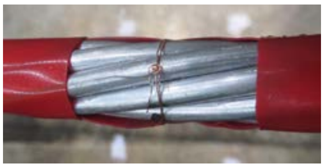


Figure 3. Dependence of the number of strands breaking on the flowing electric charge.



(a) Before test

(b) After test

(Flowing electric charge Q: 491 C, Number of strands breaking N_B: 0)

(c) After test

(Flowing electric charge Q: 583 C, Number of strands breaking N_B: 3)

Figure 4. Photographs before and after tests on OP23.

OP23 are less broken than those of OP30. It is considered that these results are due to the different ratios of steel to aluminum in the strands. In the following chapter III, analytical investigations will be performed.

III. CALCULATIONS

A. *Calculation Methods and Conditions*

Calculations were carried out using the method developed in [6]. This section summarizes the calculation methods and conditions. Fig. 5 shows the flowchart used to calculate the melting characteristics of OPGWs due to DC arc. By using the arc conditions (e.g., current, duration, polarity, gap length) and OPGW conditions (e.g., the size, type and number of strands), the quantity of heat and its area transferred to the OPGWs from the arc are calculated, and the amount of melting of the OPGWs due to the arc is calculated.

In this paper, the strands of the OPGWs were assumed to be broken when half of a cross-sectional region of the strands was melted completely, even if its length along the OPGWs axis was small, because the melting part of the layer can be blown off by the tensile force applied to the strands and by the arc jets that spout from an arc root on the strands. Although the arc currents in the tests have a ripple component as described in chapter II, the arc current was assumed to be constant to

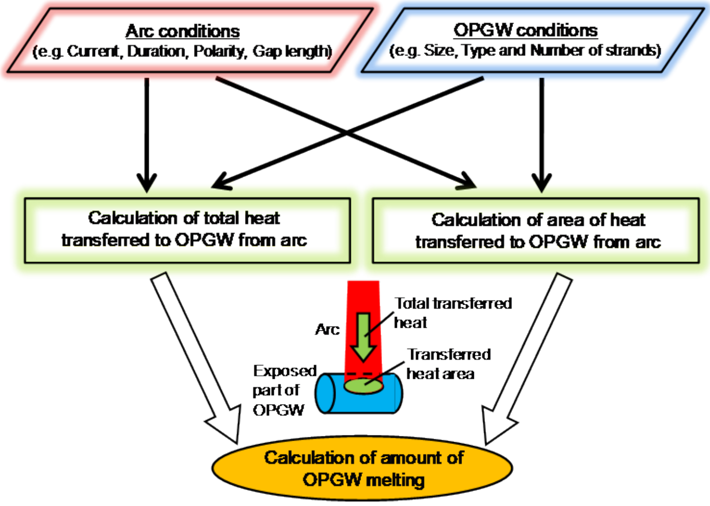


Figure 5. Flowchart for calculations [6].

simplify the calculations. Therefore, the arc current was set to 19.4 kA, which was the time-averaged value in the tests. The OPGWs used in the calculation are shown in Table I. Although the material of the central part of the aluminum-clad steel strand was steel, the material in the calculation was iron since it is the main component of steel and its thermal properties are easily obtained from references.

1) *Heat Transferred to OPGWs from the Arc and Its Area*

The total heat P_{total} transferred to the OPGWs from the arc is expressed by

$$P_{total} = P_{ele} + P_{conv}\ , \tag{1}$$

where P_{ele} is the heat due to electrons emitted from or absorbed into the OPGWs, P_{conv} is the convective heat transfer due to the arc jet spouting from the counter electrode.

The transferred heat area A_h for P_{ele} and P_{conv} was estimated as the area that came in contact with the arc using the following equation:

$$A_h = \mathrm{MIN}\ (I_{DC} / J_{DC}\ , A_{ex})\ , \tag{2}$$

where MIN is a function giving the smallest value in the brackets, J_{DC} is the current density on the OPGWs, A_{ex} is the exposed area of the OPGWs mentioned in chapter II. J_{DC} for aluminum and iron are 60.0 and 33.8 A/mm^2, respectively, and independent of its polarity, which were estimated using the diameter of the arc root on the electrode measured in [9].

2) *Simplification of the Cross-sectional Structure of OPGW Strands*

In the case of an actual strand, as shown in Figs. 1 and 6 (a), the central part is iron (the main component of steel), which is covered with aluminum. In the calculation, the cross-sectional structure of the strand was simplified, as shown in Fig. 6 (b), to an aluminum layer on an iron layer. The outer diameter D and the cross-sectional areas of the aluminum layer and iron layer in Fig. 6 (b) are the same as those in Fig. 6 (a). It was assumed that the heat transferred from the arc was injected into the aluminum layer, which was subsequently melted and removed, whereupon the heat from the arc was injected into the iron layer.

B. Calculation Results

Fig. 7 shows the experimental and calculation results of the flowing electric charge Q required for three strands to break (Q_{B3}). Although the calculated Q_{B3} was slightly different from the experimental value, the calculated Q_{B3} for OP23 was approximately 20% higher than that for OP30, which was similar to the experimental results. Fig. 8 shows the individual values required for the iron and aluminum parts of three strands to break. This figure indicates that most of Q_{B3} was required for to break the iron part of the strands, and therefore the values of Q_{B3} increased with the ratio of iron area in the strands.

IV. Conclusions

In this paper, we describe experimental and calculation results for the melting and breaking characteristics of 80 mm^2 OPGWs denoted as OP23 and OP30, in which the strands were 23AC and 30AC, respectively. In DC arc tests simulating a lightning strike, the peak value of arc current was 24 kA and the duration was 20 – 30 ms. As a result, the flowing electric charge Q_{B3} required for three strands to break was 583 C in the case of OP23 and 467 C in the case of OP30. In the calculations, the heat transferred to OPGWs from the arc and its area were calculated, and the cross-sectional structure of OPGW was simplified, and the amount of the OPGWs melted by the arc was calculated. It was found that Q_{B3} for OP23 was higher than that for OP30, which showed a similar tendency to the experimental results. Furthermore, the calculations clarified quantitatively that that most of Q_{B3} was required for to break the iron part of the strands, and therefore the values of Q_{B3} increased with the ratio of iron area in the strands.

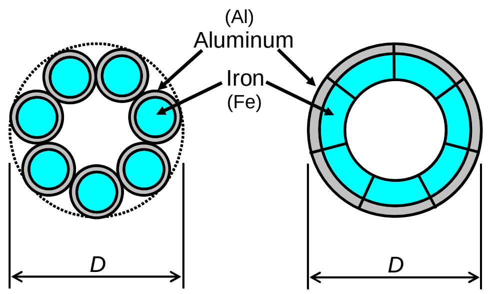


Figure 6. Simplification of cross-sectional structure of OPGW strands.

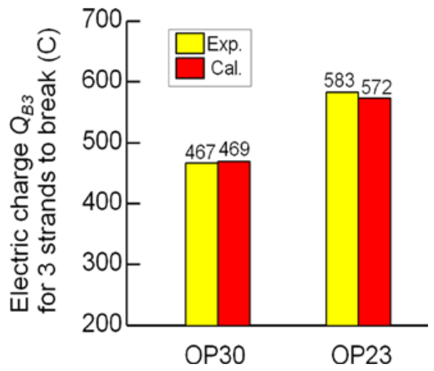


Figure 7. Flowing electric charge required for three strands to break.

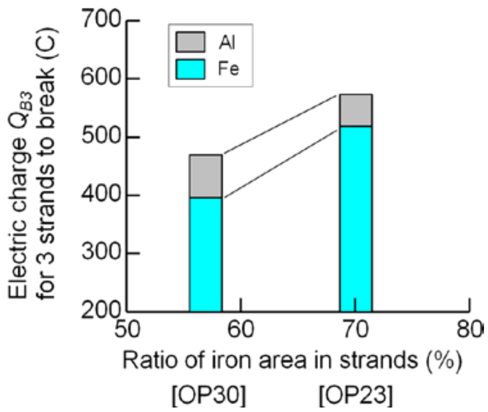


Figure 8. Breakdown of flowing electric charge required for three strands to break.

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