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PERFORMANCE TESTING OF AN OPTICAL GROUND WIRE COMPOSITE

PREIZKUŠANJE ZMOGLJIVOSTI KOMPOZITNEGA PODZEMNEGA OPTIČNEGA KABLA

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An optical ground wire (OPGW) composed of different materials was presented in detail before delivering the product to the communication and electrical-energy markets. The performance level of its composite structure differs from the performance of the original material. Therefore, to measure whether the OPGW had reached the required quality, it was exposed to several tests simulating the real working conditions to detect the behavior of the composite structure. These included the stress-strain/fibre-strain and tensile tests, aeolian vibration, galloping, creep, short circuit, temperature cycling and lightning tests. Thus, the technical story of OPGW designed to serve the environment was explained in details and the test results were interpreted. The required material improvements to the master alloys made due to the failures of the composite conductor (OPGW) under heavy test conditions were also explained so that approval could be obtained.

Keywords: OPGW, lightning strike, creep, aeolian, composite structure, fiber failure

Optični podzemni kabel (OPGW), sestavljen iz različnih materialov, je bil predstavljen do podrobnosti, preden je bil proizvod poslan na trg komunikacij in energije. Zmogljivost kompozitne strukture se razlikuje od osnovnega materiala. Da bi preizkusili zmogljivost kompozitnega materiala in izmerili, ali OPGW doseže sprejemljivo kvaliteto, je bil kabel izpostavljen različnim preizkusom, ki so simulirali realne razmere. To so natezna napetost – raztezek vlakna, eolianske vibracije, galopiranje, lezenje, kratek stik, spreminjanje temperature in preizkus z bliskanjem. Podrobno je predstavljena celotna zgodba razvoja OPGW in vpliva okolja, razloženi pa so tudi rezultati preizkusov. Razložene so izboljšave osnovnih zlitin, potrebne zaradi napak v kompozitnem prevodniku (OPGW), da bi se doseglo soglasje za uporabo.

Ključne besede: OPGW, udar strele, lezenje, eolianske vibracije, kompozitna struktura, porušitev vlaken

1 INTRODUCTION

The OPGW cable today forms an integral part of any power company's transmission network and is utilized for the mission-critical circuit control ensuring the optimum operational efficiency and protection. The OPGW cable is defined as a composite cable which serves as a conventional overhead ground wire with the added benefit of providing the optical-fiber communications. An optical communication carrier can be completely separated from the power-transmission line to form an additional revenue stream, whilst the cable serves the traditional purpose of conducting fault currents to the ground and protecting the power conductors against lightning strikes. With proper design considerations, the OPGW cable has proven its reliability in protecting the optical fibers from electrical, mechanical, and environmental stresses[1]. With an increasing demand for more information transmission, such as the widespread use of the internet in the recent years, a much higher fiber-count OPGW is needed. The previous study shows the structure and the main test result of a stainless-steel tube with optical fibers in the stainless-steel tubes used instead of the conventional aluminum pipes in an extra-high multi-core OPGW[2]. Thus, a technical story of OPGW designed for a long-term reliability in the real working conditions was explained and the test results interpreted. Remedies for the failures of the composite conductor (OPGW) under heavy test conditions required material improvements that were also explained to reach approval in field conditions.

The composite conductor used in the experiments is composed of one stainless-steel tube with fibers, six galvanized steel wires and 12 AA–6101 aluminum-alloy wires at the outer layer (**Figure 1**)[3].

2 CHARACTERISTICS OF OPGW IN A STAINLESS-STEEL TUBE

2.1 Stress-Strain/Fiber-Strain and Tensile Test

The objective of this test is to monitor the optical characteristics and verify the mechanical characteristics of OPGW under the test up to the breaking load. An OPGW sample was installed in a hydraulically activated, horizontal test machine[4–7]. A displacement transducer was fixed to the conductor to measure the cable elongation over the 8 m gage length. The gage length for attenuation measurements was taken for the length under tension. The conductor elongation, the output signal from the optical power meters and the conductor tension as measured by a load cell were monitored using a digital-data logging system. After completing the tests, if

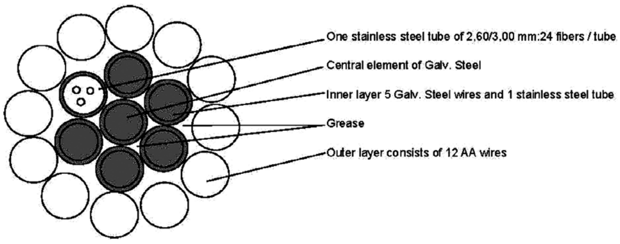

Figure 1: Design properties of OPGW
Slika 1: Sestav OPGW

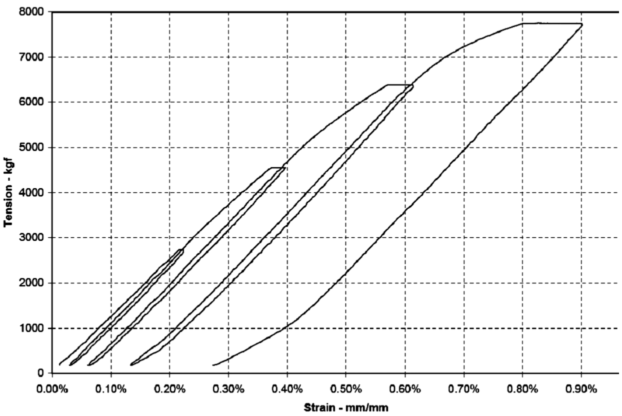

Figure 2: Load plotted against conductor strain
Slika 2: Obremenitev v odvisnosti od raztezka prevodnika

the fiber elongation at 0.45 % of conductor elongation is greater than 0.01 % and if at 72 % of RTS the temporary increase in the fiber attenuation is greater than 1 dB/km, as compared to the value measured before the test, and there is a measurable permanent increase in the fiber attenuation that is greater than 0.02 dB/km, the test shall be considered unsuccessful. Some results of the completed test are presented in **Figures 2** and **3**. **Figure 2** shows the data at the load (conductor tension) plotted against the conductor strain. On the other hand, **Figure 3** shows optical attenuation and the load/conductor tension plotted against time.

2.2 Creep Test

The objective of the creep test is to measure the room-temperature, long–term tensile-creep properties of the conductor. The data from this test are used to assist in the calculation of the sags and tensions. The test was performed according to IEC 61395. The length of the sample between the dead-end clamps was 15 m. The test was carried out in a temperature-controlled laboratory at 20 °C ± 2 °C. In line with the Aluminum Association's method, the long-term tensile creep of the cable under a constant tension is taken to be the permanent strain occurring between 1 h and the specified test time.

The last reading during this test was taken at 1000 h. A log-log plot of strain versus the elapsed time for LVDT (the linear variable differential transformer) is shown in **Figure 4**. On the completion of the test, the best-fit straight line was fitted to the LVDT data and extrapolated to 10 years (87000 h).

The equation of the line:
$Strain = A^*(Hours)^B \rightarrow y = 8.5073E - 0.5\ X^{1.3965E-01}$

2.3 Temperature-Cycle Test

The objective of this test was to verify the good performance of the fiber when the cable is subjected to extreme thermal cycles. The test was performed in accordance with EIA/TIA-455-3A. A reel with approximately 761 m of an OPGW cable was placed in a 5 m × 6 m × 4 m environmental chamber. Three thermocouples were placed in the environmental chamber to measure the temperature. Two were placed on separate 25 cm cable samples and located on either side of the cable reel. The third was located under the first layer of the cable reel. All twenty-four fibers were spliced to form one continuous loop. The total test-fiber length was approximately 18.3 km. The cable was subjected to two thermal cycles. Each thermal cycle started with the chamber temperature of 23 °C, which was then lowered to –40 °C and held at this level for a minimum of 16 h. The chamber temperature was then increased to 65 °C and held at this level for a minimum of 16 h. To com-

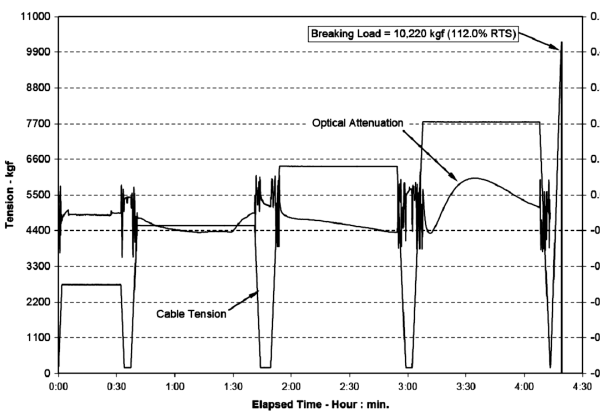

Figure 3: Optical attenuation plotted against time
Slika 3: Prikaz optičnega dušenja v odvisnosti od časa

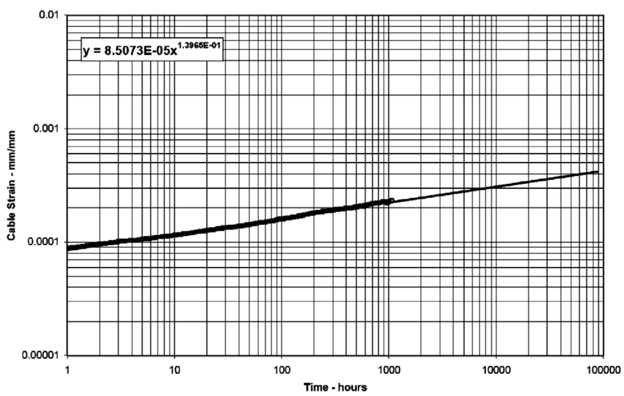

Figure 4: Cable strain versus time
Slika 4: Raztezanje kabla v odvisnosti od časa

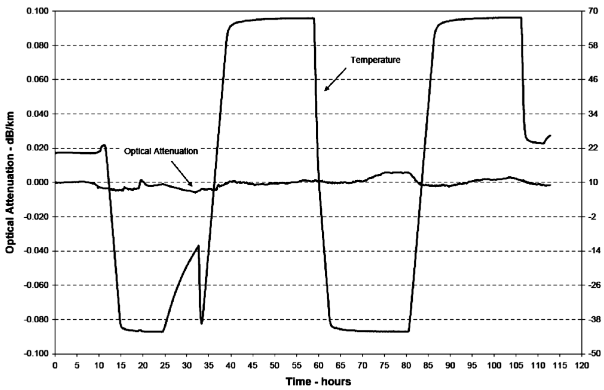

Figure 5: Records of the heat-cycle test of OPGW
Slika 5: Zapis iz preizkusa cikličnega segrevanja OPGW

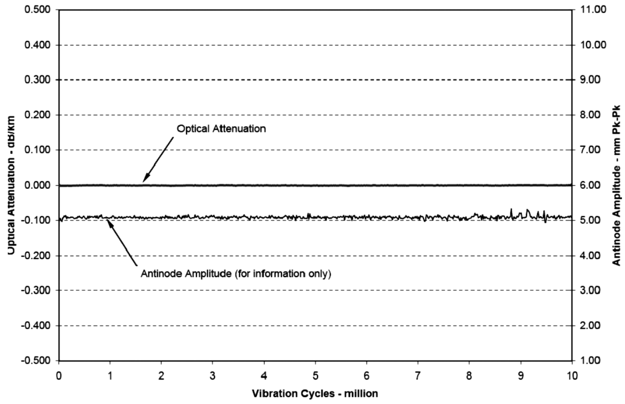

Figure 6: Aeolian-vibration test results
Slika 6: Rezultati preizkusa eolijskih vibracij

plete the cycle, the chamber temperature was returned to 23 °C. All the temperature transitions were conducted at a rate of less than 20 °C/h. The chamber temperature was based on one of the thermocouples on the 25 cm cable samples, located on one side of the cable reel. The cable-reel temperature and the optical data were recorded every five minutes throughout the test.

The optical attenuation and the chamber temperature versus time are shown in **Figure 5**. The variation in the optical attenuation due to the temperature was no greater than 0.006 dB/km. The maximum allowable change in the attenuation, between the extreme temperature limits, is 0.05 dB/km.

2.4 Aeolian-Vibration Test

The objective of the aeolian-vibration test is to assess the fatigue performance of OPGW and the optical characteristics of the fibers under typical aeolian vibrations. The tests were performed according to IEC 60794-1-2, Method E19 and IEC 60794-4-1. Thus, OPGW was pre-tensioned to 1795 N and an initial optical measurement was taken. OPGW was then tensioned to 17 903 N or 20 % of the RTS cable and the exit angles of the cable from the suspension clamp were measured. The initial target vibration frequency was 54.4 s^{-1}, which is the frequency produced by a 4.5 m/s wind (i.e., frequency = 830 ÷ diameter of OPGW in mm). The actual vibration frequency was the system resonance that was nearest to the target frequency and provided a better system stability, while the target free-loop peak-to-peak antinode amplitude was 5.08 mm or one third of the OPGW diameter. This amplitude was maintained at this level in the first free loop from the suspension assembly towards the shaker. The amplitudes in the passive span and the section between the shaker and the dead end in the active span were maintained at the levels no greater than one third of the cable diameter. OPGW was subjected to 10-million vibration cycles. Optical measurements were taken for 2 h after the completion of the vibration cycles.

All twenty-four fibers were spliced to make the total fiber length of 720 m (24 × 30 m). The test sample was terminated beyond both dead ends so that the optical fibers could not move relative to OPGW.

Dissection: After the completion of 10 million cycles, the cable was dissected down to the stainless-steel tube and visually examined. Active dead end: There were no visible signs of breaks, cracks, failure or discoloration of any of the dissected components of OPGW (**Figure 6**). Passive dead end: There were no visible signs of breaks, cracks, failure or discoloration of any of the dissected components of OPGW. Suspension: There were no visible signs of breaks, cracks, failure or discoloration of any of the dissected components of OPGW.

2.5 Galloping Test

The objective of the galloping test is to assess the fatigue performance of the fiber optical ground wire and the optical characteristics of the fibers under typical galloping conditions. The test was performed according to IEC 60794-4-1. For that aim, an initial optical measurement was taken one hour prior to the test. The difference between the reference and test signals for the initial measurement provided an initial base reading. The change in this difference during the test indicated the change in the attenuation of the test fiber. The cable was subjected to 100 000 galloping cycles in the single-loop mode. The free-loop peak-to-peak antinode amplitude was maintained at the minimum of about 0.8 m or 1/25th of the distance from the dead end to the suspension-clamp length (i.e., 20 m). Optical measurements were taken for two hours after the completion of the galloping test. The galloping frequency at the start and during the test was 1 s^{-1} without any variations. The free-loop antinode amplitude in the active (driven) span was maintained at approximately 0.9 m. The free-loop antinode amplitude in the passive span varied between 0.3 m to 0.4 m during the test. The tension in the cable fluctuated between 529 N to 1432 N during the galloping. After the completion of 100 000 cycles, the cable was dissected

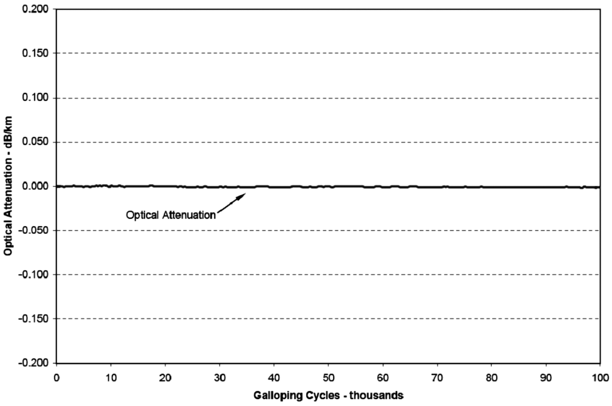

Figure 7: Galloping-test records of OPGW and attenuation of fibers
Slika 7: Zapis preizkusa galopiranja OPGW in optično slabljenje vlaken

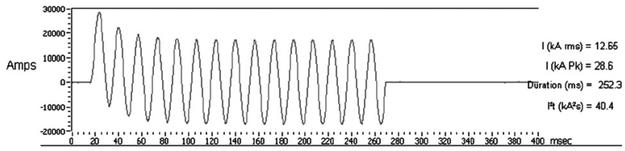

Figure 8: Applied short-circuit arc current and its time
Slika 8: Uporabljeni tok kratkega stika in njegovo trajanje

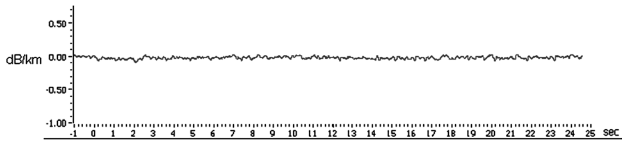

Figure 9: Attenuation range for OPGW when a lightning strike is applied
Slika 9: Področje optičnega slabljenja vlaken OPGW pri uporabi udarca strele

down to the stainless-steel tube and visually examined. Active dead end: There were no visible signs of breaks, cracks, failure or discoloration of any of the dissected components of OPGW. Passive dead end: There were no visible signs of breaks, cracks, failure or discoloration of any of the dissected components of OPGW (**Figure 7**). Suspension: There were no visible signs of breaks, cracks, failure or discoloration of any of the dissected components of OPGW.

2.6 Short-Circuit Test

The objective of the short-circuit test is to verify if OPGW can withstand repeated short-circuit applications without exceeding optical, physical or thermal requirements. The test was performed in accordance with the TEIAS Specification and IEC 60794-1-2, Method H1.

The cable was first subjected to two low-level calibration shots and then ten "official" shots. The purpose of the calibration shots was to ensure that the current level was correct. For the "official" shots, the target values for the electrical parameters were: the parameter target energy value of 109.5, the minimum kA^2s^{-1} fault current of 14.8 kA, the duration of 0.5 s, the maximum possible asymmetric waveform to be symmetrical after the 3rd cycle for each shot, the fault current and the duration may vary slightly from the target values. The objective was to achieve the minimum energy level for each shot. To ensure that optical signals were stable, the power meters were powered on and operating for at least one hour before the first shot. The optical measurement was normalized to zero before the first official shot. The cables were visually inspected for birdcaging or other damage during the test. The optical and temperature data were being acquired for one hour after the tenth shot. The cable was maintained at the temperature of 40 °C during this period.

As specified by IEC 60794-1-2, Method H1, the acceptance criteria of the product are summarized below:

a) The temperature immediately after the current pulse shall be less than 180 °C inside the optical unit. The temperature inside the optical unit is measured by thermocouple.
b) The attenuation increase during the tests shall be less than 1.0 dB/km. There shall be no change in the attenuation after the cable has cooled down to 40 °C.
c) There shall be no irreversible birdcaging. The cable and hardware shall be dissected after the test and visually examined for damage at each dead-end assembly and at the midpoint of the span. Each separable component of the cable shall be inspected. There shall be no signs of birdcaging, excessive wear, discoloration, deformation or other signs of a breakdown (**Figures 8** and **9**).

2.7 Lightning Tests

The essential function of OPGW in transmission lines is to guard the aerial conductor from the lightning strikes and its secondary job is to transmit the signals of data and communications. The excessive lightning energy generally flows through the outer layer of the OPGW conductor. However, when this energy jumps from the clouds to an OPGW conductor, a small region on the outer layer is liable to overheating. Therefore, the conductivity of the material used in an OPGW conductor, including both electrical and heat transfer, should be as high as possible. If not, regional melting occurs as seen in **Figures 10 a, b** and finally the wires are broken. These **Figures 10 a, b** refer to the first trial of the lightning test. In this test, 2 × 10 m OPGW samples, connected in parallel to measure the attenuation of the fibers and the effects of the overcurrent, failed due to a lightning strike.

The test was realized under an amplitude of 200 A, with a charge of 100 C and within the time of 500 ms. The main acceptance restriction is to keep the resistance increase below a 20 % change. This corresponds to three wires breaking at the outer layer. However, at first the trial 9–10 wires were broken.

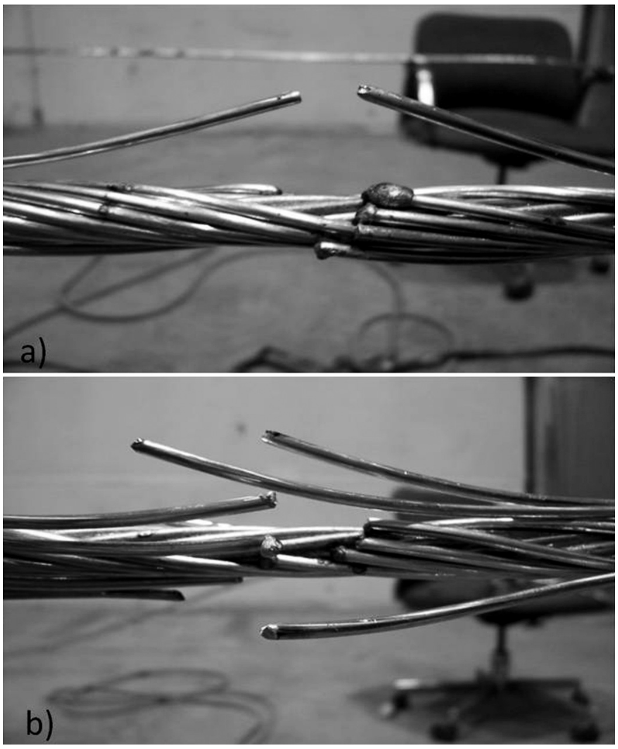

Figure 10: a, b) Spot melting of AA-6101 aluminum-alloy wires due to an application of lightning strike

Slika 10: a, b) Točkasto taljenje aluminijeve žice AA-6101 zaradi udarca strele

Therefore, the AA–6101 aluminum alloy was modified with AlB_2 (**Figure 11**) at the casting stage and then the conductivity of the wires increased from 52.5 % IACS to 57–58 % IACS.[3] The second test was thus performed with modified wires and stranded with a short lay length to obviate the arc between the wires. The second trial met all the requirements perfectly (**Figures 12 a, b**).

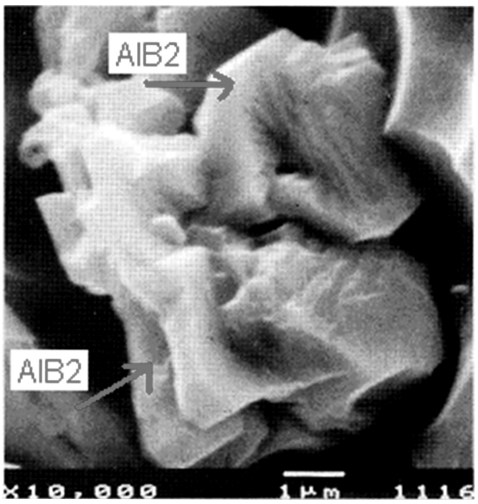

Figure 11: AlB_2 master alloy used to increase the conductivity of the AA–6101 aluminum alloy by inoculating it in the casting stage in a foundry tandish[3]

Slika 11: Osnovna zlitina AlB_2, uporabljena za povečanje prevodnosti aluminijeve zlitine AA-6101 z inokulacijo med ulivanjem v livarski vmesni posodi[3]

3 RESULTS

Before a new OPGW product, prepared with a combination of different materials, is introduced to the market, it should be exposed to several tests to determine its mechanical and electrical behaviors under simulated working conditions. Here, the required important tests were applied to the OPGW composite structure. The tested product passed most of them perfectly, but the lightning test destroyed it completely. Therefore, the designed and constructed composite structure should be changed or the conductive material must be modified.

4 DISCUSSION

The initially designed and constructed OPGW conductor successfully passed most of the tests defined previously, except for the lightning test. As a remedy, AlB with AlB_2 phases of the master alloy was fed into the molten AA–6101 alloy as 3 kg per ton. Then conductivity of the AA–6101 wires increased from 52 % IACS to 57–58 % IACS. An increase in electrical conductivity also causes an increase in heat conductivity. When the above modification is applied other properties such as tensile strength, elongation, 1 % elongation strength, etc. remain constant.

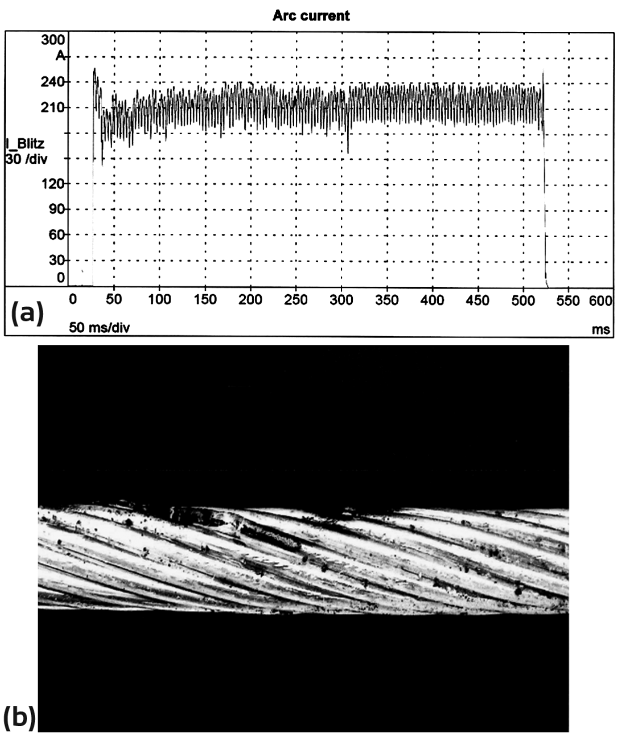

Figure 12: a) Lightning arc, b) view after a strike to the OPGW conductor without broken wires on the outer layer

Slika 12: a) Oblok bliska, b) po udaru v OPGW prevodnik brez porušenih žic na zunanji strani

By modifying the wires and reducing the lay length of the conductor, a new test sample was manufactured. Then a lightning strike was applied again. Now the results met the requirements and the standard used in the test and the product passed perfectly all the required tests.

5 CONCLUSION

The design, construction and modification of an OPGW aerial conductor using a combination of different materials is presented by explaining its behavior under type tests before introducing it into the communication and energy markets. This research also shows that a lightning strike is the hardest test applied to the conductor. OPGW can resist the lightning strike when we strand the wires tightly, decrease the lay length and increase electrical conductivity by inoculating it with AlB_2 in a tundish at 750 °C. The short-circuit test applied to OPGW is not the only way of determining its performance in the event of lightning.

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