Marek OLESZ, Leszek S. LITZBARSKI, Bolesław BARSZCZ, Kamil KĘDZIERSKI, Bartłomiej ANDRZEJEWSKI

OPEN ACCESS

DOI: 10.15199/48.2025.05.31

Application of materials science in the investigations of power cable damage

Zastosowanie inżynierii materiałowej w badaniu uszkodzeń kabli energetycznych

***Abstract**. The article describes the application of confocal microscopy and Raman spectroscopy in the diagnostics of high-voltage power cables. This issue is presented on the example of a failure that occurred during the start-up of a 110 kV cable line. Positive results of tests conducted by the cable manufacturer and during line acceptance indicated good cable insulation parameters. Material tests excluded the presence of hidden cable defects. In the tested sample, significant erosion of the working core was observed as a result of the impact of the short-circuit current. The depth of erosion allowed for the estimation of the short-circuit current intensity and the time of burning of the electric arc. Based on the above premises, it was determined that the cable was damaged as a result of external interference (sabotage).*

***Streszczenie.** Artykuł opisuje zastosowanie mikroskopii konfokalnej i spektroskopii Ramana w diagnostyce wysokonapięciowych kabli energetycznych. Zagadnienie to zostało przedstawione na przykładzie awarii, która nastąpiła w trakcie rozruchu linii kablowej 110 kV. Pozytywne rezultaty prób przeprowadzonych przez producenta kabla oraz w trakcie odbiorów linii wskazywały na dobre parametry izolacji kabla. Badania materiałowe wykluczyły obecność wad ukrytych kabla. W badanej próbce zaobserwowano znaczną erozję żyły roboczej powstałą na skutek oddziaływania prądu zwarciowego. Głębokość erozji pozwoliła na oszacowanie natężenia prądu zwarciowego oraz czasu palenia się łuku elektrycznego. W oparciu o powyższe przesłanki ustalono, że kabel uległ uszkodzeniu na skutek ingerencji zewnętrznej (sabotażu).*

Keywords: cable diagnostics, material testing, HV cable lines, Raman spectroscopy, confocal microscopy
Słowa kluczowe: diagnostyka kabli, badania materiałowe, linie kablowe WN, spektroskopia Ramana, mikroskopia konfokalna

Introduction

Material investigations are an important part of technical diagnosis of electrical power facilities because it allows to determine the current condition of the diagnosed object and helps to estimate its expected life [1]. In addition, they can indicate potential causes of damage and failures of investigated facilities. In recent years, the availability of advanced measurement techniques such as X-ray diffraction (XRD), scanning electron microscopy (SEM) and various spectroscopy techniques has improved. Therefore, interest in these methods in the area of electrical facilities diagnostics of electrical objects has increased. Material science is successfully applied in the case of diagnosis of PV modules [2]–[4], as well as for checking of surge arresters [5]–[7]. Material tests have also found wide application in the diagnostics of medium (MV) and high voltage (HV) cable lines [8]–[10]. Factors leading to damage to cable lines include: overvoltages (atmospheric, short-circuit and earth-fault), aging effects related to, for example, water penetration or treeing, improper quality of cable work during installation, low quality of materials and accessories used, and mechanical damage during earthworks [11]. Based on available literature data [12], it can be concluded that in the case of MV and HV cable lines, the main cause of damage is puncture of the cable connector. In second place are external causes, including: destruction or intentional damage. Failures related to puncture of a cable section or cable head constitute only a small part of all incidents.

This article describes the application of Laser Scanning Microscopy and Raman spectroscopy in the process of identifying the causes of damage to a 110 kV cable line. The presented results show the validity of using modern research methods in engineering practice.

Experimental setup

The subject of the investigations was the XRUHAKXS-WTC 1x300RMC/95, 76/132 kV cable, which is part of a 110 kV cable line. Damage to the aforementioned cable, located on a pole constituting a transition to the overhead line, caused an earth fault in the process of connecting the line. In order to determine the cause of the incident, a sample of the damaged cable was submitted for testing. A Zeiss LSM710 laser scanning confocal microscope (LSM) in the material (reflected light) and photoluminescence modes was used for characterization of the cable cross section. The laser beam of 633 and 458 nm wavelength was used. Photoluminescence (PL) spectra were collected using LSM system conjugated with Stellarnet Inc. Black-Comet CXR-SR-50 grating spectrometer in wavelength range 220-1100 nm. Laser beams with wavelengths of 458, 488, 543 and 633 nm were used to record photoluminescence spectra. Raman spectra were measured with a Labram HR 800 spectrometer (Horiba Jobin Yvon), using a He-Ne laser (λ = 632.8 nm) and a liquid-nitrogen cooled CCD detector; the Si line (520.7 cm^{-1}) was used for calibration. The beam was focused on the sample using a x20 objective, and the beam power on the sample was about 1 mW to avoid overheating. A typical exposition time for a single spectrum accumulation was about 30 s and the spectrum was determined after averaging 10 accumulations. Exposure time in some spectra has been reduced to 20 or 10 seconds due to the intense signal and related detector limitations. Figure 1 shows the approximate locations of the spots on the reference and the sample from which the spectra were collected.

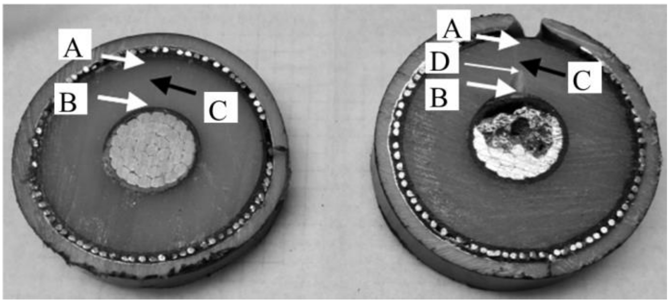

Fig. 1. Investigated sample (right side) with the reference sample (left side). Indications: arrows indicate spots A-D.

Results and discussion

During an examination of the exact location of the incident, it was found that the damage occurred above the screen protecting the L1 phase cable. The surface of the cable near the damage site was dirty and had a characteristic dent, which could have been caused by significant pressure or mechanical impact. Microscopic examinations showed that the outer sheath was damaged near the point of damage, exposing the inner layers of the cable. The place where the cable insulation is burned is characteristic of the thermal impact of a short-circuit current, because the channel surfaces are smooth and do not contain metallic deposits. Inspection of the working core of the cable indicates its significant degree of erosion associated with the melting and evaporation of Al during the short circuit. Based on the depth of melting (h), the arc burning time (t) can be estimated using the following relationship:

$$(1)\quad t = 6 \cdot h \cdot d_{avg} / (\delta_V \cdot I),$$

where δ_V - volume erosion coefficient, I - short-circuit current. The parameter d_{avg} is an average length of the electric arc defined by the formula:

$$(2)\quad d_{avg} = d_0 + h,$$

where d_0 stands for the initial length of the electric arc. In the described case, it was assumed that the effective value of the initial component of the single-phase short-circuit current is I = 5.351 kA and that the initial length of the electric arc is equal to the insulation thickness, i.e. d_0 = 15.1 mm. The erosion depth in the case in question was about 15 mm, which would correspond to $t \approx 290$ ms. Meanwhile, the actual duration of the short-circuit, taking into account the circuit breaker's own time, was only about 70 ms, which corresponds to erosion of no more than 5 mm. The observed discrepancy may indicate that the cable insulation was intentionally damaged, e.g. by drilling.

It should be noted here, that before the cable was installed, typical acceptance tests were performed at the manufacturer's. In accordance with the requirements of the IEC 60840 standard [13], a 30-minute voltage test was performed at a voltage of U = 190 kV and a frequency of 50 Hz, a measurement of the partial discharge charge (Q ≈ 1 pC) and a 1-minute voltage test of the cable sheath was performed using direct current with a voltage of 25 kV. In addition, the correct technical condition of the cable insulation was confirmed by tests carried out after the cable line was completed. They were performed in accordance with the guidelines of *Energa Operator S.A*. described in [14]. The average value of the partial discharge charge and the loss factor depended only to a small extent on the value of the test voltage, which clearly indicated a good condition of the insulation of the investigated cable.

In order to exclude a manufacturing defect of the mentioned cable, the material investigations were conducted. The LSM images of the sample near the damaged area were obtained in reflected light and photoluminescence modes. The clear and intense photoluminescence is visible in the damaged region appearing as a half ellipse shape in the middle from the top of images. For comparison, similar images were collected for a reference sample in which photoluminescence was only observed at an excitation wavelength of 488 nm. Furthermore, in the reference sample, photoluminescence was only observed near the center of the wire, which contains an additional isolating layer. Figure 3 presents the PL spectra collected in the damaged area under irradiation with a laser beam of different wavelength. In the analysis of PL spectra, the 458 nm excited spectrum is most accurate due to the presence of color filters and dichroic mirrors in the light path, which distort the shape of the spectrum at longer excitation wavelengths. The photoluminescence is characterized by wide band with two separated maxima around 505 and 530 nm. In contrast, freshly synthesized polyethylene shows PL spectra of maximum near 425 nm under 375 nm excitation wavelength. However, for the thermally aged polyethylene a strong bathochromic shift of PL spectrum is observed [15]. Therefore, most probably the PL observed in the sample comes from thermally damaged polyethylene.

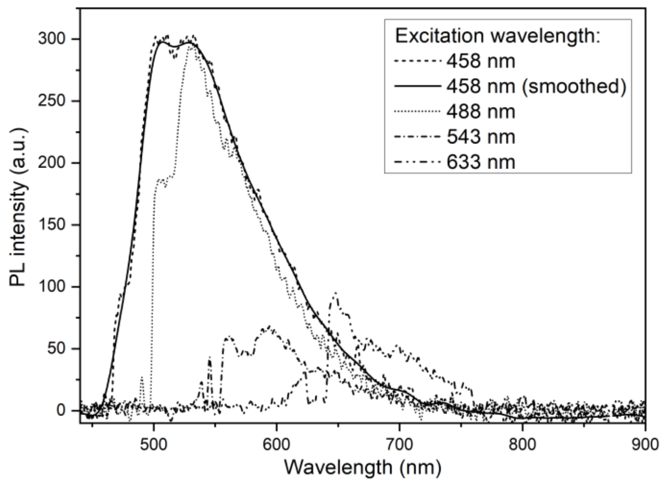

Fig. 2. The photoluminescence spectra of sample damaged area excited with light beam of varied wavelength.

In the Fig. 3A the Raman spectra of reference sample at 3 spots (RA, RB and RC) are presented. The spectra are typical for polyethylene with characteristic bands at about 1063 cm^{-1}, 1130 cm^{-1}, 1296 cm^{-1}, 1418 cm^{-1}, 1441 cm^{-1}, 2849 cm^{-1}, 2882 cm^{-1} [16], [17], and shows that investigated material is rather homogenous without significant differences between the spots.

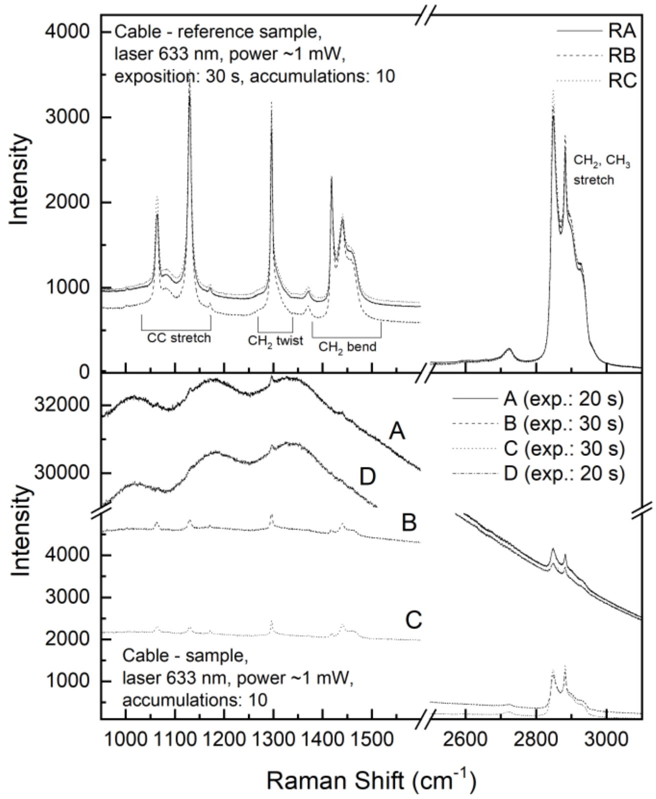

Fig. 3. The Raman spectra of the reference sample (A) and sample from the damaged part of the investigated cable (B)

Figure 3B shows the spectra recorded from the sample of the damaged cable at indicated points. It is easy to notice, that spectra at the spots A and D are completely different from the reference data. Moreover, a strong background is observed for these spots, which arises from the fluorescence of the sample. However, there is still visible some reminiscence of the polyethylene bands. The spectra at spots B and C are not affected as much as at spot A and D but the differences are still distinct. The obtained results indicate that polyethylene in the sample was decomposed severely at spots A and D. Furthermore, the investigated sample loss some of its crystallinity at spots B and C. The above-mentioned premises shows that the material changes in the damaged area are a consequence of thermal phenomena most probably related to the impact of an electric arc. The spectra measured at points A and D resemble the spectra obtained for polyethylene exposed to temperatures above 150 °C [18]. The changes observed at points B and C also indicate the melting process in the tested sample. Measurements of the reference sample taken far from the damaged location ruled out the occurrence of material defects in the investigated HV cable.

Conclusions

Comprehensive tests were carried out on the HV cable, which was damaged during the commissioning of the cable line. The inspection revealed mechanical damage to the outer sheath of the cable and a smooth channel characteristic of the thermal impact of the short-circuit current. In addition, significant erosion of the working core was observed, based on which the intensity of the short-circuit current and its disconnection time were estimated. The obtained result indicated an initial weakening of the cable insulation, e.g. due to drilling. The correctness of the cable construction is confirmed by positive results of voltage tests and partial discharge measurements carried out by the cable manufacturer. The correct condition of the insulation is confirmed by acceptance tests of the cable line. The conducted material tests confirmed that the observed changes in insulation were the result of thermal impact and not internal material defects. Summing up the above premises, it can be stated that the most probable cause of the damage was the action of third parties consisting in drilling the cable insulation. The mentioned damage must have occurred with the cable line switched off (no voltage), after the acceptance tests were carried out The described case well illustrates the validity of using materials engineering in the diagnostics of electrical facilities.

Authors: *dr hab. inż. Marek Olesz, Gdansk University of Technology, Faculty of Electrical and Control Engineering, Gabriela Narutowicza 11/12, 80-233 Gdańsk, E-mail: marek.olesz@pg.edu.pl; dr inż. Leszek Litzbarski, Gdansk University of Technology, Faculty of Electrical and Control Engineering, Gabriela Narutowicza 11/12, 80-233 Gdańsk, E-mail: leszek.litzbarski@pg.edu.pl; dr inż. Bolesław Barszcz, Institute of Molecular Physics Polish Academy of Sciences, Mariana Smoluchowskiego 17, 60-179 Poznań, E-mail: barszcz@ifmpan.poznan.pl; dr inż. Kamil Kędzierski, Faculty of Materials Engineering and Technical Physics, Poznan University of Technology, Piotrowo 3, 60-965 Poznań, E-mail: kamil.kedzierski@put.poznan.pl; dr hab. Bartłomiej Andrzejewski, Institute of Molecular Physics Polish Academy of Sciences, Mariana Smoluchowskiego 17, 60-179 Poznań, and@ifmpan.poznan.pl;*

REFERENCES

[1] A. Baryłka and J. Obolewicz, “Technical diagnosis as an important engineering tool of electrical power facilities,” *Rynek energii*, vol. 6, pp. 65–70, 2020.
[2] L. Litzbarski, M. Olesz, and K. Seklecki, “Measurement practice of photovoltaic installations leading to the determination of the actual technical condition; [Praktyka wykonywania pomiarów instalacji fotowoltaicznych prowadząca do określenia rzeczywistego stanu technicznego],” *Prz. Elektrotechniczny*, vol. 2024, no. 3, pp. 82 – 84, 2024, doi: 10.15199/48.2024.03.14.
[3] K. K. Ilse *et al.*, “Comprehensive analysis of soiling and cementation processes on PV modules in Qatar,” *Sol. Energy Mater. Sol. Cells*, vol. 186, pp. 309–323, 2018, doi: https://doi.org/10.1016/j.solmat.2018.06.051.
[4] E. E. van Dyk, A. Audouard, E. L. Meyer, and C. D. Woolard, “Investigation of the degradation of a thin-film hydrogenated amorphous silicon photovoltaic module,” *Sol. Energy Mater. Sol. Cells*, vol. 91, no. 2, pp. 167–173, 2007, doi: https://doi.org/10.1016/j.solmat.2006.08.001.
[5] L. S. Litzbarski *et al.*, “Quality Assessment of Low Voltage Surge Arresters,” *IEEE Access*, vol. 10, pp. 129313–129321, 2022, doi: 10.1109/ACCESS.2022.3226401.
[6] T. G. Zacarias and W. C. Sant'Ana, “A Bibliometric and Comprehensive Review on Condition Monitoring of Metal Oxide Surge Arresters,” *Sensors*, vol. 24, no. 1, 2024, doi: 10.3390/s24010235.
[7] K. P. Mardira, T. K. Saha, and R. A. Sutton, “Investigation of diagnostic techniques for metal oxide surge arresters,” *IEEE Trans. Dielectr. Electr. Insul.*, vol. 12, no. 1, pp. 50–59, 2005, doi: 10.1109/TDEI.2005.1394015.
[8] M. Ding, W. He, J. Wang, and J. Wang, “Performance Evaluation of Cross-Linked Polyethylene Insulation of Operating 110 kV Power Cables,” *Polymers (Basel).*, vol. 14, no. 11, 2022, doi: 10.3390/polym14112282.
[9] M. S. Kemper, C. Philippczyk, R. J. Rayzak, and V. Waschk, “A New Method for the Detection and Quantification of Residual Volatiles in XLPE Electrical Cable Using Large-Spot Raman Spectroscopy,” *IEEE Trans. Power Deliv.*, vol. 26, no. 1, pp. 3–10, 2011, doi: 10.1109/TPWRD.2010.2089704.
[10] H. Herman, G. C. Stevens, and J. L. Thomas, “Cable condition through a spectroscopic and chemometrics analysis of cable ageing,” in *2010 IEEE International Symposium on Electrical Insulation*, 2010, pp. 1–5, doi: 10.1109/ELINSL.2010.5549573.
[11] M. Olesz and A. Wysocka, “Diagnostyka kabli średniego napi{\k{e}}cia w Energa-Operator SA,” *Zesz. Nauk. Wydz. Elektrotechniki i Autom. Politech. Gdańskiej*, no. 45, pp. 53–56, 2015.
[12] Rakowska, Aleksandra, “Rozwój konstrukcji kabli elektroenergetycznych wysokich i najwyższych napięć,” *{Elektroenergetyczne i telekomunikacyjne linie kablowe : VIII konferencja naukowo-techniczna*. 2001.
[13] *IEC 60840:2020Power cables with extruded insulation and their accessories for rated voltages above 30 kV (Um= 36 kV) up to 150 kV (Um = 170 kV) - Test methods and requirements*. 2020.
[14] ENERGA-OPERATOR S.A, *INSTRUKCJA WYKONYWANIA BADAŃ LINII KABLOWYCH SN i WN*, 5th ed. 2018.
[15] K. Grabmayer *et al.*, “Characterization of the aging behavior of polyethylene by photoluminescence spectroscopy,” *Polym. Degrad. Stab.*, vol. 107, pp. 28–36, 2014, doi: https://doi.org/10.1016/j.polymdegradstab.2014.04.030.
[16] A. P. Kotula, M. W. Meyer, F. De Vito, J. Plog, A. R. Hight Walker, and K. B. Migler, “The rheo-Raman microscope: Simultaneous chemical, conformational, mechanical, and microstructural measures of soft materials,” *Rev. Sci. Instrum.*, vol. 87, no. 10, p. 105105, Oct. 2016, doi: 10.1063/1.4963746.
[17] K. B. Migler, A. P. Kotula, and A. R. Hight Walker, “Trans-Rich Structures in Early Stage Crystallization of Polyethylene,” *Macromolecules*, vol. 48, no. 13, pp. 4555–4561, Jul. 2015, doi: 10.1021/ma5025895.
[18] G. R. Strobl and W. Hagedorn, “Raman spectroscopic method for determining the crystallinity of polyethylene,” *J. Polym. Sci. Polym. Phys. Ed.*, vol. 16, no. 7, pp. 1181–1193, 1978, doi: https://doi.org/10.1002/pol.1978.180160704.