Archives of Acoustics — Vol. 47, No. 2, pp. 259–265 (2022), doi: 10.24425/aoa.2022.141654

Research Paper

Monitoring of Partial Discharges in Cable Insulation and Cable Head Using Acoustic Method

Zbigniew RANACHOWSKI[(1)*], Krzysztof WIECZOREK[(2)],
Przemysław RANACHOWSKI[(1)], Tomasz DĘBOWSKI[(1)]

[(1)] *Institute of Fundamental Technological Research*
Polish Academy of Sciences
Warsaw, Poland
*Corresponding Author e-mail: zranach@ippt.pan.pl

[(2)] *Department of Electrical Engineering Fundamentals*
Wrocław University of Science and Technology
Wrocław, Poland

(*received January 13, 2022; accepted March 7, 2022*)

The article presents the application of Acoustic Emission (AE) method for detection and registration of partial discharges (PD) generated in medium voltage (MV) cable isolation and MV cable head. The insulation of the high voltage cable is made of a flexible material whose properties are characterised by a high coefficient of attenuation of the acoustic signals. For this reason, the AE method has not been used so far to detect PD in energetic cables. The subjects of the research were the MV cable and the standard T-type cable head. The cable contained defects which were the source of partial discharges. In case of cable head the PD were provoked by thin grounded electrode which was introduced into connector opening. The results of AE measurements are presented in the form of spectrograms. Acoustic Emission was evoked when the applied voltage level reached the value of 7.5 kV for the cable and 4 kV for the cable head. The authors used the acoustic instrumentation of their own design intended for future field use. Obtaining successful results of partial discharges measurements using the acoustic method in the cable insulation makes an original contribution of the presented work.

Keywords: partial discharges; medium voltage insulation; acoustic emission.

1. Introduction

High and medium voltage cables are applied in large amounts in modern grids connecting the power plants, distribution centres, and final distribution substations. An illustrative example of the scale of planned connections is the Xlinks Morocco-UK Project (Xlinks, 2021). The wind and solar centre located in Guelmin Oued, Morocco generating approx. 3–10 GW of power electricity will be linked with Great Britain via 3.800 km of high voltage direct circuit sub-sea cable. All such facilities of high importance for providing the power supplies in a reliable, safe and in durable way require precise methods of monitoring of aging status of the installation.

The insulation of the cables and their connectors is susceptible to electrical, thermal, and mechanical stresses due to the pending exploitation. The stresses result in the occurrence of defects in the structure of insulation. The defects in turn will increase the local field strength resulting in partial discharges (PD) leading to local breakdowns (Florkowski, 2020). IEC 60270 Standard defines PD as "a localised electrical discharge that only partially bridges the insulation between the conductors and which may or may not occur adjacent to a conductor" (IEC 60270:2001/A1:2016, 2016; Lu *et al.*, 2020). The recommendation of the Standard includes test circuits and measuring systems details as well as calibration procedures and instrumentation. Generally, a PD monitoring system needs to achieve the following objectives: detection, localisation, and recognition. A PD measurement system based on IEC 60270 Standard collects the analysed signal in the electrical form. Partial discharges are a source of current pulses which can be measured in the form of voltage variations registered at the measuring impedance. A sensitive instrumentation detects and determines such PD parameters as: discharge amplitude, number of registered events per time unit and its relation to the phase of monitored high voltage. Measurement of different parameters of PD makes it possible to indicate their sources, such as: surface discharge, void or corona discharges. Due to harmful radiofrequency interferences it is highly recommended to perform the electric PD measurements in the grounded shielding cabinets.

Case studies related to monitoring of PD in Isolated Phase Buses (IPB) are described in (Singh, Hughes-Narborough, 2018). The authors report that signs of PD activity were observed mostly at loose contacts between phase bus and ceramic support insulators. The air gap created in the place of the loose contact usually was covered with traces of burning. In certain conditions (for example in presence of composite insulation with organic ingredients) burning processes may result in the phase to earth fault and a serious failure of the connectors. Pepper and Plath (2015) investigated PD behaviour in XLPE insulated medium voltage cable and provided some modifications of standard setup due to IEC 60270 to minimise test energy needs when energised large capacitive loads in field conditions. They proposed to reduce the testing voltage frequency to the range of 0.1–1 Hz. They concluded that the testing voltage frequency is of minor influence on the registered PD behaviour of the typical insulation defects. Another firm conclusion presented by these authors refers to the generation of the PD in cables. They state that "with existing PD it is only a matter of time, when the breakdown of the cable will occur later in service" (ibid., p. 1).

Other than electric and based on IEC 60270 methods of measuring PD effects are listed in (Sikorski *et al.*, 2020). Among them are high frequency current transformers operating in frequency ranges of 0.1–100 MHz and using toroidal inductive PD detector usually installed on the wire grounding of the investigated high voltage device. This provides an easy access to the monitored object, however, it does not allow for a precise localisation of the source of the generated PD signal.

Yet another UHF method, operating in the frequency ranges of 0.3–3 GHz, shows a high signal-to-noise ratio because these frequency ranges lie far above the interferences caused by potential corona discharges from the surrounding environment (Pepper, Plath, 2015). To capture UHF signals circular or square planar antennas of small dimensions are used. The antennas were inserted into investigated objects or gathered the electromagnetic radiation via special dielectric windows. Dissolved gas analysis is another method described in the literature regarding testing of power transformers. However, its application is limited to the object containing mineral oil which can be periodically extracted and sampled.

2. Acoustic method

Acoustic Emission (AE) method can be applicable to register PD effects in some circumstances in power cables and their heads. As it was mentioned in (Castro *et al.*, 2016), the electrical discharge and evoked local temperature increase result in generation of acoustic waves radiating in all directions across the surrounding medium. A flexible insulation material applied in energetic cables is characterised by a high coefficient of attenuation of the acoustic signals. However, the application of high levels of signal amplification and its proper filtering can override these limitations if thickness of the insulation od MV device is small. Energy of AE signal generated by PD falls mostly within the frequency range of 20–150 kHz (Sikorski *et al.*, 2012). The acoustic sensors operate at the earth potential and are immune to the disturbing electromagnetic interferences due to electromagnetic screening of sensor casing. The CIGRE and IEEE issued guidelines recommending the application of AE method for HV insulation system diagnostics (Cigre WG D1.33, 2010; C57.127-2007, 2018). To apply the aforementioned method, the piezoelectric sensor, signal amplifier, and data acquisition system are required. There are two main commercial suppliers delivering the appropriate instrumentation: Physical Acoustic Corporation Acoustic Emission (AE) Technology (n.d.) and Vallen Systeme GmbH (n.d.). The latter company designed the specialised software for the localisation of PD sources in large objects. The instrumentation using EA method does not allow for precise determination of the charge amount released during a PD event. Sensitivity of the AE detectors is determined either in voltage level referred to the pressure unit (volts per microbar) or in voltage level referred to the stress wave velocity unit (volts per m/s). AE measurements can serve as an indicator of faulty processes evoked in monitored device and some papers report the usefulness and versatility of the AE method (Kunicki, Cichoń, 2018; Witos, Olszewska, 2012). The latter paper describes in detail the instrumentation for monitoring of AE signals generated by PD in power oil transformers and the procedures for source location and identification.

3. Instrumentation and test procedure

The MV measurement circuit was set up according to IEC 60270. It consisted of a one phase 30 kV MV transformer. The primary winding of the MV transformer was supplied by an autotransformer enabling regulation of secondary voltage. In order to monitor the operating voltage used, it was reduced with a factor of 1/325. The voltage reduction was carried out with the help of a dual port divider. Its high voltage part consisted of a 500 pF capacitor. Low voltage part impedance consisted of a 156 nF capacitor.

The general view of the setup is presented in Fig. 1.

Fig. 1. General view of the testing setup (the MV transformer and the voltage divider).

The first object intended for testing was a section of a 24 kV energetic cable containing the reinforcing steel bandage. This type of cable is commonly used in MV urban grids in Poland. The cable contained defects which were the source of partial discharges detected using the electric measurements according to IEC 60270. The cable termination with partially removed insulating cover of the bandage is presented in Fig. 2. Steel bandage delivered a good acoustic contact with AE sensor which was mounted on it, applying a nylon Cinch cable fastener.

Fig. 2. Investigated cable termination with a partially removed insulating cover of the steel bandage.

The second object intended for testing was a standard cable head of T-type connector, produced by Nexans Euromold Interface C-Symmetrical (Thorne & Derrick, n.d.) and fixed on polymeric (XLPE) 24 kV cable. The connector was covered by polymeric insulation and, additionally, with grounded low resistive synthetic EPDM rubber acting as electrical shield. The AE sensor was located on the longer arm of the connector, as it is presented in Fig. 3. A nylon Cinch cable fastener was also used to press the sensor face to the connector body. The location of the thinnest layer

Fig. 3. View of the investigated T-type connector with a fastened AE sensor.

of EPDM rubber was chosen to provide the low level of attenuation for the propagating acoustic waves. Thin grounded electrode was introduced via connector opening to provide the partial discharges into the metal linking ring linked with high potential inside the connector arm.

Wideband differential AE sensor of type WD, produced by Physical Acoustics Corporation, was applied to register the AE signal. However, the producer at his site (Physical Acoustics, n.d.) recommends the application of the sensor within a frequency range of 100–900 kHz, the aforementioned transducer also records the EA signals within the lower frequency range of 10–100 kHz, with sensitivity loss denoting 10 dB, referring to the level of 1 V/(m/s). AE sensor of type WD was recommended as the most efficient tool for monitoring of PD using AE method in (Sikorski *et al.*, 2012). The recorded AE was in the magnitude of a fraction of a single millivolt. It was further increased in an in-house made differential amplifier shown in Fig. 4. Ultralow noise precision operational amplifiers LT1028 Ultralow Noise Precision High Speed Op Amps (Analog Devices, n.d.) were implemented in this device to realise the required signal to noise ratio. The voltage noise of the LT1028 operational amplifier declared by the manufacturer is 1 nV/$\sqrt{\text{Hz}}$. To suppress the acoustic background noise, the amplifier included a high pass filter performing the suppression of signals within the frequency band of 0–7 kHz. The amplifier included peak value detector for performing future field measurements. According to asset owners requirements field measurements scenario consists in recording of AE peak value registered in some significant locations of

Fig. 4. View of the applied in-house made differential AE signal amplifier with the connected AE sensor of WD (Physical Acoustics Corporation) type.

MV grid. As a result of the performed experiments the time constant of the peak value of the detector was determined for 100 microseconds. The rate of the long term A/D sampling frequency in the transmission mode mentioned above should be ca. 10 kilosamples per second.

After amplification (50 dB) and filtering, the AE signal was transferred to the analogue/digital conversion and data acquisition unit. The authors have applied the industrial data acquisition module of type USB-1901, produced by ADLINK Technology Inc. (ADLINK Technology Inc., n.d.). The module enabled analogue/digital conversion with resolution of 70 μV/bit, at the measuring range of ±2 V and continuous data transfer to the host computer at a speed of 250 kilosamples per second. High quality analogue processing unit allowed data transmission with a signal-to-noise ratio of 89 dB, which is a crucial factor when recording weak acoustic signals evoked by PD.

Fig. 5. Module for analogue/digital conversion and data acquisition of industrial USB-1901 type enabling recording of analogue signals and using a variable number of input channels at a programmable transmission speed. The manufactures deliver modules performing max. sampling rate of 250 or 2000 kilosamples per second.

A software prepared by the authors was capable of memorising the acoustic pulse trains lasting ca. 180 s and their further processing. The recorded data were stored for further processing in the form of .dat files containing subsequent 16 bit signal samples. To present and compare the recorded signal, its decomposition in time and frequency domain was applied. The single records were partitioned for segments constituting of 500 samples. The windowed Discrete Fourier Transform was performed for each segment enabling determining of 250 spectral lines, denoting local Power Spectral Density, each 0.5 kHz of entire signal spectrum in the range of 125 kHz. The results were presented in the form of a spectrogram, a graph with two geometric dimensions: one axis represents time and the other denotes frequency. The local level of determined PSD was represented by the colour of certain point of the image. Since the single acoustic event evoked by the release of PD lasted ca. 1 ms, it was impossible to visualise it at the spectrogram depicting 180 ss of recording. There was also a possibility of plotting a high resolution version of the spectrogram presenting a part of the entire data set. This modified spectrogram was a result of the decomposition of 300 ms of recorded signal. PSD was determined in the frequency range of 0–30 kHz here. An example of mentioned above high resolution spectrogram is presented in Fig. 10. A time dependence plot of a PSD, determined for a specific signal frequency of a highest intensity, is a useful tool for the comparison of acoustic activity of some sources of PD. Examples of such signals' visualisation are presented in Figs 7, 9, and 12.

4. Measurement results

The following diagrams show the results of recording of AE signals generated during the performed experiments. Due to the decomposition in time and frequency domains it was possible to determine the frequency bands of the highest Power Spectral Density (PSD) of active PD sources. The first test intended to determine the level of a background noise emitted in the absence of tested high voltage. This measurement session was done applying the AE sensor coupled with the MV cable bandage. Figure 6 shows a spectrogram of the measurement of acoustic background level within a 200 seconds period. The measure unit of AE signal intensity is its PSD expressed in $\mu V^2/Hz$. The most intense background noise was registered in the range of low acoustic frequencies, i.e., in the range of 6–20 kHz. The further experimental results present certain frequency band, i.e., 26 kHz ± 0.5 kHz of the

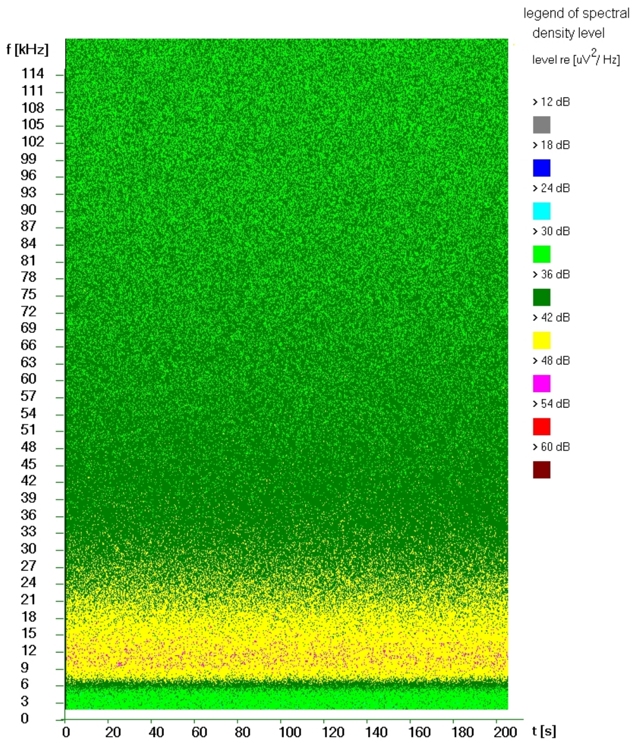

Fig. 6. Spectrogram of the AE signals recorded in the absence of the loading MV voltage.

highest AE activity. Figure 7 presents the PSD determined for that frequency (±0.5 kHz). The aforementioned level of PSD measured in the absence of tested high voltage did not exceed 10 $\mu V^2/Hz$.

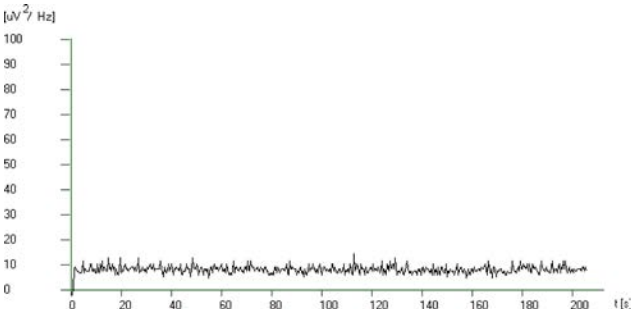

Fig. 7. Power spectral density of the recorded AE signals determined for the frequency of 26 kHz in the absence of the loading MV voltage.

During the next test, the activity of the source of PD evoked in 24 kV energetic cable with steel bandage was examined. The high voltage applied to the phase wire was gradually raised to the final level of 9.5 kV. The generation of PD resulted in charge release of approximate level of 150 pC was detected after crossing a 6 kV level of stimulation. Further increase of voltage level over a value of 7.5 kV resulted in a significant increase of PD intensity. Figure 8 presents a spectrogram containing the results of the acoustic measurements in relation to the applied MV level. The level of registered PSD in the frequency range of 6–30 kHz was remarkably higher than that registered in the absence of the MV load. On the basis of the data presented in Fig. 9 it can be determined that up to 7.5 kV the PSD at 26 kHz was twofold higher than that measured with the absence of the MV load (i.e., 20 $\mu V^2/Hz$) and after the load increase beyond the 7.5 kV the PSD level exceeded the level of 40 $\mu V^2/Hz$. A high resolution spectrogram was additionally created for the part of the record described above – starting from the 60th second from the beginning. At this moment a considerable increase of AE signal intensity was observed.

A high resolution spectrogram is presented in Fig. 10. High energy acoustic event is visible in the initial part of this graph. All potential traces of AE events caused by PD discharges (yellow poles) are depicted as short pulses of ca. 1 ms of duration, appearing within the intervals of ca. 5–10 ms.

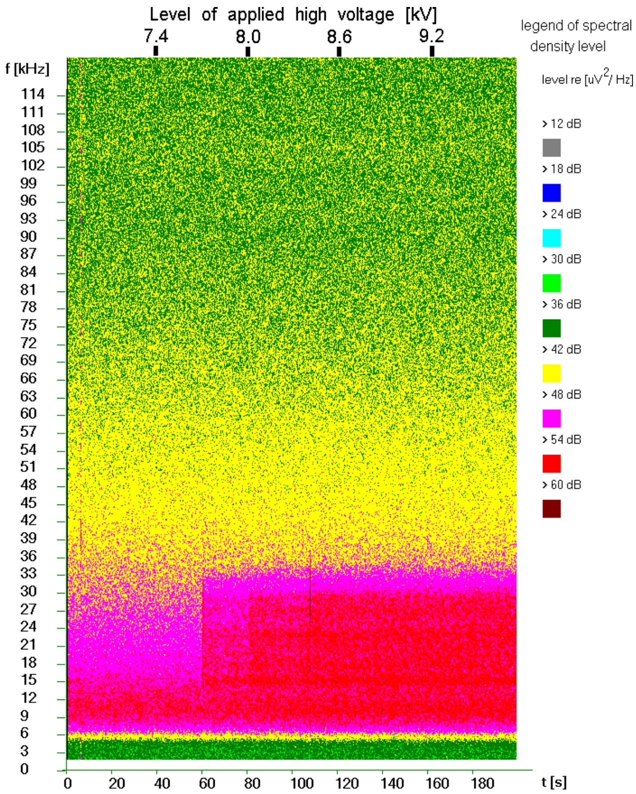

Fig. 8. Spectrogram of the AE signal recorded in 24 kV energetic cable with a steel bandage, presented in Fig. 2.

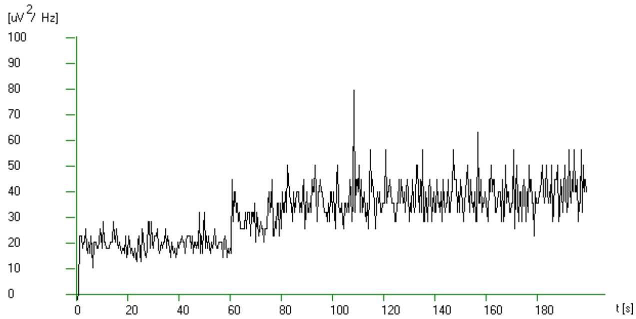

Fig. 9. Power spectral density of AE signals, recorded in 24 kV energetic cable with steel bandage – presented in Fig. 2 – determined for the frequency of 26 kHz.

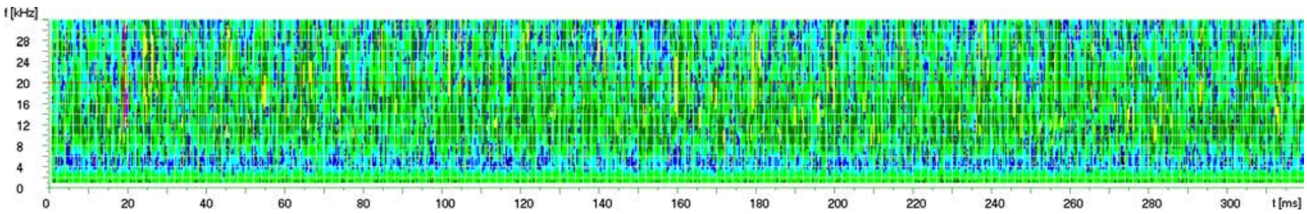

Fig. 10. High resolution spectrogram created for the part of the record presented in Fig. 8 and starting from the 60th second of the beginning of the record (at this moment a considerable increase of AE signal intensity was observed).

During the third test the activity of the source of PD evoked in the cable head of T-type was examined. The cable connector is presented in Fig. 3. The high voltage, applied to the implemented testing electrode, was raised starting with 1.5 kV to the final level of 7 kV. The generation of PD was observed immediately after switching on the voltage. It was characterised with the approximate level similar to that registered in the previous test. The increase of voltage level over the value of 6 kV resulted in an increase of PD intensity. Unlike the tendency presented in Fig. 8 it is visible in Fig. 11 that the increased level of loading voltage evokes AE signal of spectral density located also in the higher frequency bands, i.e., at 84 and 103 kHz.

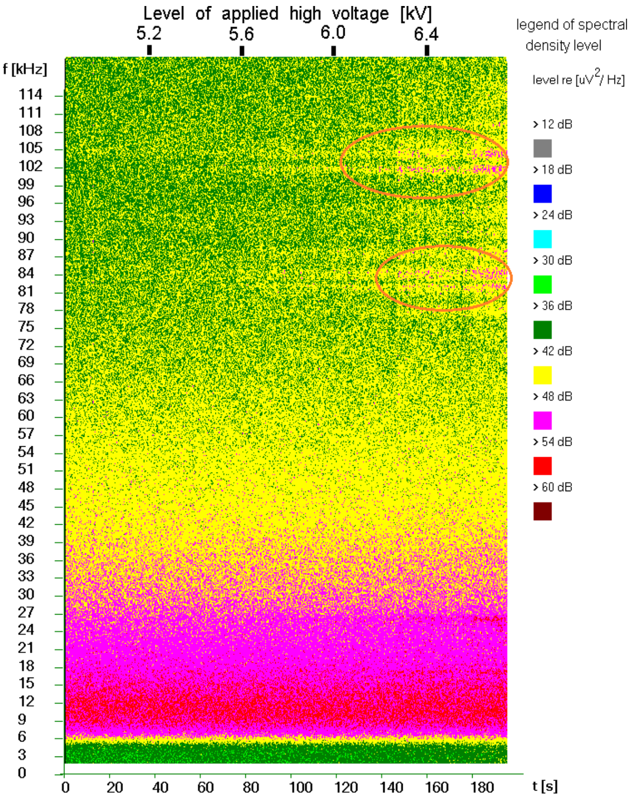

Fig. 10. Spectrogram of the AE signal recorded in the investigated cable T connector, presented in Fig. 3. AE signal activity located in the higher frequency bands is visible in the upper part of the plot.

In this case partial discharges are released into a large air cavity inside the connector, therefore their acoustic signature differed from that registered in the MV cable insulation. The levels of the registered PSD at 26 kHz and at 103 kHz are presented in Figs 12 and 13, respectively. The noticeable power of AE signals at the frequency of 103 kHz was registered at the voltage level beyond 6 kV. The presence of an additional area of the increased power of AE signals depicted in Fig. 11 leads to the conclusion, included also in (Sikorski *et al.*, 2020) and (Lu *et al.*, 2020), that

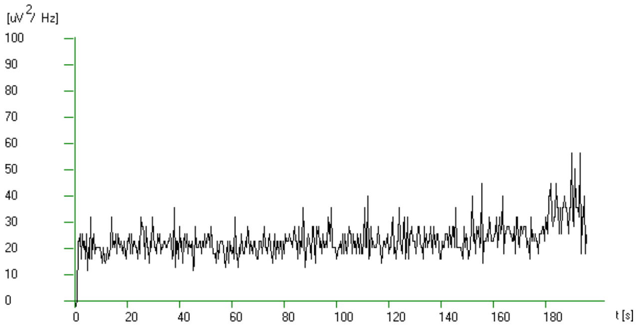

Fig. 11. Power spectral density of the AE signal recorded in the investigated cable T connector determined for the frequency of 26 kHz.

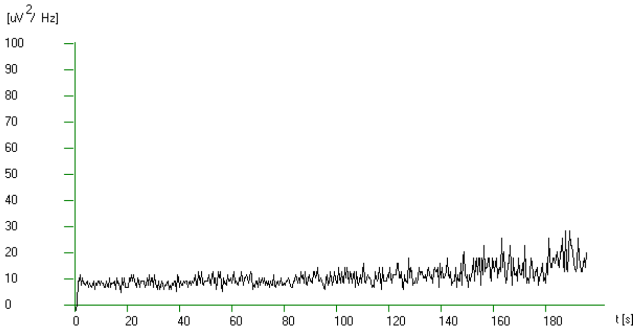

Fig. 12. Power spectral density of the AE signal recorded in the investigated cable T connector determined for the frequency of 103 kHz.

different types of PD can produce divergent spectral patterns of the recorded acoustic signals.

5. Conclusions

The aim of the presented study was to show the possibility of applying the AE method for monitoring the PD effects occurring in the insulation of energetic cables and also inside their connectors – where the wear effects due to their usage can be noticed. The authors have applied the instrumentation of their own design, intended for further field tests. A high pass filtering technique was introduced to suppress the acoustic background noise usually present around the industrial objects. The noise reduction was performed within the frequency band of 0–7 kHz.

The investigation of the AE signals generated in a 24 kV energetic cable have revealed that the AE signal level in the frequency range of 6–30 kHz was remarkably higher than that registered in the absence of the MV load. It was determined that up to 7.5 kV the Power Spectral Density measured at 26 kHz was twofold higher than that measured with the absence of the MV load (i.e., 20 $\mu V^2/Hz$ versus 10 $\mu V^2/Hz$) and after the load increase beyond the 7.5 kV the PSD level exceeded 40 $\mu V^2/Hz$. The analysis of the high resolution spectrograms enabled the authors to conclude that there were present the traces of AE events, caused by PD discharges, depicted as short pulses of ca. 1 ms of duration, appearing in the intervals of ca. 5–10 ms. The investigation of the AE signals evoked during the discharges in cable head of T type has revealed that acoustic signature differs from that registered in MV cable insulation. The PSD level registered at 26 kHz was similar to that registered in the MV cable insulation but also a noticeable power of AE signals at the frequency of 103 kHz was registered at the voltage level above 6 kV.

Measurements performed with the AE method do not require coupling with the high phase potential which is inconvenient in industrial conditions. Typical data acquisition systems enable simultaneous monitoring of several elements of MV network and reporting the condition of these objects to the asset owner to arrange the required maintenance.

The successful results of measurements of partial discharges using the acoustic (AE) method on a flexible material, constituting the housing of electrical equipment make an original achievement of the presented work.

References

1. Acoustic Emission (AE) Technology (n.d.), https://physicalacoustics.com/ae-technology/ (access: 12.01.2022).
2. ADLINK Technology Inc. (n.d.), *USB-1901/1902/1903*, https://www.adlinktech.com/Products/Data_Acquisition/USBDAQ/USB-1901_1902_1903 (access: 12.01.2022).
3. Analog Devices (n.d.), *LT1028 Ultralow Noise Precision High Speed Op Amps*, https://analog.com/en/products/lt1028 (access: 12.01.2022).
4. C57.127-2007 (2018), IEEE Guide for the detection and location of acoustic emissions from partial discharges in oil-immersed power transformers and reactors, [in:] *IEEE Std C57.127-2007 (Revision of IEEE Std C57.127-2000)*, doi: 10.1109/IEEESTD.2007.4293265.
5. Castro B. *et al.* (2016), Partial discharge monitoring in power transformers using low-cost piezoelectric sensors, *Sensors*, **16**(8): 1266–1282, doi: 10.3390/s16081266.
6. Cigre WG D1.33 (2010), *Guidelines for Unconventional Partial Discharge Measurements*, Cigre, Paris, https://e-cigre.org/publication/SESSION2010_D1-33 (access: 12.01.2022).
7. EN 60270:2001/A1:2016 (2016), *High-voltage test techniques – Partial discharge measurements*, https://standards.iteh.ai/catalog/standards/clc/c463d397-86ab-491e-b4bf-1c9617dced80/en-60270-2001-a1-2016 (access: 12.01.2022).
8. Florkowski M. (2020), *Partial discharges in high-voltage insulating systems. Mechanism, processing and analytics*, Wydawnictwa AGH, Kraków.
9. Kunicki M., Cichoń A. (2018), Application of a phase resolved partial discharge pattern analysis for acoustic emission method in high voltage insulation systems diagnostics, *Archives of Acoustics*, **43**(2): 235–243, doi: 10.24425/122371.
10. Lu S., Chai H., Sahoo A., Phung B.T. (2020), Condition monitoring based on partial discharge diagnostics using machine learning methods: a comprehensive state-of-the-art review, *IEEE Transactions on Dielectrics and Electrical Insulation*, **27**(6): 1861–1888, doi: 10.1109/TDEI.2020.009070.
11. Pepper D., Plath R. (2015), Partial discharges in typical defects of power cable systems at variable test voltage frequency-fundamental and practical considerations, [in:] *Proc. of the 19th International Symposium on High Voltage Engineering*, Pilsen, Czech Republic.
12. Physical Acoustics (n.d.), *WD 100-900 kHz wideband differential AE sensor*, https://physicalacoustics.com/by-product/sensors/WD-100-900-kHz-Wideband-Differential-AE-Sensor (access: 12.01.2022).
13. Sikorski W., Walczak K., Gil W., Szymczak C. (2020), On-line partial discharge monitoring system for power transformers based on the simultaneous detection of high frequency, ultra-high frequency and acoustic emission signals, *Energies*, **13**(12): 3271–3308, doi: 10.3390/en13123271.
14. Sikorski W., Walczak K., Moranda H., Gil W., Andrzejewski M. (2012) Partial discharge on-line monitoring system based on acoustic emission method – operational experiences [in Polish: System monitoring wyładowań niezupełnych metodą emisji akustycznej – doświadczenia ekspoatacyjne], *Przeglad Elektrotechniczny*, **88**(11): 117–121.
15. Singh A., Hughes-Narborough M. (2018), *Partial Discharge Activity in Isolated Phase Bus (IPB)*, E-CIGRE.org, Committee A1 Session, Paris, https://e-cigre.org/publication/SESSION2018_A1-203 (access: 12.01.2022).
16. Thorne & Derrick (n.d.), *Nexans Euromold Interface C-Symmetrical*, https://powerandcables.com/product/product-category/nexans-euromold-interface-c-symmetrical/ (access: 12.01.2022).
17. Vallen Systeme GmbH (n.d.), *Partial Discharge*, https://vallen.de/applications/partial-discharge/ (access: 12.01.2022).
18. Witos F., Olszewska A. (2012), The system useful for analysis of acoustic emission signals generated by partial discharges within power oil transformers insulation [in Polish], *Przegląd Elektrotechniczny*, **88**(11): 154–157.
19. Xlinks (2021), *The Morocco-UK Power Project*, https://xlinks.co/morocco-uk-power-project/ (access: 12.01.2022).