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doi:10.15199/48.2024.11.60

Application of the acoustic emission method to record partial discharges in a medium voltage switchgear model

Streszczenie. *W pracy przedstawione zostało zastosowanie metody emisji akustycznej (EA) do detekcji i rejestracji wyładowań niezupełnych (WNZ) powstających w modelu rozdzielnicy średniego napięcia. Wyniki pomiarów EA przedstawiono w formie spektrogramów. Efekt emisji akustycznej powstawał, gdy poziom przyłożonego napięcia osiągał wartość od 10 kV do 30 kV. Autorzy wykorzystali urządzenia i głowice EA do rejestracji WNZ metodą akustyczną. Zaprezentowana aparatura może być również przeznaczona do zastosowań przemysłowych. Oryginalnym osiągnięciem prezentowanej pracy jest uzyskanie pomyślnych i powtarzalnych wyników pomiarów wyładowań niezupełnych przy zastosowaniu metody akustycznej. (**Wykorzystanie metody emisji akustycznej do rejestracji wyładowań niezupełnych generowanych w modelu rozdzielnicy średniego napięcia**).*

Abstract. *The application of the acoustic emission (AE) method for the detection and recording of partial discharges (PD) occurring in a medium voltage switchgear model was presented in this paper. The results of AE measurements were presented in the form of spectrograms. The acoustic emission effect occurred when the applied voltage level reached values from 10 kV to 30 kV. The authors used devices and probes EA to record PD using the acoustic method. The presented equipment can also be intended for industrial applications. The original accomplishment of the presented work is the achievement of successful and repeatable results of partial discharge measurements using the acoustic method.*
Słowa kluczowe: wyładowania niezupełne (WNZ), emisja akustyczna (EA), rejestracja sygnałów emisji akustycznej.
Keywords: Partial Discharges (PD), Acoustic Emission (AE), Registration of Acoustic Emission signals.

Introduction

It is common knowledge that the occurrence of PD effects and their consequences are undesirable for the proper operation of devices and limit their operational life. Hence, PD detection and determination of the released charge is important from the point of view of durability and reliability of power distribution network devices. Electrical (charge) PD testing methods that have been used for years are sensitive and effective. They also perform very well under laboratory conditions. However, their use in field conditions is difficult to implement because it requires connecting the measuring equipment to high-voltage terminals. Meanwhile, the use of the Acoustic Emission method (AE) makes it possible to detect, monitor and - under certain conditions - also locate the place where the harmful effects of PD occur, related to, among others, with the degradation of insulation in devices [1]. Research conducted over the years has shown that the acoustic technique is sensitive and effective for devices with both oil and air insulation. This also applies to MV devices [2,3].

The AE method has been successfully used in situ for years, especially in the case of HV transformers, where not only sensitive detection of HV effects is possible, but also its localization [1,4,5]. Research has also been ongoing for years on the use of the acoustic method to monitor MV devices [6,7,8]. An example of devices that require monitoring for partial discharges are high and medium voltage cables. They are used in large quantities in modern networks connecting power plants, distribution centers and final distribution substations. An illustrative example of the scale of planned cable connections is the Xlinks Morocco-Great Britain project [9]. A wind-solar centre located in Morocco, generating approximately 3-10 GW of electrical power, will be connected to the UK via a 3.800 km high-voltage submarine cable. All such facilities - of great importance for reliable, safe and durable power supply - require precise methods of monitoring the aging state of the installation. The insulation of cables and their connectors is susceptible to electrical, thermal and mechanical stresses as a result of operational loads. Under the influence of stress, defects are created in the insulation structure. The defects, in turn increase the local field intensity, causing partial discharges (PDs), leading to local failures [10].

A partial discharge monitoring system must meet the following objectives: partial discharge detection, localization and recognition. The PD measurement system, based on the IEC 60270 standard, collects the analyzed signal in electrical form. Partial discharges are a source of current pulses that can be measured in the form of voltage changes - recorded on the measuring impedance. Sensitive equipment detects and determines such PD parameters as the amplitude of discharges, the number of recorded events per unit of time and its relationship to the phase of the monitored high voltage. Measurement of various PD parameters makes it possible to indicate their sources, which include surface discharges, voids or corona discharges. However, due to harmful radio frequency interference, it is strongly recommended to perform electrical discharge measurements in grounded and shielded rooms.

Partial discharge tests in a medium voltage cable with XLPE insulation showed the possibility of certain modifications to the standard system, in accordance with the IEC 60270 standard [11]. This was intended to minimize the need for test energy in field conditions, when the power supply system was loaded with high capacity. It was proposed to reduce the test voltage frequency to the range of 0.1 ÷ 1 Hz. It turned out that the frequency of the test voltage has little influence on the recorded PD of typical insulation defects. An important conclusion was also drawn regarding the generation of partial discharges in cables. Namely, it was stated that “with existing PD it is only a matter of time, when the breakdown of the cable will occur later in service”.

Based on the IEC 60270 standard, but other than electrical methods for measuring PD effects are presented in [12]. High-frequency current transformers, operating in the frequency range of 0.1 ÷ 100 MHz are used, as well as a toroidal inductive PD detector. It was typically installed on the grounding wire of the high-voltage device under test. This provides easy access to the monitored object, but does not allow for precise localization of the source of the generated PD signal. Yet another UHF method, operating in the 0.3 ÷ 3 GHz frequency range, exhibits a high signal-to-noise ratio. The above frequency range is well above the interference caused by potential corona discharges from the surrounding environment [11]. To capture UHF signals, small-sized round or square flat antennas are used. Antennas are placed in the tested objects or electromagnetic radiation is collected through special dielectric windows, where it is possible.

Description of acoustic research method

The energy of AE signals generated by PD lies within a wide frequency range. However, the largest part of the energy of this signal is in the range of 20 ÷ 150 kHz [13]. In addition, acoustic sensors operate at ground potential and are resistant to electromagnetic interference thanks to the electromagnetic shielding of their housing. CIGRE and IEEE have issued guidelines recommending the use of the AE method for diagnosing the HV insulation system [14,15]. To use the above method, a piezoelectric sensor (probe), a signal amplifier and a data acquisition system are required. Appropriate instrumentation is produced by two main commercial suppliers: Physical Acoustics Corporation [16] and Vallen Systeme GmbH [17]. The latter company has developed specialized software for locating partial discharge sources in large facilities. However, instrumentation using the AE method does not allow for a more accurate determination of the amount of charge released during a PD event.

The sensitivity of AE detectors is determined either by the voltage level related to the unit of pressure (volts per microbar) or by the voltage level related to the unit of stress wave velocity (volts per m/s). In practice, AE measurements can serve as an effective indicator of undesirable processes that occur in the monitored device. A number of studies indicate the general usefulness and versatility of the acoustic method [18,19]. The work [19] describes in detail the instrumentation for monitoring AE signals generated by partial discharges in oil-filled power transformers, as well as the procedures for locating and identifying their sources.

Test object

Figure 1 shows the test object used during the measurements, which was a model of the measurement field of a MV switchgear, with a rated voltage of U_m = 24 kV. The model consisted of a metal casing allowing, on the one hand, for the installation of AE sensors using magnetic grips, and on the other hand - due to the good propagation properties of acoustic waves - ensuring high measurement sensitivity. In order to be able to observe the phenomena taking place inside the model, one of its walls was made of a plexiglass plate. Voltage was injected into the interior of the object using a 24 kV rated overhead bushing insulator. The model's self-discharge level when fed up to 27 kV did not exceed 1.5 pC. In order to force the partial discharge to a level that would allow measurements to be made using the acoustic method, a blade electrode made of 1 mm^2 copper wire was installed at the end of the bushing insulator, which was inside the measurement field.

Measuring system and test procedure

The diagram of the testing and measuring system, which enabled the generation and measurement of partial discharges using the laboratory method, in accordance with the requirements of the IEC 60720 standard, is shown in Figure 2. The main element of the system was a 150 kV Haefely Hipotronics testing transformer. A system of filters and separation transformers was used to power the test transformer, which minimized the impact of interference introduced by the power supply network. To measure partial discharges, a Doble Lemke measuring system was used, consisting of a 1000 pF coupling capacitor, LDM-5/U measuring impedance, with a bandwidth of 20 MHz, a lower cut-off frequency of 100 kHz and a PD-SMART partial discharge analyser. All measurements were performed in a shielded test cage, that ensured a background noise level not exceeding 1 pC.

Fig. 1. The test object used during the measurements - a medium voltage switchgear model

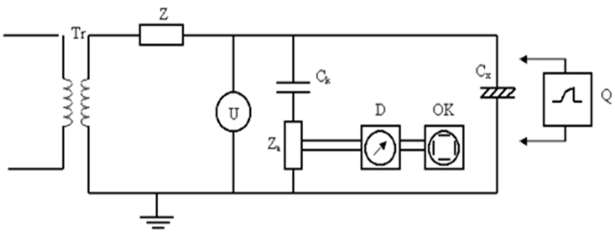

Fig.2. The diagram of the testing and measuring laboratory system for the generation and measurement of partial discharges: Tr - high-voltage transformer, Z - protection impedance/filter, C_k - coupling capacitor, Z_k - measurement impedance, D – measurement system, OK – oscilloscope, C_x – tested object.

In Figures 3, 4 and 5. are presented phase-resolved PRPD distributions obtained by the electrical method using the PD-Smart system.

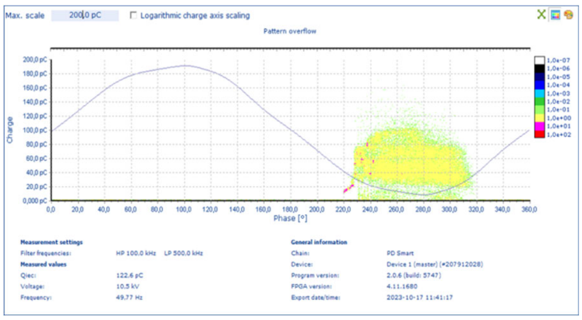

Fig.3. PD measurement results for a voltage of 10.5 kV

A useful tool for comparing the acoustic activity of some PD sources is a graph of the time dependence of the power spectral density (PSD), determined for a specific frequency of signal of the highest intensity. The recording of acoustic signals generated during partial discharges (PD) was performed in two configurations of the equipment:

- on an industrial set manufactured by Polish AE Steel company,
- on a laboratory system with a WD-type probe.

The essential element of the measuring set is a high-sensitivity acoustic emission amplifier that cooperates with the AE probe (transducer). In the case of the industrial version, the probe mounted on a brass diaphragm, registers signals in the range from 5 to 60 kHz. This probe is located in a special dustproof housing, which also contains an amplifier, a power cable and a signal output presented in Figure 6.

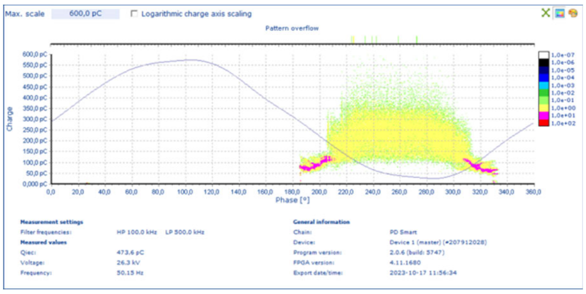

Fig.4. PD measurement results for a voltage of 26.1 kV

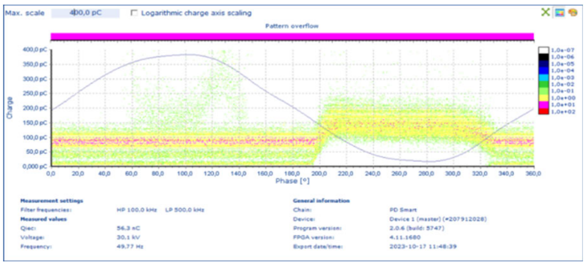

Fig.5. PD measurement results for a voltage of 30.1 kV

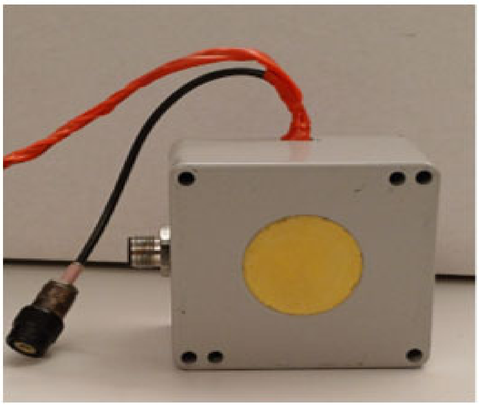

Fig.6. Industrial AE probe in a housing containing an amplifier

In the case of the laboratory version of the system, a wideband differential AE probe of the WD type, manufactured by the American company Physical Acoustics Corporation [20], is used. The manufacturer recommends using the probe in the frequency range of 100 ÷ 900 kHz. However, the transducer also records AE signals in the lower frequency range of 10 ÷ 100 kHz, with a sensitivity loss of 10 dB, related to the level of 1 V/(m/s). The WD type probe was recommended as the most effective tool for monitoring PD using the AE method in the work [13]. It was found that the sensitivity of the WD probe for PD signals is at least 4 times higher than that of the industrial sensor, among others due to the differential signal output.

The recorded AE signals have a low effective voltage - on the order of microvolts. They are amplified in a differential amplifier of own construction, shown in Figure 7. In order to obtain the required signal-to-noise ratio, in the device were used precise operational amplifiers with a very low noise level [21]. The voltage noise of the LT1028 operational amplifier, declared by the manufacturer, is 1 nV/√Hz. The amplifier included a peak detector to perform planned field measurements.

Fig.7. Differential amplifier of AE signals of own construction used in the research, with a connected WD-type AE probe (Physical Acoustics Corporation)

To suppress acoustic background noise, the amplifier includes a high-pass filter that attenuates signals in the frequency band 0 ÷ 7 kHz. After amplification (50 dB) and filtering, the AE signal was transmitted to the analog-to-digital conversion and data acquisition module. The authors used an industrial USB-1901 data acquisition module from ADLINK.INC [22] - Figure 8. The module enabled analog-to-digital conversion with a resolution of 70 microvolts per bit, in the measurement range of +/-2 V and continuous data transfer to the host computer, at a rate of 250 kilosamples per second. The high-quality analog processor allowed data transmission with a signal-to-noise ratio of 89 dB. This was crucial when recording weak acoustic signals caused by partial discharges.

Fig.8. Module for analog-to-digital conversion and data acquisition, of the industrial type USB-1901, enabling the recording of analog signals and the use of a variable number of input channels, with a programmable transmission speed. The manufacturer provides modules with a maximum sampling rate of 250 or 2000 kilosamples per second

In order to increase of the sensitivity of the equipment recording signals generated by PD, the authors of the study developed the software analysing digital signal records. This software enabled the storage of series of acoustic pulses lasting up to 180 seconds and their further processing. The recorded data was saved 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 the time and frequency domain was used. The signal was divided into segments of 70 milliseconds duration. Individual records were divided into segments of 500 samples. A windowed, short-period Discrete Fourier Transform was performed for each segment. It made possible to determine 250 spectral lines, denoting the local power spectral density (Power

Spectral Density - PSD), each at 0.5 kHz from the entire signal spectrum, in the range of 3 ÷ 125 kHz.

The results were presented in the form of a spectrogram, i.e. a graph with two geometric dimensions: the abscissa (X axis) represents time, and the ordinate (Y axis) represents frequency. The local level of the determined power spectral density was represented by the colour of a specific image point. Because a single acoustic event caused by the PD effect lasted approximately 1 millisecond, it was not possible to visualize it in a spectrogram showing 180 seconds of recording. However, it was possible to plot a high-resolution version of the spectrogram, representing part of the entire data set. This modified spectrogram was created as a result of the decomposition of 300 milliseconds of the recorded signal. Power spectral density (PSD) was determined in the frequency range 0 ÷ 30 kHz. An example of such a high-resolution spectrogram is shown in Figure 9. The prepared software, in notional units, calculated the acoustic background level during the measurement and the number of times this background was exceeded in the event of the appearance of the PD signal. As part of the existing work, the method of calculating the background and the number of exceedances was adapted to the spectral characteristics of the industrial probe.

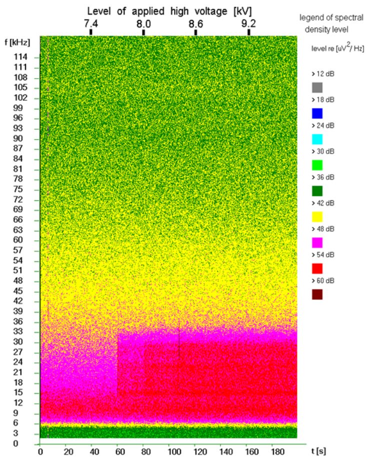

Fig. 9. Example of a spectrogram recorded during the procedure of increasing the voltage at the MV device from the level of 7.4 to 9.2 kV, described in work [23]. WD-type probe was used in the measuring system.

Below are presented examples of recording acoustic signals generated during PD effects in a medium voltage switchgear model, in two equipment configurations:

– on an industrial set,

– on a laboratory system with WD-type probe.

Figure 10 shows the spectral characteristics of the acoustic signal generated during the release of the 600-1000 pC PD charge. The signal was recorded using an industrial set and probe. In turn, the next one - Figure 11 presents the spectral characteristics of the acoustic signal generated during the release of the 460-480 pC PD charge. A laboratory system and probe was used to record the signal.

Summary

The aim of this study was to develop a methodology for acoustic testing of partial discharge (PD) in medium-voltage systems, using a specially prepared measurement system. Carried out experiments showed that the acoustic signal generated in medium-voltage systems has lower energy than that generated in high-voltage systems, but is detectable and recordable. Therefore it requires improved signal analysis procedures in the time and frequency domain.

In order to perform the tests, a special model of the measurement field of a MV switchgear, with a rated voltage of U_m = 24 kV, was made. Presented work included tests on a model experimental system using two measurement systems: an industrial and a laboratory one. The laboratory system was more than twice as sensitive. Measurements were performed using spectral analysis and spectrograms, which improved the signal-to-noise ratio and significantly increased the sensitivity of the method. The AE technique has the advantage of a relatively simple and inexpensive apparatus, but requires well-learned test methodology and signal processing, recorded in the time and frequency domain. To date, the use of the AE method in electrical power engineering appears to be disproportionate to its potential capabilities.

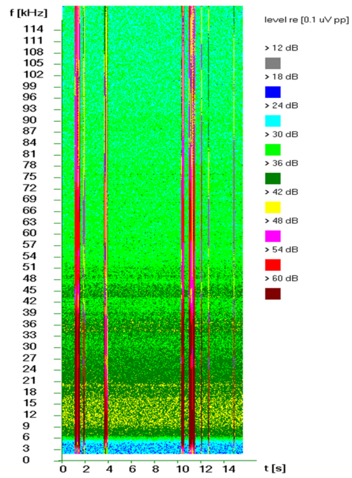

Fig. 10. A study during which the release of a PD charge of 600-1000 pC was recorded. Charge penetration into the bushing was registered in a medium voltage switchgear model. An industrial probe was used in the measuring system.

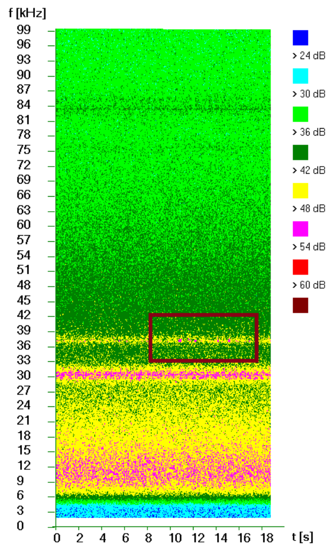

Fig. 11. Test in a medium voltage switchgear model during which the release of a charge of 460-480 pC was recorded. The recorded signals corresponding to PD effects are visible in the frame at a frequency of 38 kHz. A laboratory (WD) probe was used in the measuring system.

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