Laboratory Experimental System for Examination of Acoustic Emission Generated by Partial Discharges

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Abstract — **One of the major causes of transformer failures is dielectric breakdown. Partial discharges cause gradual insulation degradation thus partial discharge activity monitoring provides transformer state insight. This paper gives an overview of common methods for partial discharges detection and source location in transformers, with a special reference to the acoustic method as an noninvasive and interference resistant method suitable for application. For laboratory testing a laboratory experimental system for partial discharge diagnostics using acoustic emission measurement was developed.**

Keywords — **Acoustic emission, partial discharges, online measurement, diagnostics, transformers.**

I. Introduction

DIAGNOSIS and early fault detection have become of primary interest in the field of process automation, since they constitute the basis for achieving failure tolerance, reliability, safety, availability and energy efficiency of all complex engineering systems. Nowadays, great attention is paid to improving the availability, efficiency, reliability and safety of electric power grids and the corresponding infrastructure. The importance of research in this direction is manifold, and can be demonstrated through its economic benefits, the improvement of energy efficiency, system reliability and availability, and safety of people and assets.

Real-time online monitoring of parts of the electric power system and detection of potential failures, which can significantly affect the functioning of the system, are of great importance to successful system exploitation management. Transformers are among the most important components of electric power systems, both in terms of their cost and their crucial role in system operation. Therefore, online monitoring of transformers characteristics with the goal of avoiding breakdowns becomes essential, especially having in mind the growing liberalization of the electricity market, resulting in overload of electric power generation and distribution systems in excess of their projected capacities [1].

One of the major causes of transformer failures is dielectric breakdown. Partial discharges (PD) cause insulation degradation, thus monitoring of PD activity in transformer insulation enables early fault detection and reduces the risk of system failures with catastrophic consequences [2], [3]. The sudden release of energy caused by a PD produces a number of effects, which are used by various methods for PD detection in transformers [4]-[7]. Being simple, noninvasive and electromagnetic interference resistant, acoustic technique based PD monitoring is more appropriate to be used in a transformer monitoring process [4]-[20]. A monitoring system for acoustic emission (AE) measurements performs detection and location of acoustic emissions from both electrical sources (PD) and mechanical sources (such as loose clamping, bolts, or insulation parts) in oil immersed power transformers.

The goal of this comprehensive study is to investigate the PD phenomenon and its influence on transformer operation. For that purpose a laboratory system for PD diagnostics using AE measurements has been developed. The system consists of several parts: a system for partial discharges generation, a transformer tank model, a system for acoustic emission acquisition and data processing as well as a system for high voltage protection. The paper presents characteristics of the laboratory system that provides a good starting point for investigations in the field.

II. Partial Discharges Diagnostic Methods

Partial discharges are localized electrical discharges within the insulation, which only partially bridges the insulation between the electrodes [6], [21]. PD occurs when the electric field strength exceeds the dielectric breakdown strength of the insulating medium in a localized area [22]. The most common PD sources are moisture in the insulation, cavities in solid insulation, metallic particles, and gas bubbles [3]. The PD phenomenon is characterized by very short duration and great energy release, which can be attributed to various kinds of effects, such as local heating, chemical reactions, electrical current pulses through earth, voltage drop across electrodes, electromagnetic radiation, optical and acoustic energy emission. These induced effects

This work received a partial support from the Serbian Ministry of Education, Science and Technological Development, project TR32038, as well as from the Swiss National Science Foundation (Advancing Embedded Systems Research in Serbia, project of the SCOPES program).

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are used for PD diagnostics [2], [4]-[7].

Chemical reactions produce dissolved gases (e.g. hydrogen, ethane, methane, acetylene and others) in a transformer's insulating oil [23]. Therefore, dissolved gas analysis (DGA) using gas chromatography of a sample of transformer's oil can indicate the severity of the fault such as existence of PD (mainly hydrogen dissolved) [4], [23], electric arcs and overheating [17]. Although DGA is a proven low-cost and widely used technique, its main disadvantages are that it is not able to provide valuable information on the location of the failure [17] and that it is an invasive method and requires taking a transformer out of service. However, systems with online DGA monitoring have appeared recently.

The electrical method for PD detection is a conventional method defined by the standard IEC 60270 [21], [24]. Results are measured in picocoulombs or microvolts. This method enables detection and localization and type determination of the PD. It is the most sensitive method, but also very susceptible to electromagnetic interferences [8].

UHF method is based on measurements of radio waves in the frequency range of 300 MHz to 3 GHz. A major difficulty of this method is the suppression of noise and external disturbances that are similar to the PD signal, which affect the accuracy and sensitivity of detection [4], [6].

Acoustic method implies PD detection, localization and type determination based on AE measurements [4]-[20]. AE measurements are commonly performed with piezoelectric ultrasound sensors mounted on the transformer's tank wall. This method is simple and does not require expensive equipment. It is a noninvasive, interference resistant (unlike electric and UHF methods) method, and thus it is more appropriate to be used in transformer online monitoring process. However, disadvantages of this method, such as lower sensitivity, weather condition impact (rain, hail, wind), non-PD vibration sources (loose parts, cooling fans) that interfere with the acoustic signal, as well as acoustic signal attenuation during propagation through different materials, imply the application of this method in combination with other methods.

III. A System for Acoustic Emission Measurements on Transformer

Acoustic emission is a phenomenon whereby transient elastic waves are generated by the rapid release of energy from localized sources within a material. AE waves generated by a PD source are wide-banded. Due to the propagation characteristics of the insulation medium and apparatus structure, ultrasonic AE is measured in the 20 kHz to 500 kHz frequency range [4].

Piezoelectric sensors used for measurements of AE generated by PD typically have resonant frequency (for longitudinal waves) of either 60 kHz or 150 kHz. Since attenuation affects high frequencies more than low, the 60 kHz frequency resonant sensors are favorable for factory and laboratory use. In the field, however, numerous noises (or harmonics of noises) are encountered in the 20 kHz to 60 kHz frequency range, which may lead to false readings. This makes the 150 kHz resonant frequency sensors more suitable for field applications [4]. Commonly used resonant sensors give a cleaner low noise signal. On the other hand, the wideband sensor enables low and high frequencies comparison. PD source location can be determined more accurately by analyzing the higher components of the spectra of the signal measured with a wideband sensor [16].

The piezoelectric sensor is sensitive to varying electromagnetic fields such as those found in substations. In order to minimize electromagnetic interferences impact, the transducer has to be either a "differential" type utilizing two crystals (mounted out of phase for noise reduction) or a shielded single-crystal transducer with an integral preamplifier circuit. The latter is the preferred one in practice because its comparatively high amplitude, low impedance output is less susceptible to degradation due to noise pickup in the connecting cables [4].

Although piezoelectric sensors have proved to be the most appropriate for AE measurements, because of their robustness and sensitivity [25], several fiber optic sensors of different types have been developed for PD detection due to their interference resistivity. However, the sensitivity of these sensors is moderate and they show a great dependence on the technology of integration [7].

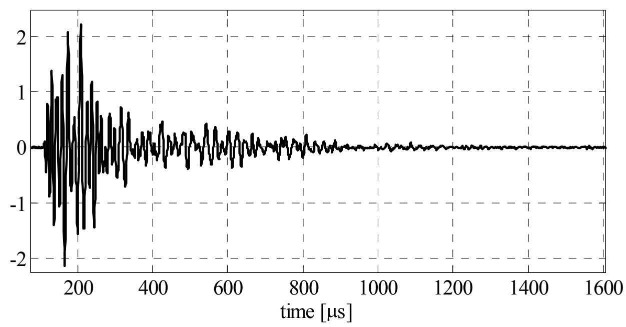


Fig. 1. A typical signal from AE generated by PD.

AE can be generated by PD, as well as mechanical and thermal sources inside and outside transformers [4]. The measured signal depends on AE source, signal attenuations, reflections, refractions and reverberation, as well as on sensor characteristics [4], [16]. Fig. 1 shows a typical waveform of one burst of PD from a piezoelectric sensor mounted on a transformer tank. The signal parameters that are analyzed are: duration time of the burst, number of bursts, rise time of the first oscillation to cross the threshold, number of oscillations above the threshold, movement of the AE signal relative to the excitation frequency [4], [25]. A significant increase either in the PD level or in the rate of increase of PD level can provide an early indication that changes are evolving inside the transformer [3].

Localization of a PD source is performed by mounting at least four sensors on the transformer's tank wall and determining the relative arrival times of the acoustic signals at each of the sensors. The reported accuracy of the three-dimensional PD localization on large power transformers was in the range of 0.3 m to 0.5 m [4], [17].

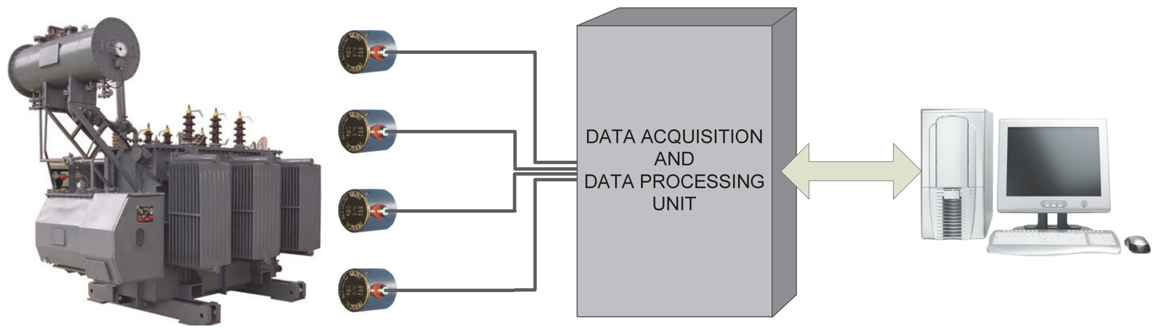


Fig. 2. Block diagram of a system for online monitoring of PD using AE measurements in transformer.

Fig. 2 shows a block diagram of a general system for online monitoring, applied on the system for online monitoring of PD using AE measurements [2]. The system consists of a group of sensors, data acquisition unit, data processing unit and a computer. Signals from sensors are collected by a data acquisition unit, which performs analog-to-digital conversion (ADC) and sends data to a data processing unit. Frequency range is determined by sensor and data acquisition equipment characteristics. Minimal required sampling frequency for AE generated by PD analysis is 1 MHz [4]. Data processing unit performs signal processing using one or more of the following techniques: processing in time domain, applying cross-correlation, using averaging techniques, processing in frequency domain, using wavelet transform [4], [26], [27]. Finally, processed data are sent to the computer using an appropriate protocol. The computer manages one or more data acquisition and processing units and presents a data and communication server.

IV. Laboratory System for Partial Discharges Examination

Before any on site examination starts, comprehensive laboratory research tests should be performed in order to investigate the phenomenon under study. For that purpose a laboratory system for PD diagnostics using AE measurements has been developed. The system is shown in Fig. 3. As it can be seen in the block diagram shown in Fig. 4, the system consists of several parts:

- system for PD generation;
  - high voltage source;
  - electrode system;
  - system for insulation irregularity generation;
- transformer tank model;
- system for AE acquisition and data processing;
  - sensor system;
  - data acquisition system;
  - electromagnetic interference protection system;
  - data processing system;
- system for high voltage protection.

A. System for PD Generation

System for PD generation provides generation of various types of PDs (internal PDs, surface PDs, corona, etc.), PD generation in solid, gas and liquid insulation system, as well PD generation using DC or AC voltage.

Electrode system is especially designed to operate with high voltage, in order to achieve a sufficient value of electric field in axial and radial directions for various PD types generation. Fig. 5 shows the tree types of electrode system configurations that are applied: plane-plane electrode, calotte-plane electrode, and point-plane electrode.

By choosing an appropriate insulation system it is possible to generate various types of PDs and to simulate different surface and interelectrode effects, according to the experiment requirements. The system for insulation irregularity generation on one side can comprise a generator of gas bubbles. Bubbles have a markedly lower electric field strength compared to electric field strength of oil, thus providing discharges at lower voltages. On the other side, insulation system can consist of a tree-layer paper sandwich structure with a void in one layer, as shown in Fig. 6.

B. Transformer Tank Model

There are several transformer tank models in the system (including one actual transformer tank) in order to investigate different influences on AE acquisition, such as shape, size, material and thickness of the tank. The characteristics of tank models correspond to those of certain types of real instrument transformers:

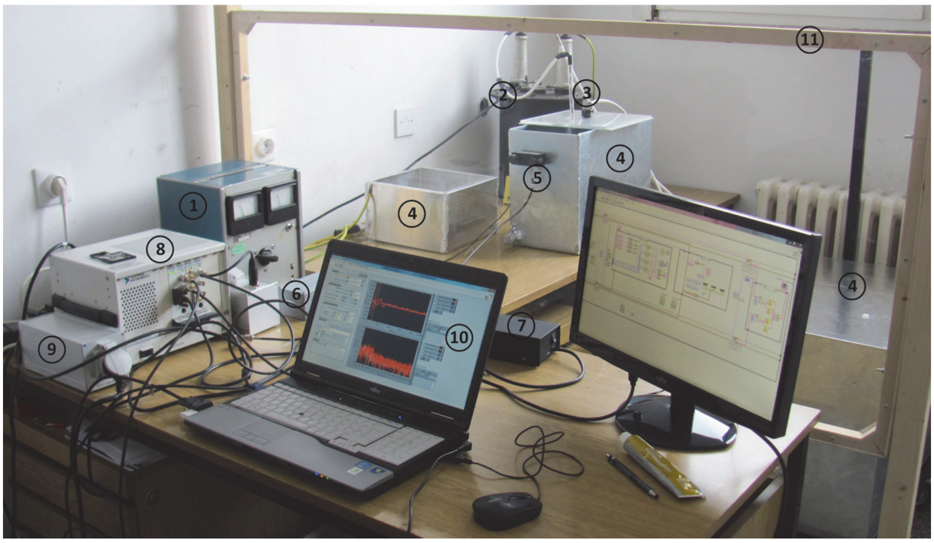
- 2 mm aluminum tank, 25 x 25 x 15 cm;
- 3 mm steel tank, 60 x 60 x 50 cm;
- 3 mm steel tank, 20 x 40 x 30 cm;
- 5 mm steel tank, 20 x 40 x 30 cm.

C. System for AE Acquisition and Data Processing

The sensor system comprises piezoelectric sensors with integrated or external preamplifiers. The used preamplifiers are designed to receive 28-30 Vdc via the same coaxial cable that transmits the amplified AE signals as well [25]. Sensors are attached to the tank using magnetic holders. The coupling agent (silicone grease) is required to improve the quality of sensor acoustic coupling [4], [25]. Three different types of sensors were chosen according to the requirements for PD measurement (posed in Section III), so that a wide frequency range is covered both with resonant and wideband sensors. The characteristics of sensors in the system are given in Table 1.

Data acquisition system is based on PXI platform consisting of:

- NI PXI-1036 chassis;
- NI PXI-Express Card 8360 for laptop control of PXI, with sustained throughput up to 110 MB/s;
- NI PXI-5124 digitizer with 2 simultaneous channels, with 12 bit resolution and real time sampling frequency of 200 MS/s; system comprises 2 modules of that kind.



1 – autotransformer
2 – high voltage source – transformer 100 V / 3 kV
3 – electrode system with sandwich structure insulation system
4 – transformer tank models
5 – sensor with magnetic holder
6 – preamplifier
7 – 28 Vdc source
8 – NI PXI platform
9 – low pass filter for interference suppression from the power supply
10 –laptop with data acquisition application (LabVIEW) and data processing application (Matlab)
11 – protection panel

Fig. 3. Laboratory system for PD examination by measuring AE.

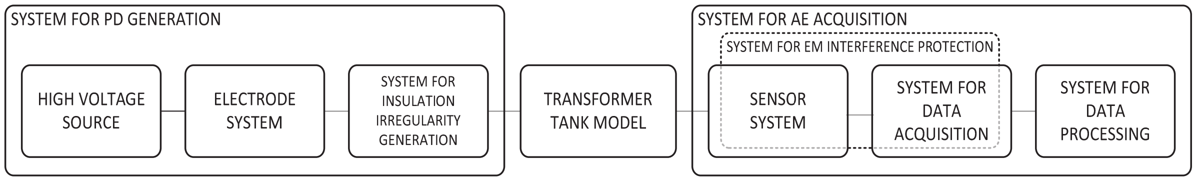


Fig. 4. Block diagram of the laboratory system.

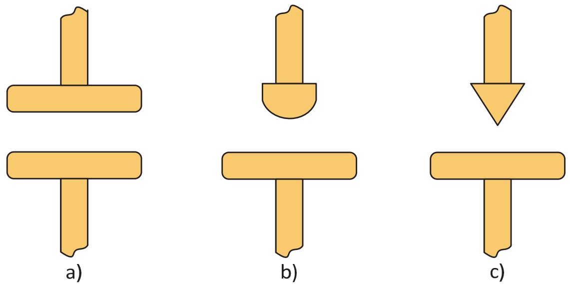


Fig. 5. Schematic diagram of electrode systems employed: a) plane-plane electrode, b) calotte-plane electrode, c) point-plane electrode.

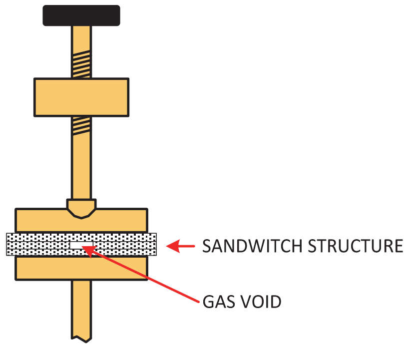


Fig. 6. Tree-layer paper sandwich structure.

Because the data acquisition system is easy for handling and transport, robust and less sensitive to electromagnetic interferences, this system is suitable for factory and laboratory use, as well for measurements in the field.

In the field it is expected that a high electromagnetic field would induce significant interferences and protection from these interferences is a request. Additional cable shielding with a copper shield is applied. Certain parts of the system are shielded in metal boxes. All shields are connected to the system ground. The system ground is realized in the form of a star with the center in PXI chassis ground. It was shown that severe electromagnetic interferences caused by discharges in air were suppressed to the greatest extent in this way.

The whole system is supplied from the same supply point in front of which a low pass filter (denoted as 9 in Fig. 3) is applied. The filter impact on interferences from the power supply, presented in Fig. 7, was measured using equipment for conducted RF emission testing.

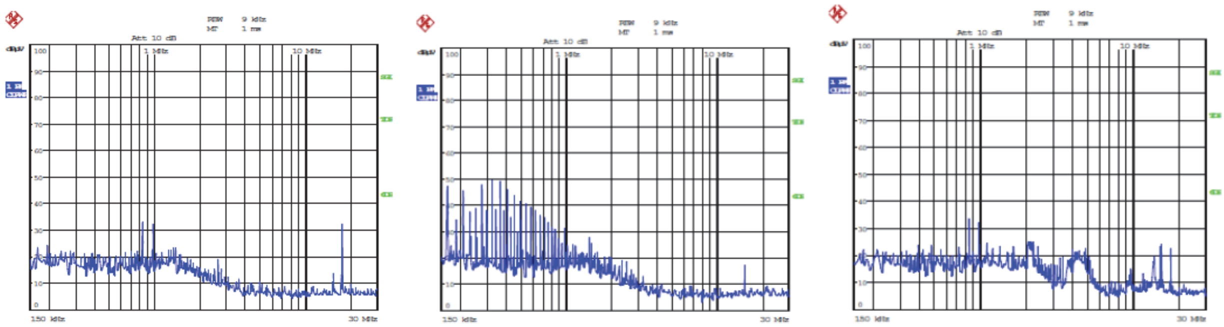
Data processing system consists of a laptop with an Express Card slot and LabVIEW and Matlab packages installed. Data acquisition program is developed in National Instruments' LabVIEW package. Front panel of the program is shown in Fig. 8.

The LabVIEW programs are based on virtual instrumentation, i.e. the use of customizable software and modular measurement hardware to create user-defined measurement systems, called virtual instruments. Virtual instrumentation presents a contemporary methodology for research, development and realization in complex engineering systems and provides easier, faster and above all more reliable development compared to traditional hardware-centered instruments [28].

The basic modular instrument for acquisition of analog signals is a digitizer, i.e. an analog-to-digital converter (ADC). NI-SCOPE is both the application programming interface (API) and driver that controls the digitizer [29] using a range of available virtual instruments for digitizer settings, data acquisition (displaying time and frequency representation of the signal), data processing and storing in a file. The measurement data are stored in a file of TDMS (Technical Data Management Streaming) format, which

TABLE 1. CHARACTERISTICS OF THE SENSORS.

Sensor Model	*Freq. Range [kHz]*	*reson. [kHz]*	*Size [mm]*	*Remp. Range [°C]*	*Connector*	*Integr. preamp.*	*Quantity*
VS45-H	20-450	275	20.3 x 22	-20 до +100	Microdot	NO	2
VS150-RIC	100-450	150	28.6 x 31.5	-40 до +85	BNC	YES	4
VS900-RIC	100-900	350	28.6 x 31.5	-40 до +85	BNC	YES	1



a) b) c)

Fig. 7. Power supply filter impact: a) ambient signal, b) emitted interferences, c) filtered emitted interferences.

provides storing well-documented and organized measurement data at high speeds [29]. Using a Matlab program, specially written for data extraction from TDMS files, a TDMS file can be loaded in Matlab for further processing and analysis.

D. System for High Voltage Protection

System for high voltage protection includes a number of precautions in order to protect people and equipment:

- protective rubber floor (especially required in the high voltage zone and in the control area);
- protective grounding;
- separated, enclosed and marked area for high voltage source; the border of the area (protection panel 11 in Fig. 3) must be at least 1 m away from the high voltage source;
- manual for high voltage handling that all participants are familiar with.

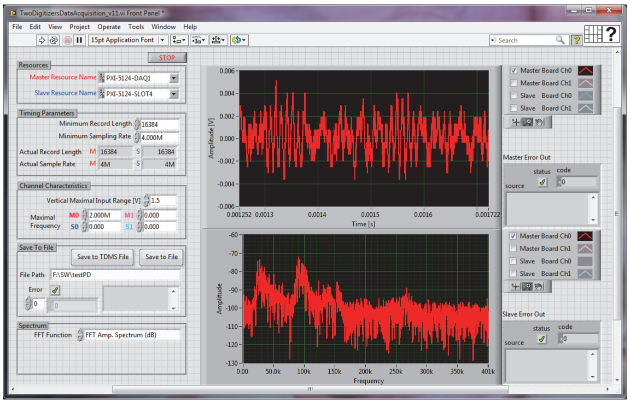


Fig. 8. Front panel of the program for AE acquisition.

In Fig. 9 an example configuration of the system for PD generation and AE acquisition is shown. A high voltage source comprises two transformers, providing 3 kVac voltage applied to electrodes. Calotte-plain electrode system is used (Fig. 5c), and a tree-layer paper sandwich structure insulation system (Fig. 6). Fig. 8 presents measured AE signal generated by PD in the system.

So far, preliminary measurements on several instrument transformers were performed in order to verify the system (without a further detailed analysis). The obtained data correctly indicated the existence of PDs. An example of measured signals on a voltage instrument transformer (Szabó és Mátéffy) with PDs is shown in Fig. 10.

V. CONCLUSION

AE method, as a simple, noninvasive, electromagnetic interference resistant method, is proven to be very suitable in many experimental and implemented systems for PD diagnostics. However, because of some disadvantages such as lower sensitivity, weather conditions impact, non-PD vibration sources that interfere with the acoustic signal, as well as acoustic signal attenuation during propagation through different materials, AE method becomes far more reliable when used in conjunction with other complementary diagnostic methods, such as DGA.

A laboratory system for PD diagnostics using AE measurements, presented in this paper, has been developed for the purpose of the comprehensive research that includes further investigation of the PD phenomenon, acquisition of a great number of AE signals in laboratory and in field conditions and development of new algorithms in order to improve AE method results. The final goal of the research is development of a device for online monitoring of instrument and power transformers.

Based on a large number of scientific papers published in recent years, and commercial systems based on the AE method for PD diagnostics in transformers and other parts of the electric power system, it can be concluded that the subject of this paper is very up-to-date and that there is room for further research.

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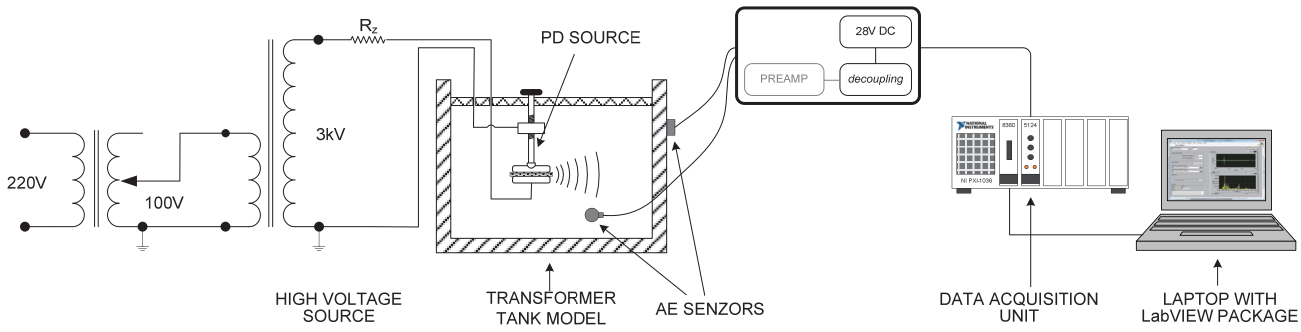

Fig. 9. An example configuration of the system for PD generation and AE acquisition.

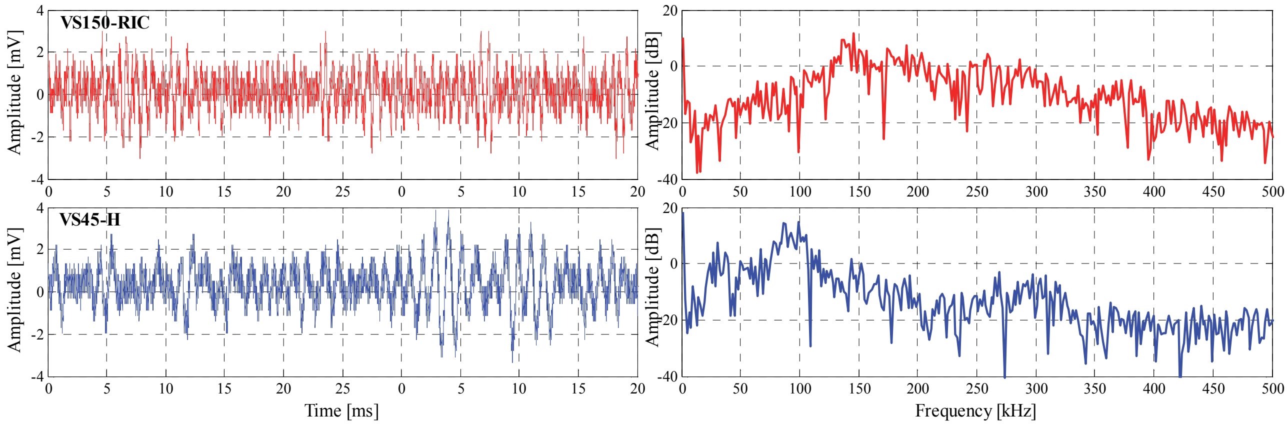

Fig. 10. The results of AE measurements with two different sensors on a real transformer with PD.

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