Metrol. Meas. Syst., Vol. 26 (2019) No. 2, pp. 403–418.

METROLOGY AND MEASUREMENT SYSTEMS

Index 330930, ISSN 0860-8229

www.metrology.pg.gda.pl

THE 8AE-PD COMPUTER MEASUREMENT SYSTEM FOR REGISTRATION AND ANALYSIS OF ACOUSTIC EMISSION SIGNALS GENERATED BY PARTIAL DISCHARGES IN OIL POWER TRANSFORMERS

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Abstract

A computer measurement system, designed and built by authors, dedicated to location and description of *partial discharges* (PD) in oil power transformers examined by means of the *acoustic emission* (AE) method is presented. The measurement system is equipped with 8 measurement channels and ensures: monitoring of signals, registration of data in real time within a band of 25–1000 kHz in laboratory and real conditions, basic and advanced analysis of recorded signals. The basic analysis carried out in the time, frequency and time-frequency domains deals with general properties of the AE signals coming from PDs. The advanced analysis, performed in the discrimination threshold domain, results in identification of signals coming from different acoustic sources as well as location of these sources in the examined transformers in terms of defined by authors descriptors and maps of these descriptors on the side walls of the tested transformer tank. Examples of typical results of laboratory tests carried out with the use of the built-in measurement system are presented.

Keywords: acoustic emission, partial discharge, multichannel system, acoustic signal detection, acoustic signal processing, signal analysis, voltage preamplifier.

1. Introduction

Partial discharge (PD) plays important role in the operation of high-voltage equipment and high-voltage power systems. Analysing the PD measurement data within them and proper interpretation of the obtained results of the analysis can inform on the technical condition of the tested object. A leading role among methods of PD examination is attributed to electrical methods [1–2]. However, along with them, there are different methods useful for evaluation of the phenomena accompanied with PDs [3–5]. Among them the leading role is played by the chemical methods with *dissolved gas analysis* (DGA) [6–7] and the *acoustic emission* (AE) method [8–15].

Examining PDs by means of the AE method is very useful, as it enables to identify and locate PD sources and helps to identify deformational processes at early stages. The AE method has also limitations caused by two groups of reasons. On the one hand, the recorded signals differ from

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Article history: received on Nov. 10, 2018; accepted on Dec. 23, 2018; available online on Jun. 28, 2019, DOI: 10.24425/mms.2019.128355.

AE pulses generated by PD sources, since the AE pulses are being changed when propagated in the medium during detection and processing of the recorded signal. On the other hand – there are external (mechanic, acoustic and electric ones) as well as internal (acoustic and electric ones) disturbances appearing together with PD phenomena.

The vital part of a high-voltage power system are oil power transformers. Examination of PDs occurring in them by means of the AE method have an additional advantage – it can be performed without expensive disconnection of the tested transformer. In oil power transformers' operation there exist – together with PD phenomena – acoustic waves whose sources are the vibroacoustic phenomena, magnetostrictive phenomena, noise of the medium, noise associated with oil circulation, Barkhausen effect and others. Such a variety of acoustic waves propagating in the studied object poses difficult tasks for the researchers. On the other hand, fortunately, the development of measurement methods and methods of data analysis constantly reduces the main difficulties and limitations of acoustic methods. In the literature there are presented solutions based on recording and analysis of signals in different frequency bands: 70–180 kHz [8, 10], 100–200 kHz [11], building expert systems involving multiple descriptors describing signals recorded in research carried out in several ways [16–21].

The authors have been dealing with PD examinations for about 30 years. For most of the research, we have used a 4-channel DEMA-COMP measurement system of our own design and construction [22, 23]. DEMA-COMP enables to monitor or register signals in real time within a band of 20–500 kHz (both in laboratory and outdoor conditions) and then to analyse the registered data in time, frequency, time-frequency and discrimination threshold domains. For this purpose, a software system using LabVIEW environment was built. Analysis of recorded signals has led us to define descriptors with the following acronyms: ADC (*Amplitude Distribution* of AE Counts), ADP (*Amplitude Distribution of Power* of AE signal) and ADNC (*Amplitude Distribution of Normalised AE Counts*) [24]. ADC, ADP and ADNC descriptors describe a so-called level of advancement of recorded signals [22–25].

For oil power transformers, the authors have proposed a research method for studying PDs by means of the AE method [26]. The method includes:

- Registration of signals at measurement points on the transformer tank providing a network covering the side walls of the examined transformer tank (during the transformer's on-line operation);
- Advanced analysis of registered signals in the area of discrimination threshold giving the authors' descriptors with acronyms ADC, ADP and ADNC for individual signals in selected frequency bands;
- Preparation of descriptor maps on the side walls of the tank of the transformer under test, location of maxima on these maps and checking whether the signals registered in these areas come from the PD sources;
- Location of PD sources.

The descriptor maps are obtained with a kriging method [27–29]. Checking whether the signals registered in areas being local maxima within the descriptors maps come from the PD sources, is carried out by means of a basic analysis of the recorded signals, in particular in the time-frequency domain [22–23, 25, 29].

Based on these experiments, the authors undertook the task of designing and construction of a new measurement system The construction of a new measurement system was caused by the desire to build a measurement system that:

- Ensures registration of signals and analysis of recorded signals in accordance with the author's description containing the basic analysis of signals in the time, frequency, time-frequency domains and advanced analysis in the domain of discrimination threshold using

the descriptors with acronyms ADC, ADP and ADNC to identify AE signals and locate PD sources, especially in oil power transformers;
- Would be much cheaper than commercial solutions;
- Can be put into production.

2. Assumptions for construction of system

In the world, there are several major global manufacturers of AE testing equipment; the parameters of such measurement apparatus are described in literature [31–32]. In Poland, an apparatus for AE examination was constructed by IPPT PAN at Warsaw. There are many versions of AE analysers named DEMA, based on solutions of firmware coming from several years [33].

Contemporarily, the development stage of AE examination falls to the period of dynamic development of computer techniques which precipitate progression in the domains of quick measurement cards and handling data acquisition; it enables a considerable progress in accuracy of measurements (based on registration of signals in real time for wider and wider frequency bands) as well as in comprehensive analysis of AE signals and chosen AE descriptors.

The authors took up a challenge to build a modern 8-channel measurement system, using the technology of precise operational amplifiers with properties considerable better than μ A741 analysers (out-of-date nowadays, applied in DEMA [33]), measurement cards from National Instruments, LabVIEW programming environment and sensors made by Physical Acoustics Corporation [31]. The chosen number of eight measurement channels enables to efficiently research oil power transformers according to the (constructed by the authors) procedure of signal registration at measurement points forming a grid on the side walls of the transformers.

The main assumptions concerning the construction of 8AE-PD system are as follows:
- Programmable gain in a wide range from 20 dB to 65 dB;
- Frequency response from 25 kHz to 1 MHz (−3 dB);
- Possibility to supply external preamplifiers and integrated sensors, standard +12 or +28 V;
- Cooperation with PAC sensors of D9241A, R6, WD and WDI types;
- Sensors equipped with a stable magnetic mount of a new type;
- Wide operating temperature range from 0°C to +40°C (for preamplifiers: −20°C÷+80°C with dynamics > 70 dB and noise < 3 μV_{RMS} – shorted input, power supply < 20 mA);
- Power supply 230 V/50 Hz;
- Resistance to damage and external electromagnetic interference;
- Capability of outdoor operation.

A measurement system with the above parameters will have measurement capabilities similar to those described in literature [31–32].

3. Design and construction of 8-channel equipment for data acquisition

The designed and built mobile system is equipped with eight fully independent measurement circuits. Owing to that, it is possible to record signals from eight points placed on the tank of transformer. A block scheme of the complete measurement system is presented in Fig. 1, where the most important elements are marked.

Inside of one casing, the following elements are mounted: measurement amplifiers, a microcontroller, a system for formation of a reference signal as well as a complete chassis PXI 1033 which contains a measurement card PXI 6133 with a power supply and an integrated controller MXI-Express.

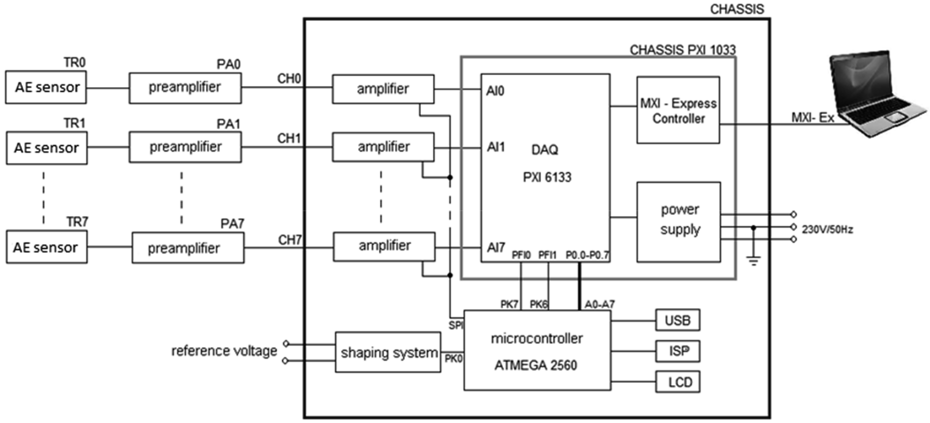


Fig. 1. A block scheme of the measurement system.

A signal from the measurement sensors, preliminary amplified in the independent preamplifiers, is delivered to the inputs of essential amplifiers (inputs CH0 – CH7). Two identical amplifiers are mounted on one plate. Such a solution facilitates disassembly of cards and ensures additional separations between particular measurement channels. Amplification of the amplifiers can be regulated in wide ranges by means of SPI bus. A reference signal is delivered to the inside microcontroller by means of a formation system. The microcontroller fulfils a few important roles:

- Controls operation of SPI bus (control of amplification and distinguishing of cards);
- Converts a reference signal and handles information transfer to DAQ card (parallel transmission A0–A7);
- Controls operation of an additional display LCD as well as USB and ISP ports;
- Initiates processing a signal by the card (PFI0 START TRIG line).

A line marked as PFI1 REF TRIG transmits a stroke signal during parallel transmission. USB and ISP interfaces are used in programming the microcontroller and enable communication, whereas the applied display LCD is used only for observation of values of chosen parameters and supply voltages. The display is placed inside the casing; it plays a supporting role. The parameters and resources of the applied ATMEGA 2560 microcontroller are sufficient to operate the system in real time.

A signal from the output of amplifiers is delivered to the analogue inputs (AI0–AI7) of measurement card PXI 6133 from National Instruments. This card enables to process 14-bit samples with a speed of 2.5 MS/sec in each of 8 channels. In the warp mode, the speed increases to 3MS/sec/channel. The warp mode is an acquisition mode that is supported by some A/D converters. It enables a shorter sample time per channel but has some restrictions. Additionally, it is possible to work in four ranges of input voltages: from ±1.25 V to ±10 V. The software written in LabVIEW environment enables to control the measurement card and the inside microcontroller. It contains programs for monitoring of signals and registration of data. The measurement card is placed in the dedicated chassis PXI 1033 together with the power supply. The MXI – Express interface ensures communication with the computer. An additional notebook is equipped with a PCMCIA PXI Express Card 8360 from National Instruments. The data from the card transmitted to the computer are written in proper sets on the hard disc. The whole system is supplied from the power network 230 V/50 Hz. Additionally, there is possible to apply the same voltage as a reference signal (internal switch).

4. Measurement amplifier

Eight measurement amplifiers are mounted on four independent plates. A block scheme of the measurement amplifier is presented in Fig. 2. The system has been designed in such a way so that the supply of preamplifiers by means of a constant component +12 V should be possible. This solution proves to be the least troublesome and it eliminates the necessity of additional wiring. The *low-pass filter* (LPF) assures resistance to a variable signal component. The first amplification stage IC1 with a small amplification (approx. 3 V/V) assures matching to impedance of the conductor.

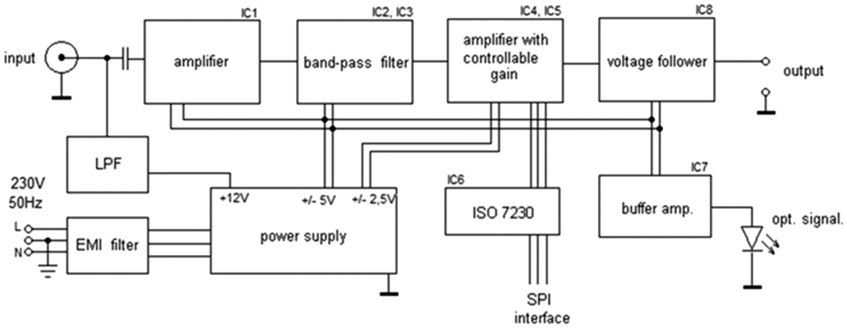


Fig. 2. A block scheme of the measurement amplifier with its supply system.

The band-pass filter has a cascade structure, composed of two independent active filters: low-pass and high-pass ones. The classic Sallen–Key's topology of second order is used in both cases. The amplitude-frequency characteristic of the band-pass filter is presented in Fig. 3. The lockout frequencies are 23 kHz and 1.35 MHz at a drop of −3 dB. The main element determining the quality of complete amplifier is the circuit with controllable amplification (IC4, IC5). In order to obtain a small power take-off, the LMP8100 systems from National Semiconductor are used. The current consumption is not greater than 5.5 mA at a symmetrical supply of ±2.5 V. An advantage of the system is a wide range of amplification from 1 V/V to 16 V/V with the possibility of changing its value with a 1 V/V step. The cascade connection of two systems enables to regulate

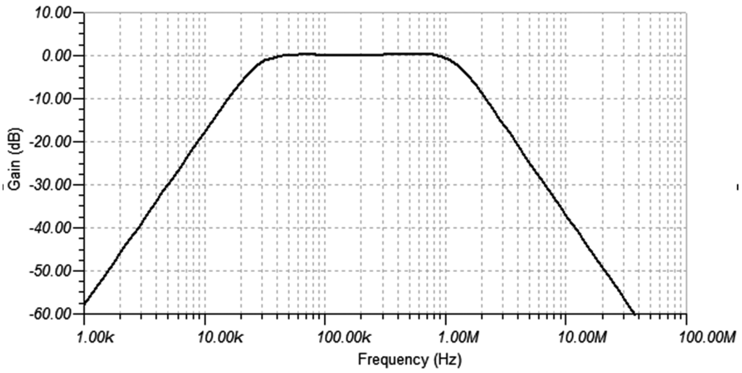


Fig. 3. The amplitude-frequency characteristic of the pass-band filter constructed on the basis of operational amplifiers IC2, IC3.

amplification in a wide range from zero up to 68 dB. The LMP8100 system is able to pass to the stand-by state when the current consumption falls to 20 μA. IC4 and IC5 systems are connected by SPI bus in a such a way that there is possible to transmit one data stream to four LMP8100 systems (a so-called daisy chain configuration).

The amplification setup for four systems needs transmission in series of 4 bytes by SDI line. SCK and /CS leads are connected to four LMP 8100 systems in the frame of one plate. The microcontroller is responsible for appropriate control of the systems. The triple-channel digital isolator IC6 ISO7230 from Texas Instruments assures galvanic insulation of SPI bus for a selected amplifier. In such a way two purposes are obtained: avoidance of harmful coupling between measurement circuits and minimization of the occurrence of inter-channel cross-talks as a consequence of using the common SPI bus. IC6 system ensures also separation of circuits from the digital mass DGND of the microcontroller and the mass GND of the whole controller.

IC8 system works in a voltage follower configuration and delivers a signal to the analogue input of the measurement card. In order to discover in an easy way either a possible damage of the conductor or the appearance of an uncertain connection, the system is equipped for optical signalization with LED diode. IC7 amplifier ensures control of the diode when the signal from a given converter is removed.

One of important problems during design of the system turned out to be a proper arrangement of elements on a printed-circuit board. Eventually, a very good repeatability of parameters of measurement circuits has been obtained. Examples of frequency characteristics of the amplifier in CH0 and CH1 circuits are presented in Fig. 4. These characteristics have been examined for different values of amplification: 20 dB and 40 dB, from the level of process control at LabVIEW. The measurement circuits have a proper transfer band: from about 23 kHz to 1 MHz.

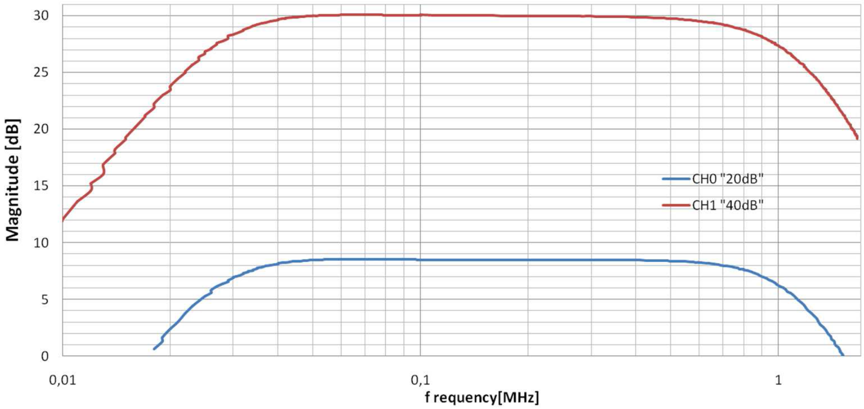


Fig. 4. Amplitude characteristics of measurement circuits CH0 and CH1.

The power supply is arranged on the amplifier plate. According to the idea which comes down to assurance of maximal separation between channels, an independent power supply is used for each circuit. For the sake of possible disturbances, interferences and inter-modulations there are neither converters nor impulse stabilizers. The traditional solution was chosen – with a grid transformer and continuous stabilizers. Additionally, hybrid EMI filters are installed from the side of power network.

5. Measurement preamplifier

Many years' experience in application of standard preamplifiers which cooperate indirectly with transducers proves some weaknesses of universal solutions. The task of a preamplifier is not only to amplify a signal but also to secure a proper input impedance, stability and capability to eliminate disturbances. In practice, an important element is also a suitable kind of casing of preamplifier and the way how it is fastened to the tank of transformer during measurements. The concept of constructing a measurement preamplifier is presented in a block scheme (Fig. 5).

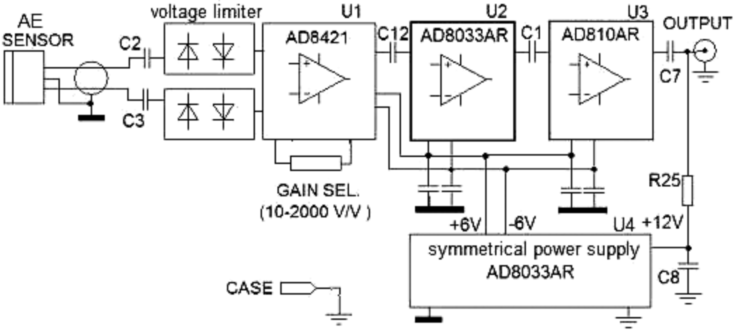


Fig. 5. A block scheme of the preamplifier with a converter and a connecting cable.

Electromagnetic disturbances coming from the power system that influence the measurement system are caused mainly by cables connecting sensors with preamplifiers as well as preamplifiers with amplifiers [35–36]. The influence of these disturbances was limited using cables with double screening. The problem associated with passage of equalizing currents and rise of oscillations in the system was solved by connecting the concentric cable into the mass only from the side of preamplifier (Fig. 5). Owing to grounding the measurement circuit with screens of the measurement cables and instruments the equalizing micro-currents can flow. Protection of the preamplifier inputs was achieved in a typical way, connecting in parallel two diodes to each input [35–36]. In such a way the input voltage, between each input and the mass, is limited to a level of ±0.6 V. A pair of quick signal diodes of BAV99 type, characterized by a small capacity of $C_T = 1.5$ pF (for 1 MHz), has been chosen. Such a choice is determined by a small leakage current which should not be greater than 2.5 μA.

The preamplifier is adjusted constructively to cooperation with sensors showing a great impedance with the differential output. An advantage of such an output is its great resistance to electromagnetic disturbances [34]. The application of a classical differential amplifier based on one operational amplifier does not satisfy the requirements. The main cause is the problem with assuring a great amplification and – simultaneously – a great input resistance. In order to obtain a great input resistance resistors of great resistances should be used at the input. In that case, in the feedback circuit resistors with very great values of resistance must be used. However, in practice it appears that such a solution is very inconvenient for its thermal instability and voltage drops caused by polarization currents. Another significant difficulty revealed during construction of a simple differential amplifier is a limitation of the value of sound reduction factor of summary signal CMRR (*Common Mode Rejection Ratio*), caused by asymmetry of the pair of resistors. Tolerances of resistors of the order of 0.1% can cause a decrease of CMRR to the value of 65 dB, even if this factor for a single operational amplifier is infinite. Eventually, using a simple differential amplifier, it is impossible to build a system with a great CMRR factor (ex. greater than 100 dB), very great amplification (greater than 500 V/V), as well as with a very small drift of the voltage and non-balanced current. Therefore, a more complex structure of measurement amplifier is applied in the designed system.

The verified configuration based on the classic 3-op-amp topology, was chosen. This topology consists of two stages: a preamplifier to provide differential amplification, followed by a difference amplifier that removes the common-mode voltage. The choice of resistors at the input gain stage does not influence the value of CMRR factor of the system, but such a value depends on accuracy of choice of resistors at the output stage and on CMRR factor of the difference amplifier stage. The system is designed in a such a way that amplification should be great at the input stage and small in the difference amplifier stage. Owing to that, it is not necessary to apply resistors with great resistances at the input stage and therefore their choice is considerably easier. Amplification of the system can be easily regulated by means of the external resistor RG (gain selection in Fig. 5). For the sake of very good parameters of a monolithic system of AD8421BRMZ type from Analog Devices, it was justifiable to give up construction of the amplifier based on discrete elements. The internal structure of the high-speed instrumentation amplifier AD8421BRMZ is based on the classic 3-op-amp topology.

U1 system in Fig. 5 is the first stage amplifier with programmable gain from 1 V/V to 10000 V/V. In this case, gain from 10 V/V to 2000 V/V is sufficient, which corresponds to the external resistor values of 1.1 kΩ to 5 kΩ, respectively. In terms of other parameters such as CMRR (max 140 dB @ 60Hz), Icc supply current (2.3 mA) and spectral density of the noise voltage (3nV /√Hz), this system is definitely the better choice than the INA110KP system used in construction of the existing preamplifiers. Note that the INA110KP system used so far is available in the DIP16 housing, making it impossible to perform an effective miniaturization of the preamplifier. The AD8421BRMZ is housed in a practical 8MSOP housing. Fig. 6 shows the amplitude-frequency characteristic of the preamplifier obtained by simulation. During the design work, particular attention was paid to the analysis of the system in terms of its own noise.

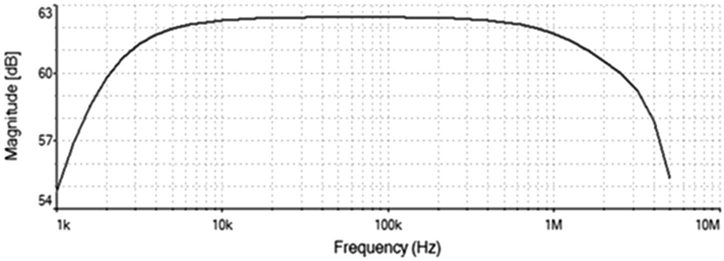


Fig. 6. The amplitude – frequency characteristic of AD8421BRMZ preamplifier (Multisim).

The results of preliminary calculations accomplished in accordance with the established methods [35, 36] indicated that the noise level converted to the input of the multistage amplifier should not be greater than 20 $\mathrm{nV}/\sqrt{\mathrm{Hz}}$.

The second stage of preamplifier (Fig. 5) is U2 system with a constant amplification G = 11 V/V. It was built based on a fast operational amplifier AD8033AR from Analog Devices. The third amplification stage U3 works in the voltage follower configuration. Its task is matching the preamplifier impedance to the impedance of concentric cable conductor (50 Ω). It was decided to select a popular operational amplifier AD810AR from Analog Devices. It is characterized by a small level of noise (2.9 nV/(Hz)1/2) and a small consumption of the supply current (approx. 8 mA).

The preamplifier is equipped with a symmetrical power supply of a constant voltage which task is converting the constant voltage +12 V into two parallel voltages ±6 V (with opposite polarization), symmetrical to the reference potential GND. A block scheme of the symmetrical power supply is presented in Fig. 7. The preamplifier (+12 V) is supplied from the block of amplifiers and the supply is delivered as a constant component by means of a concentric cable. Such a solution turns out very practical in environmental conditions because it enables to limit the number of additional conductors. It is also not insignificant that in such a way an additional separation between each measurement channel is obtained.

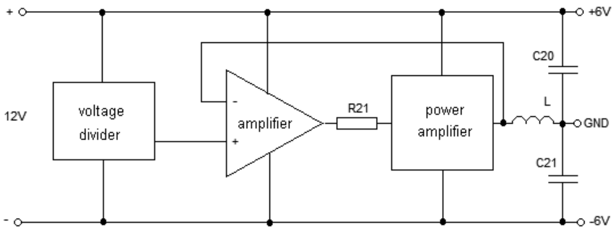


Fig. 7. A block scheme of the symmetrical power supply.

Obtaining a reference potential is assured by the voltage divider composed of the same resistors. In parallel to these resistors there are installed condensers in order to limit the dynamic input impedance of the system. Resistor R21 limits the output current of operational amplifier and protects against a possible excitation. Condensers C20 and C21, decreasing its output impedance for great frequencies, are employed to improve stability of the system. The power amplifier is built on bipolar transistors and works in a classical push-pull configuration.

Figure 8 shows the amplitude-frequency characteristics of measurement preamplifiers constructed with AD8421BRMZ and INA110KP circuits. The characteristic of the DEMA preamplifiers, which were previously used in the diagnostics of transformers, is also included in Fig. 8.

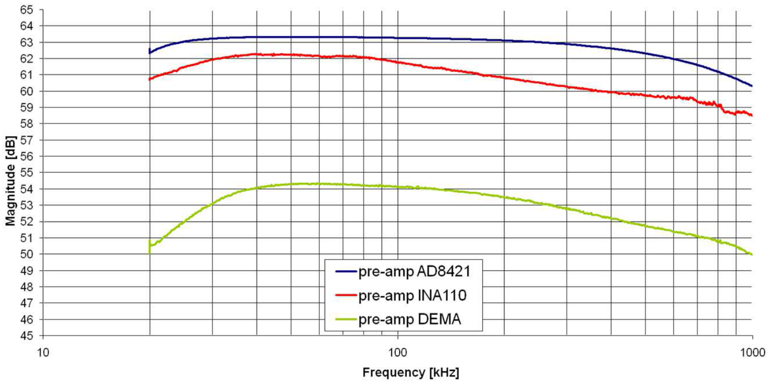


Fig. 8. Comparison of amplitude-frequency characteristics of selected preamplifiers.

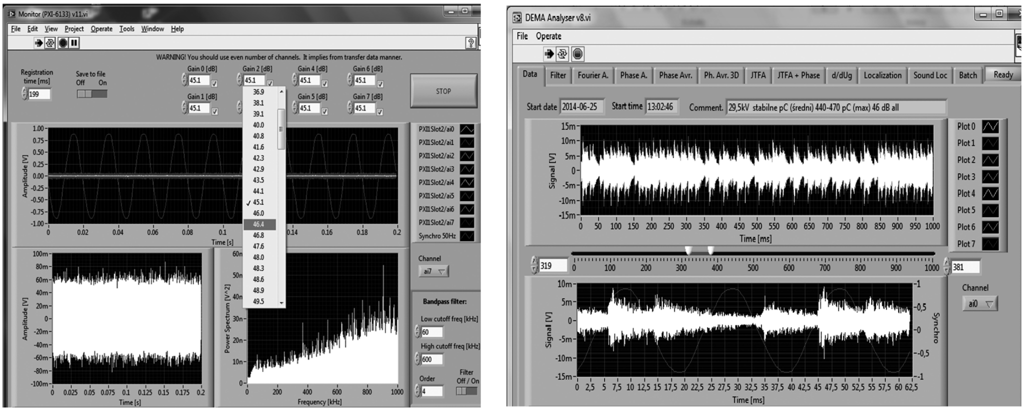
The preamplifiers designed and built with AD8421BRMZ system provide cooperation with wideband WD type (100 kHz – 900 kHz) and D9241A type (30 kHz – 180 kHz) sensors.

The preamplifiers with INA110KP system (built as the first approach) have sufficient parameter values to work with sensors operating in a frequency range from 20 kHz to 100 kHz.

6. Software

Software for 8AE-PD computer measurement system was written in LabVIEW environment and it consists of software for the measurement card and software for analysis of registered signals.

Software of the measurement card ensuring control of the measurement card and the internal microcontroller contains a program for monitoring of signals and data recording. The user interface of Monitor (PXI-6133)v11 program is presented in Fig. 9a.


a)

Monitor (PXI-6133) v11.vi

WARNING! You should use even number of channels. It implies from transfer data manner.

Registration time [ms]: 199

Gain 0 [dB]: 45.1
Gain 1 [dB]: 45.1
Gain 2 [dB]: 45.1
Gain 4 [dB]: 45.1
Gain 5 [dB]: 45.1
Gain 6 [dB]: 45.1
Gain 7 [dB]: 45.1

Channel: ai7

Bandpass filter:
Low cutoff freq [kHz]: 60
High cutoff freq [kHz]: 600
Order: 4

b)

DEMA Analyser v8.vi

Start date: 2014-06-25
Start time: 13:02:46
Comment.: 29,5kV stabilne pC (średni) 440-470 pC (max) 46 dB all

Channel: ai0

Fig. 9. The user interfaces of 8AE-PD computer measurement system programs: a) Monitor PXI-6133v11; b) DEMA Analyser v8.

The user interface of Monitor PXI-6133v11 program enables to select a monitoring or recording mode. In the monitoring mode there are active canals numbered from 0 to 7, whereas the reference channel SYNCHRO 50 Hz is chosen automatically. Amplifications are determined in each of the channels by the computer. Commentaries can be added to a recorded file. Recording data to the file is carried out after determination of the folder in which the files are written together with the measurement data. The data are written to the file at a speed of 2 mega-samples per second in each of 8 channels.

The recorded signals are subjected to basic and advanced analyses. For this purpose the software called DEMA Analyzer v8 was built. The user interface of this program is presented in Fig. 9b. Analysis of a recorded signal starts with filtering the signal in a defined frequency band. Then, the recorded signals are analysed in the time, frequency, time – frequency and discrimination threshold domains. Analysis in the time domain enables calculations within levels named as: Phase A., Phase Avr., Ph. Avr.3D. Analyses in respective domains are named: in frequency domain – Fourier, in time – frequency domain – JTFA, JTFA+Phase, in threshold domain – d/dUg. Calculations with DEMA Analyzer v8 program are performed for a selected level or for a set of levels defined in a batch file.

7. Design and construction of specialized attachments of AE sensors to side surfaces of tank of transformers

It is important that attachment of a measurement sensor to the tested object is stable. A new model of fastening holder, with a set of neodymium magnets, has been worked out [37]. Photos of the preamplifier with AE sensor in a casing as well as the preamplifiers and AE sensors fastened to the wall of the tank of a laboratory model of transformer are presented in Fig. 10.

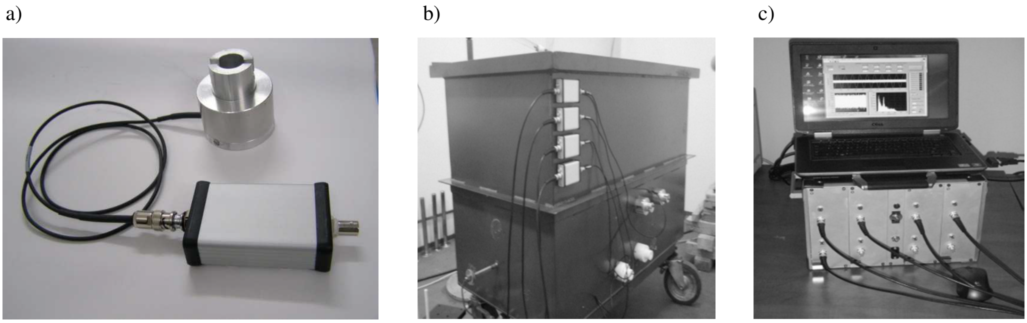


Fig. 10. Photos of: a) the preamplifier and AE sensor in a casing; b) the preamplifiers and AE sensors fastened to the wall of the laboratory tank; c) the measurement system – the panel of leading cables and computer.

8. Laboratory research carried out using 8AE-PD measurement system

The built-in measurement system has been calibrated by the Hsu–Nielsen method, and then used during the laboratory research. The research was carried out on the measurement stand whose schematic diagram is shown in Fig. 11. The stand consists of: a test set generating high voltage (with a protection and regulation system), the PD computer measurement system using the electrical method employing TE 571 measurement instrument with additional equipment, a steel tank in the form of a cuboid, a modelled PD source and the 8AE-PD measurement system.

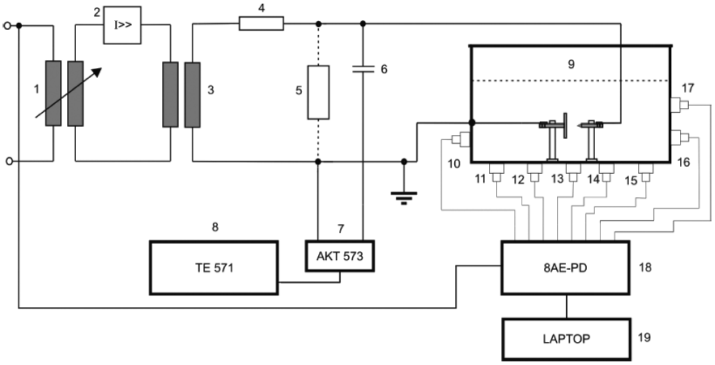


Fig. 11. A schematic diagram of the system for generating and testing PDs examined by the electrical and acoustic methods: 1 – autotransformer; 2 – overcurrent protection; 3 – high-voltage transformer; 4 – protective resistance; 5 – calibrator KAL 451; 6 – coupling capacitor; 7 – coupling four-terminal network AKT 573; 8 – TE571 system; 9 – tank with the PD source; 10–17 – AE sensors; 18 – measurement system 8AE-PD; 19 – recording computer.

Examination of PDs coming from the constructed modelled source was performed in parallel by two methods: the AE method and the electrical method. The results obtained with the electrical method, particularly the measurement of the apparent charge introduced by the PD source are the reference for the results obtained with the AE method.

During the research, for each measurement situation, the signals were recorded simultaneously in all measurement channels of the 8AE-PD system. The duration of recorded signals was 1 second and the recording was performed several times. Fig. 12 shows the calculated characteristics of an example of registered AE signal originating from PD generated by the modelled source.

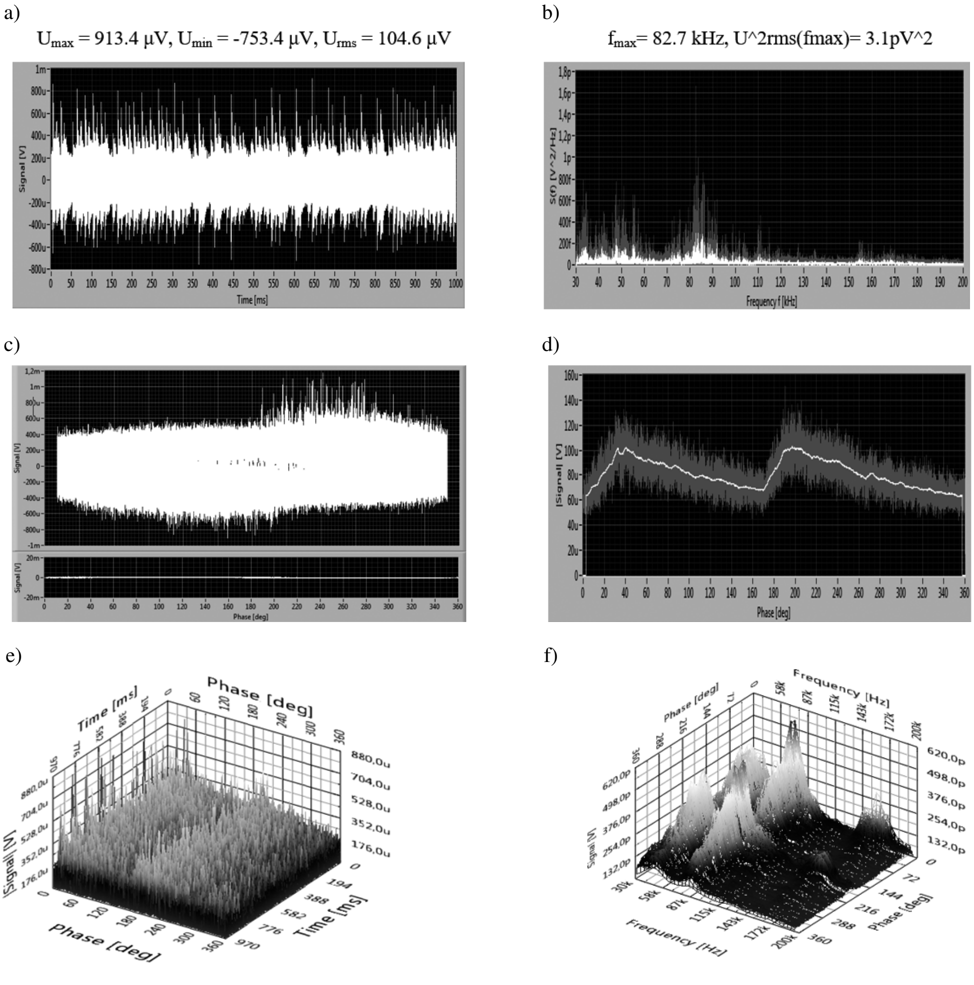


Fig. 12. A basic description of an AE signal recorded in the measurement channel with the AE sensor D9241A type at measurement conditions U = 29.5 kV, Q = 380 pC: a) the signal after filtration (U_{max} = 913.4 µV; U_{min} = 753.4 µV, U_{rms} = 104.6 µV); b) the characteristic of signal spectral power [V^2/Hz] vs. frequency [Hz] (f_{max} = 82.7 kHz, $U^2_{rms}(f_{max})$ = 3.1 pV^2); c) the signal phase characteristic; d) the averaged phase characteristic; e) the phase-time characteristic; f) averaged STFT spectrograms.

Figure 12 presents characteristics of an example of registered signal in the time, frequency and time-frequency domains. Analysis of these characteristics determines the following signal properties:

a) main bands (according to Figs. 12b and 12f): 20–60 kHz, 70–115 kHz, 155–180 kHz;

b) periodic nature of PDs is consistent with the period of supply voltage (according to Figs. 12c–12f); during the average period of supply voltage the maxima in the signal occur twice;

c) phase-time characteristics (Fig. 12e), apart from the periodic nature of PDs, visible as two "corridors" of higher signal values for respective phase intervals, reveal the stochastic nature of PDs' phenomena causing fluctuation of signal amplitude values for subsequent periods of supply voltage.

These characteristics show the properties of AE signal coming from PDs, but at the same time show the capabilities of 8AE-PD measurement system.

A detailed presentation of the results obtained during calibration and using 8AE-PD measurement system during laboratory examination of PDs is given in [38], where there are determined the limit values of the apparent charge introduced by the PD source for which the recorded signal is identified as that coming from PDs with a value of 20 pC.

9. Conclusions

The original 8AE-PD computer measurement system designed and constructed by Authors has the following properties:

- built of modern sub-assemblies;
- equipped with 8 measurement channels;
- amplification within each channel is fully controlled in a program way and has 65 dB dynamic of change of the input signal;
- provides a wide range of frequencies of recorded signals (from 25 kHz to 1000 kHz);
- the software operates in LabVIEW environment and ensures: monitoring of signals; registration of data in real time (within a band of 25–1000 kHz), basic and advanced analysis of recorded signals;
- the basic analysis is carried out in the time, frequency and time-frequency domains and presents general properties of AE signals coming from PDs;
- the advanced analysis is performed in the discrimination threshold domain, providing identification of signals coming from different acoustic sources as well as location of these sources in the examined transformers in terms of (defined by authors) descriptors (ADC, ADP) and maps of these descriptors on the side walls of the tested transformer tank;
- capability of outdoor operation;
- resistance to mechanical damages.

An example of typical results of laboratory tests carried out with the use of the built-in measurement system is presented. A detailed analysis of laboratory tests with modelled PD sources presented in [38] determined the limit values of the apparent charge introduced by the PD source for which the recorded signal is identified as that coming from PDs' source. This analysis enabled to draw a conclusion that it is possible to identify a signal generated by the modelled PD source that introduces apparent charge with a value of 20 pC.

The results obtained from laboratory tests and conclusions from these tests confirm the applicability of the presented measurement system for PD diagnosis of oil power transformers performed with the AE method.

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