Application of wavelet analysis in partial discharge detection in solid insulation systems of power equipment

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Abstract. In the paper, analysis of selection methods of partial discharge measurement data is done. Analysis of pulse shape of partial discharge is made. Selection method with application of wavelet analysis is proposed. Required properties for a mother wavelet is formulated. Experimental research confirmed the efficiency of the method of partial discharges signals selection by wavelet transform.

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Introduction

The reliability of modern high-voltage equipment is largely determined by the reliability of its insulation.

Traditional methods of the diagnostic of the insulation condition of the power equipment, power transformer (measurement of dielectric losses and capacitance of winding insulation, measurements of insulation resistance, of absorption coefficient, etc.) are not effective in a some cases, because they are aimed at identifying the common condition of isolation, while local defects, which, as a rule, occurs current circuit, cannot be detected. These methods are economic ineffective, because they are based on a preventive repair system. Thus equipment diagnostics are executed not on the actual condition of the equipment, and through certain standard time frames and it is connected with high labor consumption. Additionally, the output diagnosed equipment from the work to be difficult in some cases, if the production process is incessant, for example.

One of the most effective methods of diagnostics of the electrotechnical equipment with solid insulation is non-destructive method of isolation diagnostics on characteristics of the partial discharge (PD). Thus, it is possible to maintain control of the current condition of the equipment under operating voltage.

Nowadays the method of isolation diagnostics on the partial discharges (PD) is widely used in laboratories and in the manufactures of transformer equipment at the insulation quality control of the manufactured products in Russia [1] and in many other countries [2]. However, the insulation control of the operating electrical equipment by partial discharges are still used relatively rarely, due to the various hindrances, which level in the existing facilities are significantly higher than in benchmark testing, and conventional technique of separation of PD signals from interfering signals are not yet exist. Thus, the problem of separation the interfering signals at the measurement signals of the PD in operating conditions is relevant.

1. The analysis of existing selection methods of PD signals

The main methods which separates the PD signals from interfering signals are:

1) Frequency method. This method is based on the correct selection of frequency range in which the ratio of signal/noise is maximum, i.e. registration is not performed in the frequency bands characterized for the interfering signals.

By setting the appropriate frequency filters we can suppress interference from sources HF-communication, telecommunication, thyristor trunsducers, etc.

The disadvantage of this method is that the interference of different frequency spectrum are possible at a various controlled entities, that in the general case requires determination of the interference frequency characteristics.

2) Temporarily (phase) selection. The method is based on the signals registration in certain periods of time, synchronized with a certain phase of voltage at the object (method of the time window). The increase in the ratio signal/interference is ensured by the fact that the intervals with a high level of noise are excluded at the measurements [3]. Obviously, this method is effective only in those case when the moments of the PD and noise occurrence do not coincide. For example, voltage signals of the corona discharges in the positive half-cycle phase on the order more, than in the negative. Therefore, the ratio signal/interference will be much greater only

when the measurement will in the negative half-cycle. Also this method is effective at the interference suppression from thyristor excitation of the generators regulators.

3) The analysis of amplitude-phase diagrams (APD). The signals of the corona discharges have an especial APD significantly differ into positive and negative half-cycles of voltage. PD signals, as a rule, have almost symmetric distribution. Analysis of APD signals and their temporal parameters allows to cut off the signal of the corona discharge, having a very distinctive shape and easily identifying at APD [4]. The range of phase angles, in which signals of a corona are observed, is small, and the probability of complete coincidence APD signals from defect and corona is small. At sufficient statistics (at the sum of the measured data of more than 500 network periods) can be measured the PD signals, which amplitudesare lower in 10 - 100 times than the amplitudes of the corona discharge impulses. Signals from the spark discharges in the elements of the magnetic circuit have also highly characteristic of APD, however, the amplitude and intensity of these signals can be large, and to their background, to allocate the PD signals from defects of high-voltage isolation is quite difficult. But, though the defects of the magnetic circuit are not related to isolation, their detection is also one of the problems of diagnostics. In addition, strong vibration of the magnetic circuit leads to a rather specific dependence of the APD of these signals from the time that allows to identify this type of defect.APD method is a powerful tool and allows to not only separate the PD signals from the corona signals, but also to distinguish between PD signals from various sources. The disadvantage of this method is difficulties with separation from noise, having a wide spectrum, that leads to the impossibility of registration of the PD small amplitudes. However, APD is a convenient tool for graphical data representation.

4) Background subtraction. Signals of external interference, in general, do not differ from the PD signals, as their source may be PD in the surrounding equipment. Selection of PD signals in this case can be based on a single measurement signals of external interference at the voltage absence in the controlled object (background measurement) and at the voltage supply (measurement of the sum of the PD and an external interference signals). Subtraction of the measurement's results allows select only the PD signals (a common signal minus the background). The disadvantage of this method is that the intensity of the interference may changed in time, and consequently, the measurement of the PD in some moments of time may be unreliable. However, according to the data from [4], the method of background subtraction allows significantly reduce the influence of external noise and select the PD signals.

To suppress the corona discharge signals cannot be done by this way, because it, like the PD, appears only at the voltage applying to the object. Therefore, the separation of corona discharge signals is made, as a rule, by using of several methods, such as the analysis of the APD, frequency method and the method of selection of the signal form. The disadvantage of PD signals selection by method of the background subtracting is the necessity to shutdown equipment that is not always economically justified.

5) Amplitude method. At this selection method the conclusion on the PD presence is made at a significant (10 - 20 dB) exceeded of the signal level in comparing with data from previous measurements or with the signal levels on similar objects. This method is the most simple and allows reveal the intensive PD, but it has a low sensitivity.

6) Selection using different sensors. The method is based on the comparison of signals from various sensors, such as electrical channel with signals of acoustic and electromagnetic channels of registration. This method is most often used in the research to practice [4, 5] because it provides a sufficiently clear signal selection. The disadvantage of this method is its high cost, because it requires multiple channels of registration, and the complexity of the process, because it requires to install about 10 different sensors for a clear selection [4].

7) Selection of the form PD signal. The PD signal has an especial form of the voltage impulse [6,7,8]. Comparing the original form - templates – PD impulse with the received signal, we can register the PD presence. Using this method it is possible to distinguish different types of interference, the corona discharge, as well as views of the PS, the size and form of incorporation. Also, using the Selection of the PD signal form it is possible to determine the defect localization. Currently, however, such selection requires to apply sophisticated technical tools that are often justified in research.

8) Selection of the signal polarity. Comparison of polarities of two impulses, as a part of the diagnostic system, widely used in practical measurements. This method is used in diagnostic measurement in cable lines, bus bars, KDS [5].

The most promising method of the PD signals selection to the authors is using of wavelet analysis [9]. When using this method, in fact related to the method of selection by the impulse shape, due to the powerful mathematical apparatus enables to eliminate the main disadvantage of selection of the form of the momentum associated with the use of sophisticated technical means. The PD registration in this case,we can produce with the help of quite available analog-to-digital convertersAlso the advantages of the method of wavelet transformation is the ability to determine the location of the defect [6], and also to make selection of interference on the equipment online.

2. Analysis of the PD impulse form

It is necessary to define the PD impulse form for the successful solution of the task of the PD signals selection at the pulse form. Based on the study objectives and main requirements to the schemes of the PD registration, the scheme of the test installation was developed and presented in figure 1.

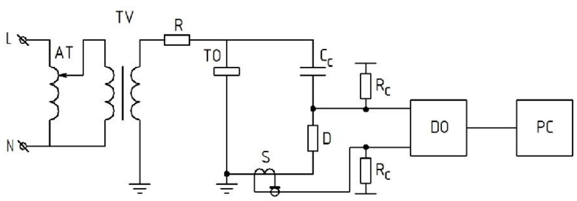

Figure 1. Electric scheme of the test installation

The coupling capacitor C_C is designed to contour with a small resistance to the currents of the partial discharges. As the coupling capacitor are used four sequentially connected capacitor, each of them has voltage rating of 15 kV and total capacity of 825 pF. Voltage divider *D* is designed for synchronization of the PD signals with the voltage on the test object for registration phase parameters of the PD pulses. The induction electric sensor in the form of high-frequency current transformer series RFCT-1 is adopted as the partial discharges sensor *S*. Voltage 10 kV feeds at thetest object *TO* through high-voltage electrode. The PD sensor *S* is installed on the wire connecting the point of the capacitor lowest potential with the ground. The screen of the sensor is also grounded to reduce interference and improve safety. Voltage divider *D* in the form of a resistor 40 Ohms is connected with the coupling capacitor in series. The resistance of the divider is much less than the resistance of the coupling capacitor at the frequency of 50 Hz, this fact provides the transfer of the safe voltage signal to digital oscilloscope *DO*. Ground point is connected to the laboratory common ground loop. The voltage transformer *TV* with a conversion ratio of 100/50000 V is used as a source of the test voltage. Test voltage regulation and control of its magnitude is on the side of low voltage by adjusting autotransformer *AT*. The sensor output RFCT-1 is connected to a digital oscilloscope *DO* using coaxial cable type RK-50 and BNC connector. A signal from the voltage divider is passed to the input *DO* on twisted pair. The matching resistances R_C of 50 Ohms are used on the oscilloscope input. The signal from the *DO* is transferred to a personal computer*PC*.

A samples of the cast insulation based on epoxy resin which is widely used in modern elements of electrical engineering complexes in the form of plates was used as a test object *TO*.

Digital oscilloscope with a bandwidth of 25 MHz; maximum sampling frequency in real time - 100 MHz, equivalent mode - 2.5 GHz was used for measurement of partial discharges.

Signal from the PD sensor goes to the first oscilloscope channel, signal from the resistive voltage divider - to the second channel. Oscilloscope synchronizes via the second channel, thus ensures sustainable of the PD registration relatively to the sinusoid of supply voltage. In this case it should take into account that register sine wave ahead of a sinusoidal voltage at the isolation sample on 90˚ as shown in [10].

The oscilloscope has a USB interface by which the measured data is transferred to computer. Software “Oscilloscope Software” allows to convert the received data into “Excel”.

Equivalent circuit of the measuring part of the installation, taking into account stray capacitances, is presented in figure 2.

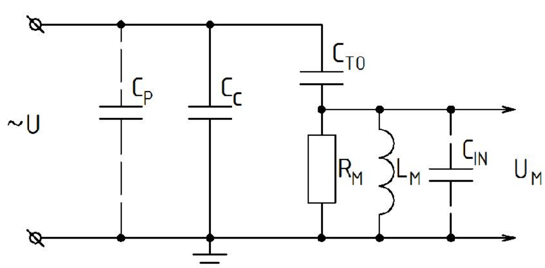

Figure 2. Equivalent circuit of the test installation

At the PD occurrence in the *TO* the voltage on the C_{TO} will change according to the expression:

$$\Delta U = \frac{q}{C_{TO}}$$

where *q* is apparent PD charge. In this case discharge current flows $i(t)=dq/dt$, in the initial moment of time $i(t)=0$.

Measurement part of the scheme includes resistances of the PD sensor R_M, L_M, the input capacitance of the measuring device C_{IN} and represents the quadripole, the operator resistance of which is determined by the expression:

$$z(p) = \frac{C'_{IN}(p^2+p/\tau_{SC}+\omega_0^2)}{p}$$

where p is a complex frequency, [tau]$_{sc}$ is attenuation time constant of registration scheme:

$$\tau_{SC} = R_M C'_{IN} = R_M \cdot \left(C_{IN} + \frac{C_C \cdot (C_P + C_{TO})}{C_C + C_P + C_{TO}} \right);$$

$$\omega_0 = \sqrt{\frac{1}{L_M \cdot C'_{IN}}}$$

where C_P is a parasitic capacitance.

The registries signal will take the form of the damped oscillations:

$$U_{IN}(t) = z(p) i(t) \cdot e^{-t/\tau_{SC}} \left(\cos \omega_0 t - \frac{\delta}{\omega_0} \sin \omega_0 t \right)$$

where $\delta = R_M / 2L_M$.

Form of the PD impulse signal on the input of the measurement device, with account the parameters of the developed measurement setup, is shown in figure 3.

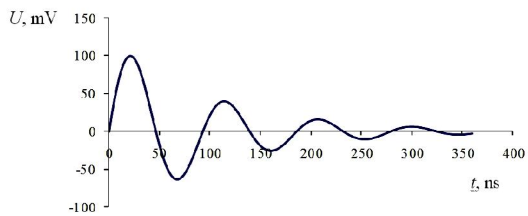

Figure 3. Impulse form of the simulated PD signal

3. Selection of optimal mother wavelet

Successful solution of the problem of separation of the PD signal from the interference is connected with the choice of motherwavelet - basis functions [psi]*(t)*, the most fully describes the shape of the PD impulses. Based on the received data of the PD impulse form (figure 3), to the PD signal as the basic functions of the wavelet transform (WT) has established requirements such as compactness, limited duration and asymmetry for the successful analysis. A necessary condition for the implementation of signal recovery using WT is basis orthonormality [8].

On the basis of analysis of different wavelets, it was concluded that the Daubechies wavelets are optimal for selection of the PD signals.

The proposed method of the PD signal selection from the interference is the following. The continuous wavelet transform (CWT) of the initial signal $f(t) \in L^2(R)$ is determined by the well-known expression:

$$CWT_\psi{}^{f(s,\tau)} = W_\psi{}^{f(s,\tau)} = \frac{1}{\sqrt{|s|}} \int f(t) \psi^* \left(\frac{t-\tau}{s} \right) dt, \quad s, \tau \in \mathrm{R}, s \neq 0$$

where s is the scale operator (the operator of the base functions compression), [tau] is the time shift operator, the symbol "*" means the complex conjugation.

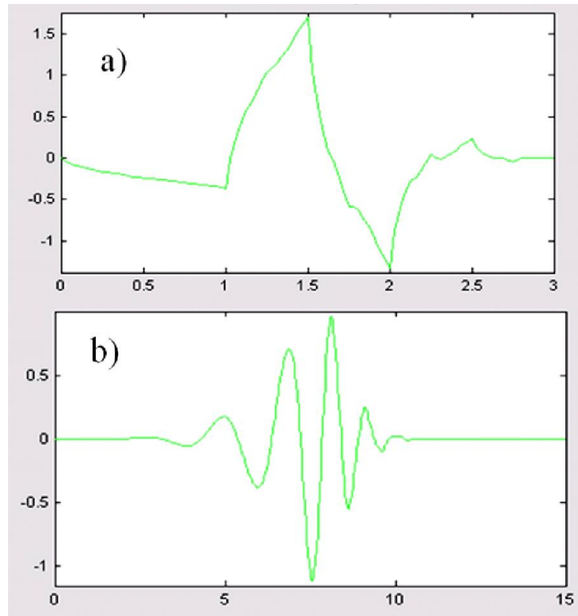

Figure 4. Forms of the Daubechies wavelets a) the second degree wavelet (db2), b) - the eighth degree (db8)

Value $W_\psi{}^{f(s,\tau)}$ represents the similarity degree between the study part of the signal *f(t)* and scaled and shifted wavelets. The scaling, as the mathematical operation, expands or shrinks the signal. The wavelet function of each scale s is multiplied with the signal and is integrated in the whole time interval. The multiplication of the wavelet with the signal in the interval, where this component is present, give a relatively high value, if the wavelet coincides with the PD signal, i.e. the spectral components, corresponding to the current value of the scale, are present in the signal. In another case the multiplication will have a small value or will equal to 0. On the basis of non-null values $W_\psi{}^{f(s,\tau)}$, i.e. values of base parameters s and t, the reconstruction of the original PD signal is realized by inverse wavelet transform of a signal *f(t)* according to the expression:

$$f(t) = \frac{1}{c_\psi^2} \int_s \int_t W_\psi{}^{f(s,\tau)} \frac{1}{s^2} \psi \left(\frac{t-\tau}{s} \right) dt ds$$

where c_ψ is the admissibility constant.

4. Aplication of wavelet transform for PD signal extraction

For experimental data processing, the developed software [10] provides implementation of some functions, such as the loading of measurement data array, selection of signals of the partial discharges from interference on the basis of wavelet-analysis, measurement of the apparent charge; calculation of partial discharges characteristics: power and average current; presentation of the PD data in the form of amplitude-phase diagrams; the construction of the amplitude-frequency characteristic (AFC) and the amplitude-phase (APC) characteristics. Amplitude-frequency characteristic is the distribution of the number of the PD impulses *N*by values of their apparent charges. Amplitude-phase characteristics express the dependence of the maximum value of the apparent charge from the phase voltage.

To confirm the efficiency of the developed software with the PD signals selection by method of the wavelet transforms was hold simulations of the signal purification in the applied package "Matlab". To do this, into the program was loaded simulated PD signals (figure 3) of different amplitudes, was introduced the interference signals of any size, then signal was cleaned.

The results of program work are presented in Fig. 5.

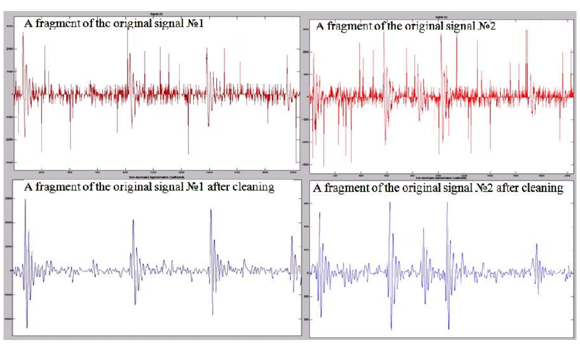

Figure 5. Results of computer simulation of partial discharge signals selectionby method of wavelet-analysis

The results of the developed program's work presented in figure 6, show the effectiveness of PD signals selection using. The number of simulated PD impulses as in the original signal and as in the signal after wavelet transforms coincide. The power of partial discharges P_{PD} in the original signal was 25 mW, and in a cleared signal - 28 mW, that is, the relative accurancy of the PD signals selection on the basis of wavelet-analysis was 12%.

A typical form of the PD impulses, registered in the scheme (Fig.1) is presented in figure 7.

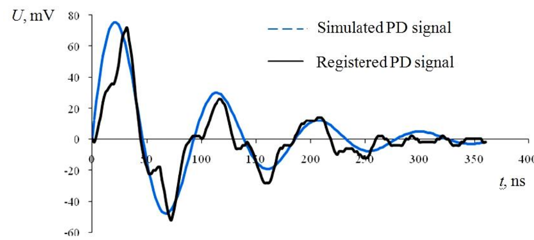

Figure 6. Waveform of the single PD impulse

As you can see from figure, the shape of the PD impulse conforms to the shape of the simulated impulse. RMS accuracy between the PD impulses obtained theoretically and experimentally is 15.8%. Thus, the results of computer simulation of theoretical PD selection can be considered fair and for experimental impulses. Total accuracy of selection of the experimental impulse of the partial discharges do not exceed 26%.

The amplitude-phase characteristics (APC) of the measured signal before and after purification from interference by developed software are presented in figures 7 and 8.

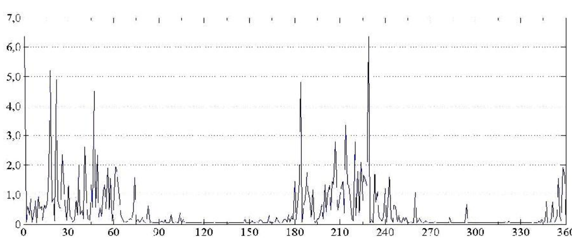

Figure 7. Amplitude-phase characteristics of the original signal

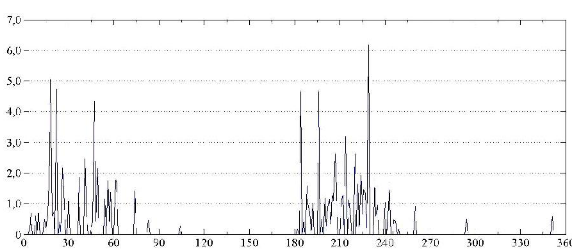

Figure 8. Amplitude-phase characteristics of the signal after purification from interference by developed software

As can be seen from the diagrams, interference selection on the basis of wavelet analysis is done successfully. This is confirmed by the fact that signals removes from phase regions of voltage decline, and partial discharges, as it is known, occur in areas of the voltage rise.

Conclusion

Experimental researches confirm the efficiency of the chosen method of partial discharges signals selectionby the impulse form on the basis of wavelet analysis. RMS accuracy between impulses of partial discharges, obtained theoretically and experimentally, is 15.8%. Thus, the diagnostic system by partial discharges, provided this software can be useful for prediction of the residual insulation resource of electrical equipment, being under operating voltage, and at the design and technology of isolation.

Investigations studies of partial discharges in isolation were performed with the help of special experimental setup. Analysis of the partial discharges impulse form confirmed a validity of choice the Daubechies wavelets as a basic function for wavelet-analysis of the PD. Developed software has shown that the method of the PD signals selection from interfering signals with by of wavelet transformations is effective.

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