

Monitoring leakage currents of suspension insulators of high voltage overhead power lines

Iosif Breido^{*1}, Vladimir Kaverin¹, Dinara Abisheva¹ and Aleksandr Kolychev²

¹Karaganda State Technical University

²Peter The Great St.Petersburg Polytechnic University

Abstract. The relevance of studying partial discharge currents (PDC) arising on the surface of suspension insulators of high-voltage overhead power lines (HVPL) is substantiated. Increasing PDC leads to increasing active energy losses and unauthorized shutdowns of high-voltage power lines due to the electric arc overlap of the suspension insulator. A laboratory bench for PDC experimental studying has been developed and manufactured. As a result of experimental studies we have determined static and dynamic characteristics of partial discharge currents; we have developed the algorithm for processing experimentally obtained results using Microsoft Excel spreadsheet editor. Recommendations have been developed for developing the hardware of the PDC sensor that allows increasing sensitivity, expanding the range of the controlled parameter and improving its dynamic characteristics in order to increase the accuracy and to expand the range of operation of the PDC sensor and to reduce the time it takes to establish its output signal. Equipping 220-500 kV power lines with PDC sensors of suspension insulators with telemetry will allow reducing the number of unauthorized emergency shutdowns of high-voltage power lines; realizing continuous current monitoring of the state of suspension insulators and receiving in real time the information of the integral value of PDC

1 Introduction

At present, when transmitting electricity, from north to south of Kazakhstan, there are used overhead power lines (HVPL) with voltage of 500 kV. An important component of the technical and economic indicators of HVPL is minimization of active losses when transmitting electricity.

According to work [1], technical losses of electricity consist of conditional constant and load losses.

Load, or conditional variable losses are the losses of electricity for heating in the longitudinal elements during transmission of the load through them. These include: losses in lines (air and cable), busbars, power transformers and current-limiting reactors.

Conditional constant losses are a part of technical losses of electricity in the elements of electric networks (transverse branches of equivalent circuits), which does not depend on the power transmitted through the elements of the network. The three components of conditional constant losses relate to climatic, i.e. to weather-related losses. For overhead power lines, according to [1], climatic losses include the losses to the corona in high-voltage power lines; from leakage currents on HVPL insulators; to smelting ice. The level of power consumption is significantly dependent on weather conditions. The most significant factor characterizing the weather is the air temperature. Losses

of electric energy in the networks due to leakage currents through HVPL insulators are caused by the fact that wetting a contaminated insulator forms a conductive medium (electrolyte) on its surface, which leads to significant increasing the leakage current. Such losses occur mainly in wet weather (fog, dew, drizzle). In case of heavy rain, contamination is partially washed away [2].

The main electrical characteristics of insulators normalized by the Rules of mounting electric sets, are wet discharge and pulse discharge voltage [2, 3, 4, 5].

The leakage current of the suspension insulator has two components: the background current, and the partial discharge current (PDC), above which the maximum permissible value arises the electric arc overlap of the suspension insulator, which leads to disconnection of the energy consumer [6].

The energy of the background current of the industrial frequency of 50 Hz is consumed for heating the suspension insulator and the earth, due to the fact that the neutral of the secondary windings of the step-up transformers is grounded.

Partial discharges are electric arc discharges on the surface of the insulator, the energy of which is spent for ionization of the surface of the insulator and the air of the environment, which lead to decreasing its electric strength and, as a result, to increasing active energy losses. Additionally, partial discharges form an ionized

* Corresponding author: jbreido@mail.ru

conductive channel and, as a result, lead to electric arc overlap of the suspension insulator with subsequent emergency disconnection of the line section from the electric power source [3].

One of the methods used for technical control of the state of the insulating properties of suspension insulators is monitoring the temperature of insulators heating using a thermal imager, which indirectly indicates changes in the leakage current, but the disadvantages of this method include its instability, since its accuracy is affected by the distance to the objects under control, wind speed, ambient temperature and especially solar radiation [7].

In addition, most HVPLs are located in inaccessible places where access to the supports in order to organize visual monitoring of the condition of suspended insulators is limited.

To solve the issues of current monitoring of suspension insulators, the methods of remote monitoring of leakage currents of high-voltage insulators with telemetric transmission of information directly from the supports have good prospects, and telemetric information can be transferred from the supports to the control center using combined systems containing radio modems and cellular communications [8].

The main disturbing factors in the control devices for partial discharge currents and channels for transmitting telemetric information using radio modems and cellular communications are the corona of high-voltage current-carrying elements of high-voltage lines, switching overvoltage and emergency situations caused by electric arc overlap of insulator strings that form electromagnetic radiation in a wide spectrum of high voltage [9, 10, 11, 12].

At Karaganda State Technical University, leakage current sensors with telemetry have been developed and their experimental studies have been carried out.

2 Methods

For the laboratory studies, a multifunctional test bench has been developed, the connection diagram of which is shown in Figure 1.

Using the T1 laboratory autotransformer, there is regulated voltage across the primary winding of the T2 transformer, which allows, in the process of experimental research, taking into account the T2 transformation coefficient, regulating voltage at the

insulator. The A5 oscilloscope is designed to simultaneously record the current values of the partial discharge current flowing through the insulator and voltage across it.

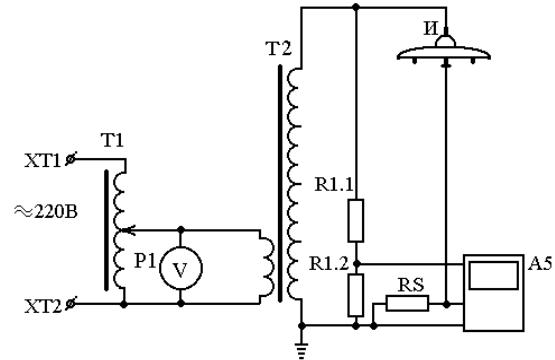


Fig. 1. Connection diagram of the bench for determining insulator leakage current characteristics.

The maximum effective voltage value on the secondary winding of the T2 transformer is 15 kV.

The studies have been carried out on plate insulators of the PS-120 type. In order to assess the repeatability of the experimentally obtained results, the studies have been carried out on six insulators, three of which worked on the supports within 10 years and three new insulators. Taking into account the fact that the average voltage drop across an insulator of this type is 12-15 kV, depending on the location of the insulator in the string of the suspension insulators, the experimental conditions correspond to the operating conditions of the high-voltage line of 220-500 kV [13, 14].

In the process of experimental studies the following parameters have been oscillographed:

- voltage at the output terminals of the T2 transformer, by means of the resistive divider R1.1 and R1.2 (Figure 1) (the voltage waveform is shown in Figure 2 in red);
- partial discharge current (PDC) flowing through the insulator at the current voltage value at the T2 secondary windings 15 kV (in Figure 2 the PDC waveform relative to the voltage diagram is shown in red).

PDC has a pulse character with the concentration of pulses in the first and third quarters of the voltage diagram. The amplitude values and pulse repetition rate of PDC are probabilistic in nature [15]. The experiments have been repeated many times on the same type of

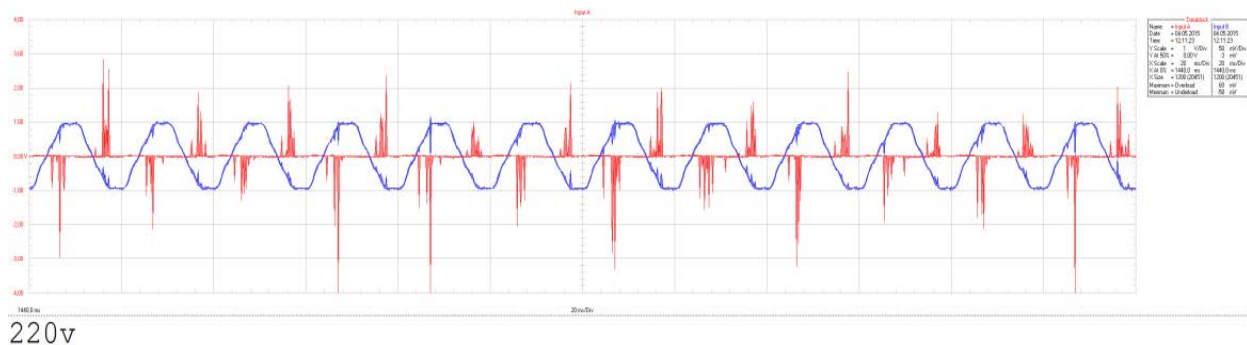


Fig. 2. Diagrams of voltage and partial discharge current.

Table 1. Sample parameters.

Sample No.	1	2	3	4	5	6	7
Sample time interval, ms	0-240	240-480	480-720	720-960	960-1200	1200-1440	1440-1680
Number of sectors	23	23	23	23	23	23	23
Number of pulses in the sample	95	104	95	111	122	120	116

insulators with different lifetimes, and in parallel, the required number of implementations has been determined by the results of processing the data by graphical-analytical methods, including:

- determining time and amplitude parameters of samples using a graphical editor and a program application for an oscilloscope of the FLUKE company;
 - developing arrays for each sample, taking into account the amplitude and time parameters of the PDC within the frames of each interval for the entire sample using the table editor Excel;
 - obtaining the dependence of the energy characteristics of the PDC distribution density using numerical methods, as well as table and graphic editors;
 - determining the minimum number of samples.
- The Table shows the sample parameters.

In order to analyze the obtained results, algorithms for their processing have been developed, the essence of which is to normalize the obtained implementations with their subsequent reduction to one period of the mains voltage. They contain the following steps.

1. Plotting oscillograms:

- the sampling time interval of 240 ms has been determined by the software and hardware capabilities of the FLUKE oscilloscope (with the time scale of 20 ms/cell of the scaling mesh of the oscilloscope screen);
- dividing the oscillograms into sectors (each sector corresponds to one half-period of voltage of the industrial frequency with their subsequent numbering), the odd numbering of sectors corresponds to the positive half-waves of the alternating voltage and the even number to the negative;
- consecutive numbering of the analyzed pulses of the PDC left to the right, in the frames of one oscillogram. Only pulses with the minimum amplitude of at least 0.1 with respect to the maximum PDC amplitude have been taken into account.

2. Determining the sufficiency of the number of processed oscillograms:

- plotting oscillograms taking into account the capabilities of the FLUKE oscilloscope with the maximum duration of 240 ms (with the time scale of 20 ms/cell), which corresponds to 12 voltage periods with frequency of 50 Hz);
- graphical analysis of partial discharges within the framework of one voltage period;
- presentation of the distribution dependencies in the frames of one voltage period for one oscillogram, for two oscillograms, etc. with subsequent comparison of normalized and reduced dependences;
- recognition of the number of processed oscillograms as sufficient if the law of distribution of the

subsequent sample of oscillograms differs from the previous one by less than 10 %;

- configuration of all numbered pulses of the PDC in the frames of one oscillogram relative to one full voltage period at the insulator.

Figure 3 shows the distribution of the PDC relative to voltage at the insulator and reduced to one network period. The PDC distribution has been carried out according to the results of processing seven oscillograms.

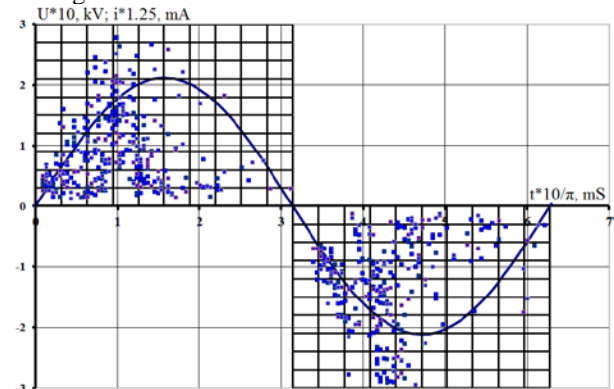


Fig. 3. PDC distribution relative to voltage at the insulator.

Determining the density of the PDC distribution relative to one period of voltage at the insulator is carried out according to the following algorithm.

1. The time intervals of the PDC occurrence relative to each half-wave of the voltage diagram at the insulator are determined.
2. The maximum amplitude of the PDC, the analyzed oscillograms, is determined.
3. The boundary values of the analyzed space of the rectangular shape are determined for each half-wave of voltage at the insulator (the vertical boundary value is determined by the maximum value of the PDC amplitude, and the horizontal value by the time interval of each half wave voltage).
4. The analyzed space is vertically and horizontally divided into ten identical intervals (the number of intervals is horizontally and vertically determined by a 10 % error (the value of which has been selected from the results of the qualitative assessment of the results of experimental studies).
5. A matrix of ten to ten sectors of the analyzed space is obtained for positive and negative half-waves of voltage at the insulator. Each member of the matrix is characterized by the total value of the PDC number, which amplitude values and time characteristics correspond to the i, j sectors.

6. The total current characteristic of each sector is determined from the expression

$$I_{ij\Sigma} = \sum_1^n I_{An}, \quad (1)$$

where $I_{ij\Sigma}$ is the total current value of each sector; n is the number of pulse discharges corresponding to the i, j sector; I_{An} is the amplitude value of the current of a partial discharge.

7. The numerical value of the total current characteristic of the i -th column of the analyzed space, is determined from the expression

$$I_{i\Sigma} = \sum_1^i I_{Aj}, \quad (2)$$

where $I_{i\Sigma}$ is the total current value of each i -th column; i is the number of columns in the analyzed space; I_{Aj} is the amplitude value of the current of the partial discharge of the j -th sector in the i -th column.

As a result of determining the total values of each PDC column (pp 6, 7), the dependence is formed in tabular form, which characterizes the PDC distribution density as the function of time for each half-wave voltage on the insulator.

8. There is built the sequence of samples, starting with one waveform No. 1; in the second sample the amplitude-time characteristics of the PDC oscillograms No. 1 and No. 2 are added, etc. The last sample No. 7 is the sum of the amplitude-time characteristics of the PDC oscillograms No. 1 ÷ No. 7.

9. The sufficiency of the number of processed oscillograms with duration of 240 ms is determined by determining the relative error of the tabulated dependence of the density of the PDC pulses distribution relative to the sample consisting of 7 oscillograms (Figure 4).

The dependences of the total TCD value ($I_{i\Sigma}$) distribution as a function of time with respect to the voltage diagram attached to the insulator have been constructed using the Excel table editor and are presented in Figure 4.

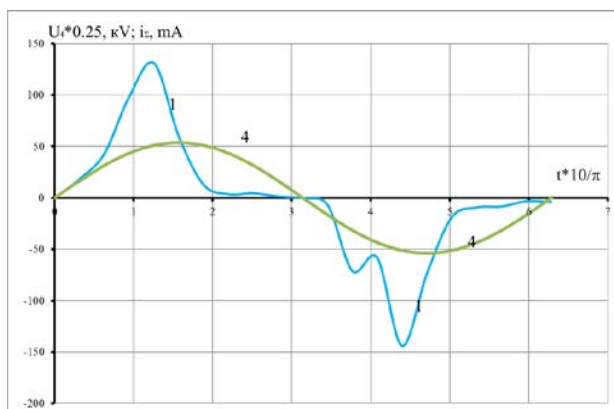


Fig. 4. PDC density dependence on the insulator voltage (oscillograms 1+2+3+4+5+6+7).

3 Results

The maximum value of PDC determined from expression 2 increases with increasing the number of oscillograms. This fact is explained by increasing the number of accounted PDCs in the i -th column. The maximum PDC value corresponding to the negative half-wave voltage is 10% more than the maximum PDC value corresponding to the positive half-wave voltage. The PDC dependence corresponding to the positive half-wave voltage has one extremum, and the PDC dependence corresponding to the negative half-wave voltage has two extrema.

The PDC pulses relative to the voltage diagram applied to the insulator have the maximum concentration in the first third quarters of the sinusoidal voltage dependence. Moreover, the same results are characteristic of all the studied insulators.

The experimental results obtained and processed by the proposed algorithms indicate that with increasing the absolute value of the voltage amplitude, with positive and negative half-waves of voltage applied to the insulator, the PDC increases.

This is natural since as the amplitude of voltage applied to the insulator increases, the frequency of partial discharges along the surface of the insulators increases, too.

At this, increasing the frequency of discharges indirectly indicates contamination or surface violations of the insulators and can be used to form systems for the continuous monitoring of the high-voltage insulators state.

Based on the presented and processed results, recommendations have been developed for the development of PDC sensors.

Determining the integral value of the currents of partial discharges of suspension insulators should be carried out using the information of the presence of partial discharges currents in the time domain corresponding to the negative half-wave voltage.

Since the intensity of pulse noise initiated by partial discharges increases at high PDC intensity, it is advisable to use time intervals where the PDC distribution density is minimal to transmit information from the HVPL supports, which will increase the noise immunity of telemetry transmission channels.

4 Discussion

Taking into account the above recommendations for monitoring leakage currents of suspension insulators, the authors have developed a sensor for the integrated PDC value of suspended insulators.

The functional diagram of the partial discharge sensor is shown in Figure 5.

The primary T1 transducer is made on the base of a transformer with an air magnet line [13]. The A1 block performs the functions of a scaleable amplifier. Using the A2 block the negative component of the high-frequency signal is selected from the output of the A1 block. By means of the A3 block there is selected the

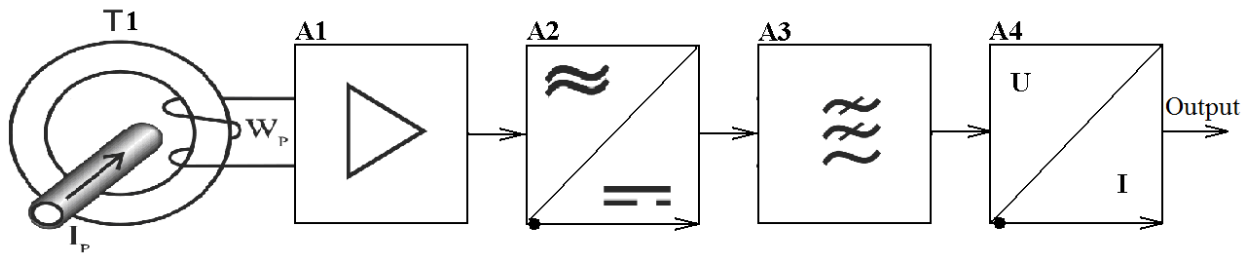


Fig. 5. Functional diagram of the partial discharge sensor.

information signal constant content. The terminal stage of the sensor is the A4 block, an analog voltage to current converter.

Using the circuitry implementation of the terminal cascades of leakage current sensors and the interrogation time, which is at least several minutes, it is simply enough to select the information signals from induced interference from the high-voltage wires of power lines.

One of the technical solutions is the use of the first-order filter with a large time constant located at the input of the controller, through which it is possible to filter out the useful signal from the interference information sent in the transmission channel. At this, the filter time constant should not exceed 0.3 time of the sampling step (time interval for the controller to interrogate the output signal of the PDC sensor).

The selection of the negative half-wave in the A2 block, Figure 5, allows implementing recommendations developed as a result of theoretical studies.

5 Conclusions

At Karaganda State Technical University, in the laboratories of the Department of Automation of Production Processes, a set of experimental studies of the suspension insulators PDC has been performed:

- a laboratory bench has been designed and manufactured for studying the suspension insulator PDC;
- the PDC static and dynamic characteristics have been determined;
- there have been developed algorithms for processing the results experimentally obtained in the process of laboratory research;
- recommendations have been developed for the hardware of the leakage current sensor.

Equipping 220-500 kV power lines with the developed PDC sensor of suspension insulators with telemetry, taking into account recommendations obtained as a result of experimental studies, will allow continuous monitoring leakage current over the surface of the insulators, and with its integral values exceeding the maximum allowable value, to localize the support and the suspension insulator with increased leakage current. This will reduce active losses, the number of electric arc overlaps of the suspension insulator when transmitting electricity, and operating costs for repair work.

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