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Письмо о принятии рукописи к публикации

Уважаемые Авторы,

Настоящим уведомляем, что рукопись Вашей научной статьи «Method for the Diagnosis of High-Voltage Dielectric Elements During Operation Based on Dynamic Registration of Electromagnetic Radiation» (Авторы: Т.Г. Галиева, Д.А. Иванов, М.Ф. Садыков, А.В. Голенищев-Кутузов, А.Д. Арсланов) была принята к опубликованию в материалах Международного научно-практического форума ASU SciTech Forum 2020 (SciTech 2020), который прошел в Алтайском государственном университете 12–13 ноября 2020 г.

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С уважением,

Протасов А.В.
Генеральный директор

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Method for the Diagnosis of High-Voltage Dielectric Elements During Operation Based on Dynamic Registration of Electromagnetic Radiation

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Abstract. The insulation of electrical equipment mainly determines the long-term and cost-effective operation of the electrical system. Therefore, the diagnosis of high-voltage dielectric elements is an urgent task for energy companies. The paper proposes a method for diagnosing dielectric elements based on the dynamic registration of electromagnetic radiation. The method involves the periodic measurement of a set of diagnostic parameters necessary for a reliable assessment of the operating state of high-voltage dielectric equipment and their comparison with reference values. The proposed method for diagnosing high-voltage dielectric elements has been tested in the diagnosis of high-voltage insulators. We have developed non-contact remote devices installed on each phase wire, measuring diagnostic parameters with subsequent computer processing of the accumulated information signals. The analysis of the set of necessary parameters allows us to draw a conclusion about the degree of operability of dielectric elements. A comprehensive monitoring system for high-voltage dielectric elements does not require the decommissioning of insulators. The processing of partial discharge signals ends with constructing the following characteristics: the amplitudes and the number of pulses in each phase interval and the distribution of the number of pulses over the amplitudes. The method allows one to control the technical condition of high-voltage dielectric elements without stopping the technological process of electric power transmission.

INTRODUCTION

The reliable, long-term, and cost-effective operation of an electrical system is mainly determined by the insulation of electrical equipment and other parts of the system. In the total cost of high-voltage equipment, the insulation component accounts for more than 60% [1]. Besides, the destruction and damage of insulation are the main causes of different accidents, such as (1) insulation overlap, (2) short circuit, and (3) ground fault. In this regard, the diagnosis of high-voltage dielectric elements is highly relevant for energy companies.

Partial discharges [PD] are the primary indicator of aging and destruction of solid insulation materials exposed to high voltage. Consequently, the measurement and analysis of PD is a promising method for diagnosing insulation of any electrical equipment [2,3]. Therefore, PDs are the result of the occurrence of local increases in the electric field strength during operation, which may exceed the electrical strength of high-voltage insulation elements. The use of the PD detection method as a means of non-destructive testing of the condition of power systems has become widespread. The presence of PD is accompanied by various physical phenomena, such as (1) acoustic radiation, (2) electromagnetic radiation, and (3) thermal radiation; thus, based on these phenomena, appropriate methods for detecting discharges are used, for example, the ultrasonic method [4], radiofrequency [RF] method [5], thermal imaging [6], and methods of electrical contact.

The main advantage of using RF for diagnosis compared to the other methods mentioned above is greater protection against interference since the main sources are recognized (telecommunications stations) and can be easily insulated. This method offers better practical applicability because it does not require precise targeting of the defect source, unlike the ultrasonic method.

The study aims to develop the methodological principles of integrated remote monitoring and non-contact diagnostic device [NDD] to monitor the technical condition and identify the residual life of high-voltage dielectric elements.

The research has the following objectives: (1) developing a mathematical model for determining a defective overhead line insulator, (2) designing a diagnostic device for recording PD pulses, and (3) conducting laboratory tests.

This paper offers a method for diagnosing high-voltage dielectric elements during operation based on the dynamic registration of electromagnetic radiation. The procedure described in the first section comprises three stages: (1) laboratory determination of the reference parameters of insulation elements (standard reference values are established for three technical conditions: defect-free, pre-defect, and defective); (2) actual measurements of insulation elements; and (3) comparison of the diagnostic parameters with the reference values, conclusion on the technical condition and residual life.

To monitor the technical condition and identify the residual life of high-voltage dielectric elements, we have used the developed NDD, which conduct remote periodic measurements of diagnostic parameters necessary for a reliable assessment of the operational condition of high-voltage dielectric equipment during operation and determination of its residual life. Analysis of the necessary diagnostic parameters allows one to draw a conclusion about the degree of operability of the dielectric elements.

Receiving antennas are often used to measure microwave radiation [7]; they can be arranged in various shapes and antenna arrays. Then, using mathematical methods, the location of the partial discharge event is triangulated in three dimensions.

Currently, the NDD is adapted for monitoring linear high-voltage insulators [HVI]; it is installed on each phase wire and operates on overhead power lines of 10 kV or more.

The devices and methods presented in this paper were developed in the laboratory of Kazan State Power Engineering University.

MATERIALS AND METHODS

Theoretical Basis

Energized insulators become radiating elements of electromagnetic waves, which allows one to measure the intensity of this radiation. This situation is associated with the process of generating an RF signal in insulators, which is based on Maxwell's equations, namely, Ampere's law, which is expressed in the following formula:

$$\nabla \times \vec{H}(t) = \vec{J}(t) + \frac{d\vec{D}(t)}{dt} \tag{1}$$

where:

$\vec{H}(t)$ – magnetic field strength;
$\vec{J}(t)$ – electric current density;
$\vec{D}(t)$ – electric flow density (all variables expressed at time *t*).

According to Maxwell's equations, even when the leakage current is minimal, due to the high voltage level applied in the insulator, there is an intense change in the electric and magnetic fields. Faraday's law (2) and the auxiliary electric field equation (3) indicate that an intense change in the electric field $\vec{E}$ causes an intense change in the magnetic field $\vec{H}$ and vice versa, resulting in an electromagnetic wave:

$$\nabla \times \vec{E}(t) = -\frac{d\vec{B}(t)}{dt} \tag{2}$$

$$\vec{B}(t) = \mu\vec{H}(t). \tag{3}$$

The PDs shunting in the HVI defects also emit electromagnetic radiation. Therefore, the RF signal of the defective insulator will differ from the signal of the defect-free one. In addition, we can determine the pre-defect HVI condition since the PD start shunting even in microcracks. As a result of studying the RF spectrum of the three categories of the HIV operating state in the laboratory, we can compare the measured parameters of operating HIVs according to the obtained standards and determine the degree of their operability.

Method of the Diagnosis Based on Dynamic Registration of Electromagnetic Radiation

To conduct comprehensive remote monitoring of high-voltage dielectric elements to control their technical condition and identify their residual life, we suggest using a diagnostic method including the following stages:

1. **Laboratory determination of the HVI reference parameters**. Using the contact bench method recommended by GOST R 55191-2012 (IEC 60270(2000) [8], one measures and establishes reference values of diagnostic parameters for the types of insulators for the examination. The diagnostic parameters include the number and intensity of PDs and their phase distribution. Thus, one sets the corresponding normalized reference values for the three technical conditions of HVI: (1) defect-free, (2) pre-defect, and (3) defective.
2. **Field measurements of the working HVI under voltage**. At this stage, field measurements of the diagnostic parameters of HVI are carried out under the operating voltage. The study aims to detect the electromagnetic radiation emitted by PDs since they can detect defects, track the rate of their development, and predict their residual life. Dynamic registration of electromagnetic radiation and measurement of temperature and humidity of the environment is carried out using the developed NDDs that are installed on each phase wire at a specified distance from HVI. The processed information enters the data collection and transmission unit, which is installed on support. Next, the information is uploaded to a cloud server for further processing and dispatching.
3. **Conclusion on the HVI technical condition**. The obtained and processed data are compared with the reference values of the same parameters measured by the contact method. Taking into account the environmental parameters, one can establish three conditions of the insulator: defect-free, pre-defect, and defective. The process of HVI diagnosis takes a long time. The measured parameters are automatically compared with those for the previous monitoring period. In case of negative dynamics of diagnostic parameters, the system warns the dispatcher, who decides to conduct an inspection, clean the HVI from contamination, or replace the defective insulator.

Then, taking into account the measured rate of aging of dielectric materials and the development of defects, the frequency of registration of diagnostic parameters and their residual life prediction is established. Defective HVIs will automatically be checked more often than defect-free insulators.

The proposed method allows one to control the technical condition of high-voltage dielectric elements without stopping the technological process of electric power transmission.

Non-Contact Diagnostic Device

For remote monitoring of the technical condition of high-voltage insulators, we have created NDDs. These devices can periodically measure a set of parameters (the number of PDs, their amplitude, localization, temperature, and humidity of the environment), which, after computer processing, allow one to evaluate the operating state of high-voltage equipment during the operation.

The tasks of the NDD include (1) receiving signals emitted by PDs, (2) constructing their amplitude-phase characteristics, (3) comparing the data with environmental parameters, and (4) preparing data for the analysis of diagnostic parameters that allow one to draw a conclusion about the degree of operability of HVI and their residual resource. The devices are installed on each phase wire near the research object at a predetermined distance. In addition, a unit for collecting and transmitting information to the cloud server is installed on support. The described insulator monitoring system is mobile and can be re-installed on different research objects.

Additionally, NDD performs the main measurements using an electromagnetic [EM] sensor and a phase sensor with a subsequent computer signal processing (Fig. 1). The microcontroller processes the signals based on the amplitude and time from the beginning of the phase interval received from the phase sensor. Furthermore, the EM sensor capable of detecting high-frequency discharges is based on the RTL-SDR module with a UART interface.

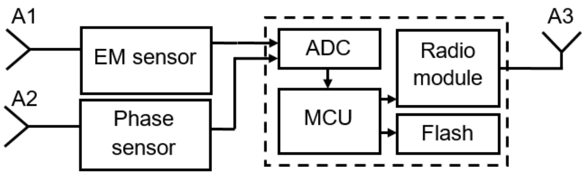

FIGURE 1. Block diagram of an NDD: A1 – EM sensor antenna, A2 – phase sensor antenna, A3 –data transmission antenna, ADC – analog-to-digital converter, MCU – microcontroller.

The signal is accepted by the receiving antenna A1, and after detection, it is transmitted to the input of the EM sensor. Fig. 2 presents the signal forms at the input and output of the EM sensor. The microcontroller processes the PD signals by the amplitude and time from the beginning of the phase interval received from the phase sensor.

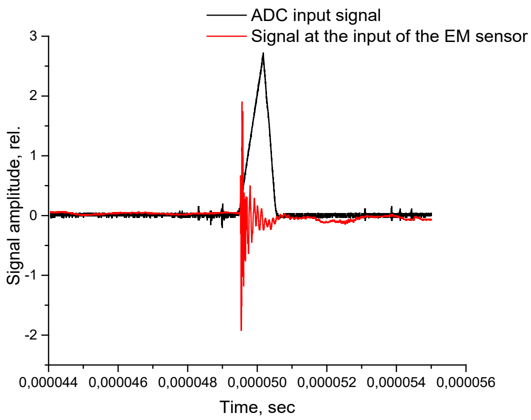

FIGURE 2. Signal before and after NDD processing.

The device provides Wi-fi or Bluetooth and USB data transfer interfaces for data transmission and subsequent analysis using stationary equipment. The comprehensive diagnostic setup includes three NDDs on phase wires and an information acquisition device for further uploading data to a cloud server, where monitoring information is available to the dispatcher.

Fig. 3 shows the NDD prototype. Having studied similar research on electromagnetic PD measurements, we have set our NDD prototype to the frequency band of 800–850 MHz, optimal for such measurements. Diagnostic devices operate on overhead power lines of 10 kV or more.

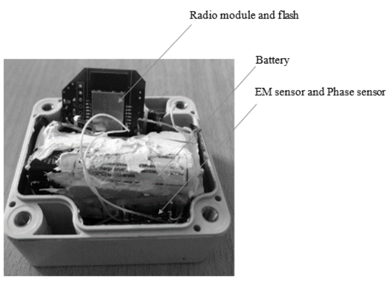

FIGURE 3. Device prototype.

Fig. 4 shows a data acquisition and transmission device installed near the NDD (e.g., on support). The device collects information from three servers, processes it, and uploads it to a cloud server for further processing and dispatching.

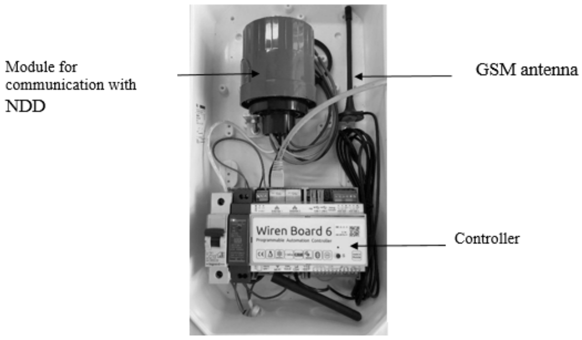

FIGURE 4. Data acquisition and transmission device.

Analysis of the set of necessary diagnostic parameters allows one to draw a conclusion about the degree of operability of dielectric elements.

Localization of Partial Discharges

To determine the PD source location, we suggest using the method of determining the difference in the time of arrival of the signal to the receiving devices [7,9,10]. The method involves the simultaneous solution of a system of non-linear geometric equations. To build the equations, one must know the coordinates of the diagnostic devices and the difference in the time of arrival of the PD pulse to each NDD. To simplify the calculations, we have taken HVI for a material point (i.e., any point of the insulator is equated to the suspension point). The method is based on measuring the difference in the time of radiation transmission from the PD to the NDD given the time synchronization and a predetermined location. If the difference in the time of receiving the signal is known, one can calculate the distance from the PD source to the NDD using mathematical processing (r_i in Fig. 5).

Suppose that the PD pulse with the coordinates (*x,y,z*) is radiated from the source position at an unknown point in time t_0 and reaches three diagnostic devices at time points t_1 - t_3, respectively.

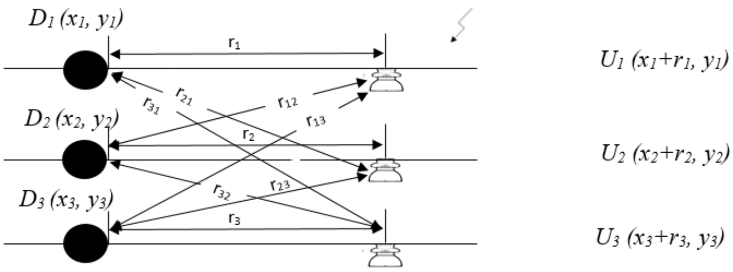

FIGURE 5. NDD installation diagram.

Given that the PD wavefront expands spherically from the source position at the speed of light, the distribution can be propagated using the following formula:

$$D = v \cdot t \tag{4}$$

where:

D – distance;
v – propagation speed;
t – propagation time.

Given the NDD coordinates, we can present (4) in the following form:

$$(x - x_i)^2 + (y - y_i)^2 + (z - z_i)^2 = (V_e * t_i)^2 \tag{5}$$

where:

(x_i, y_i, z_i) – coordinates of the *i*-th of the NDD in Cartesian space;
(x, y, z) – real coordinates of the PD event;
v_e – speed of the electromagnetic wave;
t_i – "time of flight" of propagating PD signal from its source to the *i*-th sensor.

The measurements are carried out in two dimensions; consequently, the *z* coordinate is not considered, and the equation (5) will take the following form:

$$(x - x_i)^2 + (y - y_i)^2 = (V_e * t_i)^2 \quad (6)$$

Suppose the time of flight from the PD source to NDD D_1 equals T, and the difference in arrival time between devices D_1, D_2, and D_3 is equal to τ_{1n}. In this case, we have got the following system of equations for three NDDs:

$$\begin{aligned} (x-x_1)^2 + (y-y_1)^2 &= (V_e * T)^2 \\ (x-x_2)^2 + (y-y_2)^2 &= (V_e * (T + \tau_{12}))^2 \\ (x-x_3)^2 + (y-y_3)^2 &= (V_e * (T + \tau_{13}))^2 \end{aligned} \quad (7)$$

The position of the PD source (x, y) can be calculated using the well-established method of least squares:

$$S(X) = \sum_{i=1}^{N} (Y_i(X))^2 \quad (8)$$

According to the method of least squares, the standard definition of $Y_i\ (X)$ is expressed in the following form:

$$Y_i(X) = \sqrt{(x-x_i)^2 + (y-y_i)^2} - (V_e * (T + \tau_{1i})) \quad (9)$$

The method of least squares is iterative; it gives an approximate solution to the equations. This solution is based on the number of iterations, starting from the initial value, which is improved on each iteration by using the error boundary until a convergent solution is found or the maximum number of iterations is reached.

After determining the PD number, their intensity, and location, the resulting distribution is compared with that for defect-free, pre-defective, and defective insulators. The developed method helps determine the rate of the aging process and the development of various defects, which allows one to predict the residual life of a high-voltage insulator.

RESULTS

The PD signal processing ends with constructing the following characteristics: the amplitudes and the number of pulses in each phase interval and the distribution of the number of pulses over the amplitudes. Fig. 6 presents the results of data processing.

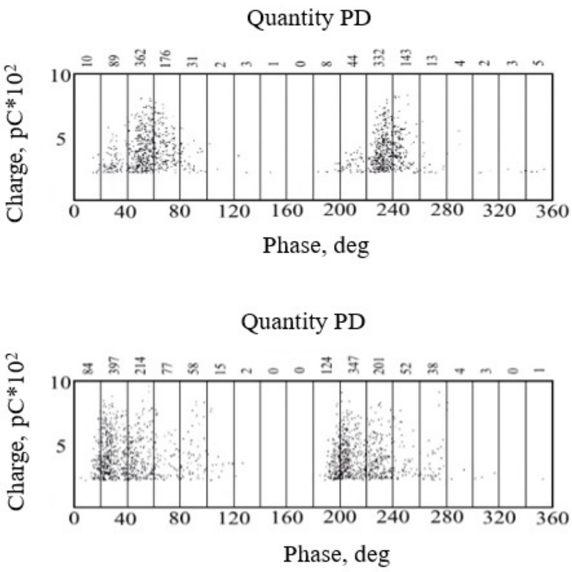

FIGURE 6. Amplitude-phase characteristic.

The defect development process is reflected in the time shift of the phase intervals of ultra-large PD generation to the interval of 0–40°. The obtained phase propagation of the pulse parameters is compared with the previously recorded distribution of the pulse signal parameters for (defect-free) HVI of the same type as described in the methodology [11]. The comparison can create a complete picture of the operability of the state of the high-voltage insulator. Furthermore, we can predict its residual life by establishing a functional time dependence of the values of diagnostic parameters on changes in the technical condition. As a result, we can draw conclusions about the compliance (or non-compliance) of the technical condition with regulatory and technical documentation requirements.

Thus, we have solved the research tasks. We have developed a mathematical model for determining a defective overhead line insulator, designed a diagnostic device for recording PD pulses, conducted laboratory tests, and obtained positive results.

DISCUSSION

Preliminary experiments have shown that the developed NDDs, using an electromagnetic sensor and a phase sensor, can measure the PD parameters and the shape of their distribution in the amplitude and frequency of repetition relative to the phase of the applied voltage. The obtained data are formed into the amplitude-phase characteristics (Fig. 6) and accumulated in the data acquisition and transmission device for many alternating voltage periods. Further analysis of the accumulated data will allow us to characterize the defects by comparing them with the PD characteristics, which, in turn, enables us to analyze the performance of overhead line insulators [12].

The method of determining the PD using RF methods is justified by sound protection from interference and the absence of the need for precise targeting of the source. Scientists widely use the method to diagnose insulation elements [7]. There are also studies on combining RF and ultrasonic techniques [13], providing more accurate data.

When developing the NDD, we have considered various ways of using and arranging the receivers for PD registration, namely, (1) the configuration of 4 Y-shaped and square-shaped receivers in operation [7], (2) the installation of an antenna array and data collection systems on a mobile platform [10,9], and (3) the simultaneous use of devices with acoustic sensors in transformers [14].

To determine the location of the defect, we have used the method of PD localization. The localization is mainly determined by two methods: determining the time difference of arrival and using a capacitive coupling [15,16].

The latter method assumes that the signal decreases with the distance to the beginning of the PD. To localize the PD in the NDD, we have determined the difference in the arrival time since this method is more accurate, as proved in the paper [16]. In the case of diagnosing high-voltage insulators, one can use the method of PD localization with the help of the NDD to determine which insulator has a pre-defective or defective condition.

We have developed methodological principles for monitoring the technical condition and identifying the residual life of high-voltage dielectric elements and carried out laboratory studies and plans to conduct field studies on the operating overhead line insulators.

In addition, we have undertaken comprehensive studies of registering electromagnetic radiation that occurs during the physical processes and their changes in the operating conditions of the main dielectric elements. Besides, we have proposed a brand-new method for diagnosing HVI was proposed, which comprises three stages: (1) laboratory determination of the HVI reference parameters, (2) field measurements of operating HVI, and (3) the conclusion on the technical condition.

CONCLUSION

We have proposed the method for diagnosing high-voltage dielectric elements, which has been tested on the diagnosis of high-voltage insulators. The method comprises three stages: (1) determining the limit parameters of the HVI, (2) measuring the actual parameters of the HVI, and (3) predicting the resource and setting the frequency of the HVI checks. In this regard, we have carried out the measurements using the developed NDD installed on the phase wires. The technique allows one to monitor the technical condition without contact or interrupting the transmission of electricity.

Also, we have suggested a non-contact remote periodic measurement of a set of diagnostic parameters using NDD, followed by computer processing and analysis of the data obtained. This step allows one to form several conclusions: about (1) the degree of operability of dielectric elements to detect defects in the early stages and (2) the compliance (or non-compliance) of the technical condition with the requirements of regulatory and technical documentation.

The developed model for assessing the residual life of the HVI by establishing the functional time dependence of the values of diagnostic parameters on changes in the technical condition of high-voltage dielectric elements will allow scientists to use it in the development of their methods for diagnosing high-voltage equipment.

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