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Remote Testing of High-Voltage Insulators

A. V. Golenishchev-Kutuzov[a], *, V. A. Golenishchev-Kutuzov[a], G. D. Mardanov[a], **, R. A. Khusnutdinov[a], and I. A. Evdokimov[b]

[a]*Kazan State Power Engineering University, Kazan, 420066 Russia*
[b]*Setevaya Kompaniya, Kazanskie Elektricheskie Seti, Kazan, 420094 Russia*
**e-mail: alex.kutuzov@mail.ru*
***e-mail: mardanov1992@mail.ru*

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Abstract—An integrated two-channel method has been suggested for remote testing of operating condition of high-voltage insulators. The method is based on concurrent registration and computer processing of partial-discharge signals that are detected by electromagnetic and acoustic sensors. Using the device that was created based on this method, diagnostic signs have been established that make it possible to distinguish between functional and faulty insulators under real service conditions.

Keywords: remote testing, partial discharges, high-voltage insulators, acoustic and electromagnetic sensors

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INTRODUCTION

Stable operation of modern high-voltage energy equipment is largely determined by the reliability of its insulating elements. High-voltage insulators (HVIs) are most vulnerable in this respect as prolonged exposure to high voltage and unfavorable service conditions lead to premature ageing of ceramic or polymeric insulating materials. As a result, various flaws occur that eventually lead to electrical breakdown or even complete HVI destruction. There are no regulations currently that would marshal testing for the presence of flaws, measuring their parameters, and estimating the effect they have on the operating condition of alive HVIs. The latest GOST (State Standard) R 191–2012 [1] and IEC 60060-1.2010 International Standard [2] provide only for occasional out-of-service tests of high-voltage energy equipment. A contact electric method of measuring characteristics of partial discharges (PDs) that uses equipment-specific test benches with adjustable high-voltage sources underlies the existing techniques of determining parameters of flaws and the effect they have on the operating capacity of insulation. Total breakdown is known [3] to be, as a rule, preceded by micro breakdowns or, in other words, electric discharges that shunt only part of the insulation between electrodes. These discharges are called partial discharges (PDs). They occur due to local surges in the strength of applied electric field in the bulk or on the surface of the insulation above its electric strength. The growth of flaws due to various factors is accompanied by increases in the intensity and in the number of PDs over particular time intervals as well as a reduction in the field strength that is required for a PD to occur; the latter is equivalent to a change in the phase of the working alternating voltage. It is these PD characteristics that are measured according to GOST (State Standard). Due to a probabilistic nature of occurrence of PDs, their characteristics may vary widely and, in practical terms, one can only set averaged values of parameters that are used to distinguish between functional and faulty insulators [4].

Various methods that are used to measure different PD characteristics make it possible to detect flaws at early stages of their formation and trace their further development, thereby assessing the current state of insulating elements as reflected in domestic and international documents and standards. GOST

GOST (State Standard) R 55191–2012 only provides for contact measurements of two main characteristics of separate PDs on a test bench, viz., apparent charge (the intensity) of a PD and the voltage at which the PD occurs. If needed, some additional characteristics (rate, repetition frequency, and average current and power) are measured, too. Experiments have shown that knowing these characteristics is not enough to assess the operating condition of in-service HVIs. As mentioned in the above GOST, given a wide range of electrotechnical products, the maximum admissible values of various PD characteristics are to be stipulated by supplementary industry specifications for particular products. However, no standard specifications have been formulated for HVIs yet. Even nowadays, damaged HVIs are still determined by visual inspection of in-service equipment for noticeable cracks, chippings, or breakdowns; this is not very informative as centimetric flaws differently affect future HVI functionality depending on the material, the dimensions, and the high voltage applied.

Under current conditions, a necessity has matured to develop remote noncontact techniques of evaluating the operating condition of high-voltage equipment, especially HVIs, which has been repeatedly emphasized in industry documents [5]. However, there are still no regulations that concern remote testing of HVIs bar some attempts at using various methods to measure the characteristics of PDs for these purposes, but mainly in power transformers [6–9].

PDs are accompanied by radiation of short (with a duration of 10^{-7} to 10^{-10} s) electromagnetic pulses in a wide frequency band of 10^5 to 10^{17} Hz and acoustic pulses in a range of 20 to 200 kHz.

Appropriate methods have been developed for detecting these types of radiation, each possessing both certain merits and significant drawbacks. The highly sensitive electromagnetic method is prone to the strong effect of radio-frequency interferences from operating equipment on the accuracy of PD measurements. While not being very sensitive, the acoustic method is rather noise immune to electromagnetic fields and has a good resolving power in terms of not only detecting a faulty insulator but also sometimes even locating the flaw. The optical and thermographic methods are effective only with no sunlight and operate only in a certain range of ambient temperatures [3].

It should be noted that the distance from measuring sensors to HVIs plays an important role in their remote testing. For suspension insulators of aerial lines the distance is $r \geq 30$ m, and for base HVIs that are used in distribution devices at electric stations and substations it is approximately 6–8 m. In this case, the most important characteristics of electromagnetic and acoustic sensors that are made as parabolic or linear antennas are the resolving power of detecting faulty insulators and the sensitivity of counterpart receivers. Angular resolving powers (θ) for electromagnetic and acoustic waves are significantly different considering propagation speeds of these waves and their wavelengths λ, as θ is proportional to λ/D, where D is the diameter or linear dimension of the antenna. Taking peculiarities of propagation of electromagnetic and acoustic waves into account (it is the far propagation zone for acoustic waves and the near propagation zone for electromagnetic waves), the linear resolution for electromagnetic sensor is 5–2 m at $r =$ 30–10 m and for acoustic sensor it is 1–0.3 m, accordingly. Consequently, even using perfect beam gain antennas and amplifiers, neither the above methods nor thermal imagers allow one to determine the locations— let alone the dimensions—of flaws remotely. There is only the possibility to single out separate faulty insulators within a range of 100 m by the electromagnetic sensor, whereas determining faulty insulators within groups is only possible when both electromagnetic and acoustic sensors are used simultaneously at a distance of up to 10–15 m.

It then follows that successful testing of the condition of insulating elements in high-voltage equipment is only possible with concurrent use of several of the above techniques. However, practically all commercial devices (both domestic and foreign) that have currently found application in testing the insulation of high-voltage power transformers and cables are mainly meant for using just one—acoustic or thermographic—method.

Therefore, underdevelopment of practical techniques and lack of regulations on testing the functionality of HVIs have become the main reason for designing an improved integrated method for monitoring the operating condition of HVIs. The method should integrate concurrent remote registration of PDs by electromagnetic and acoustic sensors and computer-assisted processing of results. Preliminary research [10, 11] has shown that the developed method can determine required characteristics of PDs and display them as the distribution of the amplitudes and numbers of PDs depending on the phase of the working voltage and the distribution of the number of PDs over the intensity.

THE STRUCTURE OF MONITORING AND MEASUREMENT PROCEDURE

PD electromagnetic pulses are registered (Fig. 1) by an AOR LA380 beam gain antenna that is connected to a broadband tunable AOR AR 5000A receiver that makes it possible to detect pulses in a frequency range of 0.5–600 MHz. Acoustic pulses are detected with an active parabolic antenna that is connected to an SDT-270 receiver that operates at the frequency of 40 kHz. The choice of the measurement frequency was dictated by factors such as the frequency dependence of wave attenuation, industrial noises, and electromagnetic interferences from surrounding electrical equipment. For example, acoustic noises prevail in a low-frequency domain (20 Hz–20 kHz), with the upper frequency boundary being limited by the frequency dependence of the attenuation ($f \geq 100$ kHz). Experiments have shown that in the interval

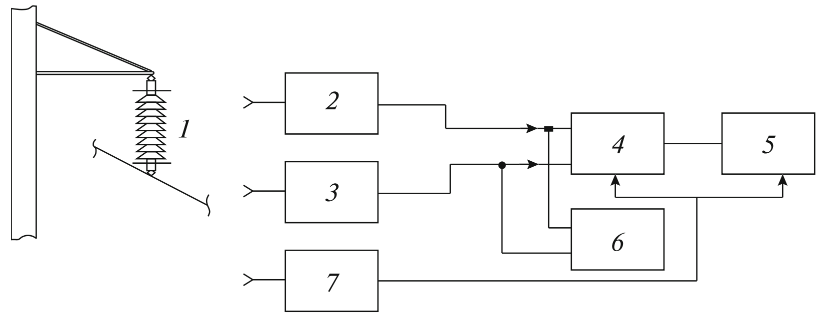

Fig. 1. Flow chart of the measurement device: (*1*) high-voltage insulator; (*2*) receiver of electromagnetic signals; (*3*) receiver of acoustic signals; (*4*) analog-to-digital converter; (*5*) personal computer; (*6*) two-channel oscilloscope; (*7*) receiver of reference signal for phase registration.

of 35–45 KHz and for a signal-to-noise ratio of ≈ 2, PD acoustic pulses can be detected at a distance of 15–25 m. Allowing for industrial electromagnetic interferences in a range of 50–200 and above 600 MHz, the bands that are preferable for detection of PD electromagnetic radiation are 20–50 and 400–550 MHz, with the intensity of PD signals being significantly higher in the latter band.

Amplified signals from the receivers are then fed to a DSO3062A two-channel digital oscilloscope that performs the function of displaying the signals from electromagnetic and acoustic receivers as gain-phase characteristics of PD pulses. The PD signals that are synchronized with the phase of network alternating voltage are supplied to a data-gathering NIUSB 6341 ADC board. The digitized signals from the electromagnetic and acoustic receivers are fed to a computer that performs accumulation, recording, and processing of information on the amplitude, repetition frequency, and phase of the signals using specially developed software [11]. The signals are accumulated in narrow phase intervals (approximately 20 degrees) for a period of 18 s that rather well reflects the stochastic nature of PD occurrence. The processing of PD signals is completed by constructing dependences of the amplitudes and numbers of signals in each phase interval and the distribution of the number of pulses over amplitudes.

The resultant phase distribution of pulse parameters is compared to a pre-recorded distribution of parameters of pulsed signals from a flawless HVI of the same type. Since the speeds of propagation of electromagnetic and acoustic pulses differ by several orders of magnitude, a phase-synchronization unit that takes the distance between the flaw and the sensor into account is used for synchronization with every particular phase interval.

The actual intensity of a separate partial discharge is determined after the receivers of electromagnetic and acoustic signals have been calibrated using a contact method that is described in GOST (State Standard) R 55101–2012, with allowance being made for the antenna–PD-source distance that is measured by a laser ranger.

RESEARCH RESULTS

A test-bench version of the developed integrated technique and device was tested at the department of industrial electronics and lighting technology of the Kazan State Power Engineering University on a batch of out-of-service functional and faulty polymeric LK70/35 insulators. It follows from preliminary research that was carried out by Kazan Power Networks that insulators nos. 1–4 had no macroscopic flaws and were fully functional (conditionally flawless). Insulators nos. 5–8 had various defects such as reach-through breakdowns of protective coating and discharge tracks along the rods and between the rod and end piece, and were therefore deemed seriously damaged and nonserviceable.

Measurements at a distance of approximately 6 m from the insulators demonstrated satisfactory comparability of the results that were obtained by the electromagnetic and acoustic methods for each insulator with the PD characteristics that were measured by a contact method, viz., the deviations did not exceed 25–30% and were mainly ascribed to the usage of different frequency bands.

The PD characteristics from a functional (no. 3) and faulty (no. 5) HVIs, which were typical representatives of each group of insulators, are shown in Figs. 3–5. It follows from the figures that quantitative values of PD intensity and the number of PDs in separate phase intervals differed by no more than 1.5 times due to the PD detection methods that were used. However, the positions of their maximum phase intervals for the electromagnetic and acoustic methods were in full accord with each other. Insulator no. 5 had a

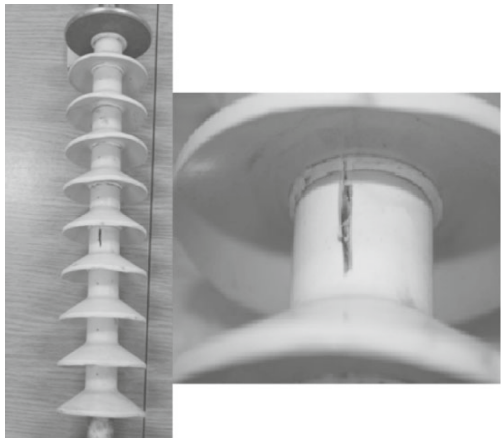

Fig. 2. LK70/35 no. 5 insulator with damaged fiberglass rod and polymer coating.

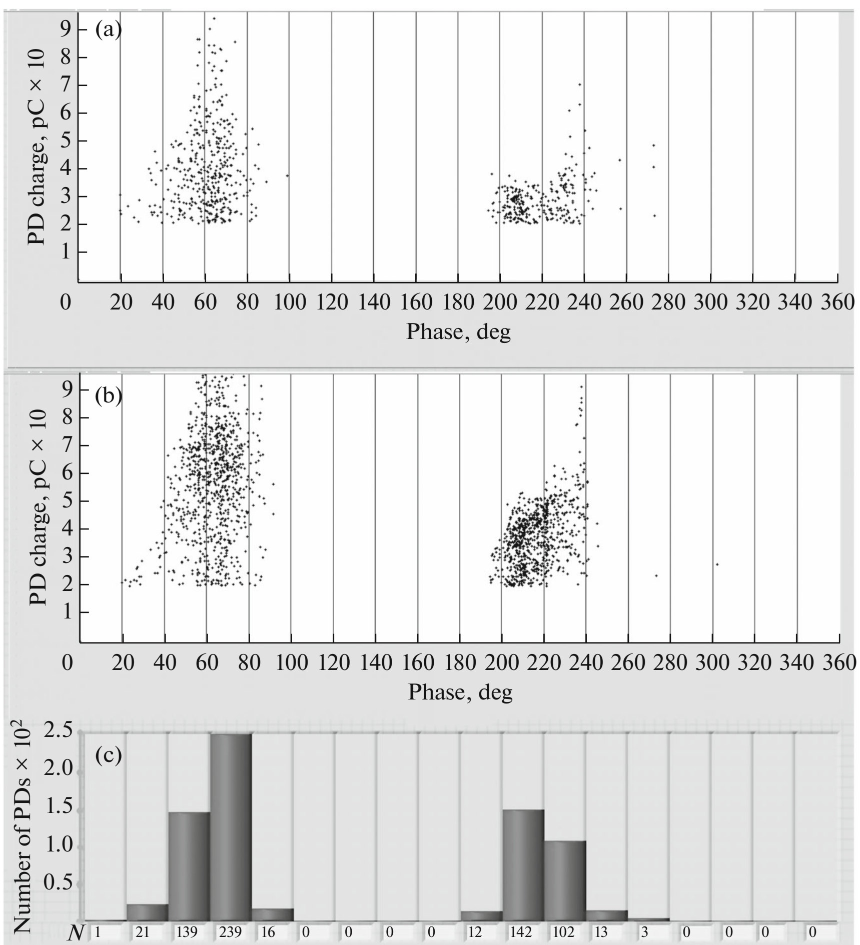

Fig. 3. PD characteristics for functional flawless insulator no. 3: (a), (b) gain-phase characteristics detected by electromagnetic (a) and acoustic (b) sensors; (c) phase distribution of the number (N) of PDs that are detected by the electromagnetic sensor.

visually noticeable damage of its fiberglass rod (see Fig. 2). The differences in the intensity and the number of PDs in the highest-intensity phase intervals and in the phase distribution of these intervals were no more 1.2–1.5 times within each group of insulators, whereas the same differences between the groups of functional and faulty insulators were no less than 3–5 times. Moreover, the first (flawless) HVI group

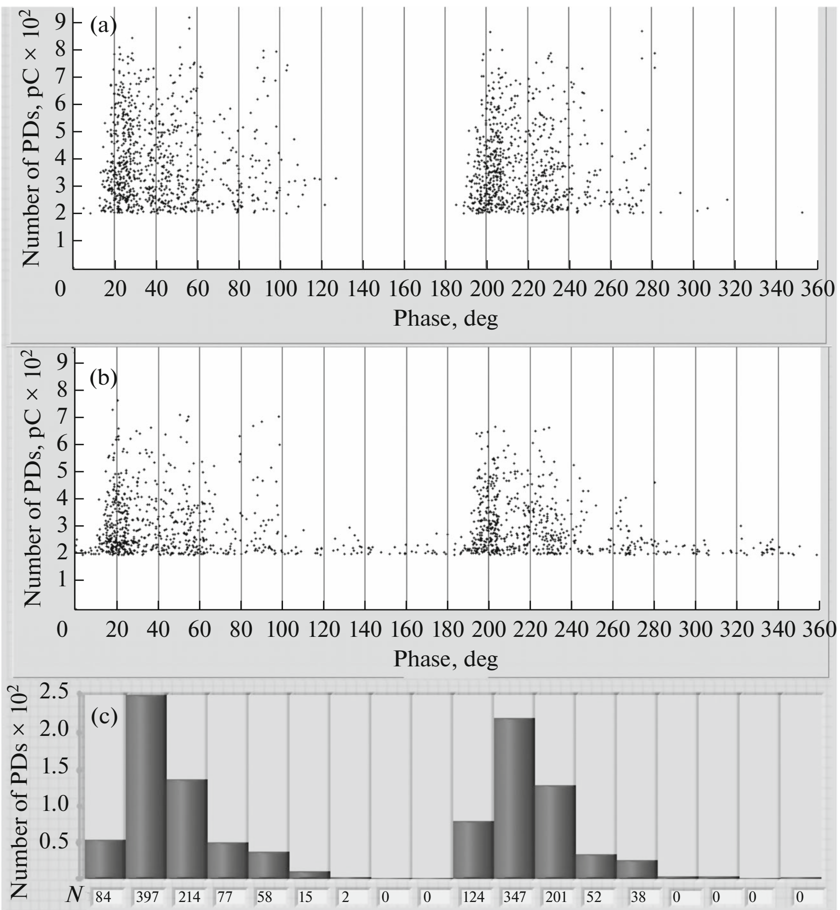

Fig. 4. PD characteristics for faulty insulator no. 5: (a) and (b) gain-phase characteristics detected by electromagnetic (a) and acoustic (b) sensors; (c) phase distribution of the number (N) of PDs that are detected by the electromagnetic sensor.

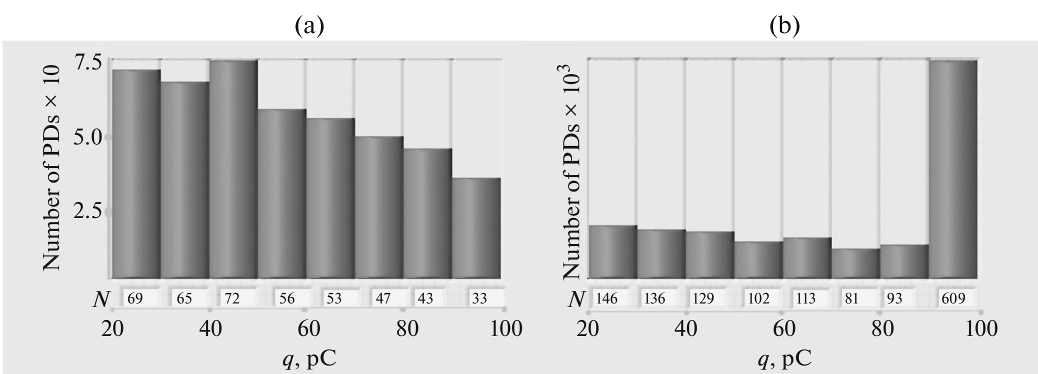

Fig. 5. Distribution of the number of PDs over intensities for flawless (a) and faulty (b) insulators.

exhibited no PDs with an intensity of more than 100 pC, whereas separate PDs with an intensity of up to 1–2 pC were typical of the second group. Based on the analysis of PD characteristics for the HVIs with the integrated method, we developed a technique for remote testing of the condition of HVIs that relies on simultaneous detection and concurrent computer-aided processing of electromagnetic and acoustic PD signals. In this technique, average values are determined in each discrete high-voltage phase interval for the intensity and number of real-charge pulses that exceed the admissible threshold values of occurrence or development of flaws as compared to reference HVI specimens. In order to improve the reliability of assessing the operating condition of HVIs, a phase shift of intervals of numbers of highest-intensity PDs is measured versus the degree of faultiness.

We suggested an in-service sorting procedure for functional and nonserviceable HVIs that employs the following most significant distinctions in PD characteristics that are obtained by the integrated method and are listed below in the order of significance:

—significant (no less than 5–8 times) increases in the intensity and number of PDs that exceed their average values of q ~ 10–20 pC and N ~ 100–200 over the highest-intensity phase interval;

—an excessive PD intensity of more than 100 pC where structure failures of the HVI material start to occur in the PD area;

—the shift of phase intervals of the number of highest-intensity PDs towards smaller phase angles by no less than 40–50°.

It is natural to expect the quantitative estimates of the changes in PD characteristics to be somewhat different for other HVI types, but qualitatively the above sorting procedure should be suitable for rejection of HVIs of different types.

CONCLUSIONS

The results of developing integrated two-channel technique and device that allow one to remotely evaluate the operating condition of in-service HVIs are presented in this work. Diagnostic signs that use a certain set of gain-phase characteristics and make it possible to distinguish between functional HVIs and faulty ones that require immediate replacements are established.

Based on the analysis of measurements, three main diagnostic signs that distinguish functional HVIs from nonserviceable ones have been formulated. These are a growth in the intensity and number of PDs over a discrete phase interval; the presence of powerful PDs with an intensity that exceeds average values across the phase interval; and a phase shift of intervals where the greatest intensity and number of PDs are observed.

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