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DIAGNOSTIC EXAMINATION OF ISOLATED BUS DUCTS

A. P. Dolin[1]

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The paper offers a review of the procedure for diagnostic examination of isolated bus ducts with air insulation. Characteristic examples of isolated-phase and three-phase bus duct defects revealed during visual inspections and thermal imaging are provided. The results of lab-based measurements and acoustic location of partial discharge (PD) in the insulation systems with various defects (cracks, wet and contaminated surfaces) are discussed. Typical amplitude-frequency characteristics of the PD acoustic signals during the development of insulator defects (defect images) were obtained. The results of generator bus duct diagnostics using electromagnetic and acoustic instruments are presented.

Keywords: isolated bus ducts; diagnostic examination; particle discharge.

Isolated bus ducts with air insulation are designed to operate within networks with an electric voltage of up to 35 kV and include isolated-phase bus ducts (e.g., generator bus ducts) and isolated bus ducts with a common shield for all three phases. The paper analyzes the procedure for examining isolated bus ducts based on the experience of performing diagnostic examination of more than 500 bus ducts in active electrical installations, as well as the results of lab-based studies and analytical calculations.

The shields of bus ducts are usually made of technical aluminum, while bus lines are made of electrotechnical aluminum alloys. Bus lines are supported on post insulators. Generator conductors (buses and shields) and some other bus ducts have an annular cross-section. The outer surface of the bus lines, as well as the inner and outer surfaces of the shields are painted to increase radiation heat transfer. The color of the outer surface of the shield (white or light-gray) also provides the minimum heat absorption from solar radiation in open electrical installations.

The bus duct shields protect the conductor buses from external effects, while induced currents reduce the level of magnetic field strength of the bus ducts. The bus duct design provides high reliability of power transmission, while the use of isolated-phase bus ducts almost completely eliminates fault occurrences.

The shields of the modern generator bus ducts are made continuous, electrically connected at the generator and transformer, and grounded in one point (Fig. 1*a*). In this case, the current induced inside the shields has an equal value and opposite direction relative to the current passing through the bus duct. Therefore, the strength of magnetic field of the bus duct outside of the shields is almost zero. This provides high electrodynamic resistance of the bus ducts, complete electromagnetic safety of the personnel, and no magnetic field effect on the equipment, including automated equipment and safety controls.

The bus ducts manufactured up to about 1980 had "open" shields. Sections of the shields (typically, up to 10 m long) are insulated and grounded in one point (Fig. 1*b*). Such bus ducts demonstrate reduced losses (and, hence, heat generation) compared to the continuous-shield bus ducts given the same conductor sizes and materials. The main disadvantages of the "open"-isolated bus ducts are as follows: shielding (field strength reduction) of the magnetic field of the buses by only 40 – 60%, and the use of rubber (currently, being replaced with silicone) insulation between the shield sections.

Diagnostic examination of the isolated bus ducts during operation includes a visual inspection of the bus ducts, thermal imaging, conducting examinations or tests to assess the condition of the post insulators.

When performing a visual inspection of the bus ducts, it is important to first examine the shielding for possible damage, assess the condition of standard insulation, as well as the color of the shields. During inspection of the bus ducts, it was found that the shield seal can sometimes be broken as a result of damaged aluminum shells, compensators, wear of insulation seals of the sections, etc. Such damage can lead to ingress of moisture and dirt into the shielded space, which eventually causes insulator defects.

The bus ducts are usually inspected for paint condition, and compliance of the bus duct shield color with the factory

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[1] Science and Technology Center «Electrical-Engineering Diagnostics and Service» (STC «EDS»), Moscow, Russia; e-mail: apdol@mail.ru

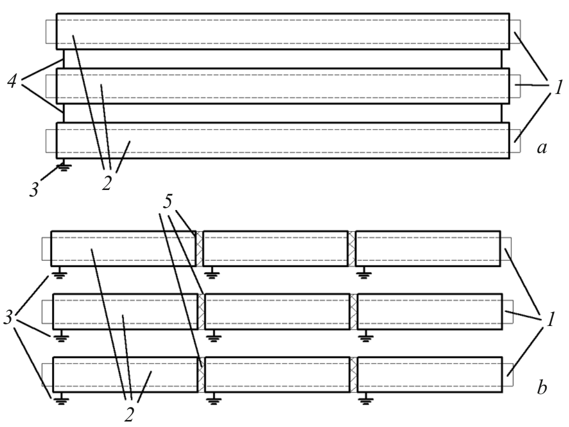

Fig. 1. Schematic diagrams of generator bus duct shield connection: (*a*) electrically connected and grounded in one point; (*b*) isolated; *1*, buses; *2*, shields; *3*, ground; *4*, shield jumpers; *5*, insulation seals.

requirements (in case of outdoor installations). It should be noted that painting of bus ducts and shields provides temperature reduction under operating conditions due to increased radiation heat transfer compared to unpainted bus ducts. In addition, in case of the outdoor installations, changes in shield color affect the level of absorbed solar radiation (while maintaining the radiation heat flux) [1].

According to the procedure described in [1], the temperatures of isolated-phase bus ducts were calculated for different shield colors using EKRAN EDS V2 software [2]. For example, under rated electric currents of bus ducts utilized in outdoor installations, the shield and bus duct temperatures increase by 7 – 12% if the shields are painted red as compared to white. To illustrate the color effect, Table 1 shows the temperatures of isolated-phase bus ducts (type TENE-20-10000-300U1) with shields painted white (standard) and red (e.g., phase *C*) during summer period in the central and southern parts of Russia at an ambient air temperature of 40°C.

It should be mentioned that the calculated temperatures of isolated-phase bus ducts have been compared multiple times with the test data, and the obtained results confirmed high accuracy of the analytical method.

As follows from the data shown in Table 1, the change in shield color of the bus ducts compared to the factory color leads to an increase in bus duct temperature under operating conditions, and hence, during faults. In a number of cases, this may result in the heating temperatures of the bus ducts exceeding the permissible values.

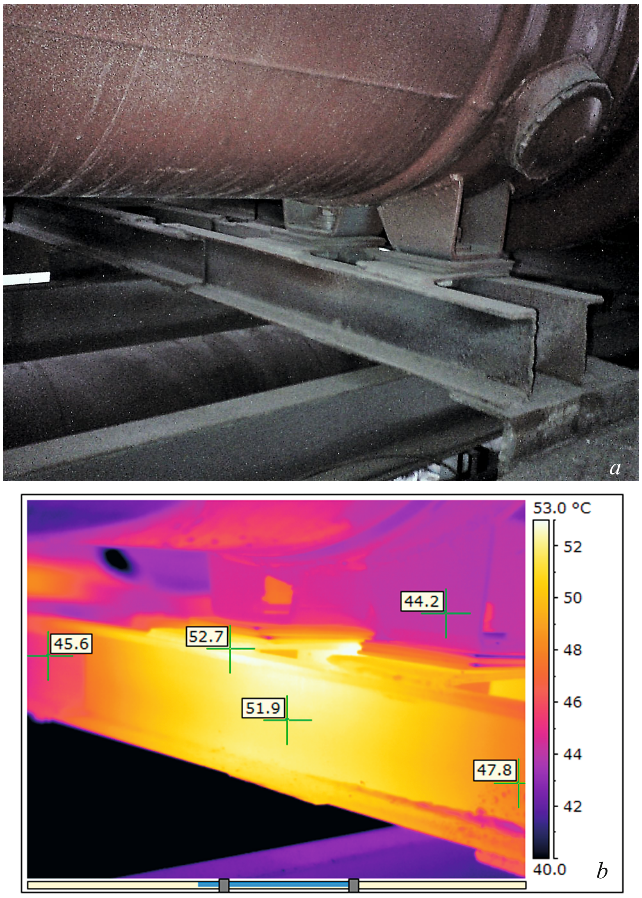

Fig. 2. Bud duct shield installation zone (*a*) and thermogram of this zone under operating conditions (*b*) when insulation is lost.

In case of bus ducts with continuous shields (Fig. 1*a*), the presence and correctness of installing the short-circuiting shield jumpers are also monitored. During repairs, there were cases when smaller cross-section shield jumpers were installed or even dismantled. When using smaller cross-section shield jumpers, their heating temperature increases, which can be monitored by using thermal imaging. There were instances when smaller cross-section jumpers were heated to 150°C under the operating conditions.

The absence of one standard jumper causes the appearance of voltage on the bus duct shields. For example, in case of TÉKN-20/60-160 bus duct with only one jumper installed, an increase in electric potential along the length was 0.5 V/m at an operating current of more than 6000 A. Over the bus duct length of 180 m, the voltage reached 90 V relative to the ground, which was confirmed by the calculations based on the procedure described in [1, 2], as well as direct measurements.

TABLE 1. Calculated Heating Temperatures of TENE-20-10000-300U1 Bus Duct Conductors Under Rated Electric Current

Shield color	Calculated heating temperature, °C	
	bus	shield
White	104/105.8	69.5/71.4
Red	103.9/113.3	69.3/79.9

Notes. 1. Numerator — heating temperature in the protective distribution device (PDD); denominator — heating temperature in the open distribution device (ODD). 2. Permissible heating temperature: bus — 105°C; shield — 80°C.

Thermal imaging of the bus ducts under load also allows detecting excessive heating in the bus duct support elements area, when standard insulation is lost. To illustrate this situation, Fig. 2 shows the attachment areas of the shields with insulation defects relative to the supporting structures of the isolation-phase bus ducts along with the thermogram of these areas.

The most “problematic” assembly of the isolated bus ducts are the post insulators, which may develop cracks, fractures, and surface contamination during operation, potentially resulting in insulator flashover. Short circuit to ground along the damaged (or contaminated) insulator may require disconnecting the circuit (first of all, generators).

Monitoring the condition of the post insulators of the isolated bus ducts according to [3] is performed by using an in-

Fig. 3. Damaged insulator.

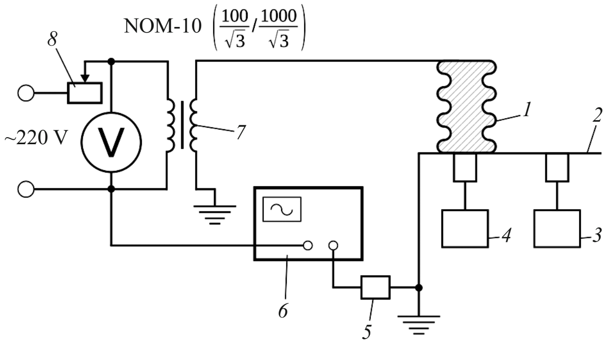

Fig. 4. Testing schematic.

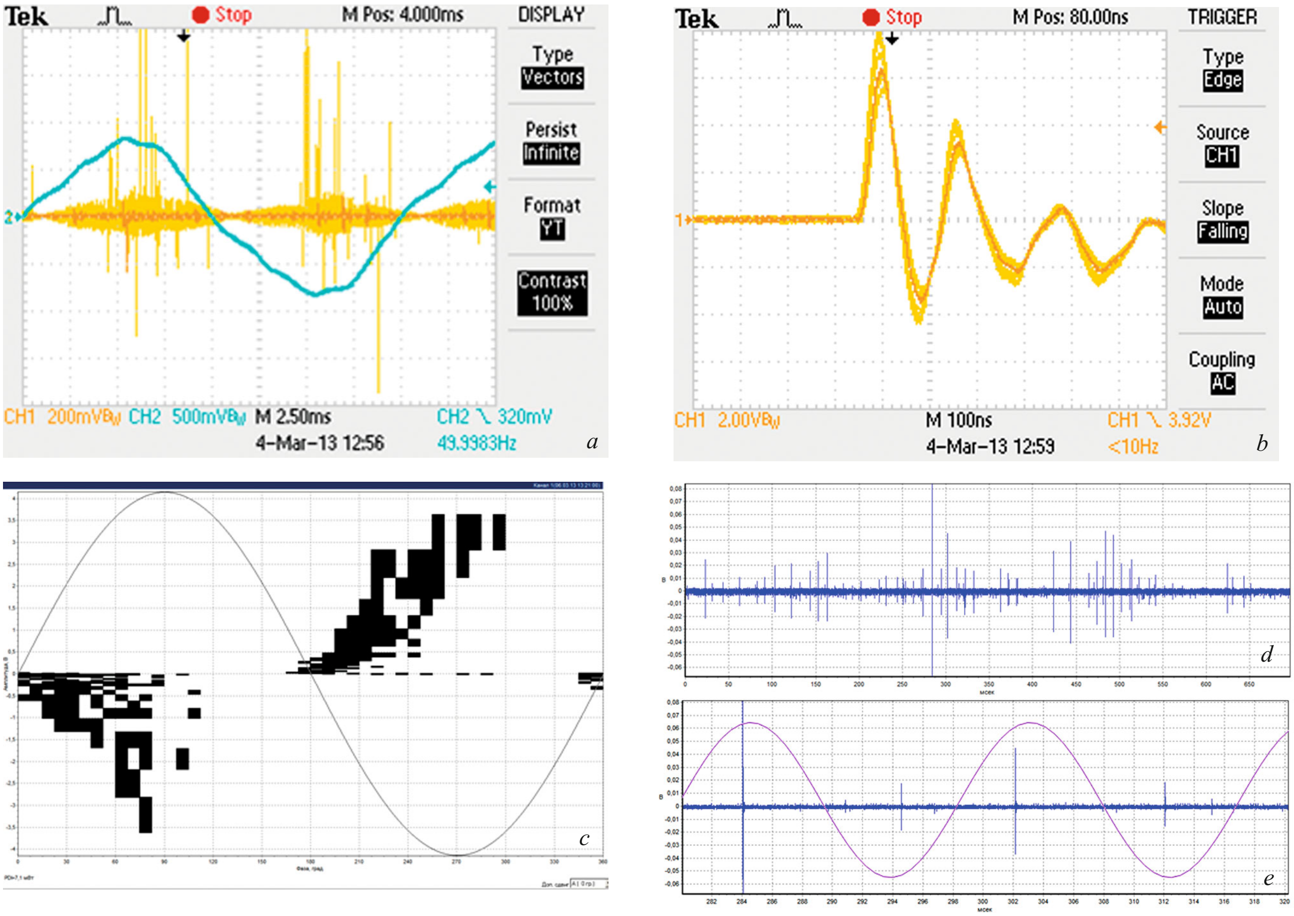

Fig. 5. Oscillograms of electric and acoustic signals from wet and contaminated insulators (no cracks).

creased voltage of industrial frequency. Such monitoring is performed during commissioning and/or major repairs of the bus ducts. This represents a destructive control method. Meanwhile, the experience of operating isolated bus ducts indicates the need to periodically monitor their insulator condition, especially after 15 – 20 years of operation.

High voltage testing requires taking a bus duct out of service and performing "bus isolation" in the connection points (including generator, switching device, power and measuring transformer outputs). In case of breakdown, insulators must be replaced before the bus duct is put back into operation. The duration of such testing, including preparatory and remedial repairs, may require several working shifts. In addition, in some cases, by using an increased-voltage test, it was not possible to locate the defective area and replace the defective insulators in a timely manner.

In recent years, monitoring partial discharge in the bus duct insulation during operation became an alternative to the increased-voltage testing. This is a non-destructive diagnostic control method, which does not require taking the equipment out of service and is realized by using induction and/or acoustic methods. However, during partial discharge (PD) location, various interference and signals are recorded, which are not related to post insulator defects (floating potential discharges, external discharges, acoustic "noise" caused by vibrations, etc.). This complicates the process of identifying developing defects.

To gain experience in determining the nature and level of the defects developing inside the isolated bus duct insulators, and to identify the appearance of the defects, a model testing was performed using a bus duct model with an insulator having a crack in a porcelain body (Fig. 3), and with an undamaged insulator having a dry, wet and contaminated surface. Figure 4 shows the schematic diagram of the experimental setup.

A voltage of up to $10/\sqrt{3}$ kV (relative to the ground) was applied to an experimental insulator *1* through a NOM-10 type voltage transformer *7*. The voltage was controlled by a resistor *8*. The voltage was controlled on the lower voltage side. A 5 mm thick aluminum plate *2*, which simulated the bus duct shield, was attached to the insulator. Plate *2* was grounded. The discharge phenomena were controlled using an oscilloscope *6* and sensor *5* (of high-frequency current transformer). In addition, the location of discharge phenomena was performed using an acoustic sensor *3* and an AR200 type instrument, as well as an electromagnetic (induction) sensor *4* and an R400 instrument.

A voltage constituting 0.5, 0.75, and 1.0 of the rated insulator voltage was applied. The three PD measurement systems used in parallel were based on direct measurement performed by: sensor *5*, acoustic sensor *3*, and induction sensor *4*. As a result, samples of characteristic insulator defects were obtained. The level of defect development to a certain extent can be assumed proportional to the level of applied voltage.

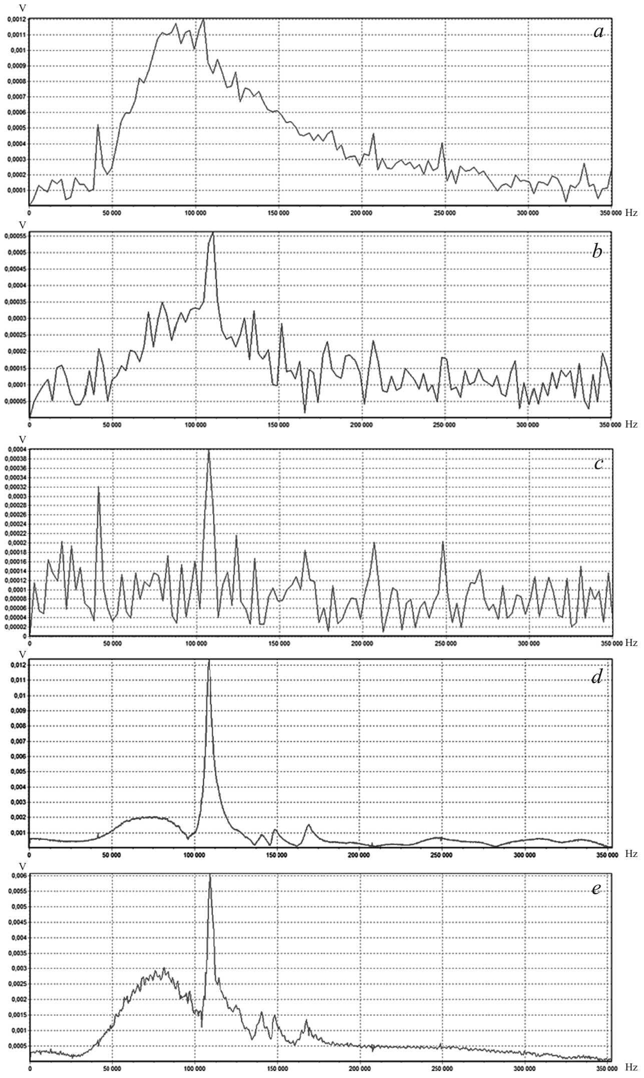

Fig. 6. Typical amplitude-frequency characteristics (images) of acoustic signals during the development of insulator defects accompanied by partial discharges: *a*, wet and contaminated surfaces; *b*, developing wet (contaminated) crack; *c*, developing dry crack; *d*, developed dry crack; *e*, developed wet, contaminated crack.

The measurement results are illustrated in Fig. 5, which shows the discharge activity oscillograms at 2.5 msec/div (*a*) and 100 nsec/div (*b*); amplitude-phase pulse distributions of signals (accumulation mode) recorded by R400 with electromagnetic sensor (*c*), and acoustic signal obtained by AR200 at 50 msec/div (*d*) and 2 msec/div (*e*). Periodically varying curves shown in Fig. 5*a*, *c*, *e*, represent operating voltage.

Figure 6 shows the amplitude-frequency characteristics of the partial discharge acoustic signals of the insulators tested in the laboratory under various defect scenarios associated with wet and contaminated surface, development of wet (contaminated) and dry cracks, etc.

As a result of testing, the following data were obtained.

No discharge phenomena were recorded using dry, nondamaged insulator.

Both wet and contaminated insulators without cracks demonstrated discharge phenomena that were recorded (Fig. 5*a*, *b*). Based on the signal processing results obtained using R400, the achieved voltage level was 3.7 V (Fig. 5*c*). The acoustic sensor recorded discharges with prevailing signal levels of 20 – 40 mV. In rare cases, the signal level reached more than 100 mV. The amplitude-frequency characteristic of the acoustic signal (with the maximum amplitude shown in Fig. 5*d*, *e*) demonstrates a broad spectral band (Fig. 6*a*) having a maximum around 110 – 120 kHz.

In case of a dry insulator with a crack, discharge phenomena were recorded by all methods at all levels of test voltage. The acoustic sensor detected a large signal level with a period of 10 msec, which corresponds to the half-period of the network voltage. It is important to note the amplitude-frequency characteristic of the acoustic signal with an explicit peak around 120 kHz (Fig. 6*g*), as well as high level of electromagnetic signal recorded by R400.

The most important are the results of testing contaminated and wet insulators having a crack. The acoustic signal represents irregular pulses, but there is a clear 10 msec interval between them. The spectrum of this signal has two distinct peaks at about 75 and 120 kHz (Fig. 6*d*).

The experimental results made it possible to confidently interpret the measurement data obtained using the operating electrical equipment. An experience gained in the process of examining more than 500 isolated bus ducts has confirmed that the main measurement technique is the acoustic method, which allows identifying the nature and level of defect development. The electromagnetic method is an auxiliary tech-

Fig. 7. PD location using electromagnetic (*a*) and acoustic (*b*) sensors during diagnostic examination of isolated bus ducts.

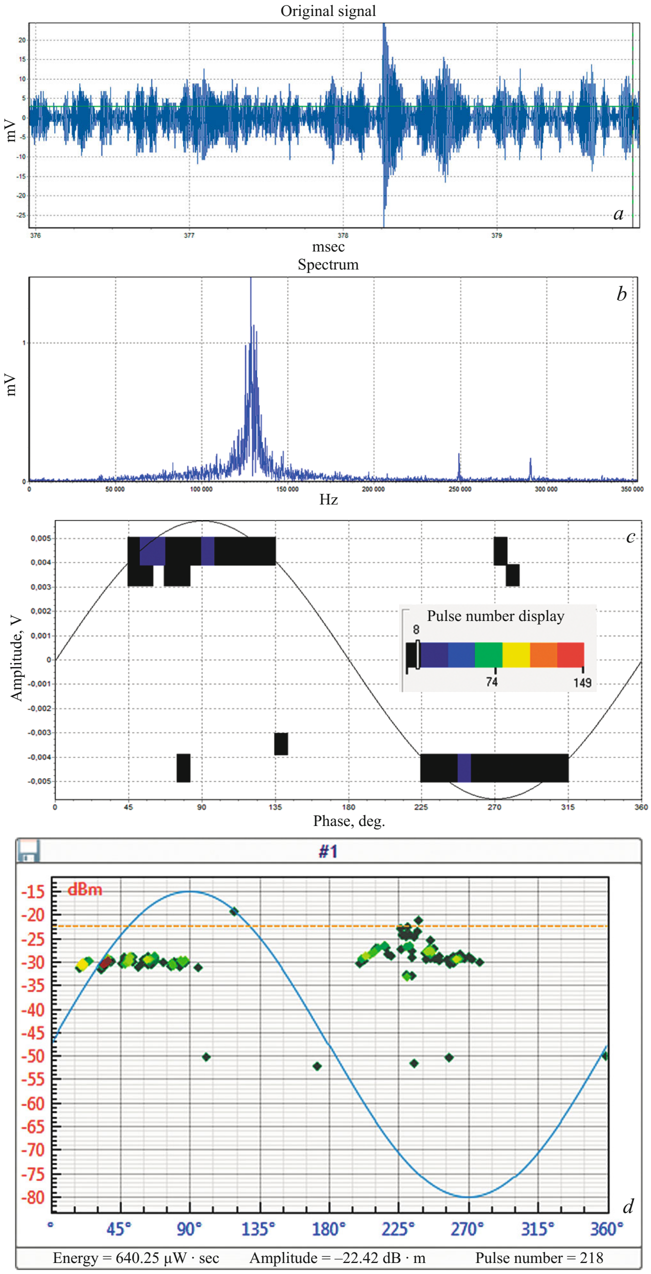

Fig. 8. Oscillogram (*a*) and amplitude-frequency characteristic (*b*) of acoustic signal, amplitude-phase distribution of electric signal pulses depending on base voltage (frequency — 50 Hz) when using electromagnetic sensor RFCT-6 (*c*) and directional microwave antenna (*d*).

nique, which allows confirming the period and intensity of electric discharges. The acoustic signal having a main spectrum within a frequency range from 80 to 130 kHz serves as a criterion characterizing the development of a defect accompanied by an electric (partial) discharge. If the signal level exceeds 150 mV (based on the AR200 calibration), the defect level requires periodic monitoring (e.g., when wet) or repair (if there is a crack).

When performing such testing, both acoustic and induction sensors are sequentially installed within each insulator belt (Fig. 7). The recorded signals are processed. In this case, the frequency of signals occurrence, their amplitude, amplitude-frequency and amplitude-phase distributions are analyzed.

As an example, Fig. 8 shows the results of acoustic and induction measurements using AR200 and R400 instruments obtained during diagnostic examination of the generator bus duct. This information was unambiguously interpreted as a defect caused by an insulator crack. When performing a diagnostic examination of this bus duct, a DimLoc device having a directional microwave antenna was additionally used. The measurement results obtained by this device confirmed a high level of discharge activity in the defective insulator area.

It should be noted that high-voltage bus duct tests that were conducted twice prior to PD measurements did not reveal a defective insulator. Periodic insulator breakdown caused a ground fault in the generator circuit and required the latter to be taken out of service.

The amplitude of the detected acoustic signals was 35 – 45 mV. In the recorded signal "noise," it was difficult to precisely establish the signal period. However, the signal spectrum (Fig. 8*b*) points to the electrical nature of the source. In addition, the signal image is characteristic of the defects seen in cracked insulators (with a dry, uncontaminated surface). The identified defect was recorded by two induction methods using an R400 instrument (Fig. 8*c*) and DimLoc with directional microwave antenna (Fig. 8*d*).

CONCLUSIONS

1. The main method of technical monitoring of the condition of isolated bus duct insulators is the acoustic location of electric discharges. The induction method is auxiliary, including the use of directional antennas, if necessary. To assess the level and nature of defect development, it is necessary to use the characteristic images of acoustic signals provided in this paper, as well as their level and the level of signals recorded by the induction method.

2. For normally operating bus ducts, it is justifiable to conduct PD measurements after 15 – 20 years of operation, and then on a periodic basis, for example, once every 5 years. After 30 years of operation, it is justifiable to use the results of PD measurements as a basis for extending the service life of the isolated bus ducts. An unscheduled control should be performed after an occurrence of a self-cleared ground fault in the bus duct.

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