X-ray Testing of High Voltage Oil-filled Electrical Equipment: Physical Background and Technical Requirements

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ABSTRACT

In this study the capability of X-ray technology to examine the internal elements of high-voltage equipment is reported for the first time. Samples of high-voltage minimum oil and SF6 circuit breakers were designed and tested to evaluate the X-ray images and compare with known artificial defects. The assessment of the influence of X-ray spectral energy characteristics on information obtained by X-ray imaging of objects having spread equivalent radiation thickness determined the technical requirements for this analysis.

Index Terms — **high-voltage circuit breakers, non-destructive testing, oil-filled electrical equipment, X-ray imaging, radiation**

1 INTRODUCTION

THE radioactive method of non-destructive testing is widely used in engineering. This method is based on registration and analysis of ionizing radiation after interaction with a controlled object and transformation of radiation passed through the object into an X-ray image [1]. To date, there is some experience of using this method for electric power equipment diagnostics.

Known X-ray systems for heterogeneous objects of large geometric dimensions are used to control the internal content of passenger luggage, vehicles and freight containers [2–4]. For X-ray analysis of these objects whose internal contents are not known in advance, a "Z back-scatter technology" is primarily used. This technology is rather expensive and complicated to implement. In case of equipment control, the X-ray diffraction of objects with known internal content is carried out; for quality control, it is necessary to have drawings of structural elements of the equipment for comparison with its radiographs. However, with regard to electric power equipment, there is little experience with X-ray control of line insulators, cable boxes, SF_6 dead tank circuit breakers and gas-insulated switchgears (GIS). Moreover, in scientific and technical literature there is a lack of information on the use of radiography to monitor the technical condition of high-voltage oil-filled equipment.

However, X-ray based non-destructive testing is of great interest for examining a large-size engineering equipment containing heterogeneous structures. It should be noted that the existing methods of monitoring the technical condition, such as high-voltage circuit breakers, based on the measurement of electrical, mechanical, physical and chemical indicators, can only indirectly identify the defects in structural elements of this equipment. The X-ray diffraction allows visualization of defects in the internal volume of equipment in various operating positions ("on", "off" or in the intermediate position of the moving contact).

Manuscript received on 10 June 2019, in final form 23 September 2019, accepted 10 October 2019. Corresponding author: V. Zverev.

DOI: 10.1109/TDEI.2019.008363

The efficacy of the X-ray method for monitoring the technical condition of such equipment is determined mainly by technical characteristics of the radiation source. X-ray diagnostics may provide an economical method to assess the condition of high-voltage equipment.

Assessment of the technical condition of switching devices and other high-voltage equipment using X-ray enables fast detection of most of the defects associated with a change in geometric dimensions of internal elements and assemblies, for example:

- deformation, wear, damage to the moving and fixed contacts;
- damage to cables, bearings and springs;
- displaced or missing structural elements.

The X-ray diffraction of high-voltage equipment can be applied not only at the place of their installation during operation, but also at the factory during the acceptance tests. This information can be very useful as reference for comparison with the results of operational measurements.

2 OBJECTS AND METHOD OF INVESTIGATION

2.1 HIGH-VOLTAGE CIRCUIT BREAKERS AS THE X-RAY TEST OBJECTS

The VMT-110 is a high-voltage circuit breaker in which mineral oil is an extinguishing medium. The three poles of the circuit breaker are mounted on a common frame and are controlled by a single drive (Figure 1a). Each pole of the circuit breaker consists of a support insulator and an insulator that encloses the arcing chamber. The contact group (moving and fixed contacts) and the elements of the moving contact control system (Figure 1b) are located inside the isolator of the arcing chamber: Fig. 1b: cable, upper roller with spring and bearing, rods with collector rollers. The arcing chamber is located inside the fiberglass cylinder (Figure 1c). Inside the support insulator there are insulating fiberglass traction rods and cables of the moving contact control system, as well as a heating device.

The VMT-110 circuit breaker consists of separate poles of large physical size (400-500 mm in diameter, 2–3 m long) and a complex heterogeneous internal structure. To date, the technology of X-ray testing of oil-filled high-voltage equipment including minimum oil high-voltage circuit breakers, has not been developed. Elements under investigation were the poles of the breakers shaped as the ribbed porcelain columns filled with transformer oil. Inside these columns are metal and fiberglass components with various geometrical dimensions, shape and location. These parameters are important for assessment of the technical state of the breakers.

Since oil and massive porcelain insulators are strong X-ray absorbers/scatters, it is required to use new instruments and analytical approaches with improved characteristics. In so doing we developed an instrumentation and analytical system (IAS) for X-ray testing of VMT-110 high-voltage minimum oil circuit breakers. This work is meaningful because thousands of circuit breakers operate in the electric power system, 1/3 of which are functional for > 25 years. Bulk replacement of these circuit breakers is unlikely in the near future for economic reasons. Thus, it is reasonable to consider the use of diagnostic techniques to extend the service life of the existing switchgear.

Figure 1. VMT-110 circuit breaker (a); VMT-110 arcing chamber internal elements (b), with fiberglass cylinder (c).

2.2 NON-DESTRUCTIVE RADIATION BASED TESTING: PHYSICS

In the radiography of technical facilities, X-rays and gamma emission quanta have identical physical properties. X-rays are emitted by electrons slowed down in a target whereas gamma emission occurs as a result of nuclear reactions.

We obtained the shaded radiographic images based on the effect of radiation attenuation when passing through a substance. Individual parts of the irradiated object attenuated the flux, providing the shadowed radiographic image.

Interaction of 0.1-10 MeV X-rays (energy typical for radiography of technical objects) with a substance generates photoelectric absorption, elastic and inelastic scattering, and electron-positron pair production [5]. All these effects lead to an attenuation of the initial radiation flow. The attenuation of radiation intensity while passing through a substance is determined by the Equation (1) that expresses general Beer-Lambert law [5, 6]:

$$I_P = I_0 e^{-\eta\delta} \quad (1)$$

where I_0 is the intensity of radiation falling on the radiated medium, I_P is the intensity of radiation that passed through the layer of an absorber of δ thickness, δ is the absorber's thickness (radiographic thickness), η is the exponent of radiation attenuation when passing through a substance.

The concept of substance load (g/cm^2) and the corresponding mass attenuation factor μ [cm^2/g] are traditionally used in radiography; then $\eta = \mu\rho$, where ρ is the density of the substance [g/cm^3].

Equation (1), a fundamental law of radiation defectoscopy [5], is true for an infinitely narrow X-ray beam (Figure 2).

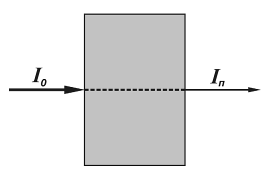

Figure 2. Attenuation of X-ray intensity when passing through a substance.

Practically the X-ray radiography differs from the scheme given in Figure 2 in two essential aspects. The radiation source has small dimensions (~1 mm), therefore at distances typical for X-ray radiography (~100 mm) it can be considered as a point source. Irradiation of an object is implemented by a conical beam whose intensity is inversely proportional to the distance from the source (Figure 3).

In practice, besides primary X-rays attenuated by the irradiated object, the radiographic recorder is also affected by scattered radiation that originates both inside the irradiated object and outside it (i.e. the interaction of X-rays with a substance that is not included in the translucent object (e.g, surrounding structures, the foundation on which the translucent object is mounted, the surface of earth, etc.). In the interaction of X-rays with these substances, as with any other, scattered radiation occurs, which can reach the detector, leading to noise in the resulting image). Physical effects of scattered radiation generation are inelastic scattering and a Compton effect according to which photon scattering on free electrons takes place, thereby changing the scattered radiation wavelength. Figure 4 shows a scattered radiation contribution to the image for a non-collimated source and recorder.

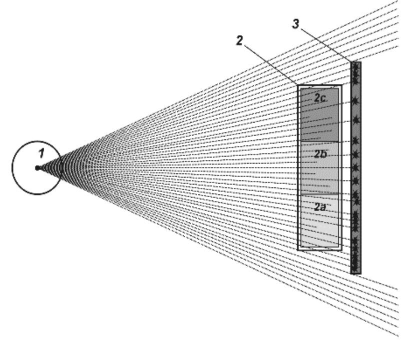

Figure 3. Idealized diagram of the shadow radiographic image generation: 1 – radiation source; 2 – examined object; 3 – radiographic recorder.

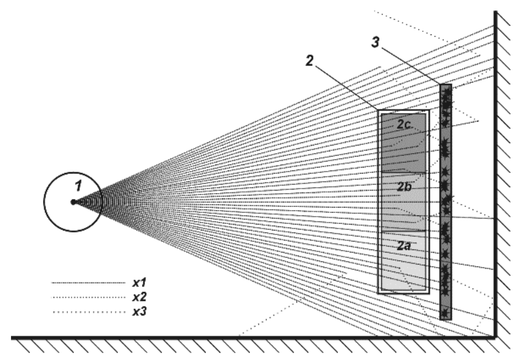

Figure 4. Realistic diagram of shadow radiographic image generation: 1 – radiation source; 2 – examined object; 3 – radiographic recorder.

Let us assume that the object consists of three parts having different equivalent radiation thickness (X-ray density):

- region 2a is of the lowest X-ray density and captures 1/4 part of X-ray quanta;
- region 2b has a bigger X-ray density and captures 1/2 part of X-ray quanta;
- region 2c has the greatest X-ray density capturing 2/3 part of X-ray quanta.

Accordingly, the signal levels on the radiographic recorder (shown by flash density) in the areas corresponding to shadow images of regions 2a, 2b, and 2c are, respectively, 0.75, 0.5, and 0.33 of the signal level in the areas not overshadowed by the irradiated object. Similarly, the object consists of three parts that attenuate X-rays to various extent, but besides pure absorption of radiation by the object, the following phenomena are presented (Figure 4):

- X-ray scattering by the irradiated object;
- X-ray scattering by surrounding matter;
- X-ray passing through the recorder without any interaction with it;
- multiple X-ray scattering.

Therefore, the radiographic recorder is irradiated and receives signal from three components:

1) Primary X-rays (x1) that carry a useful signal;
2) X-rays scattered on the radiated object (x2) that carry no useful signal;
3) X-rays scattered not on the radiated object (x3) that carry no useful signal.

Let us note that only the first component carries information about the internal structure of the examined object. The remaining two components (that are similar) provide no useful information but only distort the X-ray image. Moreover, while the latter component can be eliminated by a screen (installed behind the recorder) that absorbs X-rays, the radiation scattered by the examined object itself is fundamentally unavoidable for a non-collimated receiver.

The major physical process that causes initial attenuation of radiation (~100 keV) is incoherent scattering. This is particularly important for the elements with a small atomic number (Z_{eff}). The porcelain covers and oil in VMT-110 circuit breakers consist of such elements. Table 1 shows a quantitative relation between total radiation attenuation and incoherent scattering.

Table 1. Relation between total X-ray attenuation and incoherent scattering for different substances and radiation energies according to [7].

Radiation energy, keV	Portion of initial radiation lost while passing through 1 cm layer of the substance, %			Out of it due to incoherent scattering, %		
	Fe Z_{eff}=26	Al Z_{eff}=13	Oil Z_{eff}=5.95	Fe Z_{eff}=26	Al Z_{eff}=13	Oil Z_{eff}=5.95
100	94.5	36.8	14.3	67	85	98
200	68.0	28.1	11.8	85	97	99
300	57.6	24.5	10.4	93	98	>99
400	52.0	22.2	9.3	96	99	>99
500	48.1	20.4	8.6	97	99	>99

3 DEVELOPMENT OF INSTRUMENTS AND ANALYTICAL SYSTEMS

3.1 OVERVIEW OF X-RAY EXAMINATION OF HIGH-VOLTAGE EQUIPMENT

To date, some experience of the use of non-destructive radiation methods to test high-voltage equipment in electric power facilities has been reported [8]. Results of X-ray examination have been demonstrated for high-voltage insulators that are homogeneous structures with surface defects [9]. Evidently, these defects can be revealed by visual examination or ultrasonic acoustic emission technique.

Capabilities of digital radiography in testing high-voltage gas circuit breakers and GIS (Gas Insulated Switchgear) are analyzed in [10–13]. However, in [10] the results of X-ray testing of relatively simple small-size heterogeneous structures are represented. In addition, the radiopaque metal test objects and generated defects were located in the zones of small equivalent radiation thickness (against the radiotransparent background) or outside the examined structure, therefore the defects were clearly visible on X-ray images.

The high-voltage circuit breakers are large complex structures that consist of variable materials (steel, copper, oil, porcelain, etc). Thus, special technical means and non-destructive X-ray examination methods are to be applied to obtain the informative X-ray images. Basic characteristics of the sources used for X-ray testing of high-voltage equipment (Table 2) showed that, among the X-ray units with direct-current tube voltage only our experimental sample has maximum radiation energy > 300 keV. The size and weight of the RAPAN X-ray unit, together with a relatively simple positioning system provides the possibility of its use as a mobile diagnostic tool.

One should note that X-ray images can be obtained on X-ray films, energy-accumulating screens and digital flat-panel X-ray detector.

Laboratory studies were carried out by the authors using an X-ray film. The digital flat-panel X-ray detector was used during pilot operation. We determined significant advantages of digital flat-panel X-ray detector compared to the X-ray film. This detector allows for obtaining the image for an on-line transmission. Other important technical advantages are:

- a 10-fold smaller duration of exposure;
- a 30-fold shorter time of the digitalized X-ray image;
- no need for materials such as X-ray film and developing liquids;
- lack of need to prepare a workplace (“dark” room) for developing an X-ray film and solutions for a developing machine;
- less weight and dimensions (no developing machine with the X-ray film scanner).

Obviously, the digital flat-panel X-ray detector is preferable for the surveys at electric power facilities.

Of note, the energy-accumulating screens at the place of operation of high-voltage equipment are less convenient than digital flat-panel X-ray detector because after the X-ray analysis of each area of equipment, it is necessary to dismantle the screen for scanning in a special device.

3.2 PARAMETERS OF X-RAY IMAGING OF INTERIOR ELEMENTS OF THE HIGH-VOLTAGE CIRCUIT BREAKER

To obtain a high-quality X-ray image the intensity of primary radiation generated by an X-ray unit should be considerably reduced by the irradiated object. Minimal level of such attenuation is ~100-fold [1]. On the other hand, there is also an upper limit of X-ray intensity decrease by the irradiated object in order to maintain the quality and efficiency of X-ray examination and avoid a low level of useful signal as well as an increased noise caused by scattered radiation effect. Based on practical experience of technical object radiography the maximum level of X-ray intensity attenuation by the irradiated object acceptable for a high-quality image is ~10, 000 for a non-collimated (open) receiver (X-ray films, energy-accumulating screens, digital flat-panel X-ray detector).

Table 2. Radiation sources applied for X-ray testing of high-voltage equipment.

X-ray source	Tested electrical equipment	Emitter weight, kg	Tube voltage, kV	Maximal tube current, mA	Maximal photon energy, keV	Maximal radiated thickness (Fe-equivalent), mm	Maximal exposure rate at 0.5 m distance	Focal spot diameter, mm
Golden Engineering XRS-3* (Brazil University "Federal University of Pernambuco", ABB) [9, 11–13]	dead tank SF_6 circuit breakers, GIS	5.7	270	N/A	270	35	4 mR per 1 pulse	3
ERESCO 42/65 MF4 (China University "North China Electric Power University" together with electric grid company "Yunnan Power Grid Corporation") [10]	GIS	27/40	200/300	4.5/3	200/300	42/65	20/25 R/min *(estimate)*	3
Radionuclide source of gamma radiation based on Iridium-192 of 1.5 Cu radioactivity (Brazil University "Federal University of Pernambuc") [9]	Line insulators	19	Not applicable	Not applicable	400	80	N/A	N/A
RADIX complex* (LLC "Positivnaya energiya") [14]	Electricity consumption metering devices	6	50-150	N/A	N/A	N/A	7.5-23 mR per 1 pulse	1.2
RAPAN (experimental sample by VNIIA)	dead tank and live tank SF_6 circuit breakers, oil-filled equipment	22	500	0.5	≥400	≥60	≥12 R/min	1.5

N/A - not available
* pulsed radiation sources

Therefore, to obtain an informative high-quality X-ray image recorded by the non-collimated receiver, the range of intensity decrease of primary X-rays should vary between 100- and 10, 000-fold. This range may be termed the effective radiography region [15]. The X-ray intensity means the number of X-ray quanta propagating in a small spatial angle within the time unit. In the radiation energy region used in radiography of technical objects (~100 keV) this value is almost directly proportional to the rate of exposure.

The pole of the high-voltage minimum oil circuit breaker has the following radiation thickness in the zones of examined structural elements (Figure 5):

- minimum: 60 mm porcelain + 220 mm oil;
- maximum: 165 mm porcelain + 200 mm oil + 20 mm copper.

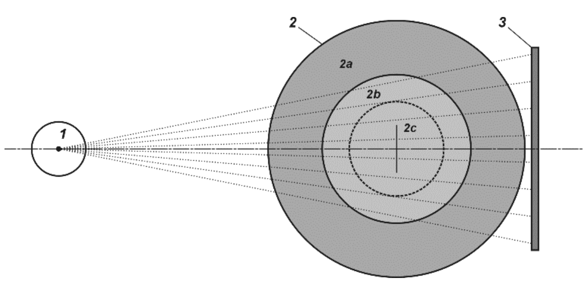

Figure 5. Diagram of high-voltage minimum oil circuit breaker pole radiography by X-rays. 1 – radiation source, X-ray unit emitter (monoblock); 2 – examined breaker pole; 2a – ribbed porcelain insulator of radial thickness from 30 mm to 82.5 mm; 2b – internal cavity of 220 mm in diameter filled with transformer oil; 2c – zone of examined elements location (≈140 mm diameter), where structural elements of ≥ 20 mm copper equivalent radiation thickness are located; 3 – X-ray image recorder.

To assess the effective radiography regions applied to X-ray units with different tube voltage values, theoretical calculation of primary X-rays intensity attenuation was carried out using data in [7] based on the quantity of quanta obtained by calculating over the entire energy spectrum in increments of 1 keV. The X-ray unit energy spectrum was simulated using Kramers formula [6]. The results of calculation are shown in Table 3.

Table 3 shows that at least 100-fold attenuation of the primary X-ray intensity for minimal equivalent radiation thickness, and <10, 000-fold for maximal equivalent radiation thickness were observed only when the X-ray tube voltage was 400-500 kV. Thus, to obtain informative X-ray images of equipment with a heterogenous structure and a spread of equivalent radiation density such as oil-filled equipment and specifically the poles of minimum oil breakers, an X-ray unit with a high tube voltage (>400kV) is required.

Table 3. Calculated attenuation of primary X-rays during radiography of the pole of a high-voltage minimum oil circuit breaker.

X-ray tube voltage, kV	X-ray intensity decrease, times		Fe equivalent, mm	
	Minimal equivalent radiation thickness	Maximal equivalent radiation thickness	Minimal equivalent radiation thickness	Maximal equivalent radiation thickness
200	403	703 000	28	81
250	279	170 000	32	86
300	209	66 400	35	90
400	135	19 300	39	93
500	96.9	8 470	41	95
600	74.5	4 600	42	96

It should be noted that application of high-energy X-rays makes it possible to obtain information about the state of internal structural elements in the zones of both small and large equivalent radiation thickness. X-ray photographs (Figure 6) showed the moving contact of live tank SF_6 circuit breaker of VGT-110 in which the porcelain insulator is similar to that used in VMT-110 circuit breaker.

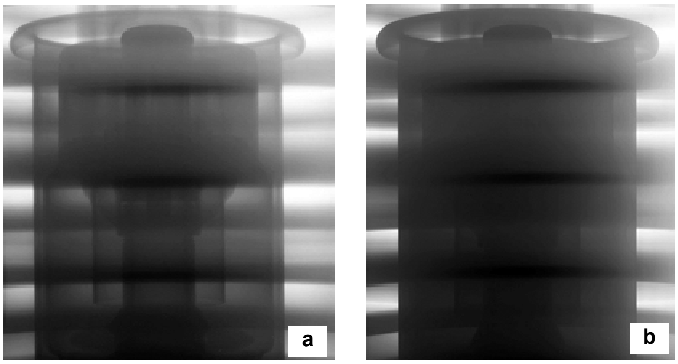

Figure 6. X-ray photographs of VGT-110 live tank SF_6 circuit breaker; X-ray apparatus tube voltage: a) 500 kV; b) 200 kV.

In the image obtained on an X-ray apparatus with the tube voltage of 500 kV, structural elements inside the copper cylinder with 3 mm thick walls can be clearly seen, while in the image obtained with a tube voltage 200 kV the copper cylinder almost completely shielded the internal structural elements. In addition, the increase of power of X-ray apparatus (increased anode current) with tube voltage 200 kV or increase of exposure time will not improve the image, since the overexposed areas are already noticeable at the top and in the right parts of the image.

Increased X-ray exposure dose will lead to the loss of information in these parts of the image, and the central part of the image will become ‘covered’ due to overexposed areas along the edges.

4 CONTRIBUTION OF SCATTERED X-RAYS TO IMAGE FORMATION

As mentioned above the scattered radiation contributes considerably to image formation. Depending on specific radiography conditions, the scattered radiation distribution on the recorder’s surface is variable and hardly predictable. Therefore, a special study was performed to estimate the degree of scattered radiation effect on radiography of high-voltage oil-filled circuit breaker (VMT-110). The X-ray testing of the porcelain insulator of the circuit breaker pole (Figure 7, top) showed that the contrast objects (a lead wire ∅1 mm used as a marker in the X-ray image and lead marking signs) were placed directly in front of the X-ray image recorder.

Distortions of a lead wire used as a marker in the X-ray image (blurring and ghosting are indicated by arrows) can be clearly seen in X-ray photograph (Figure 7, bottom). Taking into account the radiography scheme, this image reveals an additional powerful X-ray source in front of the recorder whose intensity is comparable with that of the primary source.

Only scattering of primary radiation by the irradiated object can be such a source; apparently scattering occurs on porcelain insulator edges adjacent to the recorder. This is further confirmed by X-ray radiography of a breaker pole filled with oil. X-rays scattered by the irradiated object caused considerable distortions (contrast decrease) of the image (Figure 8).

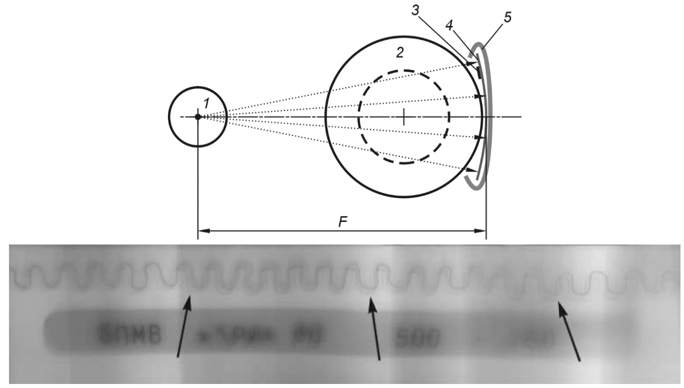

Figure 7. X-ray photograph (segment) of the pole of the high-voltage minimum oil circuit breaker with test objects installed in front of the recorder (bottom) and radiography diagram (top): 1 – radiation source; 2 – minimum oil circuit breaker pole (VMT-110); 3 – radiopaque test objects; 4 – radiography recorder; 5 – protection against back scattered radiation (lead sheet).

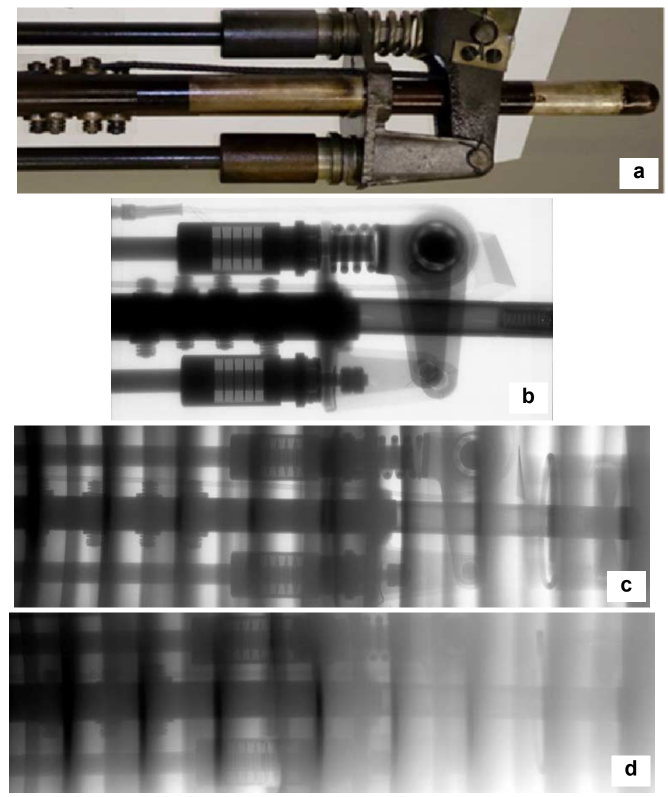

Figure 8. The moving contact of high-voltage minimum oil circuit breaker and contact control system: a) object under test; b) X-ray photograph of the object without insulator; c) X-ray photograph of the object inside the insulator without oil; d) same for the insulator filled with oil.

For quantitative estimation of scattered radiation contribution to X-ray image formation we studied the pole in the zone that contained no radiopaque elements and was filled with highly scattering materials such as porcelain, oil, and fiberglass (Figure 9). The experiment included three radiography procedures of the same zone of the minimum oil circuit breaker:

1) without collimator (a);
2) using a slit collimator of lead blocks of 50 mm thickness with ≈8 mm wide slit installed closely in front of X-ray film (b);

3) using a collimator of a lead block of 50 mm thickness with a hole of 10 mm in diameter installed closely in front of X-ray film (c).

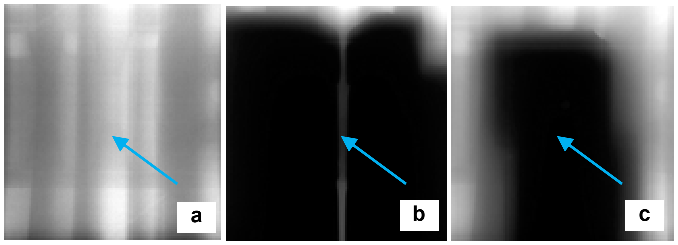

Figure 9. X-ray photographs allow to estimate the scattered radiation effect.

All X-ray photographs were obtained in similar conditions. Exposure parameters: tube voltage 594 kV, tube current 0.19 mA, focal distance 0.7 m, exposure time 5 min, focal spot size 2 mm (corresponds to the spatial angle of useful signal reception of $2\cdot10^{-6}\pi$). Images were obtained on a X-ray film Agfa Structurix D7 PbVacuPac 30×40 cm. Spatial locations of the radiation source or the irradiated object and X-ray film were not changed. All X-ray films were processed identically and simultaneously.

Optical density of the X-ray film blackening is characterized by attenuation of light passed through a negative. If the intensity of light falling on the film is designated L_0, and the intensity of light that passed through it L_i, then optical density of blackening (S) can be calculated using Equation (2):

$$S = \lg \frac{L_0}{L_i} \tag{2}$$

Photographic blackening that attenuates light 10-fold (Lg 10=1) is taken as a unit of optical density. It is evident that if the film transmits 0.01 part of light, the blackening density is equal to 2 (Lg 100=2).

Let us consider the signal level (film blackening density over a fog, i.e., the value of blackening density exceeding that of the raw processed film) in the image centers. One film was developed together with the exposed films to determine fog density S_{fog}. Its blackening density was 0.2. In Figure 9a radiation scattered by the object strongly affects the image (spatial angle of signal reception is $\approx \pi$), and film blackening density over the fog is 2.7. In Figure 9b scattered radiation is cut off for the most part by a slit collimator (it propagates only vertically along the slit; spatial angle of signal reception is $\approx 0.1\pi$), film blackening density over the fog is 0.68. Finally, in Figure 9c where scattered radiation is practically completely cut off by the collimator (spatial angle of signal reception is $\approx 0.01\pi$), film blackening density over the fog is 0.48. Thus, taking film blackening density over the fog in Figure 9c as the level of useful signal without any effect of scattered radiation, we obtained the following: in Figure 9b scattered radiation contributed additionally 0.2, and in Figure 9a 2.22 units of blackening density. The results Figures 9a, 8b correlate with the spatial angle of signal reception ($\approx 0.1\pi$ and $\approx \pi$, respectively). This can be explained as follows: since the spatial angle of useful signal is very small ($2\cdot10^{-6}\pi$), and scattered radiation comes to the recorder from the large spatial angle ($\approx \pi$), then the increase of the spatial angle of signal reception at the point of the image leads to almost proportional growth of scattered radiation recorded at this point of the image.

Of note, the level of scattered radiation exceeds the useful signal 2.22/0.48≈4.5 times. Therefore, over 80% of the signal on the non-collimated X-ray recorder can be “noise” that gives no useful data regarding the tested object.

5 PRACTICAL RESULTS AND DISCUSSION

We developed the background for IAS applicable for X-ray testing of high-voltage minimum oil circuit breakers of VMT-110 model with image recording. Technical characteristics of the system are presented in Table 4. Examples of X-ray images were obtained by radiography using IAS of a special defective sample (SDS) designed based on VMT-110 high-voltage minimum oil circuit breaker (Figures 10, 11). In spite of the demonstrated possibility to detect various defects by X-ray radiography of the oil-filled pole of the high-voltage circuit breaker, the low image contrast due to the scattered radiation effect was visible. Definitely, elimination of this drawback is necessary.

6 INCREASING X-RAY IMAGE INFORMATION USING SCANNING IRRADIATION

To reduce the scatter effect, a scanning method of X-ray image formation can be used. Narrowly collimated X-ray source and linear X-ray recorder move synchronously along the tested object and consecutively, line-at-a-time, form its X-ray image (Figure 12). Scanning based on the above scheme assumes X-ray radiography of the object by a fan-shape radiation beam located in the plane perpendicular to the longitudinal axis of the scanned object. The narrowly collimated fan-shape radiation beam, similarly to Figure 9b, produces considerably less quanta of scattered radiation. In addition, in such a scheme the most part of scattered radiation is cut off by a receiver collimator (3' in Figure 12) that significantly increases image contrast in the X-ray photograph.

One important advantage of X-ray imaging based on the scanning principle is the fact that all lines of the image are obtained in the same geometrical projection (e.g., perpendicular as in Figure 12). This allows for prevention of image distortion of extended elements of the scanned object, and opens up the possibilities to process the X-ray image. For instance, one can ‘deduce’ the image of ribbed porcelain cover that may be non-informative, thereby considerably improving visualization of internal structural elements.

It should be noted that the proposed scanning system for obtaining X-ray images differs from the known technical solutions used in airports or in computed tomography. The main difference is the scanning system moving relative to the measured object and the object located at the operating site

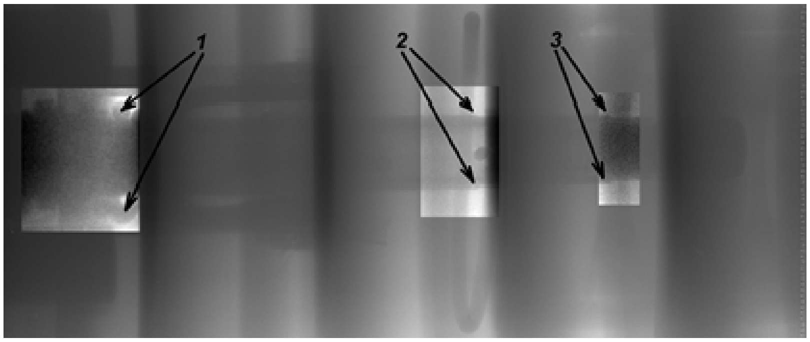

Figure 10. X-ray image patch of SDS pole (with porcelain cover and oil) with defects: 1 – damage of upper roller of pulley block, 2 and 3 – decrease of moving contact diameter.

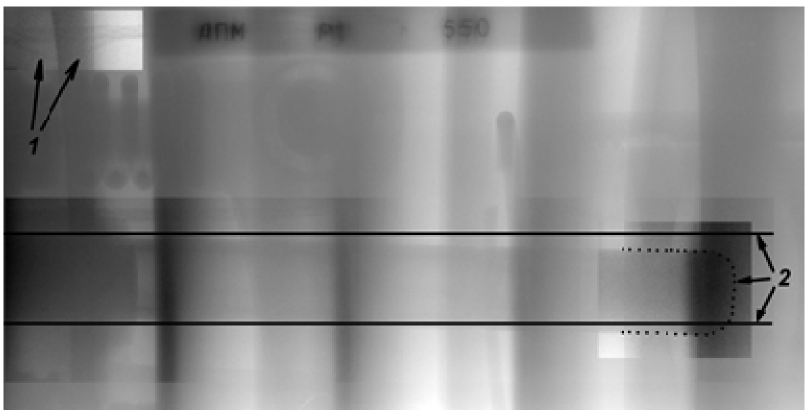

Figure 11. X-ray image patch of SDS pole (with porcelain cover and oil) with defects: 1 – damage of pulley block rope, 2 – bend of moving contact (solid lines show rails continuation, dotted lines – end of moving contact).

Table 4. IAS basic technical characteristics.

System configuration	X-ray apparatus (including X-ray emitter monoblock, power supply panel, control panel), positioning system, image recorder (a pad with X-ray film), automatic developer, scanner with a slidec module, PC (notebook)
X-ray unit type	With continuous anode voltage, monoblock, with directed radiation output
Maximum anode voltage	400 kV
Maximum anode power	200 W
Focal spot size	1.5 mm
X-ray escape	Side, 70°×40° (in operation, constricted by a collimator to 32°×24°), with 5 mm copper radiation filtering
Maximum thickness of radiated objects	At least 40 mm in Fe equivalent
Minimum size of detected defect	1 mm in Fe equivalent
Single X-ray photograph time	Maximum 15 min
Emitter weight (monoblock)	18 kg
Ambient air temperature while operation	-35..+40°C (X-ray apparatus, positioning system, image recorder)

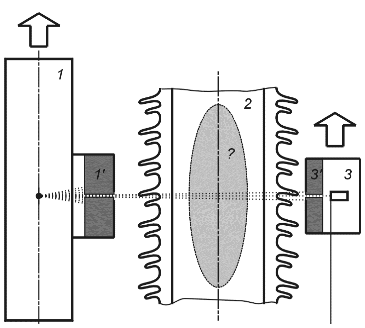

Figure 12. Scheme of scanning X-ray examination: 1 – radiation source; 1' – source collimator; 2 – scanned object (high-voltage minimum oil circuit breaker pole); 3 – linear X-ray recorder (receiver); 3' – receiver's collimator.

without dismantling. This imposes a number of essential requirements on the design of the scanning system, in particular, the synchronization mechanism and the mechanism of precise movement of the source and the X-ray receiver. Solving these problems will significantly reduce the time of X-ray examination.

7 CONCLUSIONS

1. This is the first multiparametric study of X-ray testing of high-voltage equipment whose internal elements have a complex heterogeneous structure and a considerable equivalent radiation thickness.
2. Informative X-ray examination of high-voltage minimum oil and gas circuit breakers is possible using X-ray (sources of high energy (>300-400 keV), in particular, continuously operating units with anode voltage of >400 kV. The experiment with 200 kV and 500 kV tube voltages confirmed theoretical calculations of X-ray energy characteristics for necessary and sufficient attenuation of primary radiation intensity for testing the heterogeneous objects.
3. The main source of spurious X-ray radiation that gives no useful information and distorts the image is the porcelain insulator of a circuit breaker. The level of 'noise' in the image can be up to 80% leading to the contrast decay in the X-ray photograph.
4. Increased X-ray image informativeness for highly engineered objects with differential thickness, large metal elements and massive polymer or porcelain insulators, and transformer oil, requires a considerable decrease of scattered radiation effect on the recorder. This can be achieved using the scanning X-ray system with the slit collimation of the radiation source and the X-ray recorder.

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