X-ray digital imaging detection system for high-voltage equipment inspection

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Abstract. In 2019 a portable diagnostic X-ray system was developed and tested for the inspection of high-voltage equipment (HVE). The system operates based on discrete radiography and is referred by the authors as the first generation X-ray system. As a result of critical analysis of the first generation system, it was further proposed to create a second generation mobile scanning system for HVE digital radiography which is for the first time applied in the power engineering. A physical and mathematical model was developed to establish the relationship between the energy spectrum of the source X-ray radiation and the contribution of this radiation to the image generation during HVE radiography. Using this model, the authors assess the efficiency of the unique X-ray machine used in the first generation X-ray system.

The main technical requirements for the second generation X-ray system, implementing digital scanning radiography, for examining HVE in operation are given.

1 Introduction

To conduct the visual inspection of the internal elements of high-voltage equipment (HVE) it needs to be disassembled. And the disassembly of the equipment, minimum oil and SF6 circuit breakers (CB) in particular, requires down-conductor disconnection, oil drain or SF6 pumping, and its dismantling using lifting machines. After finishing the visual inspection, it is necessary to assemble and install back the HVE, refill it with an insulating medium, and reconnect down-conductors. In order to increase the efficiency of monitoring the HVE technical condition and reduce equipment downtime, new technologies that allow either to exclude some of these activities or to reduce the required time are needed [1, 2].

X-ray inspection, for example, of high-voltage CB allows you to quickly identify most of the defects associated with a change in the size of the internal elements and structural assemblies [3]:
- deformation, wear, damage to the moving (bending, burning, scuffing, etc.) and fixed contacts (damage to the housing, violation of the placement order of lamellas, etc.);
- damage to cables, bearings and springs of the moving contact control system;
- fastener defects and burnouts of inner shells;
- displaced or missing structural elements (fasteners, etc.);
- foreign bodies (chips, etc.).

The worldwide experience has been gained in HVE radiography using radioisotopes, constant and pulsed X-ray generators, and betatrons as sources of ionizing radiation. As a rule, X-ray films, photoluminescent storage screens, and digital flat-panel detectors are used as X-ray detectors [4–7]. At the same time, the experts in the field of X-ray nondestructive testing showed that thanks to X-ray digital imaging systems it is possible to obtain a better image quality compared to film systems [8, 9]. It was also confirmed that X-ray digital imaging technology allows to completely replace the film radiography in most practical application cases. It should be noted that all the above-mentioned X-ray systems for HVE inspection implement the so-called discrete radiography – when a full-size X-ray image is generated with simultaneous irradiation of the entire surface of the radiation receiver.

However, discrete radiography has two main disadvantages: distortion of images of extended elements on radiographs and an increased level of radiation hazard during HVE inspection. Moreover, the existing systems, though being portable, need special solutions for their positioning and reliable fixing, which usually requires more time to prepare for conducting HVE inspection.

Depending on how radiographs are generated, X-ray systems can be divided into two generations: the first generation X-ray systems are those that implement discrete radiography, and the second generation X-ray systems are based on scanning radiography.

The purpose of this work was to develop technical requirements for a mobile diagnostic X-ray system of the second generation, which can provide operational monitoring of the HVE technical condition and ensure the minimization of the radiation-hazardous zone.
2 Portable diagnostic X-ray system of the first generation

In 2019 a portable diagnostic X-ray system was developed to examine the technical condition of the internal structural elements of 110 kV minimum oil CB. The system has been tested and put into operation at electric utilities [10]. The first generation X-ray system consists of the following main functional elements:
- X-ray machine with a collimator, power supply and control panels;
- digital flat panel detector (X-ray receiver);
- positioning system;
- software for processing digital X-ray images.

The main feature of the monoblock X-ray machine of constant action is a sectioned X-ray tube with a maximum voltage of 400 kV. This device is one of a kind in terms of penetrating power of radiation (60 mm in Fe-equivalent) considering its moderate weight (22 kg). A filter (copper plate) is installed at the exit window of the X-ray tube, which makes it possible to significantly reduce the level of radiation scattered by the test object and improve the contrast on the X-ray image of the internal elements of heterogeneous structures with massive porcelain insulators. The collimator mounted on the X-ray machine forms a 32°×24° pyramidal beam [11].

It should be noted that the X-ray machine feasibility is determined by the energy of the radiation quanta that contribute the most to the resulting X-ray image.

3 Physical and mathematical model of HVE radiography

The physical and mathematical model of HVE radiography includes an X-ray machine with its own radiation spectrum, a test object and the medium in which the radiation propagates. The initial energy spectrum of the radiation emitted by the X-ray tube target (the distribution of the number of ionizing particles according to their energy) is described in the physical and mathematical model of HVE radiography in accordance with the Kramers equation [12]:

\[ I(E) = k \cdot i \cdot Z \cdot \left( \frac{E_0}{E} - 1 \right), \]  

where \( k \) is the coefficient of proportionality (\( k = 10^{-9} \)); \( i \) is the current, carrying through the X-ray tube; \( Z \) is the atomic number of the anode material; \( E_0 \) is the maximum photon energy in the spectrum.

According to equation (1), if \( E \to 0 \) then \( I_E \to \infty \), which means one can set lower threshold energy at 10 keV when calculating the energy spectra. Such a limitation does not affect the calculation results, since the emitters (monoblocks) of the X-ray machine almost completely absorb radiation with energy up to 15 keV.

The change in the energy spectrum of X-ray radiation during the object inspection is described in the physical and mathematical model of HVE radiography proposed by the authors using the Beer-Lambert law [12, 13]:

\[ I_n = I_0 \cdot e^{-\gamma \delta}, \]

where \( I_0 \) is the intensity of radiation incident on the translucent medium; \( I_n \) is the intensity of radiation that has passed through a layer of matter with a thickness of \( \delta \); \( \gamma \) is the attenuation coefficient; \( Z \) is the atomic number of the element; \( \lambda \) is the wavelength of radiation.

Since the X-ray machine has an external filter, the source spectrum (Fig. 1a, graph 2, or Fig. 1b) contains a very small fraction of low-energy quanta (up to 120 keV). The fact that the voltage on the tube is very high for this type of X-ray machine makes it possible and efficient to apply the filtering of the initial radiation (Fig. 1a, graph 1). The ratio of the areas of graphs 2 and 1 corresponds to the fraction of X-ray machine radiation quanta transmitted by the external filter [14].

Fig. 1. Energy spectrum of X-ray machine radiation: 1 – energy spectrum of initial radiation; 2 – energy spectrum of radiation after passing through an external filter.

The efficiency of X-ray machine can be assessed by comparing its radiation spectra obtained without the test object and with it. To do so, firstly, the convolution of the spectra of the initial radiation and radiation emitted after passing through the test object should be calculated. Therefore, we need to obtain the product of the functions of these two energy emission spectra:

\[ S(E) = I_0 \cdot I_n \]  

where \( I_0 \) is the intensity of radiation that is incident on the translucent medium; \( I_n \) is the intensity of the radiation that has passed through the test object and is involved in the radiograph generation.

Secondly, we need to determine the fraction of the radiation energy that has passed through the test object and participates in the X-ray image generation. Thus, the percentage ratio of the convolution area of the radiation energy spectra to the area of the initial radiation energy spectrum is calculated:

\[ P(E) = \frac{\int_{E_0}^{400} S(E)dE}{\int_{E_0}^{400} I_0(E)dE}. \]
Using the graph of the initial radiation energy spectrum combined with the convolution graph of the energy spectra of the initial radiation and radiation emitted after passing through the test object, it is possible to estimate the region of the X-ray machine radiation spectrum that most effectively produces an X-ray image. This region (Fig. 2) is located between the convolution peak of the energy spectrum of radiation (2) and point (3). It characterizes the energy of X-ray quanta that contributes the most to the resulting X-ray image.

![Image](image1)

**Fig. 2.** Evaluation of the X-ray machine efficiency in inspecting VGT-110 (a) and VMT-110 (b) poles: region 1 – energy spectrum of the initial radiation; region 2 – convolution of the spectra of the initial radiation and radiation emitted after passing through the test object; point 3 – the upper limit of the radiation energy spectrum, the quanta of which contributes the most to the X-ray image generation.

Thus, analysis of the applied X-ray machine efficiency shows that the fractions of radiation energy involved in the generation of X-ray images of VGT-110 (Fig. 2a) and VMT-110 (Fig. 2b) are 40% and 36.5%, respectively. It is important to note that, according to [14], the efficiency of machines with 250 kV tube voltage in X-ray imaging of the same test objects is 8-9%.

### 4 Inspection of VMT-110 CB in the field

The results of X-ray inspection of VMT-110 CB in operation using the developed first generation X-ray system are presented. The X-ray system is mounted on the CB pole (Fig. 3). The positioning system (S) is attached to the CB frame. The X-ray machine (M) with a collimator (C) is mounted on the first pole of the positioning system, and a flat-panel digital detector (D) is mounted on the second pole.

![Image](image2)

**Fig. 3.** X-ray inspection of VMT-110 minimum oil CB in the field.

The assessment of the technical condition of the contact rod of the CB moving contact was carried out using two X-ray images (Fig. 4a and 4b) obtained in two mutually perpendicular views (Fig. 3, position 2). According to the assessment results, there were no such defects as deformation, wear, burning of the contact surface, decrease in the height of the contact part of the moving contact [15].

At the end of radiography, the examined CB was disassembled (Fig. 4c). The further visual inspection of the CB internal elements confirmed the absence of the defects mentioned above.

Thus, it was confirmed that it is possible to assess the condition of the examined CB assemblies using X-ray images. Therefore, there is no need to disassemble the equipment, which can significantly save time and reduce labor forces.

![Image](image3)

**Fig. 4.** Inspection of the condition of the contact rod of VMT-110 CB moving contact: (a) X-ray image obtained in the first view; (b) X-ray image obtained in the second view, perpendicular to the first one; (c) contact rod of the moving contact of the disassembled CB.

### 5 Technical requirements for mobile X-ray systems of the second generation

The further development of mobile X-ray systems is caused by the need to increase the efficiency of the HVE inspection and to improve the mobility and versatility of the applied technical solutions, as well as the need to significantly reduce the level of radiation hazard during radiography.

Taking into account the accumulated experience in the field of X-ray nondestructive testing and the results of assessing the X-ray machine efficiency, it seems appropriate to use the same X-ray machine that the first generation X-ray system was equipped with as an emitter for HVE radiography.

Unlike discrete radiography, the scanning system operates as follows: a narrowly collimated X-ray source and a linear radiographic recorder move synchronously along the object, obtaining its X-ray image line by line [16]. The data received from the linear recorders are digitally processed in the control unit of the scanning system and transferred to the software as pixels. When scanning is completed, a full-size X-ray image is generated from the received pixels. Compared to discrete radiography, the X-ray digital
imaging detection systems have the following advantages [3]:
- reduction of the "noise" level on X-ray images by at least 4 times due to the radiation collimation;
- obtaining all lines of the image in one geometric projection, which makes it possible to avoid distortion of the images of object extended elements (for example, CB poles);
- expanding the possibilities of post-processing of the resulting image on a digital radiographic image;
- ensuring a reduced level of radiation hazard during HVE radiography in the field (reduction of the radiation-hazardous zone around the X-ray system during exposure by at least 2 times).

To increase the efficiency of the HVE inspection, the scanning speed needs to be at least 0.5 m/min. At the same time, the HVE can have a housing with a diameter of up to 1 m with a total radiation thickness of the test object up to 60 mm in Fe equivalent. The resolution of the X-ray image should be no more than 1 mm in the original scale of the equipment.

The selected vehicle for a mobile scanning X-ray system must meet the following technical requirements:
- being able of riding unpaved and public roads;
- having overall dimensions that provide high mobility on substations;
- having all-wheel drive and optimal carrying capacity to ensure the ability of riding muddy roads;
- having structural elements and auxiliaries that ensure the protection of the scanning system from the precipitation, dust and other external factors during transportation and storage;
- being equipped with a radiation-safe operator cabin;
- providing an automated workplace in the operator cabin.

The positioning of the scanning system is carried out by a crane-manipulator installed on the chassis of the X-ray system. The manipulator must provide positioning of the scanning system from one position of the parked X-ray system (from 1 m to 7 m vertically from the ground and 2 m horizontally to either side of the central position).

6 Conclusions

1. A critical analysis of the developed and tested portable diagnostic X-ray system of the first generation is presented. The choice of X-ray machine is vital for HVE radiography.

2. Based on the previously developed physical and mathematical model for HVE radiography, the feasibility of the applied X-ray machine was assessed. It is shown that with an increase in the tube voltage, the fraction of radiation energy involved in the formation of X-ray images increases as well.

3. The X-ray tube with the maximum photon energy of 400 keV, used in the first generation X-ray system, surpasses in its efficiency all known X-ray machines, taking into account its weight and size.

Assessing the proposed X-ray machine showed it is reasonable to use the machine in a mobile scanning system of the second generation.

4. The main technical requirements for mobile diagnostic X-ray systems of the second generation, which implement digital scanning radiography and provide operational examination of the HVE while reducing the radiation-hazardous zone around the X-ray system, are proposed.

References

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