New device for the quality control of the high-voltage electrical insulator

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Abstract. During the operation of high-voltage electrical equipment, its insulation ages, its properties deteriorate, and the electrical strength decreases. To avoid sudden breakdowns of insulation and maintain the necessary level of reliability of high-voltage electrical equipment, the state of its insulation must be periodically monitored. The device described in the article is intended for preventive testing and diagnostics of heterogeneous high-voltage insulation of electric machines, power oil transformers and cables with paper-oil insulation. In particular, the integral assessment of high-voltage insulation aging, its humidification and remaining operational life can be based on the use of the absorption phenomenon (the accumulation of internal absorbed charge). Self-discharge and return voltage are measured to assess the insulation condition. A block diagram of the device for monitoring the electrical insulator quality is given as well as the formulae for determining the spent and remaining operational life of the tested insulation. The proposed device will increase the operational reliability of high-voltage electrical equipment.

1. Introduction

Electrical equipment and its insulation should be reliable for accident free work. During the exploitation process electric insulator ages, its properties deteriorate, its electric strength lowers [1-3]. To avoid sudden breakdowns of insulation and maintain the necessary reliability level of electrical equipment, the insulation state should be periodically monitored [4-6].

The issue of monitoring the state of insulator is particularly acute due to the fast growing of the share of electrical equipment that has worked its standard term. In this case, it is necessary to determine the remaining insulator resource for reasonable extending of the electrical equipment operational life [7, 8]. As the practice shows, the remaining life of electrical equipment can and should be determined not by the time worked, but by the actual technical state of its insulator based on the measurements. One can see how to do this below.

Objective – development of new technical equipment to objectively control the state of heterogeneous high-voltage insulator and determining its remaining operational life using the absorption phenomenon.

2. Materials and Methods

The developed device described in the article is intended for preventive testing and diagnostics of high-voltage insulation of electric machines, power oil transformers and cables with paper-oil insula-
tion. In particular, it may be used for integral assessment of high-voltage insulation aging, its humidification and remaining operational life based on measurement of self-discharge and return voltage.

One can objectively assess the quality of insulation, the level of its aging and remaining operational life by measuring parameters caused by internal absorbed charge within heterogeneous insulator, which is insulation of high voltage electrical machines, power oil transformers and cables with paper-oil insulation [9, 10].

To create effective non-destructive methods for testing the state of the main insulation of high-voltage power electrical equipment, absorption phenomenon is used (accumulation of internal absorbed charge). The state of insulation and the degree of its aging can be assessed according to leakage current [10, 11], absorption current as well as the absorption coefficient which is the ratio which is defined as the ratio of the one-minute value of the insulator resistance to its fifteen second value [9, 12].

The absorption coefficient (or polarization index in the United States) provides an objective assessment of the insulation state since it takes into account the absorption charge in the insulation system. However, monitoring the absorption charge according to the absorption current is inconvenient because the absorption current is small and industrial interference greatly distorts it. Therefore, it is more convenient to use other methods for detecting the absorption phenomenon. For example, in practice, it is possible to use the method of measuring the self-discharge and return voltage [9, 12].

The self-discharge voltage is measured at the test object after it is charged from a constant voltage source and its disconnection from this source. In this case, the electrical capacitance of the insulator is discharged over time to its internal resistance. Figure 1 shows the dependence of the self-discharge voltage \( U_S \) on time for a 1000 kV/A distribution transformer with different exploitation terms. Power supply voltage is 2500 V. Each curve of the graph represents the sum of damped exponentials with the same signs and different time constants. It is shown in [9, 12] that the most informative is the self-discharge voltage measured at the 15th second after the start of the measurement. It is defined as \( U_{S15} \) and used as an assessment of aging and the state of isolation. The dependence of \( U_{S15} \) on the operating time changes almost linearly, decreasing by an average of 30 V per year. By the end of the operational life, the speed of reduction of the self-discharge voltage lowers slightly. The dependence of the self-discharge voltage \( U_{S15} \) measured at the 15th second of the operating time of the transformer \( \tau \) can be expressed by the equation of a straight line: \( U_{S15} = 1000-30\tau \). Here, \( \tau \) is the operating time, years.

![Figure 1](image.png)

Figure 1. Time dependence of self-discharge voltage for distribution transformers with different operational life: 1 – new transformer at installation; 2 – after 10 years of operation; 3-after 28 years of operation.
Spent time resource is

$$\tau = \frac{1000 - U_{S15}}{30}. $$

Remaining resource is

$$\tau_0 = \tau_{stand} = \frac{1000}{30} - \frac{1000 - U_{S15}}{30} = \frac{U_{S15}}{30}$$

where $\tau_{stand} = \frac{1000}{30}$ is the standard insulator resource.

As an assessment of the insulation state, along with the self-discharge voltage, the return voltage is also used (Fig.2). It is measured after disconnecting the charged insulation from the power supply and a short-term discharge to the ground. Herewith, the insulator struck capacity becomes equal to zero, but the internal absorption charge does not have time to discharge in a short time. Due to this fact, a return voltage $U_R$ is formed at the insulator terminals. Therefore, the return voltage curve has its maximum. In [12], it is recommended to use the value of the return voltage $U_{R30}$ measured at the 30th second after the start of the testing to assess the aging and state of insulation.

For assessing it is recommended to use indicator $P$, determined according to Fig. 2 by the following formula [8]:

$$P = U_{\text{max}} \cdot t_{\text{max}}.$$ 

Figure 2. Time dependence of return voltage for a distribution transformer with different operational life: 1 – new transformer at installation; 2 – after 10 years of operation; 3 - after 28 years of operation.

As practice shows, as the insulation ages, maximum value of the return voltage $U_{\text{max}}$ as well as the time of its forming $t_{\text{max}}$ both change. For distribution transformers, the $P$ index is proportional to the remaining resource. It equals 6000 V-s for new insulator in distribution transformers. For transformers that have run out of life, it tends to zero, decreasing by an average of 200 V-s per year.

The remaining resource $\tau_0$ is measured with the formula [12]:

$$\tau_0 = \tau_{stand} = \frac{1000}{30} - \frac{1000 - U_{S15}}{30} = \frac{U_{S15}}{30}$$
Transformers which have $P = U_{\text{max}} \cdot t_{\text{max}}$ less than 300 V·s are considered worn out of insulator more than for 90% and are needed to be replaced by new ones.

Within the international practice, to assess the state of paper-oil insulation of cables according to the return voltage, the following ratio of essential parameters is used. It is called $p$-indicator (Fig.3) [24]:

$$p = \frac{U_{R,\text{max}}}{s \cdot t_{\text{max}}} = \frac{t'}{t_{\text{max}}}$$

where $U_{R,\text{max}}$ is the maximum value of the return voltage, $t_{\text{max}}$ is time at which the maximum return voltage is observed, $s$ is initial front of the return voltage curve; $t'$ is the time at which a straight line drawn at the angle of the initial front $s$ of the return voltage curve reaches the maximum value of the return voltage $U_{R,\text{max}}$. The $p$ coefficient increases with humidification and aging of the insulator. This trend is observed for paper-oil insulated cables and power oil transformers.

![Figure 3. Time dependence of the return voltage for a paper-oil insulated cable.](image)

3. Results.
So, the aging of insulation without its destruction, as shown by research, can be assessed by the nature of polarization processes [13, 14]. Based on the measurement of the parameters described above, a conclusion is made about the state of the insulation and its remaining resource [12].

The block diagram of the proposed device for quality control of the electrical insulation is shown in Fig.4 [15]. The device comprises a test voltage source 1, reference resistor 2, charge key 3, discharge key 4, discharge resistor 5, first voltage constant multiplier 6, test object 7, break blocking contact of the charge key 8, closing blocking contact of the charge key 9, closing blocking contact of the discharge key 10, two-channel digital meter with the storage device 11, display 12, differentiating element 13, zero-comparator 14, light indicator 15, first peak detector 16, second peak detector 17, time counter 18, first voltage multiplier unit 19, second constant multiplier 20, first digital indicator 21, control unit with outputs “Charge”, “Discharge”, “Start” and “Zero setting” 22, clock pulse generator...
23, control unit 24, second voltage multiplier unit 25, voltage division unit 26, second digital indicator 27, first 28 and second 29 output terminals of the device.

The device works as follows. In the initial state, at the output of the control unit 22 the signals are formed, according to which the key 4 is open, and the electrical capacities of the test object 7 are discharged through the discharge resistor 5 having a small resistance. After the condensers of the test object 7 are discharged, according to the rules of the device, within one minute the control unit 22 send the signal for opening key 4 and then – key 3.

![Block diagram of the device](image)

**Figure 4.** Block diagram of the device for quality control of electrical insulation.

At the specified position of the keys 3 and 4 starts the charge of the test object 7 insulator. Blocking contact 9 is open and the voltage proportional to the leakage current of the test object 7 is applied at the second information input of the two-channel digital meter 11. Output signal “Start” of the control unit 22 starts clock pulse generator 23. The signals of 1s frequency go form the clock pulse generator output to the first control input of the two-channel digital meter 11 and the voltage values proportional to the leakage current are stored in the memory of the meter 11 every second (or optionally after 5 seconds).

After one minute of the insulation additional charge and the disconnection of the charge key 3, the discharge key 4 closes for a short time $\Delta t$ equal to 5 seconds, during which the struck capacity of the test object 7 is completely discharged through resistor 5 up to zero, and the capacity due to the internal absorbed charge, it remains practically undischarged, since the internal absorption charge cannot change “instantly”, in this case for a short period of time $\Delta t = 5$ s. After the time $\Delta t$ discharge key 4 opens. Charge key 3 remains open. The process of measuring the return voltage, which is formed due to the charge of the struck capacity by the internal absorption charge, begins. Voltage at the output of the first voltage constant multiplier 6 is proportional to the return voltage. It is fed through the closed blocking contact 8 and 10 to the second information output of the two-channel digital meter with the storage device 11, which records the measured return voltage every second for one minute. At the be-
ginning of the measurement, the control unit 22 gives the signal “Zero setting” which zeroes the peak detectors 16 and 17; the time counter 18 start counting from zero, too.

The value of the maximum return voltage is recorded by the first peak detector 16. The initial front $s$ of the return voltage (maximum value of the return voltage derivative at the initial time at the output of the differentiating element 13) is recorded by the second peak detector 17. When the return voltage reaches its maximum, its first derivative equals to zero as well as the signal at the output of the differentiating element 13; zero-comparator 14 stops the time counter 18 which is shown by the light indicator 15. The signal is stored at the output of the time counter 18. It is proportional to the changed time $t_{\text{max}}$ indicating the maximum return voltage $U_{\text{max}}$.

The first voltage multiplier unit 19 multiplies $U_{\text{max}}$ and $t_{\text{max}}$ values and gives the results on the digital indicator 21 display. This value corresponds to the remaining resource $P$ of the insulation operational life. In practice, it is convenient to use the measuring of the relative remaining operational life of the insulation, estimating it in comparison with the operational life of the new insulation, measured when installing high-voltage electrical equipment.

The second voltage multiplier unit 25 multiplies the values of $s$ and $t_{\text{max}}$, the signals from 16 and 25 units’ outputs are fed to the input of the voltage division unit 26. It is then fed to the second digital indicator’s input 27, which displays the parameter value:

$$p = \frac{U_{\text{max}}}{s \cdot t_{\text{max}}}$$

After that, the device turns off.

The technical and economic effect of the proposed device is determined by increasing the operational reliability of the tested high-voltage electrical equipment due to a more objective assessment of the electrical insulation state and its remaining operational life.

4. Conclusion.
1. Different physical values relied to the absorption phenomenon are considered as well as their use as the means of assessment of the state of heterogeneous high-voltage insulators.

2. The device is developed to objectively monitor of the state of heterogeneous high-voltage insulators as well as to determine its remaining resource using estimates of the insulation state based on the absorption phenomenon.

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