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TECHNICAL INSPECTION UES

VNIITF ROSATOM

Novosibirsk State Technical University NETI

Study Committee D1

Materials and Emerging Test Techniques

Paper D1-PS1-10606

Research on the causes of damage to high-voltage oil-filled current transformers with a gas blanket

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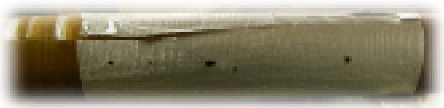
Motivation

- The failure of the internal insulation of high-voltage oil-filled current transformers (CT) is followed by the formation of gas inclusions in the liquid phase. Critical partial discharges (PD) are developed in gas inclusions, causing insulation fault within a relatively short time.
- The formation of gas inclusions is caused by: PD, local overheating, cavitation in the internal insulation, a sharp change in the ambient temperature.



Objects of investigation

- To study conditions of gas inclusions formation depending on ambient temperature changes.
- To give recommendations for optimizing the design of CT with a gas blanket.

Gas equilibrium in CT

It is known that an increase in temperature and pressure in the nitrogen – transformer oil system leads to an increase in the solubility of nitrogen in transformer oil. The research results show that the specific increase in nitrogen solubility within 20-45 °C temperature range is 0.2–0.8 % for each degree of temperature increase, depending on the type and brand of oil used, its chemical composition, and degree of aging.

- **The thermodynamic distribution coefficient K(T)** depends exponentially on the reciprocal absolute temperature T:

$$K(T) = A\exp(\Delta H/RT).$$

where A is an empirical coefficient; T = t +273.15; ΔH is the activation energy; R is the gas constant.

Based on the experimental data, it is possible to obtain empirical dependences of the solubility of gases in transformer oil on temperature:

$$K = 3.3\exp(-1061.8/T).$$

The equation is valid for sealed nitrogen – transformer oil system.

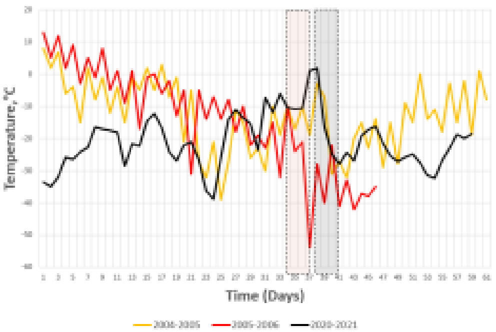
When a bubble is formed in the liquid, the condition for the mechanical equilibrium of the bubble of radius r in the liquid can be expressed as:

$$p_b + p_s = p_h + 2\frac{\sigma}{r},$$

where p_b is the gas pressure in the bubble; p_s is the saturated steam pressure; σ is the coefficient of surface tension; p_h is the hydrostatic pressure, which is the sum of the liquid column pressure p_{lc} and external pressure p_{gb} (pressure of the gas blanket), $p_h = p_{lc} + p_{gb}$.

If the partial gas pressure in the bubble is less than the gas pressure at which equilibrium is established, then the gas diffuses from the transformer oil into the bubble that increases to the size at which equilibrium is reestablished. With the inverse ratio of the gas concentrations in the bubble and transformer oil, the bubble size decreases due to the diffusion of gas from the bubble into the liquid. These processes are rather slow and take several minutes.

Abnormal changes in ambient temperature



- **Important circumstances affecting the conditions for the formation of gas bubbles in the liquid**: absolute value of the ambient temperature change and its rate.
- The formation of gas inclusions in the CT insulating system **results in** the voltage decrease of the PD occurrence and their intensity increase.

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Calculation of pressure in the gas blanket under different operating conditions of CT

- **Case 1.** The case is considered when there is an uneven distribution of temperature over the volume of CT, in particular, the temperature of the gas blanket and the volume of the oil.

Charles's law

$$P = \frac{P_0 T_1}{T_0},$$

where **P** and $\mathbf{P_0}$ are current and initial pressure values respectively; $\mathbf{T_0}$ and $\mathbf{T_1}$ are initial and current temperature values respectively, (K).
Thus, when the pressure decreases, the size of the microbubbles in the paper-oil insulation increases due to the gas diffusion from the surrounding liquid. This leads to a decrease in the voltage of the PD occurrence.

- **Case 2.** The specified case applies to the operating conditions of the CT when the temperature change is even throughout the entire volume of the CT.

Clapeyron-Mendeleev equation

$$\frac{PV}{T} = \mu R,$$

where **μ** is the number of gas moles in the gas blanket, **P** is the pressure, **V** is the volume, **T** is the temperature in the gas blanket, **R** is the universal gas constant.

Taking into account that when the volume of oil changes the volume of the gas blanket changes as well, the following equation can be used:

$$P = \frac{P_0 T_1}{T_0(1 - TkV(T_1 - T_0)V_{m0}/V_{g0})},$$

where $\mathbf{V_{g0}}$ and $\mathbf{V_{m0}}$ are the volumes of the gas blanket and transformer oil at the initial temperature respectively.

This case is more dangerous than the first one, since it also includes the decrease in the volume of liquid, which causes an additional pressure decrease in the equipment. This leads to a greater decrease in the voltage of the PD occurrence.

- **Case 3.** The process of establishing gas equilibrium in the CT with a slow change in the CT temperature is analyzed.

Equation for the gas pressure in the gas blanket:

$$P(T) = P(T_0)\cdot\frac{T}{T_0}\cdot\frac{33\exp(-10618/T_0)+\chi}{33\exp(-10618/T)\cdot(1+TkV(T-T_0))+\chi(1-TkV(T-T_0))},$$

where χ is V_{g0} / V_{m0}.

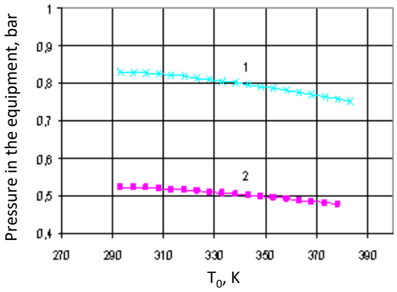
This case is the most difficult to analyze and should be reviewed individually. When heated, the solubility of the gas increases, in some cases this can lead to a pressure drop in the equipment, that causes the PD voltage decrease. Such case can be realized with a small ratio of the volume of the gas cushion to the volume of oil.

- **Case 4.** The transformer oil was not saturated enough with gas at the time the CT was put into operation. So its saturation will occur under operating conditions.

$$P(T) = P(T_0)\cdot\frac{T}{T_0}\cdot\frac{\chi}{33\exp(-10618/T)\cdot(1+TkV(T-T_0))+\chi(1-TkV(T-T_0))},$$

As the temperature decreases, the pressure usually decreases as well, which leads to a decrease in the PD ignition voltage and to an increase in the apparent charge of PD.

Dependence of the pressure in the CT, arising from a relatively rapid cooling of the equipment



- 1 – the third and first cases combined, the gas equilibrium in the gas blanket and oil was established before the commissioning;
- 2 – the fourth and first cases combined, the equilibrium of the gas in the gas blanket and oil was not established before the start of operation.

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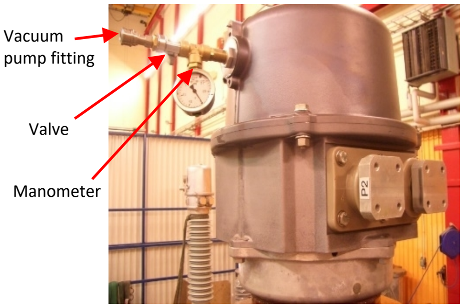
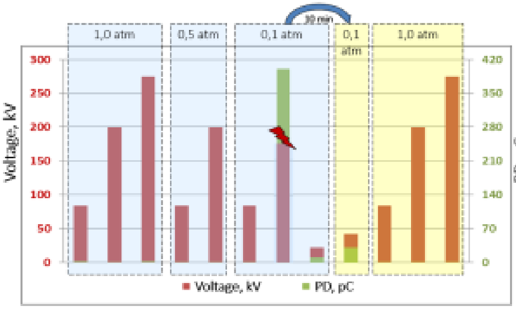
Experiments

- Transformer oil samples were taken before, in the process, and after the CT tests to carry out chromatographic dissolved gas analysis (DGA). The samples for DGA were also taken 5 days before the start of high-voltage tests, immediately before the start of tests, and immediately after the first and second series of tests.
- Additional samples were taken from the CT in 1, 6, and 9 days after high-voltage tests to reveal the dynamics of the distribution of gases over the CT volume.

CT modifications made before tests



The results of PD measuring in the CT insulation during the second series of tests



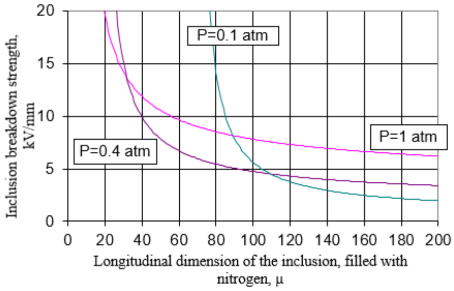
Test results

- The analysis of the obtained results can be carried out based on the Paschen curve, reconstructed as the dependence of breakdown strength E_{bs} on the longitudinal size of the air pore at various pressures (figure below), following the equation:

$$E_{bs} = \frac{B \cdot p}{C + \ln(pd)},$$

- For nitrogen B = 275 V/(cm.torr), C = 0.645, the equation is valid in the E/p range from 27 to 200.

Calculation of the breakdown strength considering that the pore is filled with gaseous nitrogen



Conclusions

- The analysis of the performance of the internal HV insulation of CT with a gas blanket under various operating influences leading to an imbalance in the gas – transformer oil system is presented.
- A relationship between the pressure in the gas blanket, the value of the test voltage, and the value of the apparent charge of the PD measured at the CT terminals was established.
- A mechanism for the formation of gas inclusions in the HV insulation of CT has been proposed with the following stages: dissolution of gas from the gas blanket in transformer oil – violation of molecular-kinetic equilibrium with a sharp decrease in pressure in the gas blanket – growth of gas microbubbles due to gas diffusion into an expanding microbubble – PD occurrence in a microbubble.
- General recommendations are given for optimizing the design of CT and other HV oil-filled equipment.
- The obtained results and recommendations can be used for all types of HV oil-filled equipment with a gas blanket.