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Physical simulation of heat exchange between 6(10) kV voltage instrument transformer and its environment with natural convection and insolation

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Abstract. This study examines the results of thermal tests on a 6(10) kV digital combined current and voltage transformer conducted in an environmental chamber. This measuring instrument consists of current and voltage transformers, featuring a resistive divider, and is used for commercial and technical electric power accounting. Ambient temperatures and levels of insolation on the transformer surface were set for the environmental chamber, with simulation of voltage transformer functioning in normal and emergency modes. We determined the time needed for the thermodynamic system to move to steady heat exchange mode, and also the final temperatures in the lower resistors and on the surface of the voltage transformer insulation cover. The results of our study have been used in developing algorithms for self-diagnostics of the thermal state of a digital combined transformer.

1 Introduction

An important task in the functioning of digital combined current and voltage transformers in commercial and technical electric power accounting in summer conditions with high ambient temperatures and levels of insolation and the possibility of grid voltage exceeding rated values is to examine the exchange of heat between a transformer and its environment.

Methods of thermal protection against overheating for voltage power transformers are widely known [1-2]. Unfortunately, thermal tests during operation of voltage power transformers, and even more so in the case of current and voltage instrument transformers are often performed according to maintenance schedules [3], which negatively impacts the efficiency of such electrical equipment [4]. Developing new systems of self-diagnostics checks for the thermal state of digital instrument transformers that determine temperature according to the most heated up electrical equipment part in real time is therefore an important task, especially in the development of "smart" power grids. Developing algorithms for thermal self-diagnostics requires data relating to physical and mathematical

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simulation of the thermal environment in which transformers operate under the influence of various unfavourable factors.

An important indicator in research conducted with the aid of software enabling simulation of heat exchange between a transformer and its environment following changes in initial conditions is the accuracy of the resulting data. Laboratory research conducted with physical models of digital transformers is one of the best methods of verifying such models.

We conducted a series of experiments in the high voltage laboratory of our High Voltage Equipment Department to study the influence of voltage, high ambient temperatures and insolation on the operating temperature of a digital combined transformer. We also studied the dynamics of the processes involved.

The digital instrument transformer [5] consists of a resistive voltage divider and current transformer (Fig. 1), several resistors being contained within the body of the instrument transformer.

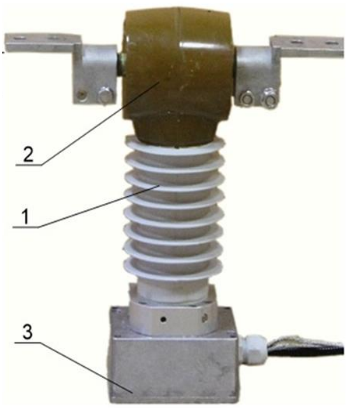

Fig. 1. External view of a 6 (10) kW digital combined transformer: 1 – primary voltage converter; 2 – primary current power converter; 3 – low voltage electronic unit.

Electrical processes occurring in resistive voltage dividers comprising groups of resistors are related to heat emission. Resistor overheating may result in measuring equipment failure.

2 Description of tests conducted inside a high voltage environmental chamber

A part of our research was conducted in an environmental chamber designed for high-voltage testing. The diagram and general view of this chamber with installed equipment are shown in Fig. 2. The environmental chamber comprises a closed, isolated structure consisting of two compartments: a warm compartment and one for a step-up voltage transformer. The warm compartment is shielded by means of PVC sheeting, and features a heating element used to maintain constant ambient temperature, creating the necessary temperature conditions corresponding to the worst transformer operating conditions, taking into account the environmental version and placement category.

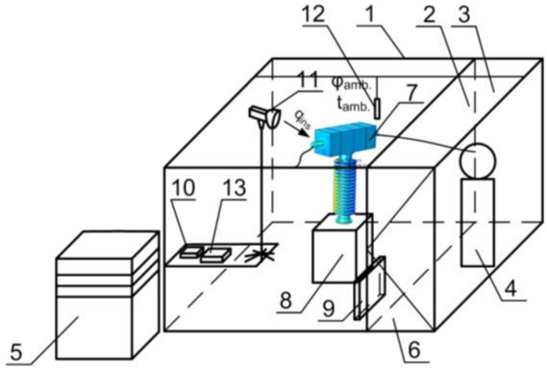

Fig. 2. Diagram of an environmental chamber in a high-voltage test laboratory: 1 – warm compartment; 2 – partition; 3 – step-up transformer compartment; 4 – step-up transformer; 5 – control panel; 6 – compartment door; 7 – test item; 8 – earthed prop for the test item; 9 – heating element; 10 – temperature measuring and controlling device; 11 – incandescent-filament lamp for simulating insolation; 12 – primary humidity and temperature converter; 13 – thermal hygrometer.

An electrode was introduced into the chamber to supply high voltage to the test item from the laboratory UIV- 150kV unit, consisting of a control panel and step-up transformer. Ambient temperature and humidity, also temperature at the resistors, were determined by means of sensors. A TESTO-875-1i thermal imager was also used to determine transformer surface temperature fields. Insolation on the collecting surface of the warm compartment in the chamber was simulated using a 250W incandescent filament lamp (Fig. 3) located on a device enabling us to change and fix lamp angle of elevation. Preliminary experiments were conducted to calibrate the values of radiation energy emitted from the incandescent filament lamp onto the collecting surface.

Fig. 3. Simulated insolation on a transformer using an incandescent filament lamp.

In accordance with electric power safety requirements, temperature sensors were placed on the lower contact cap of the lower resistors. Sensor resistance was R_s=10 kOhm at 25°C, within 1%.

A resistive voltage divider functions at various thermal conditions, and the temperature (as well as the number of temperature cycles) significantly influences both the metrological properties of the resistor, and its performance.

For a 6(10) kV voltage instrument transformer we simulated normal operating mode, with nominal voltage U_{nom}=10kV (phase voltage $U_{nom.phase}$=5.77 kV), and also emergency mode. In emergency mode, voltage increased 2.1 times in comparison with the nominal value. Voltage was changed only after the system moved into steady heat exchange mode. Thermal conditions inside the environmental chamber were maintained with an ambient temperature of t_{amb}=44°C, normal atmospheric pressure and natural convection [6] near the transformer surface.

3 Results of tests

Thermographs for transformer surface (Fig. 4) show that most heating occurred in the middle part of the resistor divider. Thus, insulation surface temperature in the area of the middle resistor was t_{surf} =109 °C, and 101°C at the upper resistor. The temperature was also lower in the area of the lower resistor.

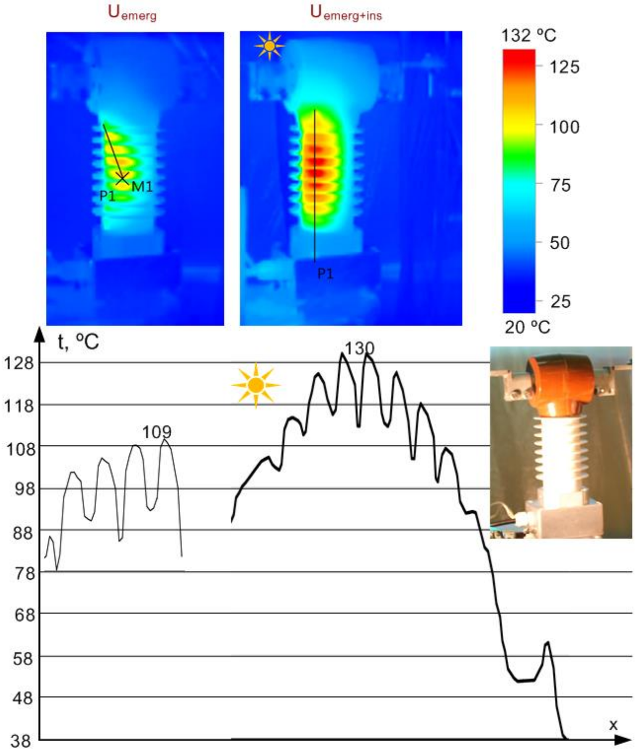

Fig. 4. Thermograph for voltage transformer surface during emergency mode in the absence of/with insolation, and also temperature charts along transversal P1.

Therefore, because of the cumulative effect of heating in the upper and lower resistors, the middle resistor warmed up more than the others, and placing the temperature sensor on the lower resistor cannot unequivocally reflect thermal conditions at the middle resistor; adjustment must be made for the cumulative effect.

Insolation in emergency operating mode intensified heating of the middle resistor even further, the temperature on the surface of the transformer cover in the area of the most heated resistor increasing to t_{surf}=130°C. Hence, the temperature on the most heated resistor, located inside the transformer, will be somewhat higher than 130°C. Here adjustment must also be made for the heat characteristics of the incandescent filament lamp (the heat stream along the lamp axis being higher than in the peripheral area).

As shown by experimental data for examination of the thermal condition of resistor dividers in a voltage instrument transformer, supplied voltage and simulated insolation have a significant impact on the thermal condition of the controlled facility (Fig. 5).

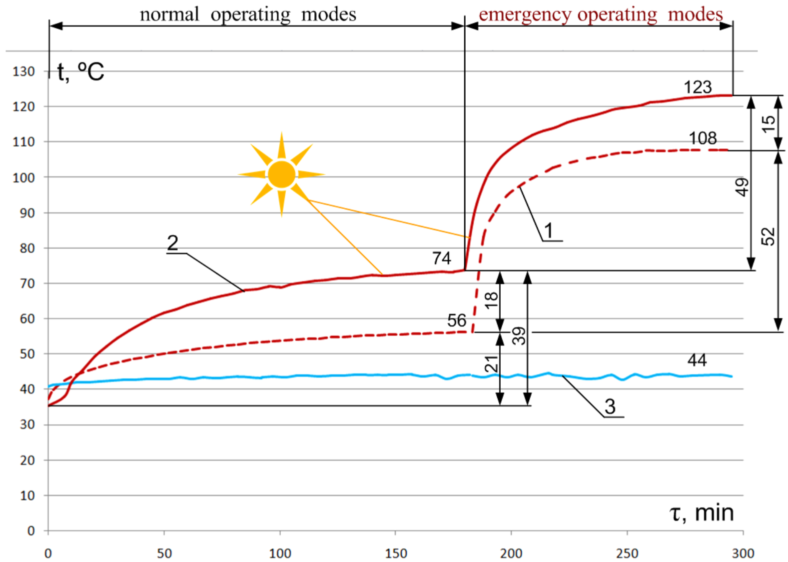

Fig. 5. Charts showing dependence of temperatures at the lower contact cap of the lower resistor and ambient temperature on time in normal and emergency transformer operating modes: 1 – without insolation; 2 – with insolation; 3 – ambient temperature.

Since the transformer being tested was energized immediately after the ambient temperature tamb in the warm compartment had reached 41°C, we may observe in the chart that air warmed up more rapidly than the transformer body, therefore resistor temperature at the moment of transformer energization was somewhat lower than the ambient temperature due to a certain heat retention in the materials of the above electrical equipment. However, self-warming of the resistors resulted in quite a rapid increase in temperature in the area of the resistors' location.

With normal voltage U_{norm} without insolation the resistor heated up to a temperature of t_r=56 °C (increasing by Δt_r=21 °C). Resistor warming from the initial state to steady thermal conditions occurred within 3 hours.

Simulating insolation on the transformer surface significantly increased the above temperature parameters. Thus, the resistor heated up to a temperature of t_r=74 °C (increasing by Δt_r=39 °C). In this case, insolation caused the resistor to warm up by a further Δt_{ins} =18 °C. Warming of the resistors from the initial state to steady thermal conditions in our experiment also occurred within 3 hours.

The simulated emergency operating mode for electric power grids logically resulted in significantly increased temperatures. In the absence of insolation, resistor temperature increased to t_r=108 °C (or by Δt_{emerg} =52 °C, that is, 2.5 times more than the increase in temperature with normal transformer operating mode). The system changed over to steady mode within 2.2 hours, with a significant rise in temperature observed during the first 20 minutes of our experiment with simulated emergency voltage.

Insolation further increased the impact of equipment operation in emergency mode. Resistor temperature rose to t_r=123 °C (increasing by Δt_{emerg}=49 °C, that is, 1.3 times more than the increase in temperature with normal equipment operating mode. In these emergency conditions, insolation caused the resistor to further warm up by Δt_{ins}=15 °C, which is comparable with the effect of insolation in normal equipment operating mode.

It may be noted that the increase in resistor temperature as a result of voltage increasing to emergency levels (Δt_{emerg}=52 °C) was 2.9 times more than the increase in temperature resulting from the effect of insolation on the resistor (Δt_{ins} =18 °C).

4 Conclusion

Our study showed that even in the most severe emergency operating modes, heating in the lower resistor did not exceed the critical value (taken as around 150 °C, according to electrical insulation material characteristics). Maximum temperatures were determined in the central part of a voltage transformer. Its thermal conditions were influenced more by simulated voltage than by insolation.

We expect the resulting experimental values to be used in the development of algorithms for thermal self-diagnostics of digital transformers, and also algorithms for temperature correction of the transformed secondary voltage. The results should be taken into account in the development and verification of mathematical models of heat exchange between a transformer and its environment.

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