Simulation of heat exchange between a digital instrument transformer and its environment for operation in emergency and unfavorable weather conditions

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Abstract. Reliable functioning of electric power grids to a large extent depends on the serviceability of each unit in the given power system, subject to the impact of various unfavorable factors, namely grid operation mode and weather conditions, such as elevated ambient temperatures, insolation and no-wind. These environmental parameters have a significant negative impact on the process of heat removal from electrical equipment, which may result in its overheating and breakdown. ISPEU staff have developed and put into operation innovative design digital current and voltage instrument transformers. The purpose of the present study is to examine the impact of insolation, ambient temperature and emergency operating modes on the thermal state of transformers. A mathematical model of heat exchange for a 6(10) kV transformer was developed and verified with the results of physical experiments conducted in an environmental chamber. Heat exchange between the transformer and its environment was simulated for a July day in Sochi in nominal and emergency operating modes, and also with various values of heat conductivity of electrical insulation sealant used. It was discovered that maximum influence on transformer thermal state is exerted by self-heating of instrument resistors at elevated voltage levels.

1. Introduction
Modern ”smart” grids [1] presuppose the use of innovative high precision measuring equipment permitting real time monitoring of various parameters of electrical equipment operation. Information received from measuring devices and processed with the aid of software enables us to more rationally organize the operation of electric power grids, taking into account all aspects of electric power generation, transmission and consumption [2,3]. Reliable functioning of electric power grids [4] to a large extent depends on the serviceability of each unit in the given power system, subject to the impact of various unfavorable factors. Among the main factors are grid operation mode, and weather conditions, such as elevated ambient temperatures, insolation and no-wind. These environmental parameters have a significant negative impact on the process of heat removal from electrical equipment, which may result in its overheating and breakdown [5]. Active work is currently being done in the field of protecting electrical equipment from overheating [6].
Staff of Ivanovo State Power Engineering University (ISPEU) have developed [7] and put into operation innovative design digital current and voltage instrument transformers.

The digital instrument transformer [8, 9] consists of a resistive voltage divider and current transformer (see Figure 1). Several resistors are contained within the body of the voltage instrument transformer. The electrical processes occurring in resistive voltage dividers comprising a group of resistors entail heat emission. Overheating of a resistor may result in failure of the measuring equipment under review.

Studying the process of heat exchange between instrument transformers and their environment in unfavorable weather conditions is an important task.

To study the impact of insolation, ambient temperature and emergency operating mode on the thermal state of transformers, a mathematical model for heat exchange in a 6 (10) kV transformer was developed [8, 9] and verified with the data of physical experiments performed in an environmental chamber [7, 10]. The result was a close similarity between computer simulation and experimental data. A diagram of the mathematical model [8] of heat exchange between a transformer and its environment in conditions of natural convection is shown in Figure 2. The model included description of thermal conductivity inside the transformer, heat transfer from its surface, heat emissions from heating elements, and also diffused and direct solar radiation.

But joint influence of emergency situations, the Sun movement and the air temperature change during the day for the actual climatic conditions of a particular city to the thermal state of a instrument transformers is not considered in previous papers [8, 9, 10].

In this paper heat exchange between the transformer and its environment was simulated for a July day in Sochi in nominal and emergency operating modes, and also with various values of heat conductivity of electrical insulation sealant used. The simulation results are also given.

2. Simulation methods and parameters

Heat exchange between a transformer and its environment was simulated using a special software product (COMSOL Multiphysics) based on the finite elements method.

The most interesting issues from the standpoint of equipment operation are those related to electric power grid operation during summer days in various operating modes for regions with high temperatures. Climatic conditions in various regions of Russia were analyzed, taking into account mean absolute maximum temperatures.

The town of Sochi, where ambient temperatures can reach 40 °C, was chosen in accordance with the above analysis. It should be noted that in recent years, this region in the North Caucasus has seen high electric power consumption related to the construction of new sports and recreational facilities. Heat exchange between the transformer and its environment was simulated for a July day in Sochi in nominal and emergency operating modes, and also with various values of heat conductivity of electrical insulation sealant used.
 Ambient temperature variations were set within a range of from 31 to 40 °C during a 24 hours period with the aid of a mathematical function.

**Figure 2.** Diagram of the mathematical model of heat exchange between a combined transformer and its environment: 1 – primary voltage converter; 2 – primary current power converter; 3 – Sun; \( t_{surf}, t_{amb} \) – surface and ambient temperatures; \( \lambda \) – heat conductivity coefficient; \( q_{el} \) – heat energy, released in converters according to the Joule-Lenz law; \( q_{rad}, q_{conv} \) – radiation and convection heat flux density, \( q_{dir}^{ins}, q_{diff}^{ins} \) – direct and diffused solar radiation; \( \varepsilon_{abs}, \varepsilon_{em} \) – coefficients of absorption and emission; \( \alpha \) – heat transfer coefficient.

Direct insolation on transformer surface was simulated by means of a process integrated in the software for describing the daily movement of the Sun for the latitude of Sochi (43 degrees North). It was previously ascertained [8] that maximum heat input from ambient sources during a day occurs in facilities facing west. For this reason, it was decided to place the transformer so that its resistive dividers would be oriented westwards (see Figure 3). The study was conducted in windless weather.

**Figure 3.** Positioning the transformer (1) relative to light sides, taking into account the Sun’s diurnal motion (2).

At midday an electric power grid accident was simulated with a 2.1 increase in voltage compared with the nominal value. In our case, an electric power grid accident was understood as single-phase short circuiting to earth, in which voltage in the undamaged phase increases to the linear value \( U_{lin} \).

It is known that with increased electrical breakdown strength of sealants \( E_{brs}, \) kV/mm, there is usually a decrease in their thermal conductivity \( \lambda, W/(m\cdot\text{°C}) \). Lower thermal conductivity leads to reduced heat transfer from warmed up measuring resistors and hence higher temperatures. We thus have the following paradox: with increased electrical breakdown strength of sealants, the operation
safety of a transformer increases, but so does the risk of its overheating. For the above simulation it was decided to examine thermal state using sealants with thermal conductivity $\lambda_1 = 0.6 \text{ W/(m·°C)}$ ($E_{br1} = 12 \text{ kV/mm}$) and $\lambda_2 = 0.17 \text{ W/(m·°C)}$ ($E_{br2} = 30 \text{ kV/mm}$). Thermal conductivity values were obtained from testing actual sealant samples in a calorimetric unit [10].

3. Results of simulation
Changes in temperature on the surface of resistors and in temperature fields on digital transformer surface over 24 hours with voltage varying from nominal $U_{nom}$ to emergency $U_{em}$ for a July day in Sochi are shown in Figure 4.

Figure 4. Changes in temperature on the surface of resistors (a) and in temperature fields on digital transformer surface (b) over 24 hours with voltage varying from nominal $U_{nom}$ to emergency $U_{em}$ for a July day in Sochi: 1, 2 – temperatures at sensor installation points and most warmed up resistor, respectively, with sealant thermal conductivity $\lambda_1 = 0.6 \text{ W/(m·°C)}$; 3, 4 – the same, with $\lambda_2 = 0.17 \text{ W/(m·°C)}$; 5 – ambient temperature $t_{amb}$; 6 – view from southeast; 7 – view from southwest.
Since according to electrical safety requirements for the digital transformer being used temperature sensors may only be placed on the lower resistor, the results of our simulation contain data for the lower resistor and the most warmed up resistor in the divider. Since most insolation is experienced on surfaces facing south, the Sun moves from east to west, and the resistors are oriented westwards, the drawing shows temperature field dynamics on surfaces facing south-eastwards (6) and south-westwards (7).

The study revealed that transformer thermal state is influenced most of all by self-heating of measuring resistors at high temperatures. Thus, if a sealant with thermal conductivity $\lambda_1$ is used, the temperature of the most warmed up resistor rises from 58 to 115 °C (an increase of 57 °C), the peak temperature being attained at 5 pm. Using a sealant with thermal conductivity $\lambda_2$ resulted in an even sharper increase in temperature - from 73 to 183 °C (an increase of 110 °C). Using a different sealant material resulted in a sharp increase in resistor temperature in emergency operating mode, by 68 °C.

Poor heat transfer from the resistors is related to increased resistance to heat transfer ($R_2=0.15 \text{ (m}^2 \cdot \text{°C})/\text{W}$) in the sealant layer with low thermal conductivity $\lambda_2$ (see Figure 5). For the first variant, sealant layer resistance $R_1$ was just $0.04 \text{ (m}^2 \cdot \text{°C})/\text{W}$. It should be noted that a temperature of 183 °C is inadmissible for transformer operation, and sealants with thermal conductivity $\lambda_2$ should therefore not be used for the above resistive voltage divider design. To use such sealants with thermal conductivity $\lambda_2$, resistor resistance must be increased several times, which unfortunately leads to increased angular measuring error in about the same proportion. The accuracy class for the digital transformer used in this study is 0.2 (in accordance with IEC 60044-7).

At night, resistor temperatures changed equidistantly to the ambient temperature. Insolation had an additional impact on transformer thermal conditions. Thus, if during the period 17.00 – 24.00 the ambient temperature fell by 8 °C, resistor temperature decreased by 13-14 °C with the same heat input $q_{el}$. Insolation warmed the resistor up by 5-6 °C. The most warmed up surface was the western side of the voltage converter at 5 pm. The highest temperatures were noted in the area of the upper resistor (see Figure 5).

![Figure 5. Temperature fields $t$, °C, and heat transfer resistance for device components of device $R$, (m$^2 \cdot$ °C)/W, in longitudinal cross section (a) and along the surface (b) of a resistive voltage divider in emergency operating mode at 5 pm on a July day in Sochi.](image-url)

It should be noted that the difference in temperature $\Delta t$ at the points of installation of the sensor and the most warmed up resistor changes sharply during changeover from nominal to emergency operating mode, and also to a large extent depends on the materials used in making the transformer. Thus, with...
sealant thermal conductivity lowered from $\lambda_1$ to $\lambda_2$ 3.5 times, in emergency operating mode the temperature difference $\Delta t$ increased 2.7 times (from 14 to 38 °C). Insolation and ambient temperature for 6(10) kV transformers had practically no effect on temperature difference $\Delta t$ (see Figure 4), which must be related to the equal impact of solar energy on the adjacent resistors.

4. Conclusion
Simulation of heat exchange in a 6(10) kV instrument transformer for a July day in the town of Sochi revealed that the maximum impact on transformer thermal state is caused by self-warming of the measuring resistors at increased voltages, and also by heat conductivity of instrument materials. Sealants with heat conductivity of $\lambda_2$ cannot be used in the above electrical modes, since the critical operating temperature is exceeded. The most heat stressed transformer state (with resistors oriented westwards) in the above ambient conditions was obtained at 5 pm. The resulting data should be used to develop a system of thermal self-diagnostics and protection of digital transformers from overheating.

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