Development of a thermal self-diagnostics system for a digital current and voltage instrument transformer

G I Parfenov¹, E E Gotovkina², V D Lebedev², N N Smirnov¹,* and V V Tyutikov¹

¹Ivanovo State Power Engineering University, Heat Power Engineering Department, 153003, Ivanovo, Russia
²Ivanovo State Power Engineering University, Electric Power Engineering Department, 153003, Ivanovo, Russia

Email: nsmirnov@bk.ru

Abstract. Ivanovo State Power Engineering University (ISPEU) staff have developed and put into operation innovative designs of digital current and voltage instrument transformers (DCVT) based on resistor dividers performing technical and commercial electric power accounting, and also participating in work of relay protection and automation systems. Thermal self-diagnostics systems working in real time for instrument transformers do not exist in electric power engineering, while thermal examination is often conducted according to maintenance schedules, which negatively impacts the reliability of electrical equipment functioning. Development and building of new systems of self diagnostics for instrument transformer thermal state, revealing temperatures at several points, including values for the most heated up part, in real time, is therefore a vital task, especially for controlling operation of "smart" grids. Based on the results of physical and mathematical simulation of the process of heat exchange between a transformer and its environment at different values of ambient temperature, insolation and grid voltage, methods have been developed to determine the impact of the above factors on the thermal mode of DCVT operation. Algorithm has also been developed for thermal self-diagnostics and thermal protection against overheating of instrument transformers. System of thermal self diagnostics has been developed for 6-220 kV.

1. Introduction

Ivanovo State Power Engineering University (ISPEU) staff have developed and put into operation innovative digital current and voltage instrument transformers (DCVT) [1, 2] based on resistive dividers and used in technical and commercial electric power accounting and also in the work of relay protection and automation systems. The digital transformer consists of primary current and voltage converters and also electronic signal processing units. The body of the primary converter houses several resistors. The design and geometric model of our 6(10) and 110 kV digital transformers are shown in Figures 1 and 2.

When electric current passes through the resistors (at the applied voltage) and conductor, heat is released in accordance with the Joule-Lenz law. Quite significant heat currents arise in the resistors of the primary voltage converter, while overheating of a resistor may lead to breakdown of the measuring equipment involved.

Despite considerable research into the issues relating to protection of power transformers from overheating [3] and optimization of “smart” grid operation [4, 5] using modern software [6], thermal
self-diagnostics systems for instrument transformers working in real time conditions are unfortunately still lacking.

Figure 1. External view (a) of a 6 (10) kV digital combined transformer and geometric model (b) created in software: 1 – primary voltage converter; 2 – primary current power converter; 3 – low voltage electronic unit.

Figure 2. External view (photograph (a) and computer model (b)) of a 110 kV primary converter: 1 – rubber jacket; 2, 3 – upper and lower flanges, respectively; 4, 5 – flash rings.

In accordance with the concept of “Smart electric power systems with active and adaptive grids” [7], equipment must incorporate built-in self-diagnostics functions. The introduction of thermal self-diagnostics functions in real time conditions will enable us to forecast the process of damage in instrument transformers, promptly respond under various impacts on the transformers (over voltage) and also determine and take into account changing characteristics of digital transformer primary converters affecting measuring accuracy. This will result in more reliable operation of the above equipment, and enable us to change over to maintenance according to equipment condition. The development and creation of new thermal state self-diagnostics systems for instrument transformers indicating temperature in real time at several points, including the most warmed up unit, is therefore a crucial task.

The authors of this study conducted a series of experiments in physical [1] and computer mathematical simulation [2, 8] of the process of heat exchange between a transformer and its environment at different values of ambient temperature, insolation and electrical voltage in power grids. The imitation mathematical models of our 6 (10) kV and 110 kV digital current and voltage transformers (DCVT) were verified [2].
2. Developing methods for determining the impact of unfavourable factors on DCVT operation, an algorithm and system of transformer thermal self-diagnostics

Digital transformers may be placed both in enclosed premises and in the open air, depending on their voltage class and field of application. In open air conditions, the transformer may be exposed to the effects of insolation, as well as internal heat release from electric current conducting parts and ambient temperature.

Resistors inside the voltage divider may be in an axial (a), boundary (b) or spiral (c) position (see Figure 3). The most rational position, from the point of view of resistor heat release, is the spiral one [2]. For resistors in the axial and boundary positions, the effect of the Sun on their thermal state is about the same.

This study examined resistive voltage dividers for 6 (10) kV (with resistors in a boundary position) and 110 kV (with resistors placed spirally). It should be noted that temperature sensor must be placed on the low voltage side to ensure the required insulation.

Resistors in the primary voltage converter of a digital transformer warm up unevenly according to height, while the temperature difference between the lower resistor and the warmest is influenced both by the geometry and materials of a voltage transformer, and the voltage and current; also by insolation (taking into account the geometric position of the Sun relative to the transformer), ambient temperature and other factors.

Methods of determining the impact of the above unfavourable factors on the thermal conditions of DCVT operation assume the development of imitative mathematical models of heat exchange between a transformer and its environment after a series of physical experiments for the necessary verification; heat exchange simulation with changing of such factors as electric current intensity, voltage, air temperature and speed, insolation and so on, to determine their impact on transformer thermal state; and, after conducting regressive analysis, obtaining the corresponding dependencies for identifying the temperature of the most warmed up unit. These operations must be performed during development of new DCVT designs and their modification.

Various design solutions, and also methods of placing transformers in relation to their surroundings, assume different approaches to the development of algorithms for thermal self-diagnostics.

Thus, for transformers located indoors, the temperature of the most warmed up unit $t_{\text{max}}$, °C, may be determined as

$$t_{\text{max}} = t_{\text{sensor}} + \Delta t_1(U) + \Delta t_2(t_{\text{amb}}), \quad (1)$$
where \( t_{\text{sensor}} \) – temperature of sensor located on the lower resistor, °C; \( \Delta t_1(U) \) – accumulative increment function for heating due to voltage and design solution for transformer interior layout, °C; \( \Delta t_2(t_{\text{amb}}) \) – increment function due to influence of ambient temperature, °C.

For transformers located outdoors and additionally influenced by insolation \( t_{\text{max}} \), °C, may be determined as

\[
t_{\text{max}} = t_{\text{sensor}} + \Delta t_1(U) + \Delta t_2(t_{\text{amb}}) + \Delta t_3(\Delta t_{\text{insol}}),
\]

where \( \Delta t_3(\Delta t_{\text{insol}}) \) – temperature increment function determined according to the difference in readings of temperature sensors located on the rib of the insulating envelope casing (see Figure 4), that are responsible for determining the position of the Sun relative to the lower resistor and insolation intensity, °C.

\[
\Delta t_{\text{insol}} = t_{\text{max.env}} - t_{\text{min.env}},
\]

where \( t_{\text{max.env}}, t_{\text{min.env}} \) – maximum and minim readings of temperature sensors located on the rib of the insulating envelope casing, °C. The number of sensors on the insulation casing may be either 4 or 8, which in turn complicates resistive divider design and cost.

As a result of our research, a thermal self-diagnostics algorithm was developed for a digital transformer based on a resistive divider in real time operating mode (see Figure 5), functioning as follows. The electronic unit of the digital transformer performs analog-digital voltage conversion, the current voltage being calculated. Analog – digital conversion is performed of signals from the temperature sensor located in the lower resistor, and also on the ribs of the cooler casing. Accumulative increments due to voltage, ambient temperature and insolation are determined sequentially (if necessary). The temperature of the most warmed up resistor is determined according to formulas (1) or (2), depending on the accepted measuring device position. If the calculated temperature exceeds the set alarm value for the resistive divider or the set emergency value, a message of overheating in the primary voltage converter is created and transmitted. The set temperature value is determined according to the resistor type and sealing materials used. The thermal state of primary current converters in DCVTs is determined by directly controlling their temperature according to the installed sensors.
If the sensor indicated temperature exceeds the set value, a message of overheating in the primary current converter is also created and transmitted.

Figure 5. Thermal self-diagnostics algorithm for a primary voltage converter based on a resistive divider: condition 1 – taking into account allowance for impact of ambient temperature; condition 2 – taking into account allowance for effect of insolation; condition 3 – $t_{\text{max}} > t_{\text{set value signal}}$; condition 4 – $t_{\text{max}} > t_{\text{emergency set value}}$. 
Imitative simulation for our 110 kV DCVT showed that temperature differences for the most warmed up and lower (upper) resistors to a large extent depended on the voltage (the higher the voltage, the greater the difference). These temperature differences somewhat increase with low heat conductivity sealants. The impact of ambient temperature and insulation on the temperature difference in this case (for a 110 kV voltage transformer, with the most warmed up resistor positioned above the lower resistor) is negligible.

In the case of our 6(10) kV transformer with boundary positioning of resistors, it was also shown that insolation equally affects the lower and most warmed up resistors, therefore allowances for insolation and the effect of ambient temperature were also withdrawn from formula (2).

It was established that insolation must be taken into account with spiral positioning of resistors, when the lower and most warmed up resistors are placed on different sides of the transformer.

A thermal self-diagnostics system was developed for 6-220 kV DCVTs, based on the created algorithms. To operate the system, temperature sensors are placed inside the DCVT in a definite sequence (depending on transformer design) and connected to an electronic unit for processing data in accordance with the proposed algorithm.

3. Conclusion
The developed methods, algorithms and system of thermal self-diagnostics will enable us to forecast the process of damage in digital transformers, promptly respond to various impacts on them (voltage swell), and also determine and take into account changes in the characteristics of digital transformer primary converters influencing measuring accuracy. This will result in more reliable equipment operation and enable us to change over to maintenance according to the state of the equipment. In designing thermal self-diagnostics systems for a transformer, account should be taken of its design and positioning options, and also data obtained from computer simulation of heat exchange between the transformer and its environment.

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