

THE IMPLEMENTATION AND OPERATIONAL EXPERIENCE OF TRANSFORMERS CONTROL, MONITORING AND DIAGNOSTIC SYSTEMS AT THE UNITED NATIONAL ELECTRIC POWER SYSTEM OF RUSSIA

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SUMMARY

The active implementation of integrated systems for transformers control, on-line monitoring and diagnostics (TCMD) at the Electric Power System of Russia started in 2003. To the end of year 2011 about a hundred of TCMD systems of different world vendors, including GE (Faraday), ABB (T-Monitor), Intera (SCU), Energoautomation (Safe-T) are in operation at the country. Three hundred of transformers, autotransformers and reactors are equipped by the native hardware/software sets SUMTO.

TCMD systems operate in Russia at the different climatic zones, at open substations 220-500 kV, at the thermal, nuclear and hydro power stations. Those systems are installed as with new transformers so with the old equipment having the service time up to 30 years.

At the objects of Federal Grid Company (JSC “FGC UPS”) according with the company’s conceptual documents the number of TCMD systems realize not only monitoring of transformers main parameters but also control and operative diagnostic functions. At the most crucial transformers the functions of automatic and manual LTC control, estimation of cooling systems efficiency, evaluation of the transformer overloading capacity and voltage rises recording are realized.

The accumulated experience after 8 years of developing and operating the TCMD systems permits to evaluate the results achieved, to fix the most significant problems arising when implementing the real projects, which are not resolved till now, and to discuss the ways of solving those problems.

KEYWORDS

Transformer, monitoring, operative diagnostics, gas analyser, temperature sensors, transformer oil, electromagnetic compatibility, environmental conditions, digital substations, communication channels

TCMD implementation and operational experience



Since 2003 and up to the end of 2011 three hundred of native hardware/software sets of control and monitoring systems SUMTO (fig.1) were put in operation in Russia along with the systems from the famous world vendors (GE, ABB etc.). The development, installation, bench tests and support of the operating systems over these 8 years allowed accumulating certain experience, which is the subject of this paper.

Fig.1. “SUMTO” TCMD cubicle on site.

Analysis of the data obtained during operation of TCMD systems allows making the following conclusions:

1. The implemented into industrial operation hardware/software sets (HSS) for complex control, state monitoring and operative diagnostics of the transformer equipment correspond at the most full degree to the contemporary world tendencies of origination of “intellectual” substations as the part of *smart grid*. Generally it is reasonable to implement at such integrated systems the control functions of the transformer cooling system and LTC (automatic, local and remote manual control), along with the enhanced cooling system and LTC state monitoring, transformer thermal conditions supervision, overload capability prognosis, voltage rises recording, monitoring the gases and moisture content in the transformer oil and some other parameters within the single integrated hardware/software set. Such kind of systems, implemented at the number of substations 220..500 kV, hydro and thermal power stations, can be regarded as the first elements of the future digital substations. Data exchange with other components of the substation process control system (PCS) and with the intelligent primary sensors is implemented using digital communication channels only. Only the links to the ordinary analogue current and potential transformers and to the transformer technological protections (Buchholz relays, pressure relief valves, shut-off valves etc.) remained traditional. Such integrated systems not only extend possibilities of persistent local and remote access to control and state monitoring of the station transformers, but also make it possible to save the total system cost by integrating different functions within the unified HSS. Our calculations demonstrate that the integration of control, monitoring and diagnostic functions within the unified HSS allows to reduce the total PCS equipment cost up to 20%.

2. To enable the reliable system functioning and to make system to work autonomously under the emergency conditions within the PCS, each TCMD system should have its own full-function workstation. The computer of this workstation serves also as the gateway in order to integrate the TCMD into the PCS network.

3. The implemented TCMD systems considerably extend the capabilities of the operative personnel to control the equipment conditions. For the first time in Russian practice the possibility of automatic on-line data acquisition concerning the crucial parameters of transformer equipment was enabled. Those data include dissolved gases and moisture content in the transformer oil, top oil and windings temperatures, the correspondence of the cooling system operational mode with the transformer current load, its thermal state and environment temperature, LTC state etc. It was also made possible the realization of the remote manual control of

the cooling system and LTC from the PCS operator work place or from the remote control centre.

4. The long-term archives being created by TCMD system, including the direct measurements data and the calculations results of mathematical models of transformer parameters, allow to predict the residual life resource of the transformer paper insulation, to calculate on-line the allowable transformer overload level and duration, the residual resource of LTC and pumps and fans motors.

At the same time along with the evident positive results the number of pending problems prevents to achieve the maximum effect of implementing the intellectual systems for control, on-line monitoring and diagnostics of transformer equipment. Some principal ones are as follows.

1. The technical problems and personnel qualification

1.1. Insufficient stability of primary sensors to impact of the low temperatures and electromagnetic fields.

In 2010 the report of CIGRE WG D1.01 (TF15) was published [9], where the errors analysis of different dissolved gases analysers was described. The accuracy of some on-line gas monitors was found to be not very high. In Russia one of the most frequently arising reasons of TCMD systems malfunctioning are not simple measurement errors but full monitor faults. Such monitors being used in Russia (Morgan-Schaffer Calisto, GE-Energy Hydran M2, MTE Hydrocal, Kelman Transfix) are rather sophisticated devices which are not sufficiently adapted yet to be used at the open air substations under the impact of strong electromagnetic fields and low temperatures. Experience of using Hydran M2 gas monitors in Russia showed significant number of devices outages (about 15%) owing to the faults of thermo stabilising facility of the device sensor. The typical faults reason of Calisto monitors is the damage of the output series interface (RS-485) at the real operational conditions. Insufficient durability under the external electromagnetic impacts was shown also for the pressure-gauge type temperature indicators with 4..20 mA analogue output (AKM34, AKM35, Messko MT-ST160). The necessity of special protection of analogue and digital interfaces of TCMD elements, especially for those located at the immediate proximity to controlled power equipment, against the impact of switching and lightning type overvoltages, was proved by special tests carried out at the conditions of operating substations 330 and 500 kV. Taking into account the results of these tests, all hardware of TCMD systems is equipped now by the special facilities for interfaces overvoltage protection.

1.2. The low sensitivity of the capacitive type oil humidity sensors

The effectiveness of the early diagnostics decreases significantly due to insufficient sensitivity of the capacitor type moisture in oil content sensors that are included practically in all gas and moisture monitoring devices being used for TCMD systems at the Electric Power System of Russia. The proposed sensors do not allow registering growth of the moisture content in oil in the case when the absolute value of humidity is about some ppm. Besides, at the humidity level about 2-4 ppm the monitor readings permanently are near zero and do not perceive the humidity changes in the range of little values. This leads to the situation when operating personnel begin to doubt about the moisture monitor good condition.

1.3. The errors of the pressure-gauge type temperature indicators

The experience of operating the TCMD systems in Russia showed essential errors of the traditionally used AKM34 and MT-ST160 top oil temperature indicators. Under the ambient air temperatures lower than minus 25°C the absolute measurement errors can exceed 8°C. This was proved by the results of comparative tests of AKM34 and MT-ST160 devices at the

real oil and ambient temperatures range (table 1 below). Analysis of the test results allow concluding that the metrological data of the vendors refer to the operational conditions when the capillary tubes connecting the sensor to the indicator are located at the room temperature about +20°C.

Besides, in Russia there were found many faults and breakdowns of this type of devices were fixed (up to 10% of total quantity) after transportation and fitting stages.

Test results of the resistive type temperature sensor TSPU-0104 (Pt100) with unified output 4..20 mA are also given at the table for comparing.

Table 1

| Sensor temperature in oil, °C | Indicator and capillar tube temperature, °C | AKM OTI-34 | | | MT-ST160 | | |
|-------------------------------|---|--------------------|------------------|-----------------------|-----------------------|------------------|-----------------------|
| | | Output current, mA | T, °C calculated | Measurement error, °C | Output current, mA | T, °C calculated | Measurement error, °C |
| 21.3 | -48.2 | 7.17 | 29.72 | 8.4 | 7.25 | 12.50 | -8.80 |
| 21.6 | -18.4 | 6.68 | 25.13 | 3.5 | 7.46 | 14.60 | -7.00 |
| 21.9 | 1.4 | 6.52 | 23.63 | 1.7 | 7.78 | 17.80 | -4.10 |
| 20.5 | 21.5 | 6.2 | 20.63 | 0.1 | 7.92 | 19.20 | -1.30 |
| 21.9 | 51.0 | 6.07 | 19.41 | -2.5 | 8.38 | 23.80 | 1.90 |
| 60.7 | -48.8 | 10.81 | 63.84 | 3.1 | 10.94 | 49.40 | -11.30 |
| 62.9 | -18.2 | 10.9 | 64.69 | 1.8 | 11.6 | 56.00 | -6.90 |
| 62.8 | 3.5 | 10.78 | 63.56 | 0.8 | 11.77 | 57.70 | -5.10 |
| 61.3 | 20.6 | 10.58 | 61.69 | 0.4 | 11.88 | 58.80 | -2.50 |
| 60.2 | 50.2 | 10.25 | 58.59 | -1.6 | 12.19 | 61.90 | +1.70 |
| 90.1 | -48.3 | 13.92 | 93.00 | 2.9 | 14.06 | 80.60 | -9.50 |
| 90.1 | -18.9 | 13.66 | 90.56 | 0.5 | 14.25 | 82.50 | -7.60 |
| 90.2 | 1.2 | 13.61 | 90.09 | 0.1 | 14.54 | 85.40 | -4.80 |
| 90.8 | 20.5 | 13.6 | 90.00 | -0.8 | 14.87 | 88.70 | -2.10 |
| 89.1 | 49.8 | 13.38 | 87.94 | -1.2 | 15.12 | 91.20 | +2.10 |
| | | TSPU-0104 (Pt100) | | | | | |
| Sensor temperature in oil, °C | | Output current, mA | | T, °C calculated | Measurement error, °C | | |
| -48.2 | | 4.05 | | -49.38 | -1.18 | | |
| -18.4 | | 6.45 | | -19.38 | -0.97 | | |
| 1.4 | | 8.05 | | 0.63 | -0.77 | | |
| 21.5 | | 9.67 | | 20.88 | -0.63 | | |
| 51.0 | | 12.06 | | 50.75 | -0.25 | | |

1.4. Limitations of the bushings insulation control devices

The mass transition to bushings with RIP insulation made the illusion for a short time in Russia that the necessity of on-line bushings insulation control disappeared. However, the experience of the last five years of transformers operation with such bushings showed that the consequences of the bushings failures became drastically smaller, but their number was not decrease significantly. Therefore the problem of bushings on-line control is still actual. The analysis of operational experience of widely used on-line bushing state monitoring devices based on the unbalance-compensation method (Doble Engineering Companie's IDD, USA, and DimRus Company's R1500 and R1600, Russia) demonstrated strong dependence of the measurements results on stability and symmetry of the network voltages. The magnitude and phase fluctuations of voltage vectors arising at the grid under the load variations and fault conditions lead inadmissibly often to erroneous readings of the bushing state monitors despite of using different algorithms of the data filtering, symmetrizing facilities and other contrivances.

1.5. The absence of information sufficient for configuring the analytical models

The calculation results of thermal processes, insulation deterioration, allowable level and duration of transformer overload etc. can be adequate to real processes only in case of using detailed parameters of each controlled transformer, including the cooling system type and control algorithm, type of oil in the tank, oil and windings time constants, thermal equations constants x and y and so on. It is frequently rather hard task to obtain those data from the transformers vendors, especially from abroad. In particular, it is toughly to get from the producer the parameters needed for calculation the additional power losses due to voltage unbalance and higher harmonics content, which depend largely on the transformer design details. Some more difficulties arise when configuring TCMD system for old transformer with a long period of operation. Needed information is often absent for such equipment.

1.6. Delays of the components replacement

There is another problem due to frequent outages of sensors and some other components being under the warranty service. It is concerned with the ability of fast replacement or repair of the faulted component. By authors' opinion, the devices vendors fulfil their warranty responsibilities inadmissibly slow. Sometimes it takes years to replace the damaged device.

1.7. Insufficient qualification of the manufacturers' chief-engineers

At the stage of preparing the transformer to commissioning some work should be done to configure and adjust primary sensors installed on the transformer. However it isn't rare cases when manufacturers' chief-engineers doesn't have sufficient knowledge to do this job properly. As a result sensors readings can have considerable errors or totally be doubtful. It concerns especially adjusting current input to the hot spot temperature indicators and configuring moisture sensors for real type of oil within the transformer tank. Some difficulties arise also when configuring other sensors with digital interface (bushings state monitors, new types of top oil and windings temperature sensors etc.)

1.8. Insufficient qualification of the substations personnel

Contemporary microprocessor devices and new information technologies application at the substations raised the task of organizing the training of operating and serving personnel.

The most effective method of the personnel training is using the special simulators intended to simulate the emergency situations at the controlled equipment, the outage of primary sensors and detectors or some other parts of monitoring system itself. The first training simulator based on transformers monitoring system SUMTO is realised at FGUP VEI (fig.2).



Fig.2 The training simulator SUMTO at FGUP VEI

The special testing cubicles and load imitators were included for modelling windings currents and primary sensors signals and simulating equipment operational modes and conditions that take place at the real substations. Besides, the real oil state sensors installed at the physical-chemical laboratory are connected to the simulator.

2. The absence of the proper regulations set concerning the TCMD exploitation

2.1. The absence of regulations

The TCMD systems have rather short application history and accordantly a little experimental results generalization, as compared with relay protection and automatics systems. The scanty application experience and absence of the normative documents regulating the personnel actions under the emergency conditions indicated by TCMD system, as well as the discrepancy between the readings of TCMD on-line sensors and the results of laboratory samples measuring, leads sometimes to serious mistakes.

Analysis of the events recordings and emergency journals that are stored in the TCMD servers memory, as well as the acts of the accidents investigation, shows in the number of cases an inadequate personnel reaction to control and diagnostic information including the TCMD warning and emergency messages.

For example, in September 2009 the turn-to-turn shorting occurred within the practically new autotransformer 200 MVA 330/110 kV at one of UGC FGC 330 kV substations. The reason was the moisture penetration to the winding at the fitting place of 330 kV bushing (Trench ETA type) due to bad quality of upper sealing facility mounting. The autotransformer was equipped by monitoring system FARADAY tMEDIC with the gas monitor HYDRAN M2. Before the turn-to-turn shorting discharge processes aroused that were accompanied by the gas content in oil increase that started three days before the fault. The maximum increase rate was 100 ppm for 3 hours. The fault was not prevented owing to the loss of the TCMD hardware communication with the server at this time interval and to the absence of regulation that would obligate the personnel to read the sensors readings manually at such a case.

At the similar new autotransformer 200 MVA 330/110 kV at the other substation the isolation deterioration of one of the bushings was detected by the readings of the bushings isolation on-line monitor R1500. The investigation demonstrated the moisture penetration due to bad sealing of the bushing fitting. The bushing was replaced in time and the autotransformer is in operation till now.

At Bureiskaya hydropower station the TCMD system revealed the gases in oil rise at the new unit transformer 400 MVA that was due to the constructional defects of manufacturing. In spite of this the transformer was not taken out of the operation and was damaged eventually.

As it follows from the examples cited, the list of which might be continued, the actions of the personnel were not defined by the actual regulations but by the personnel own initiative and training level.

2.2. The customers' requirements

In the number of cases the customers' technical specifications for the TCMD systems do not correspond to metrological possibilities of used primary sensors and detectors. So, it isn't unusual when customer demands to realise calculating the set of transformer short circuit and no-load operation parameters for analysis of possible deformations and evaluating the windings displacement within TCMD system. Our analysis showed that for such calculations signals of 0,2S class current transformers (CT) should be connected to TCMD system, while the usual practice is to present for this goal 10P CT's only. Furthermore, from the whole set of

transformer equivalent circuit parameters only full short circuit impedances or their inductive parts can be evaluated at reasonable accuracy.

It should be taken into account that the potential transformers (PT) are often located far enough from the TCMD hardware site. For example, the higher voltage side PT might be located at the distance up to 1000 m from the unit transformers of hydro power stations. The input circuits of modern digital meters and protective hardware are very small loads to PT, while the cable connecting PT to TCMD hardware represent the no-loaded long line. The voltage amplitude and phase might diverge notably from those at the PT secondary winding. Besides, the electromagnetic impact to this long cable is rather strong. To minimize the magnitude and phase errors due to these factors it is necessary to separate the current and voltage sensors and place the voltage meter in the immediate proximity to PT. Special techniques should be used for synchronizing the current and voltage instantaneous values sampling.

Conclusions and recommendations

1. The results survey of the first decade of different TCMD systems application at Russia allows to conclude, that those systems realize rather successful acquisition and processing data from the primary sensors representing the top oil temperature, gases and moisture content in oil, current load and other diagnostic parameters. Meanwhile the analytical models being used by most of the world vendors do not give sufficiently accurate forecasts about the resource parameters of the transformer equipment. The scheduling the repairs and other procedures of equipment life cycle control using those prognoses is rather doubtful. This problem has two aspects. The first is concerned with the fact that physical and chemical processes running within the transformer equipment are rather sophisticated and additional researches are demanded to get more accurate mathematical descriptions of different defects progression processes in real time. The second aspect relates to the circumstance that the data represented currently by the transformers manufacturers do not allow to describe adequately the deterioration processes at the non-rated conditions.

2. Taking into account that the data acquisition hardware and primary sensors (top oil and winding most hot spot temperatures, gases and moisture content, bushings and LTC monitors etc.) are located in the immediate proximity to the sources of strong electromagnetic disturbances, their external analogue and series digital interfaces have to be equipped by overvoltage protection means enabling the conformity to the hardness group and functioning mode according to IEC 61000 standard for such kind of hardware.

3. The notable number of power objects at Russia is located at the cold climate zones with winter temperatures down to minus 50°C at severe winds. The built-in heaters of the outdoor TCMD hardware for such ambient conditions have to provide the temperature rise as good as 35°C. In the case of using heaters of less capacity all hardware including primary sensors should have “military” temperature grade.

4. By authors' opinion, the application of the pressure-gauge type top oil and hot spot temperature sensors should be abandoned. Using such type of sensors that do not demand external power sources was justified 40-50 years ago by the absence of reliable secondary power supply units. Nowadays, when time before failure (MTBF) of the modern power sources riches up to 10^6 hours, this anxiety is hardly well-grounded. This is confirmed by faultless operation experience of TCMD system installed on 12 converter transformers and reactors at Vyborg B2B HVDC converter station of the Russia-Finland power link, where only Pt100-type temperature sensors are used for monitoring and cooling systems control. The transition to such kind of temperature sensors is justified by their low cost, high reliability and accuracy.

5. The thorough harmonization of the TCMD specifications with metrological possibilities of the available primary sensors is needed.
6. It is reasonable to use HV bushings state monitoring devices based on the direct measurements of conductivity current and phase voltage of each bushing from the regular PT, followed by the detecting the mutual angle. NKVV device from ASU-VEI LLC, Russia, might be an example. Such devices are installed for bushings monitoring at 80 220-500 kV transformers.
7. The now operating TCMD systems might be regarded as elements of the “digital substations” already, where all data exchange is realized using digital communication channels only (IEC 60870-5-104 and MODBUS RTU data transfer protocols were used till 2010). Just two steps are remained, it seemed, for building the really « intellectual » transformer as we understand it: moving to use the new IEC 61850 standard for unified data exchange and to equip the power transformers with digital electronic current and potential transformers. While the first step is made already by many worldwide and native vendors, the intensive implementation of digital CT's & PT's can be expected hardly in the nearest time as by the technical reasons so by the economical ones. Besides, direct connecting of numerous sensors and detectors with digital output to the station communication bus in accordance with IEC 61850-8-1 is not technically and economically justified. It is reasonable to connect those devices to the data acquisition unit located close to them, through the field bus with interface type RS485. Development of the proper international standard for data transfer within this bus would be desirable. MODBUS RTU can be chosen as an example of this standard protocol.

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