21, rue d'Artois, F-75008 Paris
http://www.cigre.org

A2-106

Session 2004

TEMPERATURE MEASUREMENT OF PRIMARY WINDINGS OF TRANSFORMERS IN THE HYDRO-ELECTRIC POWER PLANT "DJERDAP 1" RATED 380 MVA, 2×15,75 kV/420 kV, d5/d5/YN, OFWF, UNDER LOAD AFTER 30 YEARS OPERATION

R. LJ. RADOSAVLJEVIC*
Faculty of Electrical Engineering, Belgrade
A.M. POPOVIC, Elektroistok

V. MILOSAVLJEVIC
PP Djerdap 1
M. DAMJANOVIC
PP Djerdap 1

(YUGOSLAVIA)

SUMMARY

Although the temperature rise test had been done immediately after manufacturing in the factory in laboratory conditions, using the short-circuit method, it occurred as necessary to check the values of both losses and temperature rise of windings for all four transformers after 30 years operation. The purpose has been to obtain relevant data for re-designing the cooling system in order to revitalize the transformers of the plant and to increase their rated power by 10 %.

The applied temperature rise test under direct load means that the transformer operates in normal conditions, with approximately rated power. The crucial difficulty of this method is the minimization of the time needed to decrease the load from full rating down to zero, to disconnect the transformer from the mains, to ground the windings and to connect them to the prepared measuring circuitry. This is very complicated work as each transformer is connected to two 190 MVA generators.

The transformers in the plant "Djerdap 1" have two primary LV windings, in delta connection, which is not possible to disconnect. The average temperature rises of primary windings are assessed by measuring the d.c. resistance increment using a measuring circuit where two windings are producing equal and opposite magnetic fluxes, which results in very fast establishing of the measuring d.c. current. The characteristics of the measurement made is the fact that both LV windings are steadily in galvanic connection both during the measurements and during the operation on the mains, which enables the measurers to form the circuitry for measurement very quickly after the transformer is disconnected. The advantages of the method are: use of cheap and conventional instrumentation, energy saving compared to the short - circuit test method and normal operation of the transformer except two disconnections lasting about one hour when trained measuring staff is engaged.

The complete measuring procedure is presented – electric wiring, realized before the transformer was connected to the mains, as well as the heat-run process, including measurement and calculation before and after the thermal steady state has been reached. The complete test was carried out on October 2002. At this time, all necessary conditions were fulfilled – quick load reduction, prompt grounding and immediate start of resistance measuring.

The following items are further treated: measuring results of individual losses in no-load and short-circuit tests when the source of energy was one of two generators connected to the transformer, as well as the power carried out by two heat exchanger systems by the calorimetric method. In this way, all power losses are determined including the heat losses transferred via transformer tank surface under two extreme weather conditions - first, at a cold and rainy autumnal day, and second, at a hot summer day.

Keywords: Power - Plant, Hydro - electric, Transformer, Revitalization, Testing - *in - situ*, Temperature - Rise, Direct - Loading, Loss, Calorimetry, No - Load, Short - Circuit.

* radosavljevic@kiklop.etf.bg.ac.yu

INTRODUCTION

The planned revitalization of the hydro-electric power plant »Djerdap 1« foresees the increase of the rated power of each of 6 generators by 10 %. So, the question arises – how would it be possible for transformers to operate under these conditions, as they are rated 380 MVA each and because they are old over 30 years. Therefore, complicated tests are in progress, in order to state the general condition of transformers – electrical, physico-chemical and thermal - especially their insulation systems, in order to establish some initial points for revitalization. Tests had started with the first transformer being longest in service, and having most data of manufacturer's testing, so that all consequences of many years' operation may be noticed.

A very important item in the preparing the revitalization and examining the possibility of rated power increase, is the measurement of following quantities: losses, temperature rises, as well as heat losses transferred by the heat exchangers and tank surface. All of these data are necessary for the re–design of the new cooling system, consisting of two heat exchangers.

Taking into account the transformer large size (rated power, voltage and physical dimensions), see Fig. 1, the tests would be best done in specialized laboratories, but for practical reasons (they are usually not at disposal and the transformer transport would be complicated and expensive), the tests were made *in-situ*, under normal operating conditions - which requires solutions of some problems not arising in factory (or laboratory) testing. Also, special measuring devices, usually not available in power plants, are needed, so that the applications of methods as simple as possible are preferred.

Fig. 1. A transformer of the power plant Djerdap 1

Technically speaking, most difficulties arise in measuring the average temperature rise of windings. Genarally speaking, most applied methods are: the direct loading, the short-circuit and the opposition method. The direct loading method has great advantages in comparison with other two methods, due to economic and technical reasons, provided that the loading can be made stable, measuring instrumentation can be customary, and the time interval needed to measure the winding resistance may be sufficiently brief.

The heat-run test by direct loading method comprises the operation of the transformer under normal operating conditions, with approximately rated power output. In this method, a series of problems must be solved, as: quick load reduction down to zero, grounding, connecting the measuring circuitry, including the removing of disturbing noise of HV overhead conductors operating with remaining transformers of the power plant. This is especially important for the transformers in question, because each of them is connected to two generators rated 190 MVA, and so has three windings – two LV primaries and one HV secondary.

Measurement of the average temperature rise of primary windings by measuring the resistance increase [1] may be done by using various types of measuring bridges, with or without data acquisition and PC; the most applicable way is the U/I method, which is generally recommended for resistances of the order of one milliohm [2]. The principal problem is too long time interval needed for the d.c. magnetic flux to set up, due to the presence of delta connection, having a high corresponding time constant, which is not possible to reduce sufficiently without disconnecting the delta. Using the fact that the transformer has two equal primary windings (each one for the corresponding generator), it is possible, by their opposing connection, to eliminate (almost completely) the transition process, as shown in Fig. 2.

Measuring the resistance, i.e. temperature rise, is preferably made only to one primary winding having the index 2, as it is completely situated in the upper half of the transformer, i.e. in the warmer oil, which results in its higher temperature than the lower one. On the other hand, the resistance measurement of the HV winding was not done, although a measuring circuitry with

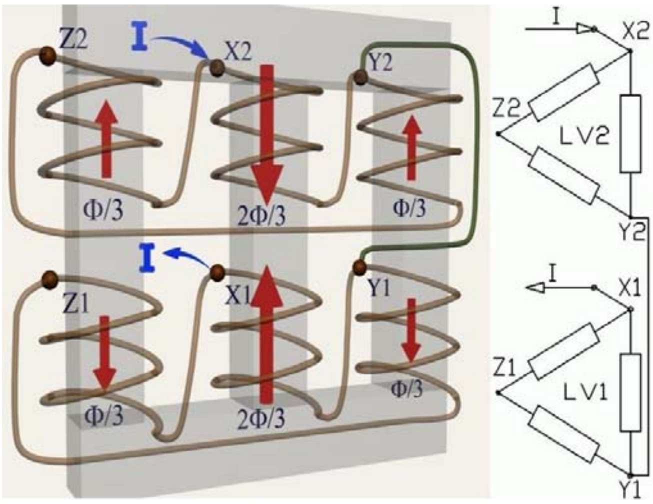

Fig. 2. Location of two LV primary windings and opposing connection for resistance measurement

compensating d.c. flux had been developed, due to the need of mounting special HV insulators. The authors have an intention to apply this measurement only later in the future when testing of the remaining transformers would be done.

Measurements of losses were made by conventional no-load method and short-circuit method with reduced current, accommodated to conditions of power plant, when energizing was obtained from one of two generators. The calorimetric measurements under full load conditions using the water flow rate into the calibrated pool under transformer are enabled the calculation of individual heat powers carried away.

1. MEASUREMENT OF TEMPERATURE RISE OF LV PRIMARY WINDINGS BY DIRECT LOADING METHOD

The basic condition for successful application of the direct loading method is the realization of the practically constant, exact or approximate, rated load, in the time interval sufficiently long to bring the transformer into the thermal steady state. This condition was easy to reach, as the plant has six generators, two of which operated at nearly full load, the following two delivered the reactive energy required by the mains. In accordance and with agreement of the Dispatching Service of Serbia, the whole power system was prepared to withstand the sudden unloading of 380 MVA (needed for the resistance measurement) without noticeable consequences, which was necessary to carry out the resistance measurement of the windings.

Before delivering energy, the transformer under test had been out of service for several days, because the regular annual maintenance was in course. This fact had been utilized for (1) measurement of cold resistances, (2) making solid and stable galvanic connections Y1 and Y2, see Fig. 3, in order to make the electric contact between two primary LV windings. This connection was maintained during the whole process of heat-run test, and therefore it must have the rated voltage of 35 kV. It connects points being at the same potential throughout the loading and has the purpose to allow the forming of the measuring d.c. circuit between the terminals X2 and X1 as well as the measurement of resistance X2-Y2, after the transformer is disconnected.

Due attention had been paid to the choice of measuring circuits and the instrumentation. Utilized are: long own experience of measuring in industry, as well as data available in literature, concerning: d.c. source characteristics [2], level of current used [2, 3], contact resistances in the measuring circuits, instrument range, magnitude of deflection, instrument resistance and particularly the way of eliminating the contact resistance in the millivoltmeter measurements, as well as choosing the way of voltmeter connecting and disconnecting [2, 4], the choice of initial measuring circuit and supplementary resistors, the criterion of checking the current stability [5], etc. In addition, the following should be mentioned: normative documents concerning the measurement of temperatures [1], temperatures of cooling media, choice of measuring procedure for winding mounted onto the middle core, etc.

Although many conditions from standards for the heat-run test have to be satisfied, Recommendations [1] leave certain alternatives to the measuring staff to choose in accordance with their experience, as for instance the manner of cooling after the transformer with OFWF cooling is disconnected.

The connection diagram for resistance measurement is presented in Fig. 4. The storage battery B with gel having the ratings 12 V and 200 Ah was used, having the capability to deliver 150 A stable within 40 minutes. Control of current was done by a regulating resistor (Rreg) 8 V, 200 A, with both coarse and fine adjustment without current breaking, capable to give minimum current of 1 A. The circuit breaker P1 for measuring current was of the standard type, three-phase, for 35 kV (only two terminals were used); it was situated near the transformer and was supplied with protection from touching and it was held open during the transformer loading. The circuit breaker P2 (diode as an alternative) serves to switch the measuring current off. The current itself was measured by means of a shunt, which was a precise secondary standard, rated 1 mΩ, 200 A. By using another voltmeter, both primary winding resistances could be simultaneously measured.

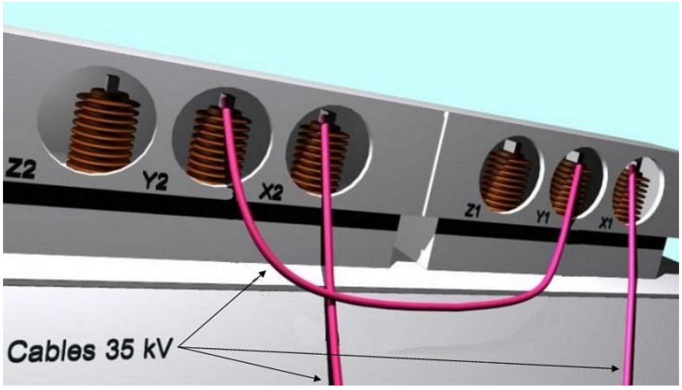

Fig. 3. Permanent connections for resistance measurements

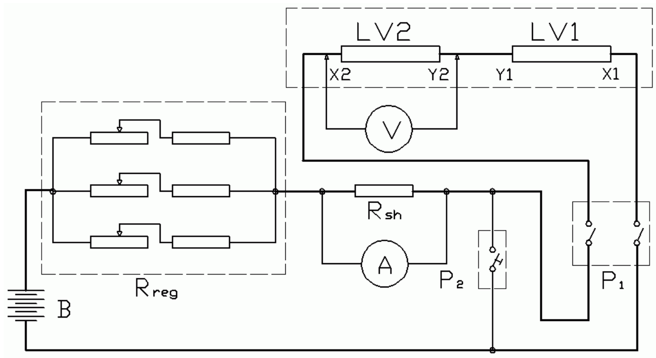

Fig. 4. Wiring diagram for resistance measurement of LV primary winding

The application of this measuring circuit made the obtaining of stable measuring current possible already in the course of current adjustment, so that the main problem of long time needed to establish the current was completely avoided.

Before the beginning of the resistance rise test, resistances of cold windings were measured first. As all parts of primary and secondary windings must have the same (cold) temperature, the transformer was left out of service for more than 24 hours, and 3 hours before the resistances were measured, both oil pumps were turned on, and the water was also circulating, which resulted in equalizing the temperatures of all transformer parts. Temperatures were measured by 13 sensors – thermoelements of type T, and applying the measuring acquisition system SR 630 and a PC. The sensors were carefully mounted in order to eliminate the effects of wind, water (rain) and other ambient factors. Positions of temperature sensors for all thermal measurements are listed and schematically presented in Fig. 5.

Unloading the generators G1 and G2, i.e. the corresponding transformer 1, was done in the central control boardroom of the power plant by simultaneously and continuously commanding to complete unload both generators down to zero. At the switching board in the machine room of the plant, members of the operating staff were present and checked the unloading of the generators by watching the conventional instruments at the switching board, until the load reached the value of 80 MW per generator, and after that they gave the command for opening their circuit breakers. In this way, the process of complete unloading of both generators from 360 to 0 MW lasted 6 to 7 seconds. After the transformer unloading was completed, the operator from the central control board commanded to switch off the circuit breaker and the disconnecting switches in the plant substation PS 400 kV, situated at the place about 600 meters far from the transformer. In this substation, a member of the staff was situated, having the task to watch the breaking off the disconnecting switches visually, and to inform the chief coordinator immediately via the permanently active communication line. The chief coordinator was present in the close vicinity of the transformer, and he was giving the following orders:

– to ground the HV terminals of the transformer by provisionally connecting first the middle phase winding, and afterwards the others;

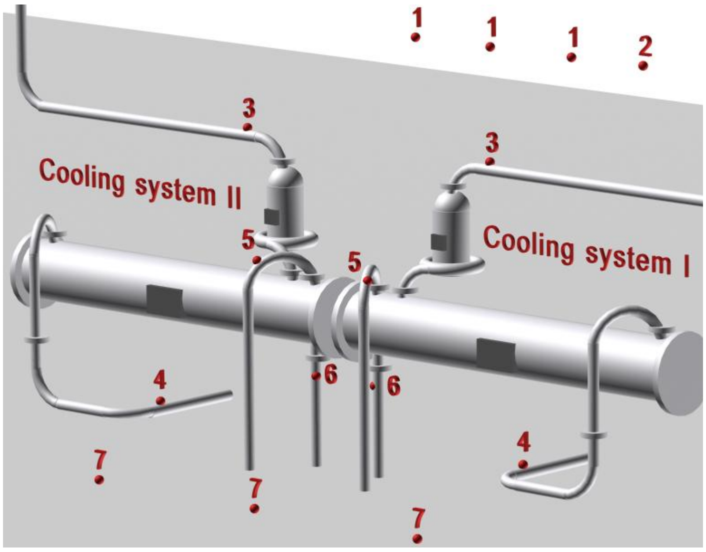

Fig. 5. Schematic presentation of two cooling systems (heat exchangers) and locations of temperature sensors

1 Tank lid (3 sensors)
2 Oil in the (thermometer) pocket
3 Hot oil inlet into 2 heat exchangers
4 Cold oil outlet from 2 heat exchangers
5 Cold water inlet into 2 heat exchangers
6 Warm water outlet from 2 heat exchangers
7 Average ambient temperature(several sensors)

– to switch on the circuit breaker P1 (Fig. 4) followed by the flow of d.c. measuring current with prescribed value, which happens practically without any transient;
– to connect the voltmeter to the points defined in advance.

For all of these operations, the trained staff had been prepared, in order to minimize the entire time needed for these manipulations. For works on the transformer, a special grounded platform had been built and mounted close to the transformer itself. The total time, lasting from the instant of load breaking-off till the moment when all conditions for measuring the first resistance value were fulfilled, was 62 seconds but in reality readings began after 75 seconds. Most of the time was used for making the provisional grounding of the HV side of the transformer. This grounding was inevitable due to disturbances caused by 400 kV overhead conductors.

The cooling procedure after switching off is not strictly defined in IEC Recommendation, Annex A [1]. Three options are offered to the testing staff: either stopping the oil circulation, or stopping the water circulation, or stopping both, due to the very vague thermal image of an OFWF transformer; all advantages and disadvantages of each recommended procedure are given in the standard. In our testing, a compromise variant was chosen – oil pumps were stopped and water circulation was left acting, because otherwise (by continuing both oil and water circulations) temperatures measured by sensors would vary very much in the course of resistance measurement, which could occasionally result in uncertain results.

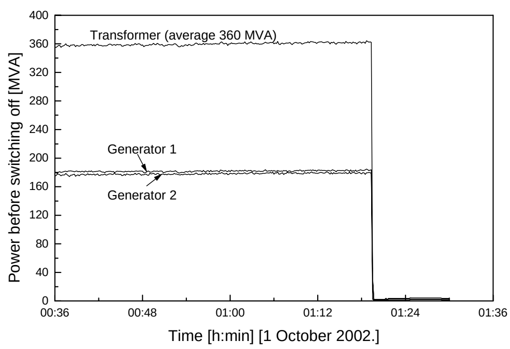

Fig. 6. Powers of both generators and of the transformer before the resistance measurement

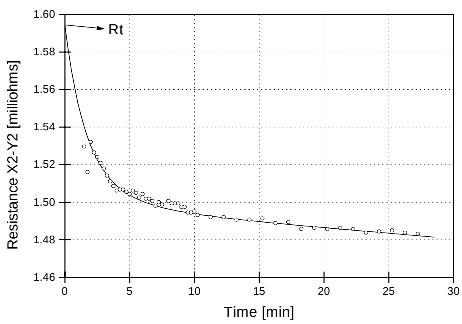

Fig. 7. Primary winding resistances and the extrapolation curve

During testing, all electrical quantities and temperatures needed for further calculation and correction have been recorded. The power flows for both generators and the transformer during a pretty long period before the unloading are shown in Fig 6.

In the diagram on Fig. 7, the values of measured resistances as the function of time are shown, together with the extrapolation curve which leads to the initial value of the hot primary winding resistance, equal to $R_t = 1{,}594$ mΩ. The curve was determined in accordance with the general procedure given in [1], Annex C3. It can be seen from this diagram that the stable distribution of points has been established approximately after 105 seconds after the load removing.

2. MEASUREMENT OF POWER LOSSES OF THE TRANSFORMER BY MEANS OF NO–LOAD, SHORT-CIRCUIT AND CALORIMETRIC TESTS

No-load and short-circuit tests were realized by removing the elastic connections between the transformer and LV busbars and interposing 3 corresponding current transformers CTs (2 × 75 A/ 5 A) and 3 potential transformers VTs (25 kV / 100 V), see Fig. 8. All of measuring transformers were put onto an insulated support directly onto the transformer lid, in the vicinity of busbars. In both tests a solid galvanic contact was made between the »P1« terminal of current transformers and busbars with 3 cable conductors rated 35 kV, supplied with specially designed connecting elements at their terminals. The »P2« terminals of current transformers were connected either to the HV winding in the case of short-circuit test, or displaced to one primary LV2 winding in the case of no-load test. The generator G2 was used as a source, having full value of rated voltage in both cases, sufficient for no-load test and delivering 31% of the rated current in the short-circuit test. The comparison of results in the factory in 1972 and *in–situ* in 2002 is shown in Table 1.

TABLE 1. Comparative survey of factory and *in-situ* measurements

Place and year of testing	**In factory, 1972**	***In-situ*, 2002.**
Magnetizing current	0,54 %	0,48 %
No-load loss	318 kW	338 kW
Rated load loss at 75°C	780 kW	754 kW (calculated)
Total rated losses	1098 kW	1092 kW
Impedance at 75°C	12,4 %	12,4 %
Heat - run test method	in short circuit	direct loading
Temperature and resistance rise		
Cold resistance X2 – Y2 (LV2)	1,3427 mΩ at 25,4 °C	1,3446 mΩ at 18,7 °C
Extrapolated resistance X2 – Y2 (LV2)	1,5293 mΩ for 380 MVA	1,594 mΩ for 360 MVA
Average temp. rise of LV2 winding (without corrections)	48,9 K	48,2 K
Corrections	7,3 K (oil drop during rated current period)	6,1 K (IEC 76 – 2, point 5.6)
Average rated temp. rise of LV2 winding above inlet water	56,2 K	54,3 K
Rated power taken away by heat exchangers	2 × 475 kW	2 × 540 kW
Top oil temperature rise	44,4 K	40,4 K
Average oil temperature rise	35,1 K	29,6 K
Water flow through the exchangers (winter – summer)	10,6 l/s	10,8 - 13,7 l/s

For the calorimetric test, the pool for scooping the hot water was first calibrated, beginning with zero elevation mark - start level in Fig. 9, where the area of pool basis is constant and has the value of 21,95 m^2 (measured by theodolite).

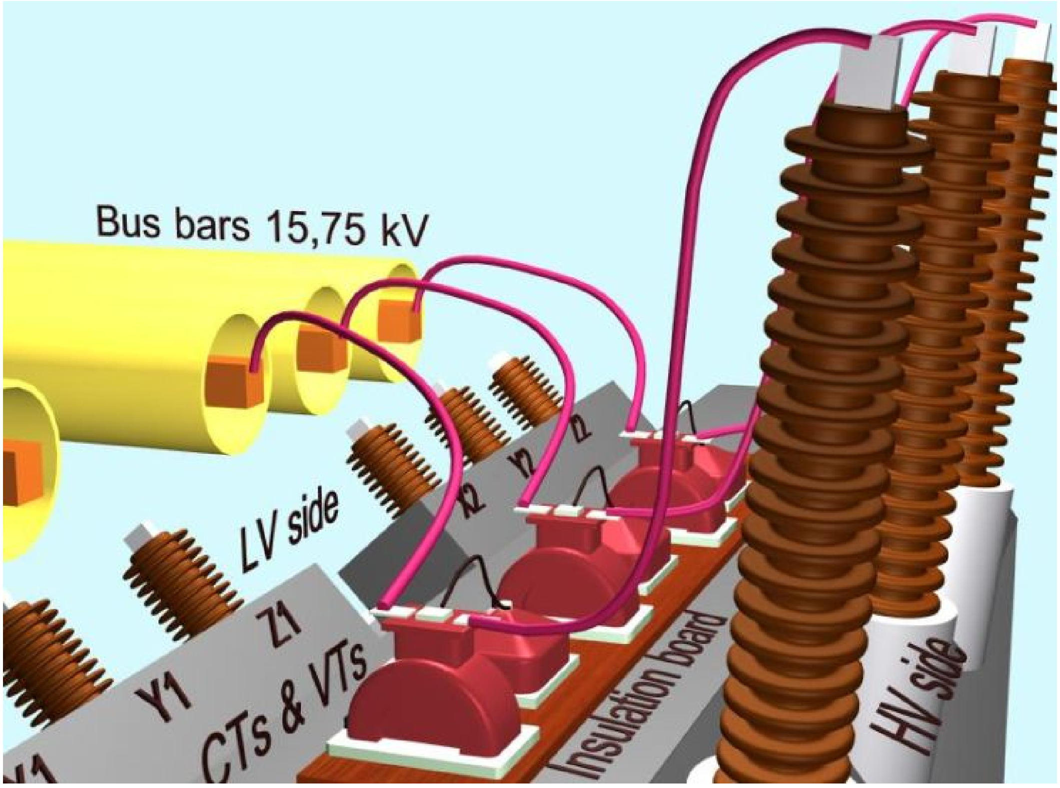

Fig. 8. Connections in short-circuit test (similar for no-load test)

Two series of measurements were made in extreme weather conditions: (1) at the cold autumnal day with strong rain (in November 2002), and (2) at a hot summer day with mild breeze and small cloudliness (in July 2003) – both with approximately rated load. In both cases, among the other quantities, characteristic temperatures were measured, particularly those of the outlet water of the heat exchangers (by means of an acquisition system), and the height measurement Δh in the pool as the function of time. In this way, the value of water flow rate q_1 [l/s] was found. The increment Δh was measured by means of a simple system, including a float, see Fig. 9.

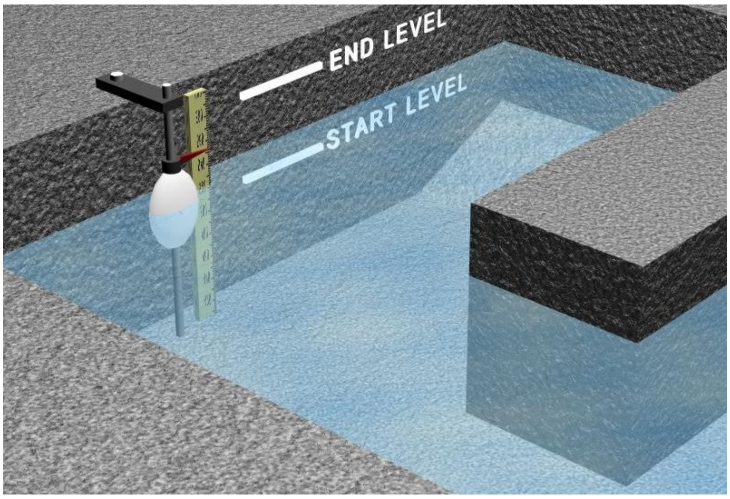

Fig. 9. The float system for measurement of the hot water flow

Following electrical quantities of the transformer were measured: both primary voltages, total current, power throughout 7 hours before the beginning of calorimetric measurements, in order to find the correlation between the electrical and thermal quantities as well as the calculation of heat brought away by the cooling system under the full-load condition. The difference between the total power loss (obtained in the no-load and short-circuit tests) and the power brought away by the heat exchangers is equal to the heat given to the ambient from the transformer tank surface (area about 160 m^2) by radiation and convection. Results of measurement and calculation for calorimetric tests in two extreme ambient conditions are shown in Table 2.

TABLE 2. Results of calorimetric tests

Ambient conditions	Cold autumnal day with strong rain (November, 2002)	Hot summer day with mild breeze (July, 2003)
Average ambient temperature	13,3 °C	31,5 °C
Average outlet and inlet temperature difference	10,3 K	8,6 K
Average water flow through individual heat exchangers	10,84 l/s	13,69 l/s
Power brought out by both exchangers	951,5 kW*	1045 kW*
Power taken away through transformer surface	140,5 kW*	44 kW*
Total dissipated power (power loss)	1092 kW*	1089 kW*
*Corrected to rated power conditions		

3. CONCLUSION

The heat-run test of a transformer may be made *in-situ* under normal operating conditions in the power plant instead of applying the short-circuit method, resulting in significant energy saving. It is important that, like in the case of factory (manufacturer' s) testing, tests can be repeated, which is especially important for transformers being in operation for a long period of time. The temperatures obtained by measurement represent an important set of parameters, which are very useful for estimating the state of insulation, subjected to aging, as well as to establish the measures for revitalization, and eventually the steps needed for increase of ratings.

For three-winding transformers, with two primary LV windings, and provided that only average temperatures of windings are needed, the heating-up test may be done by a direct load method, which is exceptionally inexpensive, so that this method has been successfully applied at the first transformer of the hydro-electric power plant Djerdap 1. Technically speaking, the measurement of HV winding temperature rise is also possible, but the wiring diagram is more complicated, because a supplementary HV insulator is inevitable; nevertheless, it is planned to carry out this test in next future on remaining three transformers.

Combining the temperature rise test with relatively simple and inexpensive short-circuit and no-load tests, together with calorimetric measurement of heat taken away by heat exchangers under two extreme weather conditions, the level of heat power taken off the tank surface was obtained. The measurements carried out have shown that the cooling system consisting of two oil-to-water heat exchangers must be re-calculated on the basis of total power loss. This conclusion had been already verified in the praxis, because almost immediately after the beginning of normal operation (in 1972) the original heat exchangers ought to be replaced by another ones having a larger capacity.

Temperatures and temperature rises obtained in the just mentioned heat-run test by the described method are nearly equal to those obtained in factory (manufacturer' s) tests, the most important ones being somewhat lower. The reason is obviously the replacement of the original exchangers by larger ones, the new cooling medium velocity being also important.

The most significant conclusion is that temperature rises of windings did not increase even after 30 years long operation. This fact may be taken as the basis for calculating all quantities relating to the rated power increase by 10 per cent, especially the necessary parameters for new cooling system, i.e. for heat exchangers.

4. REFERENCES

[1] International Standard: Power Transformers. Part 2. Temperature Rise. [IEC 76-2, 1993].
[2] G. Aleksenko: Testing of Large Transformers and Reactors. Energia, Moskva, 1978, pp. 71, 395.
[3] G. Zherve: Factory Testing of Electric Machines. Energiatomizdat, Leningrad, 1984, pp. 30.
[4] E. Kovarski: Testing of Electric Machinery. Energoatomizdat, Moskva, 1990, pp. 12, 150.
[5] O. Goldberg: Testing of Electric Machines, Vyshaja shkola, Moskva, 1990, pp. 35.