ALGORITHM OF THE MICROPROCESSOR THERMAL PROTECTION OF OIL POWER TRANSFORMERS

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1. INTRODUCTION

During the operation of power transformers the critical parameter is the temperature of the insulation hottest point (hot spot). The hot–spot temperature has to be hold under a prescribed limit. A cumulative effect of insulation aging, depending on time change of hot–spot temperature, should be less than a planed value. That is why there exists an interest to know the hot–spot temperature in every moment of a real transformer operation. This temperature depends on: a) the load of the transformer, not only of the current one, but also of the loading prehistory (the dominant thermal time constant of a transformer amounts to few hours) b) the temperature of the extern cooling medium. One of the possibilities is to measure the hot–spot temperature, which requires the application of special fibre – optic sensors. This possibility was of the highest interest in the beginning of the 80-ties but the results obtained from practical experiences are not promising. The other possibility is to calculate the hot-spot temperature using a thermal model with the following input data: the temperature of the extern cooling medium and the load. Since the thermal phenomena are quite complex it is not easy to consider all of them in the thermal model precisely. There are some simplified thermal models in the appropriate standards (IEC for example) which have limited calculation precision. The paper defines a complete algorithm for the hot–spot temperature calculation, having higher calculation accuracy then the algorithms from the IEC standard. All important elements of the thermal models aimed to the calculation of the hot-spot are summarised.

In the on-line application of the thermal model two additional practical problems appear: unknown starting hot-spot temperature and variation of the thermal parameters during long-term transformer operation. The solution of these problems is discussed by means of a thermal observer.

2. SHORT DESCRIPTION OF THE ORIGINAL THERMAL MODEL

The thermal model, aimed primarily to ONAN transformers, is based on the thermal network from Fig. 1.

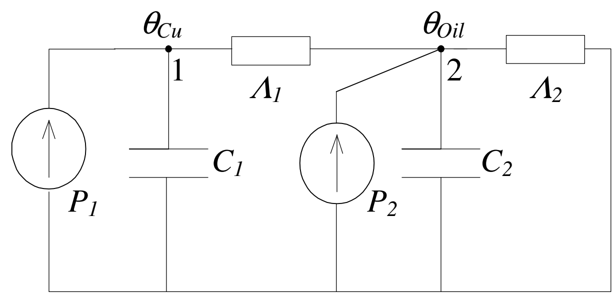

Fig. 1. The thermal network with two nodes.

P_1 Power loss in windings
P_2 Power loss in core and tank
Λ_1 Heat transfer conductance from windings to oil
Λ_2 Heat transfer conductance from oil to air
C_1 Heat capacity of the windings
C_2 Heat capacity of oil, core and tank
θ_{Cu} Characteristic copper temperature rise
θ_{Oil} Characteristic oil temperature rise

All temperature rises are calculated with respect to the temperature of the air surrounding the transformer.

The system is non-linear due to the temperature dependent thermal conductances. The most convenient and in IEC Standards (1) used dependencies are:

$$\Lambda_1 = K_1\,(\theta_{Cu} - \theta_{Oil})^{n_1} \quad (1)$$

$$\Lambda_2 = K_2\,(\theta_{Oil})^{n_2} \quad (2)$$

The parameters K_1, n_1, K_2, n_2, C_1 and C_2 are determined by the developed procedure of Radakovic and Kalic (2) from the values of measured characteristic temperatures in short-circuit heating experiment. The characteristic temperatures can be adopted liberally but preferably by using measurable temperatures: local values outside the tank and average winding temperature. The method for continuous average winding temperature measurement is developed by Radakovic and Lazarevic (3).

Temperature rises θ_{Cu} and θ_{Oil} in discrete time moments (period Δt) can be calculated from the equations:

$$\theta_{Cu,k+1} = \theta_{Cu,k} + \frac{\Delta t}{C_1}(P_1 - \Lambda_{1,k}\,(\theta_{Cu,k} - \theta_{Oil,k})) = \theta_{Cu,k} + \frac{\Delta t}{C_1}(P_1 - K_1\,(\theta_{Cu,k} - \theta_{Oil,k})^{n_1+1}) \quad (3)$$

$$\theta_{Oil,k+1} = \theta_{Oil,k} + \frac{\Delta t}{C_2}(P_2 + \Lambda_{1,k}(\theta_{Cu,k} - \theta_{Oil,k}) - \Lambda_{2,k}\,\theta_{Oil,k}) \tag{4}$$

$$= \theta_{Oil,k} + \frac{\Delta t}{C_2}(P_2 + K_1(\theta_{Cu,k} - \theta_{Oil,k})^{n_1+1} - K_2\,\theta_{Oil,k}{}^{n_2+1})$$

The power loss distribution in short-circuit heating experiment and during normal operation is considered by Radakovic (4).

3. CHARACTERISTIC TEMPERATURES

It is natural to choose the most critical temperatures: solid insulation hot-spot and top oil. In a previous work of the authors (2, 4), these values were used, where the hot-spot temperature (ϑ_{hs}) was calculated based on the following measured temperatures: mean winding temperature (ϑ_{Cua}), top-oil temperature (ϑ_{to}) and temperatures of the outer radiator surface - at the top (ϑ_{rt}) and the bottom (ϑ_{rb}). The following formula for hot-spot temperature calculation, expressed with temperature rise values, is used:

$$\theta_{hs}{}^{*} = \theta_{to} + H\left(\theta_{Cua} - \left(\theta_{to} - \frac{\theta_{rt} - \theta_{rb}}{2}\right)\right). \tag{5}$$

H represents the hot-spot factor, adopted to be equal 1.1. Instead of using the top-oil temperature also the bottom oil temperature can be used. Then the previous formulae turn into

$$\theta_{hs}{}^{*} = \theta_{bo} + \theta_{rt} - \theta_{rb} + H\left(\theta_{Cua} - \left(\theta_{bo} + \frac{\theta_{rt} - \theta_{rb}}{2}\right)\right). \tag{6}$$

From the easily measured temperatures in short-circuit heating experiment the time change of $\theta_{hs}{}^{*}$ can be defined and afterwards the thermal circuit parameters can be calculated. $\vartheta_{hs}{}^{*}$ and ϑ_{to} can be calculated in every moment of real transformer operation using the established model with the input data of current and ambient air temperature. It is shown (2) that the procedure delivers results for the temperatures $\vartheta_{hs}{}^{*}$ and ϑ_{to} with high accuracy. It is of essential importance to check the precision of expression (5), comparing the $\vartheta_{hs}{}^{*}$ value with the real hot-spot temperature (ϑ_{hs}). For that purpose, direct measurements of the hot-spot temperature are needed. Such measurements were provided on a 630 kVA, 3 x 10 kV / 3 x 6 kV ONAN transformer equipped with 112 temperature sensors (102 inside the central positioned 10 kV winding) as described by Radakovic and Feser (5).

The examination of two factors, possibly disturbing the precision of expression (5), was done. The first one is the hot-spot factor (H), taking into account non-uniform power losses in windings, change of local heat transfer coefficient over the winding height and edge effects of oil streaming at the windings ends. A constant approximate value can be applied (as recommended in (1)) if it does not cause a high calculation error. This factor influences the steady state hot-spot temperature value. The second factor is the different dynamic characteristic of measured top temperatures (oil in the pocket and at the top of the radiators) from that determining the winding-oil heat exchange (oil at the top of the cooling channel inside winding).

The analysis in (5) has shown that the maximum error caused by assuming a constant factor H (H = 1.1) is in the range [-2.08, +1.62] K; the error can be considered as acceptable and consequently the factor H can be taken as constant.

On the contrary, the quoted dynamic characteristic caused a non-acceptable error. The difference of the hot-spot temperature calculated by (6) and the one obtained by direct measurements (in short-circuit heating experiment with constant loss equal to the power loss due to rated current (8790 W), starting at transformer temperature equal to ambient temperature – experiment 1) amounted to - 8.20 K.

As the final result of the research the following procedure is established. The hot-spot temperature during one-step load increase or decrease is defined from the easily measured temperatures in the subsequent manner:

1. The steady-state top minus bottom radiator temperature difference is calculated

$$\Delta\theta_{rt,rb\,stac} = \theta_{rt\,stac} - \theta_{rb\,stac} \tag{7}$$

2. The function $f(t)$ is defined

$$f(t) = \frac{\theta_{Cu\,a} - \theta_{bo}}{(\theta_{Cu\,a} - \theta_{bo})_{stac}}. \tag{8}$$

3. The oil at the windings top minus bottom oil temperature difference is equal to

$$\Delta\theta_{to,bo} = \Delta\theta_{rt,rb\,stac}\; f(t)\,(1 - e^{-t/10\min}) \tag{9}$$

4. The hot-spot temperature is equal to

$$\theta_{hs}{}^{**} = \theta_{bo} + \Delta\theta_{to,bo} + H\left(\theta_{Cua} - \left(\theta_{bo} + \frac{\Delta\theta_{to,bo}}{2}\right)\right) \tag{10}$$

The dynamics of the windings top minus bottom oil temperature difference contains the following two components: copper minus bottom oil temperature delay and oil at windings top minus copper temperature delay. The second component can be approximately described by an exponential function with the time constant 10 min. The result of the method proposed for the experiment 1 is shown in Fig. 2.

4. PRACTICAL APPLICATION OF THE MODEL

After defining the change of the temperatures associated to the nodes of the thermal circuit during the complete

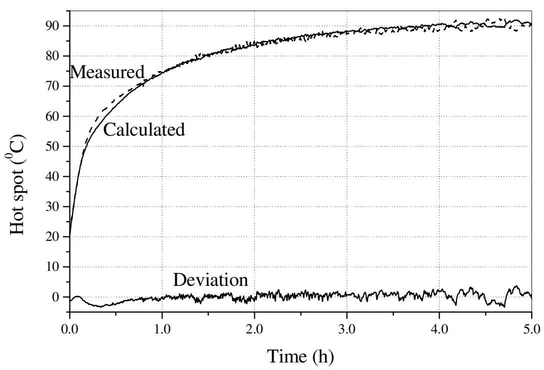

Fig. 2 – Application of the eqs. (7) – (10)

transient process of heat experiment, the procedure of the thermal parameters determination (2), extended by the precise method for the power losses distribution (4), can be applied. The temperature associated to the node 2 represents the bottom oil temperature and the temperature associated to the node 1 is calculated from the easily measured temperatures, as described above, using the hot-spot factor $H = 1.1$.

The thermal conductances define the steady-states. Their parameters can be determined from the measuring results recorded in at least two thermal steady-states. Due to a very sensitive functional form of the thermal conductances it is desirable to have more measurements in order to minimize the error in the calculation of parameters. In the case of using only two steady-states the measuring error can cause a high error in the exponents (n_1 and n_2).

Thermal capacitances are determined from one transient heating process. As the most comfortable and effective method, Nelder-Mead simplex (direct search) method in Matlab Software (6), was used.

Details of the application of the model on a 630 kVA ONAN transformer are exposed in (5). The results of the final test with the most complex daily load diagram are shown in Fig. 3. The calculated and measured temperatures of the hot-spot (upper graph of Fig. 3) and the bottom oil (lower graph of Fig. 3) are shown. In (5) the superiority of the proposed algorithm to the algorithms from the valid IEC standard and the draft of the new standard is shown.

5. THE PRACTICAL PROBLEMS IN THE APPLICATION OF THE MODEL

Two problems exist in the on-line application of the proposed model: unknown starting hot-spot temperature and variation of the thermal parameters during a long-term transformer operation.

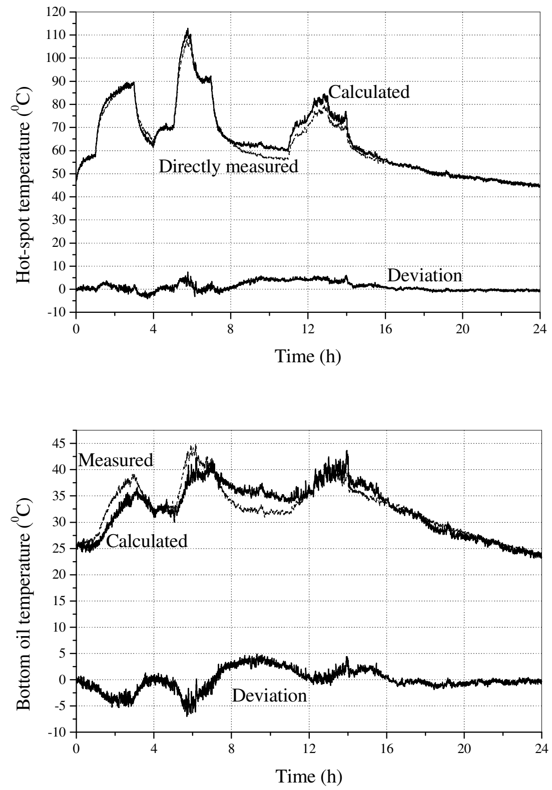

Fig. 3 – Results for the complex daily load diagram

Thermal characteristics of a transformer can change in a long term transformer operation. Therefore, thermal parameters of the model may be different from the values initially determined experimentally in the short–circuit heating experiment. Incorrect parameter values in the model can lead to an error in temperature calculation. The only practically acceptable method for detection of parameters' variation is through monitoring the oil temperature.

The thermal observer is a known technical solution for speeding up the elimination of the error caused by the guessed initial hot-spot temperature. The introduction of the thermal observer leads to implications in the calculation of the hot-spot and oil temperatures. Consequently, it affects the detection of thermal model parameters' change. The analysis of all aspects of the thermal observer is given by Radakovic and Feser (7).

5.1. Consideration of the Thermal Observer

The observer enables the calculation of non-measurable system states, using measurable system outputs. The observer is a numerical structure, containing the mathematical model of the system. The non-measurable

states of a real system are accessible from the model contained in the observer. The initial values of the non-measurable states in the model should be set as close as possible to the corresponding values in the real system. The difference in states of the model and of the real system should be eliminated as soon as possible. The real system, the model of the system "inside" the observer and their "coupling" feedback represent one dynamic structure. The dynamic of error elimination is determined by all parameters of the structure, i. e. can be controlled by adjusting the feedback parameters.
The mathematical model of the system with the observer is given in (7). The basic observer theory is well-known, but there are some factors which have to be considered in the application on real transformers. The discrepancies from an elementary case are: 1. The thermal behaviour of the transformer can not be modelled perfect, i. e. the model in the observer does not match fully to the system; 2. The matrices in the model are the function of states, disabling a correct application of the linear system theory; 3. There are the oil temperature and current measurement noise, i. e. power losses noise. All relevant parameters in the application of the thermal observer are investigated in (7). The experimental base for the investigations was the same as for the test of the thermal model of the transformer.

5.2. The Results of Thermal Observer Application

The results of the investigations were as follows. The applied observer leads to the expected faster elimination of initial guessed to real hot–spot temperature difference. Unfortunately, it also leads to the reduced precision of hot–spot temperature calculation during normal transformer operation. The importance of the precision is obvious, since the protection of the transformer is based on the calculated hot–spot temperature value. The reduced precision is caused by insufficient accurate transformer thermal model and existing measuring noise.
If no observer would be applied, i. e. the thermal model only would be used, the calculation error of the hot–spot temperature at the beginning of the calculation process (for example, during the first hour) would be too high. Fortunately, the start of the calculation process is of practical interest only after a reset of the microprocessor relay, along with the temperature inside the transformer higher than the ambient temperature.
The measured state variable, oil temperature, is not strongly influenced by a change of the thermal conductance describing the copper to oil heat transfer. Therefore it is difficult to detect the change of this heat transfer. The same holds for both applied identification techniques: with and without observer (7). On the contrary, the change in oil to air heat transfer is easy to detect (7).
The thermal observer applied can not be used as the complete solution for all the practical problems in the transformer thermal protection and evaluation of overload possibility. The observer can be used to speed up the elimination of the initial calculation error (delivering results applicable for the protection in a shorter period). After the initial period, the thermal model itself provides a higher hot–spot temperature precision and should substitute the observer.

6. CONCLUSIONS

The paper surveys the work on the improving the thermal modelling of oil power transformers. The original algorithm for the hot-spot temperature calculation is exposed. The algorithm describes the physical phenomena better and provides higher calculation accuracy then the algorithms in the valid IEC standards and in the new draft. The algorithm is convenient to be practically realised on the microprocessor thermal relay. The research of the important practical problems of unknown starting hot-spot temperature and of thermal characteristics change during a long-term operation of a transformer is also overviewed. The prospect for future work is a further research of other configuration of the thermal observer. Also, the natural step after the research and extensive experimental verification of the algorithms is the application in commercial microprocessor thermal protection and monitoring systems.

Literature

1. IEC Loading guide for oil immersed transformers, IEC Standard 60354, Sep. 1991
2. Radakovic, Z., and Kalic, Đ., 1997, Electr. Eng. (Arch. f Elektr.), 80, 205-214
3. Radakovic, Z., and Lazarevic, Z., 1996, Proc. 31st Univers. Power Eng. Conf., 481-485
4. Radakovic, Z., 2003, Europ. Trans. on Elect. Pow. (ETEP), 13, 47-54.
5. Radakovic, Z., and Feser, K., 2003, IEEE Trans. on Power Delivery, 18, 1284-1292.
6. MATLAB Version 6.1.0.450 (R12.1) on PCWIN
7. Radakovic, Z., and Feser, K., 2004: Electr. Eng. (Arch. f Elektr.), 86,, 1-8.