EXPERIENCES WITH A SELF LEARNING EXPERT SYSTEM (SLES) FOR DYNAMIC RATING OF POWER TRANSFORMERS

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ABSTRACT

The Dutch DSO Alliander is used to operate its assets in a safe, flexible and efficient way. One of the steps to achieve this is the transition from static towards dynamic rating. Because power transformers play a crucial role in the network, their dynamic rating is being studied at Alliander. This has resulted in a Self Learning Expert System (SLES) for dynamic rating of power transformers.

To further improve this SLES, a couple of new transformers have been equipped with optical fiber temperature sensors to get a continuous and direct measurement of top-oil and winding temperature. This enables obtaining accurate insight in the thermal behaviour of these transformers.

The experiences regarding the use of the SLES to fine-tune the thermal model of the transformer will be discussed. This paper presents a new top-oil temperature calculation model based on heat transfer theory. In this model the physical data (electrical and mechanical) of the transformer is used as input parameter. Because the model is a general physical description of the transformer, it is necessary to calibrate the model on the heat-run test. After simulating the top-oil temperature using the calculated parameters from the heat-run test, a deviation from the measured temperature can be observed. In order to minimize this deviation, a parameter estimation routine is developed.

INTRODUCTION

In the early stages of the development of the system for dynamic loading of power transformers, simulations of the thermal behaviour of a couple of transformers based on the IEC standard (IEC-60076-7) [1] were performed [2]. After comparing field measurements with the results obtained by the simulations, significant differences were observed. Analysis of these results revealed that the IEC standard-model does not describe the transformers' thermal behaviour well enough. Not all of the required parameters are known and the influence of the ambient conditions are not taken into account correctly. An example of the differences between calculated and measured top-oil temperature is given in figure 1.

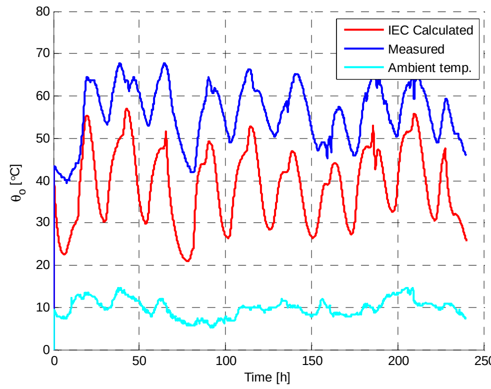

Figure 1: calculated and measured top-oil temperature [2]

It demonstrates that the calculated top-oil temperature based on the IEC standard-model is too low. When the transformer is loaded based on the calculated values, it can lead to the damage of the transformer. Therefore there is a need to develop a model which is able to calculate the top-oil temperature more accurately under all load en local conditions.

TRANSFORMER THERMAL MODEL

Top-Oil Temperature Model

The transformer will be described as a black box. This means that the transformer is considered as a single component. The physical properties like mass, heat capacity, surface area and temperature of the transformer are regarded as uniform. The combined mass and heat capacity of the transformer is determined by the amount of iron, copper and transformer oil. This information is available for each transformer. The temperature of the transformer in relation to the environment can be calculated using the model in figure 2.

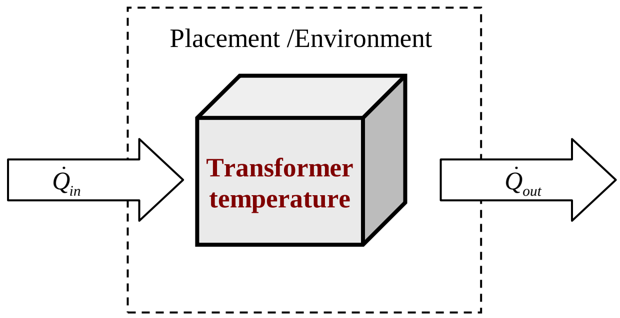

Figure 2: Schematic representation of the black box approach

$\dot{Q}_{in}$ Heat generation (sum of load loss en no-load loss)
$\dot{Q}_{out}$ Heat dissipation to the environment

The heat dissipation to the environment depends on the transformer temperature and the environmental factors. Environmental factors are:

- Ambient temperature: heat transfer by natural convection and radiation;
- Wind: increased heat transfer by forced convection;
- Precipitation: increased heat transfer under the influence of precipitation;
- Solar radiation: heat generation by solar radiation.

The placement of the transformer in the environment affects how environmental factors such as wind and precipitation influence the transformer temperature. The transformer temperature in relation to the ambient temperature can be calculated using the following differential equation:

$$\frac{dT}{dt} = \frac{\dot{Q}_{in} + A \cdot U \cdot (T - T_a)}{m \cdot c_p} \qquad (1)$$

With $\dot{Q}_{in} = P_{Cu} + P_{Fe}$

Where

$\dot{Q}_{in}$ total transformer heat generation [W]
P_{Cu} load loss (coper loss) [W]
P_{Fe} no-load loss (iron loss) [W]
A heat transfer surface [m^2]
U convective heat transfer coefficient[W/m^2.K]
m mass of the transformer [kg]
c_p heat capacity [J/kg.K]
T transformer temperature [K]
T_a ambient temperature [K]

The no-load loss is determined by de heat-run test. The load loss is described by the flowing equation:

$$P_{Culoss} = 3 \cdot I^2 \cdot R \qquad (2)$$

Where

I load current [A]
R winding resistance [Ω]

The convective heat transfer coefficient U is an empirical equation. Especially for natural convection the heat transfer coefficient can be described by the equation 3 [3]:

$$U = \frac{\left(0.68 + 0.515 \cdot \left(\frac{g\beta}{\alpha\nu} \cdot H^3 \cdot \Theta\right)^{0.25}\right) \cdot k}{H} \qquad (3)$$

Where

g gravitational constant [m/s^2]
β air thermal expansion coefficient [K^{-1}]
α air thermal diffusivity [m^2/s]
ν air kinematic viscosity [m^2/s]
H height of the transformer [m]
k air thermal conductivity [W/m.K]
Θ temperature difference (T-T$_a$) [K]

The solution of the differential equation (1) is:

$$\Theta = \frac{\dot{Q}_{in}}{U \cdot A} \cdot (1 - e^{-\frac{U \cdot A \cdot t}{m \cdot c_p}}) \qquad (4)$$

Calibration of model

The top-oil temperature model above is a general physical description of the transformer. This makes it necessary to calibrate the model on a conditioned measurement. The heat-run test is a conditioned measurement which is very suitable to calibrate the model. Figure 3 shows the top-oil temperature and the ambient temperature during the heat-run test. The final value of the top-oil temperature is reached after 10 hours.

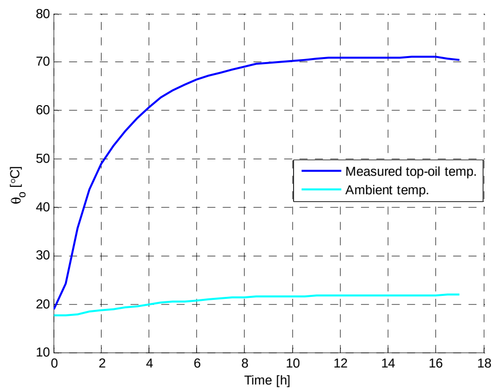

Figure 3: measured top-oil temperature during heat-run test (with $\Theta_o = \Theta + T_a$)

The heat-run test temperature curve can be mathematically described as follows:

$$\Theta_o = \Theta_{or} \cdot (1 - e^{-\frac{t}{\tau}}) \qquad (5)$$

Where

Θ_o instantaneous oil temperature rise [K]
Θ_{or} final oil temperature rise [K]
t time [s]
τ time constant [s^{-1}]

With (from eq. 4 and 5):

$$\Theta_{or} = \frac{\dot{Q}_{in}}{U \cdot A} \quad (6)$$

$$\tau = \left(\frac{U \cdot A}{m \cdot c_p} \right)^{-1} \quad (7)$$

To calibrate the model to the heat-run test a surface factor (f_A) and a capacity factor (f_{cp}) are introduced. With

$$A = f_A \cdot A_{tr} \quad (8)$$

$$c_p = f_{cp} \cdot c_{ptr} \quad (9)$$

Where

A_{tr} cooling surface of the transformer [m^2]

c_{ptr} heat capacity of the transformer, calculated conform the IEC standard [1] [J/kg.K]

The model can be fitted to the heat-run test by finding the optimal solution for the surface factor f_A and the capacity factor f_{cp}, thus calibrating the model to the appropriate transformer. In figure 4 the calculated top-oil temperature with optimal f_A and f_{cp}, and the measured top-oil temperature are shown.

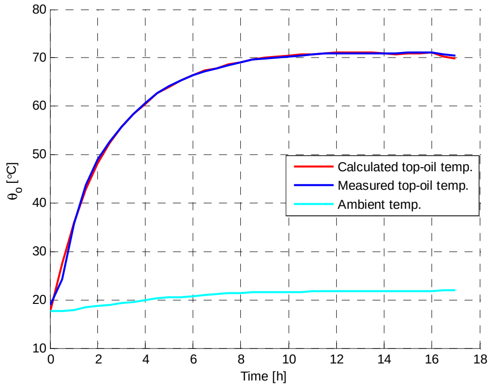

Figure 4: calculated and measured top-oil temperature during heat-run test

COMPARISON ON FIELD TESTS

Comparison for a 53 MVA ONAN transformer

A new 53 MVA ONAN transformer has been equipped with optical fiber temperature sensors to get a continuous measurement of the top-oil temperature and winding temperature. This makes the comparison between calculated and measured values possible. In figure 5 the calculated top-oil temperature with the found f_A en f_{cp} from the heat-run test and the measured top-oil temperature are shown. The calculated values are structurally smaller than the measured values with deviations up to 10 °C, even though the optimal values for f_A and f_{cp} were used for this specific transformer.

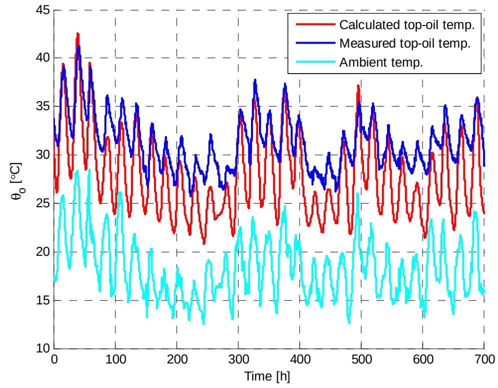

Figure 5: calculated and measured top-oil temperature during July 2009

These deviations fluctuate over time. A possible reason is that the environmental influences are not included in the model. The values of the surface factor f_A and the capacity factor f_{cp} from the calibration of the heat-run test are hardly suitable for practical measurements. The factors f_A and f_{cp} should be adapted dynamically for the practical measurements. To solve this problem a Self Learning Expert System (SLES) has been developed.

Self Learning Expert System (SLES)

The principle of the SLES is given figure 6.

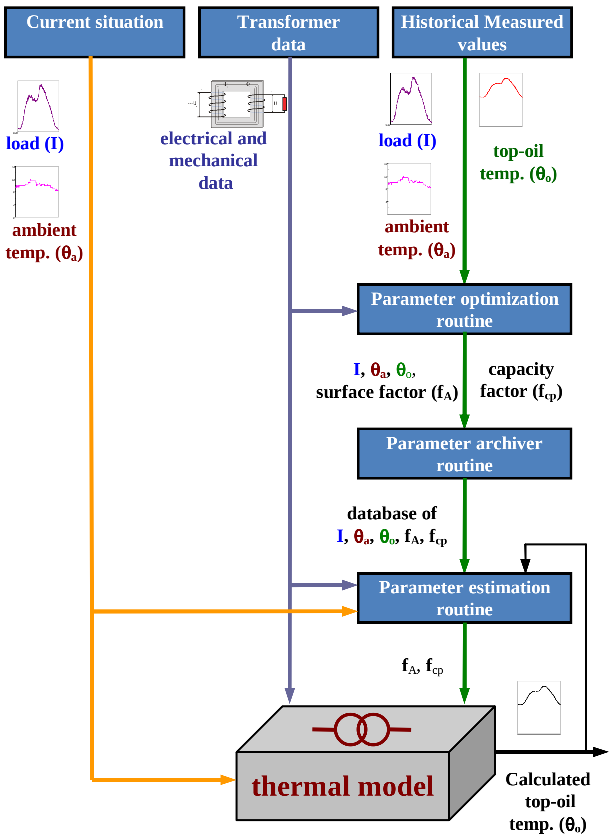

Figure 6: SLES for dynamic rating of power transformers

As equation (1) clearly shows, the top-oil temperature rise in this model depends primarily on three parameters: the load current, the ambient temperature and the top-oil at a certain time. When a set of these measured values are found, using unconstrained nonlinear minimization (Nelder-Mead method) a pair of f_A and f_{cp} can be determined that approximates the measured top-oil temperature very well, using the same calibration method from the earlier model. This procedure is performed in the parameter optimization routine. The parameter archiver routine stores this set of five parameters (the load current, the ambient temperature, the top oil temperature, the surface factor f_A and the capacity factor f_{cp}) in a database. By means of the load current, the ambient temperature and top-oil temperature at that time, the parameter estimation routine will search in the database which pair of f_A and f_{cp} is best to calculate the top-oil temperature. These two factors, together with load current, the ambient temperature and de data of transformer are fed into the model to calculate the top-oil temperature. The newly calculated top-oil temperature will be the input for the next pair of f_A and f_{cp} which will be used in the next calculation. Over time, the database may contain all possible load situations.

In Figure 7 the calculated top-oil temperature using SLES has been added. The figure shows clearly that the calculation using the parameters from SLES matches the measurements better than the calculation using the parameters from the heat-run test.

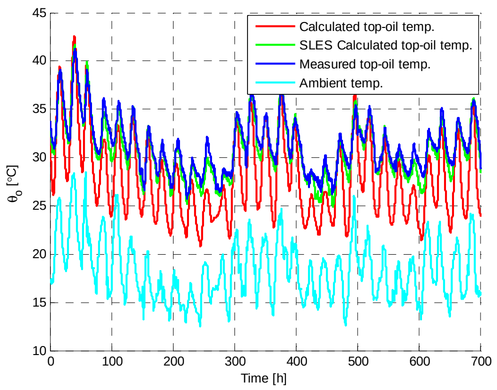

Figure 7: SLES for dynamic rating of power transformers

A particular feature of this SLES is that the exact mechanical and electrical data of the transformer is not necessary in order to calculate the optimal top-oil temperature if there is enough historical measured data available. By using the parameter optimization routine and parameters estimation routine, a pair of f_A and f_{cp} can be found to calculate the top-oil temperature closest to the measured temperature.

Comparison for a 45/66 MVA ONAN/ONAF transformer

This is an example for which the IEC standard-model does not describe the transformers' thermal behaviour well enough (figure 1). It concerns a 45/66 MVA ONAN/ONAF transformer. The calculation of the top-oil temperature for the same situation is performed again. In this case, SLES is applied instead of the IEC standard. The result of the calculation agrees well with the measurement, as shown in figure 8.

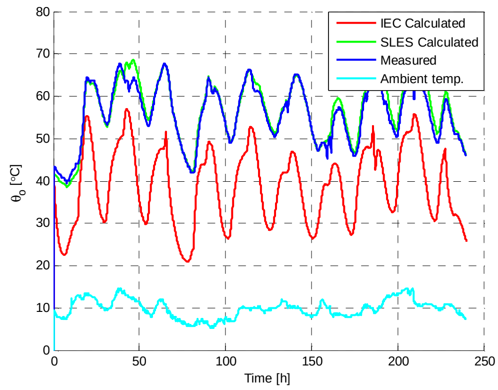

Figure 8: calculated top-oil temperature of an ONAN/ONAF transformer using IEC versus SLES

CONCLUSION

The dynamic thermal model can be calibrated to the heat-run test optimizing the surface factor f_A and the capacity factor f_{cp}.
The surface factor f_A and the capacity factor f_{cp} from the calibration of the heat-run test are hardly suitable for practical applications.
Using the parameter optimization routine and parameter estimation routine, a pair of the surface factor f_A and the capacity factor f_{cp} can be found to calculate the top-oil temperature closest to the measured temperature.
By using the SLES in combination with direct oil and winding temperature measurements on operational transformers, it is possible to accurately simulate the transformer's thermal behaviour under a wide variety of ambient and load conditions. Thanks to a better understanding of the thermal phenomenon, transformers can operate more efficiently with lower risks. This form of dynamic rating may also contribute to a more responsible and optimal investment policy.

REFERENCES

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[3] A. Bejan, 1993, "Heat Transfer", Wiley, United States of America, 335-390, ISBN 0-471-50290-1.