IMPLEMENTATION OF A MODEL-BASED DIAGNOSIS SYSTEM FOR POWER TRANSFORMERS

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ABSTRACT

A Matlab/Simulink implementation of a model-based diagnoses system for power transformers based on structured residuals is presented in this work. Process models for thermal behavior and moisture diffusion in paper are observers for transformer temperatures and relative water concentration in oil respectively. An experimental setup consisting of a medium voltage distribution transformer equipped with a controllable loading setup provides the functionality for heat runs. Both, process models and diagnosis structure are verified by comparing measured and simulated system variables. The diagnosis system is proposed to be implemented either as strictly online fault detection system for large power transformers or as an inexpensive offline evaluation method for medium voltage distribution transformers.

INTRODUCTION

Power transformers are one of the most expensive investments in an electric power system. The deregulation of the electricity market forces the power utilities to reduce maintenance costs. This leads to a lack of transformer specific knowledge inside a power utility and increases the risk of a transformer failure. Moreover, the changed market situation increases the demand for controlled transformer life-time management.

Model-based transformer diagnosis

In recent years the task of supervision and fault detection of power transformers was rather categorized by the underlying measurement technique than by the modeling concept or system architecture. Traditionally transformer diagnosis concepts were divided into *online* measurement techniques, often related with the term *monitoring*, and *offline* measurement methods. This classification means that signals utilized for fault detection are achieved with the power transformer in service or disconnected from operating voltage, respectively. Another aspect and more related to the concept of model-based diagnosis is the classification into physical subsystems such as *mechanic subsystem*, *dielectric subsystem* and *thermal subsystem*. Each of them is subject of both, offline and online measurement techniques, which are nowadays to some extend well established in the field of power transformer monitoring or testing. However, far too little concern was taken about the interpretation method of the measurement results and the integration of the subsystems into a common diagnosis scheme.

Power transformer failures

The main components that ensure the normal operation of a transformer are the windings (including cellulose insulation material), the *core*, *oil*, *cooler*, *main tank* and *On Load Tap Changer (OLTC)* [1]. From the system point of view, faults can be classified into *mechanical*, *dielectric*, *thermal* and *chemical* origins.

According to an international survey of CIGRE [2], typical failure rates for large power transformers with winding voltages up to 300 kV are in the range of 1 % to 2 % p.a. More recent figures from Germany [3] confirm that the statistical failure rates of transformers increase significantly with system voltage.

OLTC failures are the most frequent faults in power transformers. They represent the predominant part of faults of mechanical origin. However, since they represent a independent subsystem, they are not under consideration in the following work.

Faults in the winding are ranked second in failure statistics, followed by faults in the tank/oil system and faults of the terminals (e.g. bushings), accessories (e.g. coolers) and the core. Since explicit values for failure rates strongly depend on operation management, environmental conditions, manufactures etc, only this qualitative ranking is given here.

Moisture in an oil-paper insulation system

Moisture influences the rate of thermal ageing of paper. The decomposition of cellulose molecules proceeds more intensive in the presence of moisture [4]. This process can be considered as cumulative, since it produces additional water as a by-product [5].

Transformer oil shows a low affinity for water where it exists in the oil in dissolved state. At the maximum concentration of water in oil $c_{O,max}(T)$ the oil is saturated. This saturation concentration is highly temperature dependent. Above $c_{O,max}(T)$ water in oil can be found as free water in terms of suspension or waters drops, which decreases the partial discharge voltage significantly. The concentration of water in oil can be expressed as

$$c_O = \frac{m_{H_2O}}{m_{oil}}, \qquad (1.)$$

where m_{H2O} is the overall mass of water in oil and m_{oil} is the

overall mass of dry oil. It is often expressed in parts per million (PPM) e.g. µg/g.
The content of water in oil can also be expressed as a ratio of the absolute water concentration c_O and the saturation concentration. For a defined temperature and pressure the relative humidity becomes

$$h_O = \frac{c_O}{c_{O,max}} \quad (2.)$$

which is analogical to the relative humidity of air that can be expressed as the water vapor content relative to its content at saturation.
Paper can contain much more moisture than oil. It can be adsorbed to surfaces, as vapor, as free water in capillaries and as imbibed free water. The concentration of water in paper can be calculated similar to (1)

$$c_P = \frac{m_{H_2O}}{m_P}, \quad (3.)$$

where m_{H2O} is the mass of water in paper and m_P is the mass of dry, oil-free paper. The value of c_P is often expressed in %.
The concentrations of water in an oil-paper system tend to an equilibrium condition, after decaying of all transient diffusion processes. Driving force for diffusion processes of water between oil and paper are different partial vapor pressures. In the case of a homogeneous temperature distribution the relative saturation concentrations of water in oil and water in paper are identical for equilibrium.

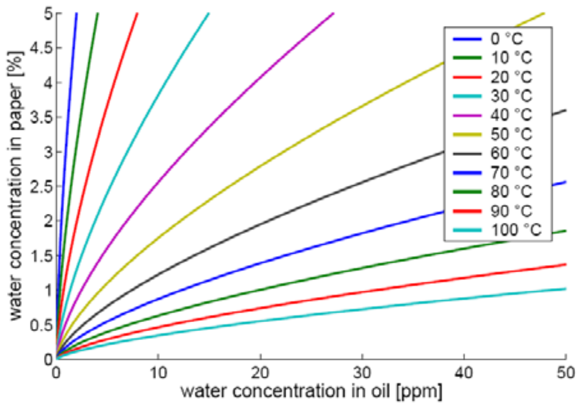

Fig. 1: Equilibrium curves for the concentration of water in paper as a function of the water concentration in oil for different temperatures.

Beside the stationary behavior, the propagation of water in oil and paper is of interest. Water in oil propagates due to convection of oil and due to diffusion caused by concentration gradients. In paper only diffusion processes are possible. Propagation effects in oil are much faster compared to diffusion processes in paper [6] and are therefore neglected for simulation purposes. It has been shown by many authors [4], [7], [8] that the diffusion coefficient for water diffusion in paper is highly temperature dependent. For an oil-paper insulation system that is subjected to varying temperature due to varying transformer load conditions, water propagation is affected by temperature dependent water solubility of paper and oil and temperature dependent diffusion coefficients.

STRUCTURE OF A MODEL-BASED DIAGNOSIS SYSTEM

Power transformers belong to the kind of equipment with comparable long life-span and high reliability. When adding a diagnosis system to the transformer the reliability of the overall system must not decrease compared to the original system. Therefore self-supervision of the transformer diagnosis system is an essential task.
As far as the aspect of fault detection is concerned, this results in a clear separation between faults of the transformer or its auxiliary equipment and faults caused by the diagnosis system. The latter may be sensor faults, misinterpreted influence of noise or modeling errors.
For the presented diagnosis system, potential sensor fault scenarios are:

- tank temperature sensor failure,
- oil temperature sensor failure,
- sensor box temperature failure,
- oil humidity sensor failure,
- load current sensor failure.

Faults belonging to the transformer itself are

- oil pump failure,
- common winding failure,
- insulation system humidity failure,
- excess winding temperature,
- excess oil/paper interface humidity.

In order to detect and to isolate faults, models predicting transformer temperatures and water concentration in oil are used as observers for measured variables.
The parity equations for a set of n variables

$$r_i(t) = y_p(t) - y_m(t), \qquad i = 1 \ldots n, \quad (4.)$$

where $y_p(t)$ are the variables predicted by the observers and $y_m(t)$ are the measured variables respectively, generate a set of n residuals $r_i(t)$.
For each residual r_i and a corresponding tolerance κ_i a binary variable ε_i is generated so that

$$\varepsilon_i(t) = \begin{cases} 0 & \text{if} \quad |r_i(t)| < \kappa_i \\ 1 & \text{if} \quad |r_i(t)| \geq \kappa_i \end{cases} \qquad i = 1 \ldots n \quad (5.)$$

The vector

$$\varepsilon = [\varepsilon_1 \ldots \varepsilon_n]' \quad (6.)$$

is the fault code or signature.
Since it is not possible to formulate a general applicable way for the generation of parity equations for non-linear systems, the equations are oriented on the natural inner structure of the system. For reasons of simplicity a pure parallel-structure was chosen to generate the residuals.
In order to evaluate the isolation properties of the residual generator, the fault code for each fault scenario is evaluated.

residual	r_1	r_2	r_3	r_4	r_5	r_6
tank temperature sensor failure			×			
oil temperature sensor failure	×					
sensor box temperature failure		×				
oil humidity sensor failure				×		
load current sensor failure	×	×	×			
oil pump failure		×		×		
common winding failure	×	×	×			
insulation system humidity failure				×		
excess winding temperature					×	
excess oil/paper interface humidity						×

Tab. 1: Fault code of the pre-assumed fault scenarios.

MODELING OF THE SUBSYSTEMS

Thermal model

The model structure of the presented thermal model has been chosen according to the requirements of the experimental setup. For an application on a real unit in the field (e.g. with forced oil circulation, forced air cooling) the required model structure has to be adapted to the topology of the transformer. In addition to that, effects that do not appear in a lab but in the field such as solar radiation or additional cooling due to wind have to be considered.
The transformer contains five major heat reservoirs which were considered for thermal modeling:

- windings (copper)
- core (iron)
- oil (mineral oil)
- tank (iron)
- sensor box (mineral oil)

Heat sources in the transformer are losses which are produced during operation:

- copper losses (load losses)
- iron losses (eddy current losses, hysteresis losses, stray losses)

Relations between heat flows and temperature reservoirs can be visualized with a *pseudo bond-graph* which represents the topology of the thermal network (Fig. 2).

Moisture Diffusion Model

In order to study the interaction of oil and paper during diffusion processes, an one-dimensional model of a enclosed transformer insulation system is proposed. The model is based on a layer of paper of thickness d_P that is surrounded on both sides with an oil volume. The masses of oil and paper are denoted with m_O and m_P respectively. The boundary between oil and paper is defined by the surface A_P (Fig. 3).
For the boundary layer between oil and paper it is assumed that it always stays in equilibrium condition. This assumption is supported by the fact that any convection velocity of oil decays to zero at the surface [6]. Therefore equilibrium curves (Fig. 1) specify the temperature dependent boundary condition for the simulation model.

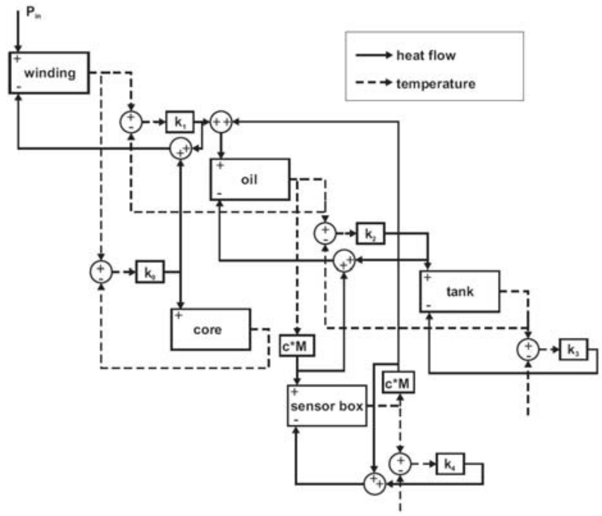

Fig. 2: Pseudo bond-graph representing the topology of the thermal network of the power transformer under test.

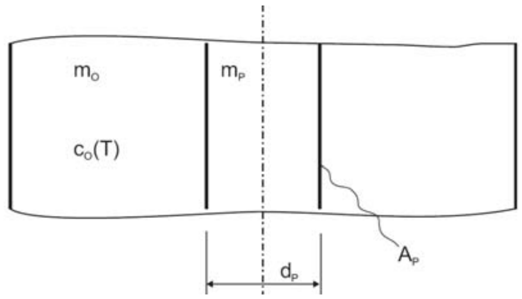

Fig. 3: One-dimensional model for simulation of diffusion processes for an enclosed transformer insulation system consisting of a layer of paper m_P, d_P and a volume of oil m_O divided by a surface A_P.

The distribution of the moisture concentration in the paper layer (interval *–d/2 ... +d/2*) follows the diffusion equation

$$\frac{\partial c_p(x,t)}{\partial t} = D(T)\frac{\partial^2}{\partial x^2}c_p(x,t). \quad (7.)$$

With the boundary conditions at *–d/2* and *+d/2*

$$c_p(-\frac{d}{2}) = c_p(-\frac{d}{2}) = f(c_O), \quad (8.)$$

where $f(c_O)$ are the equilibrium curves.
Both diffusion coefficient and boundary condition are functions of temperature and therefore also functions of time.
Simulations of moisture distribution in a transformer insulation system with the one-dimensional diffusion model are based on the assumption of an intact, enclosed system. For such a system the mass balance equation

$$m_{w,P} + m_{w,O} = \text{const}, \quad (9.)$$

where $m_{W,P}$ and $m_{W,O}$ are the mass of water in paper and oil respectively. For a non-ideally sealed system (9) has to be extended by an appropriate source term.

SYSTEM VERIFICATION

For identification and verification of the simulation model a laboratory setup was built up that has similar topology as a real power transformer unit in the field equipped with a monitoring system. The setup contains the same sensors as the unit in Fiesch (CH) which is cited in [9]. The setup was built up around a 0.4/16 kV, 630 kVA distribution transformer (Fig. 4). In order to simulate overloading conditions, load currents up to the double of the nominal current were necessary. The transformer monitoring system consists of six sensors which were installed at the transformer:

- relative water concentration in oil sensor
- tank temperature sensor
- oil temperature sensor-box
- oil temperature transformer
- load current sensor (single phase)

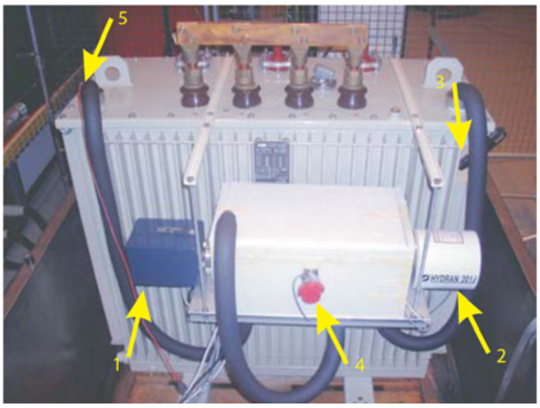

Fig. 4: Installation of the sensors at the experimental setup: 1. relative water concentration in oil sensor, 2. gas in oil sensor, 3. tank temperature sensor, 4. oil temperature sensor-box, 5. oil temperature senor, 6. load current sensor.

A Matlab/Simulink implementation of the diagnosis models evaluated sensor data recorded in a heat-run and predicts simulated values for these quantities. The resulting residuals stay into close boundaries for periods of normal operation (Fig. 5).

CONCLUSIONS

The presented diagnosis system is very valuable for units with varying load and temperature conditions, where no equilibrium condition in the moisture diffusion process is present. Short computation times imply the possibility of online operation strictly in parallel to the operation of the power transformer. This might be of interest on transformers of very high strategic importance. An alternative application would be the offline evaluation of data stored during a measurement period. During periods of unsupervised operation only the relatively inexpensive temperature and oil humidity sensors remain at the transformer. This qualifies the presented method economical for smaller transformer units, e.g. in the distribution networks.

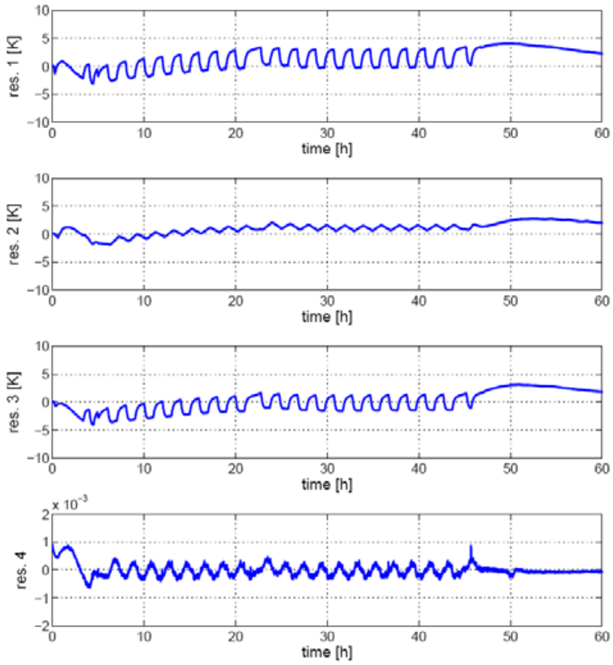

Fig. 5: Calculated residuals representing normal operation during a heat run test.

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