NEW APPROACH IN THERMAL MONITORING OF LARGE POWER TRANSFORMERS APPLIED ON A 350 MVA ODAF-COOLED UNIT

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Large power transformers belong to the most valuable and important assets in electrical power systems. The ageing of the used oil/paper-insulation primarily depends on the hot-spot temperature of the solid insulation system. Hence it is the dominant factor limiting the lifetime of the transformer. Therefore in 1996 a prototype of a stand alone thermal monitoring system was developed and installed on a 350 MVA transformer to observe the hot-spot temperature. The experiences of successfully operation during the last years encouraged us to update the system to the newest stage. The paper describes the state-of-the-art of the thermal transformer monitoring system based on new field bus technology. The advantages of a networked system and the usage of a centrally managed data base shared between multiple monitoring systems are exposed. The intention to implement new features exceeding the conventional monitoring system philosophy is discussed on an intelligent multifunction criteria Fuzzy algorithm for the control of fans of the heat exchanger units. It permits a more cost-effective long-time transformer operation management.

Key words – Power Transformer, Thermal monitoring, Hot-spot temperature, Paper/Oil-insulation ageing, Overload capability, Fuzzy controlled fan operation, Field bus technology

1 INTRODUCTION

Since large power transformers belong to the most valuable assets in electrical power networks it is suitable to pay higher attention to this operating resources. An outage impacts the stability of the network and the associated financial penalties for the power utilities can be considerably high. Nevertheless the possible damage caused to the environment in case of a burst can not be denied. The statistical data show that the windings represent a not neglectable source of transformer faults wherefore thermal stress is the most provokative factor since until now cellulose insulation is used [1]. Thermal impact leads not only to a long term oil/paper-insulation degradation it is also a limiting factor for the transformer operation [2]. Therefore the knowledge of the temperature, especially the hot-spot-temperature, is of high interest. The on-line information about the current operation condition and the calculation of current thermal stress help to avoid unexpected outages. Furthermore it allows a more efficient and profitable transformer exploitation which becomes under the competitive conditions of the liberalised energy market more and more important [3].

Thermal monitoring systems have been established due to easy temperature measurement techniques and for most applications sufficient knowledge in thermal modelling, e.g. hot-spot temperature calculation accuracy. The benefit gathered by thermal monitoring is indisputable, ranging from the instantaneous operation state up to a long-term operation strategy anyhow with high flexibility for rapid intervention if “non-normal” operation conditions will occur, e.g. for overload and emergency operation purpose. The sophisticated technology nowadays allows to combine features exceeding the conventional monitoring pilosophy, e.g. monitoring and control facilities which enables feedback between the monitoring system and other subassembly.

2 THERMAL MODELLING AND ON-LINE MONITORING

2.1 THERMAL TRANSFORMER MODEL

The determination of the temperature of the winding’s insulation hot-spot represents a very complex task. The direct measurement using fiber-optic techniques is still of no practical use. The prevalent method is by establishing a thermal model of the transformer. Due to the complexity of the heat transfer phenomena there exists no exact thermal model. A number of papers have been published proposing improvements of the thermal model from the valid IEC standard. The standard approach for hot-spot temperature calculation is through using characteristic points temperatures. Assimilable models are published in [4], [5] and [6]. The model from [5] is of special interest since it is given in the latest IEEE guide [7] as alternative temperature calculation method. A new attempt was made in [4] where a thermal model with parameters which can be in a great extend determined based on easy measurements is given. Nevertheless the most accepted model is still the model given in the IEC standard [2]. A special developed model for OD-cooled windings is presented in [8]. The hot spot temperature is calculated using the following equation [9]:

$$J_{hs} = J_a + \left(P_0 + \left(\frac{I}{I_r}\right)^2 \cdot P_{Cu,r}\right) \cdot R_{th} + H \cdot \left(\frac{I}{I_r}\right)^2 \cdot \Theta_{Cu-oil,r} \qquad (1)$$

Thereby I_r denotes the rated load current, P_0 are the no-load losses, $P_{cu,r}$ represent the load losses, H is the hot-spot factor, R_{th} is the thermal resistance and $\Theta_{Cu-oil,r}$ is the copper-oil temperature gradient under rated load condition. P_0, R_{th}, $\Theta_{Cu-oil,r}$ and H are determined by the transformer construction.

The maximal load current under which the transformer can operate for a certain ambient temperature and a maximum allowed hot-spot temperature without time limit can be calculated as follows:

$$I = I_r \cdot \sqrt{\frac{J_{hs} - J_a - P_0 \cdot R_{th}}{P_{Cu,r} \cdot R_{th} + H \cdot \Theta_{Cu-oil,r}}} \qquad (2)$$

Hereby other limiting values have to be obeyed, e.g. for the bushings or the tap-changer.

For overload purposes the maximum time allowed to operate the transformer can be calculated further as:

$$t = -R_{th} \cdot C_{th} \cdot \ln\left(1 - \frac{J_{hs,\max} - J_{hs,act}}{J_{hs,\infty} - J_{hs,act}}\right) \qquad (3)$$

The value of the maximum hot-spot temperature has to be taken in accordance to IEC 354, preferable not exceeding 140°C in order to avoid decomposition of the transformer oil usually used.

It has to be mentioned that the top oil temperature should not exceed the limit value during the above calculated time whichever has to be checked by a separate calculation for the transient top-oil temperature course. With the continuously calculated hot-spot temperature the relative thermal ageing rate can be determined using Montsinger equation:

$$V = 2^{\frac{J_{hs} - 98°C}{6K}} \qquad (4)$$

It shows that the ageing rate reduplicates with every temperature rise of 6 K. Based on this equation the total loss of lifetime can be determined and for long term operation strategy this quantity can be hold under a desired value.

2.2 COOLING SYSTEM AND FUZZY LOGIC ALGORITHM FOR FAN CONTROL

Since the cooling system is responsible for transferring the heat generated inside the active parts of the transformer to the ambient cooling medium its influence on the thermal behaviour of the entire system is obvious. The finer the cooling system capacity can be aligned to the required value the more profitable and intelligent intervention strategy can be applied. On our transformer each of the cooling unit is equipped with a fan which can operate in different modes of revolution (switched off, 360 1/min and 725 1/min). This allows a sufficient variety of different adjustable cooling capacities and thus a worthwhile application of an intelligent fan control. The control algorithm takes the following aspects into consideration:

- Constant top-oil temperature, which reduces breathing of the transformer and less moisture absorption of the transformer oil.
- Overload capability, which can be increased by pre-cooling of the transformer oil.
- Thermal ageing analysis.
- Total loss optimisation (consideration of transformer losses and losses of the heat exchangers, e.g. fans).

For the development of a suitable Fuzzy control algorithm it is necessary to establish a model of the transformer and the cooling system. Figure 1 shows the MATLAB-SIMULINK model of the total system (transformer with heat exchanger units).

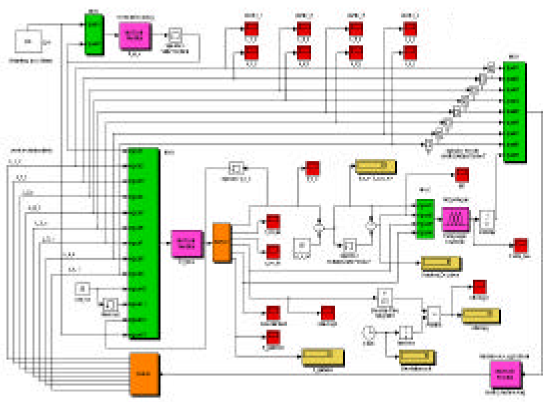

Figure 1: MATLAB-SIMULINK model to establish the fuzzy control algorithm.

As input data for the model shown in Figure 1 only the load factor, the tap changer position and the ambient temperature is required. For the simulation these values are taken from the historical data base available since 1996. The thermal model is introduced using a MATLAB function block. Within this function block most of the input parameters for the Fuzzy controller are calculated. The output quantity of the Fuzzy control block is the number of fans of a certain revolution have to be switched on or have to be switched off. The output value is determined by the Fuzzy control algorithm established with the applied Fuzzy rules and the choice of adequate membership functions. With an additional control logic block the new status of all fans is appointed.

3 CONCEPT OF THE SYSTEM

3.1 HARDWARE CONCEPT

In order to meet the main requirements of a monitoring system such as long time applicability with high reliability commercial available components are preferred [10]. Moreover a modular technology based arrangement guarantees the expandability and in case of faults a fast exchangeability of defective parts. This accounts for a minimum of maintenance costs. Another advantage of a modular design is an easy and most cost effective adaptation to the customers needs and to the technical requirements of the transformer to monitor [11]. In case of a modernisation of the thermal monitoring system the numerous existing sensor signals should be expedient for the new device also in order to save costs for new sensor equipment. Here it was not a problem because the previous applied temperature measurement technique was based on PT - 100 RTD principle which delivers standard sensor signals. This measurement technique is still the most robust and approved method in practice [12].

The above mentioned issues led to the installation of a field bus based monitoring system. Figure 2 shows the hardware system architecture. The system consists of totally 10 2-channel bus terminals for PT – 100 RTD temperature measurement in 2-wire or 3-wire connection technique. Through those bus terminals totally 20 temperatures are measured: on the transformer side 3 top-oil temperatures, on each of the four heat exchanger units the temperature of the entering and sluicing oil as well as the entering and leaving cooling medium temperatures and additionally the ambient temperature. Two further analogue input terminals are installed for the load current measurements, each determined in a single phase of the HV and the LV side of the transformer. For the acquisition of the states of oil pumps 4 digital input channels are installed. Further 8 digital input channels are used to collect the state of the four fans of the cooling units. Each of the fan can run in two different revolution modes.

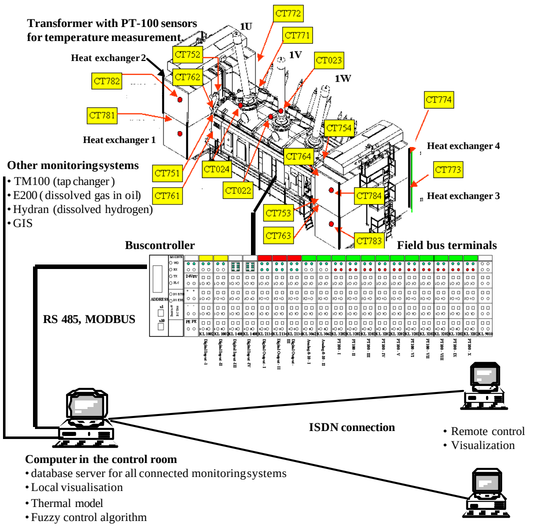

Figure 2: Transformer with sensors and field bus based. thermal monitoring system connected with the central server.

For the later implementation of the intelligent fan control without any further hardware modification anticipatory 8 digital output terminals have been installed. Later they will be used to activate the fans according to the result of the FUZZY - control algorithm result. The bus terminals are directly connected to a MODBUS bus coupler with integrated controller.

All preliminarily described components are placed in a enclosure near the transformer as shown in Figure 3.

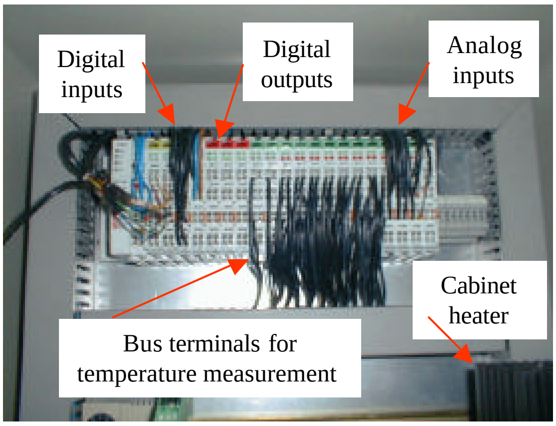

Figure 3: Field bus terminals and bus controller installed in a enclosure nearby the transformer.

To prevent the hardware from extreme climatic conditions the enclosure is equipped with a heating and a fan inside. The data acquisition system is connected with a computer via a standard serial RS 485 interface connection using MODBUS protocol.

The computer is one of the most delicate hardware component in the system. Therefore it is located in the control room in order to avoid the tough operating conditions nearby the transformer. Data processing and archiving are the main duties. Local visualisation of the data is possible but deteriorate due to the remote accessibility through a fast ISDN connection. This makes possible to administrate the system, visualise the data and to download the entire data base or only desired parts of it from any far control centre. This feature is very important since most of the substations nowadays operate without local staff.

To protect the computer from power supply breakdowns an uninterruptible power system (UPS) is installed. This guarantees that in case of a power outage after a certain time the computer is shut down regularly. Thus a damage of the database is almost impossible.

3.2 SOFTWARE CONCEPT

The basic requirement for a monitoring software is the ability to work under all popular operating systems, nowadays preferably Microsoft Windows. The flexibility concerning expanding with additional monitoring systems is fundamental. Data archiving and data visualisation is taken for granted. To meet these requirements the used software is divided into two main parts. The first part includes the main configuration facility and is also responsible for reading the data from the data acquisition units (for example the field bus coupler) and filing them in a common database. Other monitoring systems can be attached easily since several standard interface modules are provided. Other software modules and applications have access to the data base through API, ODBC and SQL standards so that full data transparency is achieved. Additional features are the possibility of defining virtual channels and introducing supplementary sub-programs for additional calculation purposes, e.g. for hot-spot temperature calculation. As a matter of course remote connectivity via accustomed modem or ISDN is supported.

The other part of the software provides multifarious options for on-line or historical data visualisation. Beneath multiple pre-defined visualisation settings also user defined presentations can be introduced and data exportation, for example into ASCII format, is offered. The visualisation can be done on the local machine (server) and on clients accessing the server by remote. From time to time backups from the data base have to be made so as to assure that no data loss happens at least over the service time of the transformer concerned. Beyond this the historical data are of use for other comparable transformers not having available historical monitoring data, that means experience in long term transformer operation can be gained and applied on other similar transformers.

4 EXPERIENCES WITH THE SYSTEM

The years of operation have shown that the thermal monitoring system mounted in 1996 was the most reliable system under all of the installed systems on the 350 MVA transformer. Within six years of service only a few failures occurred. Most of them because of power supply breakdowns in the substation due to monthly performed tests of the emergency power supply system leading to a computer crash or a software hang-up. Only a small number of failures appeared due to hardware problems or a software hang up. So it was possible to get a data archive of almost the entire time of operation since 1996.

The collected monitoring data have shown that the load factor for this transformer is quite low. During the summer months an average value of the load factor of approximately $k = 32$ % can be denoted. Whereas in the winter months the load factor is increased and averages $k = 56$%. Some peak values of $k = 75$ % appeared for a maximum duration of less than 12 hours. These values show that the transformer is loaded far below its nameplate load. It is clear that the hot-spot temperature is also low. For example the hot-spot temperature was about 82 °C for a load factor of 75 % and an ambient temperature of 21 °C, as well far away from the nominal temperature of 98 °C which is used for ageing calculations as previously shown in equation (4). It can be concluded that in this case from the thermal point of view the transformer ageing is not a serious problem.

Now the new installed field bus system works since December 2003. The practical experience has shown that using a field bus system reduces the wiring and thus the installation effort in a great extend. The system upgrade process is still not finished yet. The next steps will be building up the local and the remote visualisation feature and further the implementation of the intelligent fan control algorithm.

5 CONCLUSIONS

It was shown that due to the increased exploitation of power transformers in consequence of the liberalised energy market thermal on-line monitoring became very popular during the last years. The high amount of transformers operating near the predicted end of lifetime speeds up this tendency. Based on former experiences with the existing thermal monitoring system the presented concept was designed and installed on a 350 MVA transformer in service. The use of field bus technology showed that the wiring effort has been reduced considerably. This holds for a retrofitting on existing transformers. The availability of a huge number of input and output bus terminals has shown in practice that new applications can be realised easily without disturbing the integrity of the system by introducing separate hardware modules. Standardised interfaces allow unproblematic connection to the monitoring server. Sophisticated software techniques provide high flexibility concerning data processing, archiving, visualisation and user defined extensions. A modern central database system allows to collect important monitoring data from several systems installed. This issue simplifies the correlation process of data attained by different monitoring systems. The essential knowledge for a reliable operation of the transformer is achieved by using thermal transformer models. One task is to calculate the hot-spot temperature continuously. The overload capability of the transformer in every minute can also be determined. Enhanced models and the usage of Fuzzy logic technique allow to define operation strategies for an efficient assessment. It enables to realise intelligent multifunction criteria algorithms for control purposes. Faults in the heat exchanger units can be detected by comparing calculated and measured values.

The system proposed gives a trend-setting concept for a state-of-the-art monitoring system. The major benefit is the easy expandability in almost all hardware and software parts.

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