Benefit of sensors for on-line monitoring systems for power transformers

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Power Transformer,
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Internet

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SYNOPSIS - To increase availability and to achieve optimised operating management on-line condition monitoring for power transformers is useful and necessary. Based on the experiences with a considerable amount of systems in operation a generally applicable set-up of sensors is proposed. Furthermore the way of data acquisition, analysis and distribution by using a modern monitoring system connected to the internet is described.
By means of mathematical models the acquired measured data are converted to useful information for a reliable condition diagnosis. The evaluation of data acquired on-site shows the capability to detect problems within active part, bushings, on-load tap changer and cooling unit before they develop into major failures. Especially algorithms for the calculation of overload capacity are of increasing importance.

1 INTRODUCTION

Transformer outages have a considerable economic impact on the operation of an electrical network. Therefore it is the aim to ensure an accurate assessment of the transformer condition. Techniques that allow diagnosing the integrity through non-intrusive tests can be used to optimise the maintenance effort and to ensure maximum availability and reliability. With the increasing average age of the transformer population there is an increasing need to know the internal condition. For this purpose on- and off-line methods and systems have been developed in recent years. On-line monitoring can be used continuously during the operation of transformers and offers in that way a possibility to record different relevant stresses which can affect the lifetime. The automatic evaluation of these data allows the early detection of an oncoming fault. In order to enable a consistent utilisation of the technically possible load capacity of the transformer, statements regarding the current overload capacity, for example, can be made.

2 DESCRIPTION OF MONITORING SYSTEM

2.1 Sensor Set-up

A multitude of different measurable variables can be collected for on-line monitoring /1/. However, it is very rarely useful to use the entire spectrum. Therefore, sensor technology must be adjusted to the specific requirements of a particular transformer or transformer bank, depending on their age and condition. From the experience of more than 150 monitoring systems the following general set-up of sensors for example is proposed for the use at a 400 kV power transformer:

(1) PT100 for measurement of top oil temperature
(2) PT100 for measurement of ambient temperature
(3) C.T. for measurement of load current (single phase)
(4) Measurement of voltage at measurement tap of bushing (three phase)
(5) Measurement of oil pressure of bushing
(6) Sensor for measurement of oil humidity
(7) Sensor for measurement of gas-in-oil content
(8) Tap changer position
(9) Power consumption of motor drive
(10) Digital inputs for switching status of fans and pumps

2.2 Architecture

With the Alstom monitoring system MS 2000 the outputs of the above mentioned sensors are wired onto field bus terminals in the monitoring module installed at the transformer. Within these data acquisition units the analogue signals are digitised and send via a field bus to the monitoring server. By means of this industrial proven technology it is possible to monitor all transformers in one substation with a single system which is extremely cost effective. The erection of the server in an operating building offers the advantage that the ambient conditions (e.g. temperature, vibrations) are much more suitable for a PC. The connection to the protection and control system can be done either by dry relay contacts or a digital protocol according to IEC 60870-5-101 /1,2/.

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2.3 Distribution and visualisation of monitoring data

In order to prevent outages and save maintenance expenditures on-line monitoring systems are installed at the main equipment of the substation (power transformers, circuit breaker, disconnectors). The access to the monitoring data should be done by means of a standardised platform which is the Internet Explorer. This prevents that on each desktop PC individual software has to be installed.

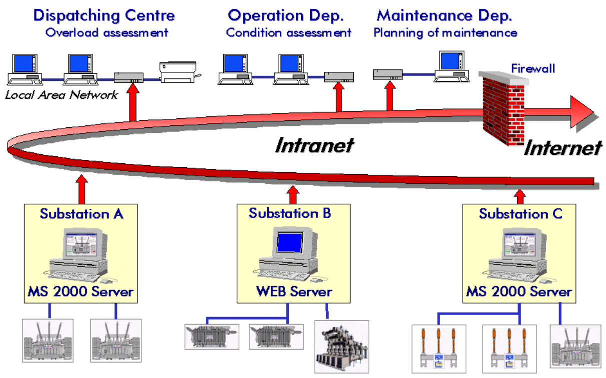

Fig. 1: Data access by use of the Internet

The user expects from a monitoring system an easy and safe access to all necessary information about the installed electrical equipment. This means not only power transformers, also GIS, circuit breakers, disconnectors are of fundamental importance /3/. The dispatching centre should be informed about loading capacity (overload calculation). The operation and maintenance department should perform condition assessment and plan maintenance procedures exactly (Fig. 1).

This wide distribution of information can be done by a web-based solution. An additional module installed on the monitoring server allows to generate HTML-based web pages, which show both on-line and historical data (Fig. 2). If the monitoring server is connected to the local area network (Intranet) of the utility, all departments will receive the necessary information. Therefore the number of users directly connected to the monitoring server is practically unlimited. Password protection gives only specific users the right of data access. By use of a firewall it is also possible to have access to the complete substation by use of the Internet.

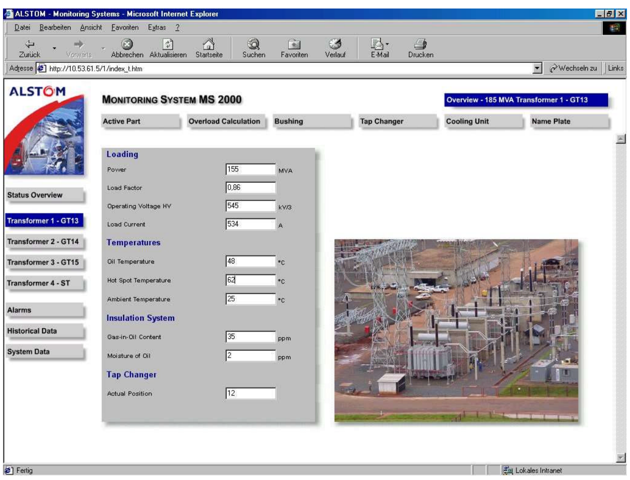

Fig. 2: Web-based visualisation of transformer condition

3 PRACTICAL EXPERIENCE

The begin of on-line monitoring was characterised by the use of some individual sensors which were dedicated to monitor only a small part of the power transformer. For example a hydrogen sensor is used to detect problems within the active part such as partial discharges or hot spots. The philosophy of concentration on a specific part of the transformer was forced by the individual experience of specific failures within an utility. This means if a utility experienced problems with bushings, the main efforts were related to the diagnostic of bushings.

But the analysis of reasons for failures of a larger population of transformers than these of a single utility showed that majors failures occur in all parts of the transformer /16/. So the wish of having a comprehensive system which not only monitors the active part but also other important and failure reluctant components such as on-load tap changer and bushings is understandable. During the last years the monitoring system MS 2000 was installed world-wide at power transformers of all major manufacturers. In the beginning utilities started to test the system with grid-coupling transformers of minor importance. Due to the good experience it is now operating at such strategical important points as nuclear power stations, pumped storage power stations, coal power stations and aluminia industry. Most of these installations were retrofitted on-site at already aged transformers. Normally the installation of sensors requires no welding at the transformer and takes about two days. The transformer has to be taken out of operation only for half a day to install the voltage sensors and the tap changer monitoring module.

3.1 Active Part

For early failure detection, the monitoring of the active part is of particular importance. It is fundamental to measure the electrical variables **load current** and **operating voltage** directly at the transformer. A bushing-type current transformers is used for load current measurement. The load current and top oil temperature are the starting variables for calculation of **hot-spot temperature** according to IEC 60354 and ageing rate of active part insulation /5/. This enables the evaluation not only of information regarding **lifetime consumption** but also of the temporary **overload capacity** of the transformer /4/.

For the assessment of the mechanical condition of the windings the knowledge of number and amplitude of **short circuit currents** is of tremendous importance. These are detected and evaluated by using a high sampling rate for the load current signal.

3.1.1 Gas-in-oil amount

For the gas-in-oil detection a **Hydran sensor** is used which reads a composite value of gases in ppm (H_2 (100%), CO (18%), C_2H_2 (8%), C_2H_4 (1,5%)). As hydrogen is a key gas for problems in the active part, an increase in the output signal of the sensor is an indication for irregularities such as partial discharge or hot spots /6/. The evaluation of this measuring signal, together with the dependency on the temperature of the oil and the load current, provides a reliable basis for the continuous operation of the transformer. In the event of an increase of gas-in-oil content, an immediate reaction can be effected via an off-line dissolved gas analysis (DGA) to determine the concentration of the other components dissolved in the oil in order to clarify the cause of the potential damage.

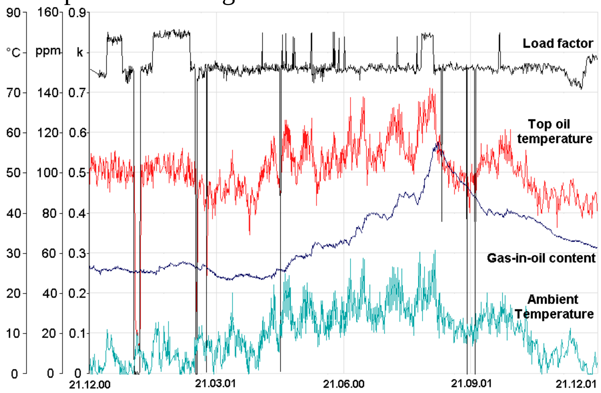

Fig. 3: Gas-in-oil amount dependent on load and top oil temperature of a 80 MVA grid transformer

In Fig. 3 the gas-in-oil amount of a 80 MVA grid coupling transformer for an aluminia plant is shown for the time interval of one year. The monitoring system detected an increase of gas-in-oil content. The reason was assumed to be the temperature increase during summer. A DGA performed in August revealed a CO content of 427 ppm of CO and 27 ppm of H2 which is in accordance with the output of the Hydran sensor (108 ppm). So the reason for the increased gas-in-oil content was the increased value of CO, which was generated because of the normal increase of oil temperature. Thus for exact interpretation of the Hydran signal the knowledge of load and temperature is needed.

3.1.2 Oil humidity

A capacitive thin film sensor is used for the detection of **moisture in oil**. There are several causes for an increase of water-in-oil content. After improper shipping and erection of the transformer on-site the oil can be contaminated with water. Breathing of the transformer can cause absorption of moisture by the oil in the conservator. Due to the fact that water is a result and also an origin of paper degradation the water-in-oil content is an important indicator for the condition of winding insulation. It is reported that 4 % water content in paper for example increases the ageing rate by a factor of about 20 /7/. So measurement of oil humidity is recommended in particular for transformers which are already aged or operate usually at high oil temperatures, because accurate calculation of ageing rate requires the input of moisture content. Up to now the transformers equipped with a sensor for oil humidity are uncritical regarding moisture in oil. So practical experience in detecting moisture problems on-line is limited, but nevertheless the sensors are needed for accurate calculation of ageing rate.

As the transformer warms up, moisture migrates from the paper into the oil. From this so called equilibrium of moisture in oil and paper also the water content in the paper can be calculated by the monitoring system /8, 9/. This value is needed for the calculation of the emergency overload time. Moisture in paper restricts the loading capacity because of the risk of bubble emission. Also the release of water drops from winding paper to oil can occur. So the acceptable limit for the hot spot temperature is dependent on the water content in the paper /10/.

3.2 Bushings

3.2.1 Detection of overvoltages

The voltage applied to the transformer is acquired at the measuring tap of the capacitor bushing by means of a voltage sensor. It acts with the capacity of the bushing as a voltage divider. This enables not only the measurement of the operational voltage but also the detection of overvoltages, because due to its design the voltage sensor has a bandwidth up to some MHz. The output of the voltage sensor is connected to a peak sampler to detect the amplitude of overvoltages by the monitoring system. **Overvoltages** represent an essential risk potential for the insulation of transformer windings. Taking into account the volume of noxious gases which are dissolved in oil deductions can be drawn about the possible damage to the insulation of the active part after the occurrence of overvoltages.

3.2.2 Change of capacitance

Failure of condenser bushings occurs often because of partial flashover of the metallic foils which are used for controlling the electrical field within the bushing. Such partial flashovers do not lead to a sudden failure of the bushing, but they are growing from layer to layer until the voltage stress of the remaining layers is so high that complete breakdown occurs. If a partial flashover of one layer occurs, the capacitance of the bushing will be increased according to table 1 by ΔC.

Voltage [kV]	Number of foils	DC
123	28	3.6 %
245	42	2.4 %
400	60	1.7 %
550	70	1.4 %

Tab. 1: ΔC for partial flashover of one layer for oil-impregnated bushings /9/

The change of the capacitance ΔC of the bushings can be detected by the monitoring system by comparing the output of one voltage sensor with the average value of the other two phases. The result is processed by averaging algorithms to eliminate imbalances of the grid voltage and variations due to temperature changes. This is assumed to be possible, because the deterioration process normally has a considerable longer time constant. This triggers an alarm and a warning

In Fig. 4 the change of capacitance of a 400 kV grid coupling transformer is shown for a time interval of two

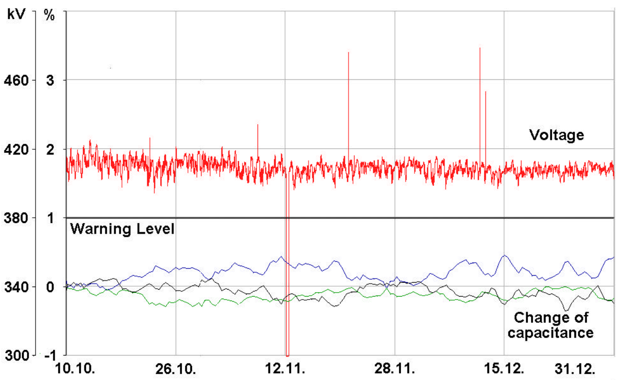

Fig: 4: Voltage and change of capacitance of 400 kV bushings

month. It can be seen that variations due to unbalanced voltages and temperature variations is in the range of 0.4 %. The signal to noise ratio is therefore sufficient to assess the insulation condition reliably. At a warning level of 1 % the monitoring system triggers a message for inspection of the bushing.

3.3 On-load Tap Changer

An important component of a power transformer and also a frequent reason for severe failures is the on-load tap changer /13/. Therefore the monitoring of this highly stressed element is a necessity.

3.3.1 Tap changer position

Recordings of the **tap changer position** and the operating current help to determine the **number of tap switching operations** and the **total switched current**. As the contact wear of the diverter switch contacts is a function of the switched load current this information is needed for performing a condition based maintenance for the diverter switch /14/. If an excessive wear situation is undetected, the contacts may burn open or weld together. To avoid these problems limiting values for the time in service, number of operations and total switched load current, can be pre-set in accordance with the maintenance instructions of the OLTC manufacturer.

3.3.2 Assessment of mechanical condition

OLTC failures are often dominated by mechanical faults in nature. Such defects can be for example broken linkage, failure of springs, binding of contacts, worn gears and problems with the drive mechanism /15/. Mechanical and control problems can be detected by measurement of the power consumption of the OLTC drive, because additional friction, extended changer operation times and other abnormalities have a significant influence on the drive current. An event record of the power consumption is captured during each tap changing process and analysed by evaluation of 6 characteristic parameters which are:

1. Time of inrush current:
The inrush current flows during a period of about 300 ms. It is related to the static friction and backlash in the linkages.

2. Total switching time:
Variation of time required for a tap changing process indicates problems with the control of the OLTC.

3. Power consumption index:
The energy consumed by the motor drive during a tap changing process divided by the total switching time is represented as the power consumption index. This value is dependent on the operation temperature and characterises the average running conditions.

4. Maximum sector 1 (S1):
During the motion of the selector contacts, the amplitude of the power consumption is monitored. This value represents the maximum during opening and moving of the selector contacts.

5. Maximum sector 2 (S2):
This value is the maximum during the closing of the selector contacts.

6. Maximum Sector 3 (S3):
The amplitude of the power consumption is recorded during diverter switch action.

These six parameters characterise each tap changing process and in case of deviations warning messages are generated. In Fig. 5 such a situation is presented for three successive tap changing processes recorded during maintenance of the OLTC. The first two signatures (A, B) show a regular tap changing process. The peaks on the curves are caused by the friction of opening, revolution and closing of selector switch /2/. Because tap changing process C differed significantly from a normal tap changing, the parameters for total switching time, maximum sector 2 and 3 and power consumption index showed abnormal variations. Based on this the monitoring system sent an alarm message to the responsible engineer.

The root cause analysis revealed that during the tap changing process C the handcrank was inserted into the drive mechanism which interrupted the process and therefore triggered the warning message. So this problem was caused by incorrect operation and not an internal problem, but this event illustrates the capabilities as an early warning system for mechanical anomalies.

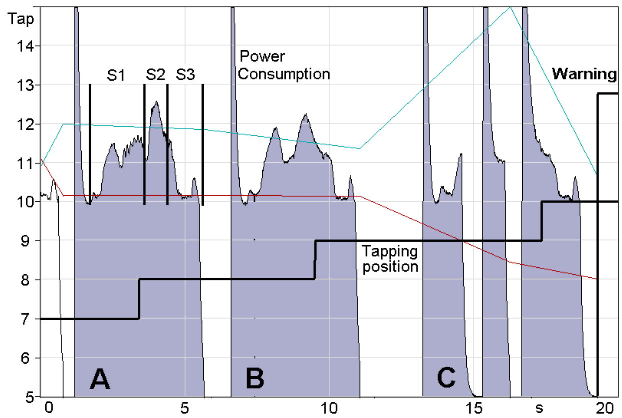

Fig. 5: Faulty tap changing process

3.4 Cooling Unit

3.4.1 Thermal resistance

The thermal resistance R_{th} describes the efficiency of the cooling unit. For air-cooled power transformers the actual thermal resistance can be calculated by the following equation:

$$R_{th,act} = \frac{J_{oil} - J_{air}}{P_0 + P_{k,n} \cdot k^2}$$

The result has to be averaged to eliminate variations due to the dynamic behaviour of load factor oil and ambient temperature. Furthermore the number of fans and pumps in operation has to be taken into account to calculate the nominal thermal resistance R_{th}.

On-line monitoring of the cooling unit of a 420kV / 600MVA grid-coupling transformer by calculation of the nominal thermal resistance Rth showed a strong increase after switching on of two additional fans which was signalled by the control system (Fig. 6). This increase triggered a warning message by the monitoring system. A local check in the substation revealed that due to a failure of energy supply only half of the cooling unit (3 fans) was in operation and therefore only three fans were running. This status was not in accordance with the information of the control system and led to the strong increase of nominal thermal resistance. With the present load and half of the cooling power the transformer could be kept in service. But it would not be possible to operate the transformer with nominal load due to the missing cooling power. This scenario shows the importance of detecting also minor failures to avoid the risk of not delivering energy

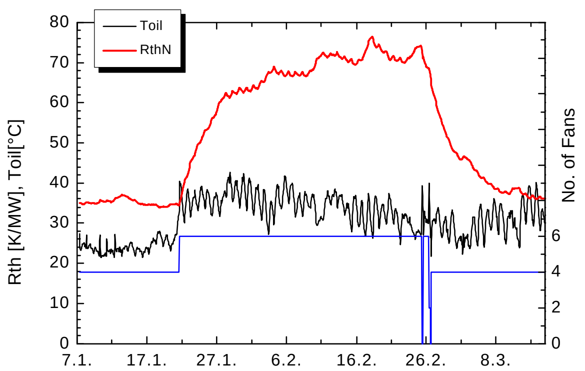

Fig 6: Abnormal condition of cooling unit detected by increase of thermal resistance Rth

4 CONCLUSION

The justification for on-line monitoring of power transformers is driven by the need of the electrical utilities to reduce operating costs and enhance the availability and reliability of their equipment. The evaluation of data acquired by an on-line monitoring system shows the capability to detect oncoming failures within active part, bushings, on-load tap changer and cooling unit. Using the benefits of modern IT-technology the distribution of information about the condition of the equipment can easily be done by means of standardised web browser technology.

When considering the installation of on-line monitoring systems size, importance and condition of a power transformer have to be analysed. Especially for aged transformers and in general at strategic locations in the electrical network on-line monitoring is necessary and valuable, because by the prevention of major failures costs for outages, repair, and associated collateral damages can be saved.

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