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Experienced-based Evaluation of Economic Benefits of On-line Monitoring Systems for Power Transformers

by

S. Tenbohlen*, T. Stirl
ALSTOM Schorch Transformatoren GmbH
(Germany)

G. Bastos
FURNAS
(Brazil)

J. Baldauf, P. Mayer
ALSTOM ELEC
(Brazil)

M. Stach, B. Breitenbauch
E.ON Energie AG
(Germany)

R. Huber
EnBW Regional AG
(Germany)

Abstract - 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.

Dependent on size, importance and condition of a power transformer the savings achievable by an on-line monitoring system are analysed. These savings can be divided into strategic and direct benefits.

Keywords: On-line Monitoring, Power Transformer, Internet, Condition Assessment, Overload Calculation, Economic Benefits

1 INTRODUCTION

The deregulation of the Brazilian electric system led the Brazilian utilities, private or public, to adapt themselves to reality. All the new electrical installations, such as substations or overhead lines, are bid by ANEEL, the national regulating agency of the Brazilian system. In this way the electrical market became very competitive. Legislation created by the agency foresees heavy penalties for unavailability of electrical equipment. In the last biddings for concession of transmission facilities done by ANEEL, penalties corresponding to 10 times the revenues are foreseen for scheduled outages and of 150 times the revenue for the first 5 hours of a non scheduled outage, and 10 times the revenue for the subsequent hours. These heavy fines forced the utilities to review their processes to reduce the number of scheduled outages and, more than that, to decrease the number of non-scheduled outages. In order to adapt to the new demands and to become competitive, Furnas took some measures with the objective to reduce outage time. Among the measures taken is the installation of intelligent systems capable to monitor power transformers on-line.

The German utilities are facing deregulation since several years. Beside availability and reliability now additional requirements have to be met. Cost reduction led to a cutback of new investments. Because of the increasing age of the transformer population, the question of remaining lifetime has to be answered now. For this purpose on- and off-line technologies have been developed to use power transformers in the optimum technical and economical manner and to give directives for the extension of lifetime (life management).

On-line monitoring systems are used continuously during the operation of transformers and offer 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 oncoming failures and performing conditioned based maintenance. In order to enable a consistent utilisation of the technically possible load capacity of the transformer, statements regarding the current overload capacity can be made.

2 DESCRIPTION OF MONITORING SYSTEM

In order to prevent outages and save maintenance expenditures Furnas decided to install on-line monitoring systems not only in transformers but also circuit breaker and disconnectors. The system designed is detailed below.

* Rheinstr.73, D-41065 Mönchengladbach, Stefan.Tenbohlen@tde.alstom.com

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 100 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*

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/.

2.3 *Distribution and visualisation of monitoring data*

According Furnas requirements the monitoring data should be accessed by remote PC located at the main offices by means of a standardised platform which is the Internet Explorer. This prevents that on each desktop PC individual software has to be installed. Internet technology alone provides the underlying foundation for web-based visualisation. Browsers and other tools for displaying HTML documents are standard equipment for free on every computer. HTML is widely recognised industry standard and is globally proven performer in flexibility and reliability. Regarding these facts a web server based on the monitoring system MS 2000 was developed. The user expects from a monitoring system an easy and safe access to all necessary information about the installed electrical equipment. . The operation and maintenance department should perform condition assessment and plan maintenance procedures exactly (Fig. 1). Allowing to follow the transformer operation remotely is of particular importance in case of non assisted substations. Another possibility is to supply operators with information about loading capacity that could allow them to decide overload criteria.

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). As 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.

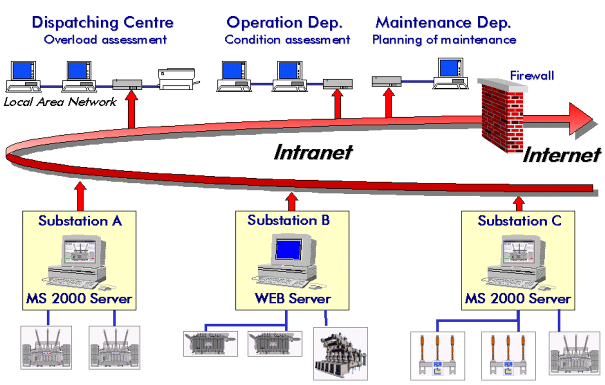

Fig. 1: Data access by use of the Internet

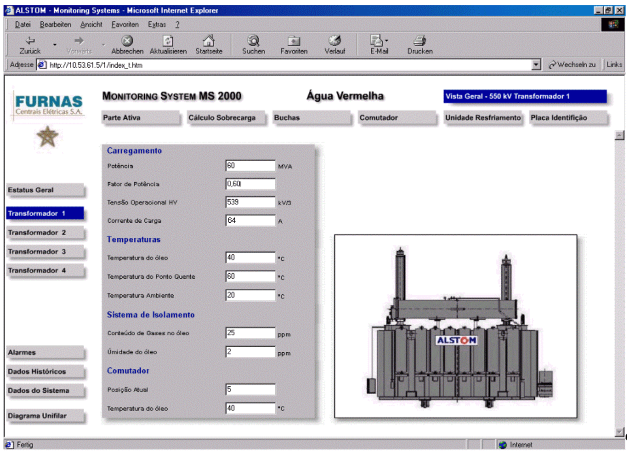

Fig. 2: Web-based visualisation of transformer condition

3 PRACTICAL EXPERIENCE

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.

Operating data recorded by monitoring systems show the capability for an optimisation of the operation and maintenance of power transformers /1,2,4/. Here, an attempt is made to document the possibilities to detect problems and avoid failures depending on the monitored part of the transformer.

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 analysis of 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.

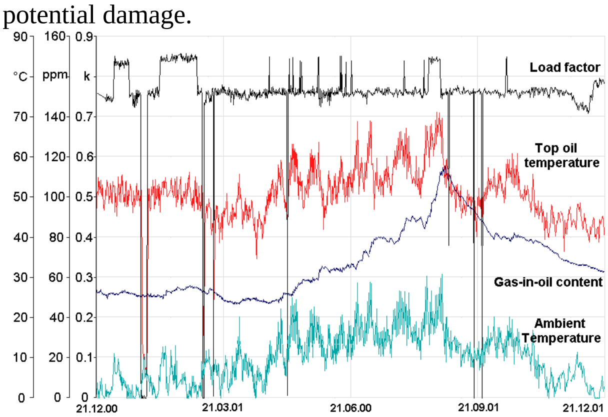

Fig. 3: Gas-in-oil amount dependent on load and top oil temperature of a 80 MVA grid transformer

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. for example, improper shipping and erection of the transformer on-site or absorption of moisture by conservator oil breathing . 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 online 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 capacitance 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 measuring error of the sensor is less than 3% determined by comparing with the output of a calibrated high voltage divider in the test field. 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 dam-

age to the insulation of the active part after the occurrence of overvoltages.
An additional module allows surveillance of the three phase voltage signal with a sample rate of 1 MSa/s. Using different trigger conditions the system detects transient events and stores simultaneously the data from all channels. In Fig. 4 the voltage of all three phases and the neutral of a 400 kV generator step up transformer is shown after a single pole earth fault due to lightning flashover at a distance of 61 km. This short circuit on Phase L1 was interrupted by the circuit breaker after 95 ms. The very steep front at the beginning can cause resonances within the winding. This information is especially important for transformers connected to GIS or HVDC switchgear. As the amplitude and form of overvoltages are often unknown equipment failure may occur which could have been avoided by well-aimed preventive measures. Also this information is very valuable in case of performing a root case analysis (RCA) after a failure.

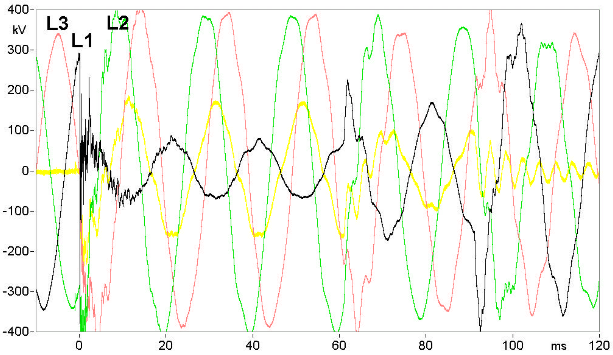

Fig. 4: Single pole earth fault on Phase L1 of a 400 KV generator transformer

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

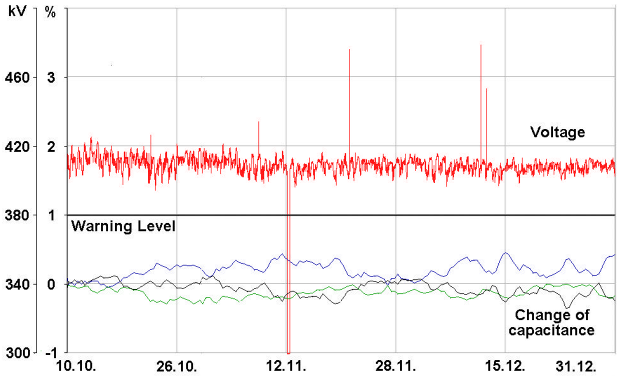

Fig: 5: Voltage and change of capacitance of 400 kV bushings

By measurement of the phase angle between the three phases also the detection of a variation of the power loss factor (tan δ) could be possible, but because of the very small change of this value and the uncertainties due to unbalanced voltages this is up to now a more or less theoretical approach and not proven technology.

3.2.3 Pressure in oil-immersed bushing

A decrease of oil pressure in oil-immersed bushings can lead to a breakdown of the internal insulation. This can be prevented by measurement of the pressure /11/. Because oil pressure is dependent on the temperature, the pressure of each phase is compared with the other two phases to eliminate this influence. If there is a leakage at bushings with gas filling as secondary insulation, the normal internal overpressure will decrease and thus generates a warning by the monitoring system.

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 /12/. 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. 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 /13/. 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. 6 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/.

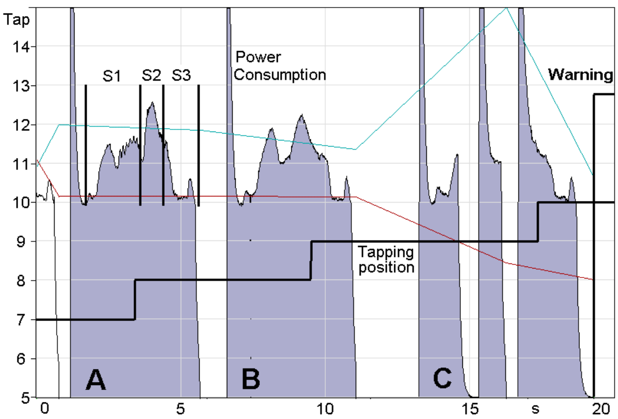

Fig. 6: Faulty tap changing process

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.

3.4 Cooling Unit

The thermal resistance R_{th} describes the efficiency of the cooling unit. For air-cooled power transformers the actual thermal resistance $R_{th,act}$ can be calculated by dividing oil temperature rise and actual losses P:

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

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}.

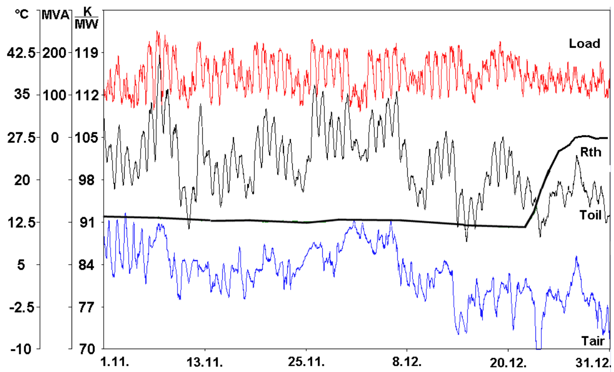

Fig 7: Calculation of nominal thermal resistance R_{th} of cooling unit

Fig. 7 demonstrates the change of thermal resistance after the failure of one out of six fans. Although the pump related to the failed cooler was kept in operation the nominal thermal resistance increased by about 18 %. Because failure of one fan does not lead directly to excessive oil temperature, this problem would not be detected without monitoring. The same applies to pollution of the coolers. So monitoring offers the advantage to perform in these cases a condition-based maintenance.

4 OVERLOAD CALCULATION

Overloading can become necessary in open electricity markets due to economic reasons or simply to ensure continuous energy supply. During an overload cycle accelerated ageing and damages have to be strictly avoided. By measurement of environmental and loading conditions the monitoring system delivers continuously

information on the maximum continuous and possible short time overload considering the actual preload of the transformer and the ambient temperature according to IEC 60354 /4, 5/. Based on a two-body equivalent circuit thermal modelling is performed and the continuous overload capacity is determined by the monitoring system. The loss of life due to this type of overloading can be prevented, if the transformer is overloaded during ambient temperature below rated conditions. Phases with high load and high ageing rate must be compensated in the long term by periods of low load with slow ageing rate. This long-term monitoring of ageing rate is also implemented in the system and gives a warning in case of excessive ageing or other problems in case of overloading. So on-line monitoring is highly recommended during this critical state of operation.
In Fig. 8 the results of thermal modelling and overload calculation are presented for an OD-cooled single phase 333 MVA auto-transformer. For top oil temperature calculated and measured values are shown. Although the oil temperature varies strongly because of load variations the deviation between measured and calculated value does not exceed 2 K and proves thereby the accuracy of the thermal model. Even in summer for this transformer a maximum continuous overload capacity of 1.3 is possible.

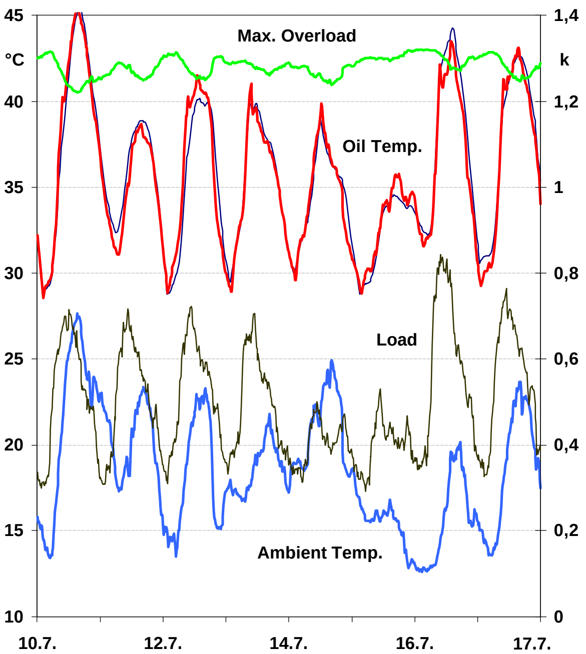

Fig 8: Top oil temperature and max. overload capacity dependent on ambient temperature

5 CONTROL OF COOLING UNIT

An intelligent control of the cooling unit by the monitoring system allows to increase the overload capacity and optimize the hot-spot temperature. Depending on ambient temperature, a specific number of fans will be switched on to dissipate the current losses. Due to this individual switching of fans controlling occurs with lower temperature variations than with conventional controlling by a fixed temperature threshold. Measurements show a reduced variation of oil level within the conservator. Subsequently the breathing of the transformer and consequently water within the conservator is reduced. Furthermore the intelligent control of cooling unit provides the opportunity for a significant reduction of noise emission of the fans.

6 ECONOMIC BENEFITS OF MONITORING

A cost/benefit analysis for a monitoring system requires hypothesis of many individual parameters which are difficult to assess. For a general approach not all of these items can be calculated exactly. In any case the prevention of major failures can be counted. The other savings have to be taken into account dependent on the specific situation.

6.1 Prevention of failures and downtimes

This part covers the cost benefits achieved by the avoidance of failures and downtimes of the transformer itself. These so-called **strategic benefits** are based on the ability to prevent major failures. Also avoidance of collateral damages mentioned in the next chapter is part of strategic benefits. The failure rate (f = 1.63%) of power transformers with a nominal voltage higher than 200 kV is taken from the failure statistic of german utilities of 1998 /14/.

HV-Voltage [kV]	Number of units	f
123	3,674	0.35 %
245	419	1.19 %
400	258	2.33 %
∅ 245 + 400	677	1,63 %

Tab. 2: Failure rate of power transformers in Germany (west) 1998 /14/

The failure risk (r_n) of each component of the transformer are according to the Cigre survey on failures of large power transformers in service /12/.
To calculate the decrease of failure rate by on-line monitoring the detection rate of major failures must be taken into account. This value is difficult to assess, because only monitoring of a considerable population for several years can give a reliable result. So at the moment only assumptions based on the actual experience can be made. According to /15/ this value is given with 71%. Here an attempt is made to estimate the detection rate of a comprehensive monitoring system for each component of the transformer. It has to be considered that without monitoring many failures seem to be instantaneous. But a close supervision would reveal a slow development into a major failure.
Because of the continuous supervision of fault gas generation, accelerated ageing due to moisture in oil or abnormal heating due to malfunction of cooling unit, it seems to be realistic to assume a detection rate of major failures in the active part (d_{AP}) of 70 %. The evaluation of internal oil pressure and the detection of early insulation deterioration leads to the assumption that the rate of detectable failures due to oil-immersed bushings (d_{Bu}) is about 80 %. Due to the extensive supervision of mechanical and electrical condition, the detection rate of failures in the OLTC (d_{TC}) is estimated to be about 75%.

The thermal model implemented in the monitoring system gives a warning in case of problems with the cooling unit (e.g. failure of fans and pumps, pollution of coolers, closed valves). This could lead to a failure detection in the cooling unit (d_{Co}) of almost 100%.

Component	**r_n /12/**	**d_n**
Winding + Core	35%	70%
OLTC	40%	75%
Bushing	14%	80%
Tank	6%	n.a.
Auxiliary	5%	100%

Tab. 3: Reasons for outages with downtimes > 1 day and detection rate by comprehensive on-line monitoring

The total probability of detecting oncoming faults by a comprehensive monitoring system can be calculated by multiplying failure rate, risk of each part (r_n) and detection rate of each part (d_n):

$$p_{tot} = f \cdot (r_n \cdot d_n)$$
$$= 1.63\%/y \cdot (35\% \cdot 70\% + 40\% \cdot 75\% + 14\% \cdot 80\% + 5\% \cdot 100\%) \approx 1.63\%/y \cdot 71\% \approx \mathbf{1.15\%/y}$$

So on-line monitoring can reduce the failure by 1.15 %/y to a value of 0.48 %/y.

To calculate the savings achieved by failure prevention this probability must be multiplied with the cost for a failure. The costs of such a failure (partly rewinding) is assumed to be half of the price of a new transformer (P_T). The yearly savings can therefore be estimated as:

$$S = p_{tot} \cdot \text{Failure costs}$$
$$= 1.15\% \cdot 0.5 \cdot P_T \text{ /year} = \mathbf{0.58\ \%\ P_T\ /year}$$

Dependent on the age and condition of the transformer the assumed failure rate of 1.54% can be higher which will increase the savings.

Taking into account only the savings achieved by prevention of major failures (p_{tot}) a **cost-benefit analysis** for a monitoring system can be performed. Based on the assumptions that the useful lifetime of the monitoring system is expected to be 10 years the **savings** are:

$$S_{10y} = p_{tot} \cdot \text{Failure costs} \cdot 10y = 5.8\ \% \cdot P_T$$

So within ten years 5.8% of the price of a new transformer can be saved. This statement is independent of the strategical importance of the transformer. Considering avoidance of collateral damages and savings due to condition-based maintenance which are also valid for the complete transformer population the financial benefits are increasingly positive.

The evaluation of **costs** for the installation of a comprehensive monitoring system shows that the percentage of the value of the monitored transformer is in the range of 1 to 7.4%. The lowest value is achieved for an installation in a power station where several G.S.U. transformers are monitored by one system. The highest value (7.4%) apply to an installation for three 40 MVA units. It has to be considered that the costs are strongly dependent on the sensor set-up and expenditures for special functionalities.

For all projects the savings exceed the costs, although only the strategic benefits of preventing damages to the transformer were taken into account. Considering collateral damages (e.g. penalties for non-supplied energy) and direct benefits the available budget for monitoring will be higher.

6.2 Avoidance of collateral damages

Collateral damages of a transformer failure can be caused due to several reasons:

* Direct damages caused by a major failure (e.g. additional destruction of equipment or injuries of people),
* Indirect damages caused by loss of energy (e.g. destruction due to stop of processes in chemical plants),
* Loss of production capacity of a power station.
* Penalties due to not delivered electrical energy.

A general applicable calculation of these collateral damages cannot be performed, because this value is of course strongly dependent on the specific technical and economic situation of the individual power transformer and the utility respectively. In the case of Brazil for example, a 5 hours non scheduled outage of a new installed transformer means loosing 750 hours of revenue.

As a further example the calculation of the economic losses due to a failure of a generator step-up transformer is analysed. This scenario happened at a German power station. The nominal rating of this power station is 1,400 MVA. Two power transformers with a rating of 1,100 MVA each in parallel step up the voltage on a level of 400 kV. After 15 years of service one transformer had a severe internal failure and had to be brought back to the factory for repair. The direct costs of this repair were covered by an insurance company, but it took 19 days to install a spare unit. This time was so short, because the spare unit was already on-site. If a transport of the spare unit had been necessary, the outage time would have been considerable longer. During this time the generator could operate with 1,100 MVA only. So the loss (L_{en}) of generated electrical energy was in this case:

$$L_{en} = 300\text{ MW} \cdot 19\text{ days} = 136.8\text{ GWh}$$

Applying simple mathematics one can determine the loss of revenues from this incident by multiplying L_{en} with the price per kWh which results in a loss of several million Euro. In case of detected problems which cannot be prevented by corrective maintenance the outage time and therefore costs can be reduced by early placing of a spare unit at disposal additionally. The transformer can be corrected on-site or in the factory with less expenses.

6.3 Use of condition-based maintenance instead of time-based maintenance

Direct benefits are cost savings achieved by changing the maintenance strategy. They include reducing expenses by reduced frequency of equipment inspections, and reducing or delaying active interventions (e.g. repair) on the equipment. For power transformers different maintenance strategies are used. So here only possible reductions in maintenance efforts are mentioned.

Active part: Because of the additional information of the Hydran sensor the time interval for taking oil samples and performing a dissolved gas analysis (DGA) can be extended.

Bushings: The monitoring system detects changes of the capacitance of the bushings. Therefore off-line measurement of power loss factor can be stopped.

Cooling unit: By thermal modelling of the power transformer the thermal resistance of the cooling unit is calculated. In case of pollution or failure of the coolers the thermal resistance is increasing which leads to a warning signal. So the cleaning intervals can be extended.

On-load tap changer: A revision of the tap changer is normally done every seven years. By the monitoring system the number of operations and the sum of switched load current are calculated. The sum of current is an indicator for the wear of diverter switch contacts. So the maintenance interval can be extended. Furthermore the mechanical condition of the OLTC is assessed which leads to a safer operation.

6.4 Higher overload capacity

To be able to operate a power transformer at a higher load than rated an overload calculation is implemented in the monitoring system. Financial profit is not only achieved from transmitting extra load but also from savings because of avoidance of investment of new transformers. This scenario happened recently in gas turbine power station where the output of the turbines was increased after some years of service. For close supervision during overloading periods the four G.S.U. transformers were equipped with the monitoring system. Not only monetary benefits which can be calculated easily by multiplying the extra supplied energy with the revenue of the kWh, but also the prevention of a blackout often has top priority; so it is strategically absolutely necessary for grid-coupling transformers.

6.5 Avoidance of investment

By the exact knowledge of the condition and therefore the failure risk the utilisation period of the transformer can be extended minimising the risk of a sudden death which is especially important for transformers at strategic important locations. Also the knowledge of transformers life is a valuable information to decide which transformer out of a whole population should be refurbished or scrapped. The benefit of a 3 year extension of lifetime and therefore the delay of a new investment can be calculated by assuming an interest rate of 5 % per annum:

$$S = 1.05^{3y}\ 1 = 15.7\ \%$$

So 15.7 % of the value of the new transformer can be saved by the extension of lifetime.

7 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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