Assessment of Overload Capacity of Power Transformers by On-line Monitoring Systems

S. Tenbohlen, T. Stirl
ALSTOM Schorch Transformatoren GmbH,
Rheinstr.73, 41065 Mönchengladbach, Germany
transformer.monitoring@tde.alstom.com

M. Stach
E.ON Engineering GmbH,
Bergmannsglückstr. 41-43, 45896 Gelsenkirchen, Germany
manfred.stach@eon-energie.com

Abstract: Overloading of power transformers can become necessary in open electricity markets due to economic reasons or simply to ensure continuous energy supply. During an overload circle accelerated ageing and damages have to be strictly avoided. In order to control overload cycles intelligent on-line monitoring systems are needed. In this contribution the on-line calculation of the overload capacity and the integration in a monitoring system are described. By measurement of environmental and loading conditions it delivers continuously information on the maximum continuous and short time overload considering the actual preload of the transformer according to IEC 60354. The presentation of practical experiences shows the considerable possibilities regarding optimization of transformer operation during normal cyclic loading and emergency cases. Also a load dependent control of the cooling unit by the monitoring system allows to increase the overload capacity and optimize the hot-spot temperature.

Keywords: On-line Monitoring System, Power Transformer, Lifetime Assessment, Thermal Model, Overload Calculation.

I. INTRODUCTION

With opening the current markets for generation and transmission of electrical energy the utilities are confronted with new operating conditions. The high demands on generation and transmission combined with modified load cycles can lead to load flows not planned before. The utilization of a power station or a grid as high as possible, and therefore of every electrical equipment gets due to reasons of costs more and more important. But due to the binded reliability of supply and therefore costs in case of failures an endangering of the electrical equipment must be avoided under all circumstances. On these reflections a controlled overloading of the electrical equipment, as for example of power transformers, can be more economically advantageous than the extension of the network. Assuming from thermal limiting currents firmly defined, basically there are two sorts of overloads [1]. Overloads which are combined with a higher conductor temperature than the rated value lead to an extremely accelerated ageing of the insulation and should therefore only be permitted in cases of emergency, like in order to prevent a system collapse. Operating conditions where load current flows above the thermal rated value, but where due to favorable ambient conditions no higher conductor temperature than the permitted temperature of ratings occurs, can be expected of the transformer. To avoid improper operating conditions an exact supervision is necessary in both cases. Monitoring facilities which can take on this task are available with modern monitoring systems [2, 3].

A thermal model which should be integrated into the monitoring system has to fulfil several criteria.

- The model should be almost independent of the transformer, which means that only a few design-dependent variables should have to be adapted. Because it has to be used for old transformers independent of manufacturer, these variables should be extractable out of the test protocols of the transformer. This prevents the use of high sophisticated models [4, 5, 6].
- The model must be sufficiently accurate.
- The sensors which deliver the input values for the model must be possible to retrofit to transformers already installed in the substation. This prevents for example the use of fibre optics for direct measurement of hot-spot temperatures.
- The model must be commonly accepted. So the authors choose a model based on the recommendations of the IEC 354 Loading guide for oil immersed power transformers [1].

II. OVERLOAD CALCULATION

A. *Equivalent circuit of a one-body system*

The thermal behaviour of the whole transformer can be displayed with the help of a one-body system. The losses P_v occurring as heat in the active part, are here framed as a current source. At the steady state the occurring losses are completely transferred to the environment by the heat transfer

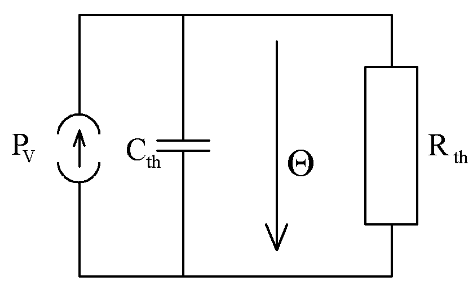

Fig. 1: Equivalent circuit of a one-body system of a transformer

Accepted paper for the *IEEE Power Engineering Society Winter Meeting*, Columbus, Ohio, 2001

resistance R_{th}. Are there any timely modified heat flows or fluctuations of the ambient temperature, additionally the heat capacity C_{th} of the transformer must be taken into account.

The temperature drop at the parallel connection C_{th} and the thermal resistance R_{th} corresponds to the overtemperature Θ of the oil in the transformer. The neutral of the circuit is at the potential of the ambient temperature. For the step response of the temperature drop at the thermal resistance R_{th} is valid:

$$\Theta(t) = P_v \cdot R_{th} \cdot \left(1 - e^{-\frac{t}{t}}\right); \qquad t = R_{th} \cdot C_{th} . \tag{1}$$

Materials of different numbers and with different specific heat capacities are used in a transformer. Due to the whole transformer is treated as one body in this equivalent network diagram, the heat capacity of the whole transformer must be built out of the heat capacities and the masses of the single components:

$$C_{th} \approx c_{Co} \cdot m_{Co} + c_{Fe} \cdot m_{Fe} + c_{Oil} \cdot m_{Oil} . \tag{2}$$

The cooling power of the cooling unit is specified by the manufacturer for a certain working point. Based on this specification the cooling power P_{cool} can be calculated for other ambient temperatures and oil temperatures. For the thermal resistance of the whole cooling plant with tank it is:

$$R_{th} = \left[\frac{P_{cool,n}}{J_{Oil\_in,n} - J_{Air\_in,n}} + O_{Tank} \cdot a_{Tank} \right]^{-1} . \tag{3}$$

By operating a transformer losses result in the heating of the active part. The losses can be classified into load dependent and load independent losses. The no-load losses P_0 have their origin in the transformer core. Their magnitude is influenced by various factors such as core design, quality of core plate material, induction and mass of core. The load losses P_k are made up of the copper losses and the stray losses in the winding ends and certain transformer parts due to eddy currents. Both loss components are proportional to the square of the load current flowing in the windings.

$$P_V = P_{k,n} \left[\frac{I}{I_n} \right]^2 + P_0 . \tag{4}$$

B. Methods of calculating the overload capacity

1) Normal cyclic loading

A higher ambient temperature or a higher than rated load current is applied during part of the cycle, but, from the point of view of thermal ageing, this loading is equivalent to the rated load at normal ambient temperature [1]. This continuous overloading means that the overload duration is at least five times longer than the thermal time constant of the transformer specified by the heat capacity and the thermal resistance of the whole cooling plant. This time constant amounts to several hours at large transformers. Wanted is now the load current the transformer can be loaded with, so that the hot-spot temperature ϑ_h amounts to 120 °C (OD cooling). The hot-spot temperature is composed of the ambient temperature ϑ_{Air}, the top oil temperature rise and the winding gradient Θ_{Co_Oil} evaluated with hot-spot factor h.

The ambient temperature is available as a measuring value. Against that the top oil temperature rise (calculated acc. (1) and the winding gradient Θ_{Co_Oil} are depending on the actual load current I of the transformer:

$$J_h = J_{Air} + (P_{k,n} \cdot \left[\frac{I}{I_n} \right]^2 + P_0) \cdot R_{th} + h \cdot \left[\frac{I}{I_n} \right]^y \cdot \Theta_{Co\_Oil,n} . \tag{5}$$

P_0, $P_{k,n}$, R_{th}, $\Theta_{Cu\_Oil,n}$, winding exponent y and the hot-spot factor h are given by the construction of the transformer or can be investigated by the heat run test. The current I, with which the transformer can be permanently loaded by the given ambient temperature ϑ_{Air}, for OD-cooled transformers can be calculated by solving the equation to I:

$$I = I_n \cdot \sqrt{\frac{J_h - J_{Air} - P_0 \cdot R_{th}}{P_{k,n} \cdot R_{th} + h \cdot \Theta_{Co\_Oil,n}}} . \tag{6}$$

For this kind of overload it is important to stress that cycles with ageing rates greater than unity are compensated by cycles with ageing rate less than unity. It is to consider that regarding the highest hot-spot temperature of 120 °C suggested by the IEC 60354 an ageing rate of 12 occurs, so that a continuous supervision of the transformer and its ageing is necessary in order to recognize intolerable operating conditions. Also the loading limits set by attached components like bushings and tap changers may not be lost out of sight.

2) Short-time emergency loading

The short-time emergency loading is an unusual load for a transformer and is caused by the occurrence of more unlikely events which seriously disturb normal system loading, causing the conductor hot-spots to reach dangerous levels [1]. For this overload operating of half an hour maximum a load factor up to 1.5 and a hot-spot temperature of 140 °C to 160 °C maximum can be tolerated at OD-cooled transformers. For calculation of emergency loading time the heat capacity of the device must be taken into account. From the total losses occurring by the required overload factor and from the thermal resistance of the cooling plant the stationary final value of the hot-spot temperature $\vartheta_{h,\infty}$ according (5) is calculated. When the hot-spot temperature of 160 °C is exceeded, gas bubbles may develop which could jeopardize the dielectric strength of the transformer. So an accurate modelling of the time constants of the transformer and its windings is necessary. Due to the oil inside the windings changes more with the time constant of the winding (several minutes) than with the bigger time constant of the whole tank, here the time constant τ_h has to be suited to (two-body system). So the hot-spot temperature is increasing from its actual value $\vartheta_{h,\infty}$ to the infinite value by:

$$J_h(t) \approx (J_{h,\infty} - J_{h,act}) \cdot \left(1 - e^{-\frac{t}{t_h}}\right) + J_{h,act} \,. \qquad (7)$$

An important precondition for the calculation of the overload duration is the exactly fixing of the hot-spot temperature $\vartheta_{h,act}$ of the transformer at the beginning of the overload. Therefore the actual top oil temperature and the hot-spot temperature is permanently calculated iteratively by the monitoring system. The time t up to the heating of the transformer to a hot-spot temperature of 140 °C results by solving (7):

$$t = -t_h \cdot \ln\left(1 - \frac{140°C - J_{h,akt}}{J_{h,\infty} - J_{h,akt}}\right). \qquad (8)$$

III. INCORPORATION OF OVERLOAD PROGNOSIS INTO THE MONITORING SYSTEM

To guarantee a reliable and economical electrical power supply, a modern equipment monitoring, especially for the utilization at power transformers, would provide a solution. Due to a continuous supervision with a monitoring system it is possible to make exact statements about the operating condition of the transformer and therefore as described by the overload prognosis to optimize the operation.

Transformer outage rate statistics indicate on-load tap-changer, active part and bushings as the most frequent cause of long duration outages [7]. Therefore the installation of a comprehensive monitoring system to warn in case of an oncoming fault is advisable for strategically important power transformers such as generator transformers. Due to an early detection of abnormal conditions it is further possible to avoid faults and than to change over from a time-based to a condition-based maintenance which can lead to a considerable reduction of maintenance expenditures. By knowing the operating life and actual condition of the transformer a high and controlled exploitation of the residual service life can be reached. In case of demand the residual lifetime can be extended by specific actions (Life-Management).

A. System description

Characteristics for the quality of a monitoring system are high modularity and flexibility, because different types and ways of erection of transformers always make an adaptation of the system to the specific requirements necessary. Because of its modularity the Alstom monitoring system MS 2000 can easily be focused on the requirements of the monitored transformer and the customers needs. A multitude of different measurable variables can be collected. However, to use the entire spectrum at one transformer is very costly and not always useful. Therefore, sensor technology must be adjusted to the specific requirements of a certain transformer, depending on its age, condition and importance [2].

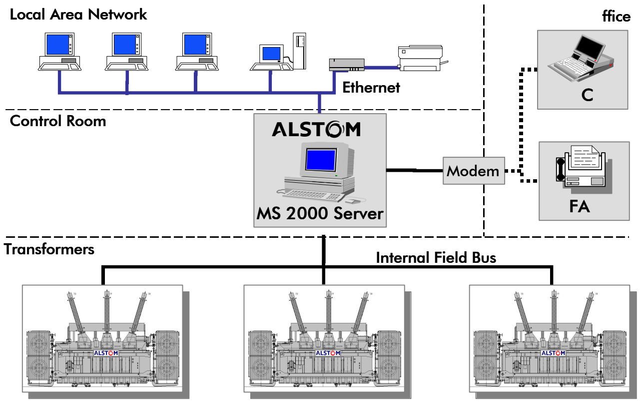

Fig. 2: Architecture of monitoring system MS 2000

A high flexibility of the monitoring systems architecture can be achieved by the use of field bus technology. Instead of many single wires only one bus cable has to be laid, on one hand the expenditures for wiring at the specific transformer are minimized. This is especially important for a fast and easy retrofitting of transformers which are currently in operation. On the other hand a supervision of a complete transformer bank with a monitoring system is realized by connection of the different decentralized monitoring modules dedicated to the individual transformers by the field bus (Fig. 2). The MS 2000 server erected centrally in a building of the substation so enables the supervision of all transformers in the power station, which means a reduction of expenditures for hard- and software. Comparing this with a solution where the PC is installed directly at the transformer the centralized server solution offers several additional advantages:

- The lifetime of the PC is not reduced by vibrations or heat of the transformer,
- the integration into the local area network for data visualization by an ethernet link is easier to achieve,
- only one telephone line is needed to have access to all transformers.

The measuring data are recorded in the millisecond grid by means of the multi-tasking and real-time capable operating system QNX. For the execution of the multiple tasks of the software, such as event controlled data processing and storage, visualization and communication a flexible process control system is used.

For the easy condition diagnosis the most important operational data of the transformer are shown in a process diagram (Fig. 3). By calling the different transformer assemblies, like active part, bushings, cooling unit, conservator and tap changer, the user gets detailed information of the current condition of the specific assembly.

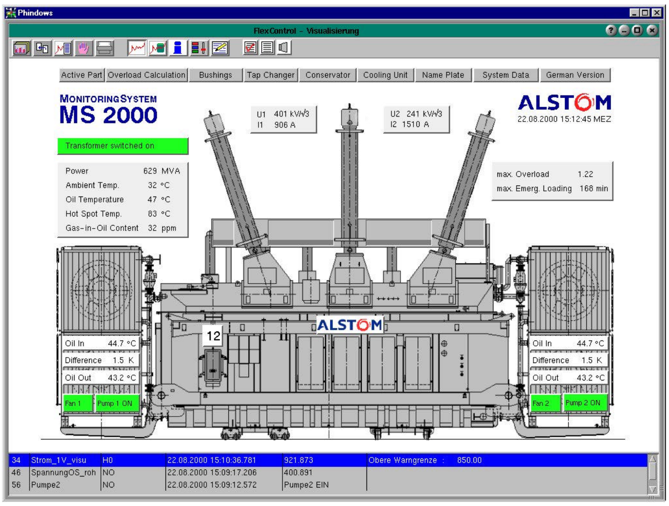

Fig. 3: On-line data screen of monitored transformer

For the extension of the monitoring system of the described overload calculation and an intelligent control of the cooling plant, it is used a PLC module included in the software. So complex calculations and control processes can be implemented with a programming language standardized according to IEC 1131-3.

The monitoring system MS 2000 can also be used to control the fans of the cooling system in a smart manner depending on load current and oil and ambient temperature. The thermal resistance of the cooling unit is adapted to the necessary value to carry away current losses by single switching of fans. This intelligent switching has some advantages compared with the conventional controlling, where fans are switched in two steps dependent on top oil temperature:

- reduction of the transformers breathing by a more constant oil temperature,
- optimizing the hot-spot temperature leads into a reduction of life consumption (Life-Management),
- by precooling the oil the short-time overload can be increased,
- decreasing of sound emission by single operation of fans.

For the incorporation of the described method of overload calculation into the monitoring system transformer specific characteristic data are used. The construction data (heat capacity and thermal resistance) are input together with the values of winding gradient, no-load and load losses determined in the test field. Based on the input variables ambient temperature and the load current every minute the output variables are automatically calculated. The thermal resistance for the different numbers of operating fans is determined during the first weeks of operation of the monitoring system by comparing calculated and measured top oil temperature. In the visualization (Fig. 4) the actual loading, relative ageing rate and the ageing rate averaged over 30 days, as well as information of the life consumption can be read [8, 9]. Additional the maximum overload for normal cyclic loading at a highest top oil temperature of 105 °C and a hot-spot temperature of 120 °C is displayed. This ensures that the user can easily control the compensation of high loading cycles with low loading cycles according to IEC 60354.

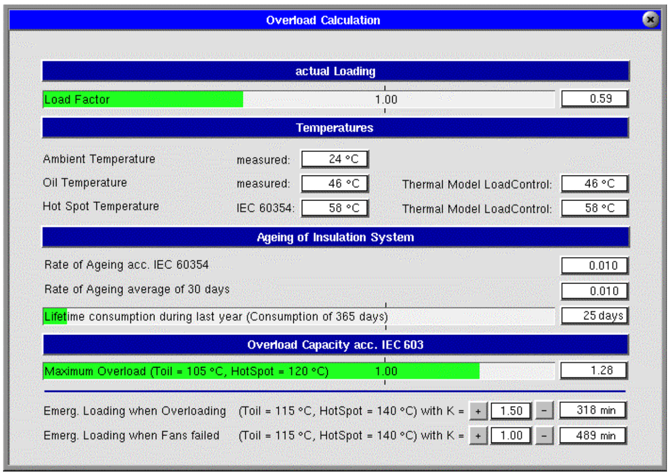

Fig. 4: On-line data screen for overload calculation

The maximum tolerable times for emergency overloading are given on one hand for overloads due to external requirements and on the other hand for abnormal conditions of the cooling plant. Based on the current temperature and load conditions the emergency operating times are investigated for a free selectable load each up to a factor of 1.5 at a top oil temperature of 115 °C and 140 °C hot-spot temperature. The remaining operating time in case of a failure of a cooling unit is also calculated. This is possible because of the knowledge of the thermal resistance which is increased in case of a failure of fans.

Because this high overloading constitutes an abnormal risk for the power transformer it is important to measure accurately also the gas-in-oil content and the moisture in oil by the on-line monitoring system.

B. Overload calculation at transformers in operation

The above described algorithm was used exemplary at a 250 MVA grid-coupling transformer and a 273 MVA generator transformer. The maximum continuous overload capacity of the grid-coupling transformer at rated operation of the cooling plant was determined in dependence of the ambient temperature according to the above described process and is shown in figure 5 for a time interval of one day. In consideration to the above mentioned remarks, here a continuous overload of about 1.3 would be possible due to an ambient temperature lower than 20 °C.

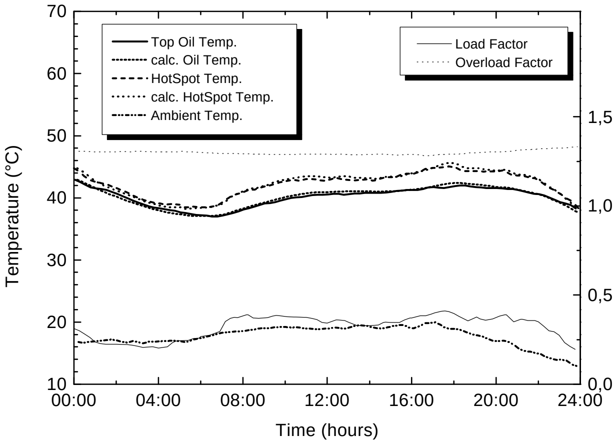

Fig. 5: Temperature changes dependent on load factor for a grid-coupling transformer (250 MVA)

In figure 5 the top oil temperature calculated according to equation 1 and 5 is displayed instead of the emergency loading time, because this shows better the applicability of the model. The calculated top oil temperature shows a good compliance to the measured top oil temperature. The hot-spot temperature is only about 3 K higher than the top oil temperature because of the low loading (app. 0.3). The reason for the high correspondence between measurement and calculation is that only small changes in ambient temperature and loading appear during the presented time interval. For this type of grid-coupling transformer this load profile is very typical. So by monitoring the difference between measured and calculated value of top oil temperature changes in the performance of the cooling unit such as pollution of radiators can be easily detected by the monitoring system. Even for stronger changes of ambient temperature and loading deviations between measurement and calculation are minor [3].

The application of the overload calculation to a 273 MVA generator transformer reveals a different result (Fig. 6). The examined transformer is water-cooled, accordingly the calculation of the continuous load is based on the dependence of the cooling element water. The transformer is situated in a pump storage station, which is the reason for the strong variations of the load factor. During low loading of the electrical network water is pumped into a water reservoir on top of a mountain. During load peaks the water is released from the reservoir and electrical energy is generated. This cycle happens several times a day which is the reason for the strong changes of the load factor.

Theoretically at water temperature of about 10 °C a maximum continuous load of 1.4 is possible. The design of the cooling plant of this transformer is the reason for this relative high value. In figure 6 the hot-spot temperatures based on measured and also on calculated oil temperature are shown dependent on the load factor. It is clearly visible that at different loads the hot-spot temperature is changing with the time constant of the winding. Although there are strong variations of the load factor the difference between measured and calculated values does not exceed 4 K. Only when the transformer

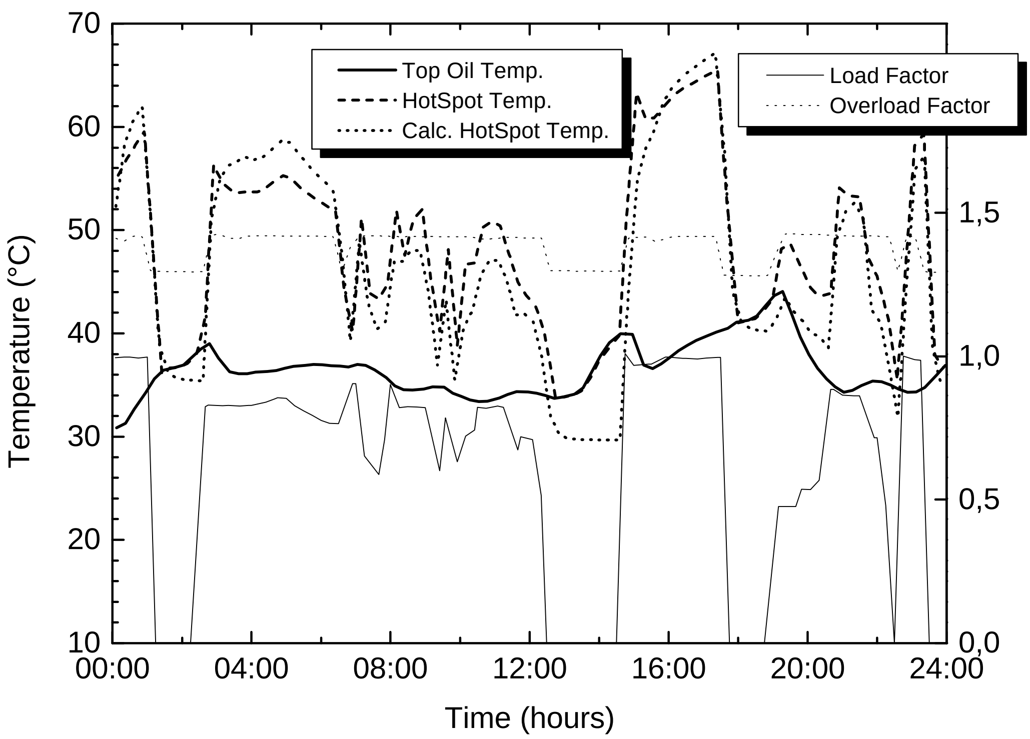

Fig. 6: Temperature changes dependent on load factor for a generator transformer (273 MVA)

is switched off (load = 0), the temperatures differ up to 10 K, which occurs for example at 14.00 h. This is due to the turning off the oil pumps in case of de-energizing the transformer. So the cooling of the active part is stopped with switching off the transformer which leads to an increase in measured oil temperature. In contrast to this the calculated hot-spot temperature dependent on the actual loading is not rising. This special controlling of the pumps is not considered by the overload calculation algorithm and results in the deviations during switching off which are of minor importance.

In this case the time up to reach the temperature limits would be considerable longer than the permitted 30 minutes with a loading factor of 1.5 (emergency operation) due to the actual low temperature of the active part (about 40 °C). But it is to be taken into account that in case of an emergency operation the initial temperature of the transformer is considerable higher and therefore the duration of an emergency operation shorter.

IV. CONCLUSION

In consideration of specific transformer design data, the overload capability of OD-cooled large transformers can be determined by an on-line monitoring system more flexible than in the tables for emergency operation. This article describes how an algorithm for the overload calculation of power transformers in combination with an on-line monitoring system can give information about free transmission capacities. In case of overload the especially important supervision of hot-spot temperature, gas-in-oil content and ageing of the active part is guaranteed. Using the in IEC 60354 recommended overload cycles, however, the transformer specific facts as age, condition and design must be taken into account in close co-ordination between manufacturer and utility.

In the near future the proposed algorithm will be validated at a 850 MVA generator transformer which is operated at full load. Furthermore an installation of hot-spot measurement by means of a fibre optic probe is planned for a 600 MVA generator transformer.

Beside an early detection of faults combined with a reduction of out-of-service intervals and the transition to a condition based maintenance the long-term benefit of the described monitoring system is to have borderline situations, such as overload of electrical equipment, safely under control.

V. REFERENCES

[1] IEC 60354: “Loading guide for oil immersed power transformers” (IEC, 1991)

[2] S. Tenbohlen, F. Figel: “On-line Condition Monitoring of Power Transformers”, *IEEE Power Engineering Society Winter Meeting*, Singapore, 2000

[3] S. Tenbohlen et al.: “Enhanced Diagnosis of Power Transformers using On- and Off-line Methods: Results, Examples and Future Trends”, *CIGRE Session 2000*, paper 12-204, Paris, 2000

[4] A. J. Oliver: “Estimation of transformer winding temperatures and coolant flows using general network method”, *IEE Proc.*, Vol. 127, Pt. C, No. 6, November 1980

[5] M. Schäfer, K. Feser: “Thermal Monitoring of Large Power Transformers”, *IEEE PowerTech*, paper BPT99-072-30, Budapest, 1999

[6] F. P. Incropera, P. D. De Witt: “Fundamentals of Heat and Mass Transfer”, John Wiley & Sons, 1996

[7] “An International Survey on Failures of Large Power Transformers in Service”, *CIGRE Working Group 12.05*, Electra, No. 88, January 1983

[8] V. M. Montsinger: “Loading Transformers by Temperature”, *Winter Convention of the A.I.E.E.*, New York, N. Y., Jan. 27-31, 1930

[9] W. J. McNutt: “Insulation Thermal Life Considerations for Transformer Loading Guides”, Trans. on Pow. Del., Vol. 7, No. 1, January 1992