Integration of Power Transformer Monitoring and Overload Calculation into the Power System Control Surface

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***Abstract*--Failures of power transformers as most valuable transmission system resources can cause high financial damage. Therefore on-site transformer monitoring was introduced in order to steadily analyze the operating conditions. Additional on-line transmission of certain monitoring values to the power system control center enables to continuously assess the transformers' internal thermal status and further the admissible overloading duration under given circumstances. If the results are immediately being displayed within the used power system control surface, the operators are given useful support in decision making, especially in critical network situations.**

***Keywords*—Power Transformer, On-line Monitoring, Thermal Model, Overload Calculation, Aging, Moisture in Oil, Visualization.**

I. Introduction

In the control centers of transmission systems numerous on-line data are gathered concerning the status of the system. Rather, available transformer information is usually limited to current, voltage and power measurements, as well as performance and status of auxiliary equipment (cooling etc.). Especially in critical system situations bearing the necessity of excessive thermal stress of transformers the operators need additional transformer information in order to assess the actual overload capacity or the admissible emergency operation duration.

Recommendations for the monitoring of large transformers are existing [1]. Monitoring systems offer the opportunity to record all relevant values in a local database. Primarily the original data collected are further dressed by local diagnosis-, evaluation- alarm- and control-systems, thus allowing for instance to detect stresses which can affect the lifetime [2]. It is also possible to poll the information via modem from a central utility site for, e.g., superior asset management. Transmission to the system operation control center was realized only very rarely; in these cases the display is on separate screens or recorders, fully independent of the human machine interface of the power system control system. In contrast, in the following an innovative approach is described, assessing values of operational interest such as the actual overload capacity and the admissible emergency operation duration of transformers from electrical and physical on-line measurement values under additional regard of quantities such as oil humidity and preloading; the results are displayed immediately within the operational diagrams of the power system control surface.

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II. Architecture of On-line Monitoring System

A multitude of different measurable variables can be collected for on-line monitoring [3,4]. Automatic evaluation of these data allows the early detection of oncoming failures and performing condition based maintenance. Active part, oil expansion tank, cooling system, on-load tap changer, cooling unit etc. as well as general conditions on the transformer site are monitored by sensors. However, it is very rarely useful to use the entire spectrum.

A. Sensor Set-up

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 on-line monitoring systems in service the following general set-up of sensors is proposed:

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

B. Local Architecture

The outputs of the above mentioned sensors are collected by monitoring modules installed at the transformer as data acquisition units, and sent via A/D converters, serial interfaces and a field bus system to a relational data base system running on a local server, Fig. 1. By means of this industrially proven technology it is possible to monitor all transformers in one substation with a single system which is extremely cost effective. Locating the server in an operating building offers the advantage of having more suitable ambient conditions (e.g. temperature range, vibrations) for a PC.

C. Distribution and Visualization of Monitoring Data

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. 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.

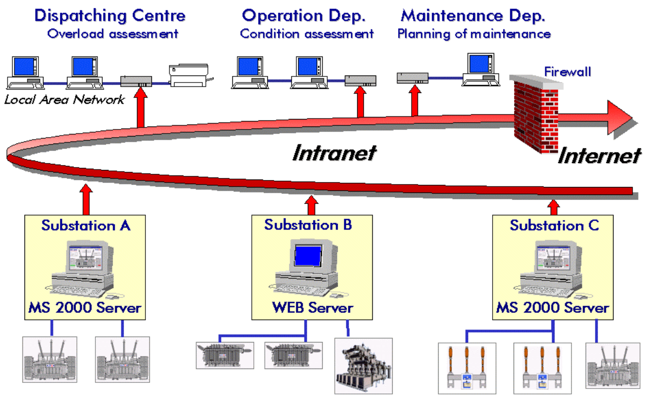


Fig. 1. Data access by the use of Intra-/ Internet.

This wide distribution of information can be provided by a web-based solution, Fig. 1. The monitoring data can be accessed by remote PC located at the main offices by means of a web browser as standardised platform. This avoids running individual software on each desktop PC. 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 within the Intranet. By use of firewall protection it is also possible to have individual access to any substation information from everywhere via the Internet. This would, for instance, allow that a specialist out of shift can analyze the transformer from his home PC in emergencies.

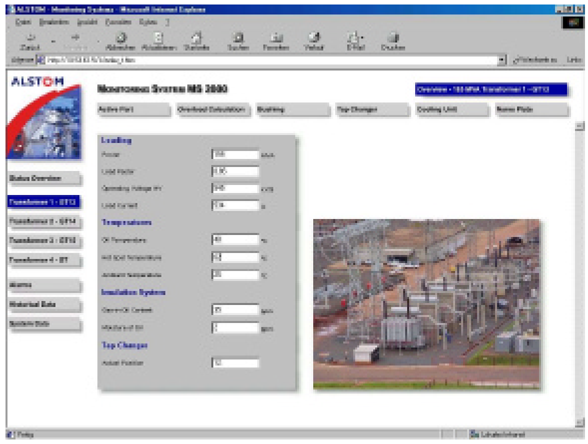
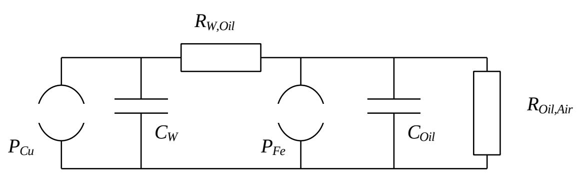


Fig. 2. Web-based visualization of transformer condition

III. CALCULATION OF OVERLOAD CAPACITY

A. Thermal Model

The overload capacity of a transformer is primarily limited by the admissible maximal temperatures of winding (hot spot) and oil (top oil temperature). In normal loading situations where the hot spot temperature does not exceed the critical value of 120°C, the current oil and hot spot temperatures can easily be calculated by means of the one-solid model according to IEC 60354 [5]. Rather, this model is not sufficient if strong fluctuations of loading occur, or if the transformer is unusually highly loaded. According to IEC 60354 the transformer must withstand an overload by a factor of 1.5 for a time period of up to 30 minutes without exceeding a hot spot temperature of up to 160°C [5]. In transformer modeling for such cases distinction between winding and oil volumes is required; a two-solid model – see Fig. 2 – has proved to represent the thermal transformer behavior sufficiently in the range of minutes [3].



$$t_W = R_{W,Oil} \cdot C_W$$
$$t_{Oil} = R_{Oil,Air} \cdot C_{Oil}$$

C_W	Thermal capacity of winding
C_{Oil}	Thermal capacity of core, oil and tank
$R_{W,Oil}$	Thermal resistance winding/oil
$R_{Oil,Air}$	Thermal resistance cooling
P_{Cu}	Winding losses (load dependent)
P_{Fe}	Core losses

Fig. 3. Two-solid transformer thermal model.

The time constant of the winding t_W usually ranges at few minutes; in contrast, the time constant determined by oil volume, core and cooling t_{Oil} is about an hour. Therefore, decoupled calculation using time steps *Dt* << t_W is admissible. In each step the winding temperature J_W is determined under regard of t_W but neglecting heat exchange core/oil volume at first:

$$J_{W(t+\Delta t)} = J_{Oil(t)} + P_{Cu}\cdot R_{W,Oil} - \left(P_{Cu}\cdot R_{W,Oil} - \left(J_{W(t)} - J_{Oil(t)}\right)\right)\cdot e^{-\frac{\Delta t}{t_W}} \qquad (1)$$

From this the hot spot temperature can conservatively be assessed using a security factor h (usually h = 1,1):

$$J_{H(t+\Delta t)} = h\cdot J_{W(t+\Delta t)} \qquad (2)$$

Subsequently, the heat exchange winding/oil volume can be calculated using $R_{W,Oil}$; the oil temperature is given by:

$$J_{Oil(t+\Delta t)} = J_{Air(t+\Delta t)} + P_{V(t)}\cdot R_{W,Oil} - \left(P_{V(t)}\cdot R_{W,Oil} - \left(J_{Oil(t)} - J_{Air(t)}\right)\right)\cdot e^{-\frac{\Delta t}{t_{Oil}}}$$

with $$P_{V(t)} = P_{Fe} + \left(\frac{J_{W(t)} - J_{Oil(t)}}{R_{W,Oil}}\right) \qquad (3)$$

The calculation of the remaining emergency operation time is activated if the final hot spot temperature cyclically assessed from the current operating conditions of the transformer by

$$J_{H,\infty} = J_{Air} + h\cdot P_{Cu}\cdot R_{W,Oil} + \left(P_{Cu} + P_{Fe}\right)\cdot R_{Oil,Air} \qquad (4)$$

would exceed the given limit. Then the time dependent increase of the hot spot temperature is prospectively calculated by a loop of equations (1,2,3) for time steps of *Dt* = 60 seconds; the calculation is stopped when the given limit temperature is reached. The number of loops stands for the remaining emergency operation time.

For the calculation of the continuously acceptable factor of overload, the permanently admissible hot spot temperature of 120°C according to IEC 60354 [5] is inserted in equation (4); subsequently this equation is solved for the current-dependent winding losses P_{CU}.

Considering the effect of overload operation on transformer ageing it has to be regarded that periods of high and lower loading are mutually compensating in the mid term range of time. But it should be mentioned that a hot spot temperature of 120^0C - which is admissible according to the standard - causes an ageing factor of 12; therefore, continuous transformer monitoring of ageing is highly recommended.

B. *Influence of Moisture in Oil*

For exact assessment of the continuous overload capacity the actual humidity of the insulation has to be taken into account, because the ageing rate is increased by humidity. There are several causes for an increase of water-in-oil content; for instance, improper shipping and erecting of the transformer on-site or absorption of moisture by conservator oil breathing. It is reported that by 4 % water content in paper for example the ageing rate is increased by a factor of about 20 [6]. So measurement of oil humidity is recommended in particular for transformers which are already aged or usually operated at high oil temperatures, because for accurate calculation of the ageing rate input of moisture content is required.

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 according to the dependencies shown in Fig. 4.

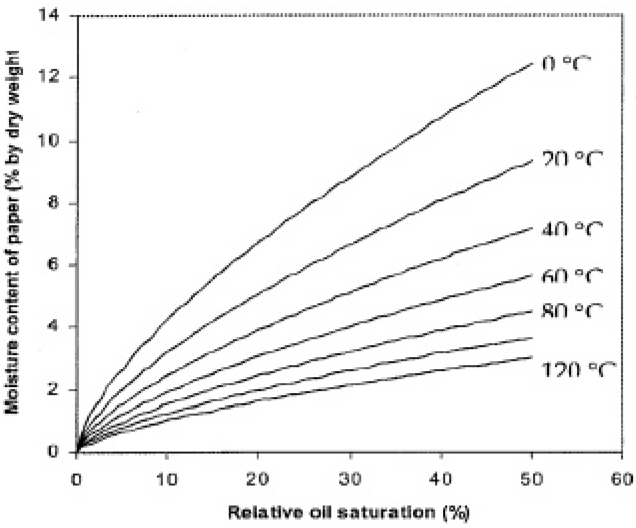


Fig. 4. Moisture content of paper dependent on humidity of oil and hot-spot temperature [8].

This value is especially 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 isolation paper to oil can occur. So the acceptable limit for the hot spot temperature is dependent on the water content in the paper and is reduced according to the following formula [7]:

$$J_{H,\max} = 166K - 13K * f_{Paper}[\%] \qquad (5)$$

IV. Verification

In order to verify the correctness of the algorithm the results of thermal modeling and overload calculation are presented in Fig. 5 for an OD-cooled single phase 333 MVA auto-transformer. Data of load factor, air temperature, the measured and calculated top oil temperature as well as the maximum admissible continuous overload are shown. Although the top oil temperature varies strongly because of load variations between 0.3 and 0.85 of rated power the deviation between measured and calculated value does not exceed 2 K, thus verifying the thermal model.

Even in summer for this transformer the maximum continuous overload capacity of 1.3 is possible.

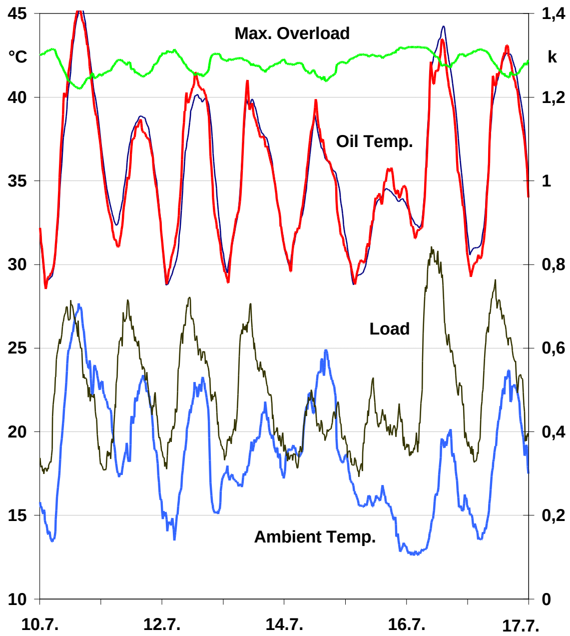


Fig. 5. Top oil temperature and max. overload capacity dependent on ambient temperature.

If the measured oil temperature permanently exceeds the calculated value, it can be concluded that the thermal resistance of the cooling unit is increased, which could be caused by pollution of coolers for example. Because this does not lead directly to excessive oil temperature as a matter of alarm indication, this problem would not be detected without monitoring. The same applies to a failure of fans or pumps. So in these cases monitoring offers the opportunity to perform condition-based maintenance actions.

V. Implementation and Visualization in the Power System Control Center

The availability of actual transformer status information in the transmission system control center is an important factor to facilitate taking operational decisions, especially in disturbed situations; here the admissible overload operating time in emergencies plays a predominant role. Generally, this can be achieved by collecting relevant transformer information from the monitoring system as SCADA data and thermal calculation as described above.

Rather, in contrast to existing approaches where transformer thermal information – if available at all – is presented on a different display in the control center, the presentation and visualization of the results should be fully integrated into the operator’s used man-machine interface where he is familiar with. This is of high perceptual and ergonomic advantage: transformer information is altogether represented at that place where the operator deals with the transformer as transmission grid component: this is in the interactive substation diagram.

An exemplary implementation of this approach was realized for the control surface of an operator training simulator [9], see Fig. 6. Thus the functionality could be demonstrated under operational realism, as well as practically experienced by transmission system operators on the occasion of regular training courses executed with this simulator [10]. Generally the implementation proved to be well accepted by the operators.

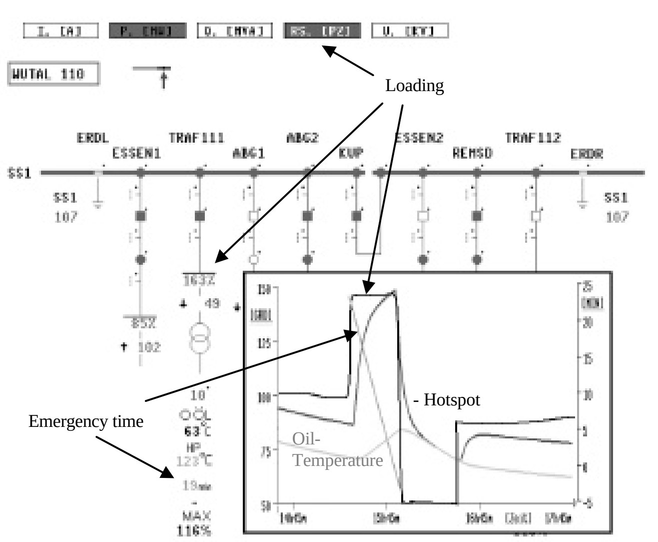


Fig. 6. Interactive operational switchyard diagram with embedded on line transformer information and additionally inserted time curves.

Fig. 6 shows the interactive diagram of a substation [11]; oil and hot spot temperatures, maximal continuous load, current overloading and the remaining admissible emergency operation time of the transformer are displayed immediately at the transformer feeder. On request, the operator can additionally insert particular time-curves; as an example this is shown in Fig. 6 for the load, oil and hot spot temperatures as well as the admissible emergency operation time.

VI. Conclusion

On-line monitoring of power transformers provides a clear indication of their status and ageing behavior. Analysis of the collected data allows prudent asset management, foresighted investment budgeting as well as operation closer to – or for certain time periods even above – limits.

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 cycle accelerated ageing has to be minimized and damages have to be strictly avoided. In order to control overload operation comprehensive on-line monitoring systems are needed.

If more detailed monitoring information is transmitted on line to the power system control center, maximal load and admissible overload operation time under given operating conditions can appropriately be assessed and the results can immediately be displayed within the used diagrams of the power transmission system operational surface. Thus, a reliable decision making support is given to the operators. They can counteract to threatening failures in time, and in particular they can react more flexibly in critical system situations and emergencies.

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VIII. Biographies

Gregor Pudlo received his Diploma degree from the Gerhard-Mercator-University in Duisburg, Germany, in 2001. Since 2001 he is with ALSTOM Schorch Transformatoren GmbH in Mönchengladbach, Germany. His areas of interest are on-line monitoring systems for power transformers and thermal calculation.

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