On-line Condition Monitoring and Diagnosis for Power Transformers their Bushings, Tap Changer and Insulation System

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Abstract - **Utilities need to reduce costs associated to operation and maintenance of installed equipment. Main ways to achieve this cost reduction are the use of on-line condition monitoring, and a shift from time-based to condition-based maintenance. Thanks to the evolution of monitoring systems, maintenance and operation people can concentrate their activity on other tasks with high added value. Besides these utilities will continue to be faced with daunting challenges due to a deregulated energy market. Increasing loading of equipment, decreasing maintenance expenditures and postponement of investments are goals to reduce life cycle costs. These measures but also can result in higher failure rates and increasing risk of major failures. So the objective is to secure a given quality of supply of electrical energy with minimized cost expenditures for services (life management).**

Index Terms - **On-line Monitoring, Power Transformer, Bushing, Tap Changer, Insulation System.**

I. The Importance of Life Management

Oil-filled power transformers, their bushings, tap changer, insulation system and auxiliary equipment are critical to the operation of every electrical power system to such an extend that their reliable and uninterrupted functioning is a key factor in profitable generation, transmission and distribution. To increase availability and optimise operating management on-line condition monitoring of power transformers is useful and necessary. Throughout the last years on-line monitoring systems have been installed in a large scale at power transformers [1, 2, 3, 4]. Based on this extensive field experience selected practical examples are analysed and discussed in this paper demonstrating the ability these systems can perform.

In addition the most reliable concepts used for comprehensive on-line monitoring (bushings, tap changer, insulation system,…) are described. The combination of different measuring methods can be seen as sophisticated tools to take decisions on the operation of the transformers. Different concepts for efficient assessment of the transformers condition can be established, where condition-based maintenance planning is a reality. The utilities network (Ethernet) can transport the information from the substation to every PC (web based visualization, **Fig. 1.**) connected to the customers Intranet. Starting from the strict point of view of monitoring it is then proceed forward with the presentation of diagnostics, prognosis and the challenges posed by the development of such tools.

The task of on-line monitoring is then to provide focused, purposeful diagnosis information, so that remedial measures can be initiated if needed should faults occur during operation.

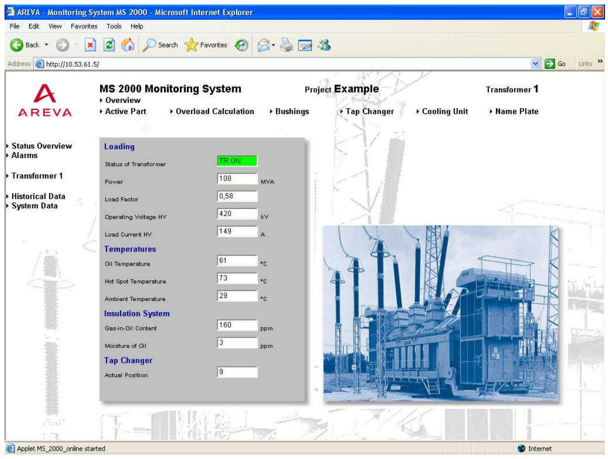

Fig. 1. On-line visualization of transformer condition and its detailed information about trending, diagnostics and prognostics

II. System description

The concept of the on-line monitoring system is employed with field bus and process control technology [1, 2, 3, 4], to be able to thus implement flexible system architectures. Such a system centers around a server with which several transformers can also be monitored simultaneously. The analogous signals of the sensors are wired on field bus terminals in a monitoring module on the transformer. Here, the analog signals are digitized and transferred to the server using a field bus protocol. The acquisition of the data takes place with millisecond accuracy. Computation values (e. g. ageing rate, overloading condition, the change in the bushing capacitance) are derived from acquired measurement quantities. The data acquisition is time-controlled and event-controlled. Thus, e. g. when a transformer is switched on, the voltages are recorded for a duration of 10 seconds with a resolution of 20 ms. In comparison, the changes in the bushing capacitance are sampled every 20 ms and saved every 15 minutes consequently the size of the database is optimized.

III. Bushing Monitoring

High voltage condenser bushings of power transformers, according to their construction and age, are amongst the most endangered components from all operating equipment used. In the past, off-line measurements like the measurement of bushing insulator capacitances and measurement of the dissipation factor were carried out successfully for determining the operational state. Today, modern microprocessor and computer technology makes it possible to carry out these procedures on-line with the help of a monitoring system. The expert system itself, with its comprehensive data storage, evaluation algorithms and diagnosis functions provides a significant contribution to the high availability of the transformer.

A. Capacitively controlled insulator bushings

In the voltage range from 110 kV upwards, modern bushings are generally designed with closely stepped capacitively control layers [5]. The insulator body is manufactured in a coil winding process. The basic insulating systems of capacitively controlled high voltage bushings can be classified as:

- Resin-bonded paper bushings (RBP)
- Resin-impregnated paper bushings (RIP)
- Oil-impregnated paper bushings (OIP)

The inner insulation structure of resin-bonded paper bushings consists of resin-coated material, which is glued under high temperature and pressure in normal ambient conditions. In the case of resin-impregnated bushings, the insulator consists of crepe paper with wrapped aluminum coatings. This is dried and impregnated in vacuum. In the case of oil-impregnated bushings, the insulating body consists of kraft paper with wrapped aluminum or graphite coatings, which are dried and oil-impregnated in vacuum. The outer insulation structure is generally made up of porcelain, or, more recently, of silicon.

What is common to all constructions is that they are subjected to very high mechanical, electrical and thermal stresses during operation. This results in ageing and hence to a change in the operational state [6]. Thus, partial breakdowns in the insulation system can affect the operational safety to such an extent that further safe operation is not guaranteed any more [7, 8].

B. Bushing capacitance C and dielectric dissipation factor tan δ

The measurement of the bushing capacitance C and the dielectric dissipation factor tan δ (**Fig. 2.**) are important parameters for evaluating the operational state of a high voltage bushing. The dissipation factor is obtained from $\tan\delta = 1/R\omega C$. In the case of a new resin-bonded paper bushing, it is in the range 0.5 ... 0.7 %. In the case of resin-impregnated bushings, it is in the range 0.25 ... 0.45 %, and for oil-impregnated bushings, values between 0.25 ... 0.5 % are normal.

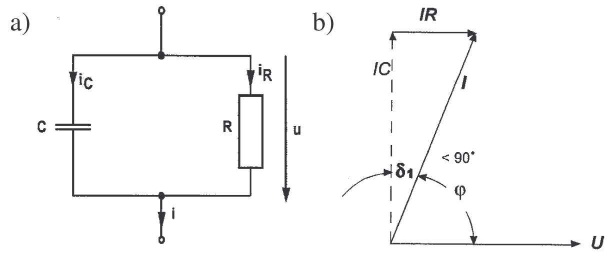

Fig. 2. Equivalent circuit diagram (a) and vector diagram (b) of the dielectric loss factor tan δ

Dielectric losses in the insulation result in a capacitive loss current in the dielectric material. The reason for this can be found in the electrical properties of the insulation structure [5].

Depending on the ageing, the bushing capacitance and the tan δ can change. **Table 1.** shows guide values for tan δ and capacitance values as examples for resin-bonded paper bushings. When these limiting values are reached, continued operation is not recommended.

U_N [kV]	tan δ [%]	Δ C [%]
123	2.0	20
245	1.5	15
420	1.0	10

Table 1. Limit values for the dielectric loss factor tan δ and capacitance increase Δ C for resin-bonded paper bushings [3]

Other reasons for a change in the values of tan δ and Δ C are external environmental influences like moisture and dirt on the outside on the porcelain. An increase in the Δ C can also be caused by an oil-impregnation in the case of resin-bonded paper bushings. Apart from a consideration of the absolute values of tan δ and Δ C, an analysis of the trend is of great importance.

Thus, an increase in the Δ C for all bushing types indicates partial breakdowns between control layers (**Table 2.**). Hence, for instance, if one of the 60 control layers of a typical 420 kV bushing breaks down, its capacitance changes by a value of 1.7 %. A short-circuit between two control layers does not directly result in bushing failure, but the likelihood of a complete breakdown of the insulation raises with increasing number of defective layers.

U_N [kV]	Number of control layers [n]	Δ C [%]
123	28	3.6
245	42	2.4
420	60	1.7

Table 2. Increase in capacitance ΔC in case of a partial breakdown between control layers for oil-impregnated bushings

C. Voltage sensor

The monitoring of the electrical measurement quantities is achieved with a voltage sensor [9]. The sensor is connected directly to the measurement tap of the bushing (**Fig. 3.**). This design allows a reliable measurement with a bandwidth of up to 2 MHz.

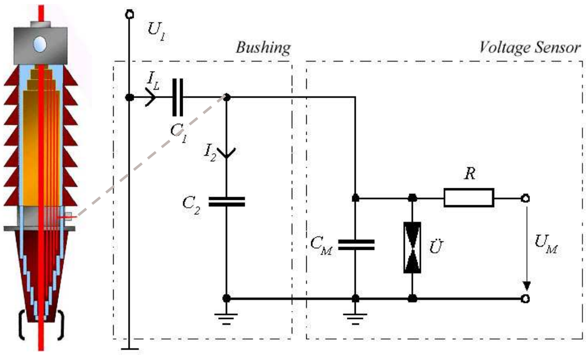

Fig. 3. Sketch of bushing and equivalent circuit diagram of the bushing and the voltage sensor

The sensor essentially consists of a capacitance C_M, which normally has values of 1 .. 2 µF. Since $C_M >> C_2$ (with $C_2 \approx 300$ pF), I_2 is practically 0. The resistance R terminates the connected coaxial cable with a surge impedance of 50 Ω. The potential divider ratio between C_1 and C_M is so dimensioned that a measurement voltage U_M of 57 V AC is set. In addition, there is an overvoltage suppressor (Ü) installed, which protects the sensor and the cable from overvoltages, and as there are no electronic components used in the sensor at the bushing, this measurement procedure is not sensitive to electromagnetic emission. Another advantage of the technology used is in the high signal-to-noise ratio owing to the transmission of a voltage signal of about 57 V AC.

D. Operating voltages and overvoltages

For the measurement of operating voltages, the capacitive voltage sensor already described is used (**Fig. 4.**). In addition overvoltages can also be detected. Transient overvoltages represent a significant endangerment potential for the insulation. Therefore, the detection and evaluation of these transients is of great significance for the evaluation of the bushing insulator reliability [4] and besides this also for the insulation system of the active part of the transformer.

Overvoltages can be caused by storm discharges and switching actions, e. g. the switching on of overhead lines and chokes. In particular, bushings of transformers in GIS or HVDC-switchgear are subjected to fast transient overvoltages. Since their size and shape are often not known, there can be a failure of operating equipment, which can be avoided by taking specific countermeasures. Furthermore, information about the amplitude of overvoltages and the combination with the on-line measures and analyzing data of the other monitoring modules is of great importance in case of root cause analysis after the occurrence of a damage.

Fig. 4. Bushing voltage sensors installed on the measurement tap of the bushings

Fig. 5. shows, as an example, three-phase operating voltages on the 275 kV bushings of a 185 MVA generator transformer together with detected overvoltages recorded over a period of 18 months. What can be clearly seen are the numerous voltage spikes in the graphs, which are caused by the overvoltages that occur. All events that influence the operational behavior are depicted in a transparent manner. The present-day technology easily allows the continuous acquisition and archiving of all the data even for longer than 18 months, across many years (life). In addition voltage fluctuations in the line voltage and network asymmetries of up to 1 % can be clearly seen from the graphs.

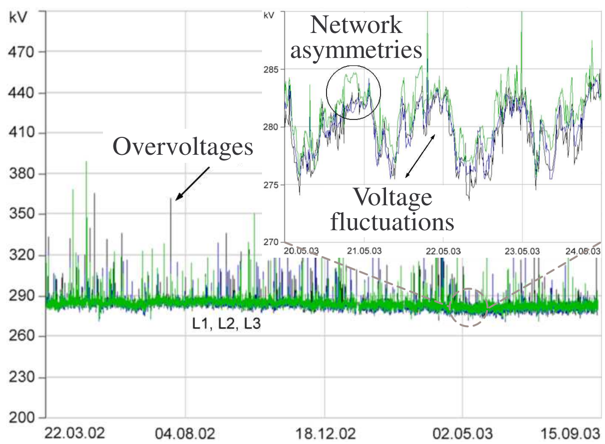

Fig. 5. Continuously monitored 3-phase operating voltages (phases L1, L2, L3) with overvoltages, voltage fluctuations and network asymmetries (period 18 months)

E. Bushing capacitance

The monitoring of the change in the bushing capacitances (Δ C) is achieved by means of a three-phase voltage measurement. Here, the output signal of a voltage sensor is compared with the two remaining phases. The result of the algorithm is based on an averaging in order to eliminate voltage fluctuations in the network in this manner. The influences of temperature can be compensated by the three-phase measurement principle. In consequence, the relative change in capacitance is used for determining the Δ C. This method has also proven itself over a prolonged time in the field [1, 2, 9] also impressing through its high signal-to-noise ratio.

If the capacitance values were to be determined separately for every phase with the help of a reference capacitance, the result would be the disruptive influence of temperature fluctuations [10].

The effect of a partial flashover of 2 layers of a 420 kV bushing is depicted in **Fig. 6.** The 3-phase operating voltages (phase L1, L2, L3) together with overvoltages of the 350 MVA regulating transformer are shown. On 27.11.2004 after only 1 ½ years of bushing operation a warning was generated automatically by the on-line monitoring system identified by a change in the bushing capacitance by 3.6 % (Fig. 6., small fig.). After switching off the transformer an off-line measurement was performed and proved the on-line determined value. The bushing was shipped to the manufacturer who also confirmed the result. Due to the installation of an on-line monitoring system a collateral damage could be prevented. In addition the system indicated that the transformer has been affected by overvoltages which could have been the most probable reason for the damage.

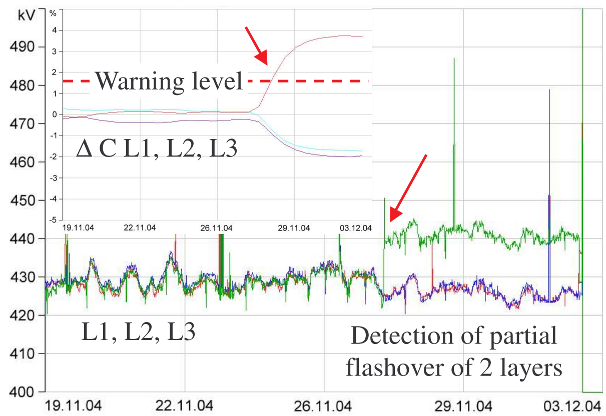

Fig. 6. Detection of partial flashover of 420 kV bushing and avoidance of collateral damage of 350 MVA regulating transformer, 3-phase operating voltages (phase L1, L2, L3) with overvoltages (large fig.), identified by change of capacitance Δ C (small fig.)

F. Dielectric dissipation factor tan δ and sum phasor

The measurement of the phase angle between the three phases makes it possible to detect changes in the dielectric dissipation (loss) factor tan δ. The difficulty in the measurement technique is in being able to detect even very slight changes. For example, a change in the loss factor tan δ by 0.1 % means that the phase changes by an angle of 0.057 °. The measurement data has to be recorded with a very high resolution in terms of time in order to achieve this accuracy. In this case, the sampling rate is 10 µs, to detect the zero crossing of the 50/60 Hz AC voltage. In addition, the evaluation algorithm carries out an interpolation to achieve further improvement in the accuracy. This ensures that detection of changes in the dielectric dissipation factor with adequate accuracy is achieved. The acquired voltage curves are transmitted to a central computer and processed digitally.

Another possible use is in the acquisition of the dissipation factor of bushings on single-phase transformers, since the voltages have to be recorded synchronously for determining the phase angle. In this case, the data is acquired on a de-centralized basis at every single-phase transformer, and analyzed on a central server in real time.

For the acquisition of the Δ tan δ, an accuracy of at least ± 0.15 % must be reached. The reason for this is that the dissipation factor for the various types of construction of bushings moves in the range of about 0.5 % (chapter III. B.) and a maximum warning threshold has to be assumed at about 0.7 %. In the case of offline measurements, it is in keeping with the current state-of-the-art to determine the dissipation factor using a reference capacitance and a reference voltage. These aids are not available on-line. Rather, in the case of an on-line measurement, as in the process described here, the voltage of another phase is used as a reference.

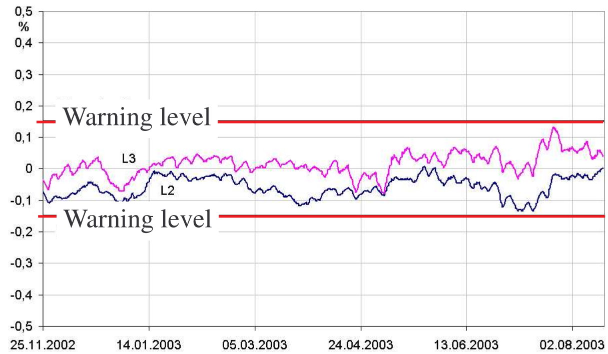

Fig. 7. Changes in the dielectric dissipation factor (Δ tan δ) of a 3-phase bushing monitoring system on a 400 kV generator transformer determined on-line

Different types of interpretation methods (change of dissipation factor vs. sum current phasor) with their advantages and disadvantages are discussed in the following. **Fig. 7.** depicts the changes in the dielectric dissipation factor tan δ of a three-phase bushing monitoring system on a 400 kV generator transformer during a period of nine months. Owing to the voltage fluctuation between the phases, the value varies in a range of less than ± 0.15 %.

In [11], a depiction of the sum vector of a three-phase bushing monitoring system is shown. Here, the vector addition of the voltages of the three phases is carried out over an analog operational amplifier and the sum vector is formed. The value determined and processed on the bushing is stored in a microcontroller. A graphical depiction is done in a polar diagram. As an example of such a measurement, **Fig. 8.** shows the polar diagram of a three-phase bushing monitoring of the transformer examined in Fig. 7. The evaluated database covers the same period of nine months. It can be clearly seen that the point cloud moves in a range of about ± 0.5 %. In addition, a warning threshold of ± 0.15 % has been shown in the diagram. It becomes clear that not all the depicted points are located within the minimum warning threshold to be assumed. The difficulty in the interpretation of this form of depiction is that the fluctuations of the three bushing capacitances overlap with the changes in the three dissipation factors. Even external disruptive influences like network asymmetries have a negative influence on the result. Therefore, a depiction of the sum vector in a polar diagram as suggested in [11] does not appear very meaningful. A better interpretation of the data is achieved by depicting the change in the dissipation factor (**Fig. 7.**).

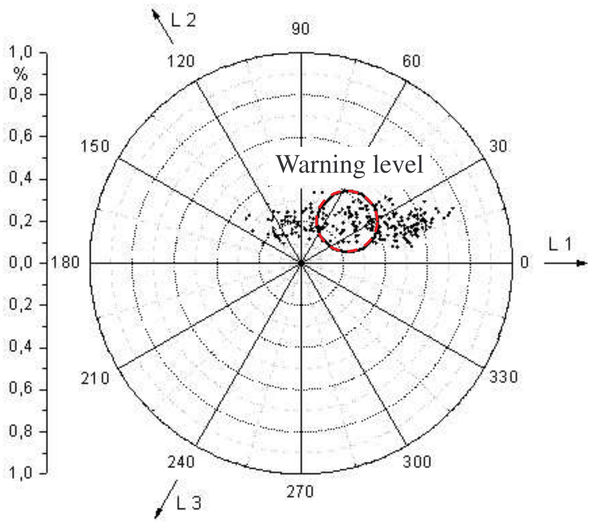

Fig. 8. Polar diagram of the sum vector of a 3-phase bushing monitoring on a 400 kV generator transformer

G. Bushing oil pressure

In addition, for oil-filled bushings, it is possible to measure the bushing oil pressure, thus detecting possible oil leaks. Another reason for changes in the bushing oil pressure is due to thermal overload or partial discharges.

Fig. 9. shows the changes in the bushing oil pressures of 400 kV bushings of a 850 MVA generator transformer over a period of 24 months. Owing to temperature influences, the value varies in a maximum range of ± 5 %. In August 2003, a significant drop in pressure was determined at the phase L1, whereupon the system generated a warning message. An on-site investigation showed that there was an oil leak involved at this phase. The leak was sealed and subsequent safe operation was thus ensured. Furthermore this case study showed that only the sensitive on-line monitoring system indicated revealed the failure. This practical example has pointed out that a supervision of the bushing oil pressure is valuable and key from safety point of view.

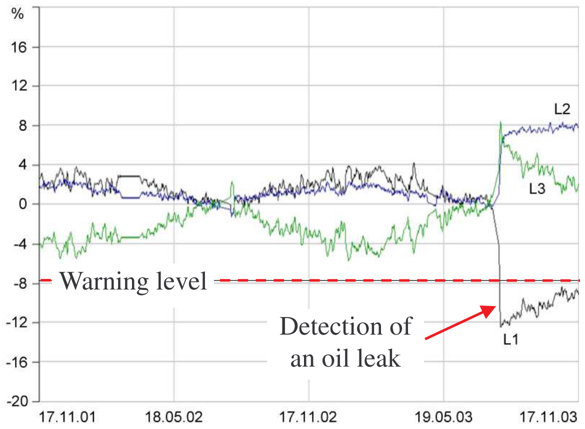

Fig. 9. 3-phase monitoring of the change in the bushing oil pressure on a 400 kV generator transformer with detection of an oil leak on phase L1

Summarizing this chapter decisive reasons for the failure of bushings can be found in the partial breakdowns of control layers, contact problems in measurement terminals, the wrong oil pressure or mechanical disturbances owing to external influences. These effects can be detected reliably by monitoring the change in the bushing capacitance and measurement of the bushing oil pressure.

IV. Insulation System and Tap Changer

To monitor the condition of the active part of a power transformer various measurement and analysing quantities can be realised. As main parameters, beside others, are to mention temperatures, loading conditions, gas-in-oil content, moisture of oil and paper insulation system. Due to space limitations in this contribution please refer to the extensive literature for practical examples [1, 2, 3, 4]. In this paper the following case study demonstrates how the condition of a power transformer can be monitored by use of a combination of active part and tap changer monitoring modules.

A 75 MVA furnace transformer was put in service in 1983 in a steelworks factory. In 2002 the 75 MVA furnace together with two more transformers of this site were equipped with an MS 2000 on-line monitoring system.

Fig. 10. shows the gas-in-oil content until major damage of the transformer. Up to 15.10.2003 the readings indicated a sudden important increase in 5 steps on a value of more than 400 ppm. Following the recommendations of MS 2000 a dissolved gas analysis (DGA)

was performed and indicated the presence of a hot-spot. To reduce the gases, an on-line degassing equipment was installed. The transformer was, however, kept in operation all the time. A correlation performed by MS 2000 of the gas-in-oil readings with the installed tap changer monitoring module indicated that the reason for the gas production could have been due to a oil/metal hot-spot in the area of the pre-selector tap changer contacts. From 22. to 28.01.2004 again the oil was simply degassed with an on-line equipment.

Finally, on 08.03.2004 at 11:00 a.m. the gas-in-oil content crossed the 1000 ppm limit. Nine hours later the transformer tripped through the Buchholz relay with a collateral damage.

This case study has demonstrated that the operating condition of the transformer was made transparent with the use of an on-line monitoring system. The company had been informed sufficiently in advance of the incident to take remedial actions, thus avoiding the collateral damage. From the first warning generated by the monitoring system on 15.10.2004 until the collateral damage on 08.04.2005 were passed app. 5 month. However the transformer was kept running all the time so that the damage occurred with the loss of production capacity for the company.

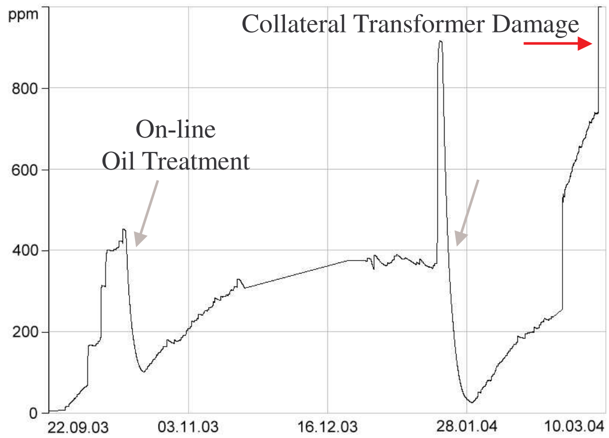

Fig. 10. Gas-in-oil content of a 75 MVA, 33 kV furnace transformer until collateral damage

V. Conclusion

In the framework of this article, it has been explained, on the basis of practical operational experiences with monitoring systems deployed in the field, how on-line condition monitoring and diagnosis can be realized.

The focus in this paper was to demonstrate how capacitively controlled bushings can be monitored on-line in a simple manner. The underlying principle of the measurement technique is based on the use of a capacitive voltage sensor that is installed at the measurement tap of the bushing. In this manner, the operational voltages can be measured, and deriving therefrom, overvoltages and transient voltages can be detected.

The change in the bushing capacitance as the most important characteristic quantity for determining the operational state can be analyzed reliably on this basis. In addition, practical examples have shown that the change in the dielectric dissipation factor can be acquired, but provides less information than the recommended simple on-line monitoring of the change in the bushing capacitance.

A critical damage of a 350 MVA grid coupling transformer could be avoided by a detection of a partial flashover of layers of a bushing indicated by a change in the bushing capacitance. Another collateral damage could be prevented by detection of an oil leak on a 850 MVA generator transformer by means of monitoring the bushing oil pressure.

Furthermore a case study of a 75 MVA furnace transformer has demonstrated the detection of its condition from beginning of a fault until collateral damage. It has been demonstrated that the operating condition of the transformer can be made transparent with the use of an on-line monitoring system. The analysing modules of active part monitoring together with tap changer monitoring have pointed out the failure cause, the problem was well known in advance.

Overall, investigations have shown that malfunctions that are building up in power transformers can be detected earlier with the deployment of an efficient on-line monitoring system and as a result, there is a lower potential for transformer endangerment.

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