Monitoring and Diagnosis of Power Transformers

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Abstract
Power transformers are one of the most important components of electric networks. These devices are very expensive and therefore diagnosis and monitoring systems will be valuable for preventing damage to them. A facility for viewing the status of transformers remotely by experts who will make an appropriate decision in case of a problem is needed to prevent premature damage to the transformers. The transformers are geographically spread and with the aid of Internet, it is possible to collect appropriate information from these transformers to a central node for diagnostic purposes under the supervision of high voltage engineering experts. The aim of this paper is to show the main problems related to power transformers and to review mitigation methods for the monitoring and diagnosis of power transformers.

1. Introduction
Power transformers are important and expensive equipments in electric energy networks. The majority of these devices have been in service for many years under different environmental, electrical, and mechanical conditions. In addition to the costs associated with equipment repair or replacement, the capital loss of an accidental power transformer outage is often counted in million dollars for output loss only /1/. Because of this economic motivation, on-line monitoring and diagnosis (M&D) system are of benefit to predict fault conditions and maintenance of the high voltage transformers. There are some sensors and measuring devices that can be installed on each transformer to collect vital data about the transformer’s condition.

The selection of the monitoring functions is determined mainly by two goals. On the one hand, the faults must be promptly recognised, so that the operator can avoid critical conditions and on the other hand, the maintenance work is planned only, if the condition of the plant requires it. The basis for the selection of the sensors and the functions are specific faults statistics and maintenance schedules dependant. The processing of the measured values represents a further aspect. Monitoring is a component of the service concept of the manufacturer. As direct expectation to a diagnostic system, the following terms are important:
- extension of the remaining useful life of the transformer,
- improvement of loading possibility of the transformer,
- higher availability and supply security,
- condition-based maintenance and repair,
- prevention of the loss and the destruction.

2. Condition Monitoring
In the last few years, companies from different business areas such as power engineering have become increasingly interested in diagnosis and condition monitoring. Condition monitoring (CM) is the process of monitoring the operating characteristics of transformer in such a way that changes and trends of the monitored characteristics can be used to predict the need for maintenance before serious failure occurs, and/or to estimate the health of the transformer.

CM is the technique that used for Condition-Based Maintenance (CBM). Before this, time-based maintenance was the only maintenance strategy for a long time. Manpower and time and money were wasted because the activity of maintenance was blind with little information about the current condition of the transformers. On the contrast, CBM will provide to operators more useful information about the state of transformers and will propose some changes in traditional maintenance program /2/.

2.1 Data acquisition systems
Data acquisition systems (DAS) are the basis for building M&D tools that enable supervision by local and remote systems. DAS will be used to obtain appropriate output signals from sensors, installed in/on power transformers. DASs and monitoring systems provide condition monitoring systems with the necessary information about the state of
equipment. Remote access to this information provides significant benefits by allowing the collection of condition-related data from wherever equipment is located. A monitoring system should deliver data and functions to analyze what happens inside the transformers. This knowledge should help to increase the lifetime of transformer operation.

2.2 Software systems and tools for M&D of high voltage transformers

Various tools and methods for M&D of high voltage transformers are actually available. Basically, they can be divided into:

- traditional diagnostic methods that have been used for many years,
- new methods that range from methods that are starting to be used and,
- methods that are still at the research stage.

Some examples of traditional methods are: dissolved gas analysis (DGA) /3, 28-30/; Insulating oil quality, Power factor testing /31/; winding resistance /32/, and thermograph /33/ . New methods include: online PD testing /34, 35/, recovery voltage measurement /36/, tap changer monitoring /37/, internal temperature measurement /38/, on-line power factor measurement, dielectric spectroscopy /39/, and winding deformation detection /40/. Some of these mentioned methods are implemented using software systems, which gives more definite indications of transformer problems than conventional analysis /41-43/. The use of software can improve the reliability and provide facilities to analyze test data. It can also be used to extract information and knowledge that is not available and not visible from the data directly using advanced information technology methods such as Data Mining /44/. The present advancement in artificial intelligent (AI) modelling techniques has enabled power engineers and researchers to develop useful artificial intelligent software for diagnosing transformer faults. For example, artificial neural network or ANN approaches are used for DGA method /45-50/. Fuzzy logic is another AI technique in power system associated with the uncertainty of changing power operational condition, numerous power system configurations, imprecise information input by human operators, disturbances and faults /45, 51-54/. Fuzzy Logic can handle complex and imprecise problems that, traditional techniques cannot handle.

Expert systems have been proposed to manage knowledge processing. An expert system is a computer program that performs a complex decision making task within a particular narrow problem domain that is normally done by a human expert. It is based on the idea of taking the knowledge from a specialist and expressing it in an appropriate representation to exploit the knowledge in the same way as the human expert does and above all with the same result. The use of expert systems for transformer diagnosis /51, 55, 56/ offers the potential of reducing the overhead required by substations to maintain the transformers.

Y. Han /57/ has mentioned four online monitoring and diagnostic systems in his survey. Table 1 shows the main features of these four systems. The first system /58/ uses a model based technique for diagnostic purpose. In model based diagnostic a model that, will be built as a reference, and then the difference between the output of a measurement model and the reference model can be observed to detect and locate faults. In this system, Diagnostic was performed using two models: (1) Gas in oil model and (2) Temperature model. The second M&D system /59/ uses some available sensors to provide warning signals and data on multiple gases, PD levels, on load tap changer performance and temperature. The Siemens system is used to monitor quantities such as Gas in oil, temperature, voltage, current, etc. /60/ . In this system, the acquisition hardware is mounted in a cubicle at the transformer and the obtained data will be sent to a PC in a control room near the transformer.

In ALSTOM system /61/, an industrial PC, can be installed next to the power transformer in a cabinet. Several transformers can be monitored with one PC installed in the control room. Different quantities in this system such as Bushing, temperature, Gas in oil, etc., will be monitored.

<table>
<thead>
<tr>
<th>Name &amp; manufacturer</th>
<th>Monitoring quantity</th>
<th>Diagnostic function</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td>MIT’s model-based system /35/</td>
<td>Gas in oil, temperature</td>
<td>Giving identified cause and decision-making for maintenance</td>
<td>Thermal model is expected to be improving.</td>
</tr>
<tr>
<td>Monitoring and diagnostic equipment, ABB /36/</td>
<td>Multiple gases, partial discharge levels, online tap changer performance, loading and key temperatures</td>
<td>Offline, DGA interpretation, PD location Prediction of OLTC failure by vibration analysis</td>
<td>Life expectancy assessment is mentioned. But no detail descriptions of the methods.</td>
</tr>
<tr>
<td>SIEMENS power transformer monitoring system /37/</td>
<td>Gas in oil, temperatures, voltages and currents, tap changer position, moisture, oil level, etc.</td>
<td>Giving alarm if some quantities are exceeding preset limits</td>
<td></td>
</tr>
<tr>
<td>ALSTOM MS2000 monitoring system /38/</td>
<td>Gas in oil, hot-spot temperature, cooling plant information, of tap changer position and current, etc.</td>
<td>Giving alarm, visual measuring data, remote diagnosis</td>
<td>Using field bus technology for data communication</td>
</tr>
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</table>

Table 1 Some developed on-line monitoring and diagnostic systems for transformer

2.3. Data pre-processing

Real world data sets are usually not directly suitable for performing data processing algorithms. Collected raw data (data collected by sensors and other source of data) usually
contain redundant and erroneous data. Missing values and noisy data are typically kind of erroneous data. An important aspect of M&D system is the accuracy of information received by the sensors and other source of information. The acquired data should be consistent and as much noise-free as possible. Data pre-processing is used to reduce the quantity of data whilst retaining useful information and improving its quantity, with minimal loss of information.

### 2.4. Monitoring

Monitoring subsystem is used to give clear information to the operator and expert about all stages from data acquisition to diagnosis. Using monitoring, faults can be detected before they lead to a catastrophic failure.

![Block diagram of M&D system for each power transformer](image)

Figure 1: Block diagram of M&D system for each power transformer.

Monitoring subsystem and other part such as diagnostic allow us to change maintenance program and predict the faults that will happen in future.

### 2.5. Diagnosis

Diagnosis contains interpretation of data to determine the current condition of a transformer. The diagnostic task has an important influence on the overall maintenance cost as well as on reliability and availability. The use of advanced technologies has the potential to greatly reduce the time and increase the accuracy of transformer diagnostics. There are many different techniques for diagnostic purposes, such as: Expert Systems, Case-Based Reasoning (CBR), Model-Based Reasoning (MBR), Artificial Neural Network (ANN), Fuzzy Logic, Knowledge-Based Systems (KBS) and genetic algorithm. Although there are additional techniques, these have the highest potential for application to the diagnostic domain. All the technologies have their advantage(s) and disadvantage(s). In most cases they cannot work alone to solve the diagnostic problems and have to complement each other to form an integrated solution. Figure 1 shows the block diagram of M&D system for power transformers.

### 3 Damage analyses

#### 3.1 Damage statistics from the utilities

An inquiry [1] over the arising damage to transformers is shown in Figure 2.

![High voltage transformers failure rate as function of power ratings](image)

Figure 2: High voltage transformers failure rate as function of power ratings.

A transformer consists of several independently working components. These components are windings and cores as
Monitoring and Diagnosis of Power Transformers

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- gases (CO, CO₂),
- aldehyde groups (Alkaline) and
- groups of carboxyl’s (organic acids).
The ageing speed depends thereby on different parameters such as:
- temperature,
- water content,
- oxygen content,
- number and kind of temperature cycles and
- material properties.

As for example, a temperature rise around 8°C causes a doubling of the relative polymerisation speed [9]. Any increase of the water content around 1 % causes a similar increase of the ageing speed (Figure 5). It is thus evident that a dry transformer can be more highly loaded with same ageing. The water-in-oil originates from air moisture in the case of “open-breather” or “oil-conservator” transformer types, and the thermal decomposition processes from paper. So the water content in the insulating paper can rise approximately around 0.2 % per year due to water penetration from the surrounding environment. On the opposite, this value is approximately 0.03 to 0.06 % for hermetic transformers. Data collected from investigations with a waste of the polymerisation degree on 400, showed that typically, the rise of the humidity due to the decomposition of cellulose varies between 0.4 and 2 %. At an operating temperature of 90°C, the water content in the oil, as a consequence of ageing, can rise to approx. 50 ppm after 2 years.

3.2.4 Thermal causes
As a thermal cause, the losses are to be specified with priority, as they result from the demagnetisation of the core (eddy current losses) and the Ohm’s resistance of the coil inevitably. Heating up and cooling processes of the insulation with high temperature gradient, represent additional load of the insulators. Also, a strongly varying load, which leads to consequent warming up and cooling processes, have additionally a negative influence on the life span of the transformer insulation.

3.2.5 Chemical causes
Organic acids are developed as ageing by-products of the solid and liquid insulations, which attack in particular the paper insulation and so to speak to, to accelerated ageing. In addition metals such as copper, iron, aluminium and zinc which exist in each transformer are catalytic, and have thus likewise an accelerating effect regarding the ageing of the insulations.

4. Monitoring of different parameters as basis for a diagnosis
In contrast to laboratory measurements, on-site measurement is disturbed by extreme and mostly influence able conditions. In particular, within the range of the high-voltage areas, within which the transformers work, precise measurements are more difficult because of electrical and magnetic perturbative fields. The inspection devices must be brought thereby to the inspection item. The measurement set-up is firmly given by the firm installation of the test specimen. However procedure must be differentiated between on-line and off-line measurement. On-line procedures make it possible to detect at any time and also during the normal operation of the transformer. Furthermore on-line measurements offer the advantage that measuring data can be pursued during a longer period with almost same operating conditions. Thus, slow changes can be detected and a warning message or command to immediate disconnection can take place, if given limit values are crossed.

4.1 Chemical procedures
With the help of chemical procedures, some failures, in the transformer insulation can be determined. One of the standard investigations is the so called “gas in oil analysis (DGA)”, with which a sample of the insulating liquid is taken from the transformer and examined. This sample, after a vacuum extraction undergoes an analysis by gas chromatography to reveal the dissolved gases. The interpretation of different quotients of low-molecular hydrocarbon connections serves thereby to the determination of the failure. As an evaluation criteria, in particular, the Triangular method after Duval as well as, the MSS procedure after Mueller, Schliesing and Soldner are used [12, 13]. The disadvantage of these procedures is, the fact that they allow only one integral evaluation to the insulation. In addition, sampling and the following treatment of the sample can affect the measurement.

As further procedures, there is for example the furan analysis (HPLC) and the analysis of free gases collected in Buchholz-relay. While with the furan analysis, vital information on the quality of the solid insulation is obtained, the analysis of the collected free gases in Buchholz-relay provides information about the range of an available failure.

Failures in the insulation of transformers filled with liquid are nearly always accompanied by gassing. The quantity and the composition of dissolved gases depend both on the insulating liquid and on the kind and the energy quantity of the underlying failure. Large failures with high energy content cause large mass of gases in short time, while the produced quantity of gases in the case of small failures, are relatively small. The Buchholz-relay in its actual form indicates only gas amounts developed since the last exhaust, however not the history of the gas emergence. So long lasting, but nevertheless low energy failures e.g. PDs lead to a continuous gas production, while failures with high-energy content like local overheating generate high gas rates within short periods. The Buchholz-relay cannot differentiate between these failures, so that only rough failure estimation is possible.

In order to make a better evaluation of the available failure, it is meaningfully to determine the gas rate. This statement makes the electronic Buchholz-relay possible, which is to serve as an extension for the Buchholz-relay, without limiting its function. This system determines thereby the history of the gas emergence, which, during simultaneous recording of the operating conditions, permits additional
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conclusions on an available failure. With the analysis of gases found in the Buchholz relay, also procedures are helpful, which consider the way of the gas bubbles up to their tie point in the Buchholz relay and the change of the gas composition over the time.

4.2 electrical procedures
For the detection of an available damage, there are different possibilities. While the chemical give a cumulative statement about the period passed since the last analysis, the electrical procedures allow a statement about the current condition of the transformer. In the following, some procedures for the on-line (e.g. Partial Discharge measurement) and off-line (e.g. measurement of the transfer function) measurement at transformers are introduced in greater detail.

4.2.1 Partial Discharge measurement
Partial Discharges result from a local failure of the electrical insulation, which leads however not immediately to a complete failure. A cause for this is inhomogeneities which can be e.g. cellulose fibre from the solid insulation, conductive impurities or also small gas areas (so-called "Micro voids"), which can occur both in the solid and in the insulating liquid.

Partial discharges are in most cases determined chemically during gas in oil analysis, since they show up typically an strongly increased hydrogen content. A continuous measurement of PD during the operation is not used at present yet, since the narrow-band measurement of the partial Discharge signals on site is expenditure and in addition, no localization of failure is possible. A diagnostic system was therefore developed which permits from the wide-band measurement of partial Discharge signals a determination of the PD source and a determination of the apparent charge converted at the defective equipment. The diagnostic procedure is based on the evaluation of the signal deformation of PD pulses within the transformer by mathematical algorithms and permits by the determination of PD location as well as the charge quantity a qualified analysis of the failure.

For this procedure, it is necessary to note the high frequency partial Discharge signals both at bushing and at the neutral point. In these data both the current pulse caused by the PD and the deformation, experienced by this impulse during its transmission by the turns of the transformer, are contained. If this deformation, experienced by the impulse is known, then it can be reckoned back from the ends of the windings of measured signals on different original places. These computations are accomplished both from the high voltage and the neutral point side. The signals calculated for the different sections of the windings compared like that are identical at the true location of the PD signal calculated from both sides [14].

A further advantage of this procedure is that the calculated signal corresponds to the actual partial Discharge signal. It is thus possible to estimate charge contents of the PD at its generation place.

The transient characteristic of the transformer winding, necessary for the computation of the deformation of the partial Discharge signal, can be determined by the

Figure 6: Fault location in a transformer coil
In order to suppress the sinusoidal spurious signals during the measurement, with the presented wide-band measuring method, optical transducers are used, which convert the PD signal directly after its decoupling into an optical signal, which will then transfer via fibre-optic cable to the test van. Thus a launching is so efficiently suppressed by spurious signals that in particular continuous sinusoidal noises are nearly no longer present, so that a digital filtering of the remainder disturbances is possibly problem-free. However the diode-rushes in the measuring is small relative to the PD signal and thus can efficiently be suppressed by digital filters, which are based on the Wavelet transformation [17].

Figures 8 and 9 give an overview of the measurement set-up on site, as well as the digital detection equipment of the measuring signals. As can be seen in Figure 8, it is clear that the PD signals are decoupled directly at bushing by means of a special, patented sensor. The signal is then amplified and finally transferred into an optical signal. This later is then transferred to the measuring instruments in the test van via a fibre-optic cable, where the digital evaluation of the PD signals take place (Fig. 9).

4.2.4 Measurement of the transfer function

Defects can be recognised by the measurement of the transfer function of the individual transformer coils such as turn short-circuits or deformations. The current measurement is compared with a “finger print”, which must be determined first as reference. Deviations with a comparison of the reference transfer function with the current transfer function point then on a failure. Whereby, with the bandwidth of the transfer function measurement, the sensitivity of the method can be increased. Such transfer function measurements can be accomplished on and offline, whereby with offline measurements, the impulse response can be determined by different procedures. Usually a network analyser can be used. Furthermore it can takes place by the evaluation of the response of a coil to a delta impulse, which is characterised by a rise time of some 100 ps. For online measurement, instead of the delta impulse a steep
switching impulse can be used [19]. The evaluation of the response to such an impulse can lead to the determination of the transfer function.

4.3 dielectric methods

The dielectric methods are used as offline procedures and permit a more exact view of the insulating system, if an extended statement about their condition is to be met. In the following, three procedures are presented briefly. From the dielectric answer of the insulating system the insulation condition can be determined.

43.1 RVM (Recovery voltage Measurement)

Figure 10 shows in principle the emergence of the recovery voltage. During the time 0 ≤ t ≤ t₁ the specimen is loaded with the voltage U₀. During the time t₁ ≤ t ≤ t₂, the clamps are short circuited. After the time t₂ the recovery voltage develops itself, which can be measured on the open clamps of the test specimen.

Figure 10: principle diagram of the emergence of recovery voltage.

In the following the processes, which take place at these procedures, are described briefly. If a dielectric material is loaded due to an electrical field E, the material is polarised due to the polarisation processes. The connection between the vector of the electrical charge density D, the electrical field E and the polarisation P described by the following equation:

\[ D = \varepsilon_0 E + P \]  

The physical constant in this equation represents the permittivity of the vacuum. The connection between the charge density D and the electrical field E in an insulating material is generally linear and with the help of a constant, which is called relative permittivity, is described as follows:

\[ D = \varepsilon \varepsilon_0 E \]  

From the equations (1) and (2) the connection between polarisation P and the electrical field E can be described as follows:

\[ P = \chi \varepsilon_0 E = \varepsilon_0 (\varepsilon - 1) E \]

The value \( \chi \) in this equation represents the dielectric susceptibility of the medium. The polarisation processes are time and frequency dependent and are caused by different phenomena in the dielectric [20].

The response function describes the memory ability of a dielectric system and supplies significant information about the insulating material. If the short-circuit is opened, the charges bound by the polarisation will be free and cause a voltage between the clamps of the dielectric. This voltage is called the recovery voltage. The recovery voltage is caused by the relaxation processes in the dielectric. The outside current during the RVM measurement is zero. The phenomenon RVM can be described with the help of the alternate circuit diagram of the dielectric. As mentioned, the slow polarisation processes of the function \( f(t) \) decrease continuously and thus the relaxation current. The current can be simulated by a sum of differential equations [21]. This sum represents together with the capacity \( C_\infty \) at power frequency and the insulation resistance \( R_0 \), the basis for the equivalent circuit diagram (Fig. 11).

Figure 11: equivalent circuit diagram for a linear dielectric.

If the voltage \( U_0 \) is applied at the clamps of this circuit the polarisation currents as well as the constant current through the resistance flow into the circuit and the capacity \( C_\infty \) is charged up. With time delays, according to the RC elements also their capacities are loaded. Depending upon duration of the load time the polarisation processes in the RC elements are partly or completely activated. A brief unloading due to a short-circuit causes first only an unloading of the capacity \( C_\infty \). With longer short-circuit time also slower polarisation processes begin with reconciliation. After opening the clamps (remove the short-circuit), the recovery voltage can be measured as consequence of the polarisation processes, which did not take place or were not finished during the short-circuit, in form of unloading in \( C_\infty \) and \( R_0 \). The amplitude of the recovery voltage is proportional to the voltage \( U_0 \).

4.3.2 PDC analysis

4.3.2.1 PDC analysis

For the determination of the ageing condition of the insulation, the PDC (Polarisation and Depolarisation Current) analysis represents a further procedure for the diagnosis of the power transformers insulation [22, 23].

With a linear and homogeneous insulating putting on a time-variable electrical field \( E(t) \) the polarisation can be defined as follows:

\[ P(t) = \varepsilon_0 (\varepsilon_\infty - 1) E(t) + \varepsilon_0 \int_0^t f(t-t') E(t') dt' \]

where \( f(t) \) describes the so-called response function of the dielectric. The electrical charge density is then described as follows:
\[ D(t) = \varepsilon_0 \varepsilon_{\infty} E(t) + \varepsilon_0 \int_{-\infty}^{t} f(t - t_0) E(t_0) dt_0 \]

The first part of this equation describes the fast polarisation processes, while the second part formulates the slow polarisation processes. If now an electrical field \( E(t) \) is applied to a dielectric material, both the bound and the free charge carriers will induce a current. The movement of the free charge carriers represents the conductivity whereas the bound charge carriers represent the dielectric displacement. The current density \( J(t) \) consists thereby, on the addition of the capacitance current and the conduction current as follows:

\[ J(t) = \sigma E(t) + dD / dt \]

\( \sigma \) is the direct current conductivity and \( D(t) \) is the dielectric displacement. If at the time \( t = 0 \), a step voltage is applied at the clamps of the insulation, the bias current can be determined from the following relationship:

\[ J_{\text{polarisation}} = E \left( \sigma + \varepsilon_0 f(t) \right) \]

In the case of insulation with the capacitance \( C_0 \), the bias current is deduced as follows:

\[ J_{\text{polarisation}} = C_0 U_0 \left( \sigma / \varepsilon_0 + f(t) \right) \]

If we now disconnect the step voltage from the insulation, we record the so-called depolarisation current as follows:

\[ J_{\text{depolarisation}} = - C_0 U_0 \left( f(t) - f(t + t_{\text{charging}}) \right) \]

With the assumption of a large charging time in comparison to the calculated response function, the second part of the above function can be neglected. The response function \( f(t) \) is then proportional to the polarisation current. In this case the response function and the conductivity can be determined from the polarisation, depolarisation current.

4.3.2.2 PDC analysis as a method for determination of water content in the solid isolation of transformers

PDC analyses was introduced by different authors as a tool for determination of the water content in the solid isolation of transformers [24]. For this purpose, during a certain time \( t_0 \), a DC voltage \( U_0 \) is applied between primary and the secondary coils of the transformer. Thus a current is generated, which drops due to the conductivity of the dielectric to a constant value. After the time \( t_0 \), the voltage is switched off and the circuit is short circuited over an ammeter. Thereby, an opposite depolarisation current flows, then in the time it falls to the value zero (Fig. 12).

On the basis of a model of the transformer main insulation, which is set up with the help of the polarisation characteristic, humidity content and geometry of the main insulation defined by samples of a material, the polarisation current can be determined. From the comparison of computation and measurement statements, information about the humidity in the main insulation can be obtained.

4.3.2.3 Measurement of the dielectric response in the frequency domain (FDS)

This method is based on the generalisation of the well-known tan \( \delta \) measurement at power frequency. The difference with the conventional tan \( \delta \) measurement consists in the fact that, in place of one measurement at power frequency, many measurements at different frequencies are performed. Mathematically, the former introduced measured values (PDC) can be transferred into the frequency domain with the help of a Laplace or a Fourier transformation. The current density in the frequency domain \( J(\omega) \) under the influence of the field \( E(\omega) \) can be described as follows:

\[ \tilde{J}(\omega) = \frac{\sigma_{\text{dc}}}{\varepsilon_0 \omega} + \chi'(\omega) - \frac{\sigma_{\text{dc}}}{\varepsilon_0 \omega} + \chi''(\omega) \]"
determined. At very low frequencies the measurements are very time consuming.

4.4 further procedures

4.4.1 Temperature measurement

The overload capacity of a transformer is limited among other things by reaching the permissible maximum temperatures of coil and oil. For the determination of the hot spot temperature after International Electrotechnical Commission (IEC) 60354 different procedures can be used. A complex however relatively exact method is the measurement of the temperatures along the coil and the core with the help of an integrated fibre-optic cable. With the help of Raman effect, the temperatures in different places along the fibre-optic cable can be determined. This technology which was tested originally on cables, has the disadvantage that, the integration of the fibre-optic cable must take place during the production of the transformer, so that for operating transformers, this method is unsuitable. In addition this procedure is relatively cost-intensive. In monitoring systems offered presently, another method are used. With this procedure the temperatures on different places are measured, in order to then compute the hot spot with the help of a thermal model. This procedure can be used in principle for all transformers and is therefore not only more favourable, but also more universally applicable.

5. Summary

Transformers are some of the most valuable assets in power networks. Only slight faults may lead to a failure of the whole transformer. An overview of failure statistics collected from utilities in the last years and the fact that many of the installed transformers have already a high age. Nowadays, the majority of them are approaching or exceeding the age of 25-30 years. With increasing age there are potential risks of extremely high monetary losses due to unexpected failures and outages. In order to conserve transformers “health”, valuable monitoring and diagnosis are of prime importance. Field experiences have revealed that the leading cause of failures arises in the active component and in the tap changer. The failure can be caused thermally, electrically, dielectric or mechanical. In order to diagnose transformers, suitable sensors have been developed worldwide to perform reliable diagnostics and monitor online/offline the operating state.

The most frequently applied sensors are:
- For the monitoring of bushings the capacitive divider in the bushing is used.
- The hot spot temperature is determined over the measurement of the load current.
- With the help of the Hydran sensor the quantity of hydrogen dissolved in the oil can be detected on line.
- For the determination of the oil humidity, a sensor (from Vaisala), which measures the relative humidity in the oil online is available.
- The humidity in the paper can be measured either directly with a paper humidity sensor or can be computed indirectly from the oil humidity and the temperature provided, the transformer is in thermal equilibrium.
- With the measurement of the transient oil pressure, a possible loosening of the clamp forces of the coil can be determined.
- With the measurement of the tap changer capacitance drive, a monitoring of the tap changer can be performed.

The measurement of different parameters takes place either online or offline. The measuring procedures can thereby be chemical, electrical, dielectric or other procedures.

Chemical procedures:
- One of the most common procedures that usually take place offline is the gas in oil analysis.
- Furan analyse provides, among other things, a statement about the condition of the cellulose.
- The determination of the humidity in the oil and in the paper can provide information about the insulation condition.

Electrical procedures:
- The PD measurement, is still usually accomplished offline. There are already electrical procedures, which permit a detection of the source of PD beside the intensity of the PD. The PD’s can be located under certain conditions acoustically.
- With the help of the determination of the transfer function, which can take place on-line or offline, a mechanical deformation of the coil can be determined.

Dielectric procedures:
- From the determination of the dielectric response of the insulation in the time or in the frequency domain, the insulation condition can be determined.
- The procedures in the time domain are RVM (Recovery Voltage Measurement) and PDC (Polarisation Dependence Current) measurement. In particular, the PDC measurement has been found to be a valuable procedure for the determination of the humidity of the cellulose.
- The determination of the dielectric response in the frequency domain is made by the measurement of tan δ and capacity over the frequency range from 0.0001 Hz to 1000 Hz.

6. References

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2524


