Possibilities of the Diagnosis of Power Transformers on Site

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Abstract
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Introduction
As consequence of the liberalisation of the electrical power supply in the last years the need and the interest in measures rose for the life span extension and load optimisation of the components of the electrical power supply strongly. For this purpose the knowledge about the condition of the component is of great importance.
Transformers are one of the most important and most cost-intensive components of the electrical energy grids. In addition, worldwide the transformers are relatively old. Many of the power transformers in the electrical power supply approach the end of their normal age. Although many of these transformers are still in operation, the danger exists that signs of ageing and possible damages of the isolation are present already, which a life span reduction and a loss of the transformer can entail. The basis for the development of suitable monitoring and diagnostic systems forms the disturbance and damage analysis.
The selection of the monitoring functions is determined mainly by two goals. On the one hand the errors 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 error statistics and maintenance plans. The processing of the measured values represents a further aspect. The 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 remainder of the 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 Damage analysis

2.1 Damage statistics from the utilities
An inquiry /1/ over the arising damage to transformers shows fig. 1. The comparatively highest damage arises as expected at 380 kV transformers. It is shown with the fact that almost 80% of the errors are due to mechanical, electrical and dielectric stresses. Fig. 2 /1/ shows the proportional distribution of the damaged transformer components. The diagnostic measures must consider the frequency and the importance of the errors at the different transformer components. A further value, which besides should be considered, is the age of transformers. A view of the age structure of transformers of a large German utility makes clear that most transformers have already a high age (fig. 3 /2/). Fig. 4 shows the age structure of 380 kV transformers /2/. A view of the error rate in dependence of the time shows that starting from approximately 25 years the error rate rises rapidly (fig. 5) /3/, whereby a punctual revision causes a shift of the error rate around approximately 5 years.

2.2 damage causes
The damages in transformers can be caused through
- electrical
- electromagnetic
- dielectric
- thermal and
- chemical stressness.

Earlier statistics /1/ show that the most frequent causes for long outage damages are appropriate in tap changer, active component and in bushings (see also table 1) /1/.

2.2.1 electrical causes
In the isolation it can come locally to overstressing. The consequence is an ageing of the insulating oil and the cellulose, which leads to an acid generation and pollution in the oil, an increase of the water content, gas and mud formation and to a decrease of the breakdown voltage. The water can lead to an acceleration of the depolymerisation of the cellulose. The ageing of cellulose can be accelerated except by water also by oxygen and temperature /4/. fig. 6 shows the relation between relative depolymerisation velocity as well as water content and temperature.

2.2.2 electromagnetic causes
High forces in the coil, which can lead to a deformation of the coil, can be caused e.g. as consequence of short-circuits in the net. These deformations can lead to breaking the paper insulation in particular with aged papers. The consequence is first the generation of partial discharge and finally the breakdown.

2.2.3 dielectric causes
The quality of the paper isolation in a transformer depends on the polymerisation degree (number of the glucose rings and chains) of the paper. During ageing the chains are up-smelled consisting of glucose rings and develop:
- water,
- 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.

A rise in temperature around 8°C causes a doubling of the relative polymerisation speed. An increase of the water content around 1% causes a similar increase of the ageing speed (fig. 6). It is thus evident that a dry transformer can be more highly loaded with same ageing. The humidity in a transformer can take place from penetration of the water from the outside or result via decomposition processes from paper and oil. So the water content in the paper isolation can rise approximately around 0.2% per year due to water penetrating from the outside with an open transformer, while this value is with a closed transformer with approximately 0.03 to 0.06%. The rise of the humidity due to the decomposition of cellulose varies between 0.4% and 2% depending upon investigation with a waste of the polymerisation degree on 400. With an operating temperature of 90°C the water content in the oil in consequence of ageing can after 2 years rise on approx. 50 ppm.

2.2.4 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. There each heating up and cooling of the isolation represent an additional load of the insulators, also a strongly varying load, which leads to corresponding warming up and cooling processes, have additionally a negative influence on the life span of the transformer isolation.

2.2.5 chemical causes

Organic acids are developed by the ageing of the solid and liquid insulators, which attack in particular the paper isolation and so that lead to a far 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 insulators.

3 monitoring of different sizes as basis for a diagnosis

In contrast to laboratory measurements the on-site measurement is disturbed by extreme and mostly influenceable 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-lines. On-line procedures make it possible to detect at any time and also during the normal operation of the transformer. 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 be taken place a warning or in the border line a disconnection immediately, if given limit values are crossed.

Problems can follow with a such measurement however from the operating conditions of the respective transformer. In addition, these problems can result on the one hand from the noisy environment, which exist on site, and on the other hand can in the measuring procedure be justified, which does not permit the normal operating conditions. In this case then an off-line measurement must be accomplished. This can be accomplished regularly e.g. on the occasion of the maintenance work at the transformer or also only after being present special findings e.g. a gas in oil analysis. In contrast to on-line measurements the investigations with off-lines offer the opportunity of measurements and examinations, which are otherwise not feasible. So e.g. different stressing forms and measuring methods can be used. The measurements can take place with different working stress levels, whereby the influence of outside disturbances is smaller. Some of the usual sensors for the monitoring are introduced briefly in the following.
Bushings:
For the determination of overvoltages the usual capacitive dividers can be used. Thereby into most executions the existing measuring connection is inserted. The hereby attainable frequency range of the measuring signals is about 2 MHz. This is sufficient for the measurement of transient procedures, caused e.g. by lightning’s or switchings. A breakdown between two layers of the bushing-capacity causes a change of the isolation of the bushing. By a 3-phase stress measurement the change of the bushing capacity can be determined.

Thermal monitoring of the active component:
The load current is an important initial value for the determination of the hot spot temperature according International Electrical Commission (IEC)60354. For the calculation of the overload capacity and the controlling of the cooling system serve the oil and the ambient temperature as inputs.

Solved hydrogen in the oil:
Solved hydrogen in the oil is an indicator for certain errors e.g. the occurrence of PD in the isolation. There are meanwhile in addition, sensors (e.g. Hydram of the company GE /), with whose assistance the hydrogen content in the oil can be measured permanently.

Oil humidity:
The permanent measurement of the oil humidity permits a recognising of an inadmissible insulating oil condition. In addition, the humidity of the active component can be recognised. There are sensors, for example the HMP228 of the company Vaisala /, which can determine the humidity content of the isolating liquid continously.

Humidity in the cellulose:
An important parameter, which accelerates the ageing of cellulose, is the water content in the cellulose. The water content in the cellulose can be determined from the water content in the liquid with well-known temperature. Since however due to variations in load the temperature constantly changes, reaching of the equilibrium between the humidity in the oil and the humidity in the cellulose is not always given. For a determination of the humidity in the cellulose from the humidity in the oil however the equilibrium is the condition. For this reason a sensor was developed, which can be installed in a field-free area in the transformer liquid and which measures humidity directly in the cellulose. The sensor consists of paperlayers, which are clamped between two electrodes. From the change of the capacity and the conductance of the arrangement due to the humidity in the paper the paper humidity is determined.

Transient oil pressure measurement:
By the measurement of the transient oil pressure, e.g. when a transformer is switched on, a loosening of the coil and thereby the reduced resistance to short-circuits can be determined //. During the coil vibration measurement beside the highly sensitive measurement of the oil pressure fluctuations the causing transient coil stream e.g. switching on and short-circuit stream are registered. With the coil vibration measurement among other things the following mechanical influences of the structure of the coil can be detected:
- reduced axial coil windings clamping forces due to thermal-oxidative ageing of the paper insulation or transport damage
- winding deformation due to short-circuit stresses
- inadmissible contraction of the paper isolation and thus reduction of the axial clamping forces by overheating of the coil.

Tap changer:
It is to be taken from the table 1, that the tap changer represents one of the most frequent failure causes. This makes the necessity for the monitoring of this important component clear. The number of switchings and the total current on the contact can be determined by
the recording of the tap changer position and the working current. These data are necessary for condition-oriented maintenance of the tap changer, since the burn-up of the contacts is a function of the switched load current. By recording and evaluation of the energy consumption of the tap changer drive with a staggering procedure information about the mechanical condition of the switch is received. Thereby the power consumption is proportional to the torque at the drive shaft. The different stage procedures have specific finger prints. From this, changes of the torque, caused by mechanical disturbances, can be detected.

3.1 chemical procedures
With the help of chemical procedures, the errors, which developed since the last such measurement in the transformer isolation can be determined. The procedures are however cumulative, i.e. it is not possible to say, when exactly the detected errors for the first time arose. One of the standard investigations is the so called “gas in oil analysis (DGA)”, with which a sample of the liquid insulant is taken from the transformer which can be examined. From this sample then after a vacuum extraction with following analysis by gas chromatography the gases desolved are determined. The interpretation of different quotients of low-molecular hydrocarbon connections serves thereby to the determination of the error. As an evaluation criteria in particular the Triangular method after Duval as well as, the MSS procedure after Mueller, Schliesing and Soldner are used [10, 11]. The disadvantage of these procedures is in the fact that they allow only one integral evaluation to the isolation. In addition sampling, and the following treatment of the sample can affect the measurement.

As further procedures, are for example the furanaanalysis (HPLC) and the analysis of free gases collected in Bushelz-relay. While with the furanaanalysis conclusions on the quality of the solid isolation are possible can the analysis of the collected free gases in Bushels-relay give information about the range of an available error.

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

In order to make a better evaluation of the available error, 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 conclusions on an available error. With the analysis the gases found then in 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. In the last years also a set of systems came on the market, which allow on-line determination of some chemical characteristic data during the transformer operation. Beside the water content is for example also the hydrogen, solved in the isolating liquid. Increased hydrogen values are always a sign for an error in the insulants, so that a rise of this value can indicate the necessity for further investigations. It is in the meantime also possible to seize during the operation of the transformer all gases, which are needed for a gas in oil analysis.
3.2 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 permit the electrical procedures 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.

3.2.1 Partial Discharge measurement

Partial Discharges results from a local failure of the electrical isolation, which leads however not immediately to a complete failure. A cause for this inhomogeneities can be e.g. cellulose fibre from the solid isolation, conductive impurities or also small gas areas (so-called "Microvoids"), which can occur both in the solid and in the isolating liquid. Regarding the weight of the damage caused by the PD must be differentiated between the solid and the liquid isolation. While in the insulating oil following the liquid leads to a self healing can in the solid isolation the fibre of the cellulose be damaged, which leads to an acceleration of ageing.

Partial discharges are in most cases determined chemically during gas in oil analysis, since they show up typically in a 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 localisation of error 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 error. 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, which this impulse experiences during its transmission by the turns of the transformer, are contained. If this deformation, which the impulse experiences is known, then it can be reckoned back from the ends of the windings of measured signals on different places of origin. These computations are accomplished both by the high voltage and from the neutral point side and 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 /12/.

A further advantage of this procedure is, that this 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 is necessary for the computation of the deformation of the partial Discharge signal can be determined by the dismantling of the total transfer function of the transformer winding in partial transfer functions of the individual coil windings. This procedure is based on the modelling of the transformer winding and the comparison of the model with transfer function measured on the real transformer winding/13/. Fig. 8 shows schematically this procedure.

To clarify the described procedure fig. 9 shows the measured signals at both ends of the coil. From fig. 9 it is to be recognised clearly that the reckoned back signals at clamp 3 agree, so that the PD generation place can be located here. A substantial problem with the wide-band measurement on site consists of the fact that the measurements are affected by different spurious signals. Above all continuous disturbances, as sinusoidal spurious signals, which are caused e.g. by broadcast or other communication services, are usually inevitably and not a priori suppressible. It is necessary to reject these spurious signals with digital filter techniques without modifying the information signal significantly in form and amplitude, since otherwise no efficient evaluation of the measured PD can take place. In particular a separation between the PD signals and possibly arising pulse-type disturbers such as corona discharges will only be made possible after such a digital filtering /14/.

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 /15/.

Fig. 10 and 11 show the measurement set-up on site as well as the digital detection of the measuring signals. As in fig. 10 it becomes clear 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, which with a fibre-optic cable is transferred to the measuring instruments in the test van, where the digital evaluation of the PD signals take place, what in fig. 11 is represented.

3.2.2 Acoustic PD measurements

Acoustic methods represent a further possibility for the measurement of PD signals, which seize the pressure fluctuations due to a PD. Here several sensors in or at the transformer vessel are attached, whereby the sensor signals must be seized afterwards simultaneously, which often means a substantial measuring expenditure. With the help of different digital techniques, which are based e.g. on the triangulation method, afterwards a rough detection of the PD can take place, whereby however a determination of the apparent charge does not take place, since a necessary calibration, how it is with the electrical procedures standard, cannot be accomplished. The methods are used on-line and have the advantage that spurious signals can be suppressed as far as possible/16/. a serious disadvantage are however that the sensitivity of the measurement depends on the PD location. So e.g. PD signals, which have their origin on the core side of the coil, can be hardly recognised, since the absorption of the signal then is usually too large.

3.2.3 UHF PD measurements

UHF (Ultra High frequency) PD measurements were used first for GIS (gas isolating switchgears), whereby some advantages showed up, why this method transferred also to transformers. With usually on-line accomplished UHF measurements the effects of the PDs with frequencies over 300 MHz are regarded. Thus exists a not insignificant expenditure regarding the measuring instruments, since beside special amplifiers for these high frequencies also spectrum analysers are used, in order to select certain favourable frequency ranges. A further problem is that the sensors cannot be attached as during the acoustic PD measurement to transformers simply at the vessel. The sensors are applied e.g. on holes milled into the transformer vessel or integrated, if possible, inside the transformer. Since the expenditure is comparatively large for sensor mounting, often only 1 or 2 sensors are used, whereby then only one statement about it is possible whether a partial Discharge activity is present or not. A determination of the apparent charge is not possible here similar as with the acoustic measurements and a localisation is possible only if several sensors are used. Besides also spurious signals must be considered with the measurements, whereby during the measurements around approximately 1 GHz with priority portable radio services are to be regarded as interference sources. There are meanwhile also beginnings, which acoustic and UHF measurements combine, in order to reduce on the one hand the measuring expenditure and to achieve on the other hand a more exact localisation.

3.2.4 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 an error. 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 off-lines, whereby with off-line measurements the impulse response can be determined by different procedures. Usually a network analyser can be used. Furthermore it can take 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. By the on-line measurement instead of the delta impulse a steep switching impulse can be used /17/. The evaluation of the response to such an impulse can lead to the determination of the transfer function.

3.2.5 measurement of short-circuit impedance
The measurement of short-circuit impedance is in principle a simplification of the transfer function measurement, whereby the transient characteristic is measured here only with a particular or few discrete frequencies and not over a continuous spectrum as with the transfer function method. From a comparison with a reference value, which is usually determined after production of the transformer, then an evaluation of the mechanical deformation of the coils can be achieved. The procedure exhibits however uncertainties, so that in some cases also large deformations cannot be recognised, because sensitivity depends similarly as during the transfer function measurement on the selected frequency range.

3.3 dielectric methods
The dielectric methods are used as off-line procedure and permit a more exact view of the isolating system, if an extended statement about their condition is to be met. In the following one three procedures are presented briefly. From the dielectric answer of the isolating system the isolation condition can be determined.

3.3.1 RVM (Recovery voltage Measurement)
With this procedure first for a certain time DC voltage is applied at the clamps of the test specimen according to fig. 12. Here p(t) represents the step response of the dielectric. The first part in this diagram as answer of an idealised step voltage symbolises the fast polarisation processes p(t = to) = p∞. This part can be taken up neither in the time nor in the frequency range. After longer time all polarisation processes are terminated and the polarisation reach its endpoint p(t = ∞) = ps. After removing DC voltage the clamps of the test specimen are short circuit for a certain time. After removing the short-circuit a voltage at the clamps of the test specimen develops itself due to the polarisation and depolarisation effects, which is called recovery voltage. Fig. 13 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.

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:

\[ D = \varepsilon_0 E + P \]  

(1)

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:

\[ D = \varepsilon\varepsilon_0 E \]  

(2)

From the equations (1) and (2) the connection between polarisation P and the electrical field E can be described as follows:
\[ P = \chi \varepsilon_0 E = \varepsilon_0 (\varepsilon - 1)E \] (3)

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 \( /18/ \).

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 know 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\( /19/ \). 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. 14).

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 length 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 \( U_0 \).

### 3.3.2 PDC analysis

#### 3.3.2.1 PDC analysis

For the determination of the ageing condition of the isolation the PDC (Polarisation and Depolarisation Current) analysis represents a further procedure for the diagnosis of the isolation of power transformers\( /20, 21/ \). With a linear and homogeneous insulant putting on a time-variable electrical field \( E(t) \) the polarisation can be defined as follows:

\[ P(t) = \varepsilon_0 (\varepsilon - 1)E(t) + \varepsilon_0 \int_{-\infty}^{t} f(t - t_0)E(t_0)dt_0 \] (4)

\( f(t) \) here describes the so-called response function of the dielectric. The electrical charge density is then described as follows:

\[ D(t) = \varepsilon_0 \varepsilon_\infty E(t) + \varepsilon_0 \int_{-\infty}^{t} f(t - t_0)E(t_0)dt_0 \] (5)

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 put on to a dielectric material both the bound and the free charge carriers cause a current. The movement of the free charge carriers represents the conductivity whereas the bound charge carriers represents the dielectric displacement. The current density \( J(t) \) consists thereby of the addition of the capacitance current and the conduction current as follows:

\[ J(t) = \sigma E(t) + dD(t) / dt \] (6)

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

\[ J_{\text{polarisation}} = E(\sigma + \varepsilon_0 f(t)) \] (7)

In the case of isolation with the capacity \( C_0 \) as follows the bias current is as follows:

\[ J_{\text{polarisation}} = C_0 U_a (\sigma/\varepsilon_0 + f(t)) \] (8)

If we now disconnect the step voltage from the isolation we receive the so-called depolarisation current as follows:
\[
J_{\text{depolarisation}} = - C_0 U_a \left( f(t) - f(t + t_{\text{charging}}) \right)
\]

(9)

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.

3-3-2-2 PDC analysis as a method for determination of water content in the solid isolation of transformers

PDC analyses is introduced by different authors as a tool for determination of the water content in the solid isolation of transformers/22/. For this purpose for a certain time \( t_l \) 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 \( t_l \) the voltage is switched off and the circuit is short circuited over an ampèremeter. It flows thereby an opposite depolarisation current, then in the time it falls to the value zero (fig. 15) On the basis of a model of the main isolation of the transformer, which is set up with the help of the polarisation characteristic, humidity content and geometry of the main isolation defined by samples of a material, the polarisation current can be determined. From the comparison of computation and measurement statements about the humidity in the main isolation can be determined.

3.3.2.3 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 to the conventional \( \tan \delta \) Measurement consists of the fact that in place of one measurement with power frequency many measurements with different frequencies are accomplished. Mathematically the before introduced measured values 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:

\[
J(\omega) = \frac{i \omega \varepsilon_0 \varepsilon_r \chi'(\omega) - i \sigma_{dc} + \chi''(\omega)}{\sigma_{dc} + \chi''(\omega)} E(\omega)
\]

(10)

In this expression \( \chi'(\omega) \) and \( \chi''(\omega) \) are the parts of the complex susceptibility of the material and \( \sigma_{dc} \) is the direct current conductivity. This expression shows that the current consists of two components. The one component is in phase with the electrical field (the so-called resistive part) and the other is the so-called capacitive part. The portion of the current, which is with the field in phase, represents the losses in the material, which come due to two different mechanisms. For the one range the movement of the free charge carriers (direct current conductivity) is responsible and for the second part the reorientation of the bound charge carriers (relaxation losses) is responsible. The measurement of capacity and \( \tan \delta \) with power frequency by measuring bridges is well-known and state of the art.. With the help of a new system IDA 200/23/ much broader frequency ranges between 0,0001 Hz and 1000 Hz can be measured. The measurement principle can be described as follows: with the help of a digital signal processor a sinusoidal signal with desired frequency is produced, which is strengthened and set on the test specimen. The voltage at the test specimen and the current caused thereby by the test specimen are measured. From this both the capacity and the dissipation factor \( \tan \delta \) of the test specimen as a function of the frequency is determined. With very low frequencies the measurements are very time consumer.

3.4 further procedures

3.4.1 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 Electronical 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 then temperatures in different places along the fibre-optic cable can be determined. This technology which was tested originally at cables has the disadvantage that the integration of the fibre-optic cable must take place during the production of the transformer, so that for transformers in the operation this method is unsuitable. In addition this procedure is relatively cost-intensive. In monitoring systems offered at present 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.

3.4.2 reduction of the humidity
Water absorption of the solid isolation caused from outside by the penetration of the water or by depolymerisation of the cellulose, causes a swelling of the isolation and extension of the coil length. In the case of a drying process it can shrink again, whereby a shortening of the coil length is caused. Thus the clamp forces are reduced. The coil must be retightened again. Thus a mechanical damage can be caused. A drying process of the solid isolation with heating and vacuum, how it is accomplished for new, not impregnated transformers is applicable with restrictions also for aged isolations, saves however some disadvantages and dangers. First the transformer must be switched off and the isolating liquid be emptied. If the drying process does not take place on site a transport of the transformer is necessary. If the transformer is old and the degree of polymerisation (DP) of the cellulose already strongly degraded the danger that by the drying process the fragile paper is finally destroyed, exists. The problems mentioned led to the development of a careful drying procedure for the liquid and the solid insulant. This procedure can be used with old transformers for the extension of the period of operation or with new transformers for the increase of the entire lifetime, whereby the gas in oil analysis is not affected. The procedure is to be seen as life-accompanying measure, since it takes continuously the water out of the solid isolation. The liquid insulant is used as carrier for the water and replaces thus during the drying process each dried water molecule directly by an oil molecule, without the impregnated isolation is affected. A continuous drying process of the isolating liquid with vacuum has the disadvantage that beside the water also the solved gases are at least partly removed, which falsifies the gas in oil analysis. With the new system presented here the isolating liquid is led by a cellulose filter, whereby it is on the one hand cleaned and on the other hand cooled. Like already Fabre and Pichon 1960/24/ proved is the equilibrium of the humidity of insulating oil and cellulose in such a manner that at high temperatures water turns from the cellulose into the liquid whereas at low temperatures water is taken up from the cellulose. In the cooled filter therefore the water from the isolating liquid collects, and the isolating liquid leaves the filter with a reduced water content again. With this system water contents under 1 ppm are attainable. With the help of a sensor the condition of the filter can be controlled so that after saturation of the filter an exchange can be arranged.

4 summary
A view of the damage statistics of the utilities in the last years and the fact that many of the installed transformers have already a high age, make the necessity for monitoring and diagnosis visible. The most frequent damage arises in the active component and in the tap changer. The errors can be caused thermally, electrically, dielectric or mechanical. To the diagnosis first the necessary parameters must be taken up with the help of suitable sensors.
For this 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 hydrogen solved quantity of the oil can be detected on line.
- for the determination of the oil humidity it gives a sensor (Vaisala ), which measures the relative humidity in the oil on-line.
- 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 in the equilibrium.
- with the help of the measurement of the transient oil pressure a possible loosening of the clamp forces of the coil can be determined.
- with the help of the capacity of the tap changer engine a monitoring of the tap changer can take place.

The measurement of different parameters takes place on-line or off-lines. The measuring procedures can thereby be chemical, electrical, dielectric or other procedures.

Chemical procedures:
- one of the most common procedures that usually takes place off-line, is the gas in oil analysis.
- The gases collected in the Buchholz Relay are analysed and consulted together with the solved gases for a diagnosis.
- auran analyse makes among other things a statement about the condition of the cellulose possible.
- The determination of the humidity can supply in the oil and in the paper statements about the isolation condition.

Electrical procedures:
- to the electrical procedures belongs the PD measurement, which is still usually accomplished off-lines. 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 off-lines, a mechanical deformation of the coil can be determined.

Dielectric procedures:
- with the help of the determination of the dielectric response of the isolation in the time or in the frequency domain the isolation condition can be determined.
- The procedures in the time domain are RVM (Recovery Voltage Measurement) and PDC (Polarisation Depolarisation Current) measurement. In particular the PDC measurement showed up as 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 in a frequency range from 0.0001 Hz to 1000 Hz.

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Fig. 1 error rates of transformers as a function of the voltage level

Fig. 2 distribution of the damaged transformer components

Fig. 3 transformers of a large German utility

Fig. 4 380 kV machine transformers of a large German Utility

Fig. 5 example of the error rate as a function of the age
Table 1 damage causes of power transformers with down-times more than 1 day

<table>
<thead>
<tr>
<th>Component</th>
<th>Percentage</th>
</tr>
</thead>
<tbody>
<tr>
<td>Tap changer</td>
<td>40 %</td>
</tr>
<tr>
<td>coil + core</td>
<td>35 %</td>
</tr>
<tr>
<td>bushings</td>
<td>14 %</td>
</tr>
<tr>
<td>vessel</td>
<td>6 %</td>
</tr>
<tr>
<td>Accessoires</td>
<td>5 %</td>
</tr>
</tbody>
</table>

Figure 6 The relative depolymerisation velocity at different water content and temperature

Fig. 7 humidity sensor

Fig. 8 localisation of PD
Fig. 9 analysis of measured PD signals

Fig. 10 signal decoupling and transmission

Fig. 11 signal detection and evaluation
Fig. 12 polarisation due to a step voltage with the amplitude U0

Fig. 13 principle diagram of the emergence of recovery voltage

Fig. 14 equivalent circuit diagram for a linear dielectric

Fig. 15 circuit diagram of the PDC measurement