Multi Channel On-Line Monitoring System for Power Transformers

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Abstract
Monitoring of power transformers provides useful information about the current operation condition and can avoid unexpected outages. Furthermore it supports the decision concerning the transformer operation under competitive conditions within liberalised energy market.

On-line monitoring allows detecting a failure at any time and also during the normal operation of the transformer. On-line measurements offer also the advantage that data can be pursued during a longer period with almost the same operating conditions. Then, slow changes can be detected and a warning message or command for an immediately trip-off can take place, if limit values are crossed.

The combination of an on-line monitoring system for partial discharge measurement, tan δ measurement of the high voltage bushings and the measurement of the winding transfer function seems to be an efficient system. In this contribution the single monitoring system as well as the combined system will be described. In addition the practical measurements in the laboratory will be presented including the developed sensors and the software.

1 Introduction
Existing on-line monitoring systems are very often related to single parameters, showing weak points within a transformer under operation condition like partial discharge measurement, dissolved gases analyses and moisture in oil, bushing power factor and capacitance, frequency response analysis, on-load tap changer torque and current of the motor drive as well as ancillary information like oil level, oil flow meter and transformer temperature.

The installation of several monitoring systems is not economic but a modular design of a monitoring system starting with the most important parameter to detect failures within a transformer seems to be reasonable, because the system can be completed depending on the individual requirements of the user.

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In contrast to laboratory measurements, on-site measurements are disturbed by noise. In particular, in the high voltage area of the power transformers precise measurements are more difficult because of electrical and magnetic perturbative fields. The measurement set-up is firmly given by the installation of the test specimen. However procedure must be differentiated between on-line and off-line measurement.

Problems can result from the noisy environment, on site, and from the measuring procedure, which may by not possible under normal operating conditions. In this case, an off-line measurement must be accomplished regularly, e.g. on the occasion of the maintenance work at the transformer, or after relevant observations of measured data, e.g. a gas in oil analysis. In contrast to on-line measurements, the off-line investigations offer the opportunity of particular measurements and examinations, which are otherwise not feasible, e.g. different stress forms and measuring methods. The measurements can take place at different stress levels, whereby the influence of outside disturbances is smaller. Some of the usual parameters for the monitoring are introduced briefly in the following.

- Partial discharge measurement
- Transformer dissolved gases and moisture in oil
- Bushing power factor and capacitance
- Frequency response analysis
- Ancillary such as oil level and oil flow meter
- Transformer temperature
- OLTC torque and current motor drive, acoustic emission, relative temperature, control relay timing.

2 Transformer Failures
Failure statistics of large transformers can be used to inform which component is more important in condition evaluation of transformers. In Fig. 1 the failure rate of some components are presented for power transformers with and without on load tap changer [1].

Earlier statistics show that the most frequent failures with a long outage are the tap changers (40%), winding and core (35%) and bushings (14%). These components represent about 90% of damages in transformers. The most frequent failure of tap changer operation is the incorrect contact operation.
The important questions of transformer monitoring are as following:

- Is it normal?
- Is there a fault?
- Is the fault serious?
- Is it fit for service?
- What is its reliability?

Dissolved Gas Analysis and Power Factor and Capacitance / $\tan \delta$ measurement answer the first two questions effectively and transformer condition assessment can answer the last three questions actually. However condition assessment needs to evaluate the main features of the transformer as following [2].

- Current circuit (Electrical)
- Electromagnetic circuit (Magnetic)
- Dielectric system (Dielectric)
- Mechanical structure (Mechanical)
- Cooling system (Thermal)

These methods can be divided into five categories according to Fig. 2.

### 4 On-Line Monitoring System

Thermal and DGA Condition monitoring for power transformer are well-known manners and therefore only PD monitoring for PD localization, PF&C monitoring of bushing and on-line monitoring of FRA are introduced here.

**PD Monitoring:** PD results from a local failure of the electrical insulation and leads however not immediately to a complete failure. Inhomogeneity in electrical insulation, such as cellulose fibre from the solid insulation, conductive impurities or also small gas areas which can occur both in the solid and in the insulating liquid, is the main cause for PD. Insulating oil can lead to a self healing, but solid insulation such as fibre of the cellulose can be damaged and leads to an acceleration of deterioration.

In most cases, PD is determined chemically by gas in oil analysis, since the hydrogen content in oil increases strongly. A continuous measurement of hydrogen during the operation is used at present but this method can not localize the failure within the windings. A monitoring and diagnose system was therefore developed to localize PD with the wide-band measurement of PD. This method allows at the same time to evaluate the apparent charge of PD [3].

**Bushing Monitoring:** High voltage transients, caused by lightning or switching surges, can damage the insulation. Any breakdown between two layers of a bushing causes a change in the insulation of the bushing. Insulation breakdown can be detected or monitored due to partial discharge monitoring and a short circuit between two layers can be monitored due to the measurement of the bushing capacitance.

Paper ageing process, depends primarily on temperature and water content. Power factor and dissipation factor are good indicators to determine water contain in insulation, temperature condition and each short circuit between bushing layers.

**Winding Monitoring:** Winding defects such as deformations, short circuit and core defects can be recognised by the measurement of the transfer function of the individual transformer coils. The measurement is compared with a "finger print", which must be determined first as reference by the manufacture.

FRA results show that this method is sensitive to intern short circuits between some turns of transformer winding and can be used to recognize the intern short circuit at the first step as an indicator for winding diagnostic.

The on-line monitoring with the TF methods uses transient over voltages from the power grid [4, 5]. Switching and lightning generate an impulse overvoltage.

A transformer can be excited with an external signal, similar to the off-line monitoring of TF, through its bushing tap or via a non-invasive capacitive sensor (NICS), installed on the surface of bushing. The measurement can be performed in time and frequency domain similar to off-line measurement [6].
**Multi Channel Monitoring System:** Monitoring equipment, which should be mounted permanently on the transformer, must primarily be reliable and at low cost. One method to achieve a low cost system is the combination of different monitoring systems using simultaneous parts. Measuring instruments for PD, PF&C of bushing and FRA are similar, therefore a monitoring system can be used instead of three monitoring systems (Fig. 3).

![Multi Channel Monitoring System](image)

**Fig. 3** Proposed condition monitoring system

### 4.1 On-Line PD Measurement
PD monitoring and diagnostic procedure is based on the evaluation of the signal deformation of PD pulses within the transformer by mathematical algorithms and permits the determination of PD source as well as the charge quantity. For this procedure, it is necessary to record the PD signals (from 30 kHz up to 5 MHz) both at the bushing and at the neutral point.

A schematic of the PD measuring system is shown in Fig. 4. This system contains of two units which one installed on the transformer and consists of a capacitive sensor, a quadripole (AKV) to decouple PD and reference (50 Hz) signals, a wide band amplifier and some electro optical converters. The other unit is installed on the ground of the transformer and converts optical signals to electrical, amplifies the PD signal, does filtering and converts into digital signals. Signal processing is performed by standard software and industrial computer [7].

![PD on-line monitoring system](image)

**Fig. 4** PD on-line monitoring system

The both PD pulses will be deformed during its transmission from the source inside the transformer to the measuring points of the transformer. If these deformations are known by sectional winding transfer function, then the source location can be identified by reckoning back the true PD signal from the measured signals at the end of the winding and the neutral point.

### 4.2 On-Line Bushing Monitoring
The voltage applied to the transformer is acquired at the measuring tap of the bushing by means of a voltage divider or by non-invasive capacitive sensor (NICS) installed on the surface of bushing near to the ground potential. An air gap capacitive sensor (AGCS) as a normal capacitor is located on the transformer near the high voltage lead to the bushing. This enables to measure the actual voltage at the bushing [8].

![PF&C on-line monitoring system](image)

**Fig. 5** PF&C on-line monitoring system

### 4.3 Winding On-Line Monitoring
Transfer function monitoring in frequency domain is based on a sinusoidal voltage with different frequencies applied to the bushing as input signal and measured via voltage divider or NICS and the current in the winding measured as output signal via a Rogowski coil installed on the neutral point of transformer [9].

![Winding on-line monitoring system](image)

**Fig. 6** Winding on-line monitoring system

In the time domain measurement, an impulse voltage with amplitude of several 10 V was used as input signal and the winding current is measured as output. The measuring units for PD are also used to measure the FRA signals and therefore only a signal generator to generate the input signal is required. Fig. 6 shows the system for monitoring PD, PF&C and FRA.
4.4 Multi Channel Monitoring System

Adding the monitoring systems of PF&C and FRA to the SpeedCommander 7.lnk PD monitoring system, a multi-channel monitoring system is established. Fig. 7 shows the developed measuring system for PD and PF&C.

5 Practical Results

A 220 V / 100 kV, 5 kVA oil immersed high voltage transformer was considered to evaluate the feasibility of the Multi Channel On-Line Monitoring System. A 110 kV high voltage bushing model with 40 layers was installed separately on a structure and considered as the bushing to be monitored. The capacitance between high voltage conductor and bushing tap was 123 pF.

The high voltage transformer was energizing the bushing via an electrical bus bar. The voltage applied to the bushing was measured via a high voltage coupling capacitor. A NICS, installed on the surface of bushing near to the ground potential, was used for bushing condition monitoring. An AGCS as a reference capacitor was installed under the high voltage lead. The transformer, the bushing model, the measuring system, the sensors and the coupling capacitor are shown in Fig. 8.

An impulse generator was installed near to the bushing and protected against the high voltage. The impulse signal was applied to the bushing model through the bushing tap and used as input signal to the transformer for the FRA measurement. The high voltage winding of transformer was equipped with a Rogowski coil to measure the output. Fig. 9 shows the impulse generator and the bushing terminal.

To simulate PD in bushing insulation, a shield air gap was installed and connected between two layers of the bushing. With increasing applied voltage, corona inside the shield air gap starts. The corona signals were measured at the bushing tap and the coupling capacitor. As calibration signal, an impulse signal was applied to the bushing and measured at the bushing tap and the coupling capacitor. The results are shown in Fig. 10.
Fig. 10 Measured applied impulse signals at bushing tap and coupling capacitor

Fig. 11 shows the measured voltage (50 Hz) and corona impulses at the coupling capacitor and the bushing tap. The results show the corona in the negative cycle of voltage signal at 90°C. The polarity of the measured corona signals were in the opposite because the corona source was placed between the bushing layers.

Fig. 11 Measured PD signals at bushing tap and coupling capacitor and the 50 Hz voltage signal at bushing tap as reference

Using NICS and AGCS, the measurements were repeated. The results are shown in Fig. 12. The impulse voltage at AGCS could be measured, but the peak value was lower compare to the measured impulse at the bushing tap.

For FRA measurements, the transformer was connected to network and an impulse signal was applied to the bushing tap and the voltages at the bushing tap and the neutral point of transformer were measured. The voltage at the bushing tap contains the power frequency voltage (50 Hz) and the impulse signal and both signals were separated by the quadripole. The voltage at the neutral point contains only the impulse signal. The applied impulse signal will be deformed and damped after travelling in the transformer winding. The measured impulse voltages at the bushing tap and at the neutral point and the voltage of 50 Hz measured at the bushing tap are shown in Fig. 13. The measured impulse signal at the neutral point is shows separately in Fig. 14.

Fig. 12 Measured PD signals at AGCS and 50 Hz voltage signal at NICS and AGCS as reference

Using the impulse voltages at the bushing tap and at the neutral point, the transfer function of the transformer can be calculated.

Fig. 13 Measured impulse signals at bushing tap and neutral point and 50 Hz voltage signal at bushing tap

The measurements show that a multi channel monitoring system can be used to monitor PD, PF&C of bushing and FRA. Due to the limitation of pages, only the results of the measurements are shown. The calculation of the PF&C, FRA and the localization of PD sources from such measurements are described in [6-9].
The measured impulse signal at the neutral point of transformer

6 Conclusion

A monitoring system which can evaluate the condition of a transformer can avoid more premature damages. Such monitoring systems become more and more economic. One method to achieve a low cost system is the combination of different monitoring systems in one unit whose parts could be used commonly. Some parts of the measuring instruments for PD, PF&C of bushing and FRA are similar and therefore only one monitoring system instead of three monitoring systems is required. The monitoring system can also support the system protection because the FRA measurement can support differential relay to detect intern short circuit in transformer winding. The winding displacement within a transformer, caused by a short circuit fault can be evaluated by the on-line FRA monitoring system.

7 References