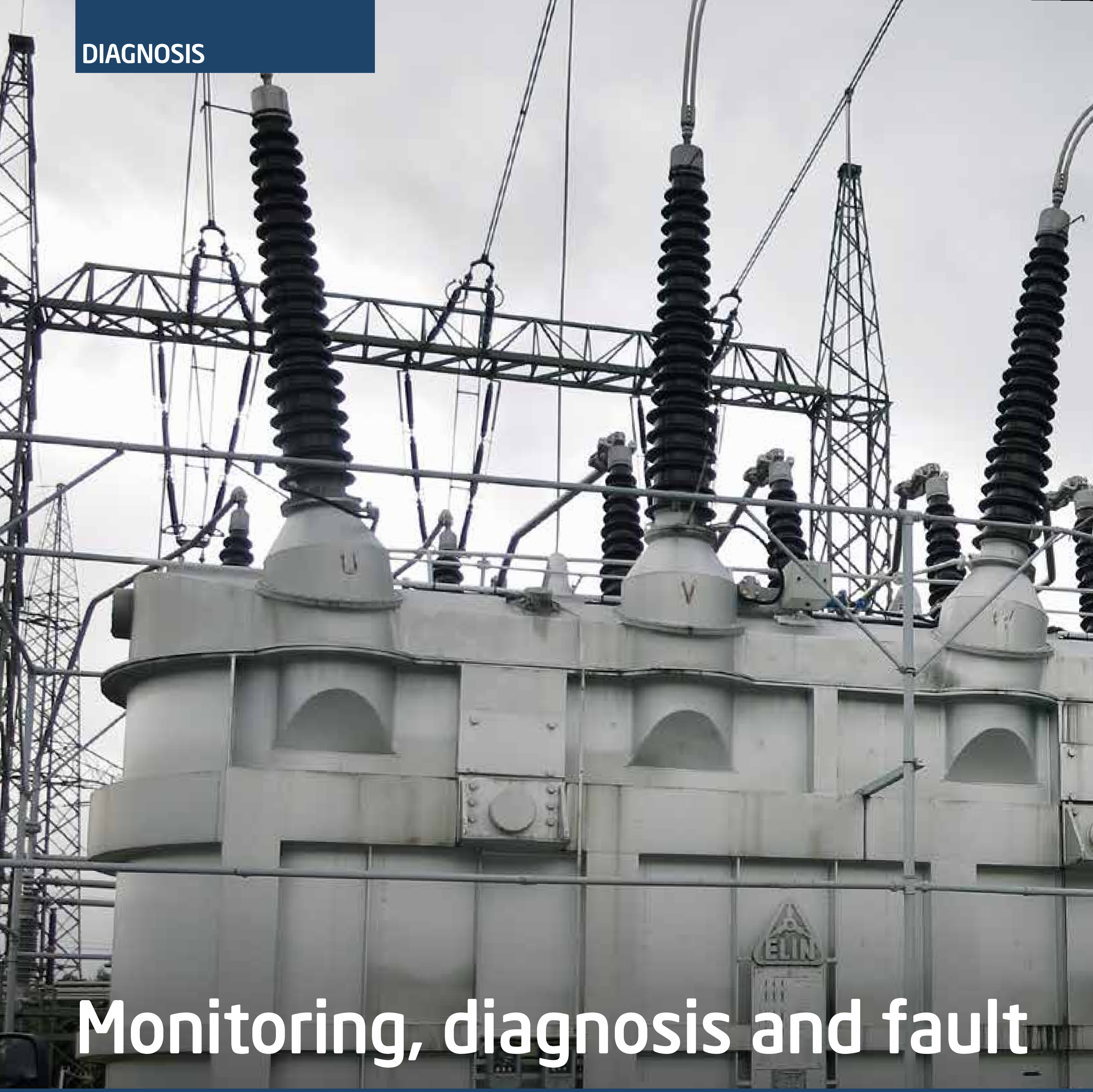


Monitoring, diagnosis and fault

ABSTRACT

An old transformer showed high concentrations of hydrogen and methane detected by the dissolved gas analysis which is usually performed at least annually as a routine test on bigger transformers. The utility decided to install a monitoring system for measuring gasses in the oil, partial discharges according to the IEC 60270 standard and additionally in the ultra-high frequency range, capacitance and dielectric loss factor at 220 kV bushings, and for detecting transient over-voltages.

Different challenges were faced during design and installation of the diagnostic system and during the evaluation of the monitoring data. One year after installation, the monitoring system detected a strong increase of hydrogen and methane and also of partial discharges at 220 kV bushings. This initiated further diagnostic measurements. Partial discharges were detected and located. After opening the transformer the faults were identified. The damage was so serious that it was decided to scrap the transformer. This way the monitoring system could prevent a bigger damage in the substation.

KEYWORDS

transformer, monitoring, condition diagnosis, dissolved gas analysis (DGA), partial discharge (PD) measurements, fault location, capacitance and dissipation factor monitoring

Michael KRÜGER, Udo RANNINGER, Laurentiu Viorel BADICU

> **A monitoring system was mounted on an old transmission transformer 130 MVA, 230/115/48 kV due to high concentrations of hydrogen and methane in the oil, detected by the dissolved gas analysis**

finding on a power transformer

Experiences and challenges during monitoring, diagnosis and evaluation

Introduction

A monitoring system was mounted on a 130 MVA transmission transformer with 230/115/48 kV because of high hydrogen and methane concentrations dissolved in the oil, detected by the Dissolved Gas Analysis (DGA) (Fig. 1). The system contained a gas sensor for four fault gasses. Additionally, Partial Discharge (PD) measurements were performed with sensors at the bushing measuring taps and with an Ultra-High Frequency (UHF) sensor inserted in the transformer tank. The monitoring system also allowed checking the state of the bushing's insulation with absolute values of the Capacitance (C) and dielectric Dissipation Factor (DF) by utilizing nearby voltage transformers as reference. Different challenges were faced during design and installation of the diagnostic system and during the evaluation of the monitoring data.

Monitoring of the capacitance and dielectric dissipation factor of the bushings

Traditionally, the sum-of-currents method is used for bushing Capacitance (C) and dielectric Dissipation Factor (DF) measurements [1]. The current phasors of the three bushings measured at the bushing's test taps are added to obtain the imbalance current. While the influence of differences in the bushing's capacitances

Figure 1. 230/115/48 kV transformer

> **If the sum-of-currents method is used for bushing dissipation factor measurement, the imbalance of the voltages can cause a change of tangent delta reading of more than 0.5 %, triggering a false alarm**

can be eliminated by calibration, the three phases of the voltage system must have exactly the same magnitude, and the angles between the phases must have exactly 120 degrees. In real cases, this is not given. Fig. 2 shows the changes of the tangent delta of a sum-of-currents system over 30 days [2]. As illustrated, the imbalance of the voltages would cause a change of tangent delta reading of more than 0.5 %. The voltages of the three phases can get asymmetric by unbalanced loads or by asymmetric induction from high currents in nearby overhead lines. Oil impregnated paper bushings may have tangent delta values of 0.25 %, and an increase to 0.5 % could be alarming. This shows that this method is hardly suitable for accurate and reliable measurements.

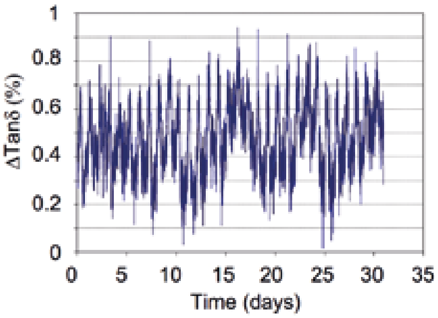


Figure 2. Tangent delta of a sum of currents method over one month

It is therefore necessary to get absolute values for the capacitance and the dielectric dissipation factor of the bushings. In the laboratories, a nearly loss-free capacitor is used as reference. In substations or power plants, the reference signal can be taken from the same phase of a second transformer which is switched in parallel, or from voltage transformers which are connected to the bushings. In the described case, the reference signals were taken from a group of voltage transformers in the same substation. The principle of the described system is shown in Fig. 3. The system allows simultaneous measurement of the capacitance and the dielectric dissipation factor of the bushings, partial discharges in the bushings and in the transformer tank, and transient over-voltages in the high voltage grid.

The DF values are very stable with absolute measurements if the reference signal is taken from Voltage Transformers (VT) which are connected to the bushings.

In case of the 230/115/48 kV transmission transformer, the utility decided to continuously monitor absolute values of DF and C of its Resin Bonded Paper (RBP) bushings. The reference signal was taken from a group of voltage transformers in the substation. A temperature sensor at the bushing's flange allowed for an adequate temperature correction. This sensor also recorded the humidity in the ambient air.

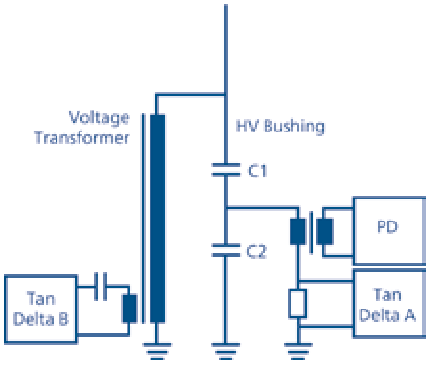


Figure 3. System for the simultaneous measurement of capacitance, dissipation factor and partial discharges

The diagnosis of the bushing was performed by analyzing the capacitance and dissipation factor trends, their magnitudes and rates of change. Additional off-line diagnosis is recommended in cases when the capacitance and/or the dielectric dissipation factor values rise significantly. Fig. 4 shows the trend diagrams of DF and the ambient humidity at the monitored bushings. It can be seen that the DF slightly increased when a high humidity was recorded, which may have been caused by moisture on the surface of the bushing's insulators. The results showed that the bushings seemed to be in a good condition. The monitoring system consisted of one acquisition unit connected to the bushing's taps and to an UHF sensor at the oil drain valve, and one acquisition unit connected to the voltage transformers. The scheme of the whole monitoring system is shown in Fig. 5.

> **Dissipation factor values are very stable with absolute measurements if the reference signal is taken from voltage transformers which are connected to the bushings**

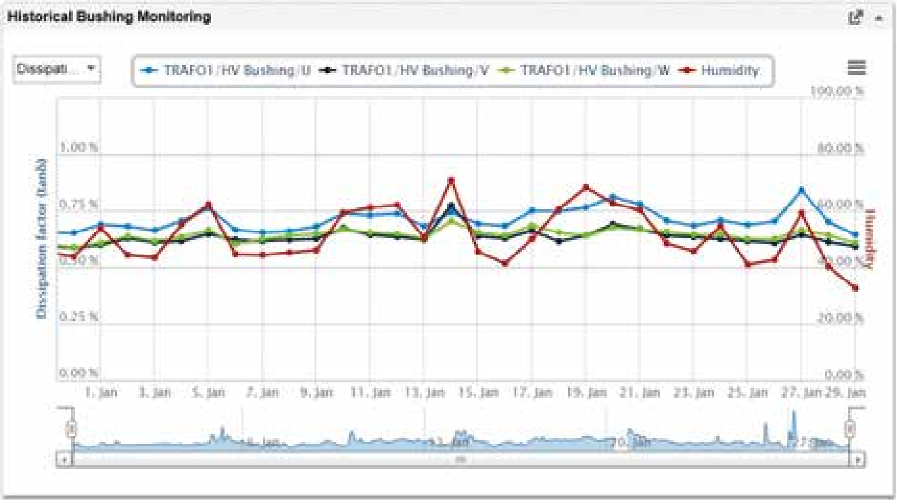


Figure 4. DF trend of 3 phases and trend of humidity (red line) with absolute measurements

> **The dissipation factor slightly increased when a high humidity was recorded, which may have been caused by moisture on the surface of the bushing's insulators**

Monitoring of Partial Discharges (PD)

The PD activity was measured conventionally at the bushing measuring taps according to IEC 60270 [3], and unconventionally by placing an UHF sensor inside the transformer tank. The tank wall acted as Faraday cage and screened the UHF sensor from interference coming from outside. By correlating the PD events, measured at the bushing's taps, with the UHF signals from inside the tank, electromagnetic interference signals from outside the tank could be sorted out by the software [4]. Additionally, an acoustic method was applied for detecting a precise localization of the PD sources. All these methods are complementary.

Conventional method

The PD signal was synchronously detected at the measuring tap of each 220 kV bushing via bushing adapters. The same adapters were used for C and DF monitoring. Over-voltages arrestors in the adapter protected the bushing taps against high voltages. After installation, the PD system was calibrated for different measuring frequencies and bandwidth because the calibration factor varies with the frequency. In this way no further calibration was needed even if the measurement frequency of the measurements was changed during monitoring. For each point of the trend, Phase-Resolved PD patterns (PRPD) and 3 Phase Amplitude Relation Diagrams (3PARD) are available.

The PRPD patterns are complex with overlapped signals from different PD sources and from interference signals (Fig. 6). In order to separate clusters of different PD sources, a synchronous multi-channel PD evaluation technique was applied [5]. The 3PARD diagram visualizes the relationship between amplitudes of a single PD pulse in one phase and its crosstalk signals into the other two phases. By repetition of this procedure for a large number of PD pulses, PD sources as well as noise appear as a clearly distinguishable concentration of dots in a 3PARD diagram. By examining individual clusters in the 3PARD diagram, a separation between noise and PD phenomena is possible. The back-transformation to PRPD patterns of the clusters 1 and 2 is presented in Fig. 6.

> **External electromagnetic interference signals could be sorted out during PD measurement by the software correlating PD events measured at the bushing's taps with the UHF signals from inside the tank**

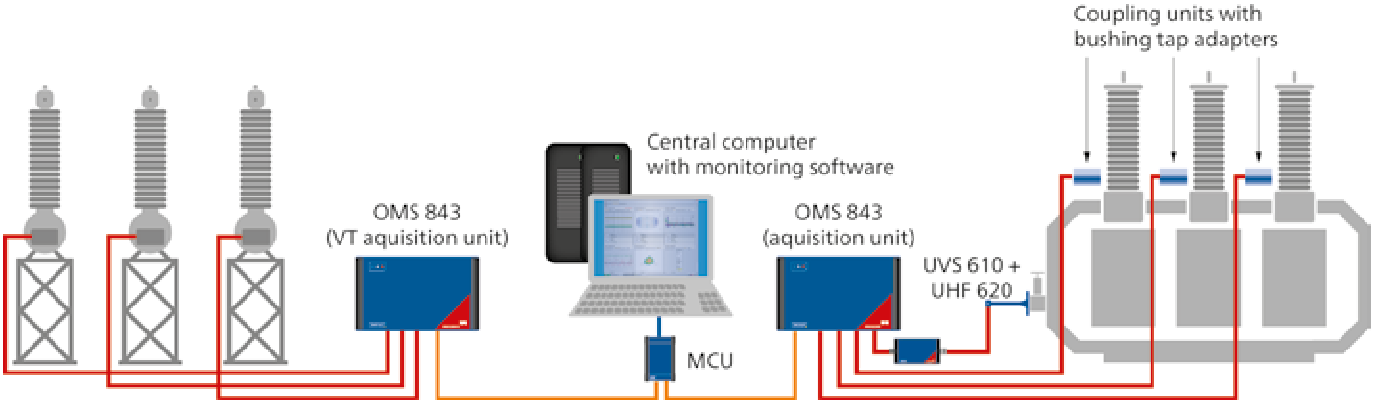


Figure 5. Monitoring system *MONTRANO (Absolute measurement with VT reference)*

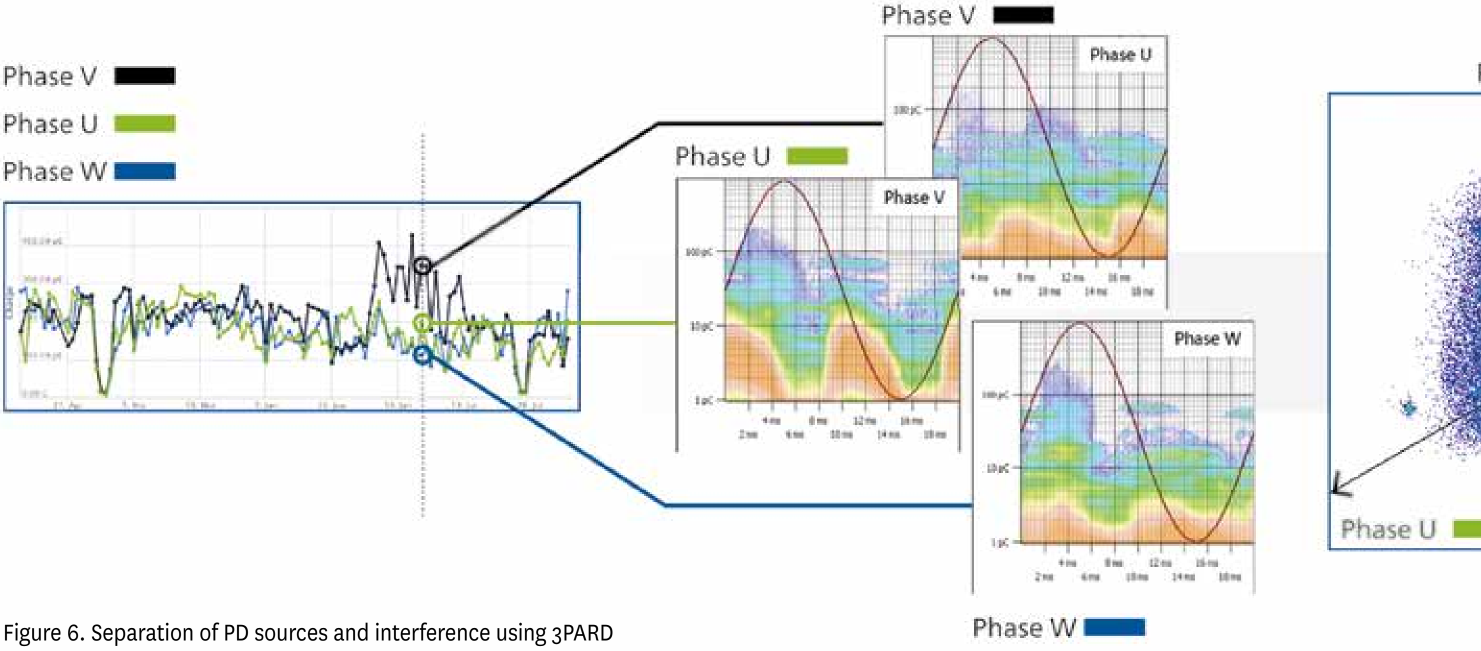


Figure 6. Separation of PD sources and interference using 3PARD

> **In order to separate clusters of different PD sources, a synchronous multi-channel PD evaluation technique was applied**

In Fig. 6 the patterns of the phases U, V and W are shown without filtering and with 3PARD filtering. The pattern of the cluster 1 in the 3PARD diagram indicates the presence of partial discharges at phase V. The highest amplitude of the signal was detected at phase V, but signal crosstalk to phases U and W is also visible. The PRPD pattern of the cluster 2 in the 3PARD diagram appears to be generated by partial discharges in the vicinity of phase W. The other clusters visible in the 3PARD diagram are most probably generated by external interferences.

Unconventional UHF Measurement

The used UHF converter UHF 620 is able to measure signals in the frequency range from 0.1 to 2 GHz by installing the antenna type sensor UVS 610 inside the transformer's tank. For this application the centre frequency was set to 560 MHz with a bandwidth of 70 MHz because in this range the signal to noise ratio was good. The amplitude of the UHF signal had been increased since May 2014 within 2 weeks.

PD Monitoring versus DGA Analysis

The increase of the PD signals measured at the bushing taps and at the UHF sensor over a period of three months went hand in hand with the increased gas values detected by the gas sensor. The concentration values of the most relevant fault gases are presented in Table 1.

The increase of Hydrogen (H_2) and Methane (CH_4) concentrations confirmed the presence of the PD activity, while the increase of the Carbon monoxide (CO) and Carbon dioxide (CO_2) concentration indicated a paper deterioration, probably as an effect of the on-going PD activity.

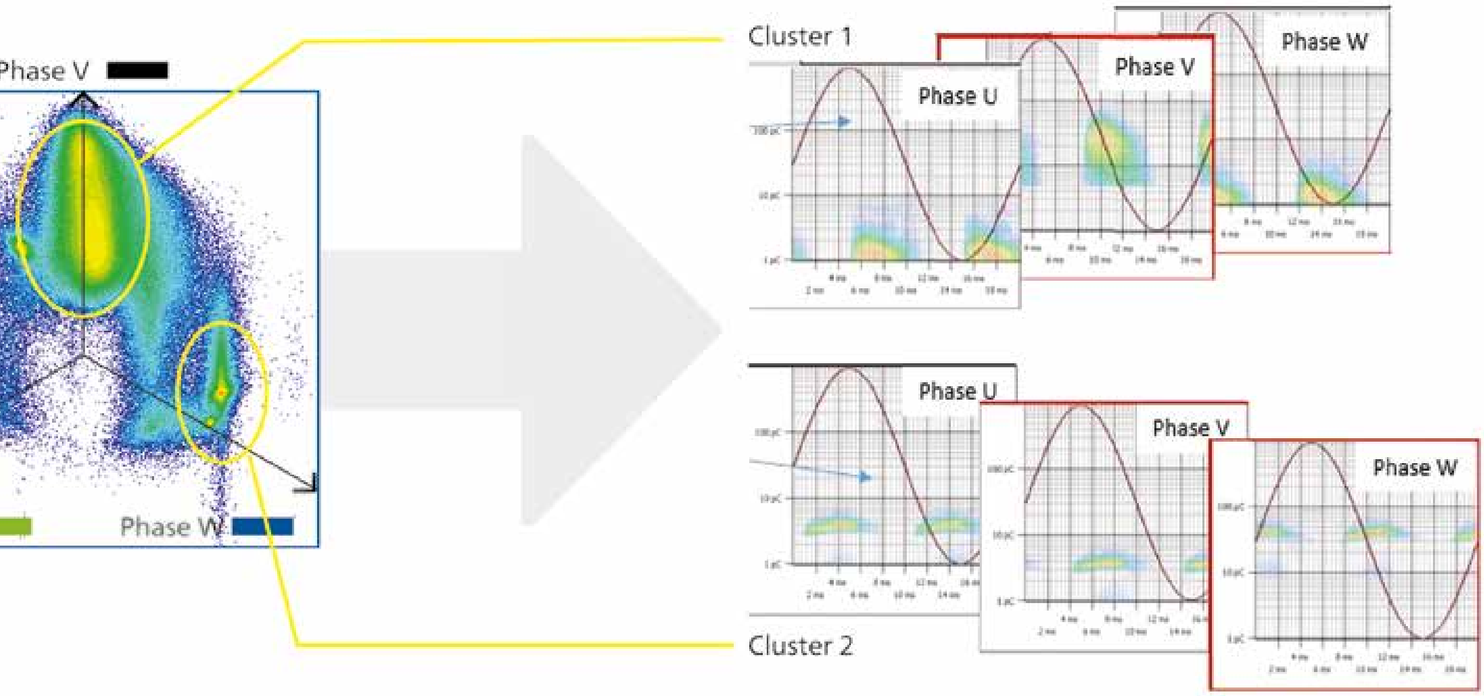
Table 1. Gas content in ppm

Sampling date	H_2	CO	CO_2	CH_4	C_2H_2	C_2H_4	C_2H_6
01-Apr	576	557	3821	150	11	116	19
15-Apr	433	416	3016	115	9	92	15
15-May	966	835	5952	226	21	179	32
12-Jun	1212	808	5797	225	21	171	30

Fault investigation and fault location

The transformer was taken out of service and further measurements were carried through. First, a PD measurement system with eight PD measurement channels was installed at all bushings on the 230 kV and 115 kV side, at the neutral

> **The increase of the PD signals measured at the bushing taps and at the UHF sensor over a period of three months went hand in hand with the increased gas values detected by the gas sensor**



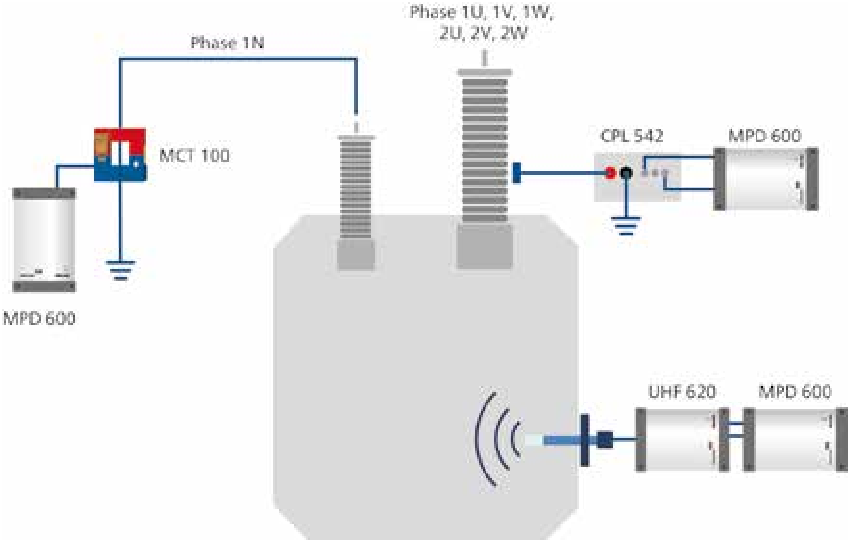


Figure 7. Scheme of MPD600 channels at bushings and UHF sensor

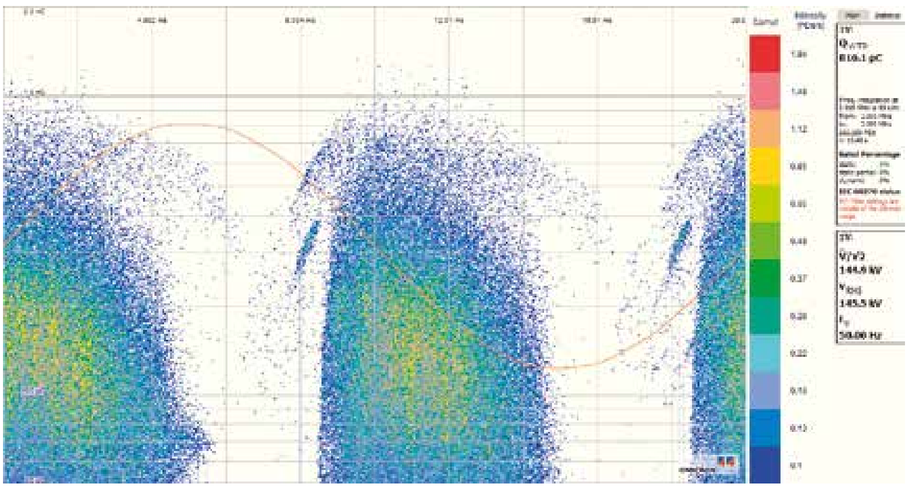


Figure 8. PD patterns at bushing phase 1V

1N of the 230 kV windings, and at the UHF sensor (Fig. 7).

The PD patterns measured with MPD 600 showed good correlation to the results of the monitoring system. Fig. 8 shows PD patterns at bushing phase 1V.

Acoustical fault location

Partial discharges do not only emit electromagnetic signals in the HF and UHF frequency range, but they can also emit acoustic signals in the ultrasonic frequency range. In many cases they can be received by ultrasonic microphones at the tank wall. Fig. 9 illustrates this principle.

> **Partial discharges can emit acoustic signals in the ultrasonic frequency range**

The propagation of acoustic waves to the microphones is different. So, arrival times of the acoustic signals at different sensor positions lead to time differences. With triangulation algorithms, the PD source can be located [5]. In this case, the PD location system PDL 650 with ultrasonic microphones at the tank wall was used to locate the fault. Fig. 10

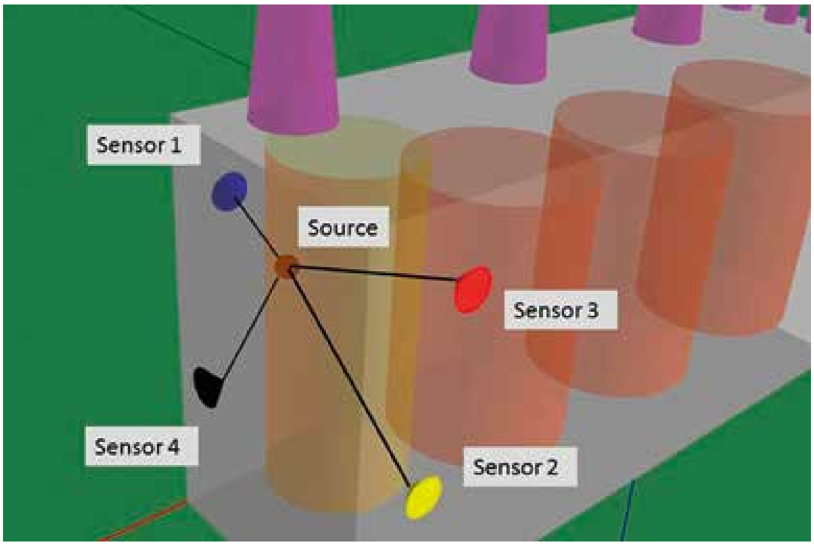


Figure 9. Acoustic PD location with ultrasonic microphones (sensors)

> In the case study acoustic signals were detected by ultrasonic microphones at the tank wall, and by triangulation algorithms, the PD was located at the oil end of the 1V and 1W bushings

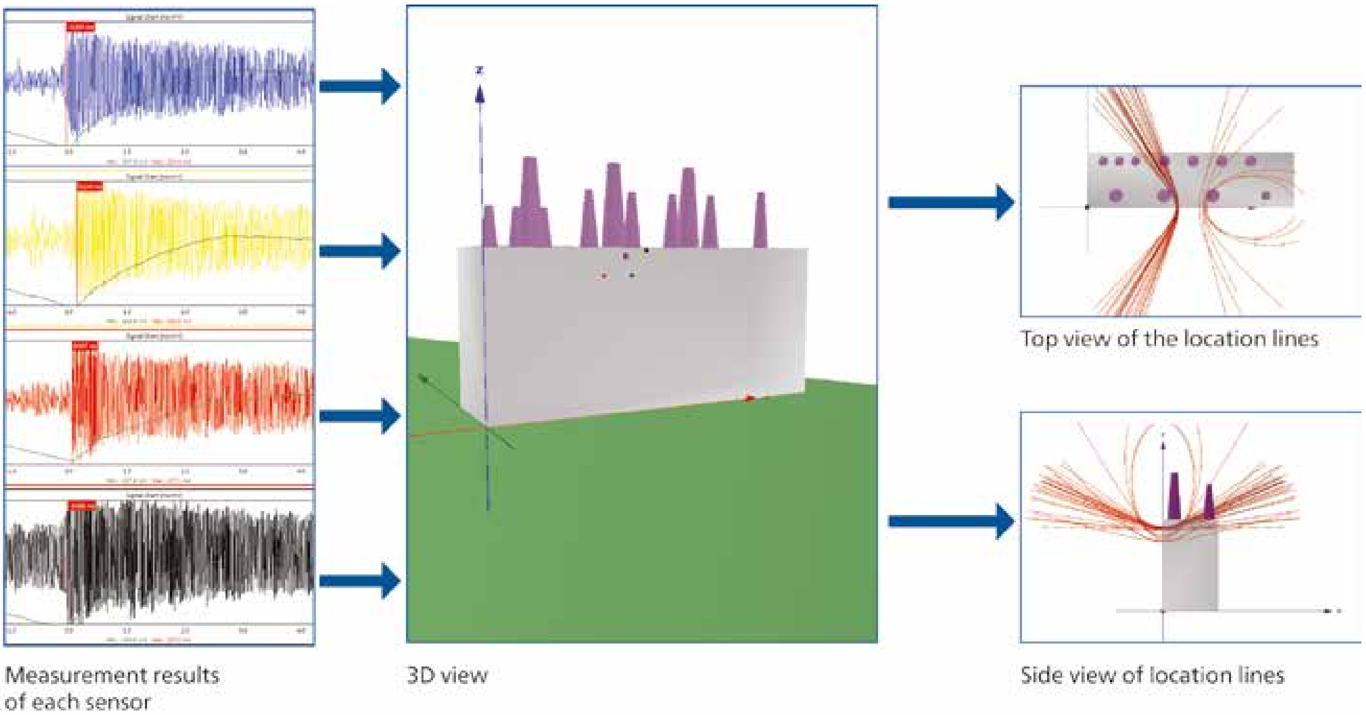


Figure 10. Acoustic signals (left) and PD position of PD (yellow circle)

shows one localized PD point (within the yellow circle) and calculated location lines from several potential PD faults in the PDL software. The faults were located at the oil end of the 1V and 1W bushings (Fig. 10).

The bushings were removed and the damage at the leads between windings and bushing could be seen (Fig. 11). Due to partial discharges, X-wax was produced at the insulation paper and inside the windings. X-wax is a solid material which is formed from mineral oil as a result of electrical discharges and which

Figure 11. Traces of PD at the bushing lead

> **The bushings were removed and the damage at the leads between windings and bushing could be seen**

consists of polymerized fragments of the molecules of the oil. If it is built inside the oil ducts, the cooling of the transformer can be blocked.

A repair of these faults would have meant that the transformer had to be rewound at least partially, at worse completely. Due to the age – the transformer was built in 1967 - and the condition of the transformer, it was decided to scrap it prior any hazard in service.

Conclusions

Modern monitoring systems enable a reliable control of power transformers. Gas sensors inform about the actual status of fault gasses which can be generated by different insulation faults. Voltage transformers which are connected to the high voltage bushings provide a stable and accurate reference signal for absolute capacitance and dielectric dissipation factor measurements for bushing assessment with an accuracy comparable to offline measurements, but under real operation conditions on the field. Therefore, insulation faults in the bushings can be recognized, and located, at a very early stage. Online partial discharge measurements in a substation or power plant are often disturbed by interference from other live parts. Only with synchronous multi-channel systems in connection with modern filtering methods like 3PARD the measurement of partial discharges can give meaningful results. Due to the extreme small inductance of the bushing's capacitance C1, bushings can also be effectively used for detecting and measuring fast transient over-voltages. This gives important information not only for the stress of the transformer and its bushings, but also of other assets in a substation or power plant. The described case study shows that with modern monitoring, systems faults, in addition to traditional DGA measurements, can be recognized in an early stage and catastrophic faults may be prevented.

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