MONITORING OF A DISTRIBUTION TRANSFORMER AT WINCHELSEA SUBSTATION

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Abstract
The paper describes the results of on-line monitoring of a 5/7 MVA, 66000/22000 V distribution transformer installed at a POWERCOR Zone substation near Winchelsea in Australia. As a previous dissolved gas analysis recorded high levels of hydrogen and methane, an additional monitoring system was installed. The additional system measures the absolute values of bushing insulation capacitance and dissipation/power factor, providing high accuracy in the field. Absolute measurements are performed taking the reference signal from a group of voltage transformers located in the same substation. Temperature compensation is performed to reduce the uncertainties of the measurements. Partial discharges in bushings are measured at bushing measuring taps using a conventional method and inside the transformers in the ultra-high frequency range with an antenna installed inside the oil drain valve. The advantages provided by both methods are combined to better identify and localize the source of partial discharge. The monitoring system also detects transient voltages directly at the bushings to assess their impact on transformer health. The system employs advanced techniques of multi-channel and multi-spectral partial discharge source and noise separation. Relative humidity of the air is permanently measured and stored in the database. The modular design and user-friendly management of the system are also described. The paper includes the condition assessment of the transformer based on the recorded results of the installed monitoring system and from dissolved gas analysis.

Background

The transformer is a 5/7 MVA ONAN/ONAF 66000/22000 V Dyn1 unit constructed in 1998. It was initially put into service in a city environment in Melbourne where it operated predominantly on a fixed tap and without any problems until removed from service in 2007 as part of a major upgrade project. Later in 2007, the transformer was relocated to Winchelsea Zone substation (figure 1), a rural environment where it was placed in service to replace a failed transformer. Once again operation was on a fixed tap until 2009 when the tap changer was put into automatic operation and used to provide voltage regulation for the station. The unit was not heavily loaded and gave no indication of any problems until the annual oil sample dissolved gas analysis (DGA) result from February 2010, which indicated 5400 ppm of hydrogen. The dissolved gas ratios indicated that partial discharge (PD) was taking place.

In order to better monitor what was occurring, an on-line DGA monitor was installed giving 4 hourly readings. Initially the monitor recorded less H_2 ppm, but it was quickly realized that this was actually a false reading due to the fact that the detection limit for hydrogen of 3000 ppm had been exceeded and, counter-intuitively, this was causing the monitor to read low.

The transformer was then partially de-gassed. The results for the next three years are shown in figure 2. As can be seen, the hydrogen and methane levels showed a steady increase, which seemed to indicate that PD was ongoing.

Figure 1

Monitored transformer at Winchelsea Zone substation

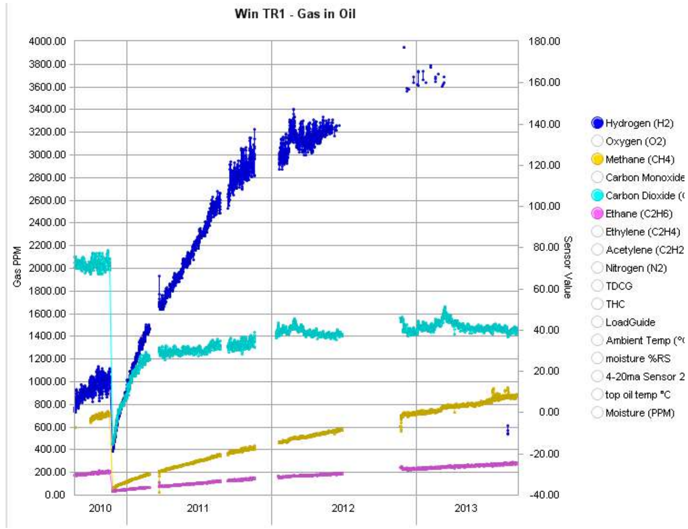


Figure 2
On-line DGA results

There have been several attempts to measure PD with limited success up until the installation of the continuous OMICRON monitoring system, which has confirmed the PD activity and facilitated some further analysis.

The installed monitoring system combines accurate measurement of the bushing capacitance and dissipation/power factor with grid transient recording and PD measurements (figure 3). It provides remote assessment of the dielectric integrity of transformer and bushings with high accuracy comparable to off-line testing. The following parameters are continuously monitored:

- Capacitance and dissipation/power factor of high voltage (HV) bushings;
- PD level at the bushings and inside the tank;
- Transient over-voltages at the HV bushings.

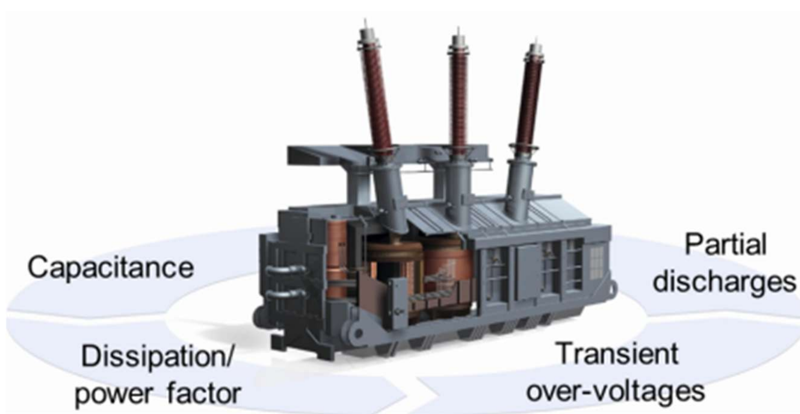


Figure 3
Parameters continuously monitored

Project-specific system design

Accurate measurement of capacitance and dissipation/power factor

Traditionally, the sum-of-currents method is the most common method used in monitoring of bushing capacitance. The leakage currents measured at the three bushing taps are added to obtain the imbalance current. The changes of the system voltage phase angle due to the daily load variation lead to significant changes of the bushing capacitance and dissipation factor, introducing a measuring error [1]. To increase the sensitivity of the measurements, reference and comparison methods have become more and more popular [2]. Both these methods require a reference signal for calculation of dissipation factor and capacitance. Depending on the source of the reference signal, relative or absolute measurements can be performed (figure 4) [3]. With relative measurements, the bushing-to-bushing comparison or dual transformer comparison is performed, while with absolute measurement reference signal is taken from voltage transformers (VTs) of the substation. Grid unbalance, like phase shifts or changes in the system voltages can have a misleading impact on the relative measurements of capacitance and dissipation factor. The simultaneous ageing of the reference and test bushing cannot be detected. To reduce the impact of these uncertainties (figure 5), absolute measurements are recommended at the Winchelsea substation. The reference signal is taken from the LV side of a group of VTs located near the monitored transformer. This pure resistive signal (U_{VT}) is compared with the mainly capacitive leakage current (I_B) measured at the bushing tap of the transformer. The corresponding vectors of these two signals are rotating in the same four-quadrant coordinate system (figure 6) and the capacitive current $\vec{I}_B$ always leads in revolution. The angles between the reference axis and the two vectors are permanently measured and, by computing the difference between them, the angle φ and the power factor cosφ are obtained. The dissipation angle (δ) and dissipation factor (tgδ) can be calculated accordingly. The temperature correction of the dissipation factor values is performed [4]. It takes into account the OIP (oil impregnated paper) type of the bushing. The formula (1) is used to calculate the bushing capacitance C_B. The I_B current is measured by the monitoring system, while the U_{High} value is directly taken from VTs.

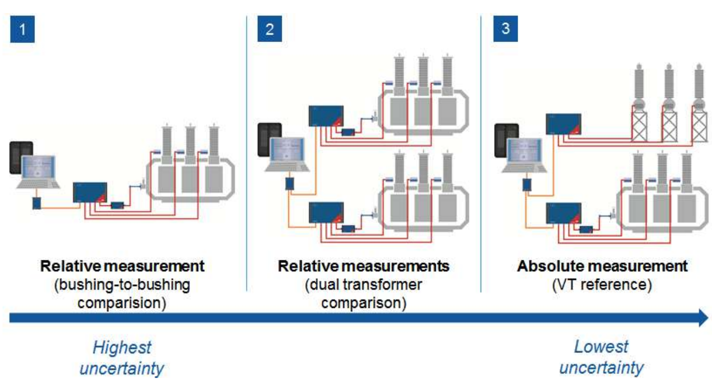


Figure 4
Architecture of the monitoring system applied for comparison and reference method

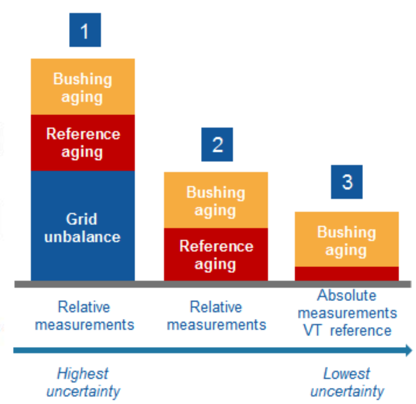


Figure 5
Sensitivity/uncertainty introduced by each method

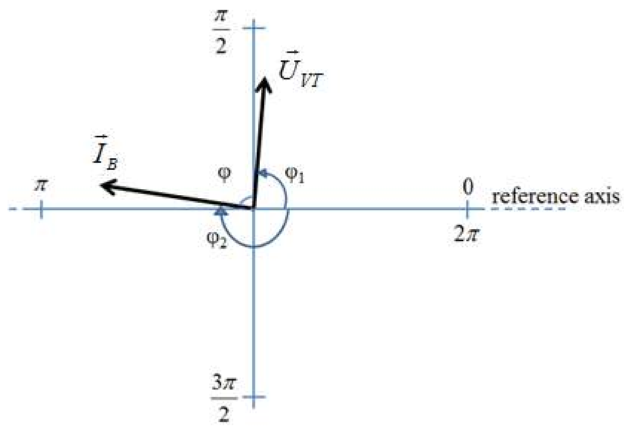


Figure 6
Vector representation of the U_{VT} and I_B in a four-quadrant coordinate system

$$I_B = 2 \cdot \pi \cdot f \cdot C_B \cdot U_{High} \Rightarrow C_B = \frac{I_B}{2 \cdot \pi \cdot f \cdot U_{High}} \quad (1)$$

The accuracy of the monitoring system is < ±0.8 pF for capacitance measurement and ±0.01 % for dissipation factor measurement. The 0.5 class of VTs also has to be taken into consideration (Table 1).

Table 1
Voltage error and phase displacement for measuring voltage transformers [5]

Class	Percentage voltage (ratio) error ±	Phase displacement ±	
		Minutes	Centiradians
0,1	0,1	5	0,15
0,2	0,2	10	0,3
0,5	0,5	20	0,6
1,0	1,0	40	1,2
3,0	3,0	Not specified	Not specified

Combination of conventional and unconventional PD detection

Two methods are recommended for PD measurements: the conventional method (according to IEC 60270) with sensors at the bushing taps and an unconventional ultra-high frequency (UHF) method with a sensor placed inside the transformer tank. With the conventional method, the PD signal from each tap is synchronously acquired by a three channel acquisition unit. The central frequency of the digital band pass filter of the acquisition unit is selected to reach the optimal signal-to-noise ratio. To obtain more detailed information about the type and location of the insulation PD defects, the unconventional UHF PD measurements in the frequency range between 100 MHz and 2 GHz with an antenna installed inside the oil drain valve are performed. The presence of external noise in this frequency range is low and radio or mobile phone signals are easily recognized and eliminated from the measurements. PD activity inside the bushings insulation and close to the end winding area is mostly detected with the conventional method while the rest of the tank is covered by the UHF antenna. Even if the PD signal is measured in a different frequency range, the obtained PRPD diagrams have very similar patterns that makes recognition of the defect´s type easier (figure 7). The signal detected by the UHF antenna is synchronized with the signal detected at the bushing taps. Furthermore, the measured pulses in the UHF range, mostly coming from internal PD activity, can trigger the start of conventional measurements. Thus a better separation between internal and external PD pulses can be obtained.

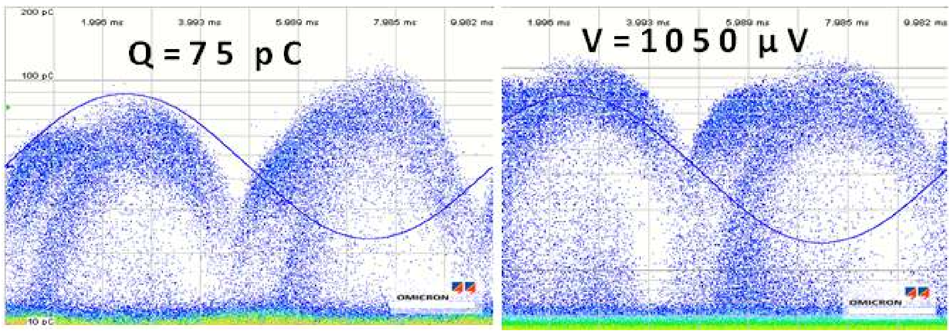


Figure 7
Example of PRPD patterns measured by conventional method (left) and UHF method (right) for a known internal PD defect.

Measurements of transient over-voltages

The voltage transients appearing at the bushings and propagating into the windings create thermo-electrical stress and accelerate the aging of the insulation. The number of the transients and their shape (rise time, magnitude and duration) are important parameters. The magnitude of the lightning-induced transients is reduced below 2 p.u. (phase-to-ground voltage = 1 p.u.) by surge protective devices [6,7], but the fast transients coming as a result of operations in the substation can also be dangerous [8]. The magnitude and shape of the transients strongly depends on the power grid configuration, length of the lines, type of connecting HV equipment [6]. Figure 8 shows the waveform of the transients when a cable, gas insulated line (GIL) or overhead line (OHTL), all with the same length of 50 m, are connected at the transformer. In figure 9, the variation of transient peak magnitude as a function of the length of connecting terminals are presented. At the Winchelsea substation, the OHTL of 30 km and 40 km are connected to the monitored transformer. As a result, transients of high amplitude are expected to appear at the bushings of the transformer.

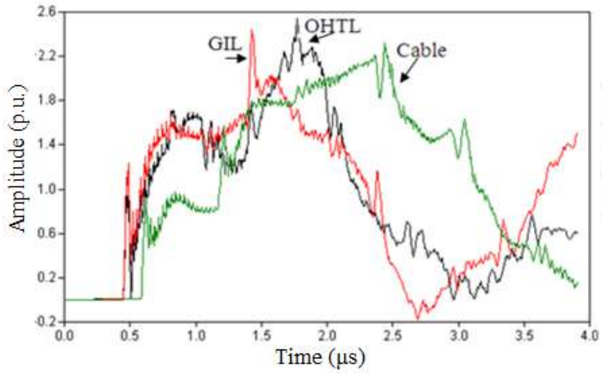


Figure 8
Waveform of the transients when a cable or GIL or OHTL is connected at the transformer [7]

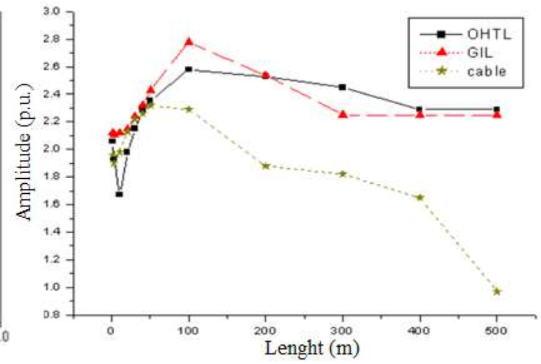


Figure 9
Variation of peak magnitude of transients as a function of the length of terminals [7]

User-friendly visualization of monitoring data

The monitoring software runs on a central computer. It can either be directly accessed on-site or remotely using a trusted network via the convenient web-based interface. The software is a management tool for system configuration, continuous data acquisition and visualizing real-time or stored measurement data. There are two modes of collecting monitoring data: permanent mode and periodic mode. During the permanent mode, the data is acquired every second, compared with threshold values and displayed in real time. When this data is within normal margins, the values are displayed in green (figure 9) and are not stored in the database repository. In the periodic mode, data is measured at specific, defined intervals or at the occurrence of a violation of the predefined threshold values. In this mode, all measuring data is stored in the database.

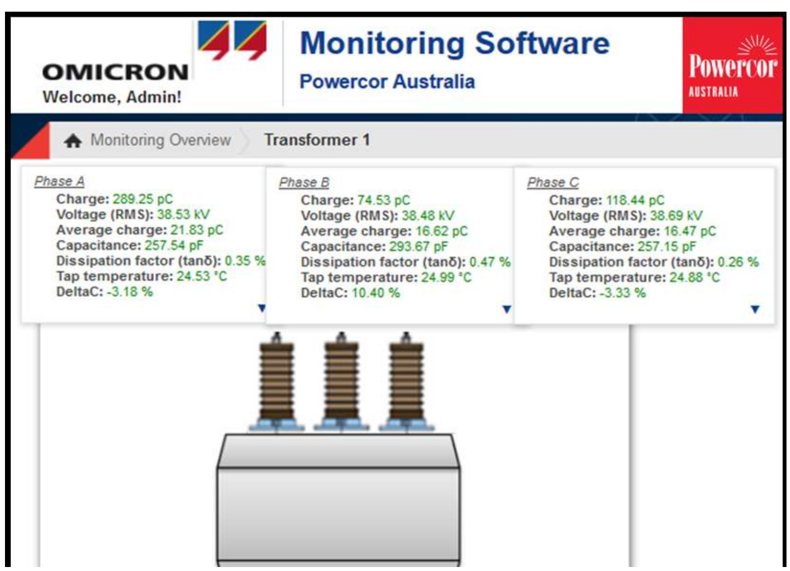


Figure 9. Real-time data displayed in the graphical user interface

System installation

The architecture of the monitoring system is shown in figure 10. For each bushing, one capacitive tap sensor to measure PD, capacitance and dissipation/power factor is installed (figure 11). It is equipped with multiple redundant protections to guarantee safe operation. The ambient temperature and relative humidity are also measured within the same tap sensor to compensate the measured values. The UHF antenna is put inside the oil drain valve located in the upper part of the tank (figure 12) and is connected to UHF down converter and finally to the fourth channel of the acquisition unit. The outdoor monitoring server and communication modem are mounted on the tank of the transformer (figure 13).
Only two VTs (phase B and phase C) were available for reference**.** The calculation of the dissipation factor for phases B and C is based on the reference signal taken from the VTs installed on these phases. To calculate the dissipation factor of the bushing installed on phase A, the reference signal is taken from both VTs. The resulting reference voltage vector follows the changes of the other two phases in a dynamic way. During the commissioning, calibration of the monitoring system was performed and the level of alarms and measuring intervals was selected in the monitoring software. The threshold values for dissipation factor and capacitance were chosen based on the recommendations in the standards and experience:

- Dissipation factor

The diagnosis of the bushing is performed by analyzing the trend of tgδ, the magnitude and its rate of change. When tgδ reaches a predefined level of alarm – 0.7% (table 2) [9] – continuous operation is no longer recommended. On the other hand, bushings with values of tgδ above a predefined level but with stable trend may stay in operation. When tgδ doubles the value over six months, off-line investigations and additional measurements are recommended.

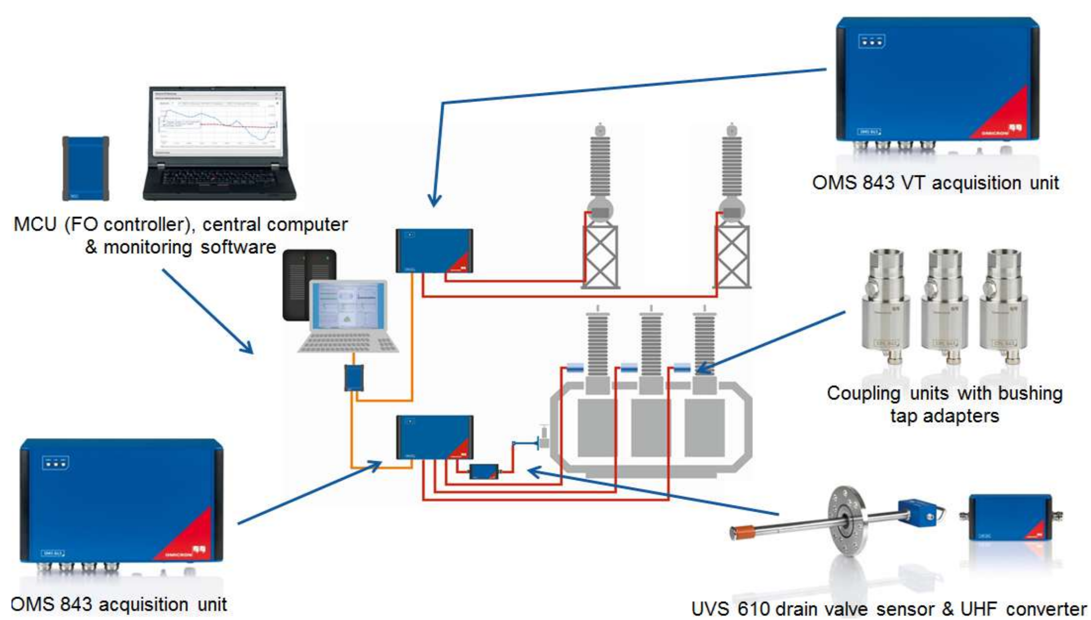


Figure 10.
Architecture of the installed monitoring system

Figure 11.
Tap sensor for C, tgδ, transients and PD measurements

Figure 12.
UHF antenna installed in oil drain valve

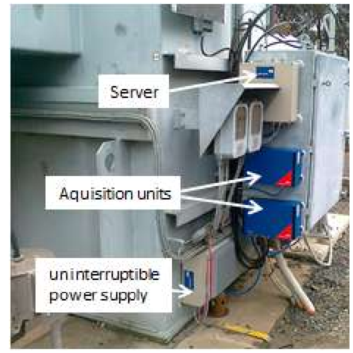


Figure 13.
Server, acquisition units and UPS

- Capacitance

The diagnosis is performed by comparing the capacitance values from on-line monitoring with the values from off-line measurements. The difference between them gives the capacitance variation ΔC that has to remain within certain limits. The change of bushing capacitance when one insulation layer is short-circuited for bushings of different rated voltage is presented in table 3 [10]. As the detailed information about the bushing design (number of insulation layers) is not available, the limits of ΔC variation was estimated to be a maximum 10%, taking into account the type of the bushing and its rated voltage. Such a defect does not necessarily lead to the total failure of the bushing, but it creates a higher electric field on the healthy layers.

Table 2
Acceptance level of dielectric losses for bushings of different design (at 20°C) [9]

Standards	***RIP***	***OIP***	***RBP***
DF (tanδ) IEC60137	<0.7%	**<0.7%**	<1.5%
PF IEEE C57.19.01	<0.85%	**< 0.5%**	< 2 %

Table 3
Voltage class and change of capacitance for condenser type bushings [10]

Voltage in kV	***No. of layers***	***Change in %***
123	14	7.1
245	30	3.3
420	40	2.5

PD detection with the conventional method requires a calibration of the measuring system according to IEC60270. To fulfill this requirement, PD pulses of a known charge are injected in the current path of the bushing and measured at their taps. The threshold for alarm level has to be related to the routine acceptance test level, 500 pC at 1.5Um according to IEC60067-3 and IEEE C.57.12.90. Different types of the defect generate signals of different apparent charge magnitude and PD pulse repetition rate. The decision about the criticality of measured PD signals requires analyses of PD patterns. Wide bandwidth or narrow bandwidth UHF measurements can be applied. In wide bandwidth measurements, the highest magnitude of the UHF signal is measured in the frequency range from 100 to 2000 MHz. In this case the noise can influence the result of measurements. To overcome this, narrow band measurements are

performed in the selected frequency range. With the transformer out of service, the spectra of the UHF signal are acquired and the external noise is identified. The central frequency and the bandwidth of the measurements are selected in the "clean" area of the spectra. The spectra are verified when the transformer is back in service and the frequency range of the measurements can be adjusted if necessary.
The amplitude of the transient over-voltages is calculated and expressed as a function of the phase-to-ground voltage and is displayed in p.u.

Periodic measurements are initiated in equidistant, one-hour time spans. The duration of the periodic measurement is normally 1 min. During this time, all scalar values (i.e. dissipation factor, capacitance, charge, repetition rate of the PD pulses, etc.) as well as images (i.e PRPD - phase resolved partial discharge patterns, 3PARD – 3 phase amplitude relation diagram [11], magnitude and shape of transient over voltages, etc.) are stored in the database.

Analysis of the results

Capacitance and dissipation factor

The example of the trend of capacitance variation (ΔC) is presented in figure 14. The maximum value of ΔC measured over the period of four months is compared with the threshold value (figure 15). The ΔC in phase B is the highest but still below the maximum 10 % limit of change. The three-phase trend of the dissipation factor is shown in figure 16. All the values are below the threshold values predefined for OIP bushings [9] and their trend is stable. A comparison between the highest on-line measured value for each phase and the predefined threshold is shown in figure 17.

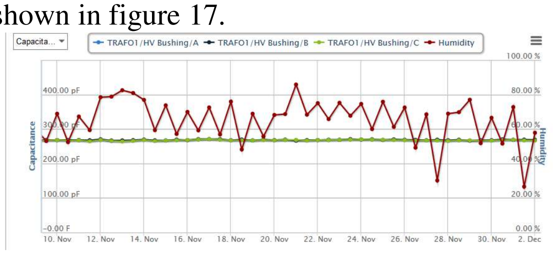


Figure 14
Three phase capacitance and ambient humidity variation (red trend)

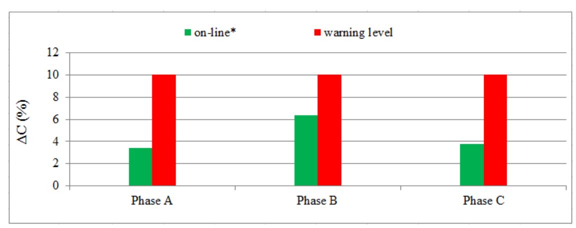


Figure 15
Comparison between the highest capacitance variation (green) and the threshold limit (red)

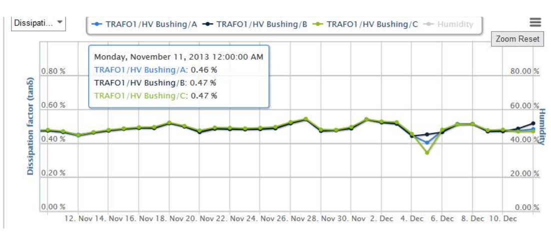


Figure 16
Three phase dissipation factor variation

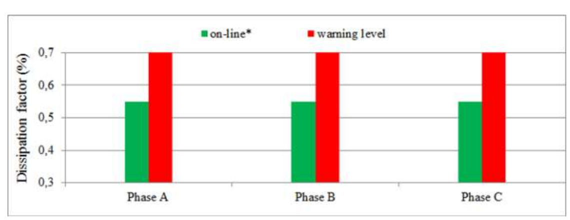


Figure 17
Comparison of the highest measured value of dissipation factor with the threshold limit

PD monitoring

PD monitoring with the conventional method

The three-phase PD trend is presented in figure 18. At each point visible in the trend diagram, PRPD patterns and 3PARD are available.

Figure 19 depicts the PRPD patterns of the PD signal acquired by the three-channel synchronous system. They are complex patterns with several PD sources overlapped. In order to separate clusters of different PD sources, a synchronous multi-channel PD evaluation technique is applied [11]. The 3PARD diagram (figure 20) visualizes the relationship between amplitudes of a single PD pulse in one phase and its crosstalk generated signals in the other two phases. By repetition of this procedure for a large number of PD pulses, PD sources within the test object as well as outer noise appear as a clearly distinguishable concentration of dots in a 3PARD diagram [11]. By examining individual clusters in the 3PARD diagram, a separation between noise and PD phenomena is possible.

Figure 21 shows the back transformation to PRPD pattern of the clusters 1 and 2. The patterns of the clusters 1 and 3 appear to be generated by bubbles and surface discharge with the highest amplitude in phase B (cluster 1) and phase A (cluster 3). Similar PRPD patterns were reported in [12]. The shape and phase position of the patterns of the clusters 2 (phase A) and 6 (phase C) may indicate partial discharge activity inside the voids of the insulation system [12]. The clusters 4 and 5 are generated by external interferences

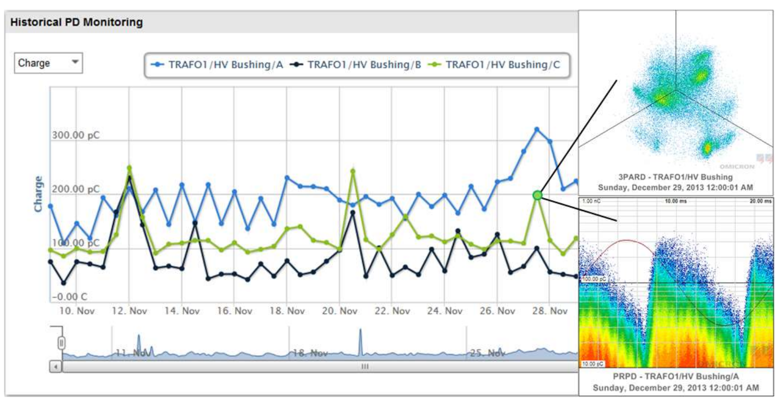


Figure 18
Three phase PD trend

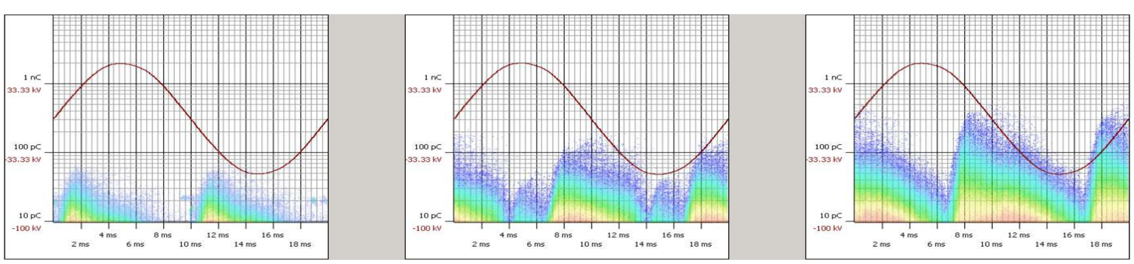
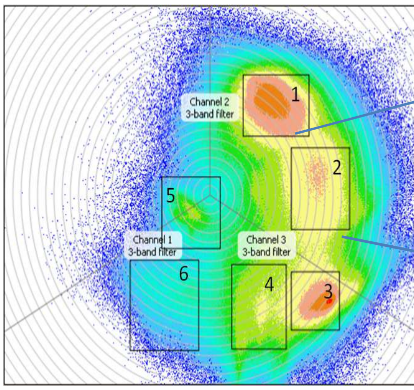


Figure 19
Three phase synchronous PRPD patterns

PD monitoring with unconventional UHF method

Performing a frequency sweep, two spectra of the signal are obtained (figure 22). The upper spectrum is built based on the maximum amplitudes of the time domain signal acquired at each value of the frequency during the sweep. The lower spectrum corresponds to their minimum amplitudes. Internal PD activity is always visible on the upper spectrum while external interferences (corona discharge, radio waves, GSM) are visible on both spectra.



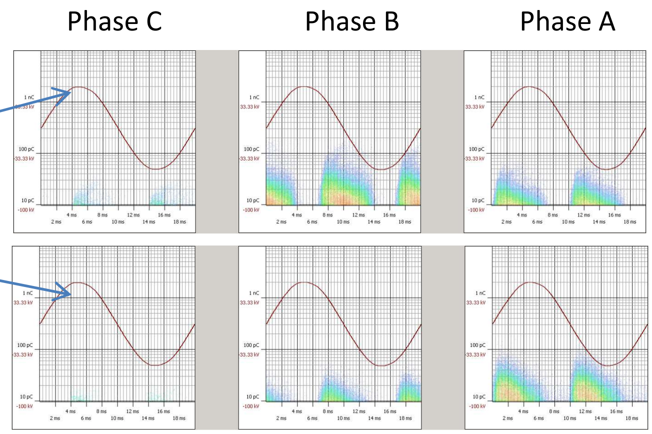
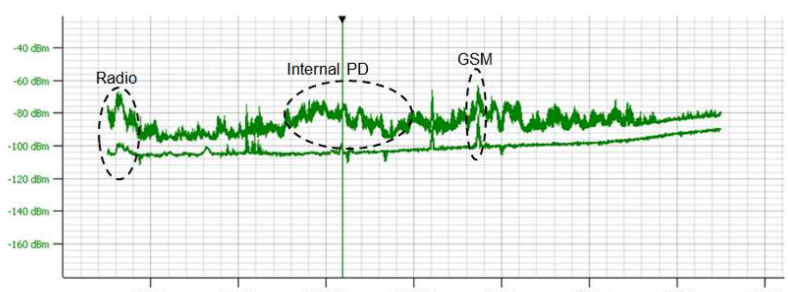


Figure 20
Equivalent 3PARD diagram

Figure 21
Individual PRPD patterns of the selected clusters

Internal PD activity was identified in the frequency range from 450 to 650 MHz. The PRPD pattern corresponding to a central frequency of 600 MHz is presented in figure 23. The signal detected during the on-line monitoring was synchronized with a 50 Hz signal taken from the measuring tap of the phase A. It can be seen in figure 23 that the phase of the voltage where the PDs occur is the one characteristic to internal discharges. Furthermore, it indicates a possible location of the PD activity, namely, in the vicinity of phase A. The PRPD patterns of frequencies between 1 GHz and 1.4 GHz were checked and no internal PD activity was found.



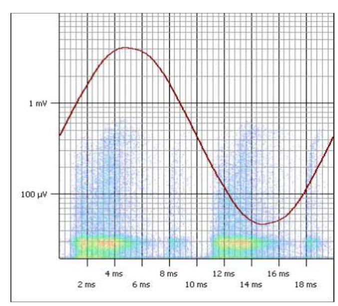
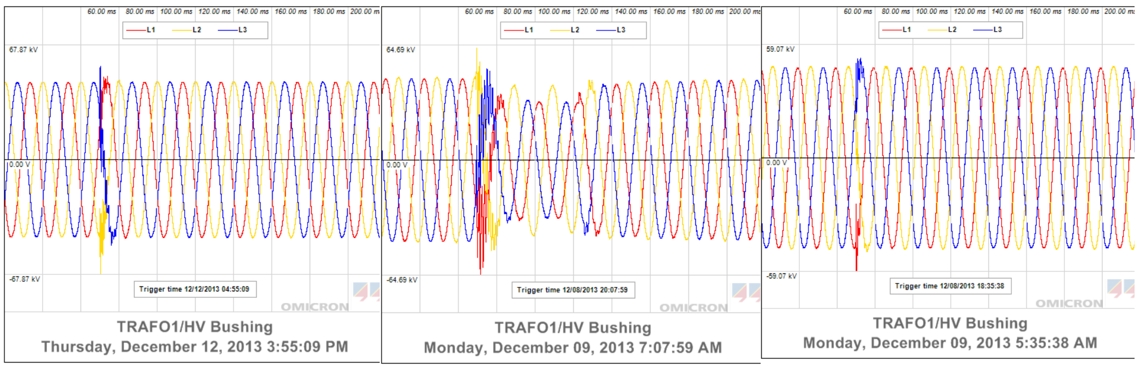


Figure 22
Frequency sweep diagram

Figure 23
PRPD pattern

Transients

Thirty transient over-voltages with the amplitudes between 1.25 and 1.77 p.u. were recorded in four months after installation of the system (figure 24).
The transient with the highest amplitude (1.77 p.u.) is shown in figure 24a. Figure 24b and c show other transient over-voltages recorded during the monitoring period. Even with such amplitudes, these transients represent a threat to the insulation of the bushings and windings because of the resonant phenomena which can lead to higher voltage distribution between the turns. The number of transients cannot be controlled but their monitoring can help identify defective equipment which generates over-voltages, near the transformer.



a b C

Figure 24
Time stamp and shape of the transients detected at the bushings

Discussion

As the dissolved gas ratios in the DGA system indicated that PD is taking place, the OMICRON on-line monitoring system for PD, bushing capacitance and tgδ was installed on the distribution transformer of POWERCOR. The PD activity was confirmed with both conventional and unconventional UHF measurements. The synchronous multi-channel evaluation technique separated clusters of different PD sources. Furthermore, it indicated a possible location of the PD source in the vicinity of phase A.

The bushing capacitance and tgδ values remain within acceptable levels indicated in the literature.

Concerning DGA analysis, high concentrations of H_2 and CH_4 indicate oil decomposition under PD activity [13]. The presence of high quantities of CH_4 and C_2H_6 indicate an extreme overheating of the mineral oil and adjacent metals. A low concentration of CO suggests that PD activity may not take place in the vicinity of the paper insulated parts.

It is intended to carry out internal inspections following the installation of a replacement transformer at the site, planned for late 2014 or early 2015.

Acknowledgement

OMICRON sincerely appreciates the high level of support and co-operation of POWERCOR in enabling this trial to proceed and with the installation of the monitoring system.

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Biography

Laurentiu Viorel Badicu is HV Application Engineer at OMICRON Energy Solutions GmbH, Berlin, Germany since 2012. He is responsible for maintenance of the installed on-line monitoring systems, customer trainings, performing site measurements (partial discharge, dissipation/power factor, capacitance etc.) and data evaluation. His interest covers also aspects related to the ageing mechanism and condition assessment of the insulating materials.
He received the Dipl.-Ing. and the Ph.D degrees in electrical engineering from University “Politehnica” of Bucharest, Romania in 2008 and 2012, respectively.

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Alan McGuigan has had a long and diverse career in all aspects of the electrical supply industry. He is past member of the Institute of Engineers, Australia.
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His preferred job description is “to have fun playing with Plant”.