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Brief Career Summary

My professional career directly started after completing my theoretical and practical thesis concerning high voltage testing on rotating machines at the company Maintenance Partners Belgium, a group company of Mitsubishi heavy Industries Ltd. With this company, I started as application engineer for partial discharge and loss factor testing of new designed VPI and Resin rich insulation systems, as well on rewound and repaired high motors and generators in the workshop. Later on, in 2010, I became Reliability Engineer at the same company. At that time the focus was mainly on on-site partial discharge testing (off-line & on-line) of rotating machinery, approximately 400 machines per year. Beside the partial discharge testing on machines, several other predictive tests as well on transformers belonged to the daily tasks such as:

- Load measurements/monitoring
- Winding resistance and inductance measurements
- Various DC-insulation resistances tests
- Dielectric loss analysis
- Recurrent surge oscillation measurements
- Surge testing
- Ring flux tests and Elcid core tests
- Hi-pot testing
- Basic Vibration analysis
- Ultrasound measurements
- Sleeve Bearing examination and Basic Shaft Alignments
- No load/load loss measurements
- Transformer turns ratio and winding resistance testing
- Polarity and phase displacement testing

In August 2012, I followed my passion for Partial Discharge analysis and started as Application/Service Engineer at Power Diagnostix Systems GmbH. Here, I'm mainly active with service related jobs such as on-site Partial Discharge Diagnosis and Fault Location on distribution and power transformers, MV and HV cables and rotating machines worldwide. Beside the consulting jobs, I take care of various training sessions concerning different high voltage applications and commissioning of PD-equipment and monitoring installations worldwide.

PD
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On-site Services on Power and Distribution Transformers

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Abstract - Changing maintenance strategies due to several restructurings in the power sector and related delayed investments in substation equipment, have led to an increasing demand for on-site acceptance testing, re-commissioning and localization of PD in power and distribution transformers. Modernized electronic based mobile test sets have simplified such on-site diagnosis. Further developments in the branch of partial discharge testing since the early nineties have caused new editions of standards including stricter test procedures and evaluation criteria. As a side effect, the service support in laboratories and on-site consulting for partial discharge pinpointing showed an increasing trend as well. Using the several different analysis techniques and methods simplified locating insulation deficiencies within the complex network of transformer windings.

Keywords: on-site acceptance testing; service support; mobile test systems; Partial Discharge; troubleshooting methods

1 Introduction

The power sector worldwide experienced strong restructuring due to several stricter environmental measures and criteria for exhaust emissions for instance. The efficiency of older thermal power stations using brown coal or fossil fuels suffered strongly under required investments to get the exhaust gasses within European Regulations. Several older power stations were closed or replaced by renewables or combined cycle systems. Often, the substation equipment was replaced while the transformers were kept in place. Those that remained open, conducted serious restructurings, which had a major impact on budgeting for maintenance of the installations. As a result, maintenance strategies have been changed during the past decades from corrective to preventive maintenance and nowadays even to predictive maintenance, where various periodic measurements and/or monitoring data determine the corrective actions to be taken. The scheduled investments to replace the growing amount of service-aged power equipment in substations and power plants are currently often postponed, and hence, on-site partial repairs to achieve a certain life time extension became important. As a side effect, on-site testing and re-commissioning of power and distribution transformers turned into an increasing demand. On the other hand, units that have been replaced had to be constructed at economical cost. Besides this, nowadays, the order specifications include high demanding special requests in terms testing compliant with the relevant standards. As a result, high voltage test bays and laboratories had to innovate and invest in improving their measurement setups and equipment for factory acceptance testing in order to meet with the latest standards, and hence, such optimizations of the measurement setups required valuable site support.

2 On-site Services

2.1 Partial Discharge Testing at Site

Tremendous transportation/on-site installation costs and the increased awareness for the need of on-site testing showed serious developments and re-engineering of existing older and bulky mobile test systems. Today, electronic based three-phase power sources are used, which are optimized for transformer partial discharge acceptance testing or witnessing during a so called after installation test [1]. A partial discharge test is often requested in addition to the standard commissioning tests such as the transformer turns ratio, phase displacement, insulation, and winding resistance testing for instance, after having discovered some irregularities, or alternatively, when the fingerprint taken with the sweep frequency response analysis after repair shows any deviations since erecting the transformer on-site. Also human erroneous actions with high voltage equipment during commissioning of such installations can result in the need for re-testing of the transformers insulation integrity by applying a separate source AC withstand voltage test, whether or not combined with partial discharge testing.

Hochspannungsprüfungen an Transformatoren vor Ort

Fig. 1: Inverter based AC mobile test system

2.2 Support with PD Testing in High Voltage Laboratories and Test Bays

Not only the on-site life extension repairs on existing transformers or commissioning of new power units resulted into an increasing demand for high voltage testing services on-site, but also the service support required in the high voltage laboratories and high voltage test bays of manufactures and service groups is an important branch of the on-site services. Since the end eighties/early nineties, the relevant standards such as IEEE C57.113 [2] and IEC 60076-3 [3] have specified the partial discharge measurement as a standard test to be performed along with the short (ACSD) and long (ACLD) duration induced voltage tests as part of the factory acceptance test (FAT) for new power transformers with a design voltage U_m > 72.5 kV for transformers compliant with IEC and respectively with a design voltage U_m > 115 kV for transformers built compliant with IEEE standards. Experienced test engineers worldwide are currently completing such testing successfully and the larger test bay setups are completely modified and optimized in terms of meeting the partial discharge standard´s requirements. With the developments made the past years in the field of partial discharge testing, several revisions, addendums, and new editions have been released. In contrary to the first versions, these new editions, released the past years, focused as well on the performing partial discharge testing as a special test on oil filled transformers having a design voltage U_m < 72.5 kV [4] and dry type transformers with U_m > 3.6 kV [5]. Thus, manufacturers and service groups need to follow such new agreements and specifications to get their transformers designed or repaired and tested to be compliant with these new standards requirements. In contrary to the past, when partial discharge testing was often considered as "black magic", nowadays, the end customers are more and more aware of the importance of partial discharge testing, and, hence, of the evaluation criteria and measurement setup requirements as well. Whereas the PD measurement was a "not mandatory" suggested special test, it is today specified as part of tenders and order specifications. Feedback from the test field showed that smaller transformer test bays, which were not yet familiar with partial discharge testing, faced some difficulties with optimizing their test setup to achieve the defined ambient noise levels, for instance. Thus, as mentioned above, offering service support in optimization of test bays and high voltage labs, assistance with acceptance tests, and training sessions is an important task.

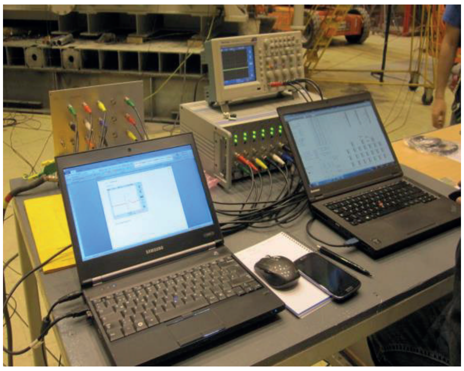

Fig. 2: Test setup during on-site service assistance

Besides supporting with PD-measurements and setup optimizations in factories, the AC mobile test system based mobile test systems (see fig. 1) can support the acceptance testing of large single-phase transformers. Regular three-phase motor-generator test sets can usually just run with 10-15% phase imbalance. The material needed for the Steinmetz circuit in order to operate a three-phase machine in single-phase regime is often not available. As an alternative, the mobile test system can be operated as "generator" providing the required power into the test bay´s bus-bar system. Running the three inverters with 0° phase shift offers the full 2MVA for single-phase induced voltage testing.

2.3 On-site Consulting

As a third branch of the on-site services, Power Diagnostix offers on-site consulting to support the localization of partial discharge sources within transformers. Such requests are often triggered by an abnormal behavior of the transformer during operation, a permanently installed partial discharge monitor, or either by tripping the established thresholds for the online dissolved gas analysis monitors (DGA), increasing hydrogen levels within consecutive oil sample analysis, or with more prominent problems causing a warning by triggering the Bucholz relay. In such cases, an off-line in-depth verification is strongly recommended. Such testing requires a mobile test system to be brought onsite and a full preparation by means of disconnecting the transformer from the grid. Besides this, when testing at elevated voltage, the unit has to be commissioned before and after the induced or applied voltage test. Power Diagnostix can assist with regular commissioning tests such as insulation resistance and polarization index measurements, transformer turns ratio, and phase displacement testing.

Fig. 3: On-site partial discharge measurements

On the other hand, consulting services with partial discharge pinpointing may be required in high voltage test bays for complicated cases with new, or repaired power transformers, which do not meet the evaluation criteria defined by the relevant standards. In this case, the local power supply of the test bay, often motor-generator test sets in combination with a step-up transformer, can be used instead of the mobile unit.

3 Partial Discharge Testing

3.1 General

Since many years, partial discharge measurements are a proven method in order to detect ongoing insulation deterioration or design related failures within power and distribution transformers. According to the transformer´s voltage class, a partial discharge test can be a routine or special test. Where diagnostic testing and or troubleshooting are not restricted to any regulations, acceptance testing must be completed with respect to general requirements as specified in the relevant standards. Although both kind of tests have a different approach, the intention of both is the generation of phase resolved partial patterns. Pattern recognition, by studying the relation between positive and negative pulses, typical clustered shapes, and respectively the phase position of the accumulated pulses can tell more about the nature of typical insulation failures. Not only statistical data behind the pattern are of importance, but as well having an understanding of the winding design and of the properties of insulation materials. Further, the basics of gas physics are required to make the picture of a certain failure complete.

Fig. 4 shows the typical ϕ-q-n pattern of a point-plane configuration discharge, in case, a non-shielded connection from an open air bushing to an overhead line with a sharp edge in vertical direction causing a non-symmetrical field. The asymmetrical pattern was recorded during an applied voltage test whereas the frequency of the Trichel pulses increased with the applied voltage.

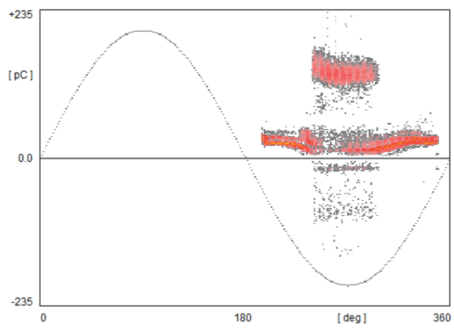

Fig. 4: Asymmetrical pattern due to a sharp point

Instead of the asymmetrical field of the Trichel discharge in fig. 4, the second pattern in fig. 5 shows a symmetrical ϕ-q-n pattern of micro voids in the silicon fat of a cable bushing T-connector. Similar patterns can be found in epoxy resin cured winding components or remaining air pockets in casein glue exposed to an electrical field surrounding transformer coils whereas each single sine wave shaped trace represents an individual void.

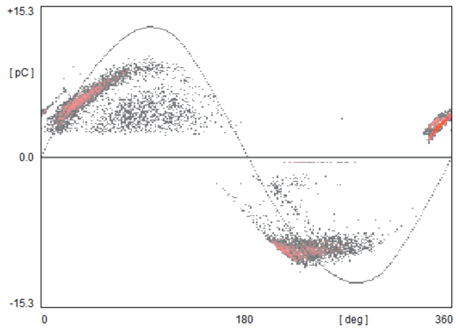

Fig. 5: PD pattern of gas inclusions in silicon fat

The relevant standards for acceptance testing of dry type and oil filled transformers mention that the partial discharge measurements have to be performed compliant with IEC 60270 [6]. In general the test circuit for both types of transformers are very similar. While for larger units the capacitive test tap of the condenser bushing is used to decouple the measurement signals, a regular coupling capacitor is used to decouple the measurement signals directly from the winding terminals of the cast resin insulated dry type transformers.

Besides the decoupling, the calibration should be compliant with the circuit as described in IEC 60270 and the PD test has to be conducted via the induced principle. For wide band PD detection, which is strongly recommended, following measurement frequencies have to be respected:

Lower corner frequency:

(f_1) : 30 kHz ≤ f_1 ≤ 100 kHz

Upper corner frequency:

(f_2) : ≤ 500 kHz.

Measuring within the recommended IEC bandwidth offers an excellent measurement sensitivity covering partial discharge origins hidden deeply within the winding. Moreover, within the IEC range, the original impulse properties of the high frequency partial discharge pulses shall be less hampered and distorted by high frequency effects, such as strong attenuation, dispersion, reflections, and resonances. Such effects become more prominent at elevated measurement frequencies [7]. On the other hand, measuring this lower frequency range requires an optimized test setup including appropriate filtering to manage the background noise limitations.

3.2 PD Measurement Systems

Generally, as per standards, partial discharge testing should be performed together with induced voltage tests. During such tests, all signals from the high voltage, low voltage, and neutral bushing, even the regulation or tertiary winding are of importance to have an overview of the PD signal distribution to all transformer bushings. To improve the overview and find possible relations between electrical signals derived from the various measurement points, usage of a multi-channel partial discharge detector supporting parallel acquisition is strongly recommended. Besides the parallel PD and RIV acquisition, each signal path can be synchronized with its operating or applied phase to ground voltage so that phase-to-ground and/or inter-phase problems can be clearly distinguished. In case of noisy environments or with regular diagnostic measurements, where the criteria of the standards don´t have to be strictly considered, PD testing may be performed at elevated frequencies. Therefore, the partial discharge detector comes with a 0–10 MHz spectrum analyzer with variable center frequency. Thus, due to its versatility, this partial discharge detector can be used for regular acceptance tests and troubleshooting.

Fig 6: ICMsys8, PD acquisition unit

Decoupling of the required high frequency partial discharge pulses and voltage signals in order to map the required phase resolved partial discharge patterns (ϕ-q-n) is generally done using the capacitive test tap provided with condenser bushings. Fig. 7 shows the typical quadrupole fitted to the test tap. These coupling units provide both the partial discharge and divided voltage signals to the acquisition unit.

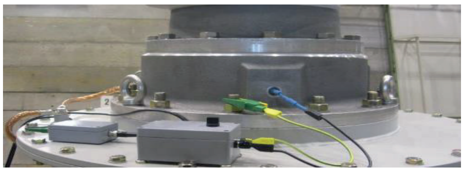

Fig. 7: Quadrupole and preamplifier fitted to the tap

Alternatively, for smaller low voltage or tertiary bushings having no potential tap, or even to connect directly to the high voltage winding terminals of cast resin insulated transformers, coupling capacitors can be used instead. Finally, wide band preamplifiers are fitted to the quadrupole's or coupler's PD output acting as both amplifier and impedance converter to adapt to the 50Ω of the RG58 coax cable in between [8]. Besides covering the requirements according to IEC60270, the quadrupoles and couplers support measuring higher frequency ranges as well. As an alternative for the regular couplers to be used along with the multi-channel instrument, several other accessories and sensors are available, such as HF-CTs, acoustic sensors, antennas, UHF flange, and drain valve sensors to cover the needs for test bays in transformer factories and the desired tools for service groups during on-site testing or troubleshooting.

3.3 AC Mobile Test Systems

Flexibility is one of the key words in the service branch. Mobile test sets offer a flexible solution for on-site testing of smaller distribution transformers as well as large power transformers. In contrary to the older bulky motor generator test sets often consisting of two or more containers including the step-up transformer and controls, the AC mobile test system is an inverter based three-phase power source. Such units come in a 40ft standard container including the three 450kVA inverters, capacitive and inductive compensation banks, 2MVA step-up transformer, high-voltage filters, and a reactor/coupling capacitor combination for resonant applied voltage testing. Besides the power and filtering hardware, the mobile set is equipped with a voltage and fiber optic load current measurement system in combination with a power analyzer for tests, such as the no-load/load losses, and an 8-channel true parallel PD and RIV detector designed for transformer acceptance testing. In order to cover a wide range of transformers, the windings of the step-up transformer are tapped and the 12 different configurations can easily be changed by jumpers on the air-bushings, offering a voltage range from 8,5kV to 90kV that can be optimized according to the required load. To meet the requirements of the induced voltage testing, the three inverters, 450kVA each, cover an output frequency range from 20-200Hz. Thus, in case of a 50Hz or 60Hz transformer, testing can be easily done on 100Hz or 120Hz, respectively, so that the transformer under test does not suffer core saturation under influence of the defined elevated test voltage levels.

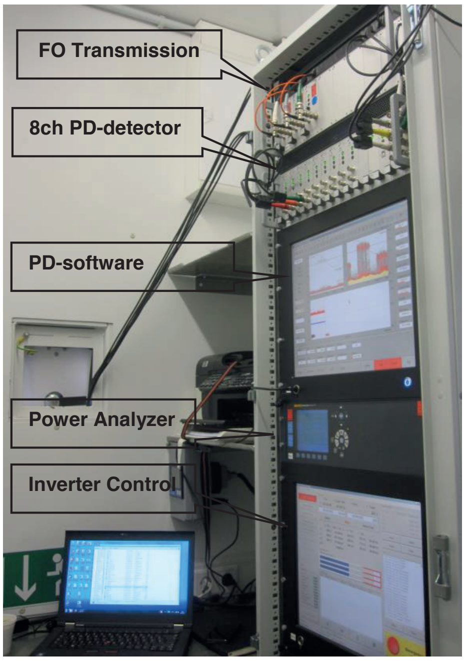

Fig 8: Mobile Test Systems control room

Besides the single or three-phase induced voltage tests, the mobile system set supports applied voltage tests up to 500kV using a resonant circuit. The resulting resonant frequency is given by the reactor´s fixed inductance (400H) and the capacitance of the transformer under test. Considering the full power of 2MVA, a current 4A is available at 500kV [1].

Fig. 9: On-site transformer acceptance test

The mobile test system is usually fed by a 400V diesel generator set, where the power requirements for a regular induced voltage test depend on the capacitance and no load losses of the transformer to be tested. In case of an applied voltage test in resonance regime where the required active power is generally <20kW, the mobile test set can make use of an 80kVA auxiliary generator fixed on the tap axle of the truck, and in case, operates fully self-contained.

Hochspannungsprüfungen an Transformatoren vor Ort

Fig. 10: Setup for applied voltage testing on-site

For applied voltage test on smaller transformers up to 50kV and 100kV, Power Diagnostix recently introduced a smaller test set embedded into a van-trailer combination. The unit consist of a 500kVA resonant test system having three taps of respectively 25kV,40kV, and 50kV in order to have the full power available in different voltage ranges. Without the trailer, the mobile laboratory comes with a 100kV/7.5kVA high voltage transformer.

Fig. 11: Mobile HV test system for medium voltage applications

4 Factory Acceptance Testing vs. On-site Acceptance Testing

Factory acceptance testing in shielded test rooms, optimized for partial discharge testing, and on-site acceptance testing in the often noisy environment of substations or power plants cannot be fully compared. Although both ways of testing have a different approach, the measurements must be carried out with respecting standards, such as IEC60076-3 [4] and IEC60270 [5]. It stands to reason that on-site testing is not always evident. Preparation of on-site testing is a high demanding task. Besides installation of the mobile test system nearby the transformer, which usually takes an hour or two, the unit has to be disconnected from the grid, and provided with electrodes in case of open air bushings, preventing external corona to interfere the PD measurements for instance. Fig. 12 shows corona shields mounted on 500kV open air bushings during an on-site applied voltage test.

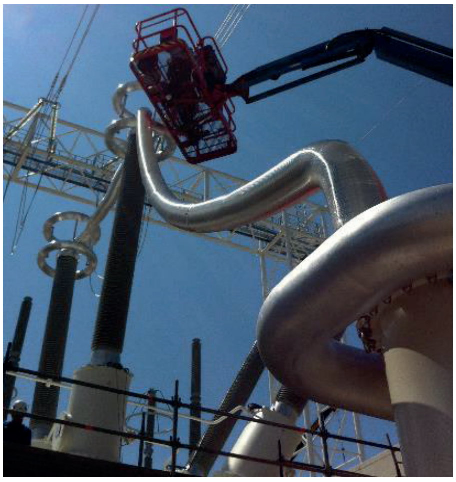

Fig. 12: Mounting of shielding and PD free HV line

For an induced AC voltage test, the voltage is usually applied via the low voltage bushings of the transformer using shielded high voltage cables. For a three-phase induced voltage test, the 2MVA step-up transformer of the mobile test system [1] can operate in a three-phase regime by running the inverters with 120° phase shift. Alternatively, when a single-phase induced test is required, the three inverters will be operated with 0° phase shift, offering the full power at the step-up transformer. The test voltages used after partial repair or re-commissioning may be different from the ones as specified in the standards for new transformers. Often, 80% of the defined levels are chosen as per agreement between the owner of the unit and service company or manufacturer. With the induced voltage tests, the phase-to-ground and inter phases withstand strength of the line terminals and winding insulation are tested. However, as per IEC [4] and IEEE [9,10] standards, not only the induced voltage tests are routine tests, but also the separate source AC withstand voltage test is part of the scope of the acceptance tests. With such tests, the main purpose is testing the integrity of the phase-to-ground insulation, which does not require the transformer to be magnetized. In contrary to the induced voltage tests, the applied voltage test may be performed at rated frequency +/-20%. In test bays, large AC Hi-pots or cascade transformers are used to approach the required test voltages. These units can then be used in case of service support during factory acceptance testing. For on-site acceptance testing, the AC mobile test system supports applied voltage tests up to 500kV in series resonance regime (see fig 13).

Fig. 13: On-site PD testing on 500MVA current limiting reactors

Although partial discharge testing during applied voltage testing is not a routine test, it might be helpful to perform PD testing to have a better understanding in case of troubleshooting on phase-to-ground problems or PD activity in the barriers between the high and low voltage windings. In case of PD testing in conjunction with the applied voltage test, a PD free overhead line (see fig 12) has to be installed, between the reactor and the transformer´s bushing. Obviously such preparations are not always easy to complete on-site. Alternatively, in case of transformers with shielded HV cable termination, or oil cable boxes, special PD free test adapters may be required to inject the test voltage via the switchgear for instance. Undoubtedly, the most important parameter to be considered with partial discharge measurements, whether it is in the factory or on-site, is achieving acceptable background noise levels. First of all, applying a clean sine wave is of importance. Therefore, appropriate filtering is required preventing high frequency disturbance pulses coupling into the measurement circuit via the high voltage power supply. Older test bays are usually equipped with motor-generator test sets in combination with a step-up transformer. With such units, switching pulses from rectifier systems or brush noise often create sensitivity issues. In more recent test bays, similar inverter based systems are used as in the latest mobile sets. For this sort of power supply, it is important to control and suppress IGBT switching noise by appropriate filtering. Usually, for inverter based sets, filtering is applied on the LV side after the inverter, and at the HV side after the step-up transformer. Any residual noise originating from the source shall be excluded by the high pass filter of the PD-acquisition unit. Alternatively, switching pulses can be cancelled out using the noise gating feature embedded in the PD detector. Once the power source is de-noised, the ambient noise can be estimated. In shielded test rooms, the ambient background is usually well controlled to below <10pC, while in power stations for instance, the environmental noise can easily reach several hundred pC when respecting the frequency limitations as per IEC 60270 [6]. Usually, the transformer tank offers sufficient shielding for the transformer winding. However, open air bushings may act as antennas. Spectrum analysis can directly provide more information concerning the noise behavior.

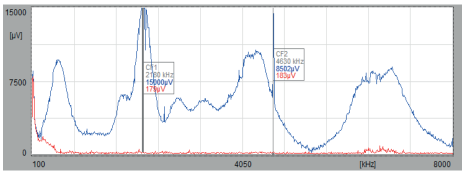

Fig. 14: Transformer signal-to-noise spectrum

Fig.14 shows an example of a typical transformer spectrum. The blue trace represents the calibrator pulse, while the red trace shows the ambient noise. Studying the signal-to-noise ratio should result in a better understanding of the interesting frequency span for the measurement. In addition, measuring in resonance areas can be prevented. However, as frequency limitations of the IEC60270 have to be considered, it is mainly a matter of getting the noise suppressed instead of elevating the measurement frequency. Validating where the noise is coupling into the measurement circuit, e.g. over the high voltage transmission line, via the mains, or even over the grounding, is the first step. Secondly, using applicable tools, such as additional line filters, ground filters, noise gating features, a spectrum analyzer with variable center frequency, or efficient software controlled high and low pass filters should make it possible to get the background controlled to the <50pC limit for oil-filled power and distribution transformers and to <100pC for current limiting reactors. However, when performing an on-site acceptance test on dry type distribution transformers, approaching <10pC becomes very critical, even when applying all possible de-noising methods and filtering. Since the repair costs and dismantling costs for dry type transformers are usually higher than the manufacturing cost, partial repairs on dry type units are not common, as they will simply be replaced, and, hence, the demand for on-site of acceptance testing for such units is very limited. Support with testing mostly takes place in the factory.

5 On-site Troubleshooting

On-site troubleshooting may be required in case transformers does not meet the defined acceptance test criteria, after a trigger by an online partial discharge, or DGA monitor, or by tripping of the transformers Bucholz relay, for instance. A root cause analysis may than lead to the nature and location of the PD source. Depending on the measurement results and PD origin, the severity can be estimated and further actions, such as applying partial repairs or installation of additional monitoring techniques can be considered. As a first step to locate the PD, a regular electrical partial discharge measurement must be performed providing phase resolved patterns during a three-phases induced regime. For a transformer that is in-service, save coupling methods are limited to e.g. installation of high frequency current transformers in ground loops or alternatively using HF antennas. Such indirect coupling methods often provide insufficient sensitivity. The best alternative in such case is switching-off the transformer for a set of off-line measurements using a mobile test system. Alternatively, when this is not possible, temporary installation of coupling units such as quadrupoles, coupling capacitors or even UHF sensors may be considered. During online tests, it might happen that site conditions limit the sensitivity, although, mostly good results can be obtained as on-site diagnostics are not strictly subjected to the standards requirements.

	1R	1S	1T	2R	2S	2T
1R	1.00 nC	69.7 pC	21.9 pC	346 pC	39.0 pC	23.2 pC
1S	47.9 pC	1.00 nC	51.7 pC	31.3 pC	254 pC	33.5 pC
1T	14.8 pC	68.9 pC	1.00 nC	18.6 pC	29.4 pC	270 pC
2R	477 pC	95.1 pC	56.5 pC	1.00 nC	94.7 pC	63.9 pC
2S	27.9 pC	326 pC	37.3 pC	62.5 pC	1.00 nC	46.2 pC
2T	104 pC	104 pC	565 pC	99.8 pC	95.3 pC	1.00 nC

Fig. 15: Cross-coupling matrix of a Yna0d1 auto transformer

After completing the calibration matrix (see fig. 15) and transformer characterization, the transformer can be energized again in order to derive the measurement results. In case of moistly conditions or non-shielded open air bushings, it is recommended to have noise-gating sensors such as disturbance antennas and/or HFCTs to cancel external corona for instance (see fig 16).

Fig. 16: Left, a disturbance antenna under an open air bushing, Right, a HFCT in the ground loop

In case of transformers in laboratories the first test results may already be available, and, hence, a first rough estimation of the root cause can be made. However, often, the tests shall have to be repeated to reproduce the results in order to get a reliable basis for the further investigation. Once the new results are available, the resulting apparent charge levels derived from all relevant bushings have to be compared with cross talk ratios as found in the calibration matrix. Defects in the vicinity of the capacitive test tap will often approach the cross coupling ratios as found during the calibration. On the other hand, relating the ratios found to the winding diagram and vector group may already point to suspicious areas within the transformer tank. Except comparing the cross coupling ratios, studying the symmetry, polarities, and distribution of the partial discharge pulses found within the phase resolved patterns can give more information concerning the defect type, geometry, and possible contact to electrodes. Since patterns may change after a certain time under influence of the applied field and the formation of by products, the original PD source might stay hidden. Therefore it is important to focus on the pattern as found with the inception voltage and development of the pattern with varying the applied or induced field.

Measurement results obtained during a three-phase induced voltage test sometimes require an in-depth verification by studying the partial discharge inception voltage and phase position, for instance, under influence of single-phase induced, or single-phase induced with elevated neutral excitation mode. Different voltage application configurations can indicate whether the partial discharge activity is a phase-to-ground, or inter-phase related defect mechanism. Beside the induced voltage test, applied voltage tests can simplify discovering activities in insulation barriers between the HV and LV winding for instance [11].

In addition to the phase domain analysis, repetitive partial discharge pulses can be analyzed in both time and frequency domain as well. Partial discharge sources located closer to the bushings tend to show a similar frequency spectrum and time domain signal as provided by the calibrator during the characterization of the transformer. On the other hand, signals transferred to the bushing tap by travelling the winding will be exposed to an increasing attenuation, or defined resonances and shall result in a reflected, or polarity swapped time domain signal showing stronger oscillations and a longer rise time than the calibrator signal injected at the bushings.

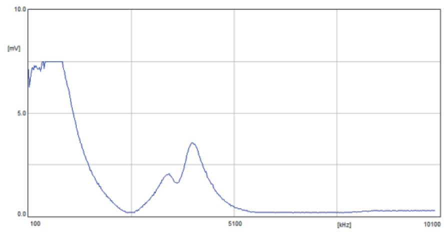

Fig. 17: Spectrum or calibrator pulse injected at the bushing tap

Fig. 17 shows the spectrum of the frequency characterization performed via the capacitive test tap. Here, the injected calibrator pulse is exposed to defined resonance frequencies.

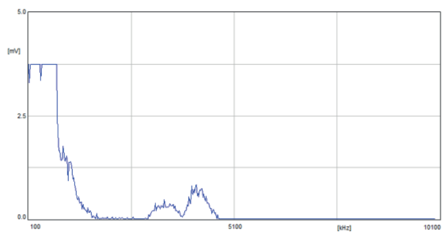

Fig. 18: PD Spectrum online

Fig 18 shows the spectrum derived from the same bushing tap under on-line conditions. In case, partial discharge activity was found and the resulting PD spectrum has been compared with the spectrum mapped during calibration. As both spectra are quasi identical and the partial discharge pulses could be detected in the higher frequency range, the PD source was presumed to be in the vicinity of the test tap.

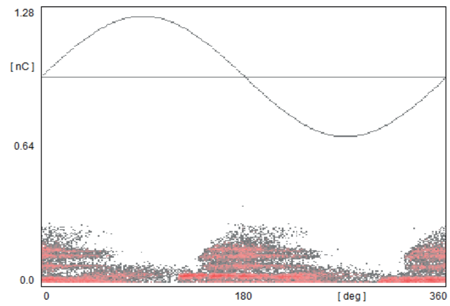

Fig. 19: PD pattern of floating corona shields in an oil bushing measured at 4.5MHz

After in-depth verification, it was found that the floating potential like PD activity was due to unsecured corona shields surrounding the high voltage cable termination to the oil bushing.

Besides studying the electrical signal response in phase, frequency, and time domain, a partial discharge source can also be located by measuring its acoustic emission. Although the acoustic response detectable at the tank wall strongly depends on the properties of the signal transmission path to the tank wall, the transmission medium, the transformers winding construction, and, respectively, the tank design, it is a proven method for partial discharge localization.

Fig 20: Acoustic sensors fitted with magnetic holders to a transformer oil bushing

In order to locate the partial discharge source, it should be possible to find acoustic signals that can be certainly correlated to the electrical partial discharge signal, and hence, acoustic signals emitted by mechanical sources or magnetostriction are neglected. Therefore, the acoustic signals are studied on a digital oscilloscope by triggering the acoustic waves on the electrical PD signal derived from the capacitive test tap, for instance [1].

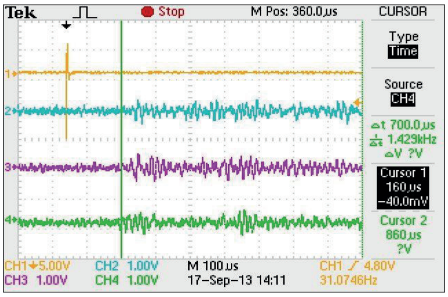

Fig 21: Scope waveforms of acoustic signals triggered on the electrical PD signal

In figure 21 the upper yellow trace represents the electrical trigger signal, while the remaining three traces show the acoustic waves measured by the Piezo electric sensors.

Using triangulation methods on three planes of a cubicle tank or three reference points around the circumference of a cylindrical shaped tank or an oil bushing can indicate to the exact position of the partial discharge source within the tank. However, due to the complex network as with transformer windings the acoustic signal may travel into various directions and get distorted, attenuated, or reflected. In this case, it is important to optimize the positions of the piezo electric sensors so that the signal path of the acoustic waves to the sensor is as short as possible. Having a straight oil path to the tank wall is the ideal situation, but cannot always be achieved. The typical propagation speed of pulses travelling a direct oil path is about 1400 ms^{-1}. However, with non-ideal conditions where no direct acoustic waves can be detected, a good understanding of the transmission path is required, in order to prevent a faulty analysis. Acoustic signals travelling the tank wall, for instance, propagate with a pulse velocity that is much faster compared to a direct oil path, respectively 5200ms^{-1}.

Once having found a certain spot on the tank or bushing wall providing acoustic waves showing the shortest time delay to the electrical trigger signal, i.e. the shortest distance to the Piezo electric sensor, a two-dimensional triangulation can be made. Having three sensors in a row with a distance of 5-10cm to each other, i.e. three sensors showing quasi similar time delays, reduces and simplifies triangulation work.

Fig 22 shows the interface of a software package designed for triangulation of acoustic signals. Here, the resulting scope waveforms of the acoustic signals provided by acoustic sensors in horizontal and vertical direction can be imported, creating the resulting three-dimensional position automatically. Apart from the available tools that simplify the analysis, the competence is still with the operator.

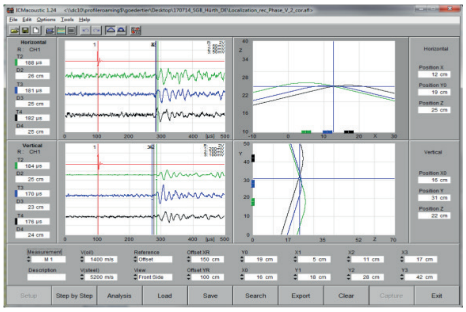

Fig 22: Triangulation software interface

6. Summary

On-site partial testing of power and distribution transformers after partial repair or re-commissioning is nowadays more simplified by using more compact electronic based mobile test systems.

The relevant standards concerning transformer testing underwent important changes with emphasis on test sequences, PD criteria,and background noise limits. With the latest editions, the focus is now as well on PD testing of transformers in the lower voltage classes. As a side effect, the need for service support and optimization of measurement setups in laboratories and test bays worldwide shows an increasing demand.

Advanced filtering techniques for the power source, noise cancellation methods for external disturbances, and spectrum analysis tools make on-site acceptance testing possible, even with respecting the defined criteria by standards. In case unexpected outage times and excessive maintenance and transportation costs are avoided.

Characterization of the transformer prior to energizing can simplify the first stage of PD localization. Beside the regular electrical PD measurements providing phase resolved partial discharge patterns (PRPD), various other troubleshooting methods, such as time and frequency domain analysis can be used to locate PD sources within transformer tanks. The acoustic measurement method has been widely used and proven to be a very appropriate PD pinpointing method.

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