Field-Testing of Cast-Resin Transformers in Wind Farms, industrial and marine Applications under constricted Space Conditions

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Abstract

Our modern life strongly depends on the availability of electrical power at any time. Therefore, the reliability of electrical power systems is of outmost importance. In that respect the integration of renewable energy resources on the one hand and the increased use of e-mobility is quite challenging. It is known that power equipment used to connect renewables face very specific and increased stress when such sources of fluctuating nature are involved.

Large scale wind and solar power often utilize transformers of different types within one farm. Smaller transformers connecting the single units to a bus feeder and several feeders than lead to the substation with one or more substation transformers which connect the farm to the power grid. While these substation transformers typically do not show reduced life expectancy compared to other grid transformers, several countries report failure rates higher than usual for the smaller transformers. This occurs especially in wind power applications and effects liquid-filled as well as cast-resin transformers. The latter are widely applied, when special measures for fire or ground water protection are required.

In both cases, most problems occur in the insulation system. Identified reasons were overheating due to very narrow design restrictions, vibrations, frequent thermal cycling, impact of frequency converter signals, high humidity and salty air. Due to this, periodic diagnostic condition assessment is requested more frequently as failures causing increasing outage costs for repair and, often even worse, non-delivered energy. A main driver in this respect is the assurance industry.

For liquid-filled transformers periodic oil analyses provides solid base for comprehensive health assessment. Based on the oil results further diagnostic measurements can be applied like SFRA, dissipation or power factor, winding resistance, TTR etc. which trigger then corrective maintenance measures if necessary.

For dry-type transformers, especially cast-resin insulated units, the application of the typical diagnostic tools is very limited due to the specifics of molded air cooled windings.

The most common reason for failure of cast resin transformers is the electric breakdown of the epoxy-resin insulation between turns or parts of the windings. In many cases, partial discharges (PD) occur before a breakdown. Therefore, by testing the windings with induced voltage in combination with a sensitive partial discharge measurement, the risk of unforeseen outages can be minimized. Main challenges are often the very constrained space conditions (e.g. in the nacelle) and high external interferences into the test circuit. This also applies for similar measurements in industrial or marine applications. In such cases, cast-resin transformers up to 72,5 kV and more than 60 MVA are in use now, sometime even equipped with LTC.

Based on practical examples, methods of performing the induced voltage test on-site with portable equipment and the application of digital PD measuring equipment for sensitive PD detection in electrically noisy environment are discussed. Several test results will be presented.

Introduction

The global wind power cumulative capacity doubled all 3 to 5 years over the last two decades. The installed electricity generation capacity was more than 480 GW in 2016. The number of installed systems increased as well as the size of the individual units. Lessons were learnt and the technology used has been optimized. Nevertheless, a significant number of outages caused by transformer failures led to unscheduled down times, resulting in high maintenance efforts, production losses and significant costs.

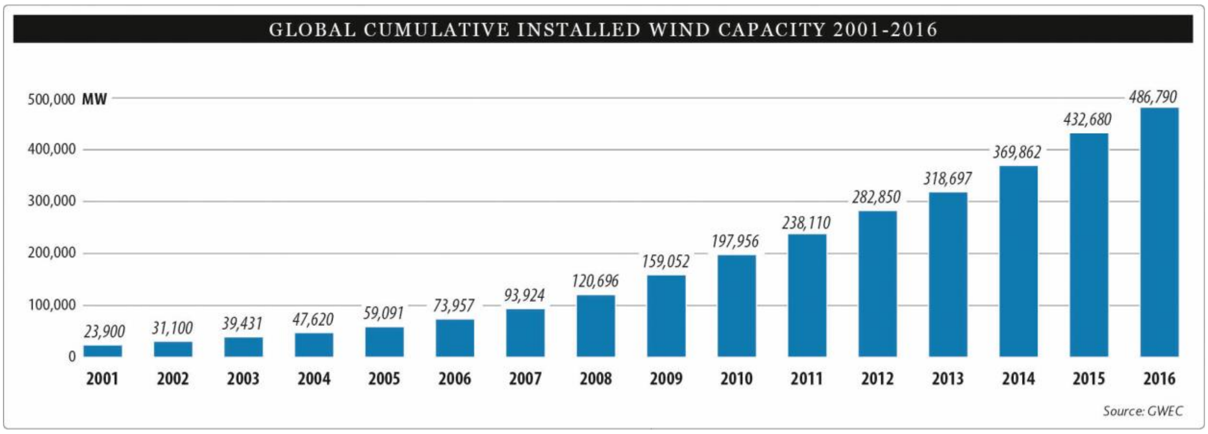


Fig. 1: Development of installed wind power capacities

In a typical arrangement, one power transformer per turbine is transferring the wind power to the connecting substation, which is then connecting the wind farm to the grid. Several wind farm operators mentioned high failure rates at these kinds of transformers ranging between 630 KVA and appr. 4 MVA, typically. For larger units up to 8 MVA, the failure rate seems to be lower. Even if the affected transformers are relatively small, they must be considered as GSU-type transformers, meaning maintenance and condition assessment are important to assure a reliable power generation. For liquid-filled transformers periodic oil analyses provides solid base for comprehensive health assessment. Based on the oil results, further diagnostic measurements can be applied like SFRA, dissipation or power factor, winding resistance, TTR, leakage reactance etc. which can then trigger corrective maintenance measures if necessary.

For dry-type transformers, especially cast-resin insulated units, the application of the typical diagnostic tools is very limited due to the specifics of molded air cooled windings. The most significant information about the condition of cast-resin transformers, especially taking into account the nature of the main failure cause – defects of the main insulation, is delivered by partial discharge measurement. Detecting partial discharges in the insulation system of a power transformer at an early stage reduces the risk of a total breakdown. This brings up two major needs: the availability of an easily transportable power source to enable PD testing and a flexible toolset to differentiate various PD sources respectively the ability to separate inner PD from external disturbances. Challenges are often remote locations, very limited space in encapsulations, tower base or even in the nacelle, a sometimes challenging, noisy electrically test environment and very small limits of PD activity inside the insulation.

The power source needs to be able to deliver frequencies higher than 50 Hz while no additional signals shall be introduced into the circuit which may appear like PD signals. For the proposed single phase excitation, the combination with multi-band PD measurement procedures is proven to be successful to separate external disturbance from internal PD on the one hand and to differentiate more than one internal sources from each other.

Partial Discharge measurements on dry-type transformers

For partial discharge measurements on transformers, the frequency of the test voltage should be higher than the nominal frequency to avoid excessive excitation current during the test. Typically, each winding of a cast-resin transformer undergoes two PD measurements in the factory. First, every single winding is tested separately before the final assembly. The manufacturers want to make sure, that no defective winding is installed because identifying a faulty one during the final test would require the upper yoke to be disassembled again. The second PD measurement then happens as integral part of the FAT (factory acceptance test) on all transformers rated 3,6 kV and above. The procedure is described in IEC 60076-11 [1] and IEEE C 57.124 [2]. Both documents are under revision at the moment. Figure 2 explains to application according to IEC. A phase-to-phase pre-stress voltage of 1,8 x U_r shall be induced for 30 seconds, followed by a phase-to-phase voltage of 1,3 x U_r for 3 minutes, during which the PD shall be measured. The stress level for units, already been in service is 80%. The maximum level of partial discharges shall be 10pC which by standard requires a background noise level not higher than 5pC.

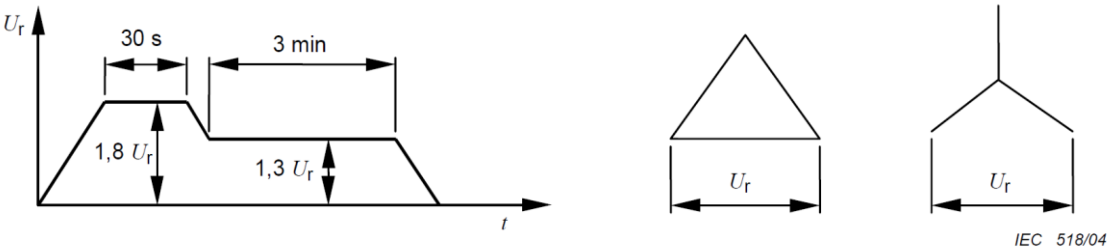


Fig. 2: PD test procedure according to [1]

Figure 3 shows the arrangement for a PD test in the factory per IEC 60076-11. It is remarkable that, even if the excitation is three-phase, the measurement of the PD signals is carried out with one PD instrument, only, utilizing a multiplexer-switch, marked by “S”. That means a PD fault in one phase, is also visible in the other – not affected – phases due to cross coupling.

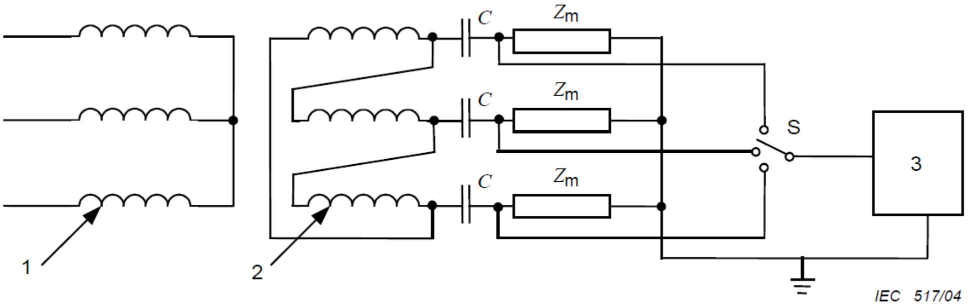


Fig. 3: PD test arrangement according to [1]

In a factory, this is typically manageable, since this is a rare case due to application of pre-tested windings. When testing an aged transformer, this can lead to increased efforts in analyzing the PD pattern to find out, which winding is really effected. Therefore, a single-phase excitation is useful for a quick identification of a problematic winding, especially as it is mostly easy to open the delta connections on the HV-side of a typical wind power transformer. In that case, the power source needed to run an induced PD test can be small and lightweight enough to be used in remote locations and under very restricted space requirements.

Qualification of a single-phase source for induced voltage testing

For on-site PD tests on dry-type transformers, a powerful voltage source is needed as the reactive power of the test object has to be compensated. Otherwise, at remote locations mobile diesel generators are not always available, too bulky to be used or even forbitten, e.g. inside the tower or nacelle. So, the source needs to be able to work on a regular power outlet. The operating frequency of the systems output voltage must be higher than the nominal frequency of the transformer to avoid excessive magnetizing currents when the rated voltage should be exceeded. To minimize the needed power, the source should deliver an output voltage with variable frequency. As the described source is also a measuring device, the impedance of the complete test circuit can be measured with amplitude and phase angle. So, the frequency can be tuned to the resonance frequency given by the main inductance of the transformer, the winding capacitance and the coupling capacitor. If the frequency is set to the maximum impedance (red curve), the needed test power is minimized (figure 4).

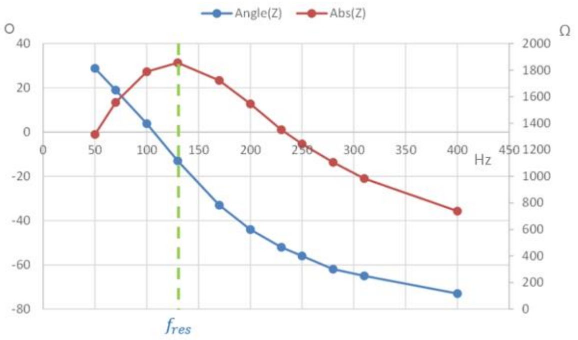


Fig. 4: Impedance of the test circuit vs. frequency

In rare cases, this resonance frequency can be too high to meet the 500Hz-criterion of IEC 60060-3 [3]. Then, additional capacitors can be used on the low voltage winding to reduce the frequency. Practical experience shows that 10-100 µF are sufficient. Due to the moderate system voltage of the transformers LV-side, the voltage requirements onto the capacitors are quite low, so that normal commercial caps can be used. Figure 5 shows the setup with a system, widely used for multiple purposes in the market, acting as the power source, an adaption transformer to connect with the rated voltage onto the transformers LV-side, compensation capacitors (in green circle) and a PD-coupling capacitor in red with PD measuring system to de-couple the PD-signals from the transformers HV-side. On the right-hand side, such compensation capacitors are visible, in this case, an oil-filled transformer had to be tested.

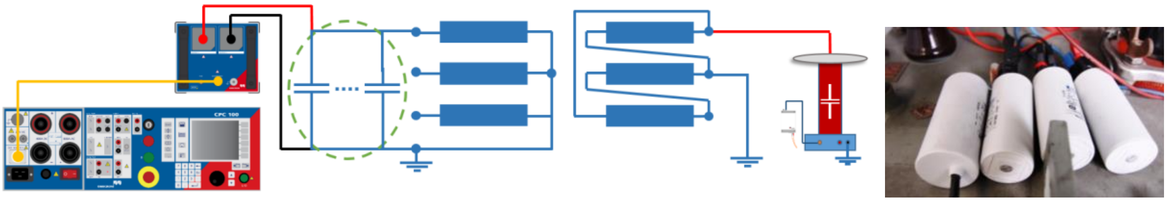


Fig. 5: Power source with adaption transformer, capacitive compensation, test object and coupling capacitor

The CPC-voltage source itself has a weight of 30kg, its built-in amplifier delivers up to 5kW at frequencies from 15 to 400Hz. A "soft switching" - design reduces disturbances by the switching semiconductors. With an additional matching transformer, the output voltage of the amplifier can be matched to the needed excitation voltage of the transformers LV side. The authors typically use a universal matching transformer, which can deliver voltages from 50V to 800V. Another important requirement regarding the source is its ability to enable a voltage calibration of the PD system on the transformers HV side. A voltage value, just calculated based on the transformers ratio is not considered to be sufficient as an un-monitored overstress of aged windings is typically seen as too risky. The source used in the measurements of this paper provides a 2-kV-output which has to be connected to the top of the coupling capacitor which enables a precise calibration of the voltage input of the PD measuring system (Fig. 6).

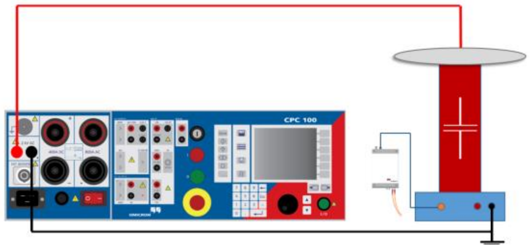
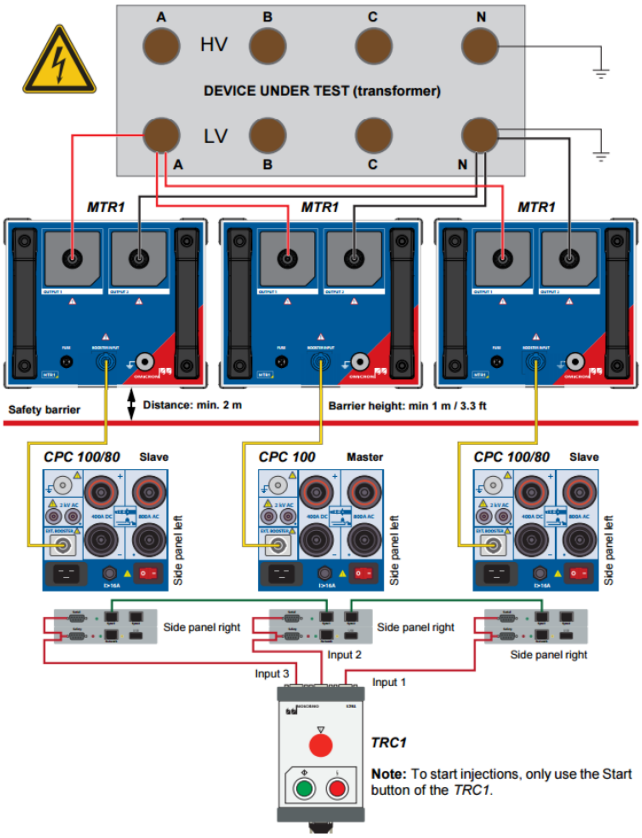


Fig. 6: Voltage calibration with the systems 2 kV-output

With a system power of 5kW, one source can be used to test transformers up to 3MVA. For larger transformers, up to three of the sources can be synchronized enable parallel operation, as schematically shown in figure 7. With a test power of 15 kVA on three normal 230V/16A power outlets, dry-type transformers of up to 25 MVA can be PD-tested.



Note: To start injections, only use the Start button of the *TRC1*.

Fig. 7: Test system for 15 kW with three CPC 100

This concept had to be proven first. Therefore, tests and measurements took place with manufacturers of cast-resin transformers as well as wind turbine manufacturers. Figure 8 shows a first test of a wind farm transformer of 6 MVA in the factory. Two sources have been used in synchronous mode. The enhanced pre-stress voltage was 52 kV for 30 seconds, followed by the 3-minute testing voltage of 42 kV. In the left part of the picture, the positioning of such transformer in the nacelle is shown.

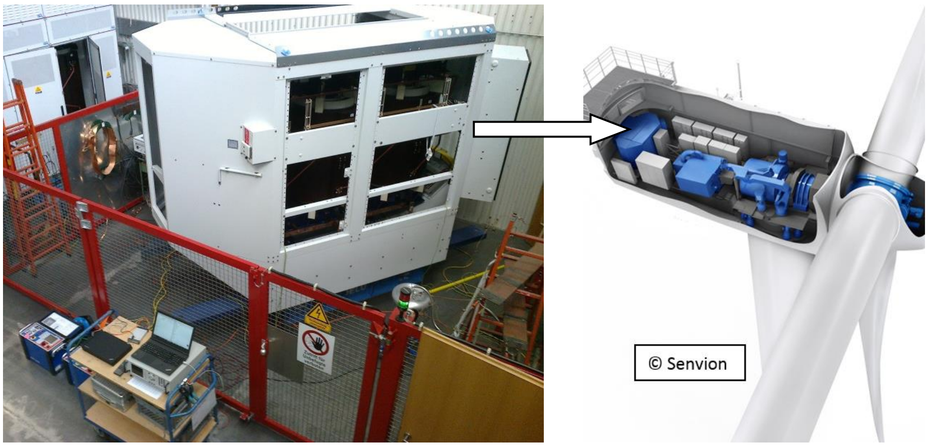


Fig. 8: Two CPC100 in synch mode in a factory, position of such transformer in the back of a nacelle

As the test was successful, the next step was to varify the applicability of induced voltage testing with PD measurement after such transformer is installed in its final position in the nacelle (Fig. 9). This test was conducted on a preparation site of a large offshore windpark. Main obstacle to overcome was the positioning of the coupling capacitor due to very limited dielectric clearances. However, this problem could be solved and PD measurements were possible. Due to the shielding behavior of the housing, a background noise level of less than 5 pC had been achieved.

Fig. 8: On-site PD-test to verify the functionality of the CPC-source on an installed transformer

The measurement of PD on cast-resin transformers on-site

Partial discharge measurements outside of Faraday cages are most often troublesome due to electromagnetic interference from the surrounding. As for XLPE cables, PD in cast-resin insulation will sooner or later lead to severe problems as these types of insulation are not self-healing, PD will erode the insulation over time and the dielectric strength will be more and more decreased. Thus, also very small levels of PD must be found and clearly identified. External interferences are often by far higher than the signals to be detected. To overcome these challenges, modern fully-digital PD instruments enable several de-noising methods which can reduce or even eliminate such noise problems. A great advantage of digital compared to analog filters is their flexibility to adapt bandwidth and mid-band frequency onto the actual measuring conditions. While for the measurement in the factory the quite strict boundary conditions of IEC 60270 [4] apply, this standard is not intended to be used on-site, even though it is recommendable to apply its rules if possible.

As the aim of on-site PD testing typically is risk assessment, the steps towards achieving the goal are reliable detection of harmful PD, identification of PD-type and a location of the PD-spot(s) if necessary. The evaluation of the pC-value describing the intensity is mostly of minor importance, especially if assets with non-self-healing insulation are to be investigated. Therefore, it is common for practical reasons to set the digital measuring filters of the PD instrument to frequency ranges with lower background noise floor. Also, a variation of the filter bandwidth can help to achieve a better signal-to-noise ratio (SNR).

Another proven de-noising technology is the usage of external hardware-gating. Here, an additional PD measuring channel can be equipped with any kind of antenna, suitable for the specific noise-interference situation. When fully synchronized measuring channels are used, the signals of the external antenna can be subtracted digitally from the reading of the measuring instrument, connected to the transformer. It is important to make sure, that the internal PD signals cannot “reach” the antenna. An example for this method can be found in [5].

Another powerful method is the utilization of multi-band measurement filters, often referred to as 3FREQ-method. This requires three PD bandpass filters, measuring every PD event simultaneously at their predefined mid-band frequencies. The synchronous consideration of three different frequency parts of the spectrum of each single PD pulse provides information on its discharge nature, signal propagation and path attenuation. A comprehensive investigation of the spectral behavior of different types of pulses is given in [6]. The proper selection of these 3 bandpass positions in the frequency domain is the key to gain the optimum benefit. With the application of the so-called “three center frequency relation diagram” (3CFRD) it is possible to discriminate pulses of different type or same type but different origin. Figure 9 shows in the left part the spectra of three PD pulses and the three digital measuring filters marked as blue bars. The red arrows indicate the response of PD pulse one at the discrete filter frequencies. These response values are drawn into the star-shaped 3CFRD diagram as shown in the right part of figure 9. The lengths of the phasors represent the measured response amplitudes and the axes indicate the respective filter frequency. By adding the phasors of the PD responses one single dot is the final representation of the initial triplet.

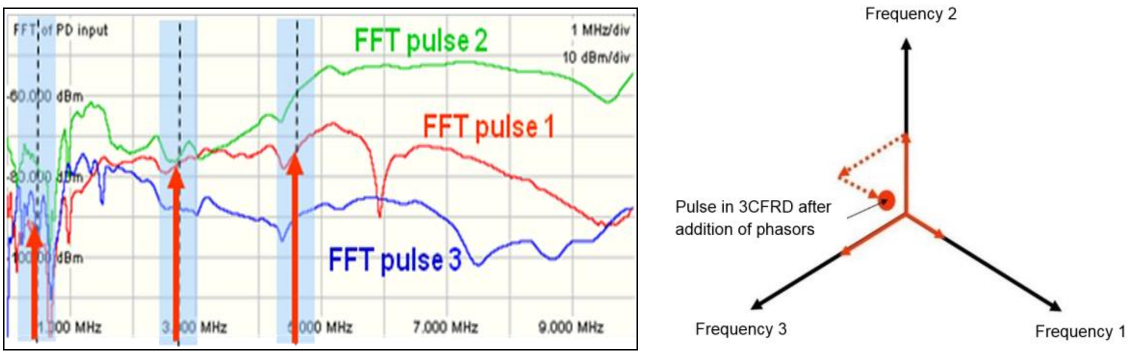


Fig. 9 FFT of three different PD pulses(left) and the corresponding 3CFRD of pulse number 1

While this method had been developed for single phase objects like CT's and VT's, insulators or bushings it has to prove its applicability for cast-resin windings, too. For this purpose, a wind turbine transformer known to have a PD defect has been measured, once again powered by a CPC as described above. Figure 10 shows the transformer during the test and again its regular positioning in the wind turbine. The 34,5-kV-transformer was tested with 40 kV and several PD sources up to 1 nC could be identified. Figure 11 shows the PD pattern left and the according 3CFRD on the right-hand side.

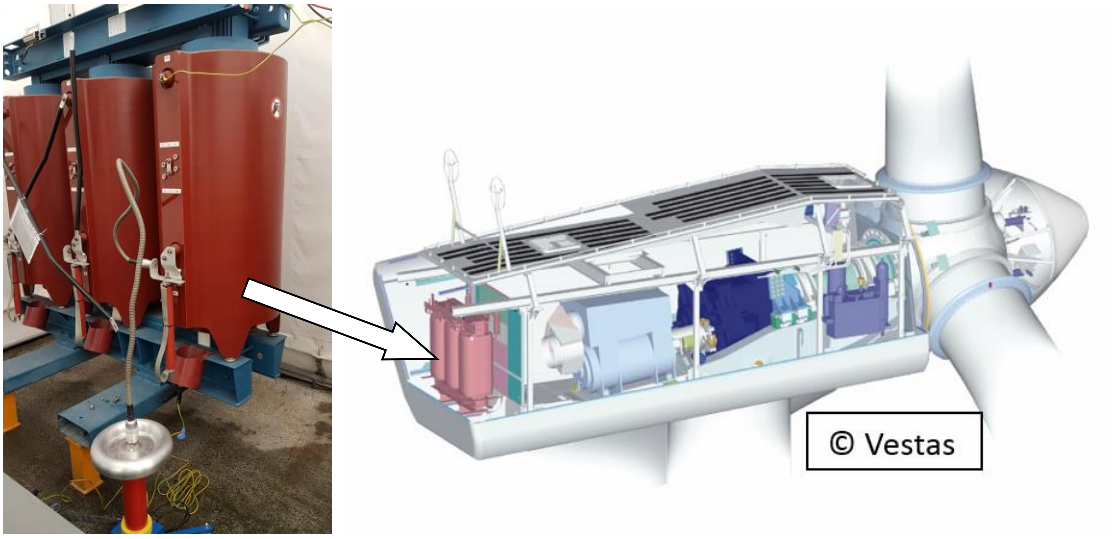


Fig. 10 PD measurement on a transformer and its position in a wind turbine

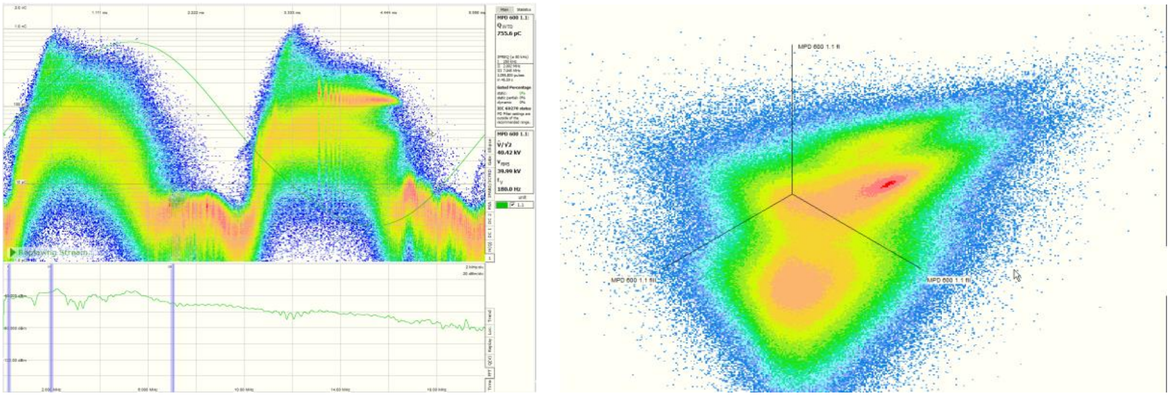


Fig. 11 PD pattern, below a pulse spectrum and the three filters(left), 3CFRD of this measurement

In a first step the background noise, mainly originating from the power source had been identified in the 3CFRD, Figure 12, left. The marked area in the lower part of the diagram is shown as PD pattern after back-transformation of the pulses in this area in right part of figure 12. The average value was about 10 pC.

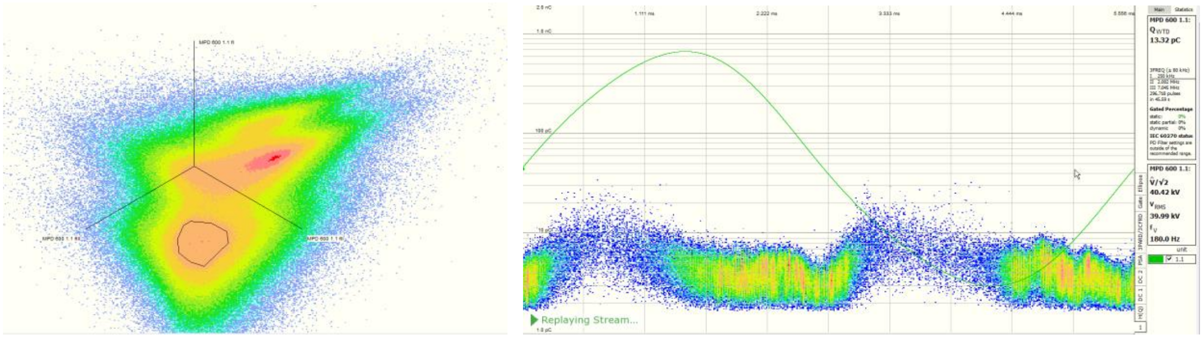


Fig. 12 3CFRD with marked cluster of background noise (left) and according PD pattern (right)

Now, with knowledge about the position of this kind of pulses in the diagram, the trigger level was set higher to "clean-up" the diagram and to ease the separation of the other remaining PD sources. Figure 13 shows the according 3CFRD. The three remaining clusters can clearly be identified. Each cluster represents another source of PD as the cluster position is reflecting their different spectral behavior.

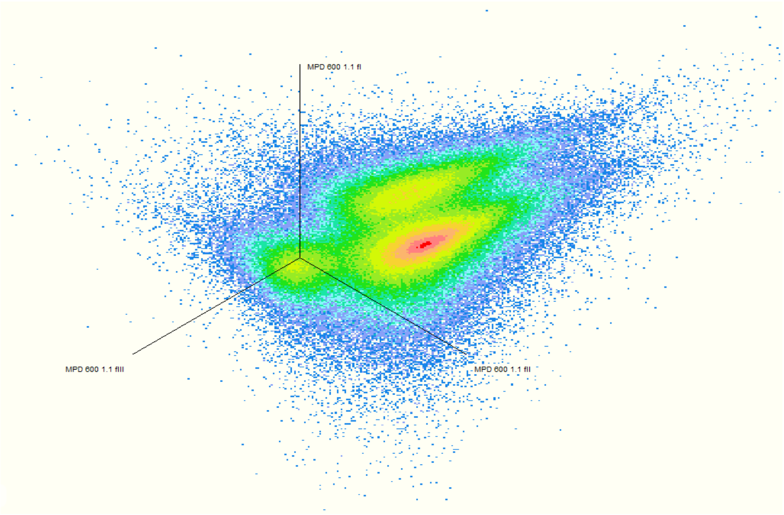


Fig. 13 Another 3CFRD of the measurement shown in fig. 11. Trigger level increased

In the next steps, every cluster can be analyzed separately for its behavior with respect to the inception and extinction voltages, hysteresis etc. In figure 14, the selected clusters are framed in the left part of the figure and shown as PD pattern on the right side. On top, a contact-related PD activity can be identified while two sources of surface discharges are to be seen below, both already with signs of carbonized tracks, an indication of PD activity over a longer period of time and proceeded destruction of insulation.

Based on the findings during the before mentioned tests and measurements, the authors started to apply the method of using one or more CPC's as a source for induced PD tests on cast-resin transformers in various industrial and marine environments as well as in the renewables industry. The 3CFRD was often used to get rid of external noise or to confirm that no PD was covered by external signals. In the following, practical cases will be described.

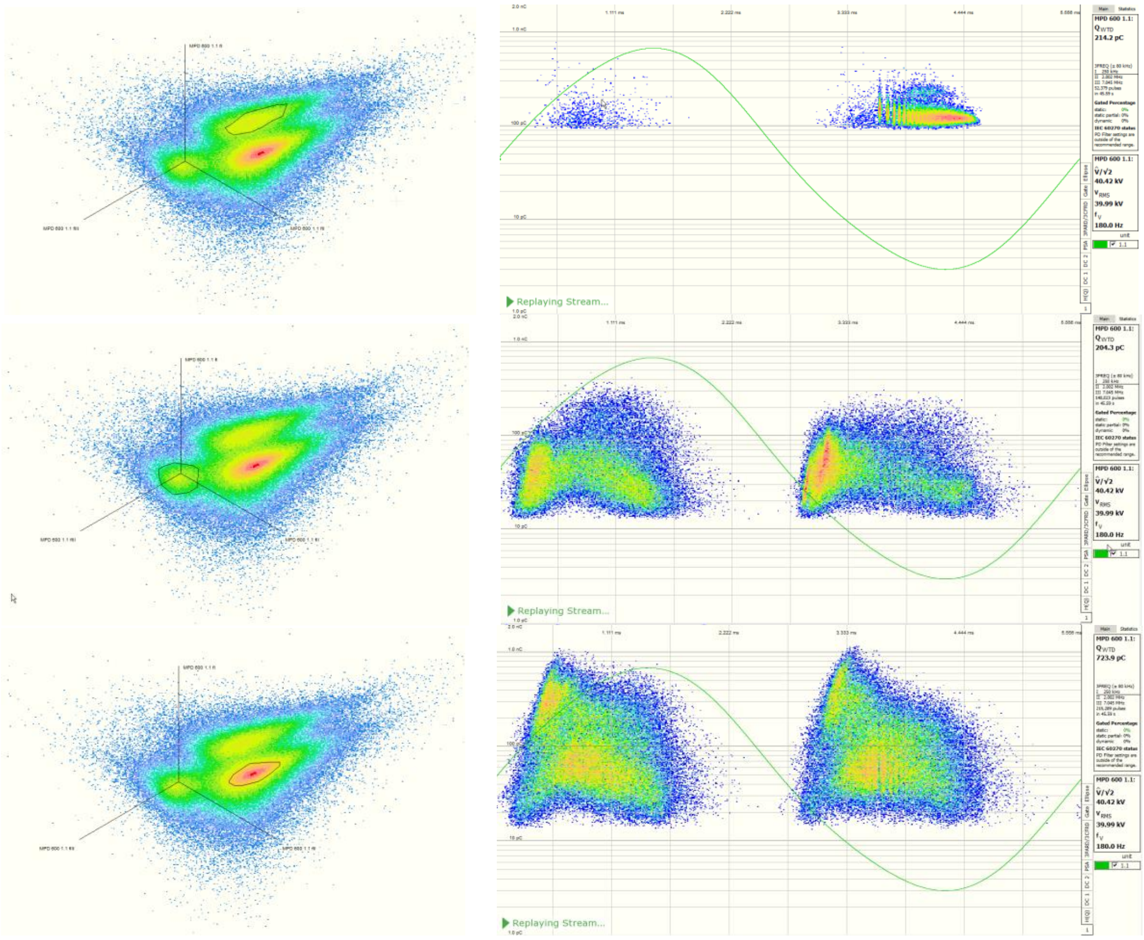
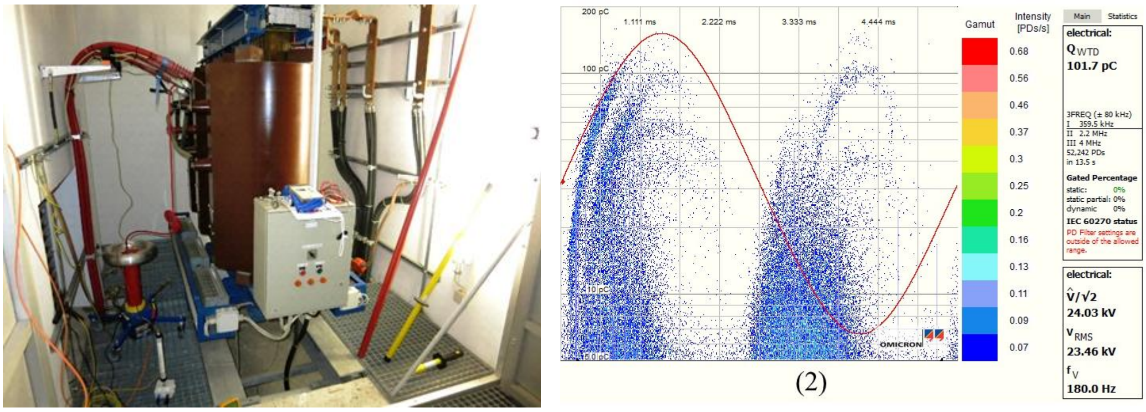


Fig. 14 3CFRD with cluster selection (left) and the according PD pattern (right)

Case 1

Partial discharges were recorded during routine testing by an online monitoring system for a length of MV cable in a huge data center. An offline-test showed clearly, that the cables were PD-free. A connected transformer, 2MVA / 20 kV was identified as the possible source of the recorded signals. A subsequent induced voltage test (Fig. 15, left) provided a clear indication of the presence of dangerous void-type discharges within the solid insulation (Fig. 15, right). As all phases were affected, a repair with exchange of the windings was not justifiable, economically. So, this transformer had to be replaced.



electrical:
Q_{WTD}
101.7 pC

3FREQ (± 80 kHz)
I 359.5 kHz
II 2.2 MHz
III 4 MHz
52,242 PDs
in 13.5 s

Gated Percentage
static: 0%
static partial: 0%
dynamic 0%
IEC 60270 status
PD Filter settings are outside of the allowed range.

electrical:
$\hat{V}/\sqrt{2}$
24.03 kV
V_{RMS}
23.46 kV
f_V
180.0 Hz

Fig. 15 PD measurement setup on a 20kV / 2MVA transformer (left) and PD pattern found

Case 2

The operator of the broken 2,5MVA transformer shown in figure 16, left, wanted to know if the transformer could be repaired or would have to be replaced. Both outer windings were cleaned intensively to remove all carbon from the surface. A partial discharge measurement revealed the windings to be PD-free, so an exchange of the middle winding was reasonable. Figure 16, right, shows transformer after repair.

Fig. 16 2,5 MVA transformer before and after repair

Another PD test was undertaken to confirm the successful repair. Figure 17, left, shows the PD pattern of this test, only consisting of a noise floor of about 17 pC. To make sure, no “hidden” PD is covered, 3CFRD has been applied. The diagram showed only one cluster. This has been framed and after an inverse filtering, showing all pulses outside the frame, no PD was visible anymore. This confirms the absence of PD pulses within the noise floor. The inverse 3CFRD filtering should be done carefully not to filter out any PD signals.

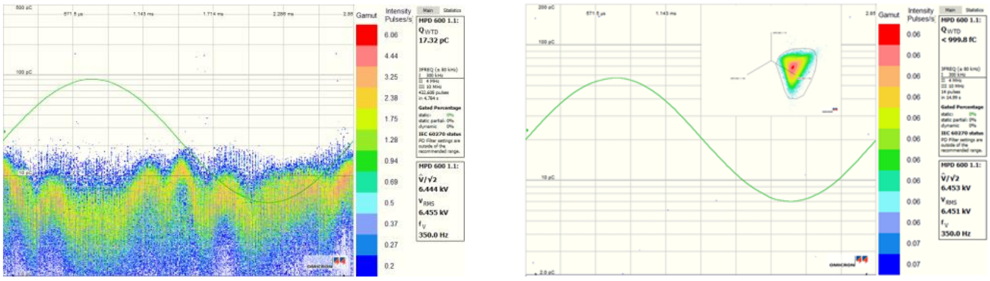


Fig. 17: Unfiltered PD measurement of middle phase winding (left) , 3CFRD and inverse filtering

Case 3

Following the commissioning of a hydroelectric power plant, PD tests were carried out to confirm the healthy condition of eight 10 MVA transformers, installed to excite the asynchronous generators. Figure 18, left, shows one of the tested transformers. An additional step-up transformer had to be used to generate the required feeding voltage of 3kV on the low-voltage side. Due to this increased power demand, three CPC’s were used to provide the necessary testing power. However, all eight transformers were tested within two days. For the PD measurement, it was required to test with filter settings according to IEC 60270, which in this case, led to slightly higher background noise due to external noise signals from nearby power electronics which could not be switched off (Fig. 18, right). Applying the 3CFRD method confirmed, that no internal PD was to be seen, even under the noise floor. All transformers passed the test successfully.

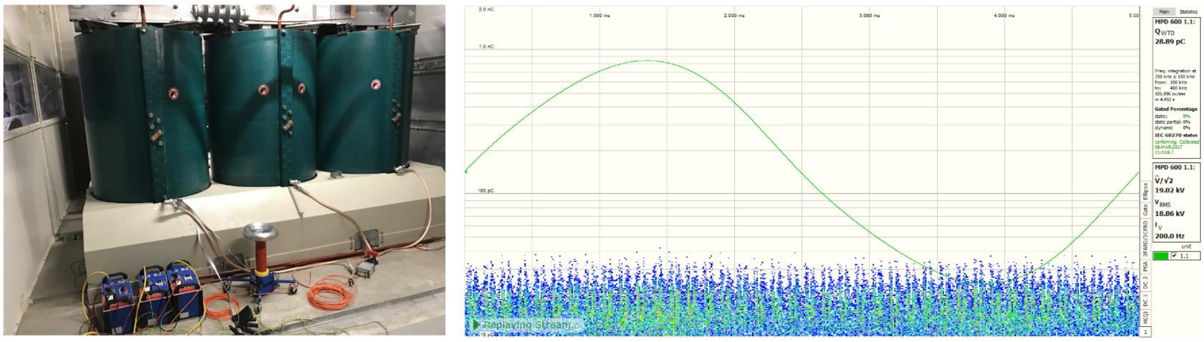


Figure 18: 10 MVA transformer under test (left), PD without characteristic PD-fault-pattern

Case 4

A routine PD measurement at a 9,5 MVA cast-resin transformer showed two phases without any PD, while the third phase had clear indications of surface discharges. After visual inspection, the assumption was, that these discharges were introduced by a contaminated surface on an inner part of the HV winding block. Under the given circumstances, it was impossible to get that area cleaned without high effort. As the transformer-owner wanted to get sure, no other harmful creepage discharge was present, it has been decided to change the setup so that field stress on the dirty area on the inner diameter could be reduced. Therefore, the coupling capacitor was connected to the other end of the winding while the HV connector has been grounded. In this case the overall induced voltage of the winding remains the same while the most inner layer of the HV winding now has a smaller voltage difference to the dirty surface. Figure 19 shows the initial result left and the measurement at the same voltage level but different voltage distribution, on the right. This result allows the assumption, that the surface PD was initiated be the contaminated area at the inner side of the HV winding. The owner established a cleaning process and is actually looking for additional measures to avoid such contamination in the future.

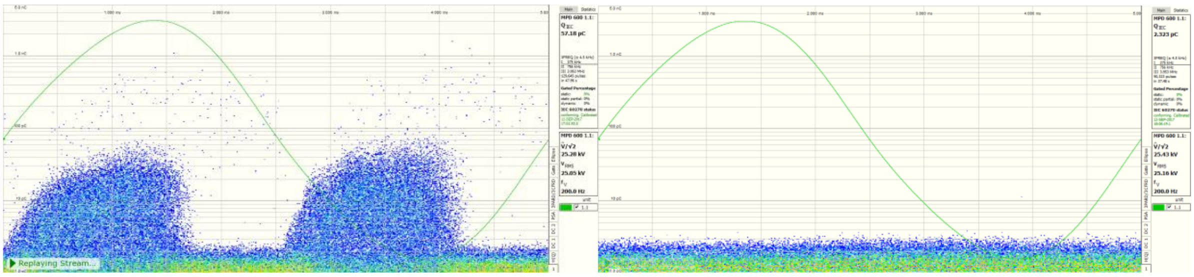


Fig. 19 PD pattern with surface discharges, left and after changing the setup, right

Case 5

Figure 20 shows a PD test setup for a 30kV / 6kV transformer of 17 MVA. To energize the 6kV side of the transformer, an additional step-up transformer was needed (left in the photo). The 10 kW power needed to excite one phase of both transformers was delivered by three synchronized CPC 100 at 350 Hz. The test voltage was 1,3 x U_r. The left side of fig. 20 shows the PD result, exemplarily of phase B. No PD impulses above the noise level of about 8pC are visible.

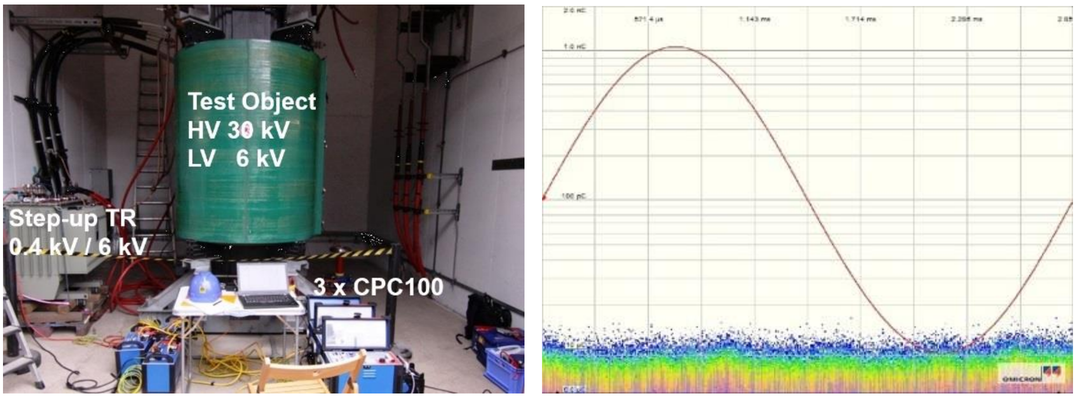


Fig. 16: 17 MVA transformer – PD test with three CPC 100

CONCLUSIONS

A modular test system including portable components with a maximum weight of 30kg makes on-site diagnostic tests on dry-type transformers up to 25MVA easily possible, especially as the base unit CPC 100 is widely used all around the industry and therefore, thousands of these units are available everywhere in the world. Next to its various other applications, the use as a flexible source for PD testing, combined with fully digital PD measurement technology opens new testing possibilities, can help increasing the reliability of modern power generation and can also create new business opportunities for service providers. Modern digital PD instruments with advanced well proven filter algorithms enable PD measurements outside of Faraday cages even under high electromagnetic interference from the surrounding.

References

1. IEC 60076-11 “*Power transformers – Part 11: Dry-type transformers*”, International Electrotechnical Commission, Geneva 2004

2. IEEE C57.124, “*IEEE Recommended Practice for the Detection of Partial Discharge and the Measurement of Apparent Charge in Dry-Type Transformers*”, Institute of Electrical and Electronics Engineers, New York, 1991

3. IEC 60060-3 “*High-voltage test technics, Part 3: Definitions and requirements for on-site testing*”, International Electrotechnical Commission, Geneva 2006

4. *IEC 60270 “High-voltage test techniques – Partial discharge measurements”* International Electrotechnical Commission, Geneva 2015

5. A. Kraetge, K. Rethmeier, S. Hoek, M. Krueger, “*Modern de-noising strategies for PD measurements on transformers under challenging on-site conditions*”, Cigré SC A2 & D1 Joint Colloquium, Kyoto, Japan, 2011

6. A. Kraetge, K. Rethmeier, M. Krueger, P. Winter, „*Advanced noise suppression during PD measurements by real-time pulse waveform analysis of PD pulses and pulse-shaped disturbances*”, IEEE ISEI, San Diego, 2010