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ON-SITE PARTIAL DISCHARGE TESTING OF DISTRIBUTION CLASS CABLES USING VLF AND POWER FREQUENCY EXCITATION

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ABSTRACT

The ongoing deregulation of the energy market has had up to now a strong impact on the maintenance strategies of most utilities. Especially, the increasingly service aged population of distribution class cables influences the reliability of the distribution network. Thus, field-testing is required to assess the severity of the degradation and to determine the cables, which require urgent replacement. Different methods are available for the high voltage excitation of the cables under test. The fixed frequency resonant test set running at 50/60Hz power-frequency offers a perfect match of the service condition, but such test sets are comparably heavy and costly. Other solutions, such as variable frequency resonant test sets, damped oscillating wave, or very low frequency (VLF) excitation offer more cost-effective testing solutions.

KEYWORDS

Partial discharge location, PD mapping, VLF, resonant test set, tan delta, field-testing.

INTRODUCTION

Partial discharge activity is a prominent indicator to assess the grade of degradation of high voltage equipment. The mapping of the partial discharge activity versus the cable length allows identifying cable partial discharge as well as weak accessories. However, strong differences exist between polymeric cables and mass-impregnated cables. Historically, partial discharge measurements on cables were increasingly applied since the change to polyethylene (PE) and later cross-linked polyethylene (XLPE) as insulation material for the majority of power cables.
Improved signal acquisition and processing made this technique also applicable to non-shielded field environments. However, care must be taken to adequately filter the high voltage source and to reduce pickup of ambient noise.

OCCURRENCE OF PARTIAL DISCHARGE

The solid and liquid insulation materials used for insulating power cables can tolerate an electrical field that exceeds by far the normal operational field strength typically applied with cables and other high voltage equipment. Thus, to enable partial discharge, it requires an imperfection that has a lower inception field, such as a gas inclusion, or, alternatively, which strongly increases the local electrical field within the insulation, as a sharp metallic inclusion, for instance. Both types of imperfections can happen during production, may remain undetected during initial testing, or evolve during service.
Partial discharge, an electron avalanche, requires a free initial electron that is being accelerated in the electrical field strongly enough to trigger the avalanche.
With the low-energy surface of an embedded spherical cavity in fresh polyethylene, no such free electron is available to have the partial discharge incepting, although the internal electrical field of that gas bubble is larger than the inception field (E_{Str}). Thus, no partial discharge occurs until such free electron is provided by de-trapping of space

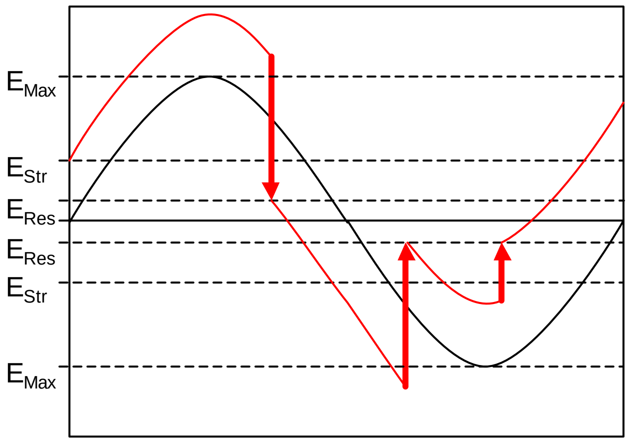

Figure 1: Internal E field with low electron availability

charges or by a photon of the natural radioactivity. This natural radioactivity – radioactive soil, gasses, cosmic photons – cause about $2 \cdot 10^{6}\,m^{-3}s^{-1}$ free electrons. Thus, the statistical delay to have a cavity discharge in fresh polymeric material incepting may reach several tens of minutes depending on the cavity's size.
Once this initial partial discharge impulse has occurred, the cavity's surface is polluted with electrons being kept with traps of comparably low energy levels. Thus, these electrons become available statistically depending on the material's properties. With fresh polyethylene (polypropylene, epoxy resin, etc.), this de-trapping time constant is in the range of tens of ms and above.
Figure 1 shows how the electrical field in the cavity reacts on the statistical delay caused by the de-trapping. Figure 2 shows a corresponding partial discharge pattern or so-called *j*-*q*-*n* pattern.

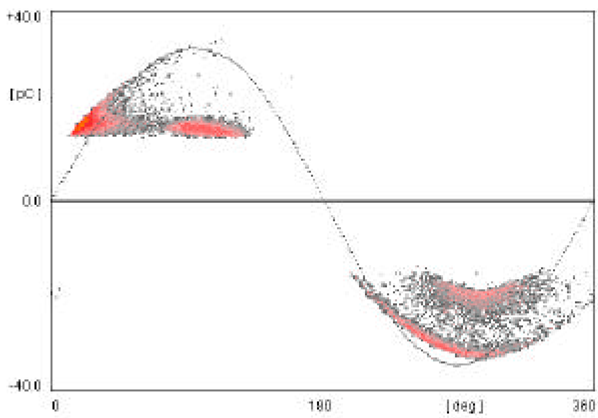

Figure 2: *j*-*q*-*n* pattern with low electron availability

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Here, the discharge magnitude reflects the phase dependent electrical field. Thus, if, for instance, the voltage shape would be triangular, the pattern shown with Figure 2 would be triangular as well. Other electrode configurations, such as a flat delamination, show other correlation between electrical field and discharge magnitude.

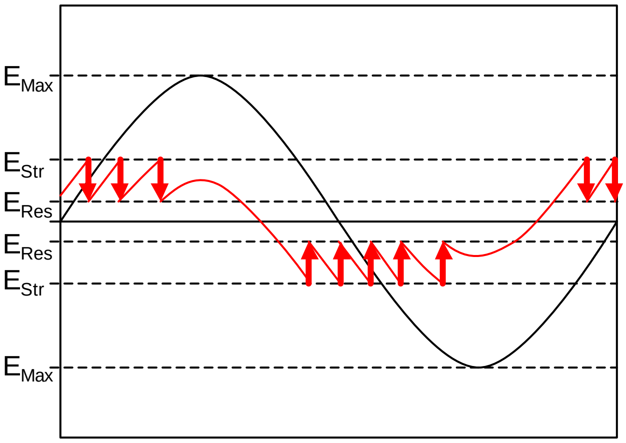

Figure 3: Internal E field with high electron availability

The same setup (gas bubble in polymeric material) is exposed to ionizing irradiation causing a much quicker detrapping (Figure 3). Thus, the electrons are available earlier and the discharge magnitude is lower (Figure 4). Accordingly, material properties, such as the ability to store surface charges or volume and surface conductivity, for example, have a strong impact on the partial discharge appearance. Humidity or corrosion of polymeric surfaces by partial discharge, for instance, as introduced during the service of the equipment, has an additional impact on the material's ability to provide free electrons and its time constant and, hence, strongly influences the appearance of the discharge pattern.

Generally, with aging (corrosion) of polymeric surfaces chains are being cracked up and the time constant of providing free electrons drops. With respect to power frequencies this time constant is negligible for metallic surfaces.

Based on such fundamental consequences of gas discharge physics [1,2,3], the analysis of the *j*-*q*-*n* pattern or phase resolved partial discharge pattern has proved to be an excellent method to identify the properties of the discharge activity, to distinguish different sources, and to draw conclusions on the properties of the materials involved with the discharge activity.

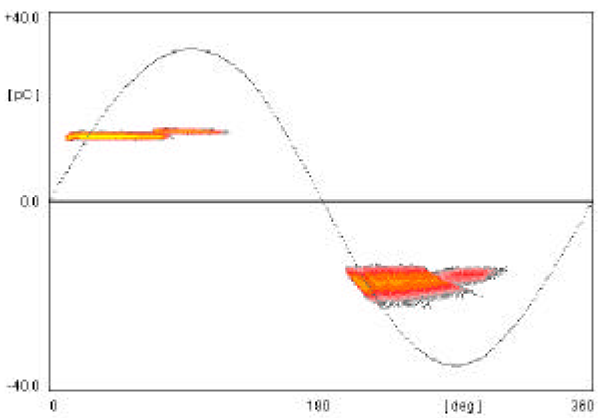

Figure 4: *j*-*q*-*n* pattern with high electron availability

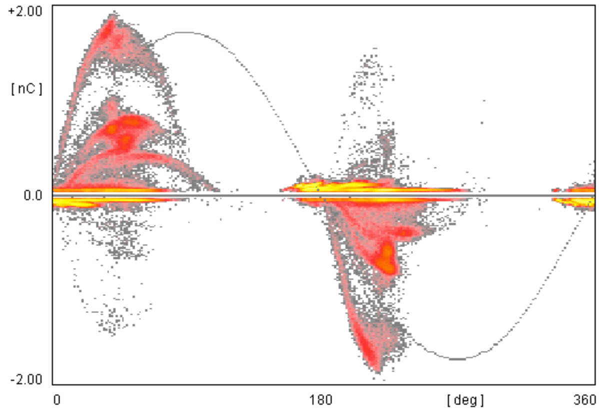

Figure 5: Partial discharge with a cable termination

Figure 5, for instance, shows the discharge activity of several flat cavities. Here, the symmetrical pattern indicates that the cavities are symmetrically within the insulation and not attached to any conductor.

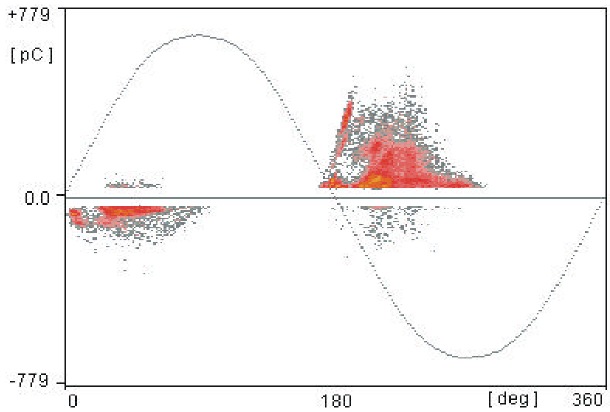

Figure 6: EPR cable - delamination of semicon layer

Figure 6, in contrast, shows a non-symmetrical pattern. Here, the delamination of semi-conductive material causes different starting conditions for the discharge activity for the positive and negative half-cycle.

PARTIAL DISCHARGE MAPPING

At their origin, partial discharge impulses have a rise of about 1ns under Nitrogen atmosphere and ambient pressure. Thus, at this origin, the current impulse, i.e., the displacement current caused by the electron avalanche, has an amplitude spectrum that is flat from DC to a couple of hundred MHz. In case of a power cable, the impedance of the cable transforms the current impulse into a voltage impulse that travels the cable in both directions. Generally, the original bandwidth cannot be maintained over distance [4]. Technically, in order to form an ideal cylindrical capacitor, a triple-extrude polymeric cable consists of three layers – the main XLPE insulation is terminated on both sides with a thin layer of semi-conductive polymeric material. These layers inherently limit the high frequency bandwidth of triple-extruded power cables. Depending predominantly on the thickness of the semi-conductive layers the transmission bandwidth is limited to 5-10MHz with a strongly increasing attenuation as a function of the frequency and the distance, of course. This location dependent bandwidth can be used for sensors embedded in accessories and for monitoring concepts [5,6].

Additionally, this layer structure causes dispersion, i.e., that the travel time is not uniform over the frequency. Thus, the originally steep front of the traveling partial discharge impulse is further smoothened by this effect and by the said attenuation and, hence, the achievable location accuracy is limited.

Compared with polyethylene cables this attenuation of the traveling high frequency impulses is substantially stronger for EPR cables. However, the strongest attenuation is found with mass-impregnated cables. Here, the reflection from the far end increasingly becomes hidden in the noise floor for cables longer than a couple of hundred meters.

The shape or frequency of the high voltage source chosen does of course not influence deriving the location of the partial discharge activity within a cable, as long as the imperfection produces partial discharge. Thus, in principle any high voltage source can be used for partial discharge location.

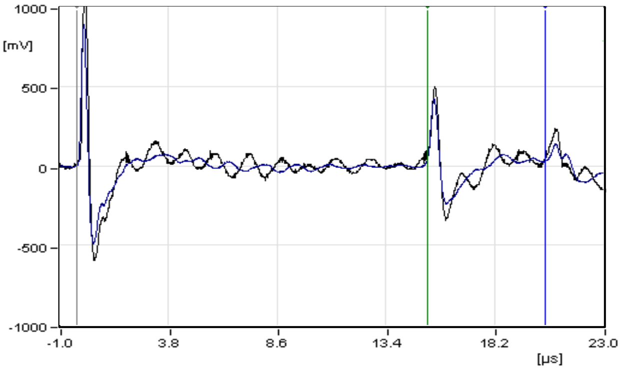

Figure 7: Reflection Pattern (blue: post processed).

Once a partial discharge occurs, it travels towards both ends, becomes reflected and produces, if viewed from one end, a typical trace of three impulses. With such trace, the time between first and second pulse corresponds to the distance from the far end, whereas the time between first and third impulse reflects the time to travel the entire cable twice. Figure 7 shows such a typical trace. Here, also the influence of attenuation and dispersion can be seen.

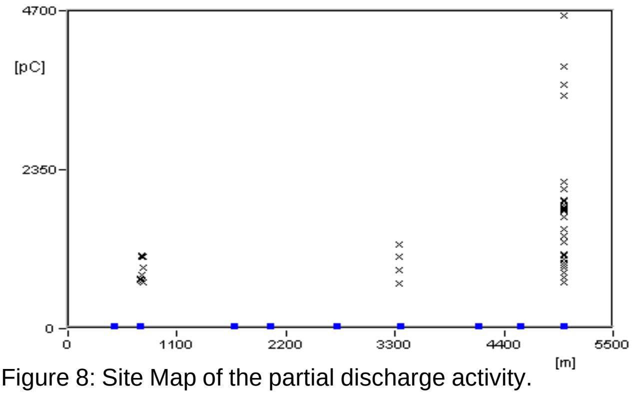

Figure 8: Site Map of the partial discharge activity.

Simple calculation produces then the discharge position with reference to the cable length [6,7,8].

Based on the valid location results the partial discharge mapping is the built (Figure 8), which shows the activities versus the cable length. Comparing this mapping with the laying plan and the positions of the joints as verified during the calibration identifies faulty cable accessories (shown as blue squares with Figure 8) or weak cable sections.

HIGH VOLTAGE SOURCES

Typically, in the test room of the cable manufacturer a transformer or a fixed-frequency resonant test-set is used. This ideally matches the normal operation conditions of the cable. When it comes to field-testing of laid cables, weight and cost considerations demand more effective solutions and the heavy and costly transformer and fixed frequency test set are not a practical option.

The variable frequency resonant test set, which uses a filter and coupling capacitor as base load, whereas the added capacitance of the cable to be tested then lowers the frequency, can be set to stay close to the nominal frequency (25Hz-300Hz). However, a typical test set for distribution class cables easily reaches a weight of 1000kg.

Using VLF (very low frequency) high voltage sources dramatically reduces weight and cost, because the power requirement of the capacitive load drops by a factor of 500, when comparing the commonly used 0.1Hz with the 50Hz. Both electronic solutions as well as electro-mechanical solutions are available. Such units are portable on a cart or can even be carried.

Finally, oscillating wave test sets, whereas charging the cable with a DC supply and discharging it into an inductor produces a damped oscillating wave. Here, as well, the frequency depends on the load, i.e. cable capacitance. Depending on the inductor's quality and the cable's tan delta, the oscillating wave more or less quickly decays.

Another special case is the VLF co-sine source. Here, a square-wave signal is combined with a transition in the range of the power frequency.

However, besides weight and cost also the impact of the high voltage frequency on the local electrical field and the occurrence of partial discharge must be considered.

As pointed out above, the partial discharge pattern reflects the different time constants of deriving the starting electron. Therefore, the appearance of a partial discharge pattern and in consequence the magnitude is influenced by the power frequency. This becomes evident, if the average de-trapping time constant of the partial discharge activity comes in the order of magnitude of the test voltage cycle. Thus, for a partial discharge activity, which has a de-trapping time constant of, say, 10ms, the measurement at 50Hz produces a well-distributed pattern. If the same activity is exposed to 0.1Hz, the 10ms time constant will be small against the 10s cycle time and, hence, the partial discharge pattern changes its appearance similar to a change as shown with Figures 1 and 3. Thus, especially with fresh polymeric surfaces, the magnitude of the partial discharge activity is not comparable between 0.1Hz and 50/60Hz. However, if it comes to service-aged, i.e. corroded surfaces, the de-trapping time constant drops and becomes also short, when compared with the 50Hz cycle. Thus, the magnitude is comparably low with both excitation frequencies. Accordingly, an activity that starts from metal surfaces with a very high availability of free electrons, such as a point-plane discharge at a metallic tip, shows similar activity with all testing frequencies (Figure 9, next page).

With all discharge activities having a high availability of the starting electron, such as corroded surfaces of incorrectly mounted accessories, for instance, oscillating wave test sets will start the activity with the first half cycle or even during the charging time. The chance to detect an embedded cavity in a freshly laid cable, however, is comparably low due to the initial statistical delay as described above.

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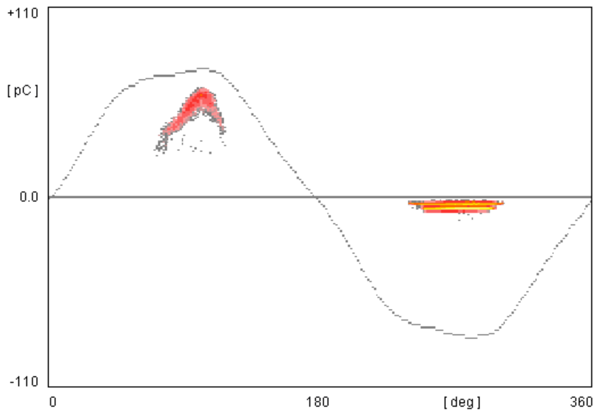

Figure 9: Point-plane discharge starting from a metallic tip

The acquisition of a *j*-*q*-*n* pattern with an oscillating wave test system is not very helpful, since it combines discharge activities, which are occurring under different voltage and, thus, do not belong together.
Another frequency dependent effect concerns the accessories. If, for instance, a stress cone has a week semi-conductive path to ground the resulting voltage drop on that path will cause surface discharge under 50/60Hz or variable frequency testing. Since the currents are 500 times smaller with 0.1Hz testing this may remain undetected, when using VLF test sets.
Generally, when selecting a high voltage source for testing of laid cables the different properties (benefits and drawbacks) must be compared.

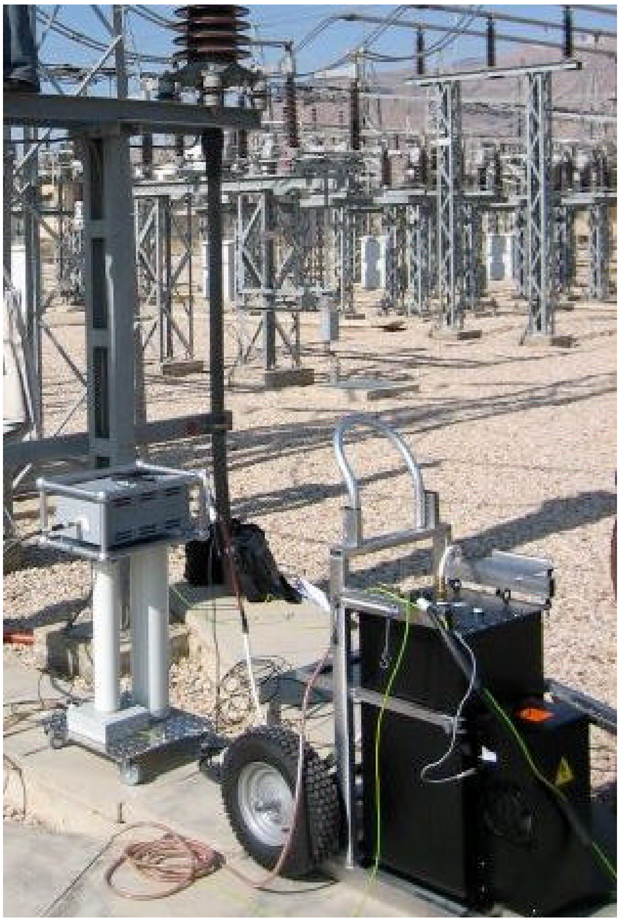

Figure 10: Setup in a substation with a 90kV$_{peak}$ VLF unit

The resonant test set comes close to the real-life conditions, but it is comparably heavy and costly. VLF testing is a very cost-effective alternative, but the effects of the large difference in the testing frequencies on the partial discharge pattern must be considered.
Thus, because of the individual weighting of the different properties and requirements for each case, no general recommendation can be given.

FIELD TEST REQUIREMENTS VS. TEST ROOM

In a test room, typically a detector for partial discharge measurement and location connects to a quadrupole in the ground lead of a coupling capacitor. Preferably, a high voltage filter is inserted between the transformer and the cable under test with the coupling capacitor. The partial discharge signal as well as the voltage signal is fed via coaxial cable. The situation is similar, when it comes to the integration of the instrument into a test van, as it is required for the variable frequency resonant test set and the larger VLF test sets. Connecting the test set to the cable follows a fixed procedure and the test van acts as reference potential.
Figure 10 shows the situation during a test with a portable VLF unit. Here, the coupling capacitor, its quadrupole and the required high voltage filter are combined into one unit. This combined filter and coupling unit, which is just inserted between the high voltage source and the cable under test, is available for different voltage classes ranging up to 150kV. Figure 10 shows a 65kV unit (TCC65) to suit a 90kV$_{peak}$ VLF source.
Figure 11 shows a setup together with a 60kV$_{peak}$ VLF unit. Here, the combined filter-coupling unit TCC45 is used to de-noise the high voltage supply and to provide the partial discharge signal as well as the signal for synchronization and voltage measurement.
Combining on-site cable testing with partial discharge measurement and location requires in general a high voltage filter, since, regardless of the technical principle, all variable frequency resonant test sets and all VLF test sets produce high frequency noise that hamper the measurements, if not adequately filtered. With the variable frequency resonant test additionally gating techniques must be applied, because the thyristor or IGBT switching impulses are too strong to be solely filtered.

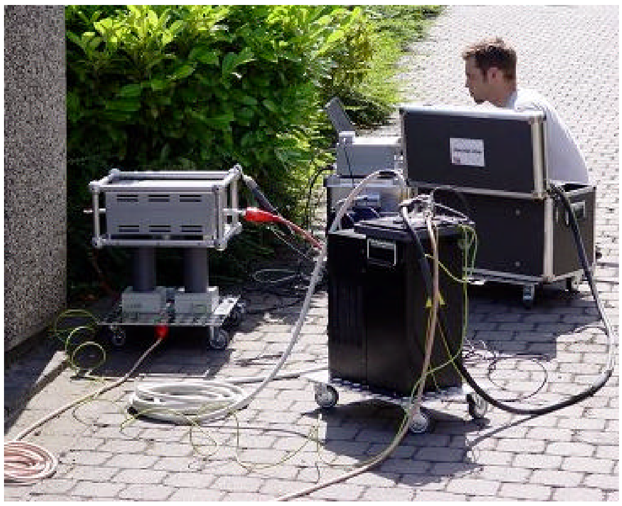

Figure 11: TCC45 - setup with a 60kV$_{peak}$ VLF unit

Figure 12: TCC25 together with a 30kV$_{peak}$ VLF unit

Figure 12 shows such combined unit (TCC25) for a lower voltage with another VLF source (30kV$_{peak}$). At this voltage level the cage around the high voltage electrode of the filter unit is not required to prevent discharge activity.

Integrating the T-filter and the coupling capacitor into one unit greatly simplifies the setup. However, especially with portable high voltage sources, care must be taken to properly ground the equipment and to double-check every connection.

An instrument to even further simplify the application of partial discharge measurements as well as tan delta analysis is currently in its final stage of development. Here, additionally, the partial discharge detector is integrated into the top box of the combined filter and coupling unit. The instrument has a multi-processor concept, is battery operated, and communicates via Bluetooth® with the notebook computer used for visualization. Thus, everything needed for the partial discharge measurement and location is built into this unit and the required remaining connections are limited to the high voltage and ground leads between high voltage source, filter-instrument-unit, and cable under test.

As with the passive combined filter and coupling units, this new system comes in different voltage classes to suit the typical application.

Besides partial discharge testing and location, this new instrument offers also convenient tan delta analysis using the coupling capacitor as reference capacitor. No modification of the setup is needed to change between partial discharge measurement and tan delta mode and the operating software presents the results in parallel.

Additionally, based on the same concept, also an instrument that covers just tan delta analysis will be introduced for VLF testing.

The instruments generally offer a wide synchronization range from VLF to >300Hz allowing a combination with all relevant high voltage sources for field-testing.

CONCLUSION

Partial discharge measurement and location can be combined with portable high voltage sources of different principles using modern signal acquisition and processing techniques. However, most of the different excitation methods produce as a side effect high frequency noise that hampers the sensitivity of the partial discharge detection and mapping and, hence, requires adequate filtering and matching. Additionally, integrating all required electronics into a combined filter, coupling and acquisition unit simplifies the setup and improves operator safety by using wireless Bluetooth® communication.

Variable frequency resonant test sets allow using excitation frequencies close to the power frequency, but are typically mounted in test vans. Further cost and weight considerations lead to the application of VLF high voltage sources. However, the partly strong deviation from the normal 50/60Hz service conditions has an impact on the detectability of some defect types and on the appearance of their partial discharge pattern.

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