On-site partial discharge diagnostics of cast-resin transformers

How well do you know the insulation condition of your dry-type transformer?

ABSTRACT

The amount of installed cast-resin dry-type transformers has been increasing steadily over the past years due to its wide application range in industrial areas and in the renewable energy sector [1][2]. The lack of mineral oil as an insulating medium allows dry-type transformers to be used in areas with high fire hazards and environmental protection requirements such as in tunnels, buildings or wind power plants. Therefore, rendering these units more and more important in the electrical grid. However, some well-established diagnostic methods, like DGA, rely on analysing the mineral oil condition. Therefore, it becomes essential to explore alternative diagnostic means, such as partial discharge measurements, to evaluate the insulation condition of in-service dry-type transformers.

KEYWORDS:

insulation diagnostics, on-site testing, partial discharge

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Partial discharge measurements help to identify incipient insulation faults in an early stage of the development of the fault

1. Introduction

The use of dry-type transformers has proven to be very successful in a range of different applications. Such equipment is often used in medium-voltage power grids in industrial plants and in the marine and civil sectors, such as in subway networks. Deciding factors for the use of dry-type transformers include low-maintenance operation and reduced fire risk. The latter can be of significance for installation in building complexes and tunnels. Furthermore, the absence of mineral oil as an insulating medium eliminates the need for oil sumps. This makes dry-type transformers particularly advantageous for use in wind turbines, as they are often installed in areas with high groundwater protection requirements or at sea.

In the context of wind turbines, the transformers, which are connected directly to the turbine generator, can be considered as generator step-up units (GSU). Diagnostic measurements and the condition assessments of these units are of corresponding significance. For liquid-filled transformers, periodic oil analyses provide a solid base for a comprehensive health assessment. Based on the oil results, further diagnostic measurements can be performed like dissipation factor, partial discharge (PD), SFRA or winding resistance measurements which can then trigger corrective maintenance measures if necessary. For dry-type transformers, especially cast-resin insulated units, the application of the established diagnostic tools is limited. One of the main differences between oil-filled and dry-type transformers is the insulation system. Instead of mineral oil that acts both as an insulating and cooling medium, the windings of dry-type transformers are, in most cases, cast in epoxy resin. Since no oil analysis is possible, a substitute tool for insulation diagnostics has to be found.

In the following text, the applicability of on-site PD measurements for the condition assessment of dry-type transformers is discussed. Typical voltage ratings are up to 30 kV on the HV side and up to 720 V on the low voltage (LV) side [3].

PD measurement offers the possibility to analyse the insulation system of each coil individually, resulting in a powerful tool for reliable on-site insulation diagnostics of medium-voltage transformers

The on-site assessment of the insulation condition can be especially interesting for transformers that are installed in challenging environmental conditions such as industrial sites or wind turbines

A dissolved gas analysis (DGA) provides initial indications about potential internal faults for oil-filled transformers, such as partial discharges or local overheating [4]. However, DGA is not applicable for dry-type transformers. Therefore, partial discharge diagnosis by means of a single-phase induced voltage test is presented. A portable test system of 30 kg [5] is used to energise transformers with power ratings up to 4–5 MVA. For power ratings up 15–20 MVA two additional amplifiers need to be installed. Combining this approach with a PD measurement offers the possibility to analyse the insulation system of each coil individually, resulting in a powerful tool for reliable on-site insulation diagnostics of medium-voltage transformers.

2. PD measurement

Partial discharge impulses are localised dielectric breakdowns that only partially bridge the insulation system. Due to the local energy transport, the solid insulation system of a dry-type transformer can degenerate over time, affecting the dielectric strength and, in the worst case, causing a dielectric breakdown. PD measurements are a powerful tool for detecting insulation defects early on and identifying incipient faults before any damage occurs. Compared to integral insulation diagnostics such as a dissipation factor measurement, local imperfections can be identified. Therefore, this measurement is part of the factory acceptance test (FAT) for every new dry-type transformer [6]. In addition, PD measurements can be performed on commissioned transformers on-site to evaluate the insulation condition. The on-site assessment of the insulation condition can be especially interesting for transformers that are installed in challenging environmental conditions such as industrial sites or wind turbines. For this purpose, both offline and online partial discharge diagnostics are suitable. In the following paragraphs, the main characteristics of the FAT and the on-site, offline PD diagnostics are compared.

After finalising all voltage withstand tests during the FAT, the PD measurement is carried out. For a three-phase transformer, a three-phase voltage source is connected to the low-voltage winding to energise the device under test. On each phase of the high-voltage winding, a coupling capacitor and a measurement impedance are installed. Either a single-channel or three-channel PD system can be used to record the PD activity on the HV coils. Using three measurement channels, all windings can be monitored simultaneously. This way, a possible cross-talk between the phases is identified, and multiple PD sources can be separated. A schematic overview of the common measurement setup is given in Fig. 1. For all offline tests, the transformer under test should be disconnected from all lines, both on the HV and LV sides.

During the induced voltage test, the transformer is energised via the LV winding, which results in an induced test voltage on the HV winding. First, a pre-stress voltage of 1.8-times the rated line-to-line voltage (U_r) is applied for 30 seconds. During this interval, possibly active partial discharges are not considered for the assessment. Afterwards, the test voltage is reduced to 1.3-times the rated line-to-line voltage and held constant for 180 seconds. In this second part of the test cycle, a partial discharge level of less than 10 pC is permissible for the transformer to pass the test [6], Fig. 2.

2.1 On-site testing

The on-site partial discharge measurement is a powerful tool to detect incipient insulation defects in a transformer. In contrast to the FAT, certain limitations are

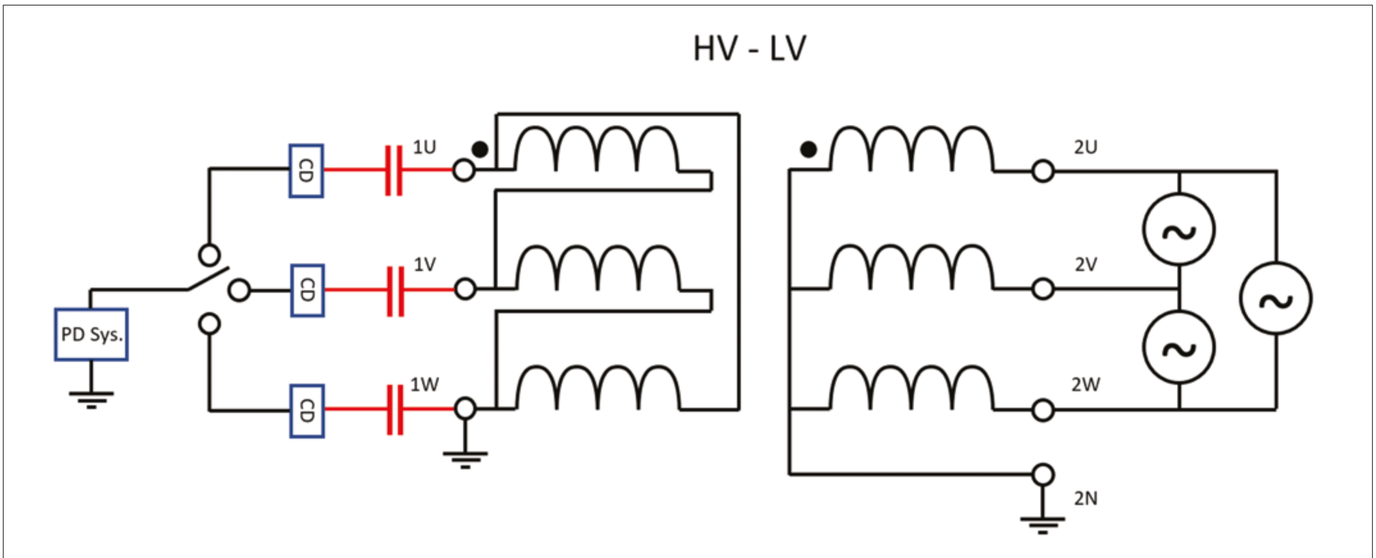

Figure 1. FAT measurement setup for an induced voltage test according to [6]

> **A portable single-phase voltage source can be used to perform on-site induced voltage tests, which also reduce the energy required for conducting the test compared to three-phase measurements**

in place when testing on-site. The device under test is in many cases installed in a confined space, which requires a portable voltage source to energise the transformer. In addition, the available testing power is limited to a conventional power supply of a wall socket. In the following text, a modified approach that differs from the FAT to account for these two limitations is presented. Instead of using a three-phase voltage source, a single-phase test system is used to excite the transformer. On the one hand, the needed apparent power to energise the transformer is significantly reduced compared to a three-phase excitation. Fig. 3 depicts the power intake in "kVA" at a nominal voltage of three distribution transformers with power ratings between 800 kVA and 1600 kVA. In the case of a single-phase excitation, the power intake is reduced by approx. 50 %.

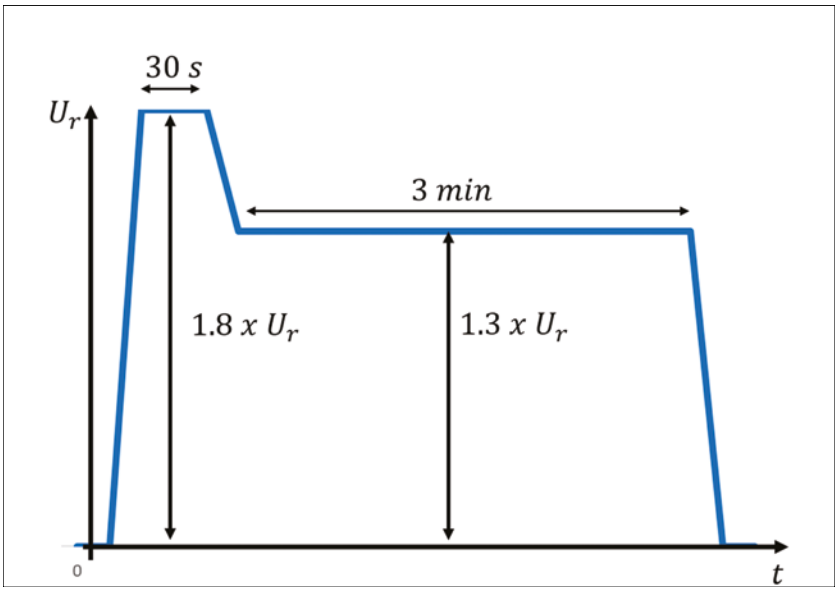

Figure 2. FAT test cycle of an induced voltage test according to [6]

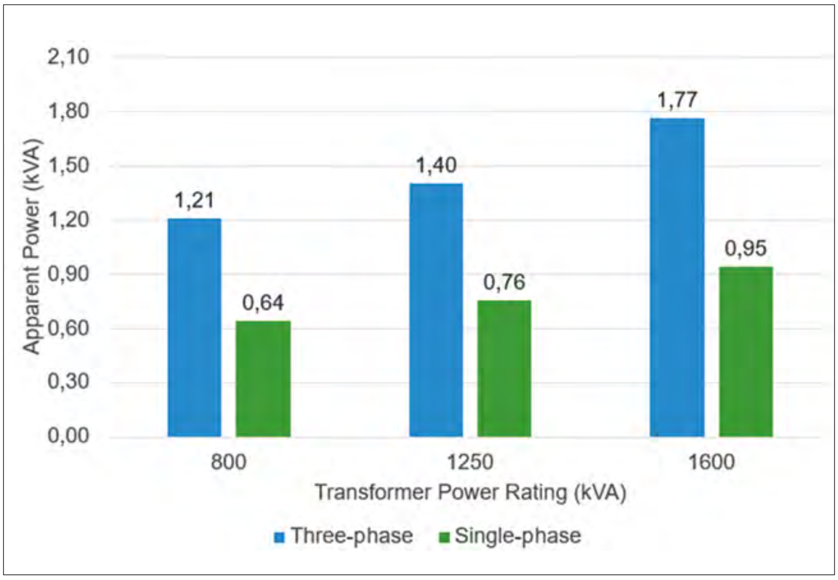

Figure 3. Comparison of power intake between a three-phase (blue) and a single-phase (green) excitation

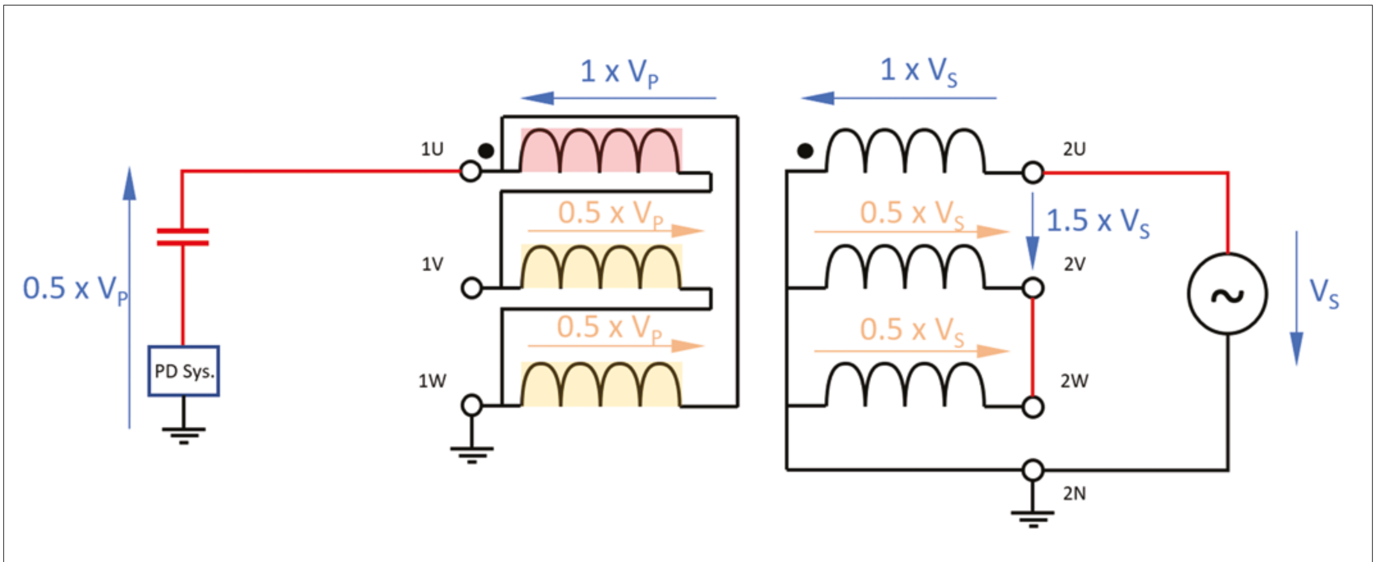

Figure 4. Setup for an on-site single-phase induced voltage test

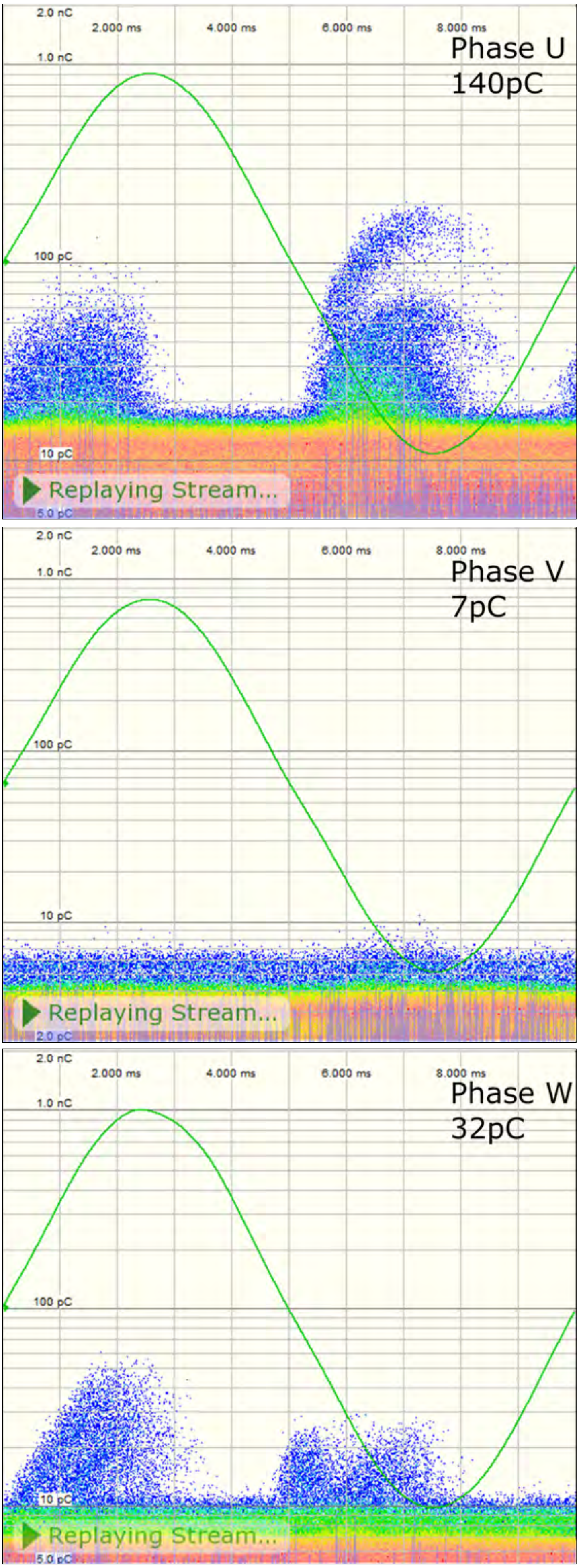

Figure 5. PRPD results of phase U (top), phase V (middle) and phase W (bottom)

By applying a short-circuit to the unused terminals of the star-winding, an equal magnetic flux distribution is achieved in those two core limbs, thus eliminating uneven induction of the voltages on the different phases

Furthermore, the inductive and capacitive components of the transformer under test form a resonant test circuit. By tuning the frequency of the test voltage to a resonant point, the maximum impedance of the test setup can be reached. Thus, the excitation current and, therefore, the power intake is further reduced, allowing the operator to energise transformers with power ratings of up to 4–5 MVA. Typically, a suitable test frequency is found in the range of 50–200 Hz.

In addition, a single-phase excitation can be helpful to narrow down a PD source since not all windings are energised simultaneously. In the following, the setup of a single-phase excitation is discussed in the example of a Dyn5 transformer in Fig. 4. As the first step, phase *1U–1V* on the HV side is measured. Therefore, the voltage source is connected to the corresponding terminals *2U–2N* on the low-voltage side. In addition, a coupling capacitor and a partial discharge system are installed at the HV terminal of phase *1U*.

One major difference between a three-phase and a single-phase excitation is the voltage distribution between the transformer windings. Energising only one coil will induce a voltage across the remaining two windings of the transformer due to the magnetic coupling. However, the magnetic flux distribution in the core limbs depends on the transformer design and the voltage frequency. Thus, some uncertainty is introduced regarding the electrical stress of the de-energised windings. By applying a short-circuit to the unused terminals of the star-winding, an equal magnetic flux distribution is achieved in those two core limbs. This way, the electrical stress on all three coils is clearly defined. Fig. 4 depicts that only phase *1U–1V* is stressed with the full test voltage U_P, while on the other two phases, only a voltage of $0.5 * U_P$ is induced [7].

The on-site PD measurement is illustrated by the case study of a 2.5 MVA 20 kV / 0.4 kV dry-type power transformer which was tested for PD activity using a single-phase induced voltage test

The complete test cycle consists of three consecutive measurements. This means each phase of the transformer is separately energised. Consequently, each of the three coils is checked for PD activity. The clearly defined voltage distribution is utilised to cross-check the PD results and draw conclusions regarding the origin and the inception voltage of the PD source.

3. Case study

The approach of an on-site PD measurement is illustrated by the following case study. A 2.5 MVA 20 kV / 0.4 kV dry-type power transformer was tested for PD activity using a single-phase induced voltage test. A setup similar to the one shown in Fig. 4 was used. In addition, a second PD measurement channel was connected to the ungrounded HV terminal. The same test cycle as recommended in [6] was applied. However, the test voltage was reduced to 1.3 x U_r during the pre-stress phase and 1.0 x U_r for the actual PD measurement. The resulting PRPD patterns of the three phases are depicted in Fig. 5.

While phase *V* appears to be PD free, clear signs of PD activity are visible on phases *U* and *W*. The discharges of up to 40 pC on phase W are identified as surface discharges and are most likely caused by surface contamination [8]. On the other hand, the discharges of up to 140 pC on phase U are classified as internal discharges. By using linear scaling and considering the impulse polarity, a strong voltage polarity dependency becomes obvious, Fig. 6.

Comparing the PRPD patterns with references in [8][9], it was concluded that the discharges are likely to originate from a void with electrode contact inside the solid insulation. Due to the polarity indication, the PD source appears to be in close vicinity of the phase terminal *1V*. Overall, the PD activity is deemed critical. Not only does the PD level exceed the factory limits of 10 pC. But the inception voltage of the internal discharges was found to be below operating voltage as well. Thus, the PD source is active during normal operation of the unit and thus likely to locally erode the insulation material. Eventually, based on the above evaluation of the PD characteristics, the operator decided to replace the unit to avoid any outages due to a possible insulation failure.

4. Conclusion

All in all, on-site partial discharge measurements are a powerful tool to evaluate the insulation condition of dry-type transformers and detect incipient insulation defects. A single-phase excitation of the transformer allows for testing and analysing each individual coil. In addition, the power intake can be drastically reduced, which renders the portable voltage source suitable to energise transformers with power ratings of up to 5 MVA. The case study shows that even in industrial environments with typically high electromagnetic noise levels, adequate PD measurements can be performed. By using multiple PD channels and advanced software filtering techniques, possible cross-talk between coils and the influence of external noise could be reduced even further.

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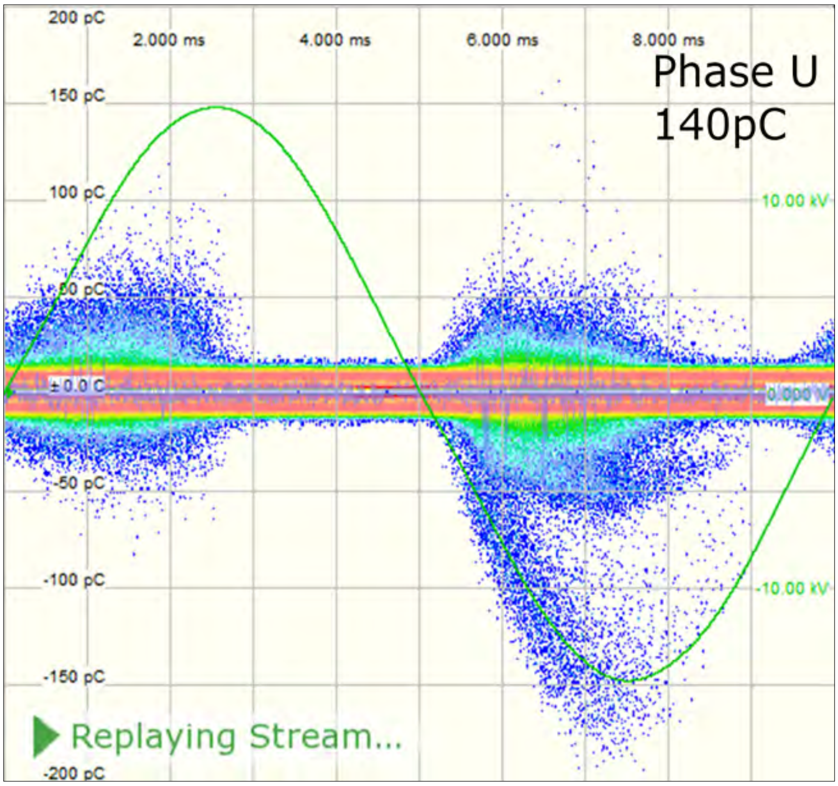

Figure 6. Discharges on phase U using a linear, bi-polar scaling

On-site partial discharge measurements are a powerful tool to evaluate the insulation condition of dry-type transformers and detect incipient insulation defects

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