Assessment of the Condition of Dry-Type Transformers by Means of Partial Discharge Diagnosis using a mobile voltage source

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Abstract

As part of the energy transition and the associated development of renewable energies, the number of installed dry-type transformers is increasing on the medium-voltage power grid. This equipment is commonly found in industrial plants and the marine and civil sectors. The common denominator in all these areas of application is that the advantages of dry-type transformers should be exploited with regard to the specific installation sites. The lack of mineral oil as an insulating medium allows dry-type transformers to be used in areas with high environmental protection requirements. Furthermore, the fire load and the risk of heavy smoke formation, such as in tunnels or buildings, is minimized. However, the lack of mineral oil and special environmental conditions also pose challenges for the diagnosis of transformers already in operation. The proven method of performing gas-in-oil analysis is not possible. Moreover, limited space and accessibility to the test object can impede on-site measurements.
This article provides an approach for assessing the condition of dry-type transformers by means of partial discharge measurements. By using a mobile, portable voltage source, a single-phase induced voltage test can be performed on site. In conjunction with a partial discharge measurement, the insulation condition of each coil can be individually analyzed and evaluated. Depending on the power class of the transformer, the required test power can vary greatly. Therefore, a modular system is used which can be extended by up to two power amplifiers. This way, transformers up to 20 MVA can be tested. Furthermore, a variable-frequency injection can reduce the reactive power requirement to a minimum.
In contrast to laboratory tests under controlled conditions, an increased level of interference from rotating machinery, power electronics and other consumers is to be expected on site. Practical examples show how, on the one hand, useful signals can be separated from the interference pulses using a synchronous multi-frequency PD measurement (3CFRD, three-center frequency relation diagram). On the other hand, different PD sources can also be separated in this way. Moreover, the issue concerning the choice of possible assessment criteria for aged transformers is discussed.

1 Introduction

The use of dry-type transformers has proved to be successful in a range of 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 particular 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.

Although dry-type transformers operate in smaller power and voltage classes compared to their oil-filled counterparts, they are an important component of the electrical power supply due to their versatility. In the context of wind turbines, the transformers, which are connected directly to the turbine generator, can be considered as GSU units. Diagnostic measurements and the condition assessments of these units are of corresponding significance. In the following, the applicability of various diagnostic procedures for the condition assessment of dry-type transformers is discussed and illustrated with case studies. In a comprehensive assessment of the condition of a transformer, the examination of the main insulation is the key priority. The focus here is on performing the measurements at the installation site of the test object.

1.1 Diagnostic Measurements on Dry-Type Transformers

Similar to oil-filled transformers, preventive diagnostic measurements can also be performed on dry-type transformers. Due to the differences in design and the use of a solid insulating material, the significance of the individual measurement procedures must be discussed again. Although conventional electrical measurement procedures, such as winding resistance or short-circuit impedance measurements, are useful in determining winding integrity, they do not provide information on the condition of the solid insulation. For oil-filled transformers, a gas-in-oil analysis provides initial indications about potential internal faults, such as partial discharges or local overheating [1]. Further measures can be taken based on the evaluation of the gas concentrations. Since this method of initial diagnosis is ruled out for dry-type transformers, other measurement procedures must be used in order to be able to obtain reliable information about the condition of the insulation. Therefore, partial discharge diagnosis by means of induced voltage testing [2] is discussed below.

1.2 Partial Discharge Diagnosis

The partial discharge measurement on dry-type transformers is part of the acceptance test [3] and is typically carried out after the completion of all dielectric measurements. The test object is energized via the LV windings, while a PD measuring system is connected to the HV windings (Fig. 1). It is connected to each of the three phases in succession.

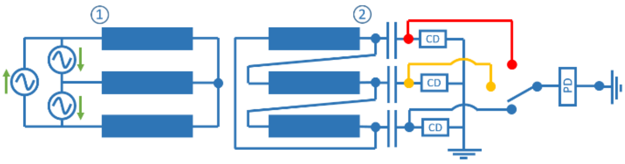

Figure 1 PD measuring configuration according to IEC 60073-11[3].
1) Excited LV winding; 2) HV winding with PD system

The test cycle includes a pre-stress phase of 1.8 times nominal voltage for 30 secs and a measurement at 1.3 times nominal voltage for 180 secs (Fig. 2). The limit value for the acceptance test is 10 pC [3].

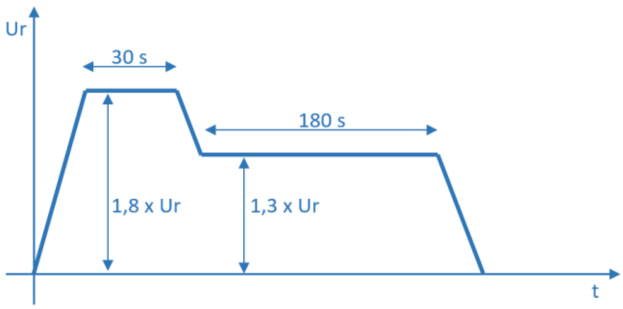

Figure 2 PD measurement test cycle according to IEC 60073-11 [3].

If a single-channel PD measuring system is used, each phase can only be considered separately despite the three phases being excited. A possible crosstalk of partial discharge impulses between multiple phases could therefore be difficult to detect. In factory tests, this circumstance is of little significance, as the probability of partial discharges in the newly manufactured coils is low. For a targeted assessment of the individual coils of transformers in operation, the single-phase excitation approach is discussed below.

1.3 Single-Phase Induced PD Measurement

For the single-phase excitation of a three-phase transformer, each coil is excited separately via the LV winding and examined for partial discharge activity. Figure 3 shows an example test setup for a YNyn0 transformer.

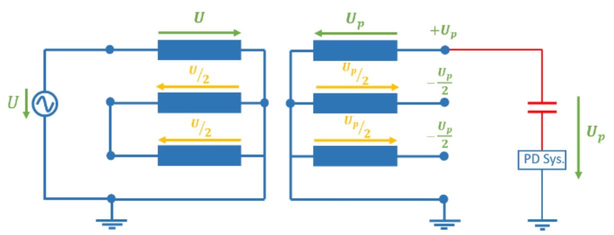

Figure 3 Test setup of a single-phase induced voltage test for a YNyn0 transformer.

The PD measuring system is connected to the corresponding HV winding, while the neutral point is grounded. The voltage stress of the main insulation corresponds to that of the operating condition.
For transformers whose HV coils are connected with a delta connection, it is recommended to use the setup as shown in Figure. 4.

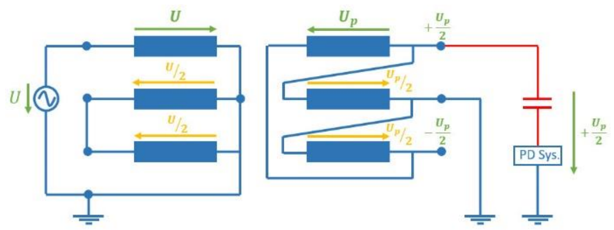

Figure 4 Test setup of a single-phase induced voltage test for a Dyn transformer.

While the electric stress of the main insulation is based on the operating condition, there is a reduced line-to-ground voltage on the terminals of the transformer. In this way, excessive stress on the line-to-ground insulation can be avoided. Furthermore, capacitors with significantly lower rated voltages can be used. This is particularly advantageous in locations with limited space, such as inside the nacelle of a wind turbine.

2 Use of a Mobile Voltage Source

2.1 Test System

The control unit has a single-phase voltage output that can generate a frequency-variable voltage of up to 250 V. This is stepped up using a step-up transformer to generate the required test voltage on the low-voltage terminals of the test object. The transformation ratio of this matching transformer can be varied while doing so to provide the highest degree of flexibility. A coupling capacitor with a PD measuring system is connected to the corresponding high-voltage terminal so that the partial discharge pulses can be measured. This method is used to test all three phases in succession and analyze the respective coil insulations. Crosstalk between the coils can be further minimized by disconnecting the coil connections.
The partial discharge activity is quantified by measuring the discharge values in pC and assessed by examining the recorded phase-resolved partial discharge pattern (PRPD pattern). Attention here is focused on making a distinction between internal partial discharges emanating from the insulation system and external discharges that may be caused by contamination or external sources. Hardware and software filters can both be employed to enable reliable statements to be made even in environments in which high levels of disturbance are present. The separation of a number of partial discharge sources and interference sources using multi-spectral measuring followed by adapted filtering—the three-center frequency relation diagram (3CFRD) measurement—is described below.

2.2 Noise Filtering

The use of a sensitive partial discharge measuring system requires that unwanted signals are also detected by the measuring circuit. This can be expected, especially in industrial environments with interference from power electronics and electrical machinery. One way to counteract this interference is to use a synchronous multi-frequency measurement (three-center frequency relation diagram, 3CFRD method). Here, a PD measurement is taken at three different measurement frequencies. Signals of different type and origin have different frequency spectra. By appropriately configuring the synchronous measuring filters, this characteristic can be used to group signals from different sources into clusters (Fig. 5).

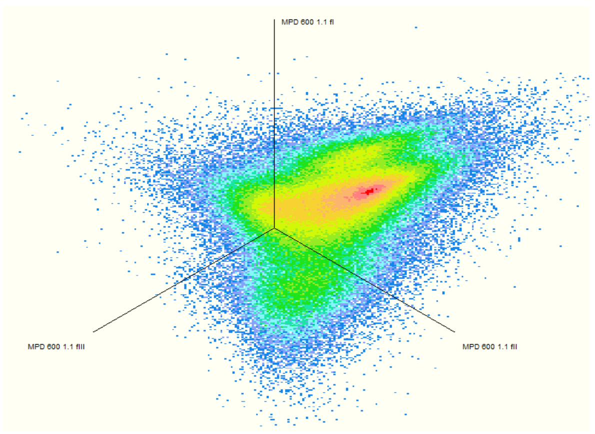

Figure 5 3CFRD of a transformer with multiple PD sources

Each cluster can then be examined in turn without it being overlain by other PD sources or emitters [4]. This enables relevant partial discharges to be separated from external interferences, as well as a separate examination of the PD with respect to the inception and extinction voltages, pattern analysis, etc. The following example illustrates the separation of the entire PRPD into individual components consisting of background noise and two partial discharge sources (Fig. 6).

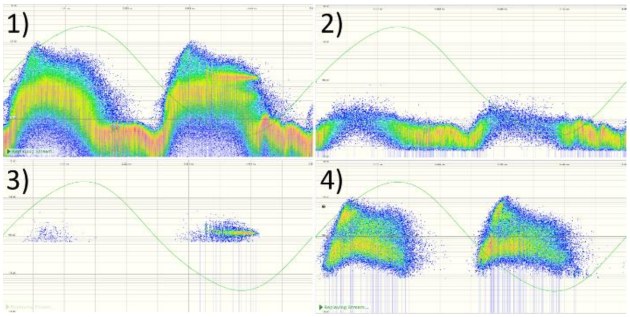

Figure 6 1) Complete PRPD, 2) Background noise, 3) Corona discharge, 4) Advanced surface discharge, after separation using 3CFRD.

By separating the individual patterns, a corona discharge can be identified. If this is hidden, together with the background noise, the discharge pattern of the critical PD source is revealed, which in this case, indicates the presence of carbonized surfaces [5].

2.3 Power Requirement

The test system has a power of 5 kVA for short-time operation. This covers the required reactive power and the magnetization losses of the transformer. The main inductance of the test object, winding capacitance and the capacitance of the coupling capacitor form a resonant circuit. A frequency adjustment of the supply voltage can therefore be used to determine an operating point with minimal power consumption. Figure 7 shows the frequency dependence of a measured test circuit impedance.

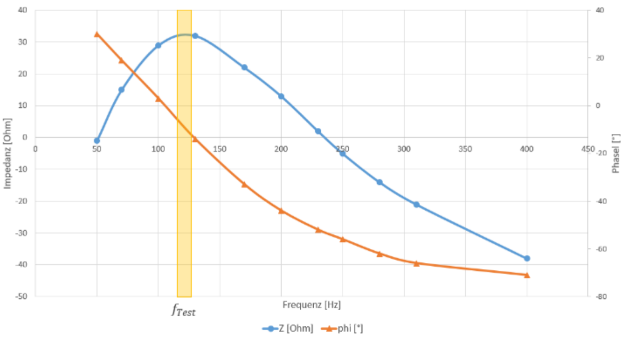

Figure 7 Frequency dependence of the test circuit impedance, amplitude (blue) and phase shift (orange).

If the frequency is set to the maximum impedance range, power consumption is reduced to a minimum. If a maximum impedance cannot be detected in the adjustable range of 50–400 Hz, additional capacitors can be installed parallel to the LV winding to achieve a resonance point.
If the required power exceeds the specifications of the test system, two power amplifiers can be added to the system in order to cover a higher power requirement. Each 18 kg amplifier is connected to the test object via a separate step-up transformer. This procedure increases the available output power by a factor of three. Depending on the design of the test object, cast resin transformers in power classes of up to approx. 20 MVA can be tested in the field.

2.4 Evaluation Criteria

As described above, the acceptance test for new transformers requires a clearly defined test cycle and a maximum PD level of 10 pC. For the PD measurement and subsequent assessment of the transformers in operation, the applicability of these criteria must be discussed. Previous on-site measurements have shown that a test cycle with a reduced test voltage is often required. If the test cycle is reduced to 80% voltage according to [3], this will result in a pre-stress phase with 1.3 times nominal voltage and a test voltage of 1.0 times nominal voltage. Equally, the assessment of the partial discharge activity should not be limited to the discharge level. Rather, the determination of the type of the PD source is of importance in order to estimate the risk potential for the transformer. The following case studies illustrate the implementation of these evaluation criteria.

3 Case Studies

3.1 Case Study 1

A 9.5 MVA cast resin transformer was examined for partial discharges by carrying out an induced voltage test. While the first two phases show no abnormalities, surface discharges can be observed on the last phase. It is believed that these come from a layer of dirt on the inside of the HV coil (Fig. 8).

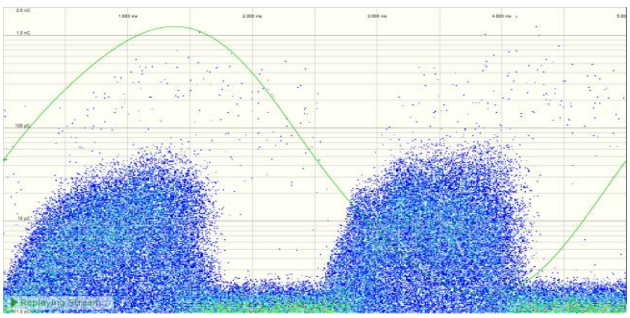

Figure 8 Surface discharges on the HV winding.

Since immediate on-site cleaning is not possible, the test setup is modified to minimize the electric field of the contaminated areas. For this purpose, the coupling capacitor is connected to the base of the coil and the ground is connected to the beginning of the coil. While the voltage of the winding insulation remains the same, there is no voltage stress on the upper part of the coil (Fig. 9).

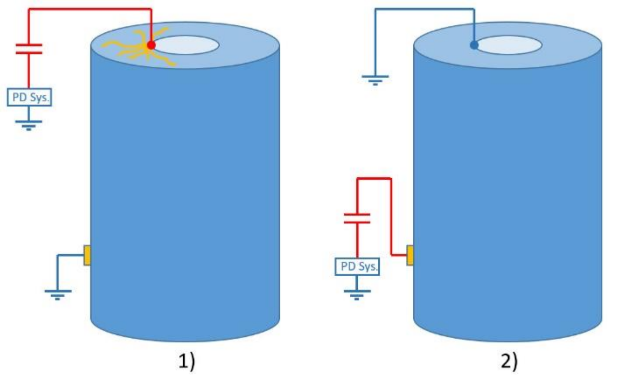

Figure 9 1) Connection of the coupling capacitor at the top of the winding, surface discharges 2) Coupling capacitor and ground swapped, free of PD.

After swapping the coupling capacitor and ground, it is possible to determine the lack of PD in the coil (Fig. 10). Since only the voltage to ground has changed between the two measurements, the partial discharges of the first measurement can be clearly traced back to the surface condition of the coil.

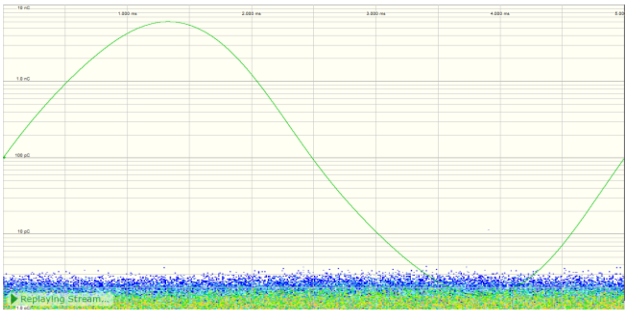

Figure 10 PRPD free of partial discharge after swapping the coupling capacitor and ground.

Since the partial discharges do not occur inside the coil and the inception voltage is below the nominal voltage, it is recommended to clean the winding in order to minimize the risk of further damage.

3.2 Case Study 2

Partial discharges were recorded during the routine testing of an online monitoring system for a MV cable (Fig. 11).

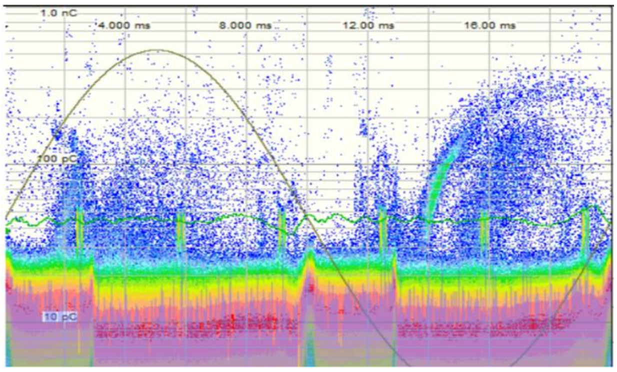

Figure 11 PRPD of cable, recorded using a monitoring system.

The PD source can be found both in the cable section and in the connected 800 kVA/20 kV dry-type transformer. Therefore, a single-phase PD measurement, which is taken using an induced voltage test, is used to test the transformer separately. In doing so, PD activity is detected on all phases with inception voltages of 16 kV, which is clearly below the nominal voltage (Fig. 12).

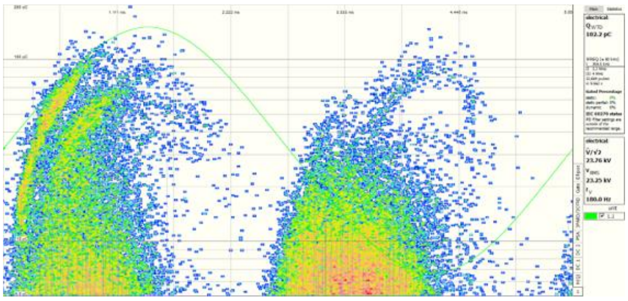

Figure 12 PRPD U-phase of the transformer, recorded during the induced voltage test.

The absence of PD in the cable is then verified using an applied voltage test. The transformer is then swapped, as it can be assumed that the partial discharges are permanently active during regular operation and continue to act on the insulation.

4 Summary

This article presents methods for testing the insulation condition of dry-type transformers which have already been installed. With the help of a mobile test source, an induced voltage test can be carried out in conjunction with a partial discharge measurement. Each coil of the transformer is excited separately which enables a targeted assessment of each winding. By adding power amplifiers, the output power of the voltage source becomes scalable. This makes it possible to test transformers up to approx. 20 MVA. Since it is not possible to take the measurements in a shielded chamber, a corresponding amount of interference must be taken into account. It has been shown that the 3CFRD method enables PD signals to be separated from disturbance signals. The practicality of the system has been illustrated using two case studies. By testing each coil individually, it was possible to detect specific sources of partial discharge and isolate their causes.

5 Literature

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[4] W. Koltunowicz, R. Plath: “Synchronous Multichannel PD Measurements”, IEEE Transactions on Dielectrics and Electrical Insulation, Vol. 15, No. 6; Dec. 2008.
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