PARTIAL DISCHARGE ALERT SYSTEM IN MEDIUM VOLTAGE SWITCHGEAR

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ABSTRACT

Partial discharge (PD) is a well-known indicator of insulation problems in high voltage equipment. We report on experience collected during the development of a new online PD detection and alert system for air insulated switchgear (AIS) installed base. The approach taken to integrate the sensor with minimal retrofit effort and operational disruption is described. Results from a test setup including a line-up of panels and different reference PD sources in comparison to a commercial PD system are presented. The effect of cables connected to the switchgear is investigated by testing the system including additional capacitive load and using a simulation for a typical geometry. We also address the question regarding the design of an alert system to be used in connection with the continuous data acquisition.

INTRODUCTION

Partial Discharges (PDs) are short electric breakdowns not leading to a complete conductive path between the high-voltage and ground or between the different phases of a high-voltage system. They are seen as one of the best indicators of problems in medium voltage insulation systems. It is assumed that in the large majority of dielectric failures, a partial discharge driven insulation degradation process is present before actual breakdown.
For this reason, PD measurement is widely used and recognized by relevant standards as an important quality check of insulating components during production, factory acceptance tests and later during the commissioning phase. Acceptance and critical levels are often defined based on the measurement approach as specified in IEC60270 [1].
The use of PD measurement for field diagnostics has also been widely reported in the literature, especially with respect to the usage of different measurement equipment. This is only applicable during a shutdown of the site and requires additional equipment to be connected.
Online monitoring provides several advantages, but also challenges, with respect to PD measurement. It provides a continuous data stream, avoiding uncertainties coming from only performing occasional measurements. It can be used to study the evolution of PD over time with the potential to flag rapid deterioration or other changes. But it is required to first develop and qualify a PD detection and alert system, which fits the application with respect to cost, performance and installation effort. One primary requirement is the easy installation in order to upgrade brown-field setups without significant downtime and changes to the system. Another challenging topic is the conversion of the measured data into key parameters describing the insulation status with the aim to trigger alarms, but also to initiate more detailed diagnostics and maintenance activities.

APPROACH TO AN ONLINE MONITORING SYSTEM FOR RETROFIT APPLICATIONS

Many measurement principles exist for PD detection. Of these only the capacitive coupling approach is currently standardized in IEC60270 [1]. A number of retrofit systems are offered with the focus on allowing for measurements without requiring a direct connection to the high voltage. Examples are acoustic, TEV, HFCT, and UHF systems. Other less common approaches use optical or chemical sensors. An evaluation of the different approaches leads to the conclusion, that some of these are not useful in switchgear systems whereas others are limited with respect to their capability to detect all relevant PD types or to their sensitivity. As part of the present study, we investigate two sensing principles: capacitive-based and a transient earth sensor (TEV).
The TEV sensor was developed by the CMTEST laboratory and is composed of the TEV sensor, an acquisition unit and a PC with a custom software for the acquisition and post-processing as depicted in Figure 1.
The capacitive-based sensor principle is similar to the IEC60270 approach. To simplify the retrofit installation, the system is integrated into the already existing voltage indicating systems (VIS) or voltage indication presence systems (VIPS). The proposed measurement system does not alter the primary function of VIS and VIPS systems while providing PD measurement. An installation kit is integrated into the low-voltage compartment and provides the possibility of exchanging PD measurement electronics without shutting down the high-voltage as well as a fail-safe functionality in case of a malfunction of the PD measurement system. The developed system is able to monitor the PDs on each power phase. This allows to localize the origin of the PD with respect to the power phase, to distinguish between line-to-line and line-to-

ground defects, and to discriminate against external disturbances. With the capability to measure the line voltage it also offers the possibility of a “Phase Resolved Partial Discharge” (PRPD) analysis. The developed PD measurement system can measure partial discharge at different frequency bands, up to 10MHz, that is, above the frequency band standardised in IEC60270.

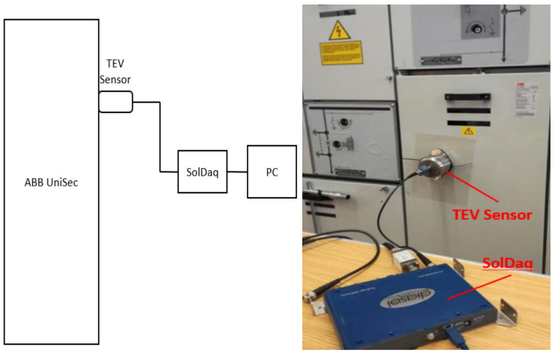

Figure 1. Setup of the TEV sensor, schematics (left) and photo of the real setup (right).

QUALIFICATION WITHIN A PILOT SYSTEM

The two systems, TEV and capacitive-based, are evaluated for their functionality on a dedicated AIS switchgear as shown in Figure 2. To allow for a range of different tests, the pilot system consists of a small line-up of panels, which are equipped with several VIS systems of different type and therefore different capacitive coupling means (post insulator, current transformers).

Measurements using two commercial PD systems are performed in parallel, which allows to qualify the detection capability and sensitivity of prototype systems. We use a conventional system, IEC60270-compliant provided by DiaSol Srl. (an academic spin-off of the University of Genova). The schematic of the test setup is shown in Figure 3.

In addition, different types of insulation defects, which are typically found in such systems are added. As an example, we show one reference PD source and the usage of a defective current transformer in Figure 4.

A calibrator was used before all measurements to qualify the sensitivity in actual apparent charge values. The measurements using the calibrator show that both systems under tests, TEV and capacitive-based, can measure with a sensitivity much better than 100pC under the tested conditions. For the capacitive-based system, Figure 5 shows, for a collection of different measurements, the strength of the calibration pulse signal of 100pC compared to the noise for two production capacitive insulators and coupled VIS (ABB and ENEL specification).

We also compared the PRPD pattern for different PD types. As shown in Figure 6, for the capacitive-based system, they are in good qualitative agreement. The number of points of the developed system was lower due to the data acquisition schedule used. The slower acquisition schedule is required to maintain the functionality of the VIS and VIPS. The measurement also shows that the performance of the online dynamic noise rejection algorithm, used to separate noise from real PD events, was working properly.

In conclusions, both prototype system are able to measure PDs with a good sensitivity and produce PRPD patterns that are comparable with commercial systems.

Figure 2. Pilot installation system showing the switchgear panels used for qualification.

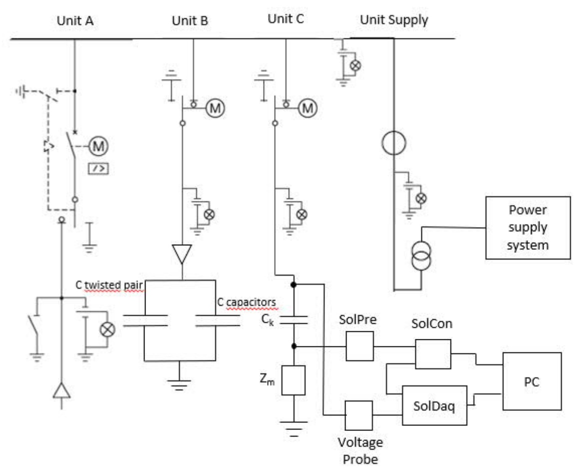

Figure 3: Schematic of the pilot installation including the position of the additional capacitors and the commercial PD system.

Figure 4: Two types of PD sources used during the qualification testing: A laboratory surface discharge producing device (left) and a current transformer rejected at acceptance test (right).

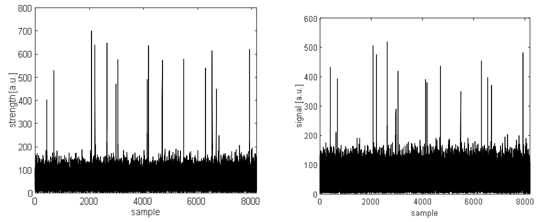

Figure 5: Collection of 100pC PD calibration pulses measured using two different VIS capacitive coupler.

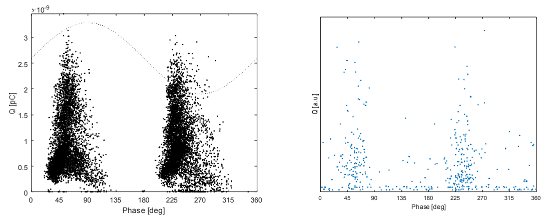

Figure 6: Comparison of a surface discharge pattern recorded by the commercial system (left) and with the online monitoring system (right).

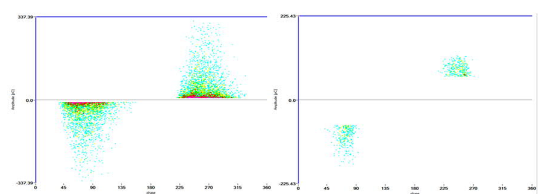

Figure 7: Comparison of the PD pattern without (left) and with (right) additional capacitors for the conventional PD system.

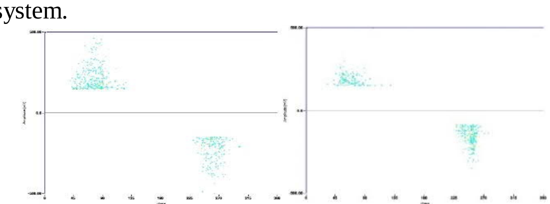

Figure 8: Comparison of the PD pattern without (left) and with (right) additional capacitors for the TEV sensor.

INVESTIGATION OF THE EFFECT OF LONG CABLES ON PD MEASUREMENT

The pilot switchgear used for the test is originally setup as standalone, that is, no cables are connected. But it is expected that long cables add a large DC capacitance and it is well known, that the capacitive measurement principle sensitivity decreases as the overall system capacitance increases. Partial discharges are indeed measured through the instantaneous voltage changes (thereafter referred to as pulses) they produce on the medium-voltage busbar. The amplitude ΔU of the pulses depends on the capacitance of the system C_{sys} and on the apparent partial discharge amplitude q_{PD} through the simple relation $q_{PD} = C_{sys} \cdot \Delta U$. The larger the system capacitance, the smaller the detectable signal in relation to the PD pulses. Additionally, the partial discharge measurement system has a lower limit in terms of pulses it is able to measure. For example, in the noiseless case, the prototype system is able to detect pulses of about 10mV on the busbar, which corresponds to an apparent charge of 10pC for a system capacitance of 1nF. The latter value is found to be a typical system capacitance value during lab-based or site-offline partial discharge measurement.

A real installation may feature much larger capacitance value, which would reduce the system sensitivity. In particular, medium-voltage switchgear is typically connected to a feeder that can connect to cables with a length of several hundred meters or even few kilometers. Under DC or low frequency conditions those cables have a large capacitance per unit length, typically few hundreds picofarad per meters, therefore resulting in system capacitances much larger than the 1nF discussed above.

To illustrate the effect on the measurement sensitivity, three capacitors with a capacitance of 3.3nF each have been connected in parallel to a long twisted-pair cable giving an overall additional DC capacitive load of about 10nF to mimic the capacitance of long cables (see Figure 3 for the test setup).

As can be seen from Figure 7, the insertion of the capacitors causes a reduction in the PDs amplitude in the case of the conventional capacitive-based measurement system. The reduction in measured PD amplitude is found to be less severe for the TEV system, as shown in Figure 8. The TEV system measures the radiated (rf) signal produced by the PD. The sensitivity of the TEV system depends therefore only on the environmental electromagnetic characteristics and is not affected that strongly by the capacitive characteristics of the system.

The capacitive behaviour of a pure capacitor does however not reflect the effect of a cable at high frequencies. Due to their long length, cables must be represented as a transmission lines. Whereas the capacitance and inductance per length for regular cables are given for low frequencies, they are operated here at high frequency, where their effect on the PD pulses is less studied.

To assess the influence of cabling on the partial-discharge measurement system we have simulated a simple medium-voltage system including the cable using the equivalent electrical circuit shown in Figure 9.

The system consists of the medium voltage busbar where partial discharges are injected on the one side. The system capacitance is represented by C_{SYS} (excluding the effects of the cable) while the elements R_P, L_S, R_S represent a first-order approximation of the medium voltage busbar system. A two-port element, modelling the medium-voltage cable, is inserted between the busbar system and an external load – representing the network impedance. The cable model is based on the approach described in [1] where the per-unit-length parameters has been computed through a finite-element simulator using the medium-voltage cable geometry given as “12/20 (22) kV single core copper unarmoured conductor” in [2].

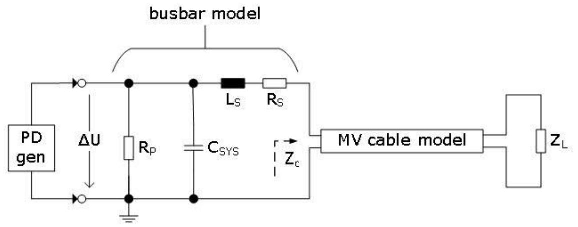

Figure 9: Equivalent circuit of the switchgear line-up and the attached MV cable used for the simulation.

The partial discharge strength has been set to 100pC, the system capacitance to 1nF, the resistor R_P to 100Ω (to simulate the overall load), the series inductance to 1nH and the series resistance to 1mΩ. Without the cable the 100pC partial discharge is expected to produce a ΔU=100mV; this is indeed the case as depicted in the simulation results shown in Figure 10(a) – the reduction to 90mV is due to the large resistor of 100Ω, which behaves as an ideal resistor even at high frequency.

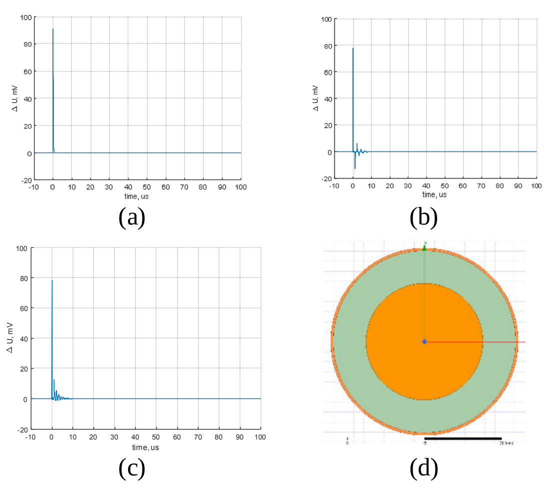

Figure 10: Amplitude of the pulses produced on the MV busbar corresponding to a 100pC discharge for the system presented in Figure 1 with C_{sys}=1nF. (a) no cable attached to the busbar, (b) with a 100m cable attached with a grounded end ($Z_L = 0\Omega$), (c) with a 100m cable attaches with an open end ($Z_L = \infty$). Subfigure (d) shows the cable geometry using for the calculation.

Figure 10 (b) and (c) show the pulses for the same partial-discharge level with a 100m cable attached and terminated by a short- and open-circuit, respectively. The pulse amplitude decreases only by about 12mV in both cases, implying that most of the pulse energy is conserved. The reason for this is that a long cable behaves as a transmission line rather than an ideal capacitor. In other words, the pulse produced by the partial discharge is travelling along the cable and a major part of the energy is reflected. Depending on the frequency, reflections cancel or strengthen each other. As partial discharges generate wideband signals, there are thus, with high-likelihood, frequency bands for which they will be visible as pulses on the busbar.

Another way to look at this phenomenon is to consider the impedance of the cable (and the subsequent load Z_L) as seen from the busbar (impedance labelled Z_C in Figure 9. This impedance was also simulated, and results are reported for the same assumed 100m-long medium-voltage cable terminated with a short- and open-circuit, respectively. The impedance consists of peaks and troughs equally spaced in the frequency domain. The cable terminated with a short has a low impedance below 1MHz and a first peak around 1MHz. On the other hand, the open-circuit cable behaves mostly like a 10nF capacitor up to 500kHz and with a first peak around 2MHz.

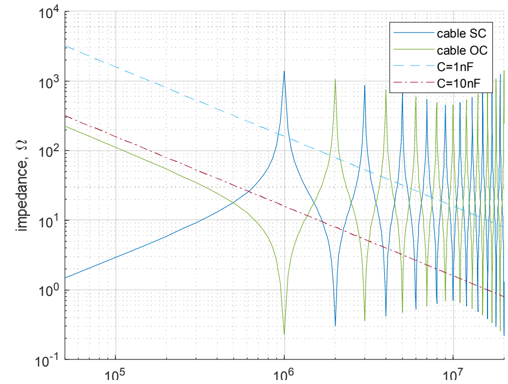

Figure 11: Cable impedance of a 100m long cable as a function of frequency. The results are also compared to the ones of a pure capacitor with different capacitance as used during the tests.

The effect of the cable impedance, together with the busbar and source impedances, is thus to shape the frequency response of the partial discharge pulse. The signal strength is reduced for frequencies where the cable impedance is lower than the system impedance. Conversely, the signal strength is mostly unchanged for frequencies where the cable impedance is larger than the system capacitance impedance. Note that real-world cables typically will exhibit smoother peaks and troughs than what is depicted in Figure 11.

The proposed online partial discharge monitoring system measures partial discharge up to 10MHz. If installed in a setup connected to a cable having an impedance as in ("cable SC"), the system can be set to measure partial discharge around 1, 3, 5, 7, or 9MHz. For those conditions, we expect to have a good sensitivity.

In summary, cables do not behave as ideal capacitors but rather as transmission lines. As such they influence the partial discharge frequency response by attenuating certain frequency bands while letting others untouched or even amplified. This behavior underlines the importance of having a capacitive-based partial discharge monitoring system that is flexible regarding the measured frequency band. Further pilot installation in different medium voltage substations and cable system network extensions are foreseen to further verify cable length behavior. On the other hand, other measurement methods, such as TEV, are less depending on the system capacitance.

CONCEPT FOR AN ALERT SYSTEM

The qualification on the pilot installation showed that the online monitoring prototype is capable of measuring PD signals comparable to commercial devices. The signal provided by this online monitoring system will be fed into an alert system. The overall system can then be deployed in field pilot applications with the intention to set different alarm levels depending on the conditions of the system.
Whereas the goal of any monitoring system is to provide prognostics capabilities, especially, an estimate of the time to failure or remaining useful life, this is still an open challenge for PD monitoring systems.
On the one hand, continuous measurement data until breakdown – needed for such an analysis – is not yet available. In addition, there is not necessarily a direct causal relation between the occurrence of PD, its evolution and the final breakdown. That is, PD can sometimes be seen as an indirect indication only without direct access to the degradation leading to final breakdown. Nevertheless, the presence of PD should be used insofar as a possibility to identify problems in the system. In a first step, the system needs therefore to be restricted to those cases where a direct relationship exists.
The general approach in online monitoring has often been to develop a system of KPIs that are then tracked over time. Thresholds – of various levels of complexity – are used to flag warnings. The warning level is assumed to be directly connected with a severity or deterioration of the insulation. Such an approach however requires the setting of thresholds by the customer, which is difficult to do.
The general idea behind the proposed online monitoring system here is different. The measurements are seen as inputs triggering further investigations. We define two alarm levels in the following way: A first alarm level ("yellow") is triggered, as soon as the measurements indicate that partial discharge is reproducibly present in the system. To do so, several simple PD-presence indicators, each focusing on specific properties of PD, are compounded. For example, detecting PD strength – according to the IEC standard – above a certain threshold (e.g. 100pC) as determined during commissioning phase. Additional indicators are the count rate, count rates for peaks above threshold, but also statistical properties that indicate the presence of PD and not of an external disturbance. The alarm is thus "yellow" only if a combination of PD-presence indicators have been triggered. Additional on-site measurement performed by a service technician should, in that case, also conclude that a significant level of PD is measurable.
A second alarm level ("red") is triggered if a "yellow" alarm is present and in addition one or several PD-severity indicators have been triggered. The PD-severity indicators are triggered if the measured PD is considered to be of a dangerous nature. PD-severity can be compounded in different ways that reflect the knowledge available about PD types and their behaviour; each combination relates to a particular failure mode. Typical properties are, for example, significant increase of the PD strength or the pulse rate over a short period of time, the identification of a specific type of PD, known to lead to rapid damages to the insulation. A service technician checking the installation should, in that case, be able to identify a damage to the system originating from the PD.
Compared to a typical online monitoring system, the advantage of the proposed alarming system are as follows: The setting of the different levels makes use of knowledge that is not specific to each failure or defect. The focus is on triggering further actions and to ensure that the alarm level is consistent with what an onsite investigation will experience. The "reasoning" behind the alarm level can be given in addition to the alarm itself, which gives an additional hint to where to search for the defect. Finally, in the case of false positive alarms, rules can be switched off, added or combination changed without changing those related to other failure causes. This approach is a first step toward a probabilistic approach as it can grow as a belief network if enough data becomes available in the future.
A first version of this alarm system has been specified and implemented and is used for a first pilot installation.

SUMMARY AND CONCLUSIONS

We have developed a prototype system that can be easily installed into an existing switchgear and with sufficient flexibility to be used for online acquisition of data. The performance of the system was tested using a realistic setup and defect types. The effect of long cables on the measurement sensitivity was assessed and found to have an influence on the prototype system, but only little on the TEV-based sensor. Capacitive-based systems need to measure PD at high frequency in order to avoid the DC capacitance effect of the cable.
We have proposed an alarm system based on two level ("yellow": PD is detected, "red": dangerous PD is present). The alarm system is based on rule-based combinations of several indicators (PD-presence and PD-severity).
The PD measurement system and the alarming system have been deployed in field test and are the first steps toward a cloud-based fleet monitoring and diagnostic solution
Further pilot installation in different medium voltage substations and cable system network extensions are foreseen to further verify the effect of cable length on PD measurement.

Acknowledgments

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