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On- and Off-Line Measurement, Diagnostics and Monitoring of Partial Discharges on High-Voltage Equipment

T. Strehl
LEMKE DIAGNOSTICS GmbH, Germany

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Abstract
The computer based PD-measurement and analysis is becoming more and more popular as a tool for assessing high-voltage equipment. The measured PD characteristics are used to identify and evaluate condition changes of the related insulation-system.

Presently, the capability of this diagnosis method is manly used in the field of the quality control and of condition-based maintenance. Considering the strategy of the diagnosis and the available external high-pot sources, the PD-measurement is carried out on-line or off-line. On-line PD-Monitoring and Alarm Systems are increasingly installed in order to reduce the life-cycle-costs and to extend the reliability and safety of the equipment and system operation.

The different latest sensor technologies to decouple the PD-signals on transformers and cables are presented and compared with respect to their field of application, the related diagnosis capability and the degree of complexity. Considering the particular field service conditions, different decoupling methods are advantageously applied.

It is demonstrated that the analysis of the measurement and monitoring results is very successful when evaluating the right array of PD-characteristics. Although, during the evaluation and estimation process of the data, the influence of each specific test object, of the measurement system itself and of ambient environmental conditions has to be considered. The design of the insulation system, the characteristic of the measuring system as well as the noise conditions are of high importance and critical regarding the respective interpretation evidence. This is demonstrated with practical measurement examples. The analysis of PD-monitoring data is always as good as the assessment guideline and the strategy of acting when exceeding a predefined level is. Because there are presently no standards for PD on-line monitoring at all, some aspects to setup helpful measurement and monitoring conceptions for trend- and rating performance are discussed.

Introduction

The system management of power equipment always needs a reasonable maintenance. Modern technical system management uses the condition of the equipment to determine what testing and maintenance procedures should be performed. It is called condition-based maintenance. For this reason both on-line and off-line procedures, are performed, and test data are collected into a computerized data base in order to evaluate them on- or off-line, respectively.

Certainly, the results are reviewed by an engineering department using their own experience or sophisticated inspection, statistical and simple comparison tools or complex analysis methods. Modern computerized expert systems can do this job with their implemented expert system software mostly based on feature extraction, database comparison and fault recognition features.

Applying a properly matching maintenance procedure the effectiveness and finally the decreasing of the costs will result.

For the estimation of the condition of high voltage power engineering equipment the Partial Discharge test is certainly the most recognized tool to assess the insulation condition. Thinking about insulation defects, we learned that they always result in partial discharges. Regardless, of whether we talk about internal voids, electrode detachments, surface erosion or other insulation destruction processes they always appear as internal or surface discharges, corona or electrical treeing phenomena and can therefore sooner or later be detected and measured as Partial Discharge signals.

Accordingly, manufacturers of equipment together with the power utility industry have a vital interest in on-site, off- and on-line diagnostics and monitoring of their high voltage systems. The goal is to locate, identify and assess the insulation problems, during the inspection of the newly produced or newly installed equipment and during the periodical or continuous test and estimation of service aged apparatus. This results in a planed and scheduled repair work, so the system reliability will increase by a reduction of unexpected failures.

Exemplary the PD decoupling, measurement and analysis at transformers, motors, and cables are demonstrated to show the capability of this powerful insulation assessment tool.

How the PD signal comes out? Sensor Technology

In accordance to the related Partial Discharge standards (like IEC, ANSI ...) the decoupling of the PD signals is usually described with a coupling capacitor and a measuring impedance connected to the test object terminals. This measurement method is definitely limited to test floor assemblies. A safety disconnection is necessary to couple the PD measurement circuit and this is mostly unacceptable for on-site tests even when applied off-line and clearly impossible for all on-line tests and monitoring applications.

A suitable sensor based decoupling, able to substitute the standard measurement circuit should at least cover the following characteristics:

- without influence on the service condition of the equipment
- at least the same life performance as the equipment at which it is installed
- easy installation of the sensors
- comparability and portability of the on-line acquired results to the off-line readings to be compatible
- inherent against ambient on-site conditions

Mainly the high frequency electro magnetical components or the acoustic characteristics of the PD signals are used for on-site PD decoupling.

Magnetic and Electric Field-Sensors
Using the electromagnetic field coupling the sensors are designed to receive the electric displacement field with a capacitive field sensor or the magnetic field of the transient PD current with an inductive field sensor.

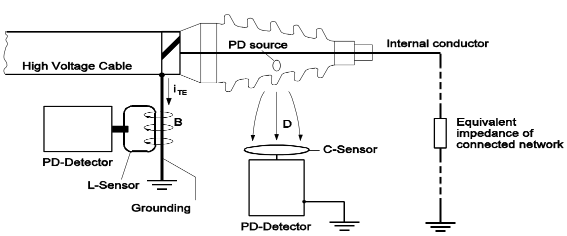
The capacitive sensor based PD measurement picks up the electric field energy of the PD pulses with a metallic electrode structure or additional metallic foil layers placed into the electric field. This is sometimes realized as a dual capacitive sensor working in differential mode to discriminate noise from critical PD.

The inductive field coupling is usually done with a magnetic field antenna, a „Rogowski coil“ or a small RF current transformer. A typical application of a magnetic field sensor locating PD faults in a large high voltage hydro generator is illustrated in the photo at figure 1. The sensor at the top of the insulating rod receives the radiated magnetic PD field. The sensor safely is attached in the area of the field grading at the end winding.

Figure 1: Inductive field coupling for location of PD affected coils in a hydro generator

The application of galvanic coupling as shield interruption or the connecting of a series impedance on low or high voltage site cause mostly a significant influence on short circuit current handling ability and is therefore not common.

The different ways of electromagnetic field coupling are principally shown in figure 2 as applicable for cable terminations (rotating machines).



igure 2: Field sensors for PD decoupling on cable terminations (rotating machines)

UHF Sensors

For the ultra broadband or the ultrahigh frequent narrowband PD measurement the sensor technology is designed to decouple the electric or magnetic field mainly or exclusively in the high frequency range. An advantageously used frequency range for that is the UHF range (0.3 GHz - 3 GHz). The related sensors are designed to couple not only the basic TEM mode but also in many higher order modes (TE_{mn}, T_{mmn}). Using the higher modes numerous discontinuities of the equipped arrangement can lead to reflections and therefore to standing waves of varying frequencies. Moreover, there are usually coupling between the different modes. The signals in the UHF frequency range can be detected by means of couplers which are usually of similar design to capacitive and inductive couplers as described before adapted to the RF demands. A typical field of application is the PD decoupling in GIS. Such called UHF sensors are installed into the vessel in an extended GIS. The sensor itself is an electric field sensor, typically a metallic plate installed in the gas pressured tube. The frequency range of detection is limited by using highpass terminating and an tunable IF terminal impedance. The decoupling itself is therefore using a narrowband range. Hence, the portability to apparent charge measurement is not possible, because the frequency distribution of the propagated PD signal determines the UHF sensor output signal directly.

Particularly for the mobile on-site application, UHF/VHF sensors for mainly decoupling the higher TM-modes are suitable. The broadband output signal is transmitted into a lower frequency range by using a waveguide oscillator. An application of this sensor technology is shown in figure 3. The sensor receives the high frequency components of the magnetic field of the PD pulses from a cable joint (fig. 3a) and at the terminal of a GIS (fig. 3b). The field components can pass the incomplete screening of the cable sheath, or OV-terminal and be received by the magnetic UHF antenna.

igure 3a: UHF sensor applied to decouple PD from a high voltage cable termination

Figure 3b: UHF sensor applied to decouple PD from a high voltage GIS terminal

Waveguide Sensors

A main interest in designing PD sensors is the ability of distinction between noise and critical PD signals. An important step to a good separating capability is the information of the propagation performance and direction of the traveling PD pulses. A specific sensor to determine the propagation direction is a PD Directional Coupler. The sensor couples energy from a waveguide to one or two output ports. This is done such that energy traveling in one direction of the waveguide arrangement mainly causes a signal at one of the two output ports of the sensor. The energy of PD signals that travels in the other direction will mainly couple to the other output ports. This sensor is characterized by its coupling factor and its directivity. The coupling factor describes how much energy is coupled from the measured test specimen into the output ports. The directivity quantifies the ability to distinguish between one and the other direction of the propagating signal. Directional couplers use both capacitive and inductive coupling. The working method is a waveguide coupler for mainly the TEM mode of the PD signals.

Directional coupler sensors are typically installed in cable accessories and GIS equipment or in transformers and generators. A directional coupler during installation in a cable splice housing to monitor the PD activity is shown in figure 4.

Figure 4a: DCD Directional Coupler Measuring System LDY-724; installation of a coupling sensor

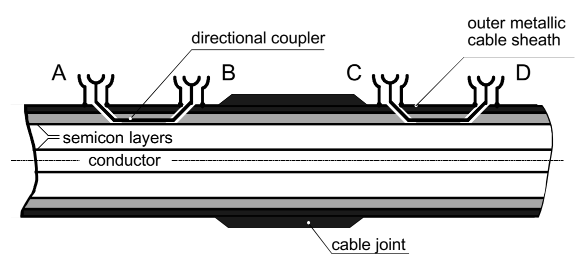


Figure 4b: Principle set-up of two sensors at a cable joint

The same technology can also be applied to stator windings in a rotating generator with sensors in order to discriminate external noise from critical internal PD signals of the winding insulation. In that case the sensors are installed in the end winding area closed to the iron core.

Using other available facilities for PD decoupling

Often the power apparatus are equipped with facilities and accessories which can perfectly be use to decouple PD signals. A commonly use method to decouple PD at power transformers is the such called bushing tap method. The capacitive taps of the transformer bushings which usually exist to measure the voltage can also be used for decoupling the PD signals via these bushing taps. For this purpose a RF transformer is connected to the bushing tap and the combination of the tap capacitance with the short-circuit-proofed RF unit is suitable to decouple the PD signals out of the transformer.

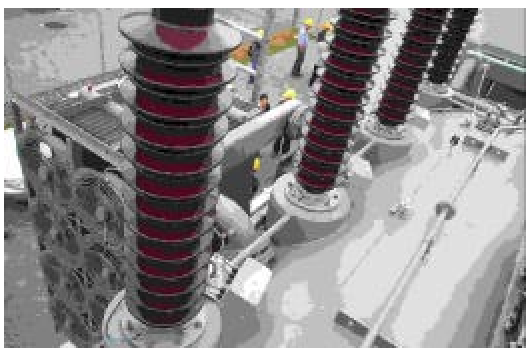


Figure 5: PD decoupling units of the monitoring system LDWD-6 installed on a power transformer

A typical installation for on-line PD monitoring of a 345kV power transformer is shown in figure 5. Each bushing tap is fitted with a decoupling device. The voltage signal as well as the PD signal is transmitted to the monitoring system for PD monitoring of the power transformer.

Another possibility to outfit equipment with PD couplers is the replacement of an existing part with one that has PD couplers implemented. Exemplary, the installation of capacitive couplers in generators is shown in figure 6. The busbar insulators of the three phases of a high voltage generator can be replaced with insulators which have a higher capacitance for PD decoupling.

The recommended capacity of the couplers is in the range of 1 to 4 nF and the capacitance itself is embedded in the insulator during the encapsulating process of the moulding resin. The capacitive coupler is than used as insulator and spacer as well as PD decoupling unit.

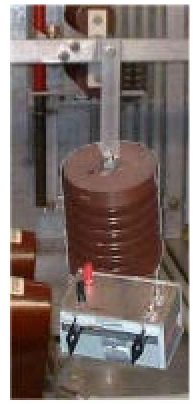


Figure 6: PD couplers installed in the bushar of a high voltage generator

Non electromagnetic PD sensors

The acoustical PD measurement is mainly used for pin-pointing of PD faults in transformers or switchgear. The sensor used for decoupling is usually a piezoelectric transducer often with an amplifier directly implemented in the transducer body. An example of PD pin-pointing at a GIS is shown in figure 7. The piezo-transducer is attached to the metallic housing of the switch gear and the acoustical signals are acquired with the

handheld PD detector LDP-5.

Figure 7: PD measurement on a gas-insulated substation using piezo electrical, acoustical measurement in connection with the PD probe LDP-5

A correlation between the electrical detected and quantified PD readings and the acoustically measured signals is not possible. The defined quantity apparent charge, which is well known from the electrical measurements, can therefore not be assessed. Furthermore, the propagation performance of acoustical waves is not transferable to the electrical modes. The propagation behavior in different insulation materials even if the dielectrics are laminated or there are acoustical reflection points is very complex to estimate to acoustical wave propagation. Hence, a useful application is PD pin-pointing and echo time measurement for PD location, not a quantified measurement.

How the PD signal is evaluated? PD Signal processing and evaluation

A main aspect of the PD signal evaluation is the quality of the assessment of the measured readings. The basic fundamental values that we can use for the PD signal evaluation are of course the decoupled PD magnitude and the measured voltage, both as a function of the time. Assuming to have characteristics, it is possible to detect the magnitude of the PD pulse, the corresponding voltage level and the corresponding phase position for each PD pulse individually. Again, using this quantities the frequency distribution of the PD activity can be derived. This is principally shown in the diagram of figure 8.

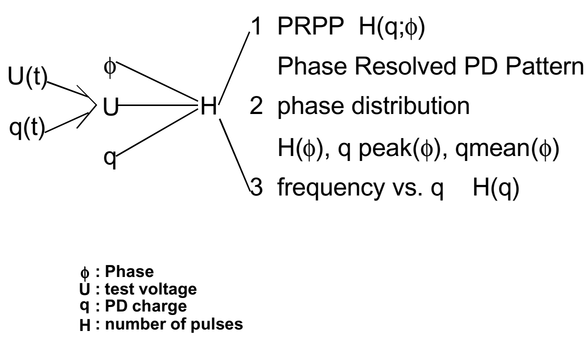


Figure 8: PD signal evaluation strategy

To make this procedure graphically clear for one type of signal representation the development of a resulting PD diagram which is well known as Phase Resolved PD Pattern (PRPD-P) is shown in figure 9.

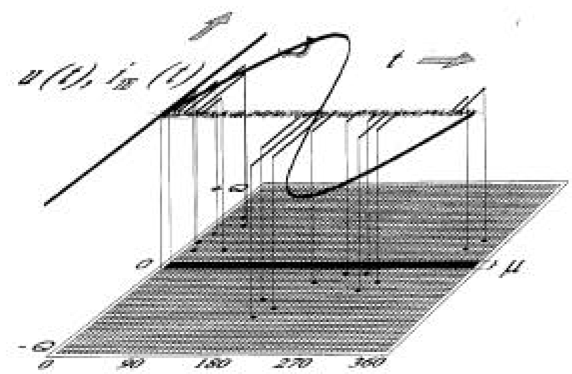


Figure 9: Classification of PD pulses by their apparent charge values and phase position

With this PD data available for all appearing pulses there follow several possibilities of PD fault recognition strategies. A very promising technology is the realization of an automatic PD Expert system. Certainly an unified mathematical modeling is not available for all occurring PD faults and only in very exceptional cases a subclass of PD phenomena can suitably be found. Therefore, all diagnostic expert system are strongly dependent of the recognition of specific symptoms. These symptoms and their qualified discovery get the key roll regarding the quality of the assessment result. The so called feature extraction module is responsible to extract physically significant features out of a PD data set. This module is followed by a classification schedule. The extracted characteristic features are subjected by a classification procedure. The classification is completed by means of comparison of the extracted feature array of the presently measured PD data with feature objects of an existing PD failure data base, where known reference data records are stored. The classification result is the probability of the failure type of the presently measured PD data compared to a data base filled with known fault types. So it can be used to recognize earlier measured fault types.

A sophisticated concept including diagnostic features of an on-line PD monitoring system is displayed in figure 10. The decoupled signals from one or more sensors are acquired in a data acquisition unit. Considering a known model of PD phenomena the analysis and diagnosis is carried out in an expert system. Consequently there are two output requirements. The basic one is a continuous data logger to record a full file history. For this purpose the PD characteristics are downloaded to a host computer at plant or network control system or to an engineering department via conventional data network systems (local area network or internet integration).

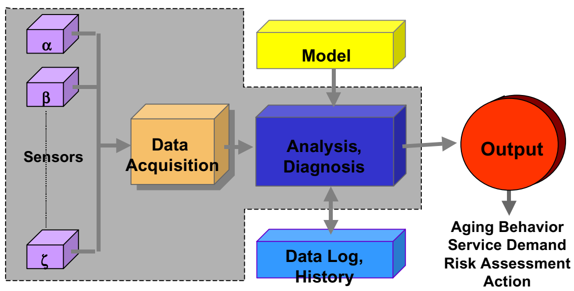


Figure 10: Structure of a monitoring system suggested by the CIGRE 33.03 TF08

The other important demand are the alarm output ports, such as pager, GSM module, modem or a network interface. Based on predefined alarm thresholds and the automatic analysis and diagnosis, an information describing the present condition is transferred by the monitoring system itself. The alarm message notifies about the system state, a necessary service demand, an impending fault risk and possibly informs about the aging behavior. Changes from previous conditions are analyzed and if a trend exceeds a specified amount the notification to adopt additional measures is send out.

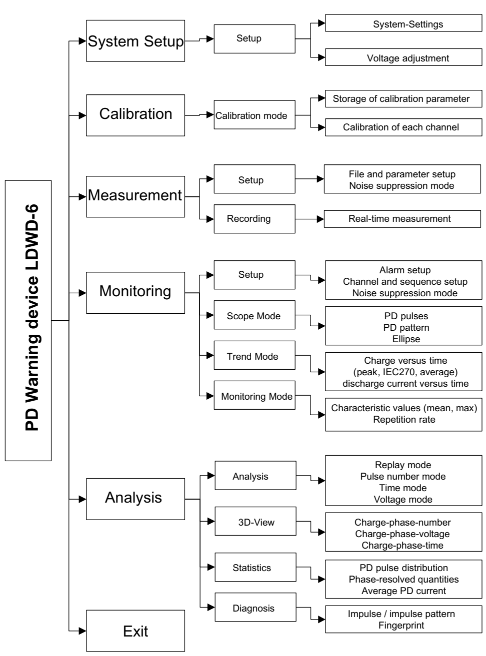


Figure 11: Software concept of the PD monitoring system

The software concept of the monitoring system LDWD-6 in figure 11 exemplary illustrates the implementation of a state of the art PD monitoring system.

Practical example of PD monitoring of power transformers

The schematic block diagram of PD monitoring for power transformers is shown in figure 12. The bushing tap couplers are connected to the decoupling impedances. For each phase the PD and voltage signal is transmitted to the PD warning device, which is installed directly at the transformer site. The monitoring system is additionally equipped with gating channels to acquire noise signals received from antennas.

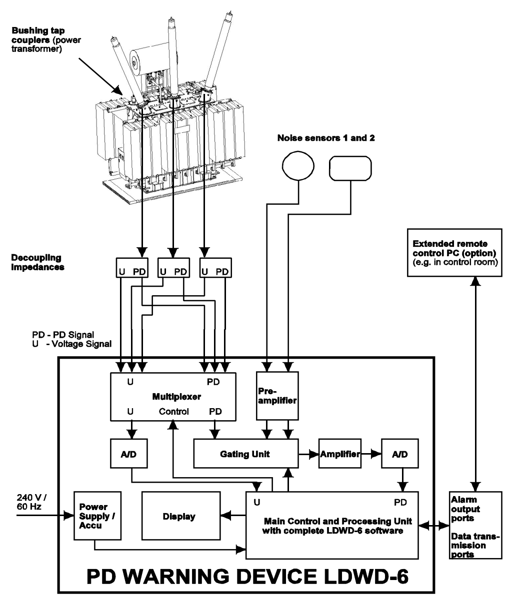


Figure 12: Block diagram of the PD monitoring system for power transformers

The system can be adjusted locally or completely be remote controlled by an extended remote computer. Independent alarm- and data transmission ports permit continuous remote data transmission and alarm messaging.

The monitoring system complies with conventional processing frequencies according to PD standards like IEC 270. Thus, the PD results are compatible to conventional off-line PD measurements. The whole experience of off-line testing can still be used to assess the PD monitoring results. A selectable wide band linear- or logarithmic single pulse processing covers a dynamic range of more than three decades. The multiplexing unit monitors all three phases simultaneously in real time. After a released alarm or forced by local or remote control the signal acquisition is running in multiplexing mode and can automatically trace the effected phase.

With a self diagnosis facility of the complete signal path the alarm recognition performance and a periodical check of the signal transmission behavior prevents an unobserved malfunction of the monitoring system itself.

Figure 13: On site installed LDWD-6

The system is equipped in a waterproofed case and installed on-site in a small cabinet were all data port connections for remote control, alarm and data transmission are connected. (See figure 13). A short time mains interruption will not lead to a monitoring interruption due to an installed no-break power supply buffer.

The monitored transformers are single phase 345 kV power transformers connected to an outside 345 kV overhead line.

With the gating channels used to suppress stochastically appearing disturbances and two additionally installed notch filters suppressing sinusoidal, harmonic interferences in the AM frequency range the noise level is reduced down to 60 pC on-line when the transformer is working in nominal load service.

Hence, alarming threshold levels a clear detection of 100pC could be adjusted. Assuming typical factory accepted PD levels of 500pC, the realized on-site monitoring assessment level is significantly lower compared to the off-line test floor accepted values. This assures a very extensive chance to detect critical PD faults in a very early stage.

The strategy of handling the PD monitoring data is scaled in four steps:

- The PD characteristics like PD magnitude, PD frequency and PD current are continuously transmitted via a data transmission port to be recorded and stored.
- The primary threshold settings will release an alarm signal/message in case of the PD magnitude, the repetition rate and the time of persistence exceed the combined alarm criteria.
- The primary alarm initiate a modified data acquisition and storage concept for a more detailed classification of the defects.
- The secondary detailed analysis and diagnosis to determine the affected phase and the type of fault starts.

Summary and future Outlook

The latest developments show that the technology of measurement and diagnosis on high voltage systems will go out of the test floors towards on-site. The systems are designed more compact and suitable for field applications. The technological progress is also characterized by the overcoming of electromagnetic and other environmental noise conditions. This progress consequently leads to new questions regarding the risk assessment of a simple measurement reading obtained during an on-site test.

The apparently simple question which PD level can safely be accepted on particular tested high voltage equipment can not be answered on-site using the same simple assessment methods applied and useful in the laboratories.

Therefore, the simple measured value acquisition must be supported with a more comprehensive diagnosis using more than one or two recognized parameters.

The answer to the assessment of a risk potential can not be based on one or two single characteristic parameters. Only the judgment of multiple parameters and the implementation of an experience based knowledge using trending analysis and sophisticated expert systems will result in a reliable answer to the complex matters, happening on-site.

So we can see the demands of the future: A measurement system for on-site application will more and more be asked to give a useful evidence about the condition of the tested or monitored object and not only a measured value. Therefore, the instruments will have implemented a particular intelligence about the tested object to be able, at least, to support a decision or better trigger autonomously a service or maintenance action before a fault happens.

Hence, more and more solutions will come out, were the monitoring instrumentation including the sensors and the evaluation devices are already an integral part of the monitored equipment.

The diagnostics and test systems left the labs and became established on-site and they find their access into the monitored and tested equipment to become a part of it.

The diagnostic instrument developed out of a measurement device is now going to be a decision assistance and it probably will take own measures instantly and directly for a better reliability of the equipment in the future.

LEMKE DIAGNOSTICS GmbH
Radeburger Str. 47
01468 Volkersdorf / Dresden
Germany

mailto: info@ldic.de
URL: www.ldic.de