PARTIAL DISCHARGE ON-LINE MEASUREMENTS WITH CONTINUOUS MONITORING AS INVALUABLE TOOL FOR ASSESSING INSULATION QUALITY AND MAINTENANCE PLANNING

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ABSTRACT
Authors share their experience with 15-channel continuous Partial Discharge (PD) monitors applied to medium voltage rotating machines, apparatus and substation equipment, using variety of PD sensors. Real life examples illustrate the condition-based paradigm “measured-inspected-confirmed-repaired” that clearly purports this totally nonintrusive and effective on-line diagnostic technology. Use of stator RTDs as PD sensors offers an inexpensive solution for attenuation problems, especially in large rotating machines. Continuous monitoring assures that high variations of PD activity will not be overlooked in comparison with periodic tests. The discussed technology will help in making intelligent and accurate maintenance decisions, significantly improving effectiveness and quality of insulation repairs.

INTRODUCTION
On-line partial discharge measurements in industrial environments face three major technical challenges: high noise in low frequency range, signal attenuation in high frequency range and significant variation of PD activity over time. The measurement system operating within 1-20 MHz range with multiple PD sensors distributed throughout the object can get around PD attenuation problem while making it easier to localize the PD activity. The background noise is suppressed through microprocessor-based signal processing (filtering). The PD sensors include Coupling Capacitors (CC) and existing winding Resistance Temperature Detectors (RTD) for rotating machines. Coupling capacitors and Radio Frequency Current Transformers (RFCT) are used in switchgear. Continuous monitoring, compared to infrequent periodical testing, assures that variable PD activity is captured and its correlation to operating parameters such as temperature, humidity, load, and system voltage is established. Adding remote communication capability to the continuous monitoring system opens the possibility for Remote Monitoring (RM), featuring automatic alarms, remote data access/storage, and instant analysis by PD experts without bringing experts on site.

NOISE AND ATTENUATION ISSUES
Industrial noise typically originates from radio communication systems, thyristors’ commutation in exciters and rectifiers, digital metering systems and electronic transducers. Radio noise is typically found in 0.8-1.0 MHz range and can be avoided by signal acquisition in a higher frequency range. Thyristor firing noise commonly has pulse widths wider than PD pulses and can be rejected by microprocessor-based signal processing. Rejecting “digital noise” is most difficult. This problem is resolved by designing “noise immune” sensors. Coupling capacitors directly connected to HV conductors are not susceptible to low frequency noise and “digital noise” commonly does not exist in HV circuits. RTD sensors implement filters that eliminate noise pulses coming from associated metering electronics.

Selection of frequency range for signal acquisition is thus critically important. While noise is the challenge at the low end of the spectrum, high end of the frequency range imposes limitation in sensitivity of PD sensors (Figure 2).

Figure 2. Spectrum of response of 80 pF coupler to a PD pulse

It is evident that there is not much pulse energy in the spectrum above 30 MHz. PD pulses also experience attenuation while propagating from the place of origin to the location of a PD sensor. Attenuation is negligible in low frequencies below hundreds of kHz, the frequency range of standard off-line test equipment. For higher frequencies the attenuation is significant [1]. For instance, attenuation along one leg of a motor stator coil can be as much as 10 times depending on the stator design. In large machines PD signal originating deep in the winding nearly disappears by the time it reaches the PD sensor in the line termination.
area. According to [2], even specially designed PD sensors can detect PD in large turbo-generators only within approximately 1 meter vicinity. In reality the PD pulse propagation mechanism in rotating machines is much more complex as it includes not only the propagation along bars and coils, but also capacitive and inductive cross-coupling in the winding as well as direct radio wave radiation phenomenon [3, 4]. Figure 3 below shows two snapshots from RTDs and 80pF coupling capacitors on a hydro generator. The stator had two sets of capacitors along the ring bus and 12 RTDs evenly distributed along the stator [5]. One can see low or no response from CCs, but high magnitudes from RTD sensors and vice-versa.

![Figure 3](image)

**Figure 3.** Independent registration of two PD events by different sensors.

To summarize, the system with multiple PD sensors circumvents the signal attenuation problems while facilitating closer localization of PD activity. This can equal the difference between a partial winding repair as opposed to replacing or rebuilding of the whole insulation system.

**WHAT VALUES SHOULD WE MEASURE?**

Selection of the most representative PD quantity remains a hot subject of discussions among the whole PD community. Since PD measurements in high frequency ranges (ultra-wide-band instruments) were not addressed in PD standards [6], scientists had to develop their own unique approaches. The main challenge comes directly from the high attenuation of PD signals at high frequencies. This means that quantities are not absolute – but rather relative in nature. Another issue is that PD magnitude cannot be used as the only value to build an analysis on. The damaging effect of PD is proportional to the charge of a single discharge, as well as to discharge repetition rate and applied voltage. The best value to be used for PD analysis, in authors’ opinion, is Partial Discharge Intensity (PDI), or “partial discharge apparent power loss” defined in ASTM D1868 standard. PDI is still relative, but being directly proportional to the damaging effect of PD activity, it has a definite physical meaning and can be expressed in mW. Furthermore, this quantity also allows meaningful calibration of a PD measuring system, particularly of sensor sensitivity to a PD event and quantification of signal attenuation in an object. Comparing different PD measuring instruments in identical conditions would allow for correlation between LF and HF measurements thus increasing confidence in PD diagnostics as a whole.

**CONTINUOUS MONITORING VS PERIODICAL TESTING**

On-line PD diagnostics lends itself ideally to continuous monitoring. A simple example in Figure 4 shows how conclusions can differ when based on periodic PD test data as opposed to continuous monitoring data.

![Figure 4](image)

**Figure 4.**
- Low PD activity conclusion
- High PD activity conclusion
- Strong upward trend conclusion

The actual test data reveal strong seasonal variation of the PD activity when correlated to ambient temperature. Continuous monitoring also excludes human induced errors in the measurement process. Maintenance activity and operating conditions of an object are clearly reflected in continuous PD data trends revealing the entire history of equipment. This facilitates a very practical and effective approach to planned maintenance. This approach is demonstrated by the following case studies examples.

**CASE STUDIES**

**13.8 kV motor**

Data taken from the line-side sensors and the winding RTD sensors revealed step changes in PD levels. Additional sensors distributed along the winding provided further intelligence for more accurate location of PD activity. Following were the events correlated to step changes in captured PD data [7]:

1. Reversal of line and neutral ends of winding
2. HV connecting leads touching
3. Replacement of the stator winding (rewind)

![Figure 5](image)

**Figure 5.** PDI trend from “A” phase coupling capacitor

Experience has also shown that, more often than not, such PD pattern is mistakenly attributed to the winding. This
often results in unnecessary expensive maintenance of the winding or its replacement. In the following figure we can see the step changes in the PD activity caused by touching leads. The PD levels significantly dropped after the repair.

**Figure 6.** Change of PD magnitudes and PD intensity from sparking between A and C phase leads

Involvement of phases “A” & “C” is also clearly reflected in the phase-resolved PD distribution graphs:

**Figure 7.** Phase-resolved PD patterns before repair

**Figure 8.** Phase-resolved PD patterns after repair

It should be pointed out that this problem was not detected by RTD sensors embedded inside the winding. This is another convincing argument for multi-sensors approach that allowed an expert to quickly pinpoint the problem.

**Figure 9.** Signs of damage on insulation of winding leads

**13.8 kV air cooled generator**

**CO2 End-Winding Cleaning**

The following example shows the effect of the oil contamination on the end turns of a 13.8 kV generator winding. It was observed that PD intensity increased immediately after cleaning. In this case the oil and resulting contamination on the winding surface seem to have significantly abridged the PD activity. This observation agreed with our past experience with two identical 13.8 kV gas turbine generators where the stator contaminated with oil showed approximately 20 times less PD activity than the clean stator.

**Figure 10.** Change of PD activity detected by coupling capacitors after CO2 cleaning, side packing and re-wedging

**The effect of winding side packing and re-wedging**

This example shows the effect of yet another maintenance procedure as observed from RTD sensors embedded in the stator winding.

**Figure 11.** Step down change of PD activity from RTDs after CO2 cleaning, side packing and re-wedging

Both routine maintenance procedures produced rather contrasting results as seen by PD sensors in different locations. The step changes in PD levels are undeniable and fully explainable. The side packing and re-wedging of the winding within the slots closes the gaps and improves the contact of the coil semi-conductive layer with the ground thus reducing discharges between coils and core. The use of CO2 as a cleaning agent could create micro cracks in the insulation surface and create additional PD activity. One can conclude that multiple PD sensors are necessary to fully understand and quantify the effect of winding maintenance procedures on the PD activity.

**13 kV Switchgear, intermittent PD activity**

In this example, a continuous monitoring system detected an intermittent warning and alarm condition in a medium voltage switchgear line-up supplied from a transformer, through an outdoor bus duct. General trending has shown seasonal variation of PD activity in incoming bus section.

**Figure 12.** Bus section “B” & “C” phases PD activity
More detailed analysis revealed that PD spikes occurred on a regular basis at around noon. Phase-resolved patterns were consistent with phase-to-ground and phase-to-phase discharges associated with the incoming bus section. In this example continuous monitoring helped to capture intermittent PD activity otherwise easily missed by periodic testing. Multiple distributed PD sensors helped to narrow the search to the incoming bus area. Discovery of water ingress in an outdoor part of the bus completed the picture. Mid-day sun heated the bus duct enclosure creating vapor resulting in sharp increase of PD activity. PD completely disappeared after repair.

Figure 13. Signs of tracking in outdoor bus support system

REMOTE MONITORING

Remote Monitoring (RM) adds a great value to continuous monitoring by relieving customers of the burden of data analysis, readily involving remote experts. Such systems continually supervise the local PD monitors for adverse conditions and automatically send alerts and notifications to plant personnel or directly to the PD support engineers. The authors have many years of experience with older dial-up modem based systems. While such systems are relatively cost effective and reliable, modern Ethernet-based systems offer not only more speed and security but also unparalleled data transmission rates.

Figure 14. Basic Remote Monitoring Scheme

However, since such Ethernet-based systems commonly share the user’s local area networks, security is of paramount importance. Use of Virtual Private Networks (VPN) and Virtual Local Area Networks (VLAN) offer safe and secure connections acceptable to most IT professionals today. Automated remote monitoring systems can identify alarm conditions, download data, notify necessary personnel and initiate analysis. Such systems should be of robust and scalable design and always include self monitoring provision (heart beat). Periodic reports of different levels can be conveniently included into a service contract eliminating additional expense of bringing an expert to the site.

CONCLUSION

Continuous PD monitoring using multiple sensors is an indispensable tool for assessment of insulation conditions in MV and HV equipment. This technology can be easily applied to rotating machines, switchgear and dry type transformers. Such systems make it possible to capture and ultimately correlate the changes in PD levels to specific operating conditions as well as repair activities. The level of understanding we get from continuous monitoring is impossible to match using periodic measurements. Continuous PD measurements assist equipment owners and operators in making informed decisions about effectiveness of maintenance procedures performed on their assets by simple “measured-inspected-confirmed-repaired” steps. Furthermore, remote monitoring adds significant value to asset management by providing accurate and instant feedback on assets performance. The collected data can also be very helpful to designers, manufacturers and repair shops to improve their service quality and reliability. Finally, the collected data will aid in filling the remaining gaps in understanding the physics of partial discharge and its impact on insulation life expectancy.

REFERENCES