IRIS POWER
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Technical Note

Can One PD Detector Be Effective in Assessing Insulation Condition on All Types of Apparatus?

There are many dozens of manufacturers of partial discharge (PD) measuring systems in the world. Almost all of them make just one general purpose PD portable instrument (and perhaps one continuous PD monitor) that the vendor claims can be used with one or more types of PD sensors on all types of medium and high voltage apparatus. To many endusers it seems logical that a single general purpose PD instrument can be used to measure PD in all types of high voltage (HV) apparatus such as power cables, transformers, switchgear and rotating machines. PD, after all, creates essentially the same current pulse no matter what type of HV equipment is being measured. However, as discussed below, such general purpose PD systems need to be very flexible, requiring lots of adjustments and "tweaking", which means a PD specialist with extensive experience is needed to produce reliable and meaningful results. Alternatively, a vendor of a "general purpose" PD system may in fact have optimized their instrument for a particular group of applications, and not been clear about this. This implies it is not optimized for other applications. As an analogy, all radio receivers are detecting broadcast radio signals, and thus it makes sense that one radio should be good for all applications. However, we all know this is not the case since there are different types of broadcast signals (AM, FM, digital), different frequency ranges, and radios for different environments, e.g. for use at home as opposed to a radio in a car or on a hike. Radio manufacturers thus make a wide range of radios that are optimized for different applications and uses, or they make a single radio that requires lots of knobs and switches and thus frequent reference to the instruction manual, to make them work properly. The same is true for PD detectors.

This Technical Note will illustrate the different ways PD detectors can be optimized. These include:

- Frequency range
- Sensor and instrument frequency range matching
- Noise environment
- Physical structure of the test object (type of electrical apparatus)
- Organic vs inorganic insulation (i.e. is PD a cause of failure, or just a symptom)
- Ease of use

Since much of the above is discussed in IEC and IEEE standards, a review of relevant PD standards is first presented.

We conclude by observing that if a PD detector can be used for all applications and apparatus, it will be optimized for none. Thus there is a risk the measurement results, and more importantly the diagnosis, will be wrong.

PD Standards

The most common standard referred to for PD measurement is IEC 60270, which is similar to ASTM D1868. IEC 60270 presents the test circuits for measuring PD, and describes the process for calibrating the detected mV magnitude of the PD pulse into apparent picoCoulombs (pC). PicoCoulombs, a unit of charge, is traditionally used for PD measurements since the damage to **organic** insulation by the discharge will be related to the number of electrons in the discharge, i.e. the charge. IEC 60270 normally assumes that a capacitor detects the PD, and that the test object is also predominantly capacitive, which is not true for transformer or rotating machine windings. IEC 60270 also requires the measurement frequency be in the range from about 50 kHz to 1 MHz. PD detection above 1 MHz is not covered by this standard.

In 2016, IEC 62478 was published. It is a complementary document to IEC 60270, and it covers the frequency range above the 60270 range. In particular, it defines the following ranges:

- Low frequency, LF -below 3 MHz (i.e. approximately the frequency range in IEC 60270)
- High frequency, HF – 3 to 30 MHz
- Very high frequency, VHF – 30 to 300 MHz
- Ultra high frequency, UHF – 300 to 3000 MHz.

In addition to detection of the PD by capacitors, this new document indicates the PD can be measured by radio/high frequency current transformers (RFCTs/HFCTs) and different types of UHF antennae. Clause 4.3.6 of IEC 62478 makes clear that above the LF range, a direct calibration into pC is not feasible. IEC 62478 identifies several practical schemes for measuring PD above the LF range on switchgear, transformers and stator windings.

There are also standards for each specific type of high voltage apparatus. IEEE 1434, IEC 60034-27-1 and IEC 60034-27-2 describe off-line and on-line PD test methods for stator windings in motors, generators and synchronous condensers. PD test standards for other equipment include:

- IEEE C57.113 for oil-filled transformers
- IEEE C57.124 for dry type transformers
- IEEE 400.3 for power cables
- IEEE C 37.310 for switchgear.

Many other standards are under development.

Frequency Range

It is clear from the standards that PD can be measured electrically from 10 kHz to over 1 GHz. Virtually all PD measurements were made in the LF range until the mid-1980s, when better oscilloscopes, A/D converters and electronics in general were commercially available for the higher frequency ranges. The advantage of measuring in the LF range is that electronics is inexpensive and one can calibrate from mV into units of charge (coulombs) for capacitive test objects, using IEC 60270. The LF range is suitable for almost all factory tests, and off-line tests at the plant, substation, etc.

For on-line PD testing, the VHF and UHF frequency ranges are by far the most common for condition monitoring of oil-filled power transformers, gas-insulated switchgear (GIS) and rotating machines. The reason for this is the greatly reduced likelihood of false indications caused by electrical noise and disturbances, for example from overhead transmission line and busbar corona, power electronics (including variable speed drives) and relatively harmless poor electrical connection sparking (especially grounding). As described in detail in IEC 62478, there is inherently a higher PD signal-to-noise ratio in the VHF and UHF ranges. Also, several different proven methods of separating noise from PD (such as time-of-pulse-propagation and pulse shape analysis) can only be implemented in the VHF and UHF frequency ranges. If an on-line PD measurement is performed in the LF or HF range, it is not possible to employ the proven techniques of pulse travel time and pulse shape discrimination methods, since the electronics cannot detect nanosecond differences in time of arrival or pulse risetime. Thus, as discussed in IEC 62478, a PD expert must examine LF and HF signals obtained with general purpose PD systems to distinguish HV apparatus PD from noise, even if using AI tools.

Mismatch of Sensor and instrumentation Frequency Range

A PD sensor must be connected to an electronic instrument to make sense of the signals. Of course, the most basic instruments are general purpose oscilloscopes or frequency spectrum analyzers. Nowadays specially designed instruments are used to measure the signals from the PD sensors. Most PD instruments have a specified frequency range, usually in one of the IEC frequency ranges above. In addition, most PD sensors have a specified frequency range. The frequency ranges of the sensor and instrument should at least overlap. If they do not overlap, then there will be a loss of PD sensitivity. For example, the most common PD sensor for on-line PD measurement in motors and generators is an 80 pF capacitor. To prevent impedance mismatches, the capacitor is connected to a 50-ohm coaxial cable and 50-ohm load. Thus the system of PD sensor and VHF instrument is a high pass filter with a lower cutoff frequency of 40 MHz, and works in the VHF range. If this sensor is connected to a LF instrument that is insensitive to PD above 3 MHz, the mismatch in operating frequencies between the sensor and the instrument will greatly reduce the magnitude of the detected PD. In this example, the PD signal will be reduced by at least 10 times (20 dB per decade of frequency), reducing the signal-to-noise ratio, and increasing the risk of false negative indications in on-line measurements. Similarly, a UHF PD antenna will not produce sensible PD signals if it is connected to a LF detector – the mismatch in frequency ranges will produce no output.

Conversely, a 1 nF PD sensor tends to have poor response at VHF and UHF frequencies due to its internal inductance, and thus would detect a smaller magnitude PD signal if connected to a VHF detector. Again, this may cause false negative indications (the user would think the HV equipment is good, when it may be failing).

Noise Environment

PD tests are performed in different noise environments, and thus the noise can affect the reliability of the measurement. Off-line PD testing in a factory can often be done in an electromagnetically shielded room and with a filtered power supply, thus noise is usually not an issue. Alternatively, the factory tests can be performed at night or on the weekend, when the rest of the manufacturing facility (and thus the noise sources) are shut down. Off-line tests done in plants and substations usually use a PD free power supply that is heavily filtered to suppress conducted noise from the ac supply. However, there may still be some radiated noise detected by the PD system, that may require expert analysis if the test is done in the LF range.

The challenge of noise obscuring test object PD is most severe with on-line testing, since the stator winding, power cable, transformer, etc. are directly connected to the power system which has many possible pulse-like noise sources, including corona on overhead transmission lines – which do not affect equipment life. The noise environment of a power plant is different from that of a transmission-class substation. Even in a power plant, a hydrogenerator plant tends to have much less severe noise than a gas turbine plant or nuclear plant (which have many auxiliary systems that can produce PD-like noise). On the other hand, some types of HV apparatus are inherently good at excluding external noise – for example the grounded outer tube in GIS is a natural Faraday shield.

Thus most vendors of on-line PD equipment tend to optimize the frequency range and noise separation methods for a particular type of HV apparatus and its noise environment. This is why most on-line PD systems for GIS and power transformers work in the UHF range, to take advantage of the Faraday shield of the enclosures to suppress high levels of external noise, and yet be sensitive to the relatively low levels of PD that may indicate pending failure (see below). The Qualitrol/Iris Power systems for measuring on-line PD in rotating machines work in the VHF range (with slightly different noise separation methods optimized for hydrogenerators, turbo generators and motors) and the UHF range for hydrogen-cooled machines (where the PD magnitudes are much smaller), to take advantage of the Faraday cage structure of the machine enclosure for enhanced PD signal-to-noise ratio. The Iris Power technology is not suitable for liquid-filled power transformers, power cables or GIS.

Physical Structure of the Test Object

Test objects like power transformers, power cables and GIS have the three phases either physically separate from one another, or have a Faraday shield (e.g. the shield in a power cable) that prevents interaction between the phases, and in particular, prevents phase-to-phase PD. Other equipment, such as stator windings and medium voltage air-insulated switchgear, have the three phases in close proximity to one-another. This permits phase-to-phase PD (if coils in different phases are too close, as may be the case in stator windings), and enhances cross-coupling of high frequency pulses between the three phases.

PD equipment and associated diagnostic software that were designed primarily, for example, for power transformer applications, would not expect phase-to-phase PD to occur if they are simultaneously detecting signals from all three phases. Thus they may misidentify any such signals as noise (to be ignored) if applied to stator windings or medium voltage switchgear. PD systems optimized for machine windings or medium voltage switchgear would not classify phase-to-phase PD (which can lead to a catastrophic failure) as noise.

Organic vs Inorganic Insulation

Most high voltage apparatus only uses organic insulation. For example, cables are insulated with polyethylene or rubber, power transformers with paper and oil, and GIS with epoxy insulators. PD impinging on purely organic insulation will rapidly age the insulation by either electric treeing or electric tracking. If PD is occurring in service, the PD will usually cause equipment failure in days or a few months. Thus manufacturers of equipment using organic insulation must do factory PD tests to ensure that PD will not occur in service. And in-service PD monitoring is best done continuously, otherwise the PD may start and cause failure between tests.

Rotating machines use a mixture of (organic) epoxy and (inorganic) mica tapes. Virtually all stator windings rated 3 kV and above have PD during service – and because mica is very resistant to PD – failure does not occur due to normal levels of PD, even after decades of years.

Many vendors of PD equipment who have optimized their system for organic-insulated equipment tend to raise alarms (especially with continuous monitors) if almost any PD is detected, since experience tells them all PD is bad. Thus many unnecessary outages have occurred when those same vendors apply their same interpretation system to stator windings, and they detect PD. In contrast, PD measurement systems optimized for stator windings know that PD is really just a symptom that aging is occurring, and maintenance can normally be delayed for years.

Ease of Use

Some of the above factors can affect how easy it is to use PD instrumentation and its associated software. There are basically two different types of PD users: specialists who are doing PD testing almost every week, and who have the time and eventually the experience to become proficient in the use of a particular brand of PD instrument and its associated software. The specialists tend to work for the PD equipment vendor, very large HV equipment manufacturers or PD test service providers. The other type of user typically works for an enduser (generation utility, grid company, petrochemical company, etc.), or a diversified test service provider, where PD testing is a small part of their job, and may be only done a few times per year. Such users will not have an opportunity to learn all the features of the instrument and associated software they own, and thus false indications are more likely.

Most general purpose PD instruments (almost all of which work in the LF or HF range) require detection frequencies to be adjusted before every test to minimize noise. Hence the measurement bandwidth may not be identical for all tests and the results may not be comparable. In addition, for on-line PD testing, post-processing software (often advertised as artificial intelligence pattern recognition or clustering methods) is always required since the inherent noise separation methods available with VHF and UHF detection are not possible. The selection of frequency and the use of post processing software tools to suppress noise adds a lot of complexity to the instrument and its software, and more importantly, subjective decisions. For example, the use of “maps” needs a lot of skills to find clusters associated with different phase resolved PD (PRPD) patterns, and to date only human experts have been proficient at this. Thus, although a general purpose PD system can be effective, it requires specialists who are very experienced with the system and very well versed with data interpretation. This is why many vendors of general purpose PD systems indicate that the endusers should use the vendors’ experts for PD analysis, especially with on-line PD measurement. Because such expertise is rare – it is usually expensive when compared to endusers’ performing and interpreting their own tests.

The alternative is a specialized PD system that is optimized for a particular type of test (off-line vs on-line, periodic vs continuous) and test object (transformer, GIS, etc.). In such specialized PD detectors, the measurement frequency and noise separation methods are preset, and cannot be changed. Although this reduces flexibility, it makes the PD system easy to use. A specialized PD system test can be performed and interpreted by normal electrical technicians and engineers with just a few days' training. Since no adjustments and fine tuning is required, most endusers can reliably collect and interpret basic data even if they use the device only a few times per year.

Thus fundamentally, general purpose PD systems can only be reliably used by PD specialists. The specialized systems can normally be used by non-specialists, that is, people working for the utility or industrial plant.

Comparison Between General Purpose and Specialized PD Systems for Motor and Generator Application

Issue	General Purpose	Specialized
Frequency	requires filter frequency selection that can be variable over time due to changing noise conditions	preset, no adjustment needed over time even if noise environment changes
Noise	high risk of false indications	automatic unsupervised suppression; statistical false positive indication rate 1.5%
Sensor/Instrument compatibility	flexible	only sensors designed for instrument can be used for best results and fully utilizing the advantages of the system in noise reduction and disturbance separation
Type of test object	applied to all test objects, may misidentify certain types of PD as noise (higher false negative rate)	designed for limited range of test objects to ensure low false indication rate
Ease of Use	requires considerable experience and frequent use	easy even for non-specialist after a few days of training

Conclusions

A single test instrument can connect to any PD sensor and at least some useful signals may be measured. However, the risk of false indications due to a mismatch between the sensor and instrument frequency range, the risk of higher false indications due to sub-optimal noise suppression, identification of the aging mechanisms that caused the PD, and determining if the insulation should be repaired immediately or many years from now, will all be adversely affected if the PD sensors, instrumentation and automated interpretation system are not optimized for the type of test (off or on-line, continuous or periodic) and the type of high voltage apparatus.

Qualitrol group makes a wide line of PD systems. For general purpose PD testing it makes the PDTech line of off-line and on-line PD systems working in the LF range (IEC 60270 compliant). These generally are used by PD specialists. Qualitrol also makes on-line PD systems that are optimized for rotating machines (the Iris Power line, that is further optimized for turbo generators, hydro generators, synchronous condensers and motors) and the DMS line of PD systems for GIS and power transformers. The Iris Power PD system will produce a high rate of false indications if used on liquid-filled power transformers, and the DMS PD system for GIS will produce a high rate of false indications if applied to a generator. By having PD systems that are optimized for the type of high voltage equipment, testing and interpretation can be performed and interpreted by non-specialists.