On-Line Partial Discharge Applications to MV Electrical Switchgear

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Abstract: Industry has been exposed to partial discharge technology, related to generators, for many years. A switchgear manufacturer has invested in the advancement of partial discharge technologies related to the on-line analysis of insulation systems for MV switchgear. Partial discharge testing has been completed on both new MV switchgear in the factory setting, as well as several older field installations. The results clearly indicate that partial discharge analysis of MV switchgear is an excellent on-line predictive maintenance tool. It has also been found that older MV switchgear designs are prone to internal corona activity. The majority of existing plants contain MV switchgear of a very old design, therefore the use of on-line PD analysis can identify areas of immediate concern. This paper shall review the applications to MV switchgear. Actual examples of pending failures, which were identified by on-line partial discharge measurements, will be presented. This new application of partial discharge technology can greatly aid in the day-to-day reliability and life-extension of MV electrical equipment.

CONDITION ASSESSMENT

Condition assessment and condition-based-maintenance are both concepts used in the application of new technologies to address equipment diagnostics while a plant is in full operation. The benefits result in the elimination of many time-based maintenance tasks, in exchange for maintenance tasks deemed necessary due to the actual condition of the equipment. This condition is monitored during normal operation, therefore allowing for planned-outages to implement specific corrective action [1].

With conventional off-line diagnostics, the condition of the equipment is not determined until an outage is underway. This traditional approach results in additional downtime and the lack of readiness to address some of the problems identified. In addition, during scheduled outages, there is usually a shortage of personnel for all of the planned activities, therefore shifting the diagnostics and testing of equipment to before the outage, allows for improved utilization of the limited source of personnel. On-line condition assessment also allows for the postponement of scheduled work on specific equipment and the resulting increase in production, or redirection of limited resources. Another identified benefit is personnel safety since the diagnostics are performed with isolation from energized circuits and this on-line diagnostics minimizes the use of test equipment to inject higher voltages to simulate actual operating conditions.

Failure Contributing Causes

A review was completed of published contributing causes for failures related to MV switchgear: bus and circuit breakers. This documented failure data is the result of end-user surveys conducted in the preparation of IEEE Standard 493-1997, IEEE Recommended Practice for Design of Reliable Industrial and Commercial Power Systems – Gold Book, 1998 [2]. This IEEE standard provides detailed data related to the reliability of many electrical components and contains Appendixes with additional details on specific electrical equipment. These Appendixes provide the specific causes, which were identified as contributing to the failure of the equipment. Appendix E presents this data for switchgear bus and Appendix K presents this data for circuit breakers. Medium voltage switchgear consists primarily of switchgear bus and circuit breakers, therefore by combining the data from these two areas, an approach was developed to present the overall contributing failure causes with their relative ranking of importance.

The IEEE documented failure contributing causes did not identify any specific initiating cause of the failures. These initiating causes were determined based on over twenty years of field experience with medium voltage switchgear systems. This allowed for the identification of appropriate on-line diagnostic technologies, which would provide a predictive indicator for each specific initiating cause.

The three (3) predictive indicators, in order of importance, were identified as:

a) Partial Discharge Diagnostics: 22.4%
b) Visual Inspections (Switchgear Enclosure and Surrounding Area): 18.1%
c) Thermographic Inspections: 12.0%

This paper addresses the newly developed application of on-line partial discharge diagnostics to MV switchgear. Also note that during the on-line partial discharge measurements, a detailed “Visual Inspection” report could also address the additional 18% of contributing failure causes related to the switchgear enclosure and surrounding area. This would result in approximately 40% of the contributing failure causes being addressed in an efficient and safe manner. The on-line partial
discharge diagnostics can be completed with all switchgear doors closed and secure, after the installation of internal PD sensors. The internal PD sensors do require an outage for installation, whereas the time required per cubicle is minimal. This maintains safety of personnel since opening of the enclosures of the energized equipment is NOT required.

PARTIAL DISCHARGE OR CORONA

Partial discharge frequently called "corona" is an important root cause of insulation deterioration. If left undetected and unattended, it will eventually cause a partially conductive path between the medium voltage and ground and/or between phases and weakens insulation.

At this point of time, the insulation is awaiting any additional stress by lightning strike, moisture or another contamination with the resultant “full discharge” across an insulation and consequent insulation breakdown. Full discharge starts as a spark between electrodes heats up the air making it a conductive media, which finally becomes an arc drawing high current until an upstream protective device interrupts the fault.

Partial discharge is small spark type discharge that occurs within an insulation (commonly across gas filled voids) or on an insulation surface at the interface with air or another gas. Partial discharge partially bridges an insulation system causing gradual insulation deterioration.

According to Paschen’s Law a breakdown voltage of about 300 volts is required in air under atmospheric pressure to create a spark [3]. For medium voltage systems, 4160 volts and above, this voltage of 300 volts can be generated across voids in the insulation system, therefore resulting in partial discharge activity. On the contrary, for 480-volt systems, we can not develop the required 300 volts across a void within the insulation, therefore we do not observe corona damage, or surface tracking on these low voltage systems.

Partial Discharge Detection

A partial discharge spark produces several physical phenomena. These phenomena includes electromagnetic pulse in an electrical circuit, electromagnetic wave radiation, acoustic shock wave emission, light emission, and induced plasmo-chemical reactions involving gas and insulation materials. Almost all of the above phenomena are used for PD detection and some of them might have an advantage in a particular application.

Electrical partial discharge detection (measurements of an electromagnetic pulse induced by PD in associated electrical circuit) is used in off-line and on-line PD diagnostics. Partial discharge is commonly an extremely fast event. Spark discharge under atmospheric pressure is formed within the nano-second time range, therefore producing high range of frequencies extending up to the Giga-Hertz range. Therefore, one can use any frequency band for PD detection.

Attenuation of the partial discharge signals occurs more rapidly for the higher frequency components. At the lower frequency range we have a large amount of various industrial interference sources such as thyristor operation, sparking and arcing, operation of broadcasting stations and so on. A choice of the proper frequency band is an attempt to balance between good PD measuring circuit sensitivity and better immunity against various sources of noise.

Our experience indicates that the range from 1MHz to 20MHz is most appropriate to detect the majority of partial discharge activity within switchgear. This is above the lower frequency range that contain most of the industrial interference and is below the high frequency range which can only detect the source of PD within close proximity to the PD sensor. A consistent range of 1MHz to 20MHz is also a very important factor to support the accurate analysis of the results of partial discharge measurements. By selecting a range that includes the majority of measurable PD activity, we can develop guidelines based on experience and databases of measured PD for equipment with various states of insulation condition.

Another important subject in PD measurements is calibration. Any partial discharge sensor produces “millivolts” output associated with a PD event. The millivolts should be converted into an apparent charge, measured in nano- or pico-coulombs. The use of a consistent frequency range for PD measurement allows for the application of calibration results (millivolts to nano-coulombs) to be applied to similar types of MV equipment. This further supports the accurate interpretation of the measured results to the condition of the insulation system.

Partial Discharge Sensing

Electrical partial discharge diagnostics uses, in general, two types of sensing. The first is to measure a voltage pulse (usually small voltage drop between MV conductor and ground caused by a single discharge) or high frequency current induced by PD in an electrical PD measuring circuit. All other PD sensing methods are a combination of the two above even, if it is not obvious.

Specially designed HV coupling capacitor is commonly used for voltage pulse measurements. Some constructive elements
having a low level of stray capacitance to a high voltage conductor can also function as coupling capacitors. As an example, a metering or relaying current transformer having capacitance of several tens of pico-Farads to a bus or the secondary winding of a potential transformer can be used as a coupling capacitor. Current sensing regarding switchgear applications can also be utilized by the placement of a radio-frequency current transformer (RFCT) on a feeder shield grounding conductor or around MV conductor.

The main challenge during on-line PD measurements is obtaining good PD readings at noisy conditions commonly accompanying normal equipment operation. A list of noise sources, but not limited to, are thyristor operation, radio-communication, switching power supplies, arcing and sparking at distant equipment, and digital communication. A choice of the right sensor configuration is 50% of the success. The choice of the PD sensor and the location of the sensor are commonly a balance between frequently contradicting requirements, such as:

- Good signal to noise ratio;
- Safety and reliability;
- Minimal invasion into an equipment design (best if no invasion);
- Competitive cost and simplicity of installation;
- Good coverage for the entire gear. Verify that none of the PD are left undetected;
- Ability for field installation without equipment shut down.

The list can be continued, but no currently available PD sensors can meet all requirements at the same time.

We divide MV switchgear for permanent sensor installation into two major groups:

- Non-noisy installations. Commonly older installations with minimum of modern metering electronics;
- Extremely noisy Installations. With modern electronics and digital communications.

In the first case, noninvasive and non-expensive PD sensors, even allowing installation without an equipment shut down, can be used. (More information can be found in [4].) In the second case, coupling capacitors (commonly 80pF) is the best solution. These sensors should be directly connected to the bus during a scheduled outage.

The first option of sensor set is shown in Figure 1. It includes RFVS (voltage sensor) connected to C0 terminal of a metering current transformer and RFCT sensor installed on a cable shield grounding conductor. Both signals are brought to a front mounted connection box installed at the door of a front compartment. Therefore, sensor outputs are accessible without opening the door.

The second option is commonly more expensive and requires an outage. Figure 2 presents IPDS (Integrated Partial Discharge Sensors) units connected to a bus. The specially designed sensors are PD free at a test voltage of 35kV and designed and tested for 95kV BIL. They were designed within specifications of existing standard 15kV standoff insulators and can easily replace existing insulators.

Another option is an initial survey and evaluation with temporary sensors. Temporary sensors are available, which are similar to those applied in non-noisy switchgear applications. The set includes RFVS sensor with alligator clips and they are mounted on a magnetic base. Another sensor is a clamp-on RFCT on an insulated handle with remote control of the RFCT opening.

Electromagnetic pulse induced by PD in a switchgear line up has a tendency to attenuate while travelling along the switchgear. There are two main root causes for such a behavior. The first is that any high frequency signal loosen
higher frequency components faster than lower frequency therefore decreasing the magnitude of its peak.

Another reason is that switchgear line ups have multiple T-connections with feeders serving various equipment. At each T-connection, we expect PD pulse energy to split in two directions. One portion of the pulse continues to travel along the gear and another portion goes into a feeder.

These two effects cause pulse magnitude to gradually decrease. This can be observed by measuring the PD signal at cubicles, which are distant from the source cubicles. The attenuation of PD signal along the line up was found to be ~0.5-0.7 per cubicle. Figure 3 shows measured on-line signal attenuation with the cubicle #08 as the PD source.

Signal attenuation creates two important consequences:
- Cubicles having partial discharges can be, in most cases, identified based on the signal magnitude distribution along a line up;
- The entire switchgear line up can not be assessed for partial discharges with sensors installed in one or a few locations.

As a rule, we install sensors in every cubicle and on some occasions in every second cubicle.

Figure 3

Partial Discharge Analysis

The main goal of plant operation is to keep equipment in service as long as possible without catastrophic failure at the minimum maintenance cost. Of course, many factors should be taken into account: safety, equipment criticality, available budget, maintenance strategy and so on, but a benefit is that insulation degradation in MV switchgear is usually a very slow process. Energy dissipation associated with a single PD event in MV equipment is measured in micro-Joules and it can take years for PD to cause a failure. Therefore, for most installations, you can plan your maintenance and/or repairs during scheduled outages, following the measurement and analysis of PD activity. (At higher voltage the energy associated with PD is higher and a fault might come much sooner.)

Many countries require the manufacturer to perform PD testing on fully assembled equipment as a final quality test. As an example, since the early 1970’s the Canadian Standards Association (CSA) has required Canadian manufacturers to perform standard production Corona partial discharge tests, on all medium voltage switchgear above 13.8 kV. The primary reason for introducing this testing was to ensure that the manufacturer of the equipment had evaluated their design from the standpoint of being Corona partial discharge free. It also confirmed that the medium voltage components were not defective and the insulation system was assembled correctly when it left the factory.

Because the standards associations and manufacturers in the USA have not adapted the requirement for Corona Partial Discharge Free equipment, it may be difficult to evaluate the causes for high initial PD measurements on existing US switchgear. For example, if the corona partial discharge readings are high, are they due to defective components, insulation deterioration or the design of the equipment? It would be to the advantage of the end user to review the designs of new MV equipment, which is planned for purchase, to verify a corona-free design, or to establish the requirement for a pre-shipment PD test of the outgoing MV equipment.

A manufacturer test is commonly based on measurements of one PD parameter: maximum apparent charge. The threshold for this pass/fail test can differ from manufacturer to manufacturer and from country to country, but 100pC is a good average number to specify.

The manufacturer test is performed in very good environmental conditions without any insulation contamination. In real-life field conditions, switchgear experiences a different environment. Humidity is high and air is saturated with conductive and chemically aggressive media. In several years of equipment operation, one might find on initially PD-free gear, a much higher discharge level than would have been accepted by a manufacturing standard. What parameters are important for on-line PD tests and, actually, what actions are recommended, if the results significantly exceed manufacturer’ criteria? The answer is complex, but sound recommendations are available based on proper analysis techniques.

Maximum PD magnitude is not a sufficient PD parameter for reliable insulation condition assessment. Several PD parameters should be considered during on-line tests:
- Maximum PD magnitude;
• PD pulse repetition rate;
• Partial discharge intensity or power;
• PD parameters rate of change or trend;
• PD behavior vs. voltage, humidity and temperature;
• PD pattern or fingerprint analysis.

Maximum PD magnitude
This parameter reflects a maximum PD pulse measured in pC (some times in mV) observed during a test with some stable repetition, commonly, 0.1-0.2ppc (pulses per 60(50) Hz cycle). The parameter can cause confusion, if used alone without knowledge on the PD type (fingerprint analysis) and pulse repetition rate. Frequently PD sparking caused by a conductor under floating potential (for example, shield lost proper connection to MV bus such as a damaged corona-ring) has very high pulse magnitude. This type of sparking occurs between two conductors and does not destroy, as a rule, an insulation but rather indicates some mechanical problems.

PD pulse repetition rate
Describes the number of PD pulses associated with the particular PD location. High pulse repetition rate might indicate severe problems even, if pulse magnitude is low and even below 100pC stated by manufacturers. High repetition rate commonly indicates that a significant area is subjected to partial discharge activity and can be associated with PD defect existing in insulation for a long time period.

Partial discharge intensity or power
An integral number combining both magnitude and repetition rate. This is commonly a good PD level indicator.

PD trend
The PD trend allows for predicting defect development rate and planning correction actions. Frequently one can see relatively small intensity discharge starting, but then growing rapidly while a high intensity discharge may remain stable for years. The first one is a reason for a repair during a short-term scheduled outage, but the second one could wait until a convenient time.

PD defect intensity depends significantly upon voltage, temperature and especially upon humidity. Many PD defects in MV switchgear are on the surface and caused by surface contamination. Humidity changes significantly surface conductivity and consequently electric field distribution along a surface. PDs can be fully suppressed by low humidity and start again, when humidity gets high. An example of a two-month continuous monitoring is shown on Figure 4. PD jumps up with high humidity.

PD fingerprint analysis
PD fingerprint is a three-dimensional phase-resolved pulse height PD distribution. It represents PD pulse repetition rate vs. pulse magnitude and 60(50) Hz phase. PDs of different types or occurring on different phases have different fingerprints. A fingerprint analysis allows the identification of PD type, distinguishes non-dangerous PDs from dangerous ones and a phase of PD occurrence.

Single test, Periodic tests or Continuous monitoring
Partial discharges can go up and down over time with voltage or temperature. Even, on some occasions, discharges on a surface can completely disappear for some time reacting to humidity change as it was shown in the extreme example presented in the above paragraph, and illustrated in Figure 4.

Each approach has its own value depending upon the current needs. We have had a very positive experience with a single test of all switchgear line-ups within a facility before a major three-year scheduled outage. Many PD locations were identified and correspondingly addressed. Were some PD locations missed? It is possible, but the customer had prioritized their limited manpower to the most critical needs. It is also highly recommended to perform a follow-up on-line PD test after the repair has been made. This verifies that the proper defect has been corrected and that another PD site does not also exist. A high PD measurement can be from more than one source, whereas usually one area can be identified by a thorough visual inspection.

Common practice of periodical PD measurements assumes 2-4 measurements per year, depending upon operating conditions and severity of discharges found. After three or
four tests most PD locations should be identified and a trend established, therefore greatly eliminating the possibility of missed PD defects. We have over two thousand cubicles in our database and most of them are tested on a periodical basis. This cycle of on-line PD measurements has proven effective in improving plant uptime.

The third method is continuous monitoring. New electronics, competitively priced and with remote communications and off-site analysis capabilities are becoming available. A continuous monitor does require an initial investment, but a substantial savings results from the elimination of periodic measurements by trained and qualified field personnel. The end-user can call an expert only in the case of real emergency and the majority of problems can be resolved by phone or e-mail, especially with the ability to download complete PD patterns via a standard modem/phone connection. A simple modem/phone connection also minimizes the need to interface with secure plant LAN systems.

The advent of the new continuous partial discharge monitor will represent a quantum step in the application of this predictive technology. For example, with current protective relays a “trip” of the protective device will follow the permanent damage of the electrical apparatus. This includes ground-fault relays, whereas ground-fault relays will limit the amount of destructive damage after the initial fault. This applies to cases such as when a MV motor bearing-seal begins to fail and lubricating oil is sprayed onto the winding insulation, therefore attracting conductive contaminants and desolving insulation compound; or a leak occurs in MV switchgear allowing moisture to slowly bridge the MV conductors to ground. In the application of a partial discharge continuous monitor, the increase in partial discharge activity can signal an alarm. The immediate investigation of the equipment will reveal the oil-coated MV machine winding, or wet MV switchgear bus, but should provide the alarm prior to the actual permanent damage and failure. This will allow for a clean-up of the insulation, repair of the defective oil-seal or switchgear leak and return to service. This is a quantum leap in improved reliability and uptime, versus existing conventional protective relays.

**ON-LINE PD MEASUREMENTS**

The description below will mainly focus on history of a 15kV class switchgear line up, which had been installed over 30 years ago in a steel mill. The line up operates in a very contaminated environment due to conductive dust conditions and continuous operation with only eight hours a month dedicated to outages. The gear has had several failures in the past. Due to production requirements, there is not an opportunity for a major outage allowing re-insulating the entire bus.

This line up has been monitored for partial discharges on a periodical basis since 1997. A continuous PD monitor was installed in the switchgear in 2001.

The line up has numerous partial discharges occurring in over 50% of cubicles. In 1998 a rapid partial discharges increase was observed in one of cubicles. Maximum pulse magnitude was slightly above 100pC with high pulse repetition rate. The subsequent visual inspection and repair revealed significant bus sleeve deterioration on the phase, which was detected and identified on-line by partial discharge phase-resolved distribution. The picture of degraded bus insulation is presented in Figure 5. The bus was reinsulated during a planned outage and put back into service.

![Figure 5](image)

In June, 2000 cubicle #1 showed a rapid increase in PD activity. Actually it had jumped from little or no PD to a relatively high level. Similar to the first case, the maximum PD magnitude was low at approximately 60-80 pC. Pulse repetition rate was very high approaching 200 ppc. Following the measurements, a very strong ozone odor was identified in this cubicle. The cubicle was visually inspected in a few days. Current transformer on the phase C showed obvious PD signs, as illustrated in Figure 6.

![Figure 6](image)
A repair was initiated to the CT with the obvious PD damage, but the inability of an immediate follow-up PD measurement resulted in a second PD source going undetected in this same cubicle. This is another case of the benefits of a continuous PD monitor, since after the repair, the continuous monitor would have indicated continuing high PD activity; and therefore provided a warning of the second PD site.

This cubicle experienced an internal fault due to the second PD site during a thunderstorm in February, 2001. The second PD site, and the probable source of the failure was corona damage which was not visible around a PT cable, or involving a second CT. Again, a continuous monitor would have identified the existence of this second PD site, following the initial repair of the obvious corona damage of the one CT.

Most recent PD test results are shown in Figure 7. It presents maximum pulse magnitude, pulse repetition rate and PD intensity for all cubicles in the line up. Cubicle #1 does not show PDs after the repair, which verifies that all PD sites have been corrected. Cubicles ## 2 and 16 have partial discharges of small magnitude and moderate pulse repetition rate. Cubicles ## 8 and 11 have high pulse magnitude up to 6,000 - 8,000pC. However, the level of discharges in these cubicles has been high since the beginning of periodical PD tests almost four years ago. It has not changed significantly since that time and these cubicles are of secondary priority. In this case, the trending function of a continuous monitor can alarm if these high levels should begin to increase.

Another 15kV line up about ten years old was tested for partial discharges as part of an initial survey and evaluation test. Only one cubicle had some level of partial discharges. Phase-resolved PD distribution (top projection) is shown in Figure 8 (left-hand-side). PD related to B-C voltage and additional oscilloscopic investigation indicated PT (also located in this vertical section) as the most probable source of partial discharges. To confirm the hypothesis, the PT was pulled out and the PDs disappeared (Figure 8, right-hand-side). Megger test showed low resistance to ground and a HiPot test indicated a cracking sound. The PT was replaced and follow-up PD testing confirmed a successful repair, and no presence of a second PD site.

In another instance with old DHP type 15kV switchgear, very similar sparking was detected in many cubicles containing potential transformers in the top compartments of each cubicle. PD fingerprint did not indicate partial discharges related to insulation. It was concluded that the PTs blades had loose connections to the HV bus. The customer recalled having problems with unstable PT readings in the past and even problems with co-generators synchronization, which were tied to the output of these PTs. One of PTs was pulled out and PD associated with this cubicle disappeared. The PT blades had a discoloration indicating high temperature at the contact. The problem was repaired during the next scheduled outage. Voltage sensing problems related to the PTs have not occurred since the above repair.

**SUMMARY**

Partial discharge technology has been successfully applied to MV switchgear. This technology has previously been employed on MV generators and MV motors in utility generation stations and industrial plants. Expected system improvements in the application to MV equipment are:

a) Reliability improvements via predictive maintenance at actual operating voltages.
b) Reduced number of unexpected outages.
c) Improved outage planning and allocation of limited outage resources.
d) Identification of deteriorated MV switchgear of older bus designs.
e) Improvements in personnel safety due to diagnostics without access to energized equipment and reduction of the use of high voltage test equipment to simulate operating voltages. Also, since all switchgear doors remain closed, this eliminates any potential relay vibration. Regardless of the preventive or predictive test methods, safety concerns should always be given the highest priority and checked prior to any actions.

The factory calibration and testing allowed for the development of guidelines for the effective placement of partial discharge sensors in new or retrofitted medium voltage switchgear.

Lastly, the advent of new continuous partial discharge monitors can result in quantum gains in the ability to improve equipment reliability, uptime and just as important, personal safety.

References:


