Abstract

The utility 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 generating 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 generating plants.

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. Thermographic surveys require a direct-line-of-sight of the equipment; therefore some opening of enclosures may be necessary unless special viewing accessories are installed.

Corona and Surface Tracking

Corona and surface tracking are two of the key root causes of insulation deterioration. If left undetected, they will eventually cause a conductive path between the medium voltage and ground, therefore resulting in a “fault.” A fault begins with a continuous conductive path, either resulting from the corona damage to insulation or surface tracking. This
initial bridging of the line-voltage to ground is called a “full discharge.” The initial full discharge can be correlated to placing a very thin piece of bell-wire between the line-voltage and ground. If this occurs, the piece of bell-wire would immediately evaporate, resulting in a large arc drawn between the line-voltage and ground. At this point, the large arc travels through the air within the path of the arc. A review of the properties of air versus temperatures indicates that at room temperature, air is the well-known good insulator; but as the temperature of air is increased to the temperature of an arc, air changes from being a good insulator to being a good conductor. This is called the ionization of air, whereby the molecules in air become ionized and allow the rapid flow of electrons. At this point, we no longer need the bell-wire, since the air has become a conductor and will allow the flow of electrons, until an upstream protective device interrupts the fault. The above scenario is also exactly what occurs when a circuit breaker attempts to interrupt an arc in air. The air space between the stationary and moving contacts, of an air circuit breaker, becomes ionized. The arc will continue through the air if not addressed by the arc-chute. The purpose and design of the arc chute is to address this ionized air, therefore extinguishing the arc.

A full discharge is therefore an “arc” which is drawn between the line-voltage and ground; therefore, a partial discharge is an “arc” which is drawn somewhere between the line-voltage and ground, but not a full discharge. Partial discharges are small arcs that occur within or between insulation materials, usually across a void in the insulation system. A void is a very small gap, filled with air, or another gas. It has been found that voids of 1 mil will breakdown at approximately 360 volts (Paschen’s Law), with a void of 0.3 mils having a breakdown voltage of 240 volts [3]. With this voltage stress across the above voids, the void is polarized and an arc occurs. 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 the arcing internal to the insulation system, or 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.

The damage resulting from this arcing within or between insulation systems has been traditionally referred to as “corona damage.” Corona is the ionization of air, therefore describes the arcing action within the air space. This arcing causes a deterioration of the insulation, which breaks down into a white powdery residue on the insulation. Another byproduct of corona is the smell of ozone, which is the result of the breakdown of air. Corona can also be observed visually if the arcing is severe and the area is in complete darkness. Lastly, corona is arcing in air, and similar to all arcing, emits frequencies from 100 kHz to 100 MHz, therefore severe corona can also be detected by radio interference. In all of the above cases, the corona must be severe, directly observable or not be shielded by metal barriers. Medium voltage switchgear contains a substantial amount of shielding by metal barriers; therefore effective detection of partial discharges must be capable of penetrating through external metal barriers and observe the actual insulation itself.
Partial Discharge Detection

Attenuation of the partial discharge signals occurs more rapidly for the higher frequency components. Therefore a 30MHz component of a partial discharge signal can be detected only if the partial discharge sensor is relatively close to the source of the PD. The 10MHz to 20MHz component can be detected at a greater distance between the source of the partial discharge activity and the PD sensor, while a 1MHz component can be detected at even a greater distance.

Studies have found that the range of 1MHz to 20MHz can detect the majority of partial discharge activity. This is above the lower frequency emission range that can interfere with normal radio signals and is below the high frequency range, which can only be detected if the source of PD is very close to the PD sensor. This 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.

When measurements are obtained for the majority of measurable PD in the 1MHz to 20MHz range, specific quantities can now be related to the condition of the equipment under test. For example, the maximum intensity (measured in millivolts) and pulses per cycle (ppc) can both be correlated to the condition of the insulation system, based on the consistent data acquisition of the 1MHz to 20MHz range of PD activity.

The above also supports the results of calibrations of measured PD activity and the actual “discharge activity” occurring within the voids of the insulation system. All partial discharge systems measure “millivolts” related to the intensity of the PD activity. The millivolts can be related to an estimated discharge activity, 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 and Shielding

There are several systems which detect “acoustic” activity, which is in the frequency range of partial discharge, if a direct line-of-sight exists between the source of PD activity and the PD sensors. These sensors are normally called ‘acoustic” sensors and can be aimed at the expected source of PD, while either listening for the acoustic signal with headphones, or looking at an analog meter. The above systems are very effective for locating surface tracking or corona on high voltage outdoor insulators. The device is aimed at each insulator while listening to the audible output. These systems do require an experience operator and the results may vary from the perceived level of acoustic signal strength form one operator to another. This is illustrated in Figure 1a.
The above acoustic systems cannot be applied to the majority of medium voltage electrical systems due to the inherent shielding of the outer metal barriers. Any metallic barrier between the source of the PD activity and the PD sensor will provide a path to ground for the PD signals. This will prevent the ability to measure any internal PD activity on the outside of these metal barriers as illustrated in Figure 1b.

MV switchgear, MV motors, MV bus duct, MV transformers and MV switches all have grounded metal barriers surrounding all electrically energized components and the associated insulation systems. This requires an electrical coupling to the conductor or a coupling to the area of internal PD activity in the insulation system (e.g. This has been previously proven by the coupling to RTDs embedded in a machine winding for MV generators and MV motors). This coupling allows for the measurement of PD activity within these MV systems. Such a coupling diagram is shown in Figure 2.

Applying a standard of the measurement of 1MHz to 20MHz of PD activity allows for detection of the majority of measurable PD activity, while also providing a consistent calibration standard with guidelines for the interpretation of the condition of the insulation system.

Advances in the development of PD sensors, with the use of high-speed electronics, noise reduction algorithms and software systems allows for accurate measurement and analysis of PD activity involving MV electrical systems. A signature pattern of partial discharges related to insulation systems allows for verification of proper noise filtering methods, therefore ensuring that proper PD measurements are being obtained.
On-Line Partial Discharge Analysis as a Predictive Tool for MV Switchgear

Several substations including transformers and related switchgear line-ups were equipped with PD monitoring sensors and systems. Radio Frequency Voltage Sensors (RFVS) and Radio Frequency Current Transformers (RFCT) sensors were installed in switchgear to monitor PD activity in line-ups, incoming buses and outgoing feeders.

In May 1998 and July 1999 the switchgear manufacturer performed off-line partial discharge measurements on several switchgear line-ups in the factory setting. Comparison of the off-line partial discharge and on-line PD field measurements were made which resulted in very good correlation. Periodic measurements and trending of these sources provides maintenance personnel with up-to-date information concerning the actual condition of the MV equipment.

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.

Partial Discharge Factory Calibration

It was important to develop a calibration procedure for MV switchgear sections to allow for correlation of factory and field measurements based on the input from various sensors at various locations [4]. Items evaluated were signal propagation along the switchgear line-up and signal cross-coupling from phase to phase. This knowledge allowed for optimization of the number and location of partial discharge sensors to be installed in typical switchgear line-ups, in the factory as well as retrofitting existing switchgear in the field. It also provided the guidelines for the proper interpretation of the on-line field data obtained after the equipment has been in service for an expended period of time.

The calibration was conducted by injecting a know charge into various locations within the switchgear line-up, while measuring the output at several partial discharge sensor locations. The injected charges simulate partial discharge activity in the vicinity of the injection site, while the various sensors provided a means to determine the optimum location of the PD sensors for maximum coverage of PD activity.
The calibration was performed to address the sensitivity for the various types of sensors applied. With the RFVS (radio frequency voltage sensor) sensors connected to the “CTs common neutrals”, sensitivity was determined to be from 13+-3 nC/V to 17 +-6 nC/V. For RFCT (radio frequency current transformer) sensors connected around the “cable shields grounding”, sensitivity was found to be approximately 6.5 nC/V. This value will depend upon the actual type and number of shielded cables connected to the load side of a breaker.

When the simulated partial discharge charge was injected between one bus phase to ground and between two bus phases (corresponding to phase to ground and phase to phase discharge) practically no difference in sensitivity was found for the RFVS sensors on CTs neutrals. The attenuation of the partial discharge signal along the line was calculated to be ~0.5 to 0.7 per cubicle.

The above calibration provide guidelines for the installation of both factory and field-retrofit PD sensors. It was found that accurate determination of PD activity requires a PD sensor within each cubicle, due to the measured attenuation along the switchgear line-up. Measurement at only the ends of the cubicle would not detect PD within the switchgear cubicles. This characteristic of the PD activity and the requirement for measurements has been verified by on-line field measurements.

**On-Line versus Off-Line Partial Discharge Measurements**

The results shown in Table 1 depict the maximum PD readings taken on the same switchgear line up. Off-Line PD measurements were obtained at the factory in accordance with the acceptance criteria from section 8.6.1.6 and Table 6 of CSA (Canadian Standards Association) C22.2 #31 [5]. On-Line PD field measurements were obtained after the switchgear was installed at the end users facility.

<table>
<thead>
<tr>
<th>Partial Discharge Testing Results</th>
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<tr>
<td><strong>Off-Line Testing</strong></td>
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<td>&lt; 25 pC</td>
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Table 1: Off-Line & On-Line PD Measurements

As can be seen from the readings above, both the Off-line and On-line readings are below the acceptable CSA 100 pC level. The On-line readings are approximately double that of the Off-line. This is attributed to the differences in the test circuit being measured. For example, both the cable and bus duct connections are terminated and on-line during the field measurements. This accounts for the PD related to the installation and/or external noise of these and other connected components, which are not present during the factory (off-line) testing.

When conducting an On-line PD field measurement, values above 100 pC, or the evidence of a high number of pulses per cycle would be indicative of potential internal
insulation deterioration, which would require additional monitoring by trending or an internal switchgear inspection.

The field testing connections are shown in Figure 3a. Figure 3b illustrates the PD instrumentation used to extract the PD signals from the internal MV switchgear PD sensors. As shown below, the PD sensors are connected at a minimum of two locations in each cubicle:

a) RFVS at the common connection of the three (3) CTs
b) RFCTs on the cable ground-shield connection.

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**Retrofit of Existing Switchgear**

Separate from the off-line and on-line testing discussed above, experience has been gained by the retrofit of existing switchgear with PD sensors at several other plants. These plants involved petro-chem, steel, pulp and paper, and other industrial sites.

It is possible to retrofit existing switchgear with partial discharge sensors. An outage is required for the installation of the RFVS and the RFCT partial discharge sensors. Both sensors are wired to a door mounted access panel. The partial discharge measurement instrumentation (Figure 3b) is connected to this access panel.

The front cubicle door access panel is shown in Figure 4. The instrumentation can be connected without requiring the opening of the switchgear door. The panel is mounted by punching two standard size holes for the PD – BNC connectors (RFVS and RFCT ports), and four (4) small corner mounting screws holes. A separate nameplate is installed on the front of the door with the four (4) mounting screws, allowing the two BNC connectors to extent out from the door. Installation per cubicle is normally less than one hour and can be completed by plant personnel with minimal instructions. The base-line PD measurements would be obtained after the equipment is re-energized for operation, or during the safe application of a simulated test voltage to the bus.
On-Line PD Measurements on Older MV Switchgear Designs

In cases of MV switchgear damage that has progressed to a near-failure state, you may observe the smell of ozone, which is emitted by the corona activity within the switchgear insulation system. In these cases you may also observe high levels of radio interference. In the above cases, the corona must be severe. Corona can result solely due to the adequate voltage potential across a void either within or between insulation systems. Clean and dry insulation will experience corona damage and much corona damage is the result of older MV switchgear designs.

For example, older MV switchgear internal bus consisted of squared-copper bar, within an insulation sleeve. This sleeve then penetrated the switchgear cells through a surrounding insulating support barrier. This design contains small air gaps, or voids, between the copper bar and the insulation sleeve, and between the insulation sleeve and the support barrier. This is illustrated in Figure 5.

At the junctions where the bus passes between cubicles, we can generate the voltage gradient to provide the 300 volts across these many air gaps. For this reason, it is common to find corona damage on older switchgear designs, at the point where the
internal bus passes between cubicles. Figure 6 and Figure 7 illustrate an example of the above type of corona damage detected by on-line partial discharge analysis.

Figure 6 shows the level of partial discharge activity for each cubicle in a MV switchgear line-up. The high levels at cubicles #8 and #9, of Figure 6, indicated that an internal inspection was required during a scheduled outage.

![Figure 6](image1.png)

**Figure 6**

On-Line Partial Discharge Detection of Sixteen (16) MV Switchgear Individual Cubicles (Cub #1 to #16)

Figure 7 illustrates the bus deterioration, which was observed at this point where the bus passed between cubicles #8 and #9. This was the line-side bus of the switchgear feeder circuit breakers, therefore was bus, which is totally enclosed by metal barriers. This bus is not visible by opening either the front or rear hinged door. It is the totally enclosed bus, which usually runs the length of the switchgear line-up.

Through the use of specially designed partial discharge sensors, the partial discharge activity can be detected behind the metal barrier assemblies, therefore allowing for on-line diagnostics of insulation deterioration associated with corona damage, on existing MV switchgear assemblies.

![Figure 7](image2.png)

**Figure 7**

Corona Damage found where Partial Discharges were detected between cubicles #8 & #9
The above example, concerning the corona damage on the line-side of the switchgear bus indicated minimum levels of PD activity at the ends of the switchgear line-up (Cubicles #1 and #16), but PD sensors at cubicles #8 and #9 identified this corona damage at the junction point between these two cubicles. This further supports the recommendation for PD sensors in each cubicle due to the signal attenuation.

Figure 8 is another example of actual on-line corona damage detected by partial discharge measurements. In this case, high levels of PD were detected using the RFVS sensor connected to the neutral of the phase CTs of this cubicle. An internal inspection found the evident tracking (white discoloration) on the in-line CT. An outage was scheduled and the in-line CT replaced.

Also identified were high levels of PD from several PT compartments. Internal inspections found dirty and deteriorated PT contacts in one case, and megger testing indicated high leakage current to ground in another case.

Surface tracking is also a deterioration mechanism for MV switchgear. An example of surface tracking is shown in Figure 9.
Figure 9 is a 4160-volt bushing from an air circuit breaker. When identified, there remained only 5/8” of undamaged insulating surface. The root cause was determined to be that the cubicle heater circuit was de-energized and never re-energized. In this case, the surface tracking developed due to the surface moisture resulting from the heaters being left in the de-energized state.

Summary

The implementation of partial discharge technology has been successfully applied to MV switchgear. This technology has previously been employed on MV generators and motors in utility generation stations. Expected system improvements 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 partial discharge testing results identify the benefits of specifying new MV switchgear to be designed corona-free and equipped with PD sensors, as well as a strong consideration to retrofit existing switchgear with partial discharge sensors; especially since many older MV switchgear bus designs are prone for corona activity.

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. The base-line partial discharge measurements obtained, either at the factory for new switchgear, or during the initial installation and calibration of retrofitted existing switchgear, allow for the required base-line measurements and predictive trending of future partial discharge measurements.

References: