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Application and Commissioning of Online Partial Discharge Technology for Medium Voltage Switchgear

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Introduction

Partial Discharge (PD) is a localized electrical discharge or spark resulting when ionization partially bridges the insulation between two conducting electrodes. PD may occur at any point in the insulation system, if the electric field strength exceeds the breakdown strength of the insulating material. Electrical equipment operating at or above 2,400 volts ac is susceptible to partial discharge/corona activity.

Left unchecked, this unwanted electrical activity can lead to total breakdown of the insulation system and catastrophic failure. PD activity can be short lived or occur over an extended period of time before it results in a phase to ground or phase to phase fault.

PD appears in one of two forms in the insulation system:

- Internal PD - Occurring in defects: voids or cavities within solid insulation
- Surface PD - Occurring across the surface of the insulation

PD activity emits energy as follows:

- Electromagnetic Emissions
  - Radio Waves (3 Hz - 300 GHz)
  - Heat (300 GHz - 430 THz)
  - Light (430 THz - 770 THz)
- Acoustic Emissions
  - Audible (20 - 20 KHz)
  - Ultrasonic (20 KHz - MHz / GHz)
- Gases
  - Ozone
  - Oxides of Nitrogen (when combined with water produces Nitric Acid)

PD occurs in voids, cracks, or inclusions within solid dielectrics, at conductor-dielectric interfaces within solid or liquid dielectrics, or in bubbles within liquid dielectrics. PD is limited to a portion of the insulation so discharges only partially bridge between electrodes.

PD in insulating materials usually initiates within gas-filled voids in the dielectric. The dielectric constant of the void is much less than the encompassing dielectric so the electric field across the void is substantially greater than across an equivalent distance of the dielectric. When voltage stress across the void exceeds corona inception voltage (CIV), for the gas in the void, PD activity is initiated.

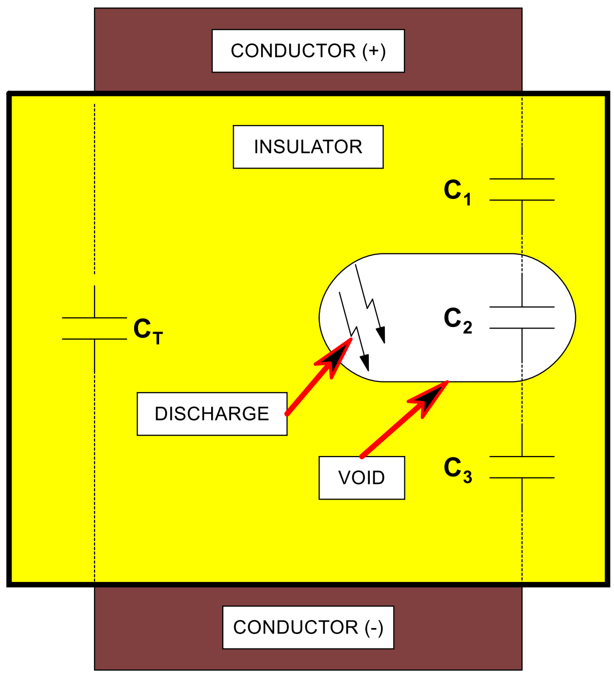

Figure 1: Partial Discharge in Solid Insulation

As illustrated in figure 1, when a discharge occurs, a small current flows in the conductors and is attenuated by the capacitive voltage divider network C_1, C_2, C_3 in parallel with C_T (total or bulk capacitance).

PD along the surface of solid insulating materials occurs if the surface tangential electric field is elevated causing breakdown along the insulator surface. This is common for overhead line insulators and can occur in switchgear insulators. This is particularly true when insulators are defective, contaminated and/or exposed to high humidity.

Application

PD causes sub-cycle high frequency current pulses (nanoseconds to microseconds transients). These appear and disappear repeatedly as voltage goes through zero crossings. PD occurs at or near both positive and negative voltage waveform peaks. These PD current pulses can be easily measured with a high frequency current transducer (HFCT) clamped around case ground of the tested component. PD severity is attained by measuring the burst interval; the interval between the end of a burst and beginning of the next burst. As insulation breakdown accelerates, burst interval decreases because breakdown occurs at lower voltage. Burst interval is critical at two (2) milliseconds since discharge is near the zero (0) crossing and facilitates propagation to continuous discharge causing major component failure.

The arcing and sparking that occur during PD activity creates high frequency electromagnetic waves that propagate away from the fault point in all directions. Measuring these high-frequency pulses identifies the presence of PD. The next step is to locate the actual point of fault. Applying acoustic emission detection, ultrasonic sensors, is effective to detect and locate PD. Bandpass filters are typically required in order to remove interference from background / system noise.

When PD activity occurs in switchgear insulation, it generates electromagnetic waves in the radio frequency range. The signal can travel through insulating materials or components. The radio frequency signal is attenuated as it passes through each surface or medium. Most of the electromagnetic pulses are conducted by surrounding metalwork but a small proportion encroaches onto the inner surface of the casing. These PD charges are small with voltage magnitudes of 0.1 millivolt to one (1) volt. This phenomenon was discovered by Dr. John Reeves in 1974 and he labelled them Transient Earth Voltages (TEVs). TEVs occur because the partial discharge creates current spikes in the conductor and these can appear in the grounded metal surrounding the conductor. This current flow escapes through metalwork joints (or gaskets in gas insulated equipment) and impinges an elevated voltage on the surface of the apparatus referenced to ground. Dr. Reeves established TEV signals are directly proportional to the condition of the insulation for switchgear of the same type when measured at the same point.

TEVs are measured in units of dB-mV. These voltages are high frequency pulse type signals flowing in the switchgear metalwork. The metalwork represents a high impedance to ground for these signals. The current flow into high impedance facilitates generation of detectable voltage spikes. This voltage is impressed on the interior of the metalwork (to a depth of approximately 0.5 µm in mild steel at 100 MHz) and loops around to the outer surface where there is are electrical discontinuities.

Electromagnetic waves generated by the partial discharge frequency create TEVs on adjacent enclosures. The surrounding enclosures act like an antenna.

TEVs are a very convenient phenomenon for online measuring and detecting of partial discharges since they are easily detected without removing panel covers and do not require connection to the energized conductor. TEV detection methodology is useful to detect PD in switchgear and surface tracking on internal components; however its sensitivity is insufficient to detect issues within solid dielectric cable systems.

Test and maintenance programs use offline and online test methods to detect PD. Offline testing is typically a periodic test for factory and/or acceptance purposes. Online testing can be periodic or continuous and is typically used for maintenance testing.

Offline testing requires the equipment under test to be removed from service so high voltage ac can be applied directly to the equipment to collect test data. PD can persist for years before manifesting into failure. Such failures can be catastrophic. It is important to verify if PD is present in newly manufactured equipment and prior to being placed into service. Verifying presence / absence of PD aides in confirming warranty conditions. Specifying offline PD testing should result in equipment that has a much higher reliability assuming tests are properly conducted. Industry standards, subject matter experts and the manufacturer should be consulted to properly define such testing specifications. A two (2) sensor remote TEV monitor can be extremely useful in locating the source of PD. The sensors can be installed on two (2) pieces of equipment or two (2) adjacent cubicles. The HMI will display the TEV severity detected at each location and more importantly it will display which location sensed the TEV first. The sensors can be moved quickly to another location until the source of the PD is located. In most situations this style of diagnostic testing located the source of PD within a few minutes.

Online PD testing technology has rapidly evolved in recent years and can be performed periodically or continuously. Periodic monitoring consists of using hand held devices that are capable of detecting acoustic and electromagnetic signals. The use of TEV probes is a more recent technology tool. Handheld equipment provides instantaneous feedback allowing detection of the presence of PD. These tools allow the technician to detect and narrow the focus to better pinpoint the location of PD when it is internal to an apparatus. Continuous online monitoring incorporates sensors, data collectors, system monitors and data analyzers; to collect analyze and report on a voluminous steady stream of data reporting on the health of an insulation system.

This type of PD monitoring system is not fool proof. Outside influences (florescent lights, local equipment operation or construction activity) can emit noise that is recorded by the system some that can emulate PD. Expert analysis and interpretation of the data is required.

Design

This paper highlights design of online PD monitoring systems for two (2) 38 kV / 200 kV BIL metal clad switchgears operating at 33 kV nominal:

- Existing outdoor walk-in aisle switchgear: (2) Bus Sections - (14) Total Cubicles
- New indoor switchgear: (3) Bus Sections - (30) Total Cubicles

The PD systems consist of the following components:

- **HUB** - Host computer with system program and visual presentation of data
- **NODES** - Sensor data collector
- **SENSORS**
  - TEVs
  - Microphone (Ultrasonic Detector)
  - Environmental Monitor (Temperature and Humidity)
  - RFCTs (Monitors Cables)
  - External Antenna - (Noise Cancellation / Outside Influences)
- **Miscellaneous Equipment**
  - Ultrabus Cables (Nodes to Hub Data Link)
  - Coax Cables (RCFTs, External Antennas and TEV to Nodes Data Link)
  - LEMO Cables (Microphones to Nodes Data Link)
  - SCADA Interface (Transmits Alarms from HUB to Local Alarm System)

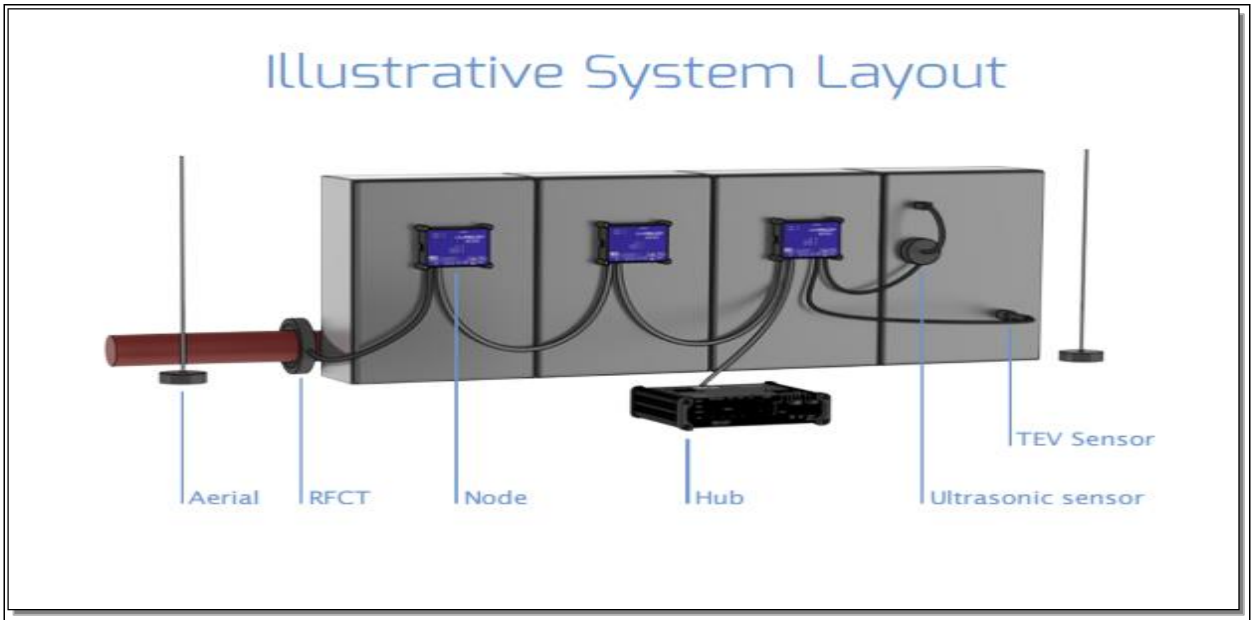

Figure 2: System Layout (Concept)

The PD selected provides a comprehensive system that monitors the key indicators for PD (except the gases). The system monitors each bus section and individual cubicle in order to capture the overall condition of the switchgear. Continuous data collection, alarming and expert analysis provides preemptive capability to identify any potential PD issues.

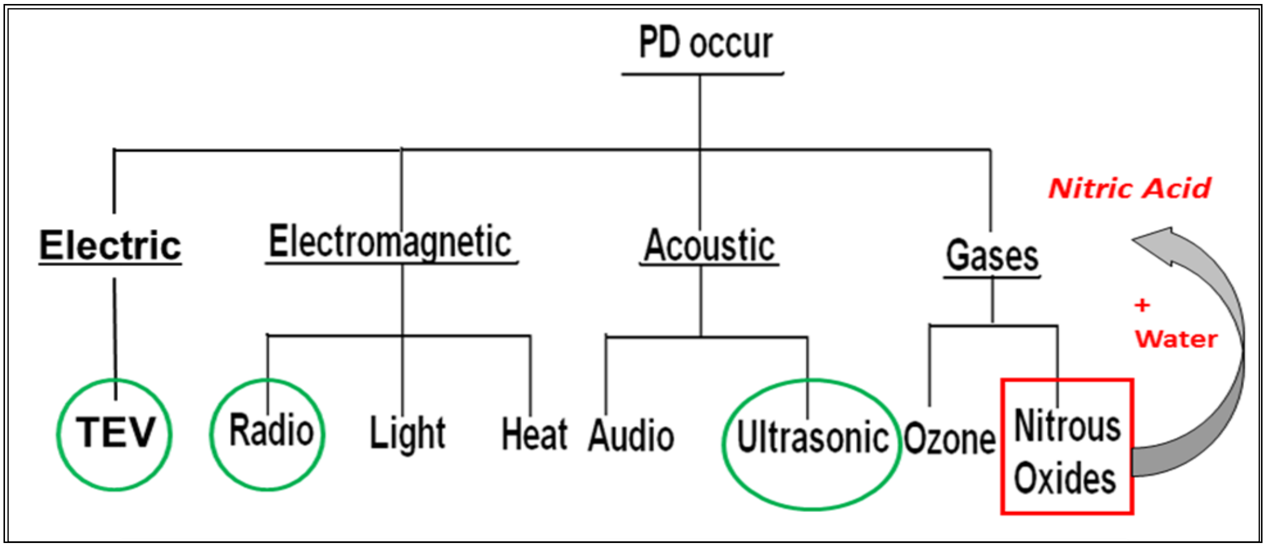

Figure 3: Selected Sensors (Metal Clad - Vacuum / Air Insulated)

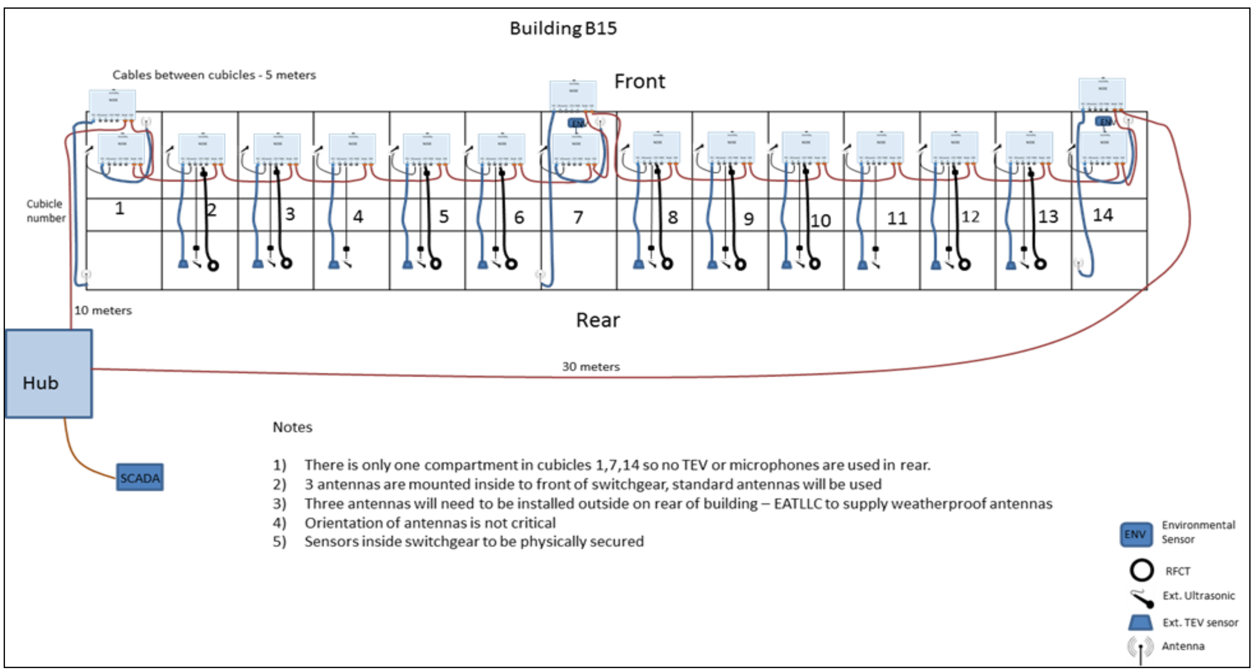

Figure 4: PD Monitoring System - Outdoor Switchgear Layout

Figure 4 shows the layout for one of the installations. The system includes output contacts for alarming and is configured for remote monitoring. Each feeder compartment (incoming and outgoing feeders) contains an overall feeder RFCT, a TEV sensor and a Microphone. The breaker compartments contain a TEV sensor and a microphone sensor. An environmental monitor (temperature and humidity) sensor is located in an area that reports on the switchgear environment. External antennas are mounted several feet away from the switchgear.

The following design constraints were identified by the user and the manufacturer:

- Interconnecting cable from NODE to HUB & NODE to NODE can't be longer than 30 meters
- Nodes mounted on switchgear and interconnecting cables can't interfere with normal day to day operation or maintenance of the equipment
- Existing switchgear - only individual feeder outages allowed for PD system installation
- Existing switchgear - no overall equipment outage allowed
- Location of sensors / equipment can't jeopardize switchgear reliability (short / long term)
- Installation of PD system can't void manufacturer's warranty
- Installation needed to comply with NEC (Requires NRTL field listing)
- Installation can't reduce switchgear design ratings / capabilities (i.e. BIL)

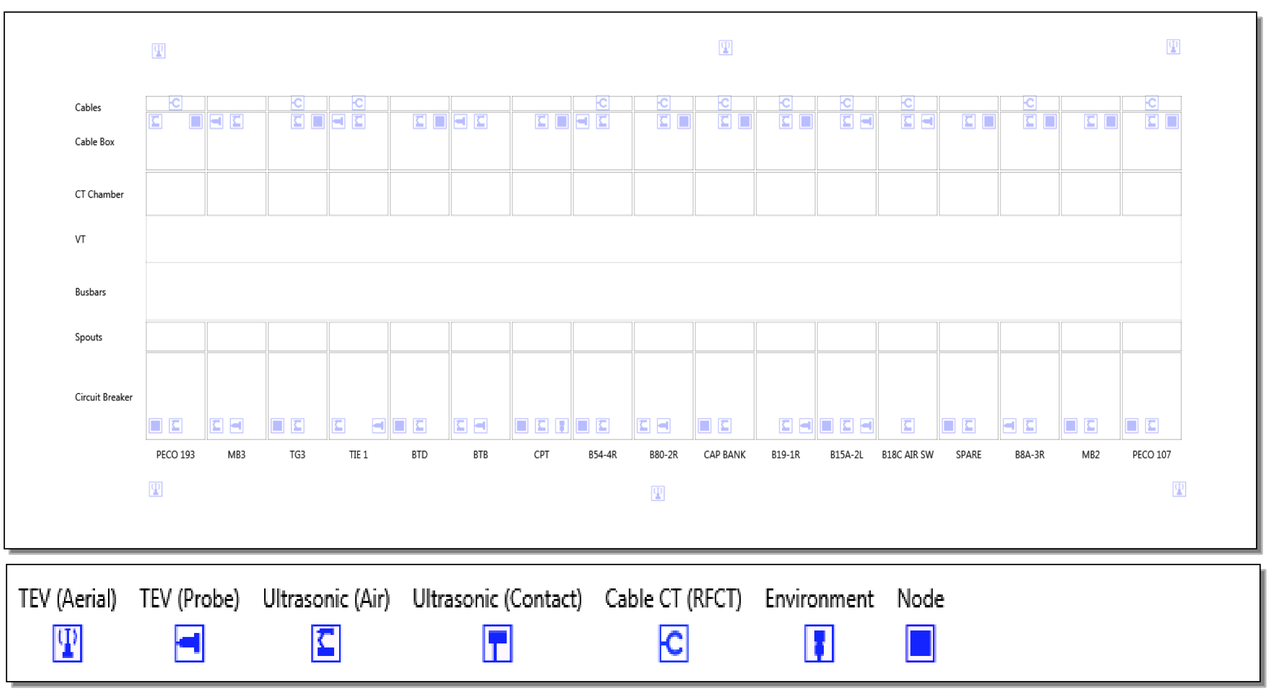

Figure 5: PD Monitoring System - Indoor Switchgear Layout

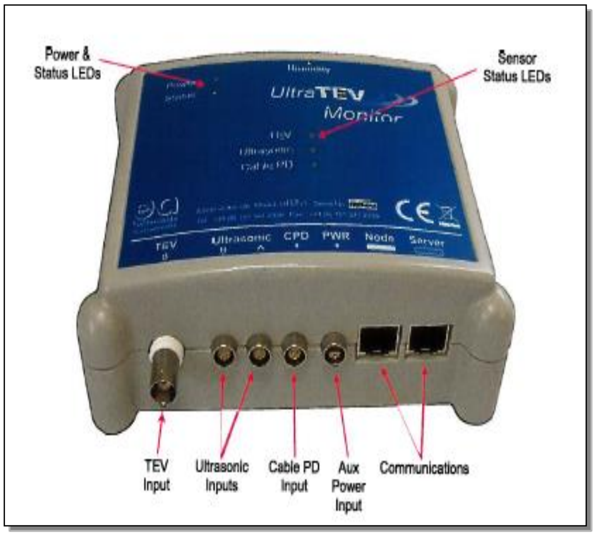

Figure 6: Node

Figure 7: Hub

Installation

The PD system uses various types of sensors that are connected to nodes via coax or LEMO cables. The nodes connected in a daisy chain and ultimately connect to the HUB using Ultrabus cables (Cat 7 cables). All of the devices are equipped with a strong magnetic base, making installation very simple. Each node accommodates two (2) ultrasonic microphones, one (1) RFCT, one (1) environmental monitor and either an external TEV or external antenna. Each node also contains a built in TEV and temperature sensor).

For the larger indoor switchgear installation the nodes were mounted on the front of the circuit breaker cubicles. Cables for sensors located in rear cable compartments needed to be brought to the front of the switchgear for connection to the node. The manufacturer supplied all the hardware, including interconnecting hardware (cables). Because there were so many cubicles to monitor and cable design is constrained to thirty (30) meters the system required two (2) hubs. The cable limitation is due to attenuation of the small signals to avoid data or system errors. Each hub is also limited to a polling capability of (22) nodes.

Since the manufacturer provides all interconnecting cables preliminary system design layout is critical. The system has to be designed and laid out so cable lengths can be identified before ordering equipment. This requires locations for the sensors, nodes and hubs to be identified early. The hub needed to be located within a (30) meter cable run. The hub also requires a reliable 115 VAC external power source. In order to ensure continuously reliable power a small stand-alone UPS was installed.

Once the location of the sensors, nodes and hubs were identified, a methodology needed to be developed to routes all the cables. The manufacture's literature depicted nodes on the front door of the circuit breaker compartment with cables draped in front of cubicle doors from node to node. The manufacturer indicated on systems with such a design, when the circuit breaker doors needed to opened the associated node and cables would be disconnected. This is not acceptable for many customers. It is not desirable to disturb the system to perform inspection or operation of the circuit breaker cubicle. To address this issue, holes were drilled in the doors and grommets were used to route interconnecting cables between cubicles. This allowed doors to be easily opened to avoid system disruption for operating or maintenance.

An additional installation challenge was the routing of sensor cables from the feeder compartment (rear cubicle) to the front of the switchgear. Several ideas were considered:

- Up and over the switchgear and through the roof
- Up and around the switchgear
- Through the switchgear interior
- Under the switchgear

Photo 1: Node Installed on Exterior Cubicle Door

Photo 2: Cable Routing to Node through the Door

For the outdoor switchgear, routing up and over the switchgear and through the roof or up and around the switchgear were not feasible since the cable length constraint could not be met. Routing cable through the switchgear was not safe since the line bus and line side stationary breaker stabs were energized. That only feasible option was to route under the switchgear. The switchgear is an outdoor, walk-in enclosure. The entire assembly sits on an I-Beam frame on a concrete foundation. When the switchgear was installed, the I-Beam frame was elevated two (2) inches above the concrete pad. This provided a gap that accommodated a 1-1/2 inch conduit. The conduit was fished under the structure between the rear cable compartment and the front circuit breaker compartment. This allowed sensor cables to be routed rear to front to the nodes.

Photo 3: Conduit Penetration - Under Floor

Photo 4: Cable Pulled In Underfloor Conduit

The new indoor switchgear has three (3) bus lineup sections. This switchgear was installed directly on a concrete foundation. Two (2) of the new sections were installed first inhibiting modification to the switchgear. For this installation half of the nodes were installed on the rear of the switchgear so that routing of cable rear to front was minimized. External wireway was installed to route cables between the front and rear cubicles. Existing wireway was used in the front of the switchgear to route the cables. The last section of the switchgear was still in manufacturing when the PD project was initiated. The manufacturer was asked to install provisions for routing cables between the front and rear cubicles for the sensor to node connections. This greatly simplified the installation of nodes and cable routing.

Commissioning

Commissioning of this system was relatively simple. Table 1 is a representative commissioning data sheet used for programming the system configuration. When starting up the system, a "System Discovery" is initiated that polls all connected devices. This polling identifies the number of nodes connected to the hub and the type and quantity of connected sensors. During discovery all of the nodes will display red and Green LEDs to assist in troubleshooting nodes that are not communicating with the hub.

If this information is confirmed as correct, an ID tag for each node and each sensor is entered into the system. The length of cable for any External TEV, External Antenna and RFCT must also be entered into the system configuration. The cable length is used to provide timing the sensors to time stamp the acquired signals. Once all the data is entered, the configuration is saved and the system is put into the monitoring mode the system is operational.

Alarms are used to provide early warning / detection of PD. There are several alarms that can be set:

- TEV dB Mean Level
- TEV Mean PPC (pulse per cycle)
- Ultrasonic Mean Level
- CPD (cable partial discharge) PC Meal Level

Table 2 shows the set points used for each alarm. Alarm level and alarm span were developed in conjunction with the manufacturer's recommendation. The alarm span indicates how long the level needs to be at or above the alarm point in order for the system to consider it a valid alarm. Outside influences, localized noise and transient over voltage can cause the measured parameter to temporarily exceed the alarm level. Alarm span prevents/minimizes false alarms by ensuring the parameter has exceeded the value and is a valid alarm.

The original system design incorporated a general alarm (dry contacts) when any monitored point alarmed. This alarm signal was sent to the site's central alarm command center, which is monitored 24/7. When alarms are received by the command center, they reach out to the appropriate department / personnel to respond. Since the owner had no prior experience with this type of system and the PD alarm data requires expert analysis relying on the command center and responding personnel was deemed insufficient. The hub is a computer running windows that has the capability to be networked. For security reasons, the owner's IT Department would not approve access to the

LAN or allow connecting the hub to the central network. To address this concern, a wireless router was installed and connected to each of the HUBs.

Table 1: Online PD Commissioning Data Sheet

Company:	XYZ	**Date:**	09-30-2014
Location:	Anywhere, USA	**Technician:**	Chris Smith
Substation:	18A	**Bus:**	Section 3-2
Voltage:	33 KV	**Current:**	1200 A
Manufacturer	EA Technology	**Date of Manufacture:**	2014

Node	Internal TEV	External TEV	Cable Length (M)	Ultrasonic A	Ultrasonic B	Cable CT	Cable Length (M)	EXT. T/H
1	TIE (F)	TIE(F) AERIAL		TIE(F)	CPT-B1 (F)	-	-	
2	FUTURE	CPT-B1 (F)		FUTURE (F)	SPARE (F) F8			
3	54 (F)	SPARE (F) F8		54(F)	80 (F)			
4	CAP (F)	N/A		CAP (F)	19 (F)			*
5	8A (F)	19 (F)		8A (F)	15A (F)			
6	SPARE (F) F1	15A (F)		SPARE (F) F1	MBT (F)			
7	160 (F)	MBT (F)		160 (F)				
8	160 (R)	160 (R) AERIAL		160 (F)		160		
9	MBT (R)	MBT (R) AERIAL		MBT (R)		15A		
10	15A (R)	SPARE (R) F1		15A (R)	SPARE (R) F1	8A		
11	19 (R)	8A (R)		19 (R)	8A (R)	19		
12	CAP (R)	80 (R)		CAP (R)		CAP		
13	54 (R)	SPARE (R) F8		54 (R)	80 (R)	80		
14	FUTURE (R)	CPTB1 (R)		FUTURE (R)	SPARE (R) F8	54		
15	TIE (R)	TIE (R) AERIAL		TIE (R)	CPT- B1(R)	TIE		

Table 2: Alarm Settings

Alarm Point	Alarm Level	Alarm Span
TEV dB Mean Level	25 dB	N/A
TEV Mean PPC Level	2.5 PPC	N/A
Ultrasonic Mean Level	18 dB	30 minutes
CPD pC Meal Level	7000 pC	30 minutes

TeamViewer (remote access program) was installed on the hub and remote computers. This system provides remote communication with the hub. The hub was programmed to send a daily email indicating that the system was functioning correctly. Also, an email would be transmitted if any monitored point alarmed or cleared. The email delineates what sensor alarmed and provides the actual level of activity. When an alarm is received, the system can be remotely accessed and viewed in one of two ways. The data can be viewed on the computer screen in real time as it could be on the local hub's monitor or the data can be downloaded. Once downloaded, the data can easily be analyzed using the manufacturer's data analysis software tool. This tool allows specific sensors to be highlighted and compared. This speeds up the data review and analysis process. This configuration also provides the OEM with direct access to the operating system which facilitates analysis of alarms, system updates and system adjustment. Teamviewer can also be downloaded as an application for both Android and Apple devices, allowing full access to the system from mobile devices.

Lessons Learned

During a periodic review of stored data, after one of the systems had been installed for several months, one (1) ultrasonic detector reading had increased above the other sensors. However, this sensor was below the alarm point (Figure 8). Looking at the data it appeared to be impacted by humidity. The user was notified of the potential situation. However, because the system was relatively new, the user was reluctant to remove the equipment from service just on this increased sensor reading. Separate ultrasonic readings were performed using a hand held instrument, which confirmed electrical activity. The feeder was removed from service and an inspection performed. An insulating barrier board was found rubbing against a 33 kV insulated conductor, causing corona to be emitted. Photos 5-7 show the inspection findings. The barrier board was removed, modified, cleaned and re-installed.

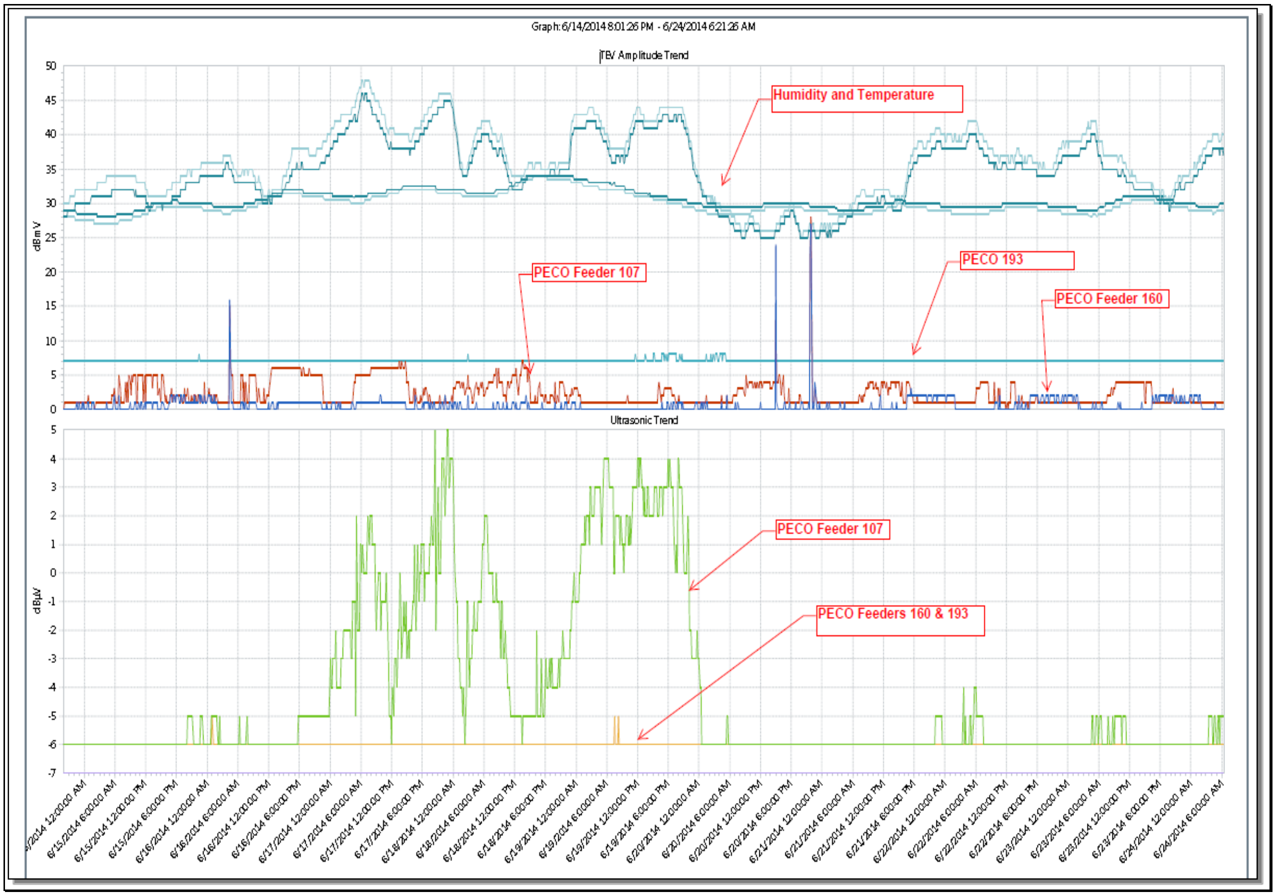

Figure 8: PD System Data

Ensure that the location selected for the hub installation is cool, dry, and clean. The hub is susceptible to overheating and difficult to clean if dirt enters the cabinet. If more than (12) nodes are utilized in one installation the Ultrabus cable must be connected in a continuous loop from hub, node-to-node, and back to the hub. If there is a break in the Ultrabus communication the hub will only communicate to the first (12) nodes. This also makes troubleshooting a communication failure difficult if the failure occurs past the (12^{th}) node. In this situation all the nodes beyond the (12^{th}) node will not communicate with the hub and will appear failed. A long Ultrabus cable can be utilized to jump from the hub to the (12^{th}) node to make discovering which node or cable is defective.

Maintenance testing was performed on the cubicle and it was returned to service. Upon return to service the ultrasonic readings returned to normal levels consistent with other cubicles. Without this PD system, it may have been years before this activity might have been detected, which could have ultimately led to an uncontrolled catastrophic in service failure.

A subsequent alarm investigation identified that the system was reporting elevated ultrasonic levels on a CPT Transformer used for supplying station service light and power. The hand held ultrasonic instrument was used and it confirmed low levels of electrical activity. The hand held instrument allowed the activity to be pinpointed to a cable pass-through insulator. A bare conductor was used to connect the primary of the transformer to the load side of the fuse. Because the alternate CPT was out-of-service at the time this CPT could not be removed from service for repair. Three months later, smoke was seen coming from the CPT cubicle. It was immediately removed from service. The PD system was interrogated and it showed that the ultrasonic detectors had gone into alarm just prior to the smoke being reported. The trouble was tracked to a defective high side fuse that had operated single-phasing the transformer. The issue with the fuse is it was tracking on the inside of the tube (the tube was made of fiberglass). This event precipitated the owner's decision to install the remote access capability. Photos 8-9 show the CPT.

Photo 5: Insulation Emitting PD

Photo 6: Insulation Emitting PD

Photo 7: Insualtion Emitting PD

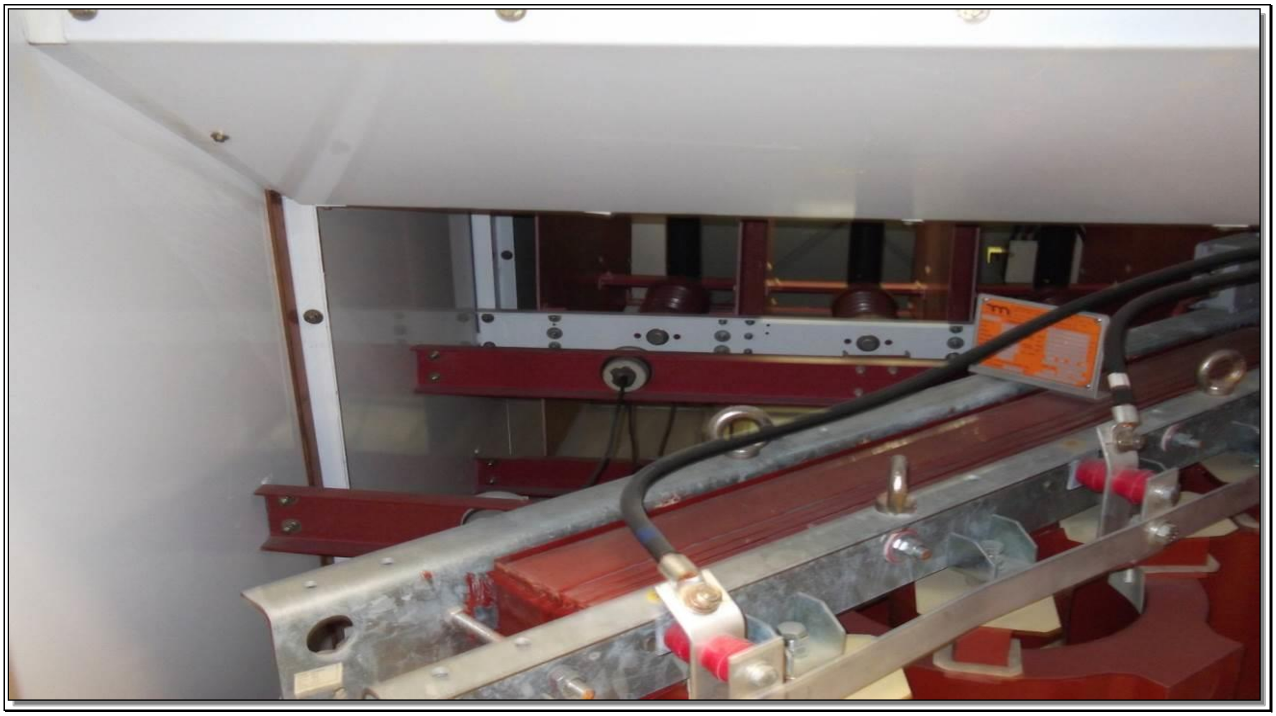

Photo 8: CPT (Top)

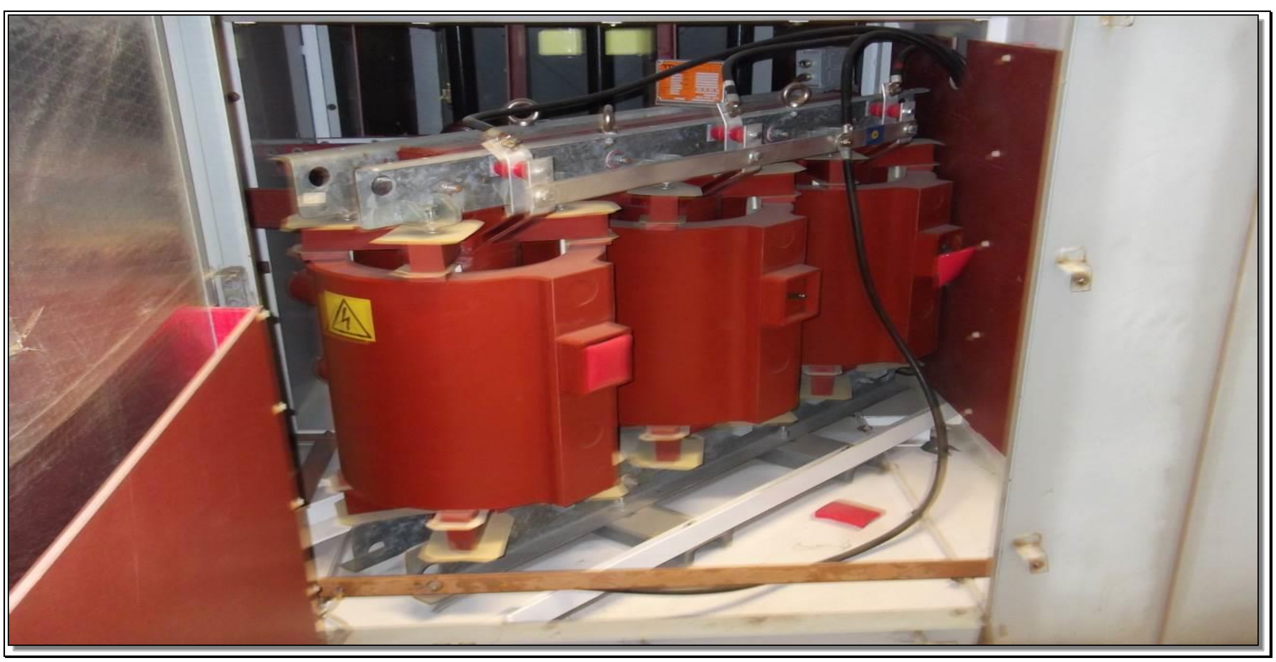

Photo 9: CPT

The RFCT is installed over the overall cable sheath ground. This RFCT is then connected to a node via a coax cable that has a metallic connector. Initially, some of the RFCT's were installed at the floor level of the cubicle. After approximately three (3) months in operation, a feeder fault in the substation feeding this switchgear resulted in the ground cable melting on the feeder compartment. The root cause was the cable sheath ground cable was not sized adequately for the design fault current levels. When the ground cable burnt open, it caused a high voltage transient which flashed to the metal connector of the RFCT. This resulted in damage to the PD system. Repairs were made to the system, and all metal connector associated with any of the sensors in the high voltage compartments were insulated with Raychem 130^{o} C tape. Adequate layers of tape were applied to protect against full line-to-line voltage.

Advanced planning is critical for a project of this complexity to be successful. The following key items should be followed to simplify the overall project, in particular the installation:

- Pre-identify the location and proposed labeling of each sensor and the length of the cable connecting that sensor.

- Once the sensor, node and hub locations are identified, carefully determine how the system will be interconnected. This phase is very critical if the system is being applied to in-service switchgear. In some cases, a total outage of the switchgear will not be possible. Identifying routing of communication cables is an important consideration - methods to consider are under the gear (if there is access), external wireways and existing wireways.

- Layout the design and sit review it with the user to fully explain the design and installation process. Don't assume the user is going to agree with the initial design approach. Owner input can have significant impact on the design and installation.

- After design is complete and cable routing identified, layout out the cable length requirement for each interconnecting cable. In some cases general cable lengths work, but, do not use a 10 meter cable when a seven (7) meter cable is suitable.

- Label each cable as you install them so they can be identified during commissioning. Each should be tested to confirm functionality prior to polling the system.

- Where nodes have two (2) ultrasonic detectors connected (A & B), the system will request where each of the detectors are located and a name for those detectors.

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