Further Experience in the Use of Existing RTDs in Windings of Motors and Generators for the Measurement of Partial Discharges

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Abstract - Over seven years has passed since the use of the Resistance Temperature Detectors (RTDs) embedded in motor and generator windings as a sensor to detect partial discharges (PD) was introduced. Over this period of time, thousands of measurements utilizing RTDs have been made. This coupled with the refinement of measurement techniques and sensor technologies has validated this approach. Use of the existing embedded RTDs in conjunction with traditional sensors, such as coupling capacitors at the line terminals, will greatly improve the diagnostics capabilities of insulation systems in rotating equipment. Methodologies and numerous examples will be presented while addressing the strengths and limitations of this technology.

I. INTRODUCTION

Online measurement of partial discharges (PD) has proved to be an effective tool in evaluating the condition of stator insulation in medium voltage electric motors and generators [1]. This method is widely used in addition to the traditional off-line insulation tests performed during scheduled outages.

When a PD event occurs a high frequency pulse is induced into the conductor. The frequency spectrum of this pulse ranges from a few kilohertz to a few gigahertz. Most online PD technologies available on the market today measure these PD events in the higher frequency bands, generally one megahertz and higher. One common problem all technologies face is that these high frequency signals attenuate quickly as they travel through the winding. Therefore, sensors commonly installed at winding terminals have a limited zone of sensitivity and provide valuable information for that zone only [4]. A generally accepted rule of thumb is that coupling capacitors installed at the line terminal of a machine will only have a zone of sensitivity of 10 - 15% of the total winding [2,5,7]. This equates to the first two or three coils on large motors and hydro generators and maybe the first bar on large turbine generators. The amount of coverage from any particular sensor is subject to the capacitance value of the sensor coupled with the design and physical size of the machine. A common sense solution is to use sensors embedded into the windings. Some of the PD technology vendors suggest installing specially designed sensors into the winding, but this approach is relatively expensive and requires an extensive machine outage and invasion into the winding assembly.

Alternatively, most of the medium voltage machines already have RTDs embedded into the winding by the manufacturer and these detectors can be used for partial discharge measurements [2,4]. The authors have over six years of experience using RTDs as PD detectors. Hundreds of thousands of records of PD data from RTDs reside in a database. A special PD transducer was designed that is installed in series with the existing RTD wiring at the RTD terminal block located on the frame of the motor or generator. The transducer does not affect the operation of the RTD or the temperature monitoring equipment connected to the RTD. The transducer only passes the high frequency PD signals to the PD instrument.

Using RTDs as a PD sensor is very effective in trending of machine PD activity when used with an analyzer that can effectively reject noise and process PD data. If sensor calibration is performed, the use of RTDs can be further applied to allow comparisons between different machines.

II. WHY RTDS WORK

A typical motor or generator will have anywhere of 6 to 12 RTDs. Many larger turbine generators will have as many as 50 to 60 RTDs.

Figure 1 shows a typical RTD. The RTD and the RTD wiring will lie in a slot between two coils. In each slot there is a top coil and a bottom coil and may be of the same or different phase. At higher voltages the coils are taped with a semi-conductive tape that keeps RTD at ground potential.

![Figure 1 - Picture of RTD found in a typical motor. RTD and wiring act as an antenna to capture PD signals occurring in the winding that is not normally detected by traditional line sensors.](image)

A. How RTDs Work As A PD Sensor

The RTD and the RTD wiring act as an antenna. As the PD pulse travels in the vicinity of the RTD and the RTD wiring the PD energy is coupled to the RTD. The pulse then follows the RTD wiring out to the PD transducer in common mode (between the RTD wires and ground) where the PD pulses are extracted from the wiring and feed to the monitor or analyzer.
As the wiring from the RTD leaves the stator slot it bundles with the other RTD wires in the machine and eventually are brought out to a terminal block on the outside frame of the machine. This is the location where the transducer is installed.

Since the RTD wiring is intertwined from all the RTDs, many of the PD signals will cross couple between all wiring before the signals reach the transducer. In order to make sense out of the PD signals an appropriate analyzer to decipher the signals for analysis is required.

Also there is a considerable amount of noise in the RTD circuits coming from the RTD power supply. The transducer must also reject this noise. Figure 2 shows phase-resolved patterns of the noise coming from the RTD power supply before and after installation of the RTD PD-transducer. The horizontal axis of each chart is the magnitude of the pulses in millivolts and the vertical axis is the phase angle of the power frequency AC waveform (0 - 360 degrees). The dots represent the number of pulses per cycle for a given magnitude and phase angle in color scale from black to bright yellow. Figure 2a shows data taken directly from the RTDs without the transducer. This noise is coming from the RTD power supply. Figure 2b shows the same machine with the RTD PD transducer installed.

One can observe classical PD patterns in Figure 2b, RTD1 at a 25 millivolt scale after noise from the RTD power supply is canceled.

The transducer is passive in nature and requires no external power and the type and ohm rating of the RTD has no affect on the functionality of the system. Figure 3 shows the RTD transducer installed on a motor. In this case, the RTD terminal block was replaced with the RTD transducer.

Sensitivity of the RTD to PD signals can vary based on RTD location (middle or end of slot) and wiring methods. This is well known and accepted. A large database of data exists, coupled with calibration tests, which allow for these differences and determination of default values based on these factors.

It must be noted that basing a decision on magnitude alone, without calibration can be precarious, no matter what sensor is used. Whether it is a coupling capacitor, a radio frequency current transformer (RFCT) or RTD. Over the last five years several improper installations of traditional coupling capacitors have been noted. Common problems include long jumper leads between the sensor and the motor terminals, sensors installed 300 feet from the motor in the switchgear, sensors connected to the neutral point on motors and sensors installed on the iso-phase bus duct side of the insulated joint with the generator. Improper installation of the coupling capacitor will affect the magnitude output detected by the analyzer connected to the capacitor.

B. Validation of the Use of RTDs AS A PD Sensor

1) Case 1

Figure 4 shows data obtained from a 16,000 HP, 13.8 kV that will be further discussed in Case 2. Clamp-on RFCTs are installed in the main terminal box on the cable shield grounds and 12 RTDs are evenly distributed around the winding.

On each oscillogram, trace 1 is the signal from the RFCT located on phase A, trace 2 and 3 from RTD01 and RTD03 located on phase A and trace 4 - RTD05 corresponding to the middle phase. In Figure 4a, the oscilloscope was triggered from a PD pulse that originates near the line terminals (RFCT - Phase A). Traces 2, 3 and 4 show no response. In Figures 4b and c the oscilloscope was triggered by a PD pulse originating near RTD01 and RTD03 respectively. As can be seen, there is no response from the other sensors.

This illustrates that PD events originating near the line terminals will be detected by the line terminal sensors, but not by the RTDs. Also the RTDs and not the line sensors will detect PD occurring near the RTDs. Therefore, for a
complete analysis, it is necessary to install additional sensors into a winding or to use RTDs to get information about the winding condition. It is strongly recommended that both traditional coupling capacitors and RTDs be used together as they compliment each other very well.

Figure 4 - PD pulse attenuation in a winding of a 16,000 HP, 13.8 kV motor. (a) Scope triggered from pulse at RFCT. (b) Scope triggered from pulse at RTD1. (c) Scope triggered from pulse at RTD3

2) Case 2

This case shows data from a 16,000 HP, 13.8 kV machine from a large petrochemical plant. This is the same motor discussed in Case 1.

The client had an upcoming outage and required an assessment as to the condition of the machine prior to the outage. To complicate matters, no traditional PD sensors were installed and an outage could not be scheduled. Split core radio frequency current transformers (RFCTs) were temporarily installed around the drain shields of the incoming cable terminations in the motor termination enclosure. The motor also had 12 RTDs embedded in the winding.

Figure 5 shows the phase resolved data from the three RFCTs located at the line terminals. All phases show PD magnitudes of around 200 - 250 mV, which are well below normal alarm levels (500 mV).

Figure 5 - Phase resolved data from the three RFCTs on the termination drain shields of a 16,000 HP, 13.8 kV machine.

Figure 6 shows phase-resolved data from four of the twelve RTDs of a 16,000 HP, 13.8 kV motor without RTD Transducer installed.

Figure 6 - Phase resolved data from four of the twelve RTDs of a 16,000 HP, 13.8 kV motor without RTD Transducer installed.

Several online tests over a three-month period were performed on this machine as well as off-line tests in a motor repair facility. During the online tests, it was noticed that there was a positive correlation between winding temperature and PD activity. This combined with the predominance of energy occurring in the negative half cycle (positive pulse predominance) indicated a prognosis that slot exit discharges existed in this machine. Defects located at slot exit points are known to have a high positive correlation with temperature and positive pulse predominance. Upon inspection of the machine in the motor repair facility multiple sites as shown in Figure 8 were evident.

One interesting aspect was that all defects were not on the highest voltage coils of each phase group. There were 6 coils per phase group and in every case, the defects shown in Figure 8 were found on the second and third coil of each phase group. This suggests that there was an inconsistency in the conductivity of the grading coating on each coil that allowed slot exit discharges to occur at lower voltages. The second coil would be the 33% of the winding and the significant PD events were not sufficiently detected by the sensors at the line terminals.

This indicates the RTDs were sensitive to the PD signals while the relatively low readings were found on the RFCTs located in the line termination enclosure. Also, the RFCTs do have a lower frequency response than traditional 80 pico-farad will detect PD occurring deeper in the winding. The RFCTs has a bandwidth of 100 kHz to 50 MHz, while a 80 pF capacitor installed on a motor will have a bandwidth of around 20 MHz to 70 MHz. This lower frequency band
allows the sensor to see farther into the winding than an 80 pF coupling capacitor; however, one needs to use effective noise cancellation technology since there can be noise in these ground circuits. In this case, there was little to no noise. In all cases presented in this paper, the frequency band of measurement is 1 MHz to 20 MHz. Sensitivities of various sensors range from 0.5 to 2 Volts per nano-coulombs (V/nC) for coupling capacitors, 0.1 – 0.8 V/nC for RFCTs and 0.05 to 0.3 V/nC for RTDs [2,5].

Figure 7 - RTD phase resolved data with RTD transducer installed to eliminate the effects of the noise generated by the RTD power supply. Same RTDs as in Figure 6.

Another interesting aspect was that while in the motor repair facility, offline PD tests were performed with the machine at room temperature. Normal operating temperature of the machine while in service was around 110°C. There was a significant decrease in PD activity to around 2 volts in magnitude. Use of both a Radio Frequency (RF) meter and an ultrasonic probe showed that all the defects shown in Figure 8 were not active.

Figure 8 - Multiple slot exit discharges were evident upon inspection of the 16,000HP, 13.8 kV machine (damaged coil in the middle).

Based on having the additional information provided by the RTDs, the customer decided to rewind this machine, since the next plant outage would be in 8 years. If the client just relied on data from the line sensors, and not performed an inspection, there is no question that a failure would occur within several months.

3) Case 3

The data presented in this case is from a 12,000 HP, 13.8 kV machine. Figure 9 shows the before and after reconditioning data from sensors located at the line terminals. The bar graphs show the PD intensity (PDI - proportional to the amount of energy in the discharges, calculated in milli-watts), Maximum Magnitude in milli-volts and Pulse count in pulses per cycle. Phase resolved data is also shown for these sensors. It is evident that the reconditioning process was effective.

Figure 10 shows the data for the same machine from two of the RTDs. The reconditioning process was equally effective as illustrated by the data.

Two additional points require emphasis. Common misinformation is in the marketplace that all that is detected by the RTDs is spurious noise. To substantiate that this is not the case, one needs to just view the phase resolved data in Figure 10 and the other case studies presented in this paper.

Figure 9 - 12,000 HP, 13.8 kV machine

a. PD intensity, Magnitude, Pulse Count
b. and c. -Phase resolved data from line terminals before and after winding reconditioning.
If all that were detected were noise, then there would be no "classical" PD distributions. Classical PD distributions show PD occurring between 00 - 900 and 1800 - 2700. If it were noise then:

1. Similar patterns would be on all channels. Noise patterns are not sensor specific.
2. One would see the same patterns both on the before and after data. In the case of Figure 6, it is the same machine, same installation. If there were noise before reconditioning, there would be noise after reconditioning.

4) Case 4
This case shows data from a 1,200 HP 4,160 volts motor located on an offshore platform. The motor was installed in 2002 and data was taken from the RTDs in November 2002 and again in November 2003. Typical PD behavior for a new machine was noticed with a decrease in PD activity over the year time period. Phase resolved data from two of the RTDs are shown in Figure 11.

Another example of a 4,160 volt motor is shown in Figure 12. This machine was taken out of service and severe looseness in the wedges were observed. Once again, classical PD patterns are found.

Figure 11 - Phase resolved data from two RTDs on a 1,200 HP, 4,16 kV machine.

Figure 12 - Phase resolved data from RTDs on a 1,300 HP, 4.16 kV machine.
5) Case 5

A Canadian pulp and paper plant has two identical 49MVA, 13.8 kV turbine generators. One machine shows very little PD activity from both the 80pF couplers and the RTDs. The second machine has similar low PD activity except that the C-phase coupler shows elevated levels. Both machines are monitored on a continuous basis. Gradual increases in PDI and pulse repetition rate were observed over the past year on the C Phase Coupler as shown in Figure 13. Starting mid March 2004, increased PD activity was observed from the C phase coupler.

Figure 13 - PDI and pulse repetition rate trend for almost one year on a 49 MVA generator. Repair made early May.

The phase-resolved data shown in Figure 14a shows the discharges are associated with the A-C phase voltage with little or no pulse magnitude predominance. Figure 14b shows the PD activity from three RTDs located closest to the line terminals. In this case the RTDs were detecting very low levels of PD activity. This indicates that value of using both types of sensors.

Figure 14 - Phase-resolved PD data before repair (a) From Coupling Capacitors. (b) From 3 RTDs near line side.

The first generator was scheduled for an outage in early May 2004 based on the manufacturer recommendations suspecting loose wedges. Based on the continuous monitoring of partial discharge activity, the first generator showed this to be of little concern. But with the increase of PD activity on the second generator, it was decided to inspect both units during this outage.

During visual inspection the first generator, no loose wedges or signs of PD activities were observed. On the second generator, initial visual inspection also showed no indication of PD activity. Off line PD tests were then performed on the second generator by applying phase to ground voltage on each phase with the other phases grounded. Little to no PD activity was observed. Based on the fact that the online PD activity was observed to be phase-to-phase type discharges, it was decided to bring in a second HV source. One HV source was connected to Phase A and the other to Phase C in order to simulate phase to phase voltage stress. Upon application of this unique test method, significant PD activity was observed. At the same time a second visual inspection was recommended with specific focus on the A and C phase connection ring bus.

Severe insulation degradation was found between the A and C phase connection buses hidden in a very restricted viewing area. As shown in Figure 15, the defect is due to improper spacing between the A and C phase connection ring bus.

Figure 15 - Signs of discharge activity between the A and C phase connection ring bus.

To repair this type of defect, a major repair would be required. Due to time constraints, temporary repairs were performed allowing another one to two years of additional operation before a major repair is required. PDI and pulse repetition rate significantly decreased while PD magnitude only dropped 20-30%.

Standard insulation tests such as Insulation resistance, polarization index and power factor tip-up tests were performed on this generator with no indication of pending problems.

III. SUMMARY

Since the high frequency component of a PD pulse attenuates very quickly, only a small portion of a winding can be monitored for PD activity from traditional sensors installed at the line terminals. Therefore, defects that produce PD that are deeper in the winding will not be detected by these traditional PD sensors.

This paper provided an update on experiences on using RTDs as a PD sensor and addressed concerns related to sensitivity, noise, data validity and applications. Hundreds of thousands of data points have been compiled into appropriate databases and analyzed.

Five case studies were presented validating the data in the use of existing embedded RTDs as a PD sensor. Four of the five cases substantiated that data received from the RTDs was of great value and if not utilized, misdiagnosis of pending problems and future failures would have occurred. In one case, the RTDs were not sensitive to partial discharges occurring on the ring bus of a generator.

An appropriate RTD transducer has been developed that is installed in series with the RTD wiring at the machine. This transducer rejects noise coming from the RTD power supply as well as extracts the high frequency component of a PD pulse. This transducer does not affect any temperature
monitoring equipment that is connected to the RTDs. Since there is considerable amount of cross coupling of signals as the PD pulses travel along the RTD wiring, an appropriate analyzer is required to decouple these signals.

Using existing RTDs as a PD sensor in conjunction with traditional sensors located at the line terminals will provide the user more information so that better decisions can be made.

The paper strongly recommends the use of both types of sensors in order to provide reliable information as to the wellness of the stator insulation of motors and generators.

IV. REFERENCES


2. C Kane, A. Golubev, I. Blokhintsev "Advances in the Continuous Monitoring of Partial Discharges in Rotating Equipment", Waterpower November 2003, Buffalo, NY


V. BIOGRAPHIES

Claude Kane has nearly 30 years of experience in the installation and preventive and predictive maintenance practices on a large variety of power distribution and generation equipment. He graduated from the Milwaukee School of Engineering in February 1973. He started with Westinghouse as a field service engineer and has held a number of technical and management positions. He has presented numerous technical papers on the subject of partial discharge at numerous IEEE conferences. He also was on the committee for the development of the IEEE Guidelines for the Measurement and Analysis of Partial Discharge on Rotating Equipment (P-1434). Claude has recently joined Eaton Electrical and is the Engineering Manager for the Eaton Electrical Predictive Diagnostics Group, based in Minneapolis, MN.

Dr. Alexander Golubev received his MS in Experimental Physics and Ph.D. in Physics and Mathematics from the Moscow Physical Technical Institute (Russia) in 1978 and 1985, respectively. He has an extensive experience in research and design in Laser and Electron Beam Generation, Plasma Coatings, High Frequency Measurements. Since 1995 he is a Manager of R&D Engineering of IPDD. This Company, is now a subsidiary of Cutler-Hammer. He develops new technologies for on-line monitoring and diagnostics of high voltage electrical equipment and provides on-site expert evaluations of equipment condition for electric utilities and industrial customers.

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