Relative Ability of UHF Antenna and VHF Capacitor Methods to Detect Partial Discharge in Turbine Generator Stator Windings

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ABSTRACT

On-line partial discharge (PD) monitoring is widely used to detect stator winding insulation deterioration. The most common type of on-line PD sensor for turbine generators is the 80 pF capacitive coupler installed at the machine terminals which detects the PD in the very high frequency (VHF) range. More recently, ultra high frequency (UHF) antennae have also been used to detect stator winding PD in large turbine generators. Both types of sensors have been installed in 16 turbine generators. This paper discusses the results from near simultaneous measurements from both types of sensors on the same machines. It was expected that the UHF sensors would have stronger discrimination of the electrical disturbances internal to the machine compared to the VHF sensors, but the VHF sensors would be more sensitive to PD. As expected, the VHF sensors were generally more corrupted by electrical disturbances. However, in about half of the machines investigated here, the UHF sensors were significantly more sensitive than the VHF sensors. Many examples of phase-resolved PD patterns that illustrate these findings are presented.

Index Terms - **Partial discharge, UHF, VHF, on-line, turbine generators, stator winding insulation.**

1 INTRODUCTION

MANY high voltage stator winding insulation problems can be detected by on-line partial discharge (PD) testing. In hydrogen-cooled turbine generators, the most likely problems that can be detected by on-line PD testing include bars that are loose in the stator slots (slot discharge), and contamination of the windings by partly conductive material that can lead to electrical tracking [1-6]. Many more insulation problems are detected by on-line PD testing in air-cooled turbine generators [5]. On-line PD testing has been routinely used to detect loose bars and winding contamination on hydrogen-cooled stators since the late 1980s [1-4]. The key issue is detecting the relatively low level of PD that occurs in high pressure hydrogen-cooled machines, when the PD could be masked by high levels of electrical interference (disturbances).

As described in IEEE 1434 [7] and IEC 60034-27-2 [8], various on-line PD methods have been developed for turbine generators, with the most popular including:

1. Capacitive couplers and instrumentation that works in the low frequency (LF) range (< 3 MHz) or high frequency (HF, 3-30 MHz) range, similar to the conventional PD detection methods described in IEC 60270, where human experts determine what PD is and what pulse-like disturbance is [3,4].
2. Capacitive couplers and instrumentation that work in the very high frequency (VHF, 30-300 MHz) range, where "time of flight" methods are used to distinguish power system disturbances from stator PD [1,2].
3. Antennae and instrumentation that work in the ultra high frequency (UHF, 300-3000 MHz) range, which suppress disturbances based on pulse shape [1, 2].

The first method has perhaps been installed on a few thousand turbine generators using PD detection capacitors of 1000-10,000 pF. The second method has been applied to many thousands of turbine generators using a pair of 80 pF capacitive couplers mounted on each phase of the generator output. The last method has been employed on about 1500 hydrogen-cooled turbine generators using a UHF antenna called a stator slot coupler (SSC) installed in the stator slots.

An initial comparison of the relative effectiveness of the second and third methods (referred to as the VHF and UHF methods, respectively) was presented from 13 turbine generators which had installed both the VHF and UHF sensors [9]. This paper presents a more comprehensive

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comparison on a larger number of machines together with more detailed analysis. First, the trade-offs involved in VHF vs. UHF measurement frequency ranges are presented, as well as the details of the VHF and UHF methods employed.

2 VHF VS. UHF PD DETECTION

A typical rotating machine PD pulse in air at atmospheric pressure has a risetime of about 3 ns (Figure 1). Based on the Fourier transform of the risetime, a 3 ns risetime results in frequency components up to 100 MHz, which is in the VHF range [10]. PD in a high pressure atmosphere will have a risetime in the sub-nanosecond region, i.e., up to the UHF range [1].

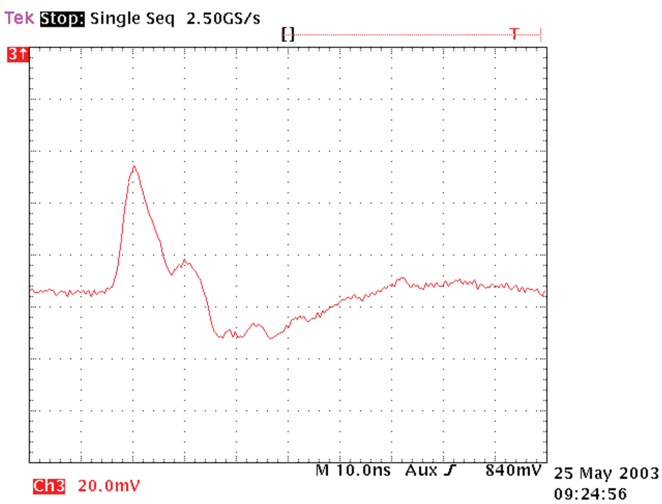


Figure 1. A single positive PD pulse from an air-cooled generator. The pulse is measured by an 80 pF capacitor connected on the generator terminal.

In general, the wider the bandwidth of the PD measurement system, the greater will be the signal that is detected, since a greater proportion of the energy is captured [7, 8, 10, 11]. Therefore, a VHF system should produce a signal of greater amplitude than a UHF measurement system. In addition, the low frequency components of the PD should suffer less attenuation as they propagate from the discharge site in the winding to the PD sensor that is usually located at or near the machine terminals. The signal loss is higher at higher frequencies due to the inductance of the coils as well as the dielectric loss in the insulation and partly conductive coating on the bar surface, which increases with frequency [12]. That is, PD further from the line terminal is more likely to be detected by a PD sensor connected at the terminals if the measurement frequency is lower. These two characteristics suggest that VHF would be the better detection range to maximize sensitivity to PD.

A theoretical analysis using communication theory shows that a higher PD signal-to-noise ratio is obtained in the UHF range, if the noise is "thermal" [13]. Thermal noise is rarely a practical issue since stator winding PD, even in hydrogen-cooled machines, is substantially higher than, for example, PD in power cables. A more likely source of electrical interference is short-risetime impulse disturbances that can originate from:

- Generator rotor winding slip ring arcing,
- Sparking of poor electrical contacts at the flexible links on the machine terminals,
- Broken post insulators on the generator output bus,
- Sliding contacts between the high voltage end of post insulators and the high voltage output bus,
- Corona from high voltage transmission lines, and
- Voltage-source variable speed drives in the generating station,
- Commutation (firing) pulses in high voltage direct current (HVDC) stations.

Such disturbances are more strongly attenuated and dispersed as they propagate to the PD sensor due to the dielectric losses and travelling wave reflections that occur in the UHF range. Also, in the UHF range, the sensors can be strongly directional [1, 2, 6]. These effects can result in a UHF sensor having an overall greater immunity to false indications caused by the above disturbances [1, 2, 7, 8].

3 PD DETECTION METHODS

3.1 VHF CAPACITIVE COUPLER METHOD

The VHF method used in this study consists of two 80 pF capacitive couplers installed per phase on the isolated phase output bus (IPB) of the turbine generators. The coaxial cable from each 80 pF capacitor is terminated in 50 ohms to prevent reflections, and thus the detection method has single pole lower cutoff frequency of 40 MHz. The upper cutoff frequency is determined by the instrument (called the TGA-B), and is 350 MHz. Therefore the system works in the VHF range. One capacitor is installed at the generator output bushing. The other capacitor is installed at least 2 m along the IPB (towards the power system). Figure 2 shows a schematic of the installation of the capacitors on one phase. Electromagnetic pulses travelling along the IPB (which primarily has an air dielectric) have the velocity of light - 0.3 m/ns.

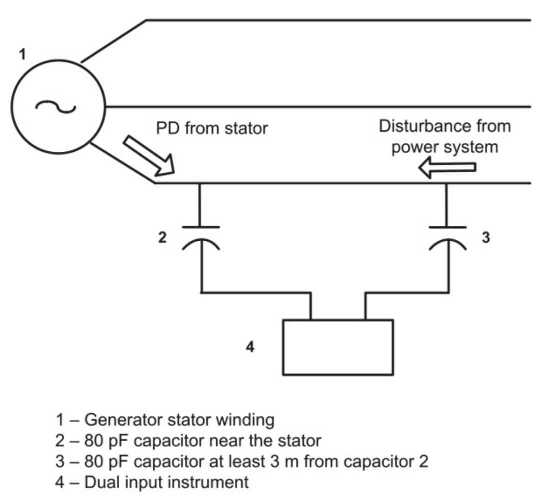


Figure 2. VHF capacitive sensor method using the time-of-flight approach to separate stator winding PD from the disturbances either from between the sensors or from the power system.

A PD pulse from the stator winding will arrive at the capacitor close to the generator (position 2) 10 ns before it is detected at position 3, if the two capacitors are for example 3 m apart along the IPB. Conversely a disturbance (for example a corona pulse) from the power system will arrive at the position 3 capacitor 10 ns before it arrives at position 2. Digital logic in the instrument determines from which direction the pulses come, based on the relative time of arrival [1, 7, 8]. If the pulses are detected at the two capacitors less than 10 ns apart (assuming 3 m between the sensors), then the disturbance (for example PD from a broken post insulator or a poor electrical connection on the IPB) is occurring between the couplers. This VHF PD detection method has been used on over 3,300 turbine generators since 1990. Figure 3 shows an example of a capacitor installed on a hydrogen-cooled turbine generator.

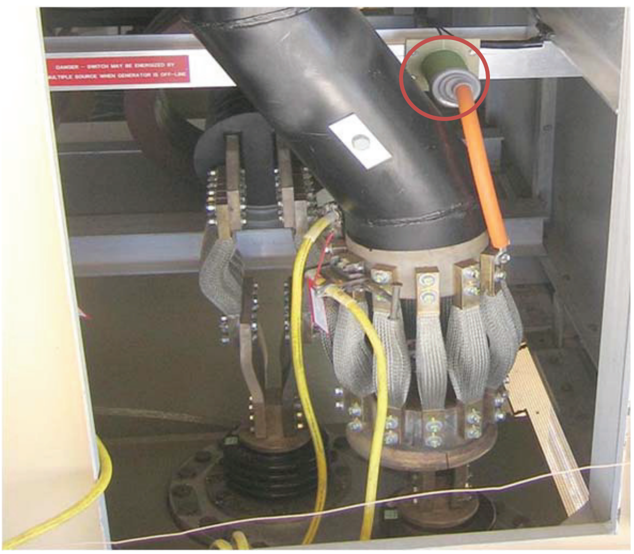


Figure 3. Photograph of an 80 pF, 25 kV capacitor (red circle) connected on the terminal of a turbine generator.

3.2 UHF ANTENNA METHOD

The time-of-arrival technique used in the VHF method was found to sometimes produce false indications of high stator winding PD [1]. This was caused by sparking that occurred between the stator winding and the detection capacitor at the generator terminals (Position 2 in Figure 2). The most common cause of this type of disturbance is sparking from poor electrical contacts at the flexible links connecting the generator terminals to the IPB (in many cases the coupler cannot be connected on the generator side of the flexible links). Another cause of sparking is from a post insulator that is < 1 m from the capacitor close to the machine terminals that is not in good electrical contact to the high voltage bus (Figure 4). Both types of sparking can lead to signals that are 10 to 100 times larger than stator winding PD. Usually these sparking sources are harmless. Although sparking from these two sources has a phase resolved pattern that is quite different from stator insulation PD, a non-PD expert may misdiagnose a good stator insulation system as deteriorated if these disturbances are occurring.

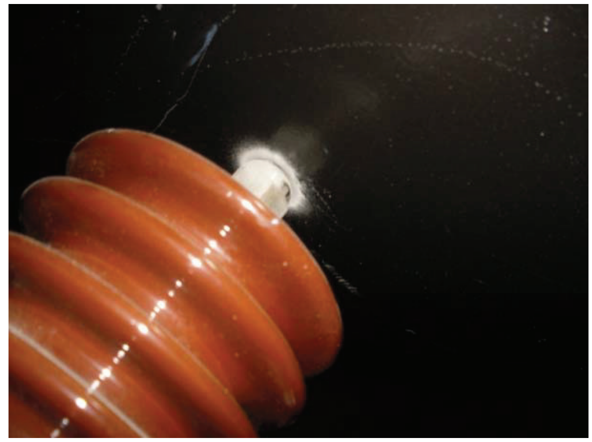


Figure 4. Photograph of a post insulator supporting the black high voltage bus in an IPB. Due to misalignment, there is a small (<1 mm) gap between the rounded nut on the top of the insulator and the HV bus, which then discharges, eroding the black paint on the HV bus. Such sparking is harmless, but can lead non-experts to believe the stator winding has high PD. Photograph courtesy Gas Natural Fenosa.

To address this issue, a UHF directional electromagnetic coupler called the stator slot coupler (SSC) was developed [1]. The SSC is a two-port antenna that is installed in the stator slots containing stator bars operating at the highest voltage in the winding (Figure 5).

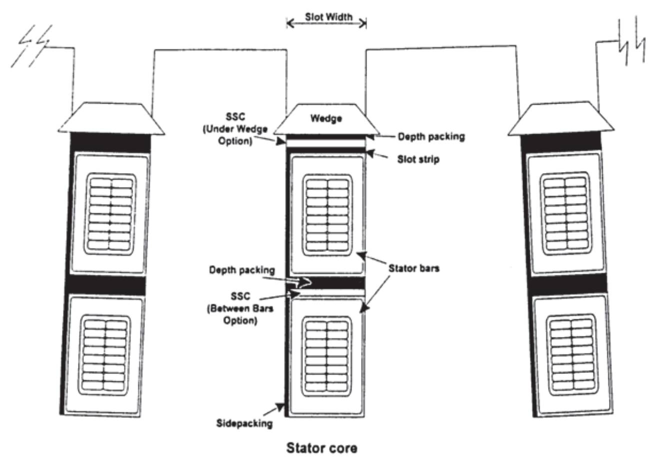


Figure 5. Locations of the UHF antennae in the stator slot.

It has a bandwidth of 10 MHz to 1000 MHz. Both simulation and practical experiments indicate that PD in the stator slot containing the antenna had a unidirectional nature, and a pulse width of 6 ns or less [1]. In contrast, disturbances from the power system, and in particular pulses due to sparking from poor connections at the terminals, were oscillatory and had a pulse width greater than 6 ns. A digital instrument then separates stator PD from all types of disturbances based on the pulse shape. The active length of the antenna is 50 cm, with a 50 ohm coaxial cable connected to each end. Using the time-of-flight principle, the antenna can distinguish pulses as originating from the endwinding, under the sensor, or from the rest of the slot in which the sensor is installed [1, 5]. Figure 6 shows an example of two antennae being installed in a hydrogen-cooled turbine generator. Over 1500 large turbine generators have been equipped with 6 or more antennae of this type.

Figure 6: UHF antennae in the process of being installed under the wedges in two slots of a hydrogen-cooled generator. The antenna is always installed at one end of the stator core.

As would be expected from a UHF sensor, PD that occurs some distance from the antenna will be severely attenuated. Depending on the stator bar semiconductive properties, this attenuation may be severe enough that PD from the other end of the slot from the antenna may be reduced by more than 50%. Furthermore, since the associated instrumentation (the TGA-S) discriminates PD from disturbance pulses based on their short pulse width and lack of oscillation, PD from other slots is usually classified as a disturbance pulse since such pulses will encounter reflections as they propagate from one slot to another, introducing pulse oscillation.

4 MEASUREMENTS

4.1 MACHINES TESTED

The "effectiveness" of the PD sensors is defined to include:

- Sensitivity to PD, and
- Ability to separate stator winding PD from disturbances with little need for test operator expertise.

To evaluate the relative effectiveness of the VHF and UHF sensors, we took advantage of the several machines that had both types of sensors installed. In most cases, turbine generators would normally have only one type of PD sensor. However, it seems that there are at least 16 turbine generators with both. This occurred because the utilities had originally installed the VHF sensors, since the removal of the rotor (which is necessary to install the UHF antenna) was not planned. When rotor removal was eventually possible, the utility took the opportunity to install the antennae in the slots, but still left the VHF capacitors installed.

Of the 16 machines equipped with both types of PD sensors, 14 are hydrogen-cooled. The generators are rated from 167 MVA to 1000 MVA. The measurements were made on the same day for both types of sensors.

4.2 CLASSIFICATION OF PD SEVERITY

In the analysis of the PD data, PD severity for each phase is assumed to be represented by the peak PD magnitude, Qm, which is defined to be the magnitude at a PD pulse repetition rate of 10 pulses per second [7, 8]. There may be 2 or 3 antennae per phase, and only the one with the highest Qm was used to represent the phase. The Qm is measured in terms of mV [7, 8].

Since the sensor detection principles are quite different for the VHF and UHF sensors, there is no reason to believe that the magnitude in millivolts will be the same for both sensor types. Hence, it is not correct to directly compare the Qm from both sensor types. Therefore, a method is needed to determine PD severity for each type of sensor that can be compared. We chose to use a published PD database which gives the cumulative statistical distribution of measured Qm [14, 15]. The most recent database is based on over 400,000 on-line PD measurements [15]. Similar databases for the VHF sensors in air-cooled generators have been independently produced by others [16]. The data in Tables 1 and 2 is based on results from about 2,500 turbine generators. Many of the measurements are repeat tests on the same machine, and thus are not statistically independent. Only the most recent PD tests are used in generating the statistical distributions. Furthermore, the only measurements used are from machines running at close to full load. Since the operating voltage of the machine, as well as the hydrogen pressure, will affect the PD activity, different statistical distributions have been found for different voltage classes and hydrogen pressure ranges. This statistical database is meant to provide a gross comparison only, due to the great variety of insulation systems, machine construction, sensor location and other variables, and not an absolute comparison of partial discharge magnitudes by means of Qm values.

Tables 1 and 2 show the cumulative probability distribution of Qm in mV for the most common pressure and voltage ranges used in the machines in this study. Figure 7 shows some of this data graphically, for hydrogen-cooled machines. For example, in Table 1, for machines operating between 16 and 18 kV, and a hydrogen pressure between 206 and 345 kPa gauge, using 80 pF capacitive PD sensors, 25% of the machines have a Qm less than 24 mV, 50% of machines have a Qm below 43 mV, 75% of machines have a Qm lower than 85 mV, etc. When specific machines are visually examined, machines with a Qm greater than the 90% level have a high probability of having a serious insulation problem [14, 17]. Thus, our experience over the past 10 years has indicated that the 90% level can be associated with an alarm for high PD. These tables enable the Qm measured by each sensor to be approximately classified on a common severity basis, according to cumulative probability.

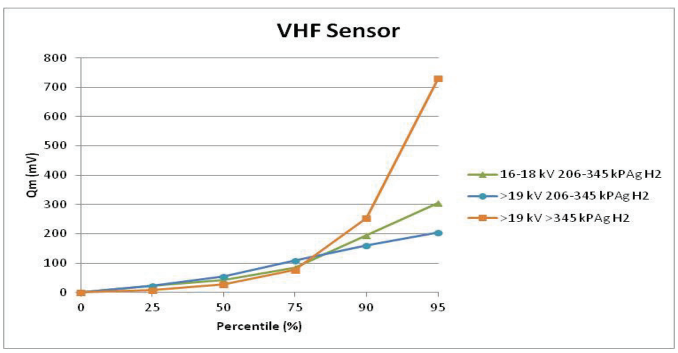
Table 1. Qm (mV) vs. Cumulative Probability of Occurrence for Turbine Generators Equipped with 80 pF Capacitive PD Sensors [15].

Cumulative Probability Range	Operating Value					
	13-15 kV	16-18 kV		>19 kV		
	Air	Air	206-345 kPAg H_2	Air	206-345 kPAg H_2	>345 kPAg H_2
<25%	55	41	24	42	23	9
<50%	124	72	43	85	55	28
<75%	265	157	85	165	108	77
<90%	529	310	194	504	161	255*
<95%	778	579	307	750	206	732*

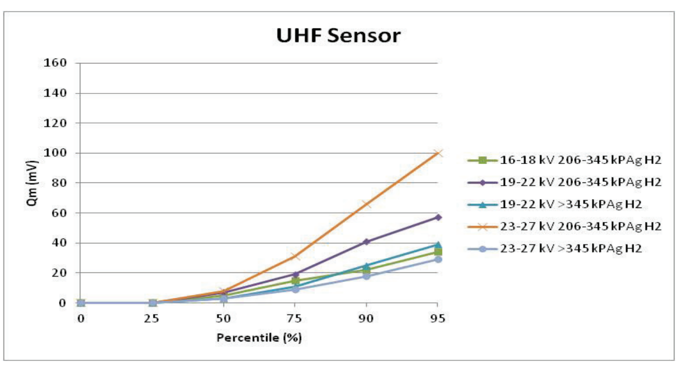
*Value from 2012 database. The 2014 database value at 90% is 548 mV, and at 95% is 951 mV, which seem to be an outlier compared to previous years.

Table 2. Qm (mV) vs. Cumulative Probability of Occurrence for Turbine Generators Equipped with SSC PD Sensors [15]. Only Slot PD is shown.

Cumulative Probability Range	Operating Value						
	11-15 kV	16-18 kV		>19-22 kV		23-27 kV	
	Air	Air	206-345 kPAg H_2	206-345 kPAg H_2	>345 kPAg H_2	206-345 kPAg H_2	>345 kPAg H_2
<25%	0	0	0	0	0	0	0
<50%	15	1	5	7	3	8	3
<75%	37	13	15	19	11	31	9
<90%	87	77	22	41	25	66	18
<95%	119	122	34	57	39	100	29



(a) VHF sensors



(b) UHF sensors

Figure 7. Cumulative probability of occurrence vs Qm for the hydrogen cooled machines

4.3 RESULTS

Table 3 shows a relative ranking of the Qm severity for 16 machines using both the VHF and UHF sensors. A column for each measurement method is devoted to the disturbance level. Neither method discards the disturbance pulses, but in fact records the number and magnitude of the disturbances. The disturbance columns show the level of disturbance as classified by the time of pulse arrival method (for capacitive couplers) and the pulse shape method (for the UHF sensors).

Six of the 16 (37%) machines had the same or very similar PD severity classification for both types of sensors (machines A, B, D, E, F and G). In these cases, no strong sources of disturbances were detected by either type of PD sensor in four of these machines. Both types of sensors measured strong disturbances from Machine B and Machine E. In all these cases the PD activity is relatively low compared to the PD statistical database.

Two of the turbine generators (12%) had PD severity classifications that were close but not the same (machines C and H). In these two machines, the PD severity assessed by the UHF method was generally higher than the VHF sensors. It is observed that the severity of PD measured was also not high.

The remaining eight turbine generators (50%) had big differences in assigned PD severity between the VHF and UHF measurements (machines I to P). The comparison indicates that the UHF sensors detected much higher magnitudes of PD activity in terms of severity ranking on seven of them, with the exception of machine O. Five of these windings are cooled by hydrogen gas at high pressures, which suppresses the inception of partial discharge. One reason the UHF sensors may be more sensitive to stator winding PD than the VHF sensors is that there is often a string of current transformers between the stator winding and the hydrogen seal bushing, current transformers at the terminals of air-cooled generators, or a potential transformer connected to the bus-bars between the capacitive sensors. These transformers as well as the gas seal bushing often have a high capacitance to ground and thus divert some of the stator PD signal to ground before it reaches the VHF sensor on the air-side of the bushing [18].

Table 3. Summary of PD and Disturbance Data from the VHF and UHF Sensors.

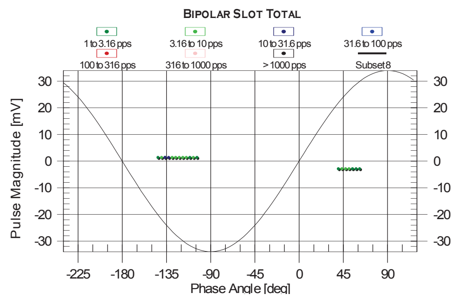
ID	Ratings			Year*	Phase	VHF Sensor Results				UHF Sensor Results**			
	MVA	kV	H_2 (kPAg)			Qm+ (mV)	Qm- (mV)	Severity Cum. Prob %	Disturbance (mV)+	Qm+ (mV)	Qm- (mV)	Severity Cum. Prob %	Disturbance (mV)^
A	350	20	270	1972	A	29	28	<50	0	0	0	<25	0
					B	0	0	<25	0	0	0	<25	0
					C	29	24	<50	0	0	0	<25	0
B	690	20	290	1999	A	12	5	<25	>1700	0	0	<50	300
					B	7	7	<25	>1700	0	0	<50	200
					C	4	5	<25	>1700	3	3	<50	300
C	1000	25	400	2003	A	0	0	<25	0	0	2	<50	0
					B	14	0	<50	0	0	0	<25	0
					C	0	0	<25	0	4	5	<75	0
D	400	21	330	2004	A	16	24	<50	27	3	3	<50	0
					B	17	19	<25	29	3	2	<50	0
					C	16	18	<25	25	3	0	<50	0
E	496	22	220	2005	A	4	0	<25	1291	4	5	<50	50
					B	10	7	<25	2250	5	5	<50	150
					C	0	0	<25	10810	5	5	<50	60
F	1000	25	380	2006	A	0	0	<25	<5	0	0	<25	0
					B	7	8	<25	<5	3	3	<50	0
					C	0	0	<25	<5	3	3	<50	0
G	480	20	320	1969	A	24	25	<50	0	0	0	<25	0
					B	11	9	<25	0	2	0	<50	0
					C	9	12	<25	0	0	0	<25	0
H	880	18	280	1975	A	0	23	<25	600	0	0	<25	0
					B	0	0	<25	500	0	13	<75	0
					C	0	0	<25	>3400	0	0	<25	0
I	176	18	300	1963	A	26	28	<50	>3400	25	31	<95	250
					B	21	21	<25	>3400	8	11	<75	100
					C	19	19	<25	>3400	5	4	<50	0
J	550	22	385	2004	A	0	0	<25	673	5	3	<75	50
					B	0	0	<25	488	3	3	<50	100
					C	0	0	<25	9250	0	3	<50	200
K	167	16	210	2007	A	13	14	<25	95	89	98	>95	0
					B	60	36	<75	39	102	109	>95	0
					C	37	50	<75	33	227	159	>95	0
L	205	15	Air cooled	2007	A	0	23	<25	0	0	612	>95	0
					B	12	24	<25	0	17	16	<75	100
					C	0	29	<25	0	787	683	>95	2500
M	200	18	Air cooled	2010	A	13	17	<25	12	11	12	<75	12
					B	12	10	<25	9	4	2	<75	10
					C	18	15	<25	49	6	6	<75	10
N	700	24	390	?	A	0	0	<25	9	6	5	<75	10
					B	5	0	<25	7	7	6	<75	10
					C	0	0	<25	7	7	5	<75	10
O	745	21	500	2010	A	454	0	<95	25	0	0	<25	20
					B	591	633	<95	50	0	0	<25	20
					C	375	372	<95	25	0	0	<25	20
P	750	24	410	2010	A	9	9	<25	15	21	18	<95	300
					B	7	7	<25	13	6	5	<95	400
					C	5	0	<25	19	24	27	<95	500

*Year of winding manufacture or rewind
**Using highest SSC readings from a phase. Only included "Slot PD" results
+ Based on time of arrival, from the power system
^ Based on pulse width

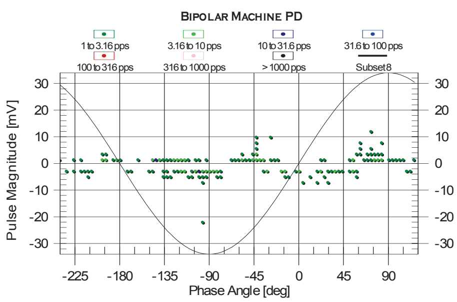
4.4 CASE STUDIES

4.4.1 MACHINE B

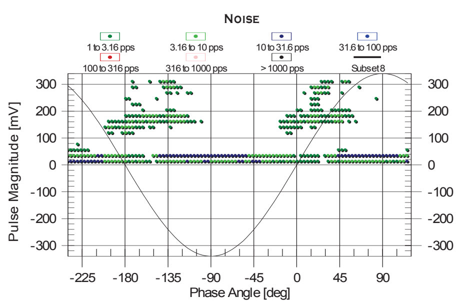
The PD occurring on Machine B is of fairly low magnitude (Figure 8a and 8b) but active disturbances are present. The UHF sensor that monitors Slot 21 of phase C captured disturbances (Figure 8c) and the VHF sensor detected disturbances over 3400 mV from phase C (Figure 8d). Thus, the disturbance separation methods were very effective for both types of sensors; however, some disturbance pulses are still apparent in the VHF PD pattern.



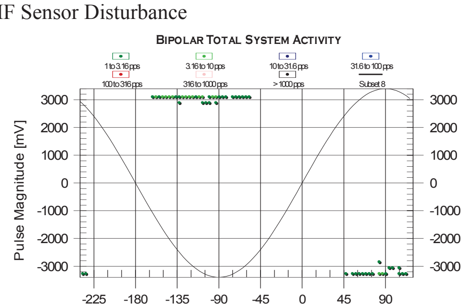
(a) UHF Sensor PD



(b) VHF Sensor PD



(c) UHF Sensor Disturbance

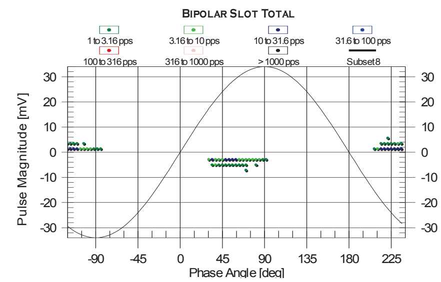


(d) VHF Sensor Distrubance

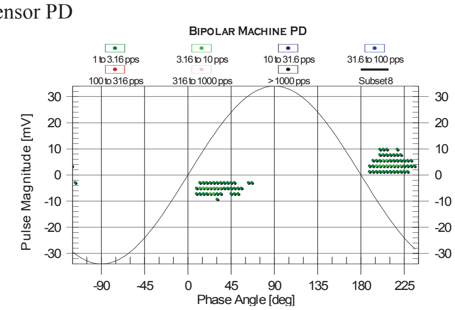
Figure 8. Phase-resolved plots of PD and disturbances in Machine B from the UHF sensor, as well as the VHF sensor. The vertical scale is the PD magnitude (dual polarity) and the horizontal scale is the 50 or 60 Hz AC phase angle. The color of the dots indicates the pulse repetition rate.

4.4.2 MACHINE E

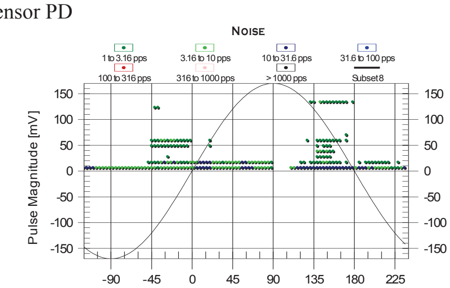
Both the UHF and the capacitive VHF sensors in Machine E are indicating low PD activity from the stator winding (Figures 9a and 9b, respectively). The figures show the data obtained from the UHF sensor installed in Slot 4 of phase B of the winding, and the VHF sensor connected to the phase-B terminal. In addition, both sensors are indicating that high level disturbances are present (Figures 9c and 9d). It is clear from the VHF sensors that the disturbance is in the IPB or from the power system (Figure 9d). The pair of VHF sensors can further differentiate that these disturbances originated from beyond the sensors (sensor number 3 in Figure 2) that is placed farther away from the generator, and not between them. This is an example of the time-of-flight disturbance separation method separating disturbances from the power system to single out PD associated with the stator winding insulation. This technique is described in section 3.1.



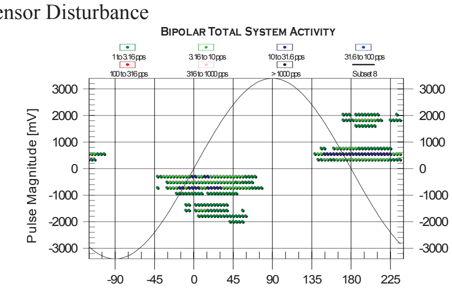
(a) UHF Sensor PD



(b) VHF Sensor PD



(c) UHF Sensor Disturbance

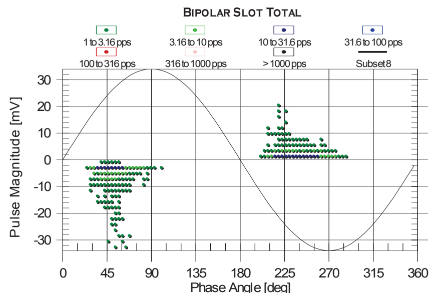


(d) VHF Sensor Disturbance

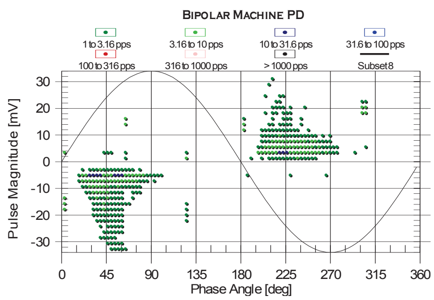
Figure 9: PD and disturbances recorded in Machine E with both types of sensors. Note that the pulse magnitude scale is much higher for the disturbances.

4.4.3 MACHINE I

The classification of PD severity measured by the respective UHF and VHF sensors is significantly different in Machine I (Figure 10), in spite of the actual PD magnitudes in mV being similar. The pulse patterns are similar and therefore likely reveal the same ageing mechanism.



(a) UHF Sensor PD

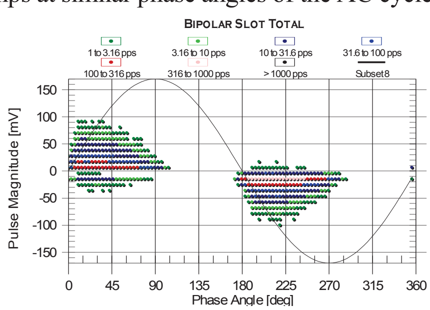


(b) VHF Sensor PD

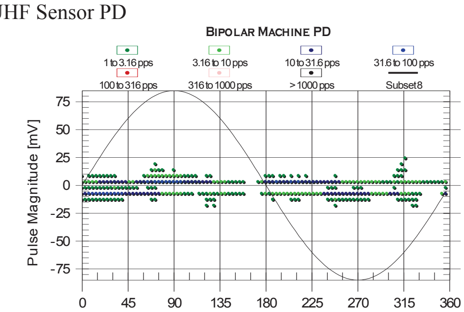
Figure 10: Phase-resolved PD plots from the (a) UHF and (b) VHF sensors in Machine I.

4.4.4 MACHINE K

The PD plots for Phase A of Machine K are shown in Figures 11a and 11b for the UHF antenna and VHF capacitive sensors, respectively. The PD plots from the UHF sensors are textbook examples of insulation PD (note that only phase A is shown and most of the PD is under the UHF sensor, hence the reversal of PD polarity from the classic polarity with which many users of the capacitive sensors are accustomed). In contrast the PD pattern from the capacitive coupler is much lower in magnitudes and less definitive for easy interpretation, although it still reveals small pulse clumps at similar phase angles of the AC cycle.



(a) UHF Sensor PD



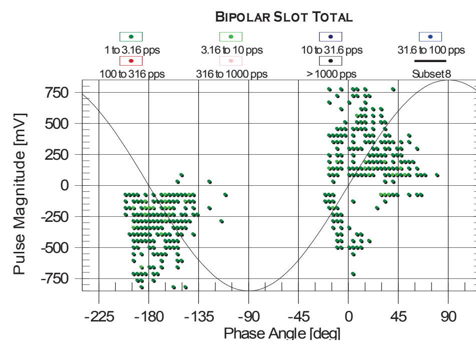
(b) VHF Sensor PD

Figure 11. PD from Machine K for both types of sensors.

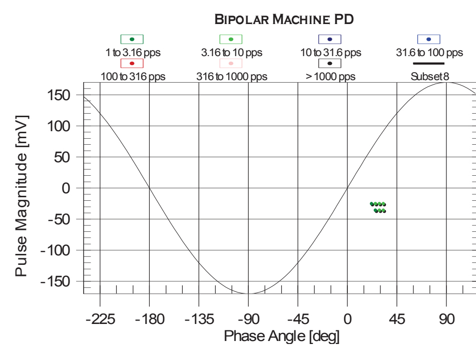
4.4.5 MACHINE L

Figure 12 shows the PD from Machine L. The UHF sensors detected much higher PD activity in both absolute (mV) terms as well as in terms of relative severity. The magnitudes of the PD activity are classified as "Over 95%" and "Less than 25%" from the UHF and VHF sensors, respectively, a great contrast and one of the extreme cases in this sample of generators studied. This is an air-cooled generator with three sets of current transformers (Figure 13) present before the terminals (i.e. between the stator and the sensor at position 2 of a typical VHF sensor installation in Figure 2).

The data in Figure 12 was collected after a repair on the stator. The Qm collected before the repair from the UHF sensors was about 1000 mV and the VHF Qm was about 150 mV. Thus the PD was much higher, and the UHF sensor was again much more sensitive than the VHF. Since the repair, the PD has been stable.



(a) UHF Sensor PD



(b) VHF Sensor PD

Figure 12. PD from the UHF and VHF sensors in Machine L.

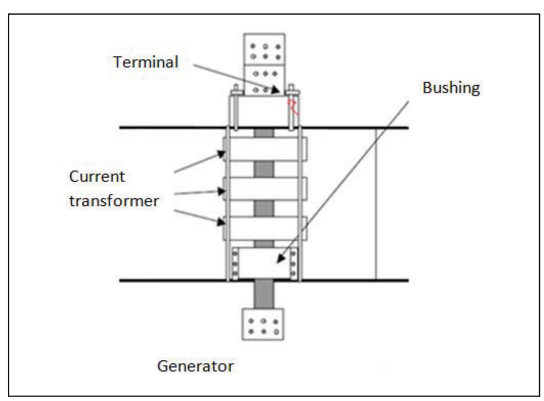
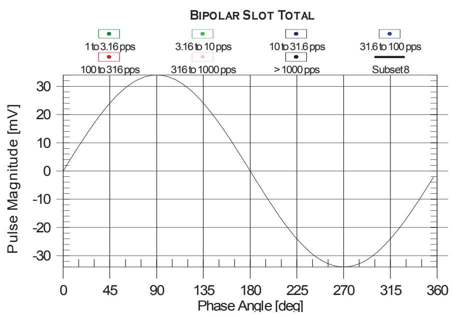


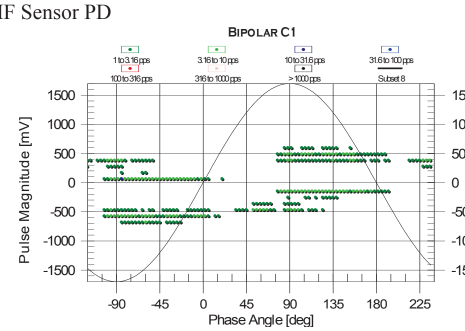
Figure 13: Sketch of 3 CTs installed between the stator winding and the capacitive sensors.

4.4.6 MACHINE O

The UHF sensors in Machine O measured no significant PD above 2 mV (Figure 14a) whereas the VHF sensor detected substantial pulse signals (Figure 15b). The patterns of the latter suggest that some of these pulses are not PD from the stator winding insulation. Hence, the UHF sensor detected actual stator winding PD while the data acquired by the VHF sensors was partly corrupted by sparking at or near the machine terminals. The VHF sensors here were configured in a way that the detection zone of the sensors closer to the generator covers a section of the outgoing IPB and so sparking on the IPB was detected as "Machine PD". To the inexperienced user, the data collected by the VHF sensor may be misinterpreted as very high PD from a hydrogen-cooled winding but it is actually sparking from the air-insulated IPB.



(a) UHF Sensor PD



(b) VHF Sensor PD

Figure 14: PD from both types of sensors in Machine O

5 CONCLUSIONS

1. Both the UHF and VHF sensors were able to detect stator PD, and in many cases with similar relative sensitivity.
2. Somewhat surprisingly, the UHF sensors were as sensitive, and sometimes much more sensitive, to stator PD than the VHF sensors. This may be due to the effect of current transformers or other devices on the machine terminals that attenuate the PD signals propagating from the stator winding to the VHF sensors on the other side of the transformers.
3. Many phase-resolved PD patterns measured with the VHF sensors still showed that the patterns are corrupted by electrical disturbances. Thus, the UHF sensors are superior at suppressing disturbances that may lead to false indications for large turbine generators operating at high voltages and hydrogen pressures.

REFERENCES

[1] S. R. Campbell, G.C. Stone, H.G. Sedding, G.S. Klempner, W. McDermid and R.G. Bussey, "Practical On-Line Partial Discharge Test for Turbine Generators and Motors," IEEE Trans. Energy Conversion, pp 281-287, 1994.

[2] H.G. Sedding, G.C. Stone, G. Beckerdite, R. Johnsen, A. Penaziev and D.M. Lam, "On-line Partial Discharge Measurements on Turbine Generators – Experience with Stator Slot and Bus Coupler Measurements", Cigre, Paper 11-207, 1998.

[3] P. Grunewald and J. Weidner, "Possibilities and Experience with Off-line and On-line Diagnosis of Turbine Generator Stator Winding Insulation", CIGRE, Paper 11-206, 1994.

[4] W. Hutter, "Partial Discharge Detection in Rotating Electrical Machines", IEEE Electr. Insul. Mag., Vol. 8, No. 3, pp. 21-32, 1992.

[5] G.C. Stone, I.A. Culbert, E.A. Boulter and H. Dhirani, *Electrical Insulation for Rotating Machines, Second Edition*, Wiley, 2014.

[6] Y. Shibuya, S. Matsumoto, M. Tanaka, H. Muto and Y. Kaneda, "Electromagnetic Waves for Partial Discharges and their Detection Using Patch Antenna", IEEE Trans. Dielectr. Electr. Insul., Vol. 17, No. 3, pp. 862-871, 2010.

[7] IEEE 1434:2014, "IEEE Guide for the Measurement of Partial Discharges in AC Electrical Machinery".

[8] IEC TS 60034-27-2:2012, "On-line Partial Discharge Measurements on Stator Winding Insulation of Rotating Electrical Machines".

[9] G.C. Stone and H.G. Sedding, "Comparison of UHF Antenna and VHF Capacitor PD Detection Measurements from Turbine Generator Stator Windings", IEEE Int'l. Conf. Solid Dielectrics, Bologna Italy, pp. 63-66, 2013.

[10] G.C. Stone, "Importance of Bandwidth in the Measurements of PD in Operating Motors and Generators", IEEE Trans. Dielectr. Electr. Insul., Vol. 7, No. 1, pp. 6-11, 2000.

[11] IEC TS 60034-27:2006, "Off-Line Partial Discharge Measurements on the Stator Winding Insulation of Rotating Machines.

[12] N. Oussalah, Y. Zebboudj and S.A. Boggs "Partial Discharge Pulse Propagation in Shielded Power Cable and Implications for Detection Sensitivity", IEEE Electr. Insul. Mag., Vol. 23, No. 6, pp. 5-10. 2007.

[13] S.A. Boggs and G.C. Stone, "Fundamental Limitations in the Measurement of Corona and Partial Discharge", IEEE Trans. Electr. Insul., No.2, pp. 143-149, 1982.

[14] G.C. Stone and V. Warren, "Effect of Manufacturer, Winding Age an Insulation Type on Stator Winding PD Levels", IEEE Electr. Insul. Mag., Vol. 20, No.5, pp. 13-17, 2004.

[15] V. Warren, "How Much PD is Too Much PD", University of Texas First Conf. On-Line Monitoring of Electrical Assets", Austin, Texas, U.S.A., 2014.

[16] M. Belec, C. Hudon and D.N. Nguyen, "Statistical Analysis of Partial Discharge Data", IEEE Int'l. Sympos. Electr. Insul., Toronto, Canada pp. 122-125, 2006.

[17] C.V. Maughan, "Partial Discharge – A Valuable Stator Winding Evaluation Tool", IEEE Int'l. Sympos. Electr. Insul., Toronto, Canada, pp. 388-391, 2006.

[18] W. McDermid and J.C. Bromley, "Experience with Directional Couplers for PD Measurements on Rotating Machines in Operation", IEEE Trans. Energy Conversion, pp. 175-181, 1999.

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