PARTIAL DISCHARGE AS A STATOR WINDING EVALUATION TOOL

Clyde V. Maughan P.E.
Maughan Engineering Consultants
Schenectady, New York 12306 USA
Email: clyde@maughan.com Web: clyde.maughan.com

Abstract: **This paper has been prepared to illustrate the value of partial discharge (PD) testing in assessing the condition of stator windings on operating generators and motors. The database of one particular PD system vendor was chosen for this study because of the magnitude of data accumulated by this company over the last 15 years. It was felt that sufficient data had been accumulated to allow useful statistical analysis of the capabilities of PD testing.**

The PD detection technology used by Iris has been installed on about 6000 generators and motors, and has inspection information from about 3600 machines. On these 3600 generators and motors, PD has successfully identified 209 potential problems that were verified by inspection to be present. In most cases, moderate corrective maintenance permitted return of the equipment to service without major repairs. An estimate of the actual number of avoided failures was not possible from the available reports. But it is clear that many potentially serious stator winding failures were avoided as a result of removal of these machines from service because of high PD readings.

No attempt has been made in the paper to provide technical background or details of the PD test/analysis processes. There are numerous technical papers and industry guides; the interested reader is referred to IEEE 1434, EPRI Reports [9, 10], and other documents in the Bibliography.

While this paper is based somewhat narrowly on data from only one company, there are several other companies involved in PD testing and evaluation. As described below in this paper, these companies have also been successful in identifying stator winding problems through the use of PD equipment.

Clearly, PD testing is a useful tool in monitoring and assessing the condition of stator windings, as well as other associated electrical equipment in the power plant. Because of the power of PD testing, it is expected that the use of PD monitoring will continue to expand at a significant rate in both utility and industrial power plants.

EVOLUTION OF PD TESTING

BACKGROUND

Monitoring of the condition of in-service generators and motors has been a difficult and frustrating challenge to equipment operators. Some of the more common deterioration mechanisms are measured only indirectly, and several are monitored not at all. Because stator winding deterioration and failure has been a major contributor to equipment problems, a high effort has focused on efforts to better monitor the condition of these windings. On-line partial discharge (PD) measurement was developed in an effort to address these issues.

Partial discharge measurement has been used as a stator winding evaluation tool for over 55 years [1]. During this period, many technical papers have been written discussing the capability of partial discharge measurement to detect winding problems and to predict winding failure. In these papers, numerous anecdotal cases have been cited to illustrate successful prediction of individual winding problems based on high PD readings [2-6]. Still, users of PD monitoring have been left with uncertainty as to just how valuable PD measurement might be in assessing the condition of the stator winding of a specific generator or motor.

In an attempt to address this concern, the “success rate” of one vendor’s database has been analyzed. The PD technology this vendor uses has been installed in about 6000 generators and motors and has received data from about 3600 of these machines, thereby accumulating a large data base of 60,342 individual-phase tests [7]. Starting in 1998, this vendor has annually published detailed summaries of the results of these tests, broken down by type of machine, type of PD sensor, voltage rating and hydrogen pressure. This has allowed the vendor to develop recommendations which, in general, suggest that units in the highest 10% of PD activity (for a given class of machine) be regarded as suspect or highly suspect. Based on this general recommendation, equipment users have removed many machines from service for further evaluation via visual inspection and off-line testing. In 209 of these cases the equipment owner has provided the vendor with the results of the evaluation.

This paper will report the results of analysis of this 209-unit data base. It will be seen that while PD monitoring is yet an imperfect test (there is no perfect stator winding test), PD is an important tool for monitoring stator winding condition.

PD SYSTEMS

On-line PD measurement requires the installation of sensors. Several types of sensors have been used: capacitors, radio frequency current transformers (RFCTs) and stator slot couplers (SSCs). [2-4] Most of the initial data for on-line PD measurement was taken using 80 pF capacitive couplers made from short lengths of high voltage power cable. These couplers were primarily installed within hydrogenerators [3]. This arrangement was sensitive only to very high frequencies. Gradually the use of epoxy-mica capacitors built into "stand-off" insulators became common as a signal sensing device. At the present time, two basic capacitive approaches are primarily used: 80 pF capacitors that read frequencies above about 40 MHz and 9000 pF capacitors that generally operate in the 100 kHz to 10 MHz frequency range. There is also some use of capacitors of intermediate range. The 80 pF capacitors have the advantage of separating out much of the "noise" that may lead to false indications of stator winding problems. However, such sensors are only sensitive to PD that is relatively near the capacitive couplers. The larger capacitors are sensitive to PD occurring further from the sensors. However, the information from these sensors requires more expertise to analyze since there tends to be more noise present.

Each of these approaches has strengths and weaknesses, but all are capable of obtaining useful information. It is not an objective of this paper to deal with these pros and cons, but rather to demonstrate the power of PD test and analysis.

It is possible that there will be some convergence of the systems over time. EPRI has had a 10-year project (now in its 8th year) aimed at resolving these issues [8, 9]. The EPRI project has also evaluated the use of electromagnetic interference (EMI) measurement of partial discharge [4, 5]. The classical PD is a time-domain assessment of PD, whereas EMI is a frequency-domain assessment. The two approaches are quite complimentary to each other, and both PD and EMI should become universally used in the industry as stator winding evaluation tools.

For convenience of analysis, the statistical analysis this paper will look in detail at only one of the PD systems [2, 3, 7]. This is not to imply necessarily a difference in capability of the various PD systems, nor is it intended to denigrate the capability of the other systems.

EQUIPMENT

Most of the PD data analyzed in this paper was collected either with 80 pF couplers, Photo 1, or antenna-like sensors – called stator slot couplers (SSCs). Photo 2.

Photo 1. An 80 pF PD sensor. (Iris)

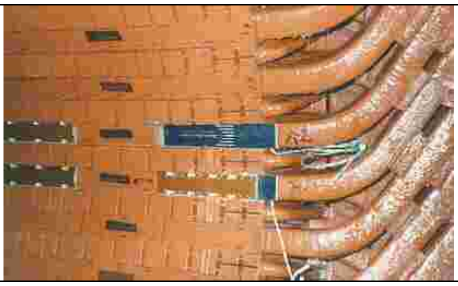

Photo 2. Two installed stator slot couplers. (Iris)

For generators, usually two 80 pF sensors per phase are installed to separate stator winding PD from electrical noise from the power system [2, 3, 10]. The PD and the noise are separated and the number, magnitude and phase position of the PD pulses are tabulated by either the vendor's PDA-IV instrument (for hydrogenerators) or the vendor's TGA-SB instrument (for motors and turbo generators).

Most users have performed the test twice per year during normal operation of the generator or motor; the test itself takes about 30 minutes to perform. In addition to the pulse phase analysis plots, the key output of the instruments is the peak PD magnitude, Qm, which is defined in IEEE 1434 to be the highest PD pulse detected at a pulse repetition rate of 10 or more pulses per second.

ANALYSIS OF DATA BASE

DATA TABULATION

Appendices I through V contains information from the 209 incidents where the on-line PD test identified stator windings (and in a few cases connected equipment) problems, and where in most cases confirmation of a problem was confirmed by an expert via visual inspection of the stator winding. In about 37 of these cases, visual confirmation of the results has not yet been possible.

The incidents are categorized by machine type. For the most part, the identification was based on Qm levels that are higher than 90% of the readings from similar machines [7]. In a few cases, incidents were identified based on a high rate of increase in PD from a previous moderate PD level. Since 209 incidents came from a population of 3600 machines, it appears that about 6% of machines were identified as having stator winding insulation issues.

SUMMARY OF ROOT-CAUSE CATEGORIES

Table I is a root-cause summary of the 209 incidents investigated in the data base. Considering the several categories selected:

Contamination. There were few incidents in this category. Perhaps this is to be expected, since most contamination materials, e.g., ambient dust, wear products and oil, tend to suppress partial discharge rather than cause partial discharge. Unexpected is that the hydrogen-cooled generators, which should be relatively free of ambient dirt, were relatively high in the assigned contamination category.

Vibration. The percentage of hydrogen-cooled generators with vibration identified as root cause is relatively high, reflecting the higher electromagnetic forces in the higher-duty hydrogen-cooled generators. The relatively high percent of hydro generators would probably be a reflection on the inadequate wedging and tying systems used on many of these units in the 1960-1970 time period. In addition, there may be cases of "vibration sparking" included in this category, and while this is not true PD, the sparking is picked up on the PD sensors.

Design/Manufacturing. This category was assigned a large amount of input from the data base. Many of the incidents were not described in detail, but were described in the reports as general PD in the endwindings, with no reported vibration. It is assumed that most of these cases resulted from close physical proximity of bars of different phases, although there may also be cases of failure of the connection between the end-arm grading and the slot grounding paint.

Operations/Maintenance. Few cases seemed to fit into this category; largely these were associated with thermal cycling and with poor connections in the electrical circuits.

Non-Generator. Generator PD detection instrumentation is also sensitive to PD with sources not originating in the stator winding. These incidents were classified in the reports as outside the generator, and might more properly not have been labeled in the generator category.

Insulation Systems. Of the 182 cases where the type of insulation system is recorded, about 40% are asphalt-mica or polyester-mica, indicating that many of these machines are old. Common use of asphalt was discontinued in about 1960 and the transition from polyester-mica to epoxy mica on new windings occurred in 1970’s.

Note that localized problems remote from the sensor may not in general be detected by PD tests, e.g., endwinding vibration, slow water leaks at connections in water-cooled windings and some types of spark erosion (also called “vibration sparking” and “Type 1 slot discharge”).

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ROOT-CAUSES OF POTENTIAL FAILURES

Stator winding failure from PD alone has been uncommon. This is due to the fact that most high electrical voltages in a generator stator winding are contained by mica insulation systems. Mica is highly resistant to PD, but if the attack is allowed to continue for a long period of time, even mica systems may fail. Conditions leading to failure are exacerbated if there are disturbances to the electrical dielectric fields from instrumentation cable, previous arcing damage from initial factory high potential test, or mechanical damage to the mica system, for example.

More usually, PD has been an indicator of other problems within the generator, e.g., stator bar vibration, failing electrical connections. Both of these conditions can lead to winding failure in a relatively short time period, perhaps less than a year.

Considering the Root-Cause Categories as to likelihood of PD resulting in winding failure:

Contamination. As indicated above, contamination in general is not readily detected by PD, Photo 3, although if the contaminant were conductive, e.g., metallic filings, PD may give an indication of pending troubles.

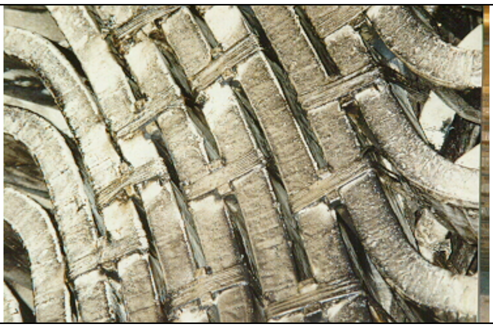

Photo 3. Contaminated stator endwinding.

Vibration. This is the most serious type of deterioration likely to be detected by PD readings, Photos 4 & 5. Particularly, bar vibration in the slot is a serious concern that PD may be expected to detect. Since this type of deterioration is fast acting – several months to a few years – early detection is important. Of the instrumentation applied to generators, only PD is likely to detect the problem prior to in-service failure. (Indirectly, bar vibration in the slots may be expected if RTD sensors in the slot are failing one after another over time.)

Photo 4. End-of-slot indications of vibration sparking.

Photo 5. Stator bar failure due to slot vibration sparking.

Design/Manufacturing. Numerous conditions on the original winding may result in generation of PD. For example, close clearances between bars in different phases will facilitate PD generation. Photo 6. Most 2-pole stator windings have three locations at each end and on each layer, around the endwinding circumference, where line-to-line voltage exists between adjacent bars. If clearance is less than about 3/16", PD is likely to be generated.

Photo 6. PD at inadequate bar spacing.

Close clearance locations between top and bottom layers of bars are likely to result in the same undamaging PD generation. Inadequate voltage grounding and grading systems will also generate PD, and this type of PD may be damaging, e.g., connection between end arm grading and slot grounding paints and improper location of grounding planes in the bar groundwall. Nothing short of a stator rewind can correct most of these conditions, but fortunately significant damage is unlikely to occur from most design/manufacturing deficiencies.

Operation/Maintenance. Thermal cycling is unavoidable where load changes are required on a generator. Significant deterioration may result, and in most cases this deterioration will not cause conditions which will result in high PD readings. Failing electrical connections may result from original manufacture or from repairs; any associated arcing may be detected as PD if readings are being taken during the short time that failure is occurring. In parallel electrical circuits within armature bars, once separation occurs arcing will cease and PD will not detect the incident. Photos 7 & 8. Thus, in general, failing connections are unlikely to be detected by PD instrumentation.

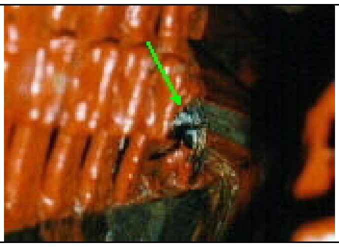

Photo 7. Failure to 1 of 28 parallel circuits in a series connection.

Photo 8. Failure of a parallel one-half bar.

FAILURE CONSEQUENCES

The data included in the 209 incident summaries were not of sufficient detail to allow more than a rough estimate of avoided costs. But because of the large number of incidents, without the PD data clearly there would be a major impact on the utilities involved. Permitting the owner to take a maintenance outage, rather than a forced outage, of itself would be a major positive impact.

Of the 209 incidents in the data bank, most would not be expected to cause in-service failure. Only those listed in the "*vibration*" category are probable candidates for service failure. But these 50 units tabulated are not an insignificant number of generators. If as many as half were to fail in service, these would represent forced outage costs associated with 25 incidents, and *unscheduled* repair costs of many millions of dollars.

Of the remaining incidents, it is unlikely that any of the "contamination" incidents would result in forced outages, and only a few of the "*design/manu- facturing*" and "*operations/maintenance*" would force an outage. Still, in each case, necessary work was permitted to be accomplished during a planned, rather than forced outage.

PD DATA FROM ADDITIONAL TESTING COMPANIES

While the analysis contained in this paper is based somewhat narrowly on data from only one company, several other companies are involved in PD testing and evaluation. A brief summary is provided below on the work of three other PD testing organizations. These companies have also been successful in identifying stator winding problems through the use of PD equipment.

Adwel. Adwel has been involved in PD work since the early days of commercial PD monitoring, initially with an exclusive license from Ontario Hydro between 1986 and 1991 [11, 12]. Adwel studies have confirmed that 500 pF pickups may detect PD signals that are not seen with the smaller 80 pF pickups. Adwel has tended to use 500 pF sensors on lower voltage machines, and 80 pF sensors on units of higher than 11 kV (Photo 9). Adwel has conducted many PD tests on generators and large motors; in some cases, machines have been shut down due to high, or increasing, PD readings, and problems have been found that correspond to the PD indications. Local repairs, e.g., cleaning and repainting a PD source, have resulted in lower PD readings upon return to service.

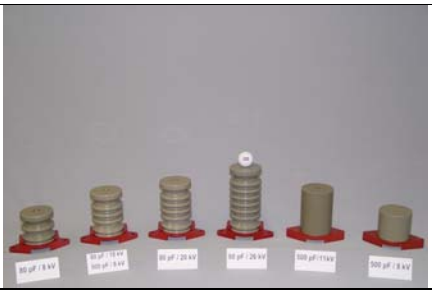

Photo 9. A selection of PD sensors. (Adwel)

Alstom. Alstom (and its component company, ABB) have had a major PD program for several years. [13] The Alstom GOLD continuous monitoring system displays the assessed condition of the stator winding as: Normal, Warning and Alarm. Data from the monitor system can be transmitted electronically to Alstom Power for an updated condition assessment of the winding. Alstom has had several “saves” with their PD system. An Alstom sensor installation is shown in Photo 10.

Photo 10. 9000 pF sensor in foreground. (Alstom)

American Electric Power. AEP has been using Electromagnetic Interference (EMI) monitoring of combustion turbine and steam turbine generators for 25 years and has evaluated about 300 generators during this period. The EMI system provides non-invasive diagnostic evaluation condition-based information on the generator stator. But EMI also provides important information on the condition of the field, collector, bearings, oil seals, exciter, bus and associated electrical systems.

The test RFCT sensor can be mounted permanently on a neutral grounding lead during a brief shutdown. Photo 11. But a temporary RFCT can be installed without the need to remove the generator from service.

EMI diagnostics has the ability to detect and classify a variety of patterns generated by low voltage and high voltage system defects. However, pattern recognition is highly judgmental and based on both training and experience. Reference paper [5] lists 17 stator and 12 system problem conditions found with EMI during the testing of these 300 generators. Interestingly, the ratio of 17 problems in 300 tests is almost identical to the Iris test experience.

Photo 11. Two RFCTs mounted on a neutral grounding lead. (AEP)

Other Testing Companies. There are additional companies making significant contributions to the industry through their PD testing services. The author apologizes to those companies not included in this paper.

CONCLUSIONS

While many electric power generators have PD detection systems installed, perhaps in the order of 5,000 in the industrial countries, this would represent less than 10% of the large generators in these countries. Considering the high capability of PD monitoring, as illustrated in this paper, continued rapid growth in the installation of PD monitoring instrumentation should be encouraged and expected.

A Closing Observation. The author recognizes that there is considerable uncertainty in the analysis supplied above, and many suppositions are made. However, the basic conclusion seems well founded: PD monitoring has identified many pending service problems, prevented a significant number of generator service failures, and has resulted in a major cost saving to the power generation industry. It is hoped that as data continue to be accumulated by PD testing companies on PD monitoring, a more definitive analysis can and will be made.

Acknowledgment: The author would like to thank Greg Stone of Iris Power Engineering for access to that company's summary of case studies, and for his valued assistance in preparing this paper. Also, thanks are due to those others who have supplied information included in this paper.

Table I. Categories of Failure Root-Causes and Insulation Systems

	Root Cause						Insulation System		
	Contam-ination	Vibra-tion	Design/ Manu	Operation /Maint	Non-Gener -ator	Root-Cause Total	Asphalt Mica	Poly-ester Mica	Epoxy Mica
Turbo, H2	2	6	8			16	7	1	9
Turbo, air	1	4	14	8	2	29	2	1	26
Hydro	3	28	83	1		115	28	32	37
Motor	3	12	20	2	3	40			39
SwitchGear	1			8		9			
Totals	10	50	125	19	5	209	37	34	111

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Appendix I. Air-Cooled Turbine-Generators

Date of Test	Generator Rating	Age of Winding	Insulation System	Problem Found	PD Levels (Qm)	Sensors	Comments
1986	117 MW, 13.8 kV	1969	Epoxy Mica	loose windings, cracks after mal synchronization	?	80 pF	PD increasing. Visual inspection.
1992	30 MW, 13.8 kV	1958	Asphalt Mica	contamination	300 mV	375 pF	visual
1996	57 MW, 13.8 kV	1994	Polyester Mica	thermal	633 mV	80 pF	similar machine failures
1996	104 MW, 13.8 kV	1994	Epoxy Mica	EW PD	338 mV	80 pF	visual
1998	94 MW, 13.8 kV	1978	Epoxy Mica	EW PD	3200 mV	80 pF	reduction after repair
2000	191 MW, 16 kV	1993	Epoxy Mica	loose bars, EW PD	3000 mV	80 pF	failed
2001	225 MW, 18 kV		Epoxy Mica	semicon, EW PD	1400 mV	80 pF	visual, reduction after repair
2002	13.8kV, 76MW	1980	Epoxy Mica	Endwinding Activity	2433 mV	80 pF	verified
1998	16kV, 200MVA	1993	Epoxy Mica	Loose Bars	2187mV	80 pF	verified
2001	115kVA, 104MW		Epoxy Mica	Phase-Ground	579mV	80 pF	verified
2001	13.8kV, 35MW		Epoxy Mica	Slot Discharge	1160mV	80 pF	verified; visual inspection confirmed phase - phase activity and marginal spacing issues
2003	13.8kV, 55MW	2003 rewind	Epoxy Mica	connection problem or sharp point of discharge isolated to phase B	1250mV	80 pF	verified; confirmed visually; heating condition and oil contamination on phase B bus
2002	13.8kV, 24MW		Epoxy Mica	electrical connections	1200mV	80 pF	verified
2005	13.8kV, 89MVA	1999	Epoxy Mica	electrical connections	8500mV	80 pF	verified, following maintenance Qm levels dropped to 158mV
2002	13.8kV		Epoxy Mica	hot connection	766mV	80 pF	verified by visual inspection
1995	13.8kV, 63MW	1995 rewound		thermal cycling	~975mV	80 pF	verified, machine was rewound
2004	13.8kV, 60MW	2001	Epoxy Mica	loose connections	>1170mV	80 pF	not verified
2003	13.8kV, 20MW	1990	Epoxy Mica	interphasal / connections	1200mV	80 pF	verified, unit failed
2003	16kV, 169MW	1997	Epoxy Mica	electrical tracking	715mV	80 pF	verified; tracking was visually confirmed
2000	13.8kV, 15MW	1968	Asphaltic Mica	Endwinding Activity	684mV	80 pF	verified
2003	13.8kV, 82MW	1998	Epoxy Mica	Endwinding Activity	285mV	SSC	verified by off line tests
2004	13.8kV, 36MW	1992	Epoxy Mica	semicon deterioration	665mV	80 pF	client email
2004	13kV, 25MW	1988	Epoxy Mica	semicon deterioration, connections	573mV	80 pF	not verified
1997	15kV, 170	1997	Epoxy Mica	Endwinding Activity	2075mV	80 pF	winding had resin injection in 2001…

2002	16 kV, 191 MW	2002	Epoxy Mica	Could not pinpoint actual failure mechanism	3200 mV	80 pF	verified
2004	16 kV, 191 MW	1993	Epoxy Mica	Could not pinpoint actual failure mechanism	3200 mV	80 pF	not verified
2004	16 kV, 206 MW	1993	Epoxy Mica	Could not pinpoint actual failure mechanism	1930	80 pF	not verified
2004	11kV, 90 MW	200	Epoxy Mica	High levels of PD coming from Bus and/or system		80 pF	not verified
2004	13.8 kV, 136 MW	2002	Epoxy Mica	Source External to the machine		80 pF	not verified
2005	13.8 kV, 20 MW		Epoxy Mica	Suspected Phase to phase discharges		1190	visual
2002	13.8 kV, 97 MW	1987	1/Sym	Increasing PD activity. Delamination/interphasal arcing and there are some Noise patterns as well	168	80 pF	Not verified
1997	13.8 kV, 107 kVa	1991		Extensive insulation degradation; coils loose in the slot	1368 mV	80 pF	Not verified

Appendix II. Hydrogen-Cooled Turbine-Generators

Date of Test	Generator Rating	Age of Winding	Insulation System	Problem Found	PD Levels (Qm)	Sensors	Comments
1984	160 MVA, 17 kV	1972	Epoxy Mica	loose coils	1150	80 pF	visual
1986	70 MW, 13.8 kV	1960	Asphalt Mica	loose windings	800 mV	80 pF	reduction after repair
1986	70 MW, 13.8 kV	1960	Asphalt Mica	loose windings	1400 mV	80 pF	reduction after repair
1992	100 MW	1971	Polyester Mica	loose windings contamination	200 mV	375 pF	reduction after repair
1996	365 MW, 20 kV	1963	Epoxy Mica	loose windings, contamination	500 mV	SSC	visual
2004	187 MW, 22 kV	1960	Asphalt Mica	thermal	400 mV	80 pF	Fast increase. Decrease in PD after rewind.
2002	20kV, 690MW, 59psi	1984 / 2000	Epoxy Mica	phase - phase	177mV	SSC's, 80 pF 's	verified; case study 1
2001	18kV, 192MW, 29psi	1959	Ashpaltic Mica	thermal dertrioration	319mV	80 pF	
2003	18kV, 360MW, 44psi	2003	Epoxy Mica	slot discharge	13mV	SSC	verified
1994	22kV, 221MVA	1960	Ashpaltic Mica	slot discharge	~500mV	80 pF	verified, rewind was delayed for 9 years
2003	13.8kV, 76MW, 20psi	1982	Epoxy Mica	connections / iron core arcing	1309mV	80 pF	not verified
2002	13.8kV, 90MW	1956	Ashpaltic Mica	decrease in activity following maintenance	94mV to 8mV	80 pF	verified by report
2002	13.8kV, 42MW	1979	Ashpaltic Mica	slot discharge	~450mV	80 pF	verified, semicon injection and rewedge done, PD levels dropped temporarily
2004	18kV, 180 MW, 30psi	1973	Epoxy Mica	Noise pulses from outside the hydrogen environment		80 pF	not verified
2002	18kV, 600MW	1976	Epoxy Mica	delamination, loose wedges	87mV	SSC	verified
2004	22 kV, 590 MW	1970	Epoxy mica	Increase in PD activity. Thermal and winding surface activity	70 mV	SSC	not verified
2004	18 kV, 380 mw	2002	Micadur	lots of excitation pulses		Bus Couplers	not verified

Appendix III. Hydro Turbine-Generators

Date of Test	Generator Rating	Age of Winding	Insulation System	Problem Found	PD Levels (Qm)	Sensors	Comments
1979	75 MW, 13.8 kV	1967	Polyester Mica	thermal	700	80 pF	visual
1980	200 MW, 13.8 kV		Epoxy Mica	loose bars	500	80 pF	visual
1981	120 MW, 13.8 kV	1971	Epoxy Mica	loose bars	>1600 mV	80 pF	reduction after repair
1981	60 MW, 13.9 kV	1959	Polyester Mica	semicon degradation	800 mV	80 pF	visual
1981	50 MW, 13.8 kV	1950	Epoxy Mica	semicon degradation	500 mV	80 pF	visual
1981	200 MW, 13.8 kV		Epoxy Mica	loose bars	850 mV	80 pF	reduction after repair
1981	120 MW, 13.8 kV	1971	Epoxy Mica	loose bars	350 mV	375 pF	reduction after repair
1981	107 MW, 13.8 kV	1970	Epoxy Mica	loose bars	400 mV	375 pF	reduction after repair
1981	107 MW, 13.8 kV	1970	Epoxy Mica	loose bars	450 mV	375 pF	reduction after repair
1981	50 MW, 13.8 kV	1950	Epoxy Mica	semicon degradation	425 mV	375 pF	visual
1984	80 MW, 13.8 kV	1974	Polyester Mica	semicon degradation	1100 mV	80 pF	visual
1984	255 MW, 15kV	1977	Epoxy Mica	thermal, semicon	1000 mV		visual
1984	62 MW, 13.8 kV	1968	Epoxy Mica	slot discharge	600 mV		visual
1984	60 MW, 13.8 kV	1959	Polyester Mica	semicon degradation	600 mV		reduction after repair
1984	60 MW, 13.8 kV	1959	Asphalt Mica	thermal	650 mV		reduction after rewedging
1986	72 MW, 13.8 kV	1955	Asphalt Mica	thermal	300 mV	80 pF	visual
1986	320 MW, 17 kV		Epoxy Mica	thermal cycling, semicon	>800 mV	80 pF	reduction after rewind
1986	74 MW, 13.8 kV	1976	Epoxy Mica	loose winding	> 800 mV	80 pF	visual
1986	50 MW, 13.8 kV	1959	Polyester Mica	semicon, thermal cycling	> 800 mV	80 pF	visual
1986	115 MW, 13.8 kV	1964	Asphalt Mica	thermal	> 300 mV	80 pF	visual
1986	115 MW, 13.8 kV	1965	Asphalt Mica	thermal	>300 mV	80 pF	visual
1986	110 MW, 13.8 kV			loose coils, EW PD	>300 mV	80 pF	visual
1986	110 MW, 13.8 kV			loose coils, EW PD	>70 mV	80 pF	visual
1986	110 MW, 13.8 kV			loose coils, EW PD	>70 mV	80 pF	visual

1986	90 MW, 16 kV		Polyester Mica	thermal cycling, semicon	>100 mV	80 pF	visual
1986	155 MW, 13.8 kV	1981	Polyester Mica	loose windings		80 pF	visual
1987	66 MW, 13.8 kV	1966	Polyester Mica	semicon	1700 NQN	80 pF	visual
1987	66 MW, 13.8 kV	1966	Polyester Mica	semicon	725 NQN	80 pF	visual
1987	68 MW, 13.8 kV	1965	Polyester Mica	semicon	>1000 NQN	80 pF	visual
1987	64 MW, 13.8 kV	1963	Polyester Mica	semicon	400 NQN	80 pF	visual
1987	64 MW, 13.8 kV	1963	Polyester Mica	semicon	900 NQN	80 pF	visual
1987	70 MW, 13.8 kV	1978	Polyester Mica	semicon	1300 NQN	80 pF	visual
1987	70 MW, 13.8 kV	1978	Polyester Mica	semicon	700 NQN	80 pF	visual
1987	75 MW, 13.8 kV	1967	Polyester Mica	semicon	1000 NQN	80 pF	visual
1987	75 MW, 13.8 kV	1967	Polyester Mica	semicon	600 NQN	80 pF	visual
1987	74 MW, 13.8 kV	1977	Epoxy Mica	loose windings	1200 NQN	80 pF	visual
1987	50 MW, 13.8 kV	1974	Epoxy Mica	semicon	1150 NQN	80 pF	visual
1987	50 MW, 13.8 kV	1975	Epoxy Mica	semicon	1100 NQN	80 pF	visual
1987	50 MW, 13.8 kV	1950	Polyester Mica	loose windings	800 NQN	80 pF	visual
1987	50 MW, 13.8 kV	1950	Polyester Mica	loose windings	400 NQN	80 pF	visual
1987	50 MW, 13.8 kV	1950	Polyester Mica	loose windings	1100 NQN	80 pF	visual
1988	80 MW, 13.8 kV	1954	Asphalt Mica	loose windings	300 NQN	80 pF	reduction after repair
1988	80 MW, 13.8 kV	1954	Asphalt Mica	loose windings	>400 NQN	80 pF	reduction after repair
1988	450 MW, 20.5 kV	1986	Polyester Mica	thermal cycling	1600 mV	80 pF	dissection
1988	450 MW, 20.5 kV	1986	Polyester Mica	thermal cycling	1600 mV	80 pF	dissection
1988	450 MW, 20.5 kV	1986	Polyester Mica	thermal cycling	1600 mV	80 pF	dissection
1988	450 MW, 20.5 kV	1986	Polyester Mica	thermal cycling	1600 mV	80 pF	dissection
1988	450 MW, 20.5 kV	1986	Polyester Mica	thermal cycling	1600 mV	80 pF	dissection
1994	227 MW, 13.8 kV	1973	Polyester Mica	thermal	1400 NQN	100 pF	visual
1994	175 MW, 13.8 kV	1982	Epoxy Mica	ring bus support PD	800 mV	100 pF	reduction after repair

1994	175 MW, 13.8 kV	1982	Epoxy Mica	loose windings	500 mV	100 pF	visual
1994	175 MW, 13.8 kV	1982	Epoxy Mica	loose windings	500 mV	100 pF	visual
1995	80 MW, 12.5 kV	1959		thermal	1600 mV	80 pF	dissection
1996	72 MW, 13.8 kV	1958	Asphalt Mica	thermal		375 pF	Rapid increase. Failure.
1996	80 MW, 13.8 kV	1955	Asphalt Mica	loose winding, thermal	215 mV	80 pF	failure
1996	80, 13.8 kV	1952	Asphalt Mica	loose winding, thermal	196 mV	80 pF	failure
1996	37 MW, 13.8 kV	1961	Asphalt Mica	grading	240 mV	80 pF	visual
1996	37 MW, 13.8 kV	1948	Asphalt Mica	?	236 mV	80 pF	failed
1996	15 MW, 13.8 kV	1952	Asphalt Mica	thermal	440 mV	80 pF	visual
1996	45 MW, 13.8 kV	1945	Asphalt Mica	thermal	650 mV	80 pF	visual
1996	36 MW, 13.8 kV	1966	Asphalt Mica	thermal	921 mV	80 pF	failed
1996	36 MW, 13.8 kV	1966	Asphalt Mica	thermal	1158 mV	80 pF	failed
1996	36 MW, 13.8 kV	1966	Asphalt Mica	thermal	1256 mV	80 pF	visual
1996	36 MW, 13.8 kV	1966	Asphalt Mica	thermal	1370 mV	80 pF	failed
1996	31 MW, 13.8 kV	1969	Asphalt Mica	thermal	1800 mV	80 pF	failed
1996	30 MW, 13.8 kV	1955	Asphalt Mica	EW PD	269 mV	80 pF	visual
1996	30 MW, 13.8 kV	1955	Asphalt Mica	EW PD	391 mV	80 pF	visual
1996	110 MW, 13.8 kV			minor loose coils	117 mV	80 pF	visual
1998	146 MW, 16.5 kV	1995		EW PD	1235 mV	80 pF	visual
1998	146 MW, 13.8	1995		EW PD	991 mV	80 pF	visual
1998	200 MW, 13.8 kV			semicon, EW PD	340 mV	80 pF	visual
1998	200 MW, 13.8 kV			loose coils, EW PD	227 mV	80 pF	visual
1998	200 MW, 13.8 kV			loose coils, EW PD	236 mV	80 pF	visual
1998	159 MW, 16.6 kV	1980	Epoxy Mica	loose bars, contamination	234 mV	80 pF	reduction after repair
1998	159 MW, 16.6 kV	1980	Epoxy Mica	loose bars, contamination	689 mV	80 pF	visual
1998	159 MW, 16.6 kV	1980	Epoxy Mica	thermal cycling	408 mV	80 pF	visual

1998	44 MW, 11 kV	1976	Epoxy Mica	EW PD	350 mV	80 pF	visual, reduction after repair
1998	120 MW, 15 kV	1992	Epoxy Mica	EW PD-endcaps	1100 mV	80 pF	visual
2000	48 MW, 13.8 kV	1976	Epoxy Mica	semicon	1400 mV	80 pF	visual
2000	74 MW, 11 kV	1973	Polyester Mica	semicon	1159 mV	80 pF	rewedged
2000	47 MW, 11 kV	1968	Asphalt Mica	thermal	1488 mV	80 pF	visual
2000	24 MW, 11 kV	1960	Polyester Mica	semicon, contamination	838 mV	80 pF	visual, high ozone
2001	90 MW, 13.8 kV		Epoxy Mica	grading coating	400 mV	80 pF	visual
2003	170 MW,	1973	Epoxy Mica	EW PD, thermal cycling	900 mV	80 pF	dissection
2003	170 MW,	1974	Epoxy Mica	EW PD, thermal cycling	1700 mV	80 pF	dissection
2004	155 MW, 15.7 kV	1984	Epoxy Mica	semicon, grading coating	1499 mV	80 pF	visual
2004	155 MW, 15.7 kV	1984	Epoxy Mica	semicon, grading coating	768 mV	80 pF	visual
1996	11.0kV, 44.4MVA	1976		Phase-Phase		80 pF	verified
1985	16.5kV, 159MW	1980	Epoxy Mica	Spacing Issue		80 pF	verified
1985	13.8kV 90MVA	1980	Epoxy Mica	Spacing Issue		80 pF	verified
2002	14.4kV, 34MW	1962		Phase - Phase	1400mV	80 pF	verified; Rag located in machine following visual inspection and PD levels dropped after removal
2002	14.4kV, 20MW	1964	Polyester Mica	Endwinding	1420mV	80 pF	not verified
2002	13.8kV, 115MW		Epoxy Mica	slot discharges	590mV	Cable Coupler	verified, white powder at stress coatings
1997	13.8kV, 55MW		Epoxy Mica	slot discharges (semicon damage)	500mV	80 pF	verified by visual inspection
2004	14.4kV,		Epoxy Mica	arcing at stress relief near system coupler	198mV	80 pF	verified by customer (pictures)
2004	13.8kV, 34MW	1993	Polyester Mica	suface discharge	623mV	80 pF	not verified
1997	11kV, 120MW	~1967		slot discharge	2000mV NQN	80 pF	verified, published paper
	11kV, 54MW	1973	Polyester Mica	semicon deterioration	1159mV	80 pF	verified
	XXkV, 38MW	1968	Ashphaltic Mica	thermal deterioration	1488mV	80 pF	verified
	11kV, 18MW	1960	Thermalastic	semicon deterioration	838mV	80 pF	verified
	11kV, 11MW	1954	Ashphaltic Mica	load cycling	317mV	80 pF	verified
2004	13.8kV, 100MVA	1985	Epoxy MicAsphalt Micaat	stress grading interface	198mV (rapid increase)	80 pF	verified

2005	13.8kV, 78MVA	2003 rewind	Epoxy Mica	Phase - Phase	~750mV	80 pF	not verified, High interphasal PD was classified as noise
2001	13.8kV, 174MW			suface discharge, interphasal	593mV (increasing)	80 pF	not verified
1999	14.1 kV, 46 MW	1976		multiple causes	1362 mV	80 pF	not verified
1998	15.75 kV, 80MW	1970			3473 mV	80 pF	not verified
	14 kV, 45.30 MW		Epoxy Mica	groundwall or surface problems	1978 mV	80 pF	not verified
2003	15.5	1990	Epoxy Resin	thermal/phase to phase/poor electrical connection	1085 mV	80 pF	not verified
2005	12.5kV, 9MW	1984	Epoxy Mica	thermal deterioration	1355mV	80 pF	not verifed
2003	23 MW, 11 kV	1958	Asphaltic Mica	surface discharge effect within the slot section (Cphase		80 pF	not verified
2003	25 MW, 11 kV	1945	Asphaltic Mica	widespread in nature; interphasal activity	1058 mV	80 pF	not verified
2003	33 MW, 11 kV	1964	Asphaltic Mica	Interphasal activity coupled with internal discharging.		80 pF	not verified
2003	31 MW, 11 kV	1958	Asphaltic Mica	Interphasal activity coupled with internal discharging.		80 pF	not verified
2003	31 MW, 11 kV	1961	Asphaltic Mica	Isolated problem in the winding	1900 mV	80 pF	not verified

Appendix IV. Motors

Date of Test	Generator Rating	Age of Winding	Insulation System	Problem Found	PD Levels (Qm)	Sensors	Comments
1995	3000 HP, 6.9 kV		Epoxy Mica	poor impregnation	300 NQN	RFCT	similar machine failure
1995	3000 HP, 6.9 kV		Epoxy Mica	poor impregnation	500 NQN	RFCT	similar machine failure
1995	3000 HP, 6.9 kV		Epoxy Mica	poor impregnation	1600 NQN (800 mV)	RFCT	rewound
1995	3000 HP, 6.9 kV		Epoxy Mica	poor impregnation	800 NQN	RFCT	rewound
1995	3500 HP, 13.2 kV		Epoxy Mica	loose coils	413 mV	RFCT	similar machine failure, reduction after rewind
1995	3500 HP, 13.2 kV		Epoxy Mica	loose coils	413 mV	RFCT	similar machine failure, reduction after rewind
1999	250 HP, 3.3 kV	1997	Epoxy Mica	poor impregnation	1162 mV	80 pF	dissection
1999	380 kW, 3.3 kV	1976	Epoxy Mica	thermal	200 mV	80 pF	visual
2000	19000 HP, 13.8 kV	1980	Epoxy Mica	semicon	280 mV (eq to 1300 mV)	RFCT	failed
2000	19000 HP, 13.8 kV	1980	Epoxy Mica	semicon	800 mV (eq to 4000 mV)	RFCT	failed
2000	3500 HP, 13.2 kV	1993	Epoxy Mica	motor lead spacing	110 mV (RFCT)	RFCT	Fast rate of rise. Failed.
2000	7000 HP, 6.6 kV	1985	Epoxy Mica	poor impregnation	1600 mV	80 pF	TVA probe, dissection, similar motor failure
2001	11,000 HP, 13.8 kV		Epoxy Mica	motor lead spacing	2750 mV	80 pF	visual, reduction after repair
2001	4.1 kV	1970	Epoxy Mica	contamination	850 mV	80 pF	visual
1998	13.2kV, 19000HP	1979	Epoxy Mica	Endwinding	4000mV	RFCT	verified
2000	13.8kV, 11000HP	1992		Damaged cable at CT	2750mV	80 pF	verified
2003	13.8kV, 25MW	1995	Epoxy Mica	Multiple Sources	1448mV	80 pF	verified DEM
2003	13.8kV, 14000HP	2000 rewind	Epoxy Mica	Manufacturing Defect	1200mV	80 pF	Verified
2001	6.6kV, 2500HP	1975	Epoxy Mica	Phase-Phase	2000mV	80 pF	Verified
2004	13.8kV, 5630HP	2000	Epoxy Mica	Endwinding	1675mV	80 pF	verified
2004	13.8kV, 3500HP	1970 / 2002 rewind	Epoxy Mica	Slot Activity (rapid deterioration)	258mV	80 pF	verified, pictures
2004	13.8kV, 27000HP	1993	Epoxy Mica	Phase-Phase	1182mV	80 pF	verified, pictures
2004	4kV	2004	Epoxy Mica	Slot Discharge (acceptance test)	1283mV	80 pF	verified, winding was replaced
1996	6.9kV		Epoxy Mica	Cross Coupling of excitation system	27mV	80 pF	verified

2004	4.1kV	1998	Epoxy Mica	arcing at slot exit		80 pF	not verified
2003	14.1kV, 220HP		Epoxy Mica	internal & interphasal	593mV	80 pF	not verified
1999	11kV, 15MW	1973		thermal delemination	1347mV	80 pF	not verified
2001	13.8kV, 800HP	1996	Epoxy Mica	connection issue	427mV rapid increase	80 pF	not verified
2003	6.6kV, 900HP	1974	Epoxy Mica	slot discharges / slot exits	1058mV	80 pF	visual
2004	13.8kV, 5000HP	2002	Epoxy Mica	Phase-Phase		80 pF	motor failed
2003	12kV, 6000HP	1980’s	Epoxy Mica	Phase-Phase	657mV	80 pF	client emails in file, inadequate spacing concerns
2003	12kV, 6000HP	1980’s	Epoxy Mica	Phase-Phase	1131mV	80 pF	not verified
	4kV,		Epoxy Mica	contamination		80 pF	verified; after cleaning PD leveled off to low levels
1996	13.8kV, 5000HP	1995	Epoxy Mica	surface discharge	>500mV	80 pF	not verified
2003	12 kV, 6000 HP	rewound early 80’s	Epoxy Mica	roundwall voids	1316 mV	80 pF	not verified
1999	13.2 kV, 6000HP	1985	Epoxy MicaC	One phase with high surface discharge	440 mv	80 pF	not verified
2004	12.5kV, 11000 hp	1998	Epoxy Mica	Endwinding		80 pF	verified – cleaning of windings
2004	13.8kV, 30,000hp	2001	Epoxy Mica	motor leads and /or terminal box		80 pF	not verified
2002	11.5kV, 2500HP	2000	Epoxy Mica	thermal delemination, interphasal	3079mV	80 pF	not verified
2000	11kV, 2500HP		Epoxy Mica	thermal delamination, interphasal	1800mV	80 pF	not verified
2004	11.5kV, 9.5MVA	1996	Epoxy Mica	surface discharge	650mV	80 pF	not verified
1996	10.25 kV	1990		voids within the insulation and loose windings and, endwinding contamination		80 pF	Verified – machine failed sometime after this test.

Appendix V. Bus and Switchgear

Date of Test	Generator Rating	Age of Winding	Insulation System	Problem Found	PD Levels (Qm)	Sensors	Comments
1996	75 MW, 13.8 kV	n/a		broken PT ground	>800 mV	80 pF	visual
2001	350 MW, 20.5 kV			PT cable dAsphalt Micage, debris in bus, poor connections	1172 mV	80 pF	visual, reduction after repair
2001	14.4kV, 20MW	1964	Polyester Mica	Bus-CT problem	1861mV	80 pF	verified; electrical tracking problem found
2000	13.8kV	1948	Polyester Mica	loose connection at or near switchgear	1770mV	80 pF	verified by visual inspection
2004	17kV	1968	Polyester Mica	contAsphalt Micaination on bus between machine and system sensor	78mV	80 pF	verified by visual inspection bus was contAsphalt Micainated with oil
2002	13.8kV		Epoxy Mica	loose connection at bus to switchgear	3200mV	80 pF	verified, connections were repaired and PD levels dropped
2000	21kV	1997	Epoxy Mica	cable connection arcing near system coupler	1041mV	80 pF	verified, ungrounded cable to VT found by visual inspection
2003	13.8kV	1992	Epoxy Mica	problem CT causing high PD	1570mV	80 pF	verified (picture)
2002	13.8kV, 21MW	1994	Epoxy Mica	loose bolts on bus insulators	2257mV	80 pF	verified
2003	13.9kV, 78MW	1990	Epoxy Mica	high noise issues		80 pF	not verified
1999	350MW	1996	Epoxy Mica	arcing bus supports	1172mV	80 pF	verified
2004	21kV, 290MW	2000	Epoxy Mica	suspected bus supports	750mV	80 pF	not verified