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Generator On-Line Monitoring and Condition Assessment

Partial Discharge and Electromagnetic Interference

Technical Report

Generator On-Line Monitoring and Condition Assessment

Partial Discharge and Electromagnetic Interference

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PRODUCT DESCRIPTION

The trend toward lengthening the generator inspection interval and limiting the extent of disassembly for inspection clearly favors greater use of on-line condition monitoring. More accurate assessment of generator component condition is increasingly important to maximizing unit availability and minimizing risk and forced outages. Techniques for partial discharge (PD) detection, in the time domain, or electromagnetic interference (EMI), in the frequency domain, are part of an armory of tools now available to utility engineers for condition-based monitoring. Because the aging of stator insulation is a major factor limiting the life of a high-voltage machine, accurate assessment of insulation system status has become a pivotal issue in reliability and maintenance decisions. This report documents EPRI's initiative to provide utilities with an objective comparison of methods for assessing the condition of stator insulation in large utility generators and their associated peripherals, based on discharge analysis in the PD and EMI domains. The report also includes a specification for PD testing of large utility generators based solely on technical and perceived scientific merit.

Results & Findings

This report is the culmination of a multiyear project to assess the efficacy of a variety of PD and EMI methods for diagnosis of anomalous conditions of the stator insulation structure in large utility turbine generators. Outages scheduled for several machines in the program have permitted inspection and verification of stator winding condition to be undertaken this year. As a consequence, this report not only highlights salient aspects of tests conducted in 2005-06, but also provides an assessment of the strengths and weakness of the various PD and EMI techniques used in light of established machine condition. On the basis of the study, a PD specification is derived and additional insight is provided on how the industry is likely to proceed with computer-based diagnosis in light of these techniques. This report should be read in conjunction with earlier EPRI reports on this subject, 1001209 (2000), 1007742 (2003), 1004958 (2004), and 1010207 (2005).

Challenges & Objective(s)

One of the original objectives of this project was to identify the methods and "best practices" that show the most promise for assessment of utility generators based on PD and EMI monitoring. Experience gained over the last few years involving a variety of methods has provided some basis for evaluating the techniques used. It should, however, be noted that it has always been EPRI's intention that the results obtained using different methods in this program were to be verified through confirmatory inspections of the monitored generators, where the opportunity for inspection was made available.

Applications, Values & Use

The goal of this research was to contrast and compare the effectiveness of PD and EMI techniques for on-line testing of turbine-driven generator stator winding insulation systems. One key challenge arose with the fact that PD measurements in inductive equipment are very difficult to calibrate, and comparison between measurements made with different equipment, gain settings, filters, and couplers are highly problematical. However, comparative measurements—taken either between phases or at different times using the same equipment and settings—are meaningful to assess technology performance and appropriate applications. Over time, it has become clear that the greatest generator operator benefit of either a PD or EMI analysis is the ability to examine unit degradation with respect to baseline signature.

EPRI Perspective

Although PD is a time-domain measurement and EMI measures activity with a frequency scan, both techniques still evaluate the same phenomenon—high frequency currents that flow as a result of electrical (partial) discharges occurring within the structure. Both PD and EMI signatures are complex and often difficult to interpret, particularly in the case of measurements in the frequency domain, where the interpretation of results depends critically on the experience of the individual taking the measurements. To some extent, testers select indices to describe the characteristics or severity of the condition being investigated. Breakdown of the characteristics into meaningful parameters is a valuable and necessary first step on the road to greater use of computer-based intelligence in problem diagnosis. This report represents the fifth in a series of studies aimed at examining the various PD and EMI methods available for evaluation of large utility generators through the use of discharge monitoring.

Approach

The project team analyzed PD and EMI assessments made at Sammis Unit 6 of First Energy Corp. as well as Marshall Units 3 and 4 of Duke Energy. They monitored PD assessments only of Unit 3 at the Lake Road Generating Station in Dayville, Connecticut. All commercial testers contributing to this study obtained PD or EMI data and then applied engineering judgment to the phase-resolved pulse counts or spectral results. Their time-honored yardsticks for evaluation included polarity predominance, phase angles of discharge groups, frequency bands involved, and evidence of cross coupling.

Keywords

Electromagnetic Interference
Stators
Windings
Turbogenerators
On-Line Measurement Systems

ABSTRACT

This report is the culmination of a multi-year project to assess the efficacy of a variety of Partial Discharge and Electromagnetic Interference methods for the diagnosis of anomalous conditions of the stator insulation structure in large utility turbine generators.

Outages scheduled for several of the machines in the program have permitted an inspection and verification of stator winding condition to be undertaken this year. As a consequence, this document not only highlights the salient aspects of tests conducted in 2005-06, but also provides an assessment of the strengths and weakness of the various techniques used in the light of established machine condition. On the basis of the study, a PD specification is derived and more insight is provided on the way the industry is likely to proceed with computer-based diagnosis based on these techniques. This report should be read in conjunction with the earlier EPRI documents 1007742, 1004958, and 1010207.

ACKNOWLEDGMENTS

It has always been the objective of this program to study techniques and not Companies. To this end, Testers are identified throughout only by alpha designators. However, it is a real pleasure to gratefully acknowledge the cooperation and continuing help of the engineers of the Testing Companies who have participated in this ongoing program. This report has benefited greatly from their accumulated experience and expertise. In particular, material and data has been used from the reports provided by these individuals. In some cases, this report has also relied on technical publicity material provided by these Companies which cannot always be referenced, but to which acknowledgement is here given. Recognizing that this is a research endeavor, several of the Companies have also contributed resources to the testing in the form of reduced or waived charges which is much appreciated.

Thanks are also due to Mr. Jan Stein who has both championed this effort and worked hard to facilitate it. Lastly, it is recognized that none of this would be possible without the close cooperation of the host sites. In that context, thanks are due to Messrs. Terry Hitchcock, Myron Horton, and Henry Reis and their staff who have facilitated the field testing.

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BACKGROUND AND INTRODUCTION

This report represents the fifth in a series of studies aimed at examining the various methods available for the evaluation of large utility generators through the use of discharge monitoring, through the use of Partial Discharge (PD) detection in the time domain, or Electromagnetic Interference (EMI) in the frequency domain. These techniques are part of an armory of tools now available to utility engineers for condition based monitoring. The aging of stator insulation is a major factor limiting the life of a high-voltage machine. As a consequence, the accurate assessment of the status of the insulation system has become a pivotal issue in both the reliability characteristics and maintenance decisions. The salient requirement is the minimization of forced outages.

It is a major function of this report to chronicle the 2005-6 tests carried out on the machines in the EPRI study as has been the practice in previous years. In that context, it will be evident from Table 1-1 that there are fewer companies undertaking the testing this year. There are several reasons for this, but, sadly, some of those testing in previous years have decided to exit the PD testing business. While it is not appropriate to comment on the commercial climate underlying PD and EMI testing, clearly the reduction in choice cannot be regarded as a good thing. Equally disappointing is the fact that the primary source of EMI testing on this program (and in the US) was not able to participate in 2005, but did return to the program to undertake some evaluations prior to unit inspections in 2006. The reason was that the facility is completely stretched with in-house work that there was no extra capacity for the EPRI program. However, there was still some testing done at all the sites.

Readers of previous reports in this series will be aware that an attempt each year is made to provide some “tutorial content” to augment the test results and machine appraisal. To this end, appendices have been previously provided on signature interpretation and EMI methodology (the PD technique is already well covered in textbooks and professional society publications). This report attempts to try to derive a specification for PD testing of large utility generators based solely on the technical and perceived scientific merit. It is recognized that this is a very contentious issue since there are entrenched commercial interests involved. It is also apparent that there is a new generation of discharge detection equipment emerging (and doubtless more currently in development) which relies more heavily on computer-based intelligence. Some innovations may well change the landscape in such a way as to require a rethink of PD specifications for large machines. However, it will take some time to determine the efficacy of such initiatives. This report also provides a window on this new initiative.

Table 1-1 documents the assignments of the Testing Companies. It has been the practice to “rotate” the Testers around the various generators in the program. As a result, since this document covers both the 2005 and 2006 testing years, there are a number of multiple assignments. The matrix is arranged so that the year appears in the column appropriate to the testing assignment. The Table also indicates the visual inspections conducted by Mr. Clyde V. Maughan which are also documented in the report.

Table 1-1
Matrix of Tests Carried Out During 2005 and 2006, Together with Inspection Schedules

Testing Entity	Sammis #6		Marshall #3 & #4		Lake Road #3	
	PD	**EMI**	**PD**	**EMI**	**PD**	**EMI**
A			05/06		06	
B	05		06		05	
C			05	05	05*	
D		05				
E				06		
F					06	
Inspection	03/28/05		#3: 09/29/06		Not Scheduled	
			#4: 03/03/06			

* Data withheld for commercial reasons.

2
SAMMIS #6: ASSESSMENT AND INSPECTION

In 2005, First Energy made a decision to take down Unit #6 at Sammis for routine inspection. Since this was one of the earliest machines in the program, it provided a welcome opportunity for a thorough inspection of the stator condition when the rotor was pulled from the machine. At that time, Mr. Clyde Maughan provided an evaluation based on a visual inspection of the interior. This is a very important aspect of the program since it is only by eventual examinations such as this that the true condition can be established and compared with assessments made on the basis of PD and EMI analysis. The unit is a 20 kV, 800 MW machine manufactured by Westinghouse in 1972. The stator winding bars are double tube-stack direct hydrogen-gas cooled and have had very high electromagnetic mechanical vibrational forces in the slots and end windings which has required considerable rework during its 36 years of operation. In 1998, there was a complete rewedging of the slots using radial springs, a rebuild of the end-winding support at the turbine end, and some core tightening.

In anticipation of this inspection, an additional PD analysis was undertaken just prior to the shutdown to supplement the EMI analysis already available. This was thought prudent since, for the last two years, only a minimal surveillance had been provided for this machine since there was fairly unanimous agreement by all those testing the machine that it was in stable condition.

PD Evaluation

A Partial Discharge assessment was made by Tester B using a “high-frequency” approach which utilized both the 80 pF external bus couplers and also the internal stator slot couplers already available on this unit. This test was conducted on March 1st 2005 just prior to the rotor removal that month. At the time of the test, the unit was loaded to 604 MW (54 MVAr), the winding temperature was 70°C, and the H_2 coolant pressure was 0.403 MPa (58.4 psig).

Bus Coupler Tests

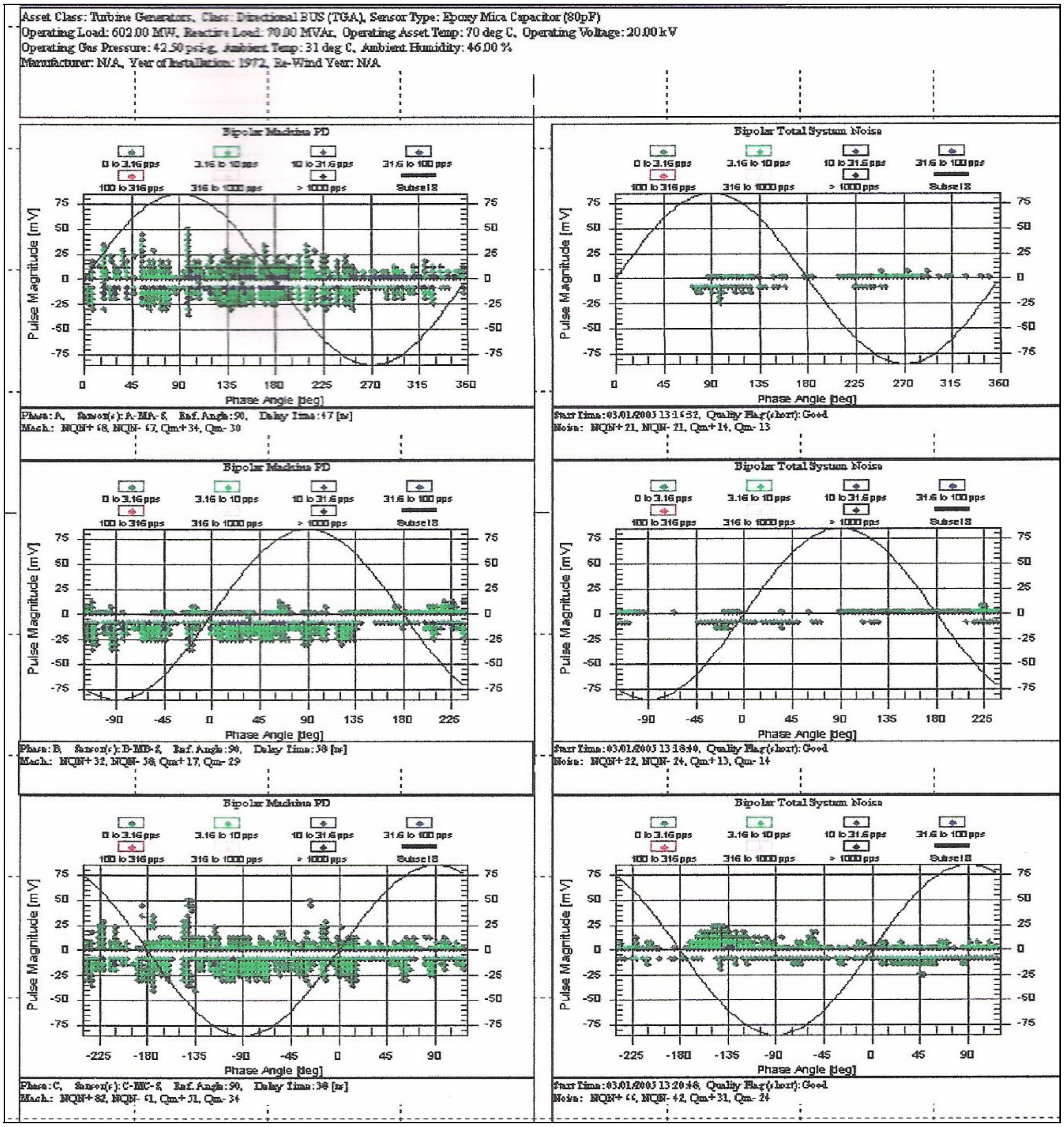
Evaluation of the unit on the basis of PD measurements taken at the line couplers is summarized in Table 2-1. The activity is characterized by the polarity-discriminated maximum discharge magnitudes, Q_m+ and Q_m- and is given in relationship to previous compatible results taken on this machine since 1999.

Table 2-1
Discharge Magnitude Trends for Sammis Unit #6

	Operating Parameters					A-Ph		B-Ph		C-Ph	
	MW	MVAr	kV	°C	H_2, psi	Q_m+	Q_m-	Q_m+	Q_m-	Q_m+	Q_m-
02/99	625	154	20.4	70	61.3	17	19	8	8	40	43
07/00	386	115	20.2	53	62	11	10	9	15	13	13
01/01	477	72	20.1	55	63	21	11	71	25	10	21
03/05	604	54	20.0	70	58.4	34	30	17	29	51	34

It is clear both that the levels (in mV) are modest and that, although there have been some changes over time, the overall change over the period of 6 years is relatively small. [The anomalous 71 mV level in Phase B in 2001 has not been repeated]. It is likely that the fluctuations are the result of variances in the ambient and operating conditions, and not problems with the winding *per se*. Activity levels are essentially unchanged, and correspond to typical levels when compared to Tester B's database.

Figure 2-1 provides a more detailed view of the PD activity on a phase plot. Since time-of-flight discrimination is being used, the three plots on the left represent activity being seen in the machine, whereas those on the right depict the system noise. The activity is seen to be occurring fairly uniformly across the voltage waveform (superimposed as a sinusoid), and not in the traditional phase positions which would be expected of major classic partial discharge behavior. The noise-like pattern could be the result of radiated interference from outside sources which could be induced into the winding as a whole and thus not rejected as external noise. It would appear that this noise was dominating any low level discharge that may be present. As a consequence, it may be concluded on the basis of this test that there is no concern that discharge activity is prejudicing the stator at this time.



Asset Class: Turbine Generators, Class: Directional BUS (TGA), Sensor Type: Epoxy Mica Capacitor (80pF)
Operating Load: 602.00 MW, Reactive Load: 70.00 MVAr, Operating Asset Temp: 70 deg C, Operating Voltage: 20.00 kV
Operating Gas Pressure: 42.50 psi-g, Ambient Temp: 31 deg C, Ambient Humidity: 46.00 %
Manufacturer: N/A, Year of Installation: 1972, Re-Wind Year: N/A

Phase: A, Sensor(s): A-MA-8, Ref. Angle: 90, Delay Time: 47 [ns]
Mach.: NQN+ 68, NQN- 67, Qm+ 34, Qm- 30

Start Time: 03/01/2003 13:16:32, Quality Flag(short): Good
Noise: NQN+ 21, NQN- 21, Qm+ 14, Qm- 13

Phase: B, Sensor(s): B-MB-8, Ref. Angle: 90, Delay Time: 38 [ns]
Mach.: NQN+ 32, NQN- 58, Qm+ 17, Qm- 29

Start Time: 03/01/2003 13:18:40, Quality Flag(short): Good
Noise: NQN+ 22, NQN- 24, Qm+ 13, Qm- 14

Phase: C, Sensor(s): C-MC-8, Ref. Angle: 90, Delay Time: 38 [ns]
Mach.: NQN+ 82, NQN- 61, Qm+ 31, Qm- 34

Start Time: 03/01/2003 13:20:46, Quality Flag(short): Good
Noise: NQN+ 66, NQN- 42, Qm+ 31, Qm- 24

Figure 2-1
Phase Resolved PD Analysis for Sammis Unit #6 from the Line Couplers. Tester B

Stator Slot Coupler Tests

Six stator slot couplers are installed on this unit which permit local activity to be assessed (as compared with the terminal couplers which provide an assessment of the winding (on a phase by phase basis) as a whole. A typical coupler is depicted in Figure 2-2(a) and these are typically fitted under the slot wedges as shown in Figure 2-2(b). Being a high-frequency stripline device, they do permit some discrimination of the discharges measured on the basis of the direction of pulse travel. In this way, strategic placement of the sensors allows some estimate of whether the origin is in the end winding or in the stator slot.

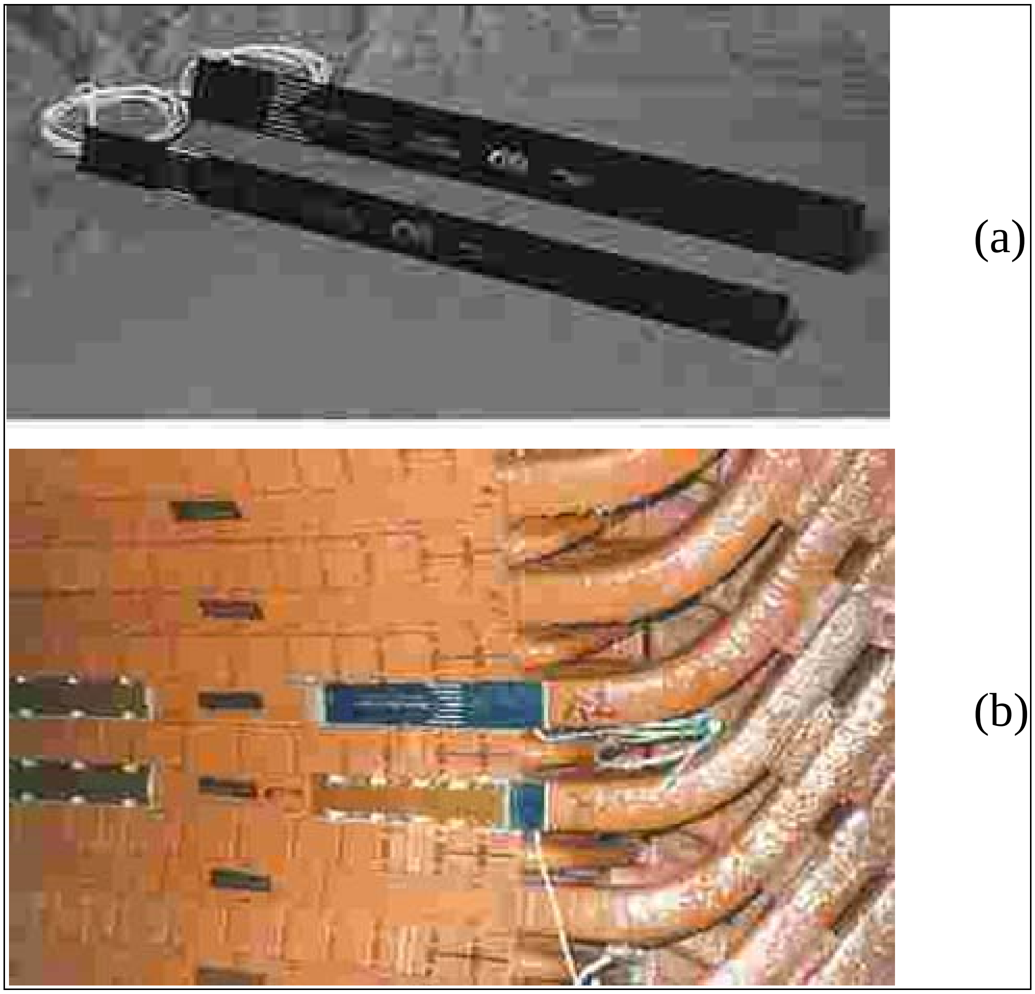


Figure 2-2
(a) Stator Slot Couplers; (b) Installation Under Slot Wedges

The six stator slot couplers embodied in the winding have also been monitored. These are inherently high frequency devices that rely on pulse risetime and amount of ringing to discriminate against noise. Electrical connections are made to both ends and by comparing signal arrival times, the direction of the signal source can be determined [1]. In this way it is possible to discriminate between signals generated in the slots and those emanating from the end windings and beyond. In this case end-winding PD was virtually non-existent (at least, in the bars being monitored) despite the finding on inspection of significant contamination in the end winding region. The discharge activity in the slots is depicted in Figure 2-3 which shows the trend over a 6 year time frame.

As with the results obtained from the bus couplers, it would appear that activity has changed little over the monitoring period. Indeed, Figure 2-3 would suggest that the activity had diminished slightly. Even though two of the sensors registered levels that would be regarded as higher than normal, the lack of deterioration over the time period would not suggest a major problem. Tester B concludes that the stator winding is suitable for service without restriction.

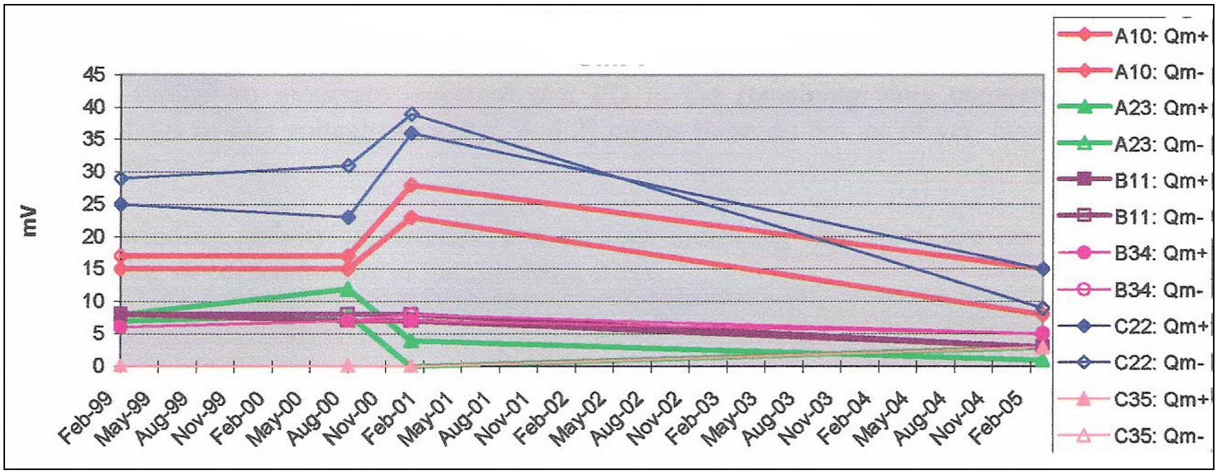


Figure 2-3
PD Activity over the Monitoring Period from the 6 Slot Couplers Installed in Sammis #6. Tester B

EMI Signature

The last available EMI signature taken on this machine prior to the inspection is depicted in Figure 2-4.

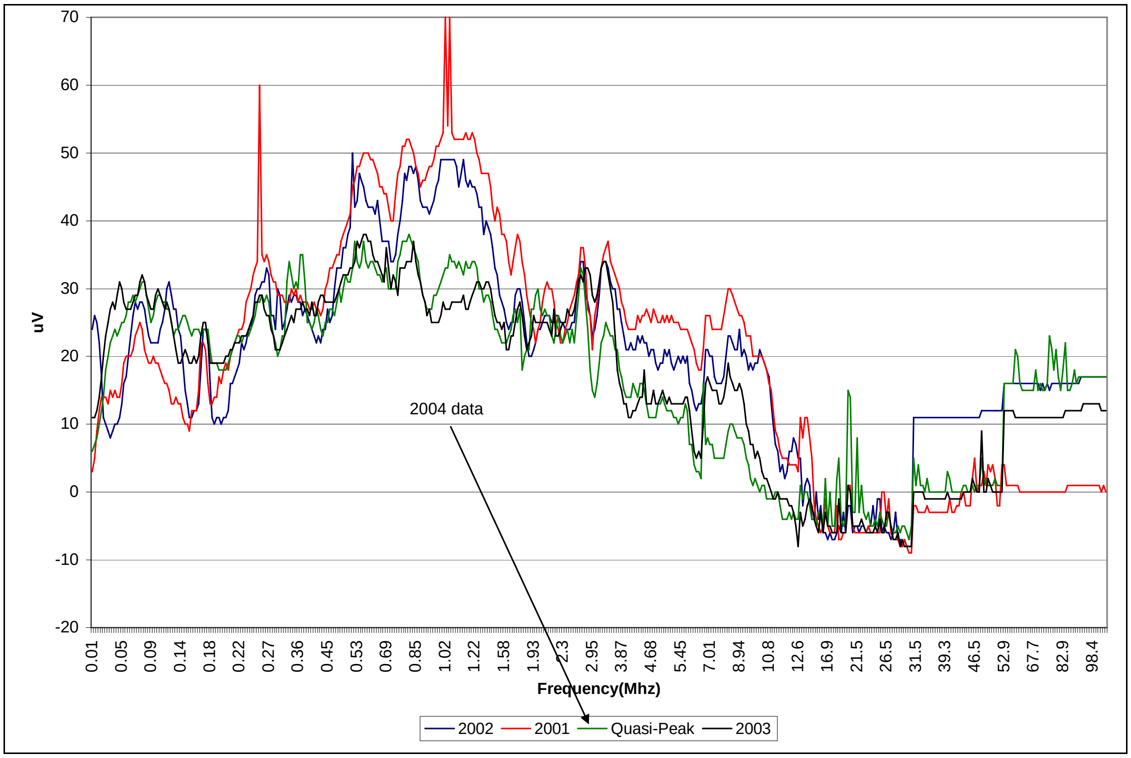


Figure 2-4
EMI Signatures at Sammis #6 from 2001 to 2004. Tester D

The latest result is shown in comparison to those taken in earlier years and clearly indicates that there has been little change in the overall spectrum. If anything the latest activity is somewhat less than in some prior years which is in agreement with the trending analysis available from the stator slot coupler results in the Stator Slot Coupler Tests Section. It should be recognized that, while the PD tests are made on the individual phases independently, the EMI measurements have been made through the use of a high-frequency current-transformer (HFCT see Figure 2-5) at the neutral of the machine. As a consequence, the results shown in Figure 2-4 represent an amalgamation of activity from all the phases. The use of an HFCT at the neutral is not a limitation of the EMI technique, but rather a practice that has been adopted as the technique has been developed. Indeed, in 2004, the EPRI program [2] undertook some comparative measurements using EMI derived from an HFCT and from line-end couplers on the same machine for comparison purposes.

Figure 2-5
High-Frequency Current -Transformer at the Machine Neutral

Unit Inspection Results and Conclusions

This inspection was conducted on March 28th 2005, after the rotor had been removed from the unit. The rotor was also available for inspection and appeared to have no outward signs to generate concern. With the stator accessible, careful examination of the slots was conducted with particular reference to the tightness of the wedges and signs of discharge activity. Similarly, the endwindings were studied for signs of wear, looseness, bracing failure and discharge activity.

In undertaking a visual inspection, it should be kept in mind that only a small portion of a stator winding can be physically observed. None of the slot area is visible on this type of Westinghouse unit. In addition, the blocking just outside the core is so dense as to preclude seeing the critical area of bars at the core ends. On most machines this would be the junction point of the slot grounding and endwinding grading materials; however, on this design of stator, the slot grounding paint is carried out to about the mid-point of the bar end arm, thus the junction area is at this location. This area can be seen on the top of the top bars, and no particular activity was seen there.

While there was very heavy oil contamination, overall the winding appeared to be in reasonably good condition, considering the age of the unit, magnitude of electromagnetic vibrational forces, string-tied endwinding tie system, and oil contamination.

Slot Wedging System

During the 1998 overhaul, radial springs and wedges with the 7-hole test system were installed by Westinghouse. While Figure 2-6 shows that there was considerable general contamination of the wedges, it is likely that this contamination is derived from wear products and dirt accumulation over the years of operation rather than individual wedge vibration or stator bar vibration. The wedges that were tested for tightness all sounded very tight, and First Energy reported that the 7-hole tests indicated satisfactory results.

Figure 2-6
"Greasing" Seen at the Slot Wedges

Endwinding

Again there was wide-spread "greasing" as seen in Figure 2-7. The so-called "grease" is a mixture of oil with the dust generated by insulation wear (and general contaminating dirt). Oil ingress is common on generators, particularly hydrogen-cooled units. This generator was particularly contaminated with oil. Recently, the amount of oil removed from the generator was reported to be many gallons per day. Generally, oil contamination is not considered to be a serious degradation mechanism to the metallic and insulation components of modern generators, but it does make inspection problematical.

Figure 2-7
Contamination Collecting from Endwinding "Greasing"

Figure 2-8 shows a portion of the CE flux shield on which a heavy layer of grease had accumulated. While this looked very much like molten metal, closer inspection suggests that it is contamination materials that have dried and hardened somewhat due to the heat of the shield.

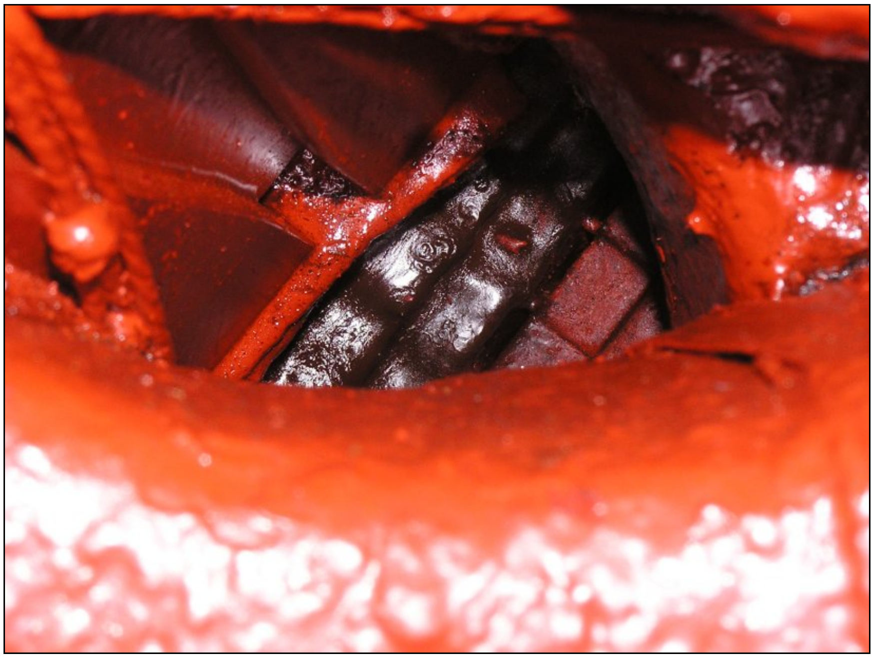


Figure 2-8
A Portion of the Flux Shield Showing Collected Contamination

Some locations on the endwinding supports also showed very heavy grease generation.

Partial Discharge

Careful inspection of the phase breaks in the endwindings revealed little indication of any PD activity. Figure 2-9 is the only block on which confirmed indications were seen (shown arrowed). While this looks very much like the widespread contamination found all over the endwindings (see Figure 2-7), the physical properties were different, and in line with that normally seen from phase-break partial discharge. Whereas the grease deposits were easily removed by wiping with a cloth, the material in Figure 2-9 was hard and dry, typical of PD deposits. This activity was not obviously picked up by any of the installed stator slot couplers whose output is shown in Figure 2-3.

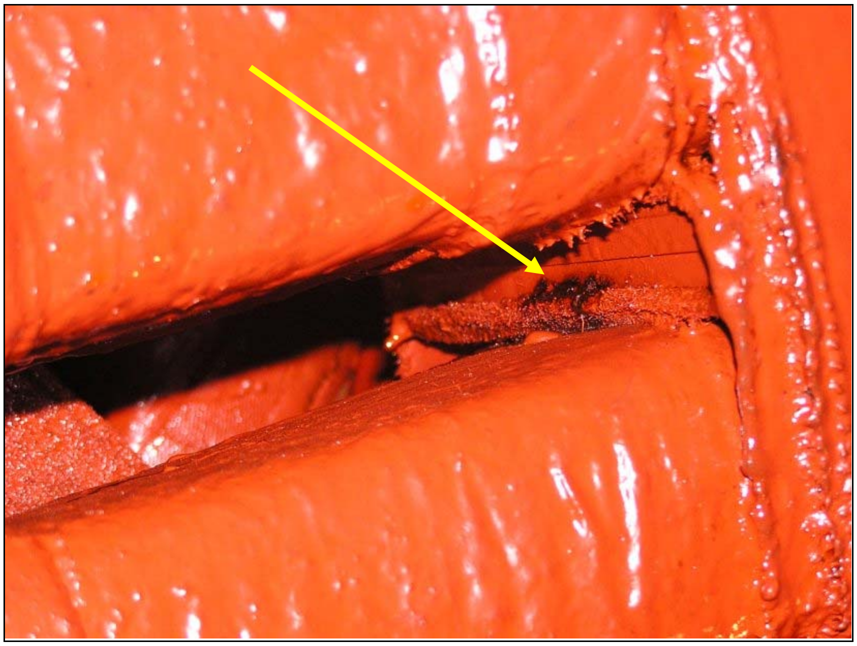


Figure 2-9
Probable Partial Discharge Activity on Blocking at Phase Break

Reconciliation with Test Signatures

While numerous areas of general concern were observed on this stator winding, there were negligible indications relating to PD. Hydrogen cooled generators are, of course, well known to have low tendencies to PD, and it is perhaps likely that the oil contamination, relatively low voltage, and high hydrogen pressure combined to keep PD on this generator at a minimum. It is very gratifying to observe so little PD activity since both EMI and PD signatures over the last 4 years have *both* indicated that activity was not excessive for a machine of this age. Indeed, the stability reported by all those who have tested this machine led to a decision only to undertake one reading annually on this EPRI program for the last few years. The trending data shown here in Figures 2-3 and 2-4 confirms that substantial discharge activity was not a problem to be anticipated at this inspection.

3

MARSHALL UNIT #3: ASSESSMENT AND INSPECTION

Tester A would normally test in a frequency range which would be regarded as high frequency (3 - 150 MHz). However, the coupler arrangements at Marshall are such as to favor the use of low frequencies (i.e. the 9000 pF couplers and the use of integral current transformers to capture the signals in the ground path). As a result, Tester A elected to undertake measurements in both high and low (80 to 200 kHz) frequency ranges which was a useful comparison. Furthermore, it is known from previous reports at this location that the labeling and reliability of the synchronizing signal provided are in some doubt. In order to test this issue, PD measurements were taken from the Phase B coupler using both the Phase B reference signal and a Phase B signal derived from the coupler itself. Figure 3-1 shows the two cases which were made to look the same by the introduction of a 45º phase shift in the reference indicating that the reference signals provided are, indeed, erroneous as was shown by a previous tester during the last round of testing [3].

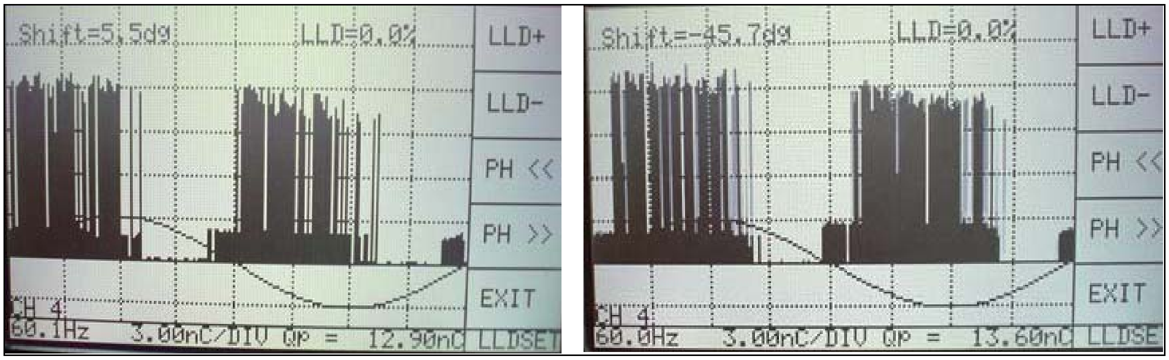


Figure 3-1
Unit #3, Phase B from Terminal Box (Left), and Phase B from Coupler with 45° Phase Shift, (Right)

2005 Assessments

In 2005, specific EMI testing was not carried out at Marshall, but a frequency domain test was conducted as part of the identification of the active spectral region in connection with combined PD analysis – see the EMI Assessments Section below. PD assessment was made, however, using both LF and HF techniques.

PD Evaluation (LF and HF): Tester A

In June 2005, the opportunity was taken of having a testing entity capable of evaluating the machine with both LF and HF techniques provide a useful comparison under identical conditions. The unit was well loaded (683 MW, 224 MVAr) with a stator temperature measured at 66°C and an H_2 pressure of 0.41 MPa (59 psi).The discharge magnitudes measured by the two techniques are provided in Table 3-1 for each phase (although a LF quantity for Phase B was not available.

Table 3-1
Comparison of Maximum Discharge Magnitudes for LF and HF Techniques for Marshall Unit #3 Tester A

	LF (nC)	HF (mV)	
		-	+
Phase A	6.2	2400	2000
Phase B	≈ 13	6400	5600
Phase C	8.5	2000	2000

The correlation between the two techniques, although not perfect, is consistant in showing most activity on Phase B. The amplitude levels are such that it is likely that much of the activity recorded is not originating in the machine but in areas external to the hydrogen-cooled winding structure. This is also suggested from the more detailed pulse height analysis shown in Figure 3-2, for Phase C on an expanded (800 mV) amplitude scale. It is likely that the low level discharges emanate from the machine winding and the activity at higher levels is external; possibly from the isophase bus duct.

PD Evaluation 2-Frequency LF: Tester C

A low frequency PD assessment was made on November 7th 2005 when the unit was loaded at 280 MW. The load had been stable for more than 3 hours which resulted in a winding temperature in the range 50 – 54°C. The hydrogen pressure was 0.38 MPa (55 psi) at the time of testing. Tester C is a little unique in that a combined technique is utilized where both time- and frequency-domain data is taken as depicted in Figure 3-3.

The EMI data is reported in the EMI Assessment Section. The signal from the PD coupler of each phase is connected to an HP 8591E Frequency Response Analyzer together with an antenna-derived ambient noise signal for use as a noise baseline reference. The frequency window used is 100 kHz - 500 MHz. The peak and average amplitudes of the spectrum of each phase are recorded, and used for a combined phase-resolved PD test, and also for data interpretation -- in comparisons with trended data.

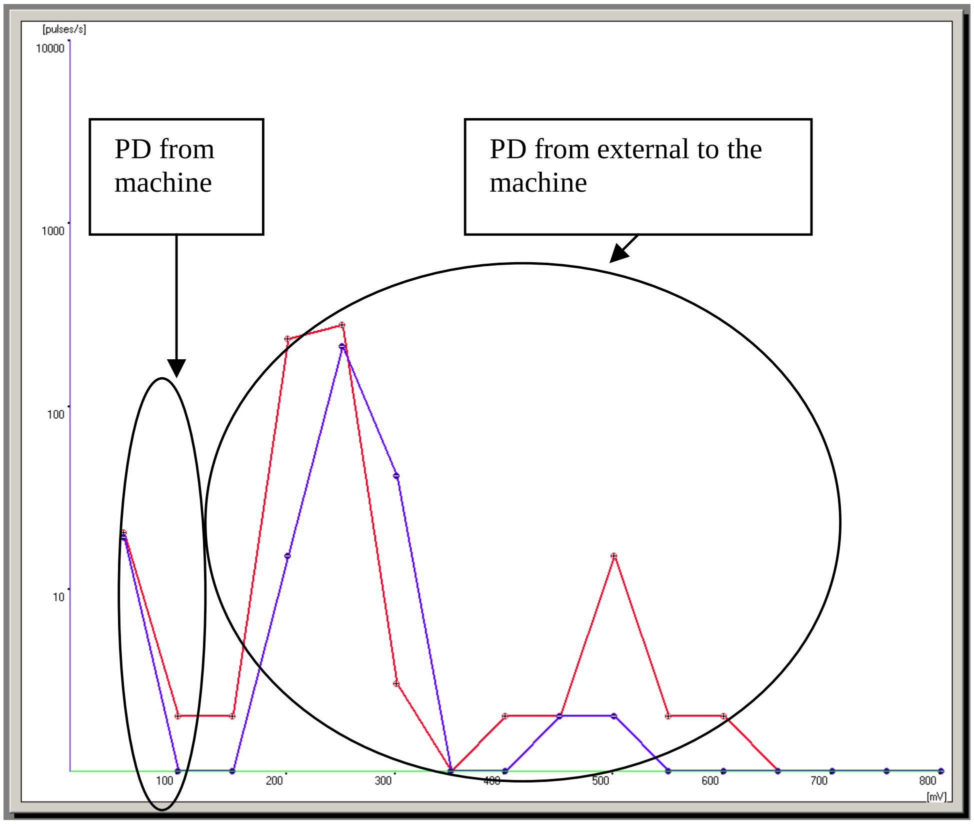


Figure 3-2
Pulse Height Analysis for Marshall #3 (HF Technique) Tester A

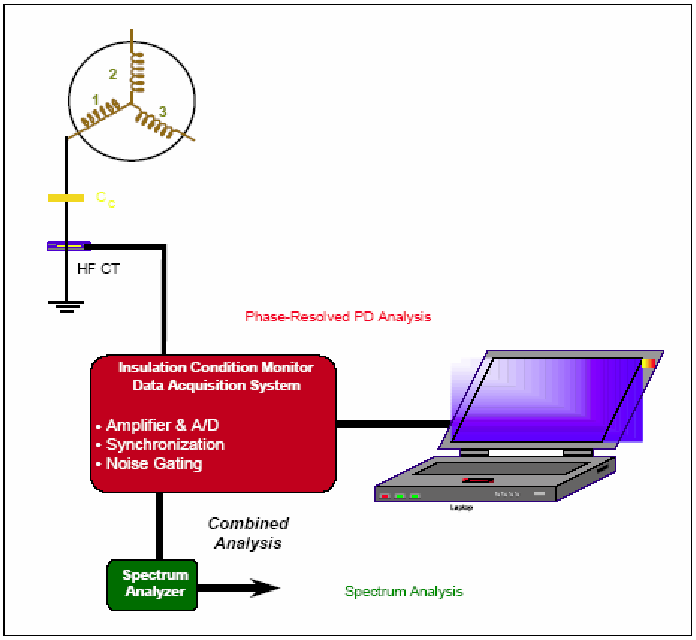


Figure 3-3
Schematic Representation of the PD Measurement System Used by Tester C

Low-frequency PD tests were conducted using a Power Diagnostix Insulation Condition Monitor System (ICM) at a range of gain settings on each phase. This is an instrument in common usage, and has two primary frequency bandwidths: 40 kHz - 800 KHz, and 2 MHz - 20 MHz. Figure 3-4 depicts a phase resolved PD plot taken for Unit #3 at the higher frequency range.

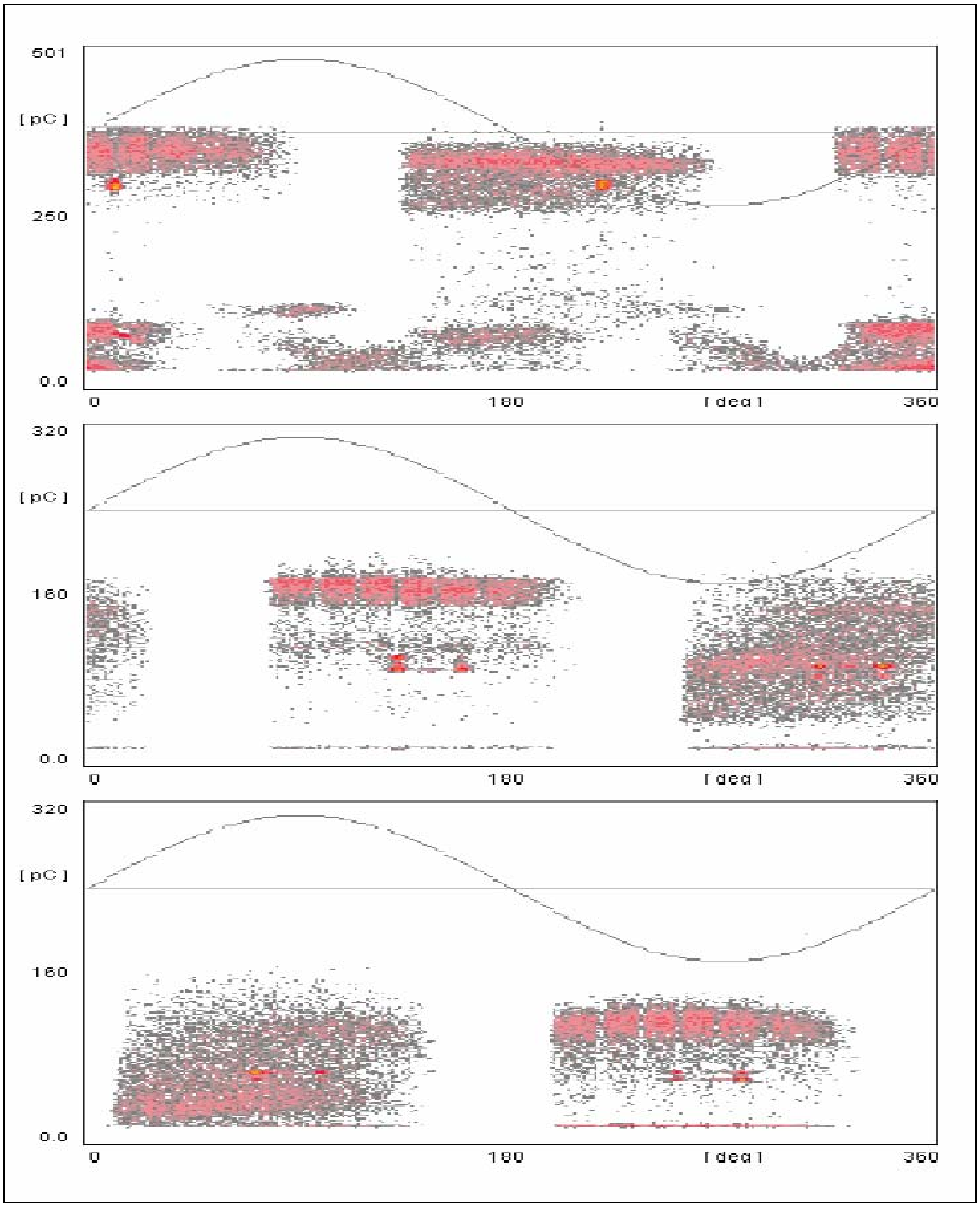


Figure 3-4
Phase-Resolved PD Spectra for Marshall Unit #3 in the Frequency Range 2 - 20 MHz. Phases A – C (Top to Bottom). Tester C

[Note: the gain is not the same for all three phases.]

Tester C indicates that line voltage was used as a reference (Phase A would be conventional), but it is not clear that the phase of the reference voltage was identified. It would appear that there was some cross talk between phases since 120° shifts are indicated in the characteristic pattern. The discharge amplitude is scaled in pC (but is presumably uncalibrated). Tester C associates the high level activity with "gap" discharges originating outside the machine envelope.

In a combination analysis, the frequency response analyzer can be used as a "narrow" bandwidth filter set to individual peaks of interest identified in the previous EMI scan. This "filtered" signal is connected to the PD data acquisition system to provide information related to the specifics of the PD pattern at each notable frequency. This has been done in Figure 3-5 where a frequency window centered on 1.29 MHz has been used. The frequency is based on the EMI spectrum given below in Figure 3-6.

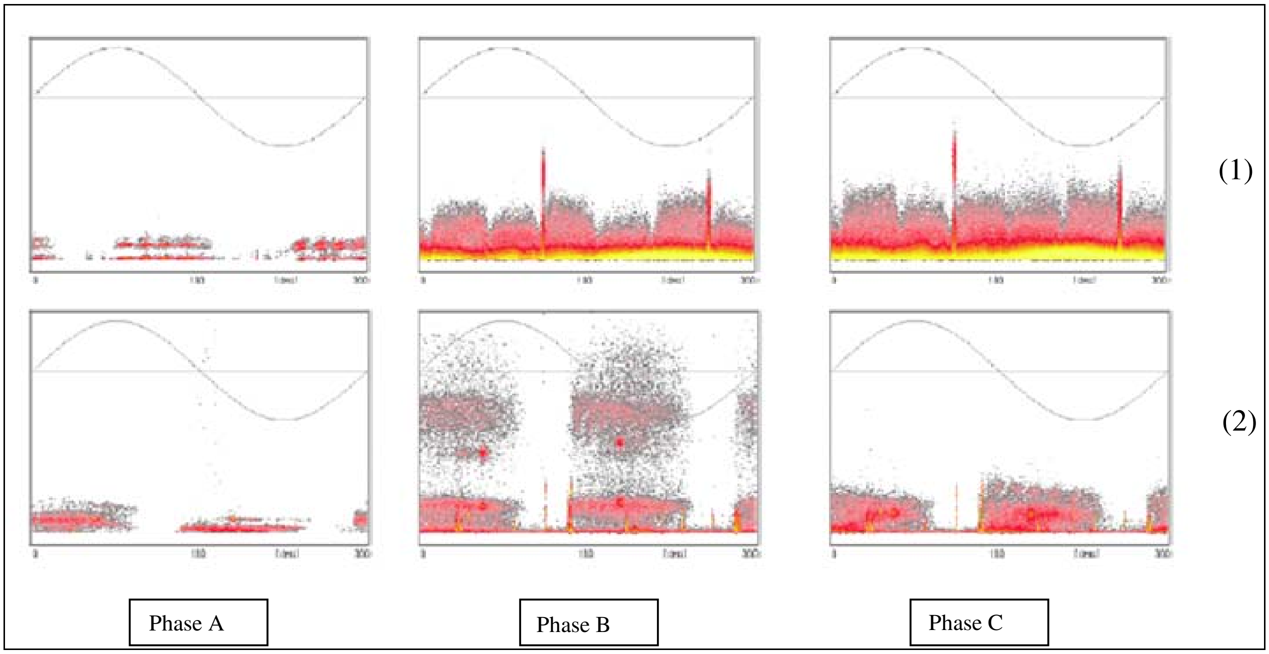


Figure 3-5
Phase-Resolved PD Analysis at a Frequency of 1.29 MHz. Marshall Unit #3. Tester C. (1) July 2004, (2) Nov 2005

It is clear that in the year which elapsed between the two measurements, Phase B has acquired some high level activity. However, comparison of Figure 3-4 and 3-5 does indicate some phase inconsistencies which once again raises the question of the correct phase reference identification. However, the appearance of this cluster of activity at this frequency is not inconsistent with the identification of external corona.

EMI Assessment

As discussed previously, Tester C also undertakes an EMI analysis in combination with the PD evaluation.

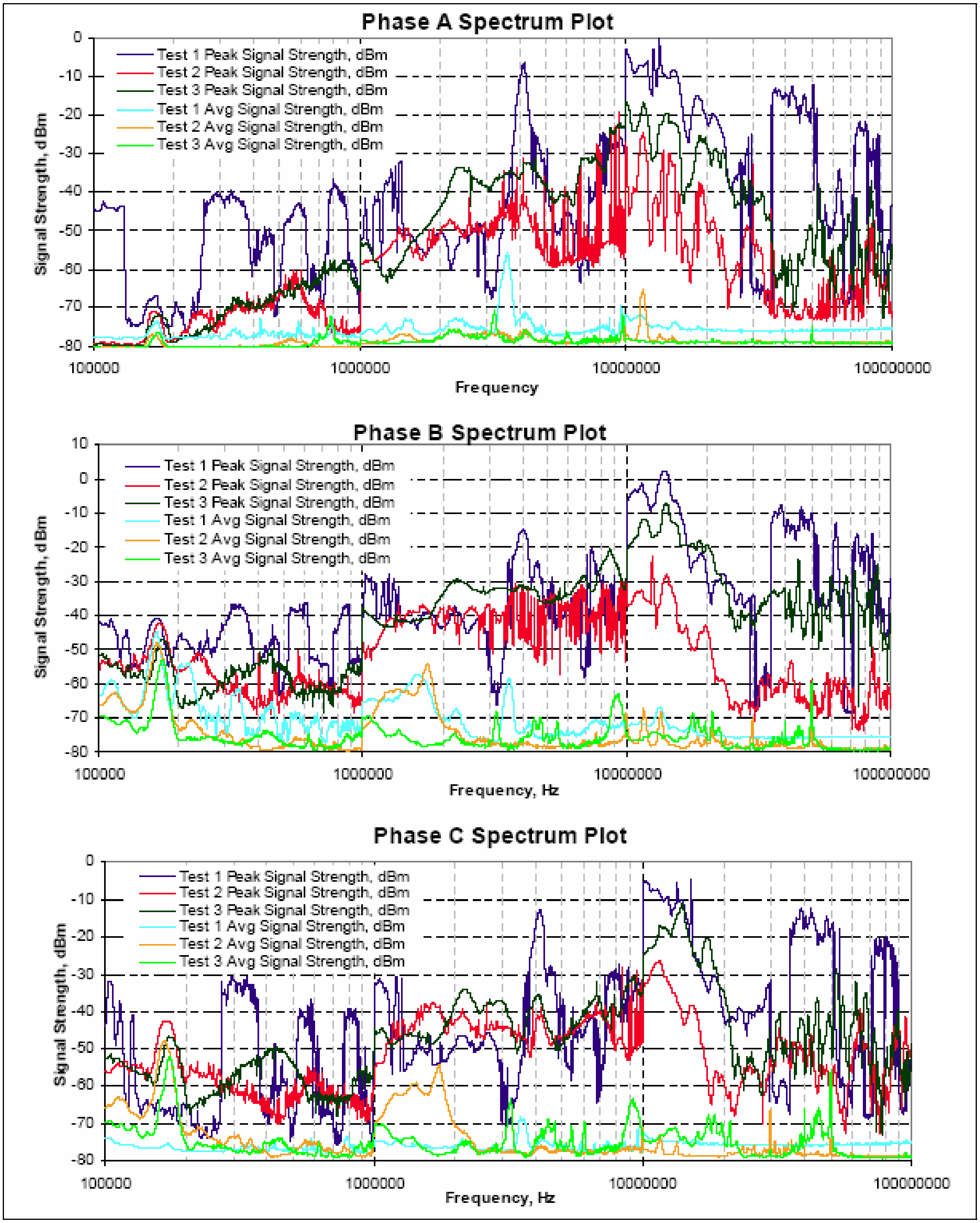


Figure 3-6
EMI Spectra for All 3 Phases of the Stator of Marshall Unit #3. Tester C

The frequency spectra for all three phases are depicted in Figure 3-6 for three tests taken in the period from 2002 to 2005. Both peak and average signals are depicted. However, these must be interpreted with caution since it is known that Duke Energy undertook some repair work on the systems (current transformers and iso-phase bus components) during this time period. In particular, the high amplitude activity above 10 MHz is likely to be the arcing discovered at the flexlinks in the machine (see Figure 4-12), and the reduction in activity with time consistent with the known repairs that were carried out. It is also of interest to compare the activity at 10 MHz with that documented in Reference [2] for the same period.

2006 Assessments

Condition assessments were made by both EMI and PD methods early in 2006 (just prior to the tear down of Unit #4 in March).

PD Evaluation: HF Tester B

A partial discharge test was conducted by Tester B on February 7th 2006. It should be reiterated that Tester B was coupling to a sensor configuration (9 nF with a built-in RFCT) which was not ideally matched or suited to the technique being employed. As a consequence the results cannot be used as effectively for pinpointing problems. Notwithstanding that, this tester did perform similar measurements on the same basis in August 2004, which provide a basis for comparison despite the less than ideal conditions. This assessment is provided in Table 3-2 which also contains the relevant operating condition from which is can be seen that the machine was similarly loaded for both tests although the power factor was different.

Table 3-2
Comparison of Maximum Discharge Magnitudes for Marshall Unit #3 Over an 18 Month Interval. Tester B

Date	Operating Parameters					PD Magnitudes (mV)					
						A		B		C	
	MW	MVAr	kV	Temp	H_2 Press. (MPa)	Qm+	Qm-	Qm+	Qm-	Qm+	Qm-
Aug ’04	674	301	24	142ºF	0.406	67	75	36	23	68	43
Feb ’06	699	67	23.5	56ºC	0.413	200	233	230	248	691	681

It is immediately apparent that the signals have increased dramatically during the intervening 18 months for all phases. This increase should be interpreted as a cause for concern. Figure 3-7 provides the associated phase-resolved discharge plot which shows that, in C phase, the activity is near to the center on the peaks of the AC cycle, with the usual polarity relationship for PD or corona (i.e. the pulse polarity opposite to AC voltage polarity). Assuming correct assumptions have been made on the phase shifts from the reference in each phase, then the pattern in C phase is typical of conventional corona on the surface of a conductor. This usually only occurs on the output bus of the generator. Thus because of the phase relationship and the subjective similarity to past patterns seen – the most likely source of this activity is the isolated phase bus of C phase. The cause may be sharp conductive points on the bus, weld splatter, a contaminated rag, etc.

Such patterns are not likely within the stator – and in fact there appears to be little conventional stator winding PD within this machine.

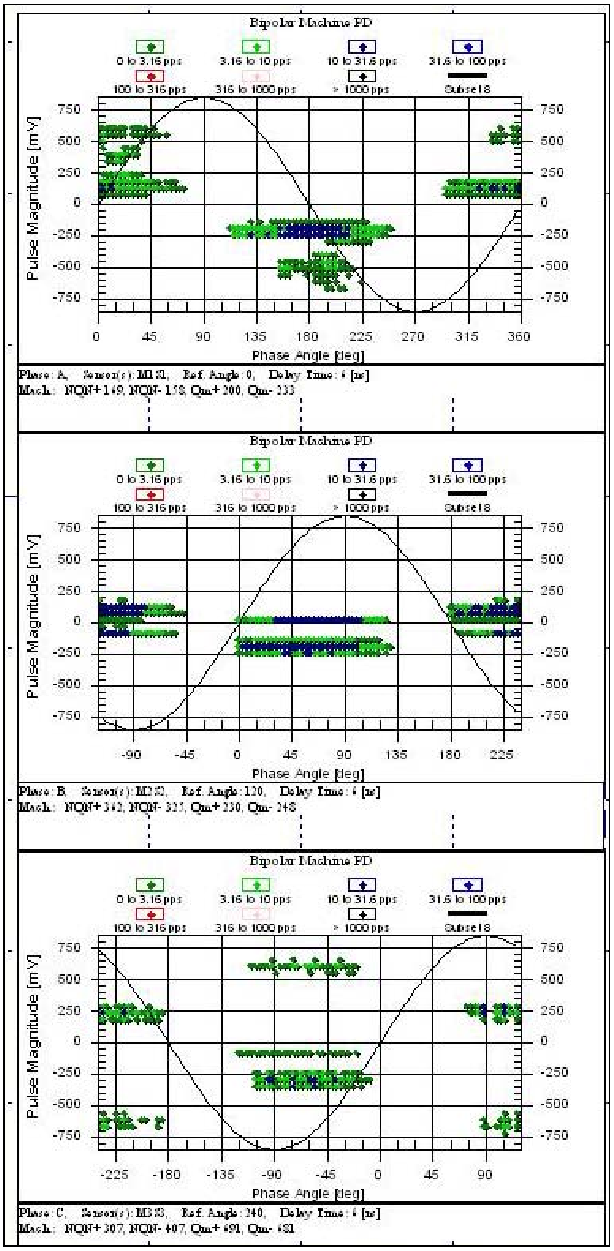


Figure 3-7
Marshall Unit #3 Phase Resolved PD Analysis. Tester B

With the assumptions about the phase reference and RFCT polarization – it may be that the high signals in A and B phases are just cross-coupled signals from C phase. (If the assumptions are incorrect – then the iso-phase bus sparking may be occurring on these other phases instead.) Iso-phase bus sparking/corona rarely leads to unit failure, but Tester B recommended that it would be prudent to examine the bus when possible (i.e. at the time of the scheduled rewind).

PD Evaluation: HF Tester A

Tester A tested Unit #3 at Marshall on February 2nd which was only 5 days prior to the tests conducted by Tester B reported in the previous Section. Again, the coupler arrangements were not ideally suited to this (HF) test. The test conditions (675 MW and 85 MVAr) were also similar to those used by Tester B reported in Table 3-2. The results are summarized in Figure 3-8 which shows the PD characteristics displayed as NQN values in comparison with identical measurements taken by Tester A in 2005. NQN (**Normalized Quantity Number**) is formally defined in reference [3], but is an integrated measure incorporating both pulse magnitude and number. Each bar in the histogram represents the output seen at couplers on each phase for either positive or negative polarity.

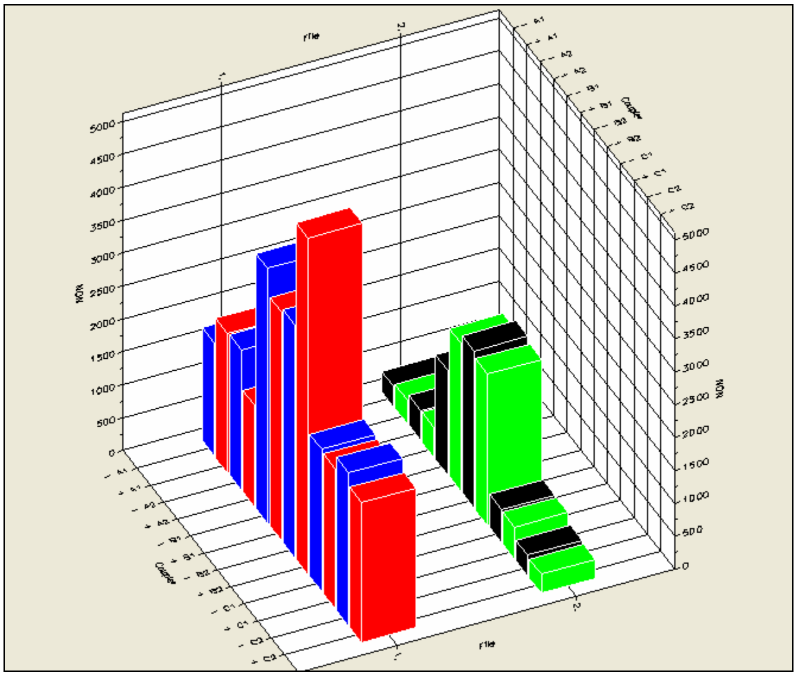


Figure 3-8
NQN Comparison for Marshall Unit #3 for June 05 (Left Histogram) and February 06 (Right Histogram). Tester A

The striking feature of Figure 3-8 is that the activity levels are shown to have decreased between the 2005 and 2006 assessments. This is in marked contrast to the results in Table 3-2 for Tester B also using a high-frequency technique, where up to a ten-fold increase in activity is indicated for both polarities based on a maximum discharge magnitude. However, one issue which might be a factor here is the fact that the previous readings with which comparisons are made were taken for a condition in which substantial reactive power was being supplied. It is known that, when there is export (or import) of reactive power, the mechanical forces on the stator bars occur at different points on the voltage cycle [4]. Changes in PD characteristics in this condition can indicate a lack of consolidation of the stator groundwall, but while this might explain the change seen if the stator was in poor condition, one would still expect consistency between the two testers. Both testers are, however, in agreement that most of the activity probably originates from outside the machine, which both conclude is in serviceable condition. Both testers do also agree that the condition of this machine is worse than that of Unit #4.

Another obvious difference between these two assessments is the issue of phase identification. Table 3-2 clearly shows most of the activity to be occurring in Phase C, whereas Figure 3-8 identifies Phase B as having the predominant activity. It has been clear throughout this study that Phase identification is an issue for PD testing that requires attention in the design of equipment. Either the phase reference needs to be derived from the phase coupler itself (through a low frequency path), or software incorporated to flag the problem based on the displacement of an identifiable PD pattern.

EMI Evaluation: Tester E

An EMI test was conducted on February 10th 2006 when the load was 705 MW and the hydrogen pressure 0.39 MPa (56.8 psi). Figure 3-9 provides a plot of the resulting spectrum captured with a quasi-peak detector. The previous EMI measurement on this machine [2] had indicated anomalous sparking in early 2004 and a bushing CT shorted turn in 2003. These featured are no longer evident in Figure 3-9, but the resonances seen above 25 MHz provide an indication that there still may be external busbar-related discharge problems persisting. These high level discharges were tracked with a hand-held EMI “sniffer” and isolated to the bus duct area under the unit. All phases showed high levels, although Phase B appeared to be the worst. Figure 3-10 provides a time domain plot of the activity taken at a frequency window centered on the peak at 63.5 MHz identified in Figure 3-9. Those skilled in the “art” of interpreting such signatures might interpret the unstable nature of the discharge pattern as due to vibration in the bus which causes changes in the discharge location. The occasional discharge having a longer time constant (i.e. having width) might also suggest that significant current was involved with this process. Tester E ascribes this signature to defective enclosure insulation or deteriorated conductor shunts.

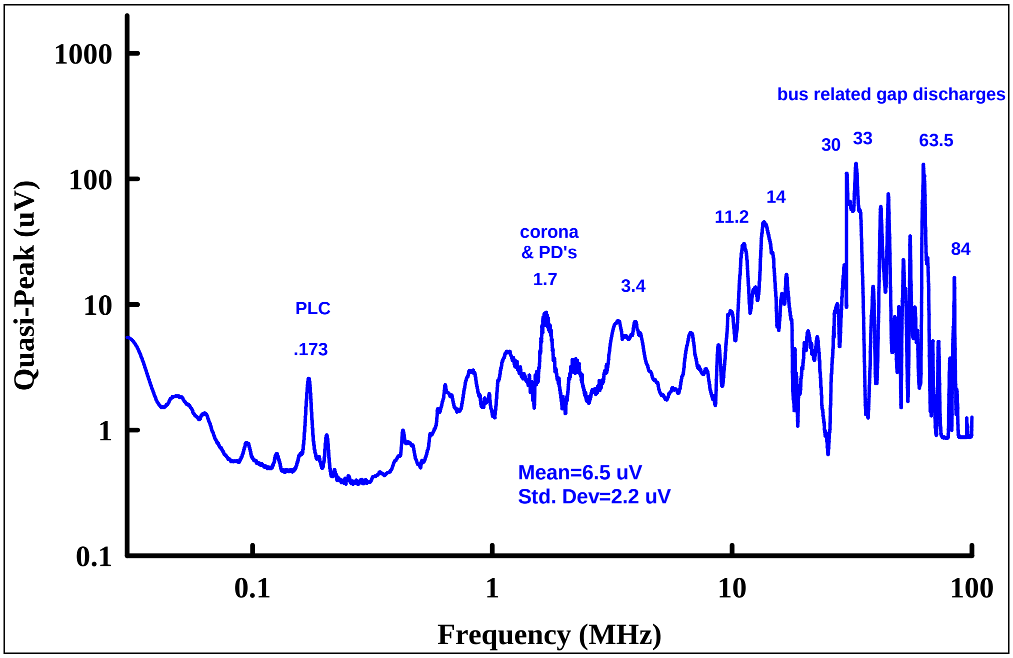


Figure 3-9
EMI Spectrum Taken at a Neutral CT of Marshall Unit #3. Tester E

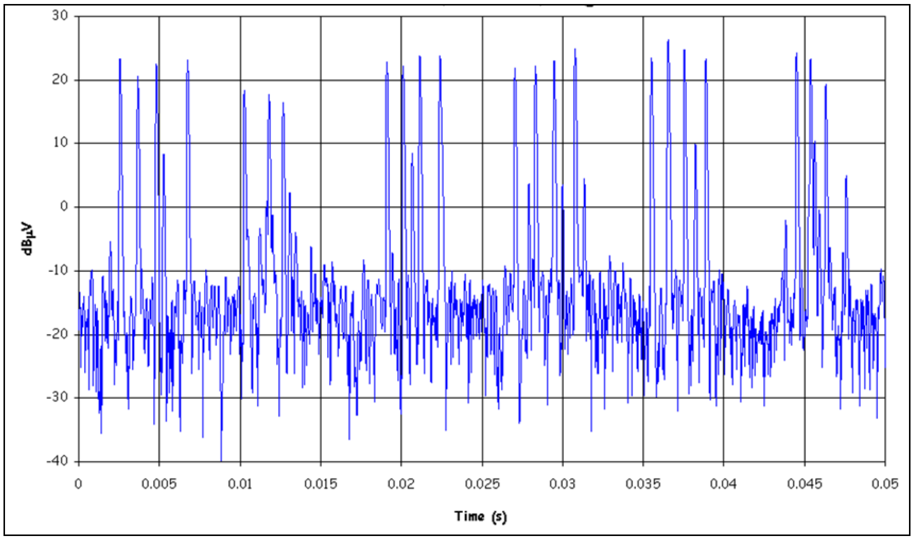


Figure 3-10
Time Domain Discharge Pattern taken at a Frequency of 63.5 MHz. Marshall Unit #3. Tester E

The modest activity shown in the frequency range 1 – 10 MHz in Figure 3-5 may indicate some activity in the stator slot area, but it is again the bus duct phenomena which would appear to dominate and required attention by the owner at the next available opportunity.

Visual Inspection

An inspection of Marshall #3 was undertaken by Mr. Clyde Maughan of Maughan Engineering Consultants on September 29th 2006. The rotor had been withdrawn by Duke Energy and scaffolding put in place to allow access to the bore of the machine. The machine had not been cleaned since the rotor had been pulled. No winding removal had been started and, consequently, the conductors were still in the slots so that the groundwall and slot packing were not visible. There was very little greasing in the slot area of the stator with the exception of a small region at the non-turbine end of the generator. In this area (within about 50 cm of the core edge) there was heavy greasing as depicted in Figure 3-11. This indicates that there had been bar vibration at the exit area of the core.

The wedges appeared tight. Although such vibration would not necessarily be regarded as serious, it was clearly sufficient to cause some abrasion products at the end of the slot (resulting in the observed greasing after absorption of oil particles entrained in the gas flow). This abrasion will tend to wear away the slot grounding paint/tape, and thus create a potential PD origin site. Indeed, there was evidence of some abrasion associated with the ripple springs (shown removed in Figure 3-12) which is consistent with the other signs of vibration. The wire from the flux probe was bonded to the flux shield and also to the outer axial winding support structure and had been severed between these two locations – see Figure 3-13. It is likely that the wires broke due to low cycle fatigue associated with the approximately 2.5 mm axial movement of the support during load change from light to full load, although it is possible that the wire debonded from the flux shield, and the wire then broke due to vibration associated with gas flow.

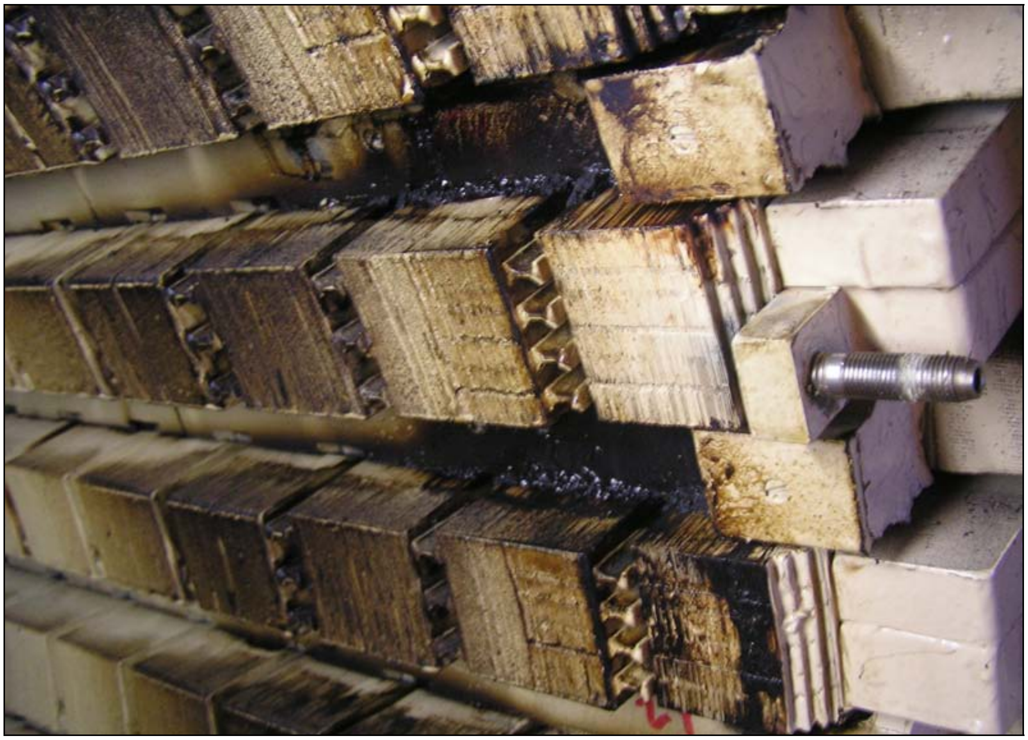


Figure 3-11
Extensive "Greasing" at the Non-Turbine End of the Stator Slots. Marshall Unit #3

Figure 3-12
Ripple Springs Removed from a Top Bar in the Marshall #3 Unit

Figure 3-13
Debonded and Severed Flux Probe Wiring (See Text)

The end-winding region at the non turbine end showed possible signs of a small amount of partial discharge. The sites found were small and not very numerous; being restricted to either regions having phase-phase voltage or slot exits. Examples are given in Figure 3-14. However, surface cleaning of the region (see insert) showed that much, but not all, of the discoloration could be removed leaving the areas affected by the discharge activity restricted to just a few mm. This is depicted by the arrow in the insert of Figure 3-14. The flux shield had lost paint in several places throughout its length. This is presumably the normal result of stray flux heating and is not a factor of concern.

The inspection of the sister unit at Marshall (#4) indicated that some arcing had been taking place on the flexlinks at the line terminals. This is depicted in Figure 4-10. The braided links on unit #3 were inspected and found to be in good condition. This was perhaps to be expected since the severe deterioration of these components had resulted in their replacement in 2003 (see reference [3]).

In summary, the winding appeared in good condition, with some evidence of some very minor PD and some end-of-slot stator bar vibration. Multiple sectioning of the bars did not reveal significant internal discharge activity and the groundwall appeared to be well consolidated with no evidence of delamination as would perhaps be appropriate to a base loaded machine subjected to infrequent thermal cycles.

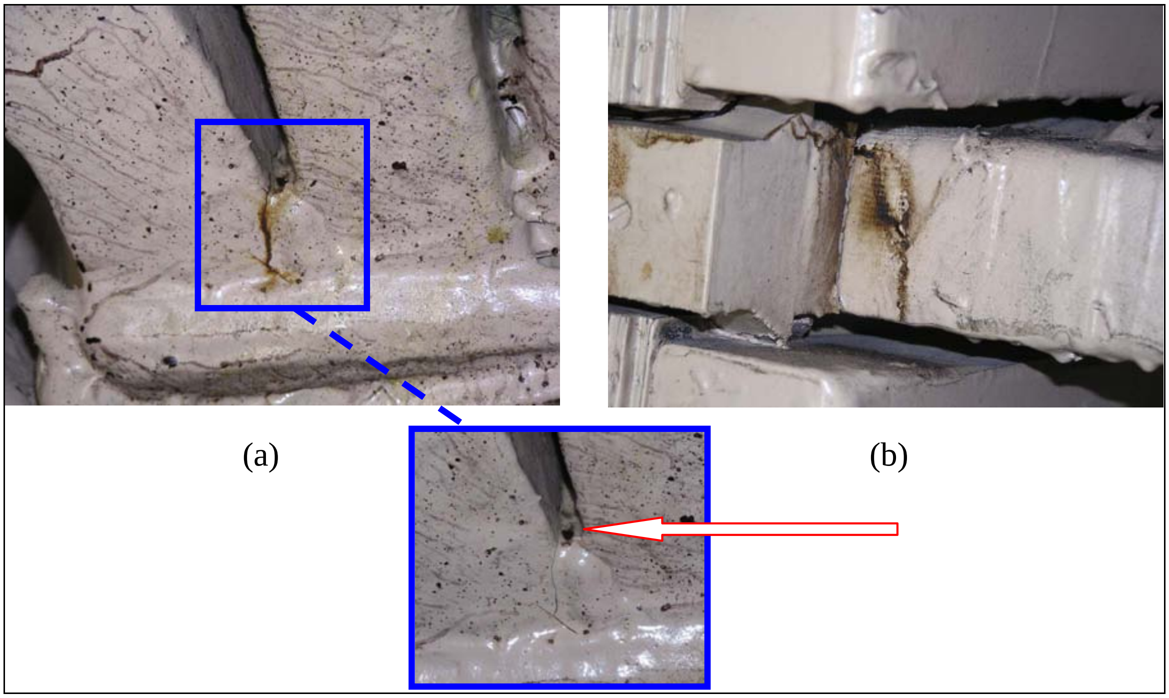


Figure 3-14
Minor Sources of End-Winding PD. Marshall Unit #3: (a) Between Phases, (b) at Slot Exit

4

MARSHALL UNIT #4: ASSESSMENT AND INSPECTION

On March 3rd 2006, Unit #4 at the Marshall station of Duke Energy was inspected (C.V. Maughan and J.K. Nelson) after the rotor had been removed, but before any stator teardown prior to a planned rewind of the unit. PD assessments of this unit were made in 2005, and, thanks to the cooperation of several of the testing companies, assessments were also made in February 2006, just before the outage to provide the opportunity to detect any very recent changes in condition. This included both PD and EMI tests. This section chronicles the assessments made and provides a description of the inspection findings together with a reconciliation.

Like Marshall unit #3, this machine is a GE manufactured hydrogen-cooled unit rated at 790 MVA at 24 kV. It was originally manufactured in 1970 using Micapal® 1 insulation. It is assumed that the decision to rewind this machine was based on the need to make appropriate investments in older units rather than an indication of significant problems.

2005 Assessments

HF PD Evaluation: Tester A

Tester A undertook both high- and low-frequency PD tests on Unit #4 in June 2005. The unit was running at close to full load (760 MW, 279 MVAr) with a stator temperature measured at 75°C and an H_2 pressure of 0.41 MPa (59 psi). 3-D phase resolved displays of the discharges measured on each phase are provided in Figure 4-1. These plots provide both magnitude and count information without the need to display the counts in color. It is clear from these plots that Phases A and B are more active than Phase C which is exhibiting particularly low levels, but nevertheless the level of discharge activity does not constitute any concern. Furthermore, comparison with similar results taken on this unit by the same tester in August 2003 [3] indicates little significant change in overall activity from which Tester A concludes that the unit is stable and in acceptable condition. The LF and HF measurements made appear to be consistent in this regard.

Since Units #3 and #4 are sister machines, it is also instructive to undertake a comparison between the units. This has been done in the summary provided in Table 4-1 which again provides maximum discharge levels determined by both the LF and HF techniques in a way that permits a comparison with Table 3-1 derived for Unit #3. The levels are clearly very substantially lower, but this may be the result of external isophase bus duct discharges surmised to have corrupted the measurements given in Table 3-1 for Unit #3.

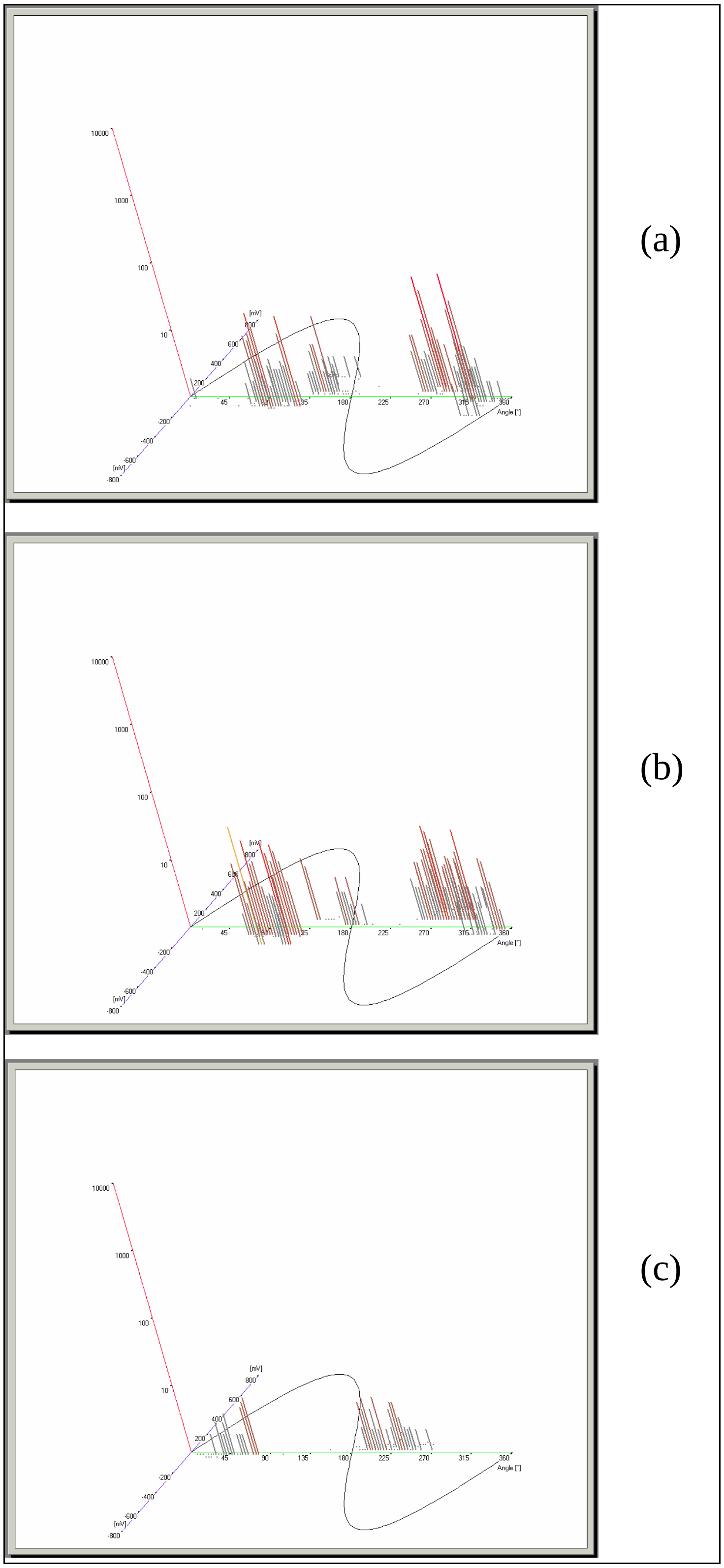


Figure 4-1
High-Frequency PD Phase-Resolved Analysis of Marshall Unit #4 by Tester A. (a) - (c) Correspond to Phases A – C

Table 4-1
Comparison of Maximum Discharge Magnitudes for LF and HF Techniques for Marshall Unit #4. Tester A

	LF (nC)	HF (mV)	
		-	+
Phase A	1.5	200	200
Phase B	1.3	175	200
Phase C	0.55	25	50

PD Evaluation, 2-Frequency LF: Tester C

An evaluation of this unit was made on November 7th 2005 when an opportunity was afforded to undertake low-frequency PD measurements at two different loadings (280 MW and 670 MW). The corresponding H_2 pressure and stator temperatures were not recorded, but there is no reason to believe that they would have been substantially different from previous tests. The methodology for this assessment by Tester C was the same as that used for Marshall Unit #3.

Figure 4-2 depicts a phase-resolved PD analysis taken at the two loading levels for a frequency band of 2 – 20 MHz. Phase A is used for synchronization. The detector gain has been adjusted so as to accommodate the largest discharges present and it is evident that there are discharges at multiple levels. The high level activity through the phase spectrum probably again represents activity external to the unit. PD within the generator is confined to the (uncalibrated) magnitudes below about 50 pC. The main purpose in adjusting the load on the machine during a PD test is to try to determine whether the bars are tight in the slots and whether the groundwall insulation is well consolidated. Clearly, in order to make this evaluation, detailed discharges from the slot area have to be examined. This has been done in Figure 4-3 where the gain has been substantially increased so as to examine the nature of the low level activity. Not only is the level here quite low, but there is no significant change in the PD characteristics as the result of the bar force change resulting from the changed leakage magnetic flux. As a consequence, one must infer that the windings in this machine are still tight.

EMI Assessment

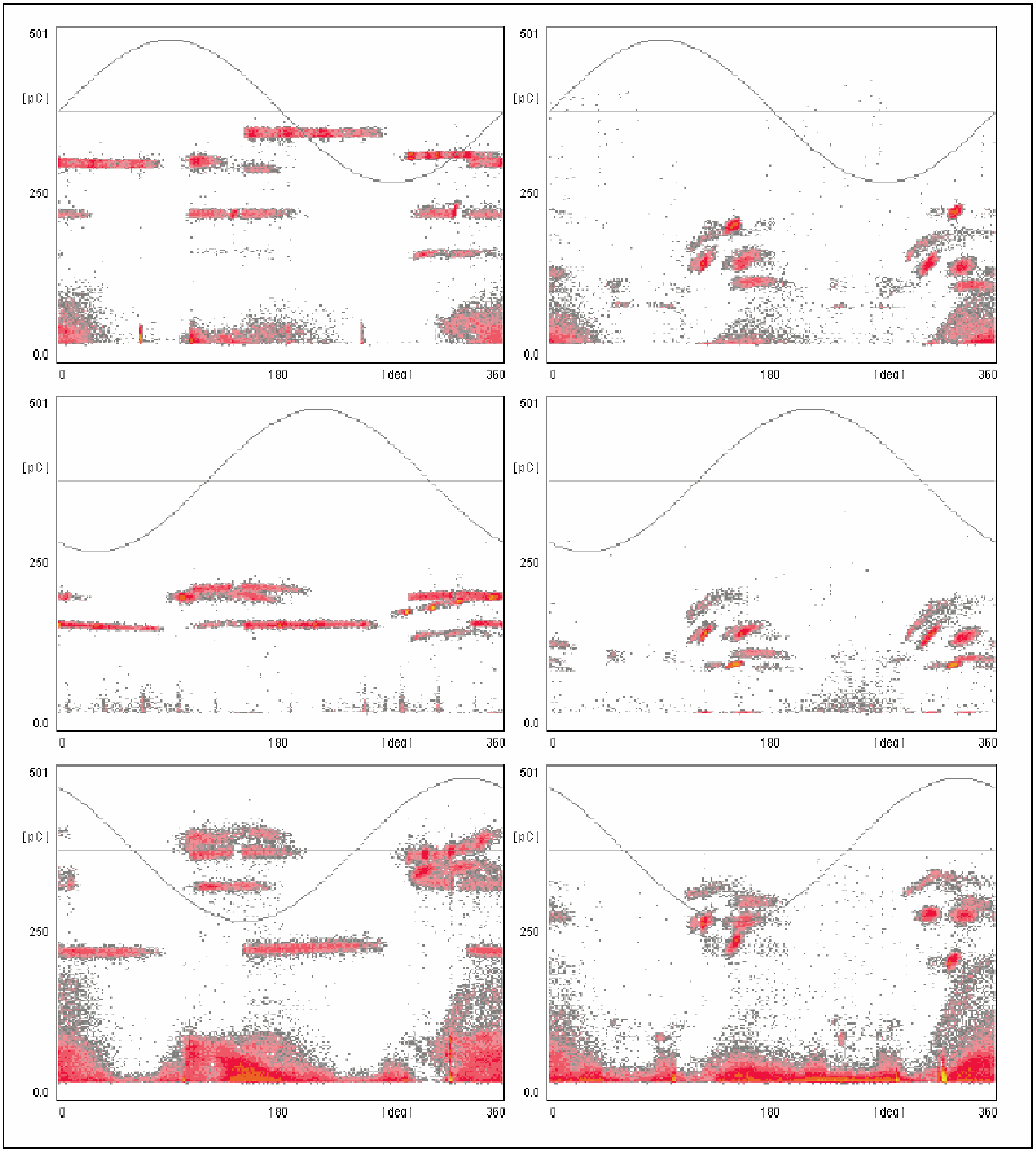


Figure 4-2
Phase-Resolved PD Analysis for Marshall Unit #4 in the Frequency Band 2 - 20 MHz. Left: 280 MW, Right": 670 MW. Phases A-C (Top to Bottom) Low Gain. Tester C

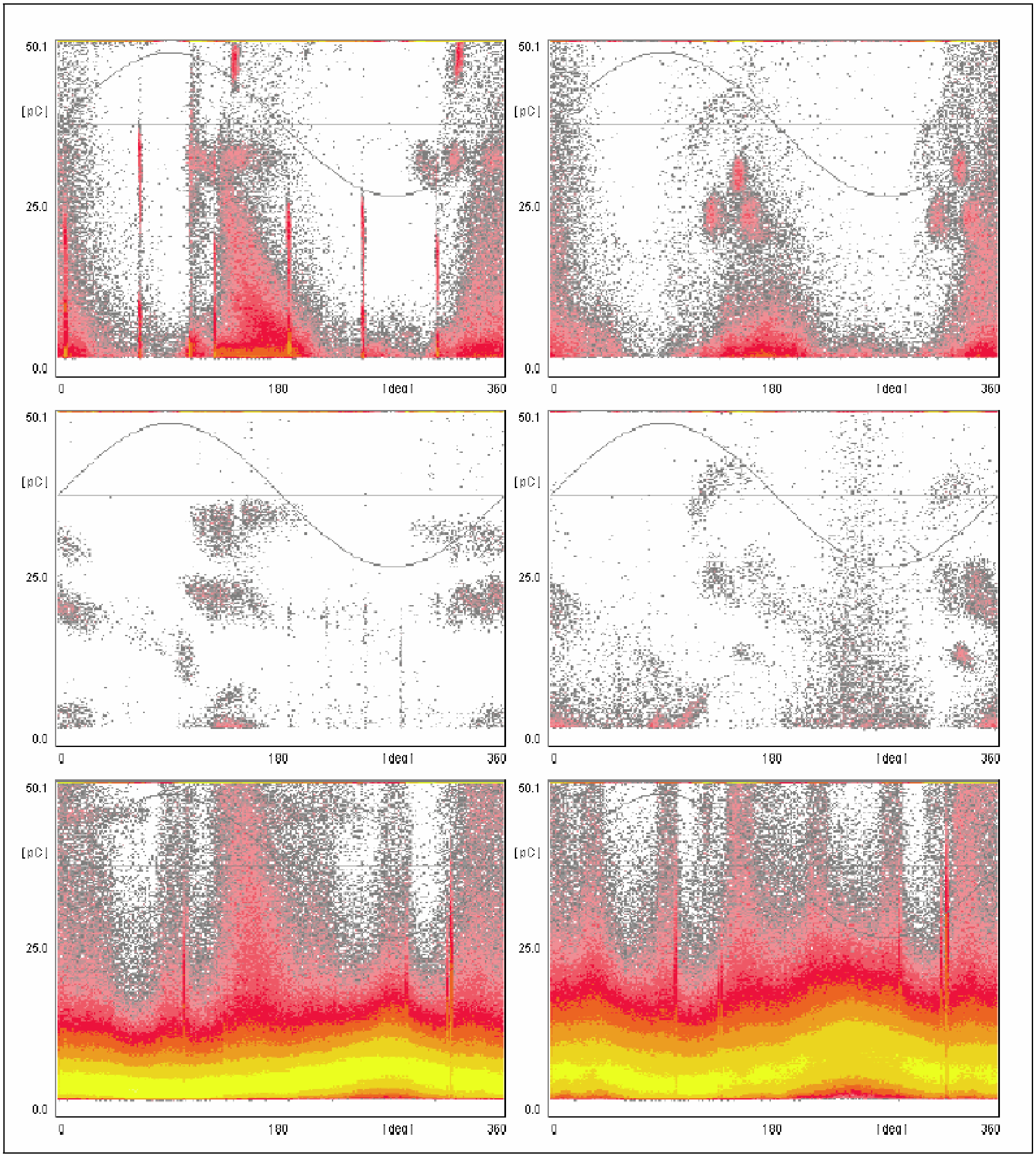


Figure 4-3
Phase-Resolved PD Analysis for Marshall Unit #4 in the Frequency Band 2 - 20 MHz. Left: 280 MW, Right": 670 MW. Phases A-C (Top to Bottom) High Gain. Tester C

The EMI spectra of Marshall Unit #4 for all three phases (top to bottom) is provided in Figure 4-4. A particular feature of these spectra is the lack of activity seen in the region below 1 MHz. This is the part of the frequency band in which discharges in the slot area usually become visible [2].

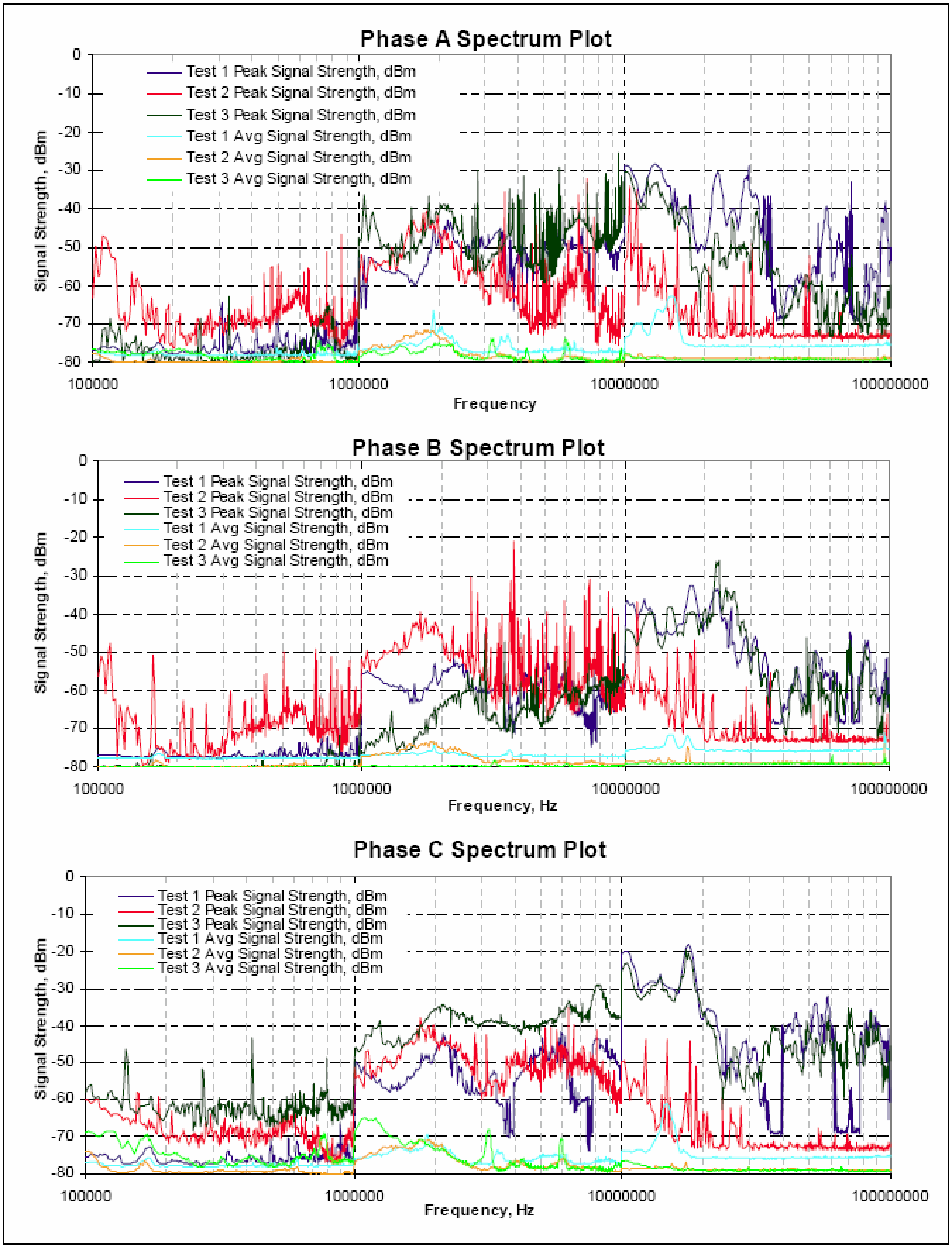


Figure 4-4
EMI Spectra for All 3 Phases of the Stator of Marshall Unit #4. Tester C

This feature would tend to reinforce the view that the groundwall of this machine is still in good condition. In contrast, the copious activity evident in the higher frequency regions is consistent with arcing conductions at the busbars or corona discharges in the external circuit.

2006 Assessments

Both PD and EMI assessments were made of the condition of Unit #4 just prior to the planned inspection. The PD measurements were both made using a high-frequency technique under less than ideal conditions since single-sided high capacitance couplers only are available.

PD Evaluation: Tester B

Tester B evaluated the unit on February 3rd 2006 at a time when the load was 699 MW (reactive power 67 MVAr) and the unit temperature and hydrogen pressure were 56°C and 0.41 MPa (60 psi) respectively. The discharge magnitudes in comparison with those taken by Tester B in 2004 are shown in Table 4-2 and the associated phase resolved plots depicted in Figure 4-5.

Table 4-2
Comparison of Maximum Discharge Magnitudes for Marshall Unit #4 in Comparison with Those Taken in 2004. Tester B

Date	PD Maximum Magnitudes (mV)					
	Phase A		Phase B		Phase C	
	Q_m+	Q_m-	Q_m+	Q_m-	Q_m+	Q_m-
Aug ’04	13	8	21	13	35	52
Feb ’06	656	657	-	556	99	98

It would appear that there has been a substantial increase in activity over the intervening 18 months; particularly for Phases B and C. However, examination of the phase-resolved plots in Figure 4-5 makes it clear that the pattern depicted does not have the phase relationships expected of activity either in the slot area or in the end-windings. As a result one must yet again question the validity of the reference signals used particularly as the signals are derived from the couplers through radio-frequency current transformers of unknown connection. Tester B, based on the similar anomalous increase also seen in Unit #3, concludes that the source of the increased signals measured is likely to result from problems in the isophase bus duct and not from the stator itself.

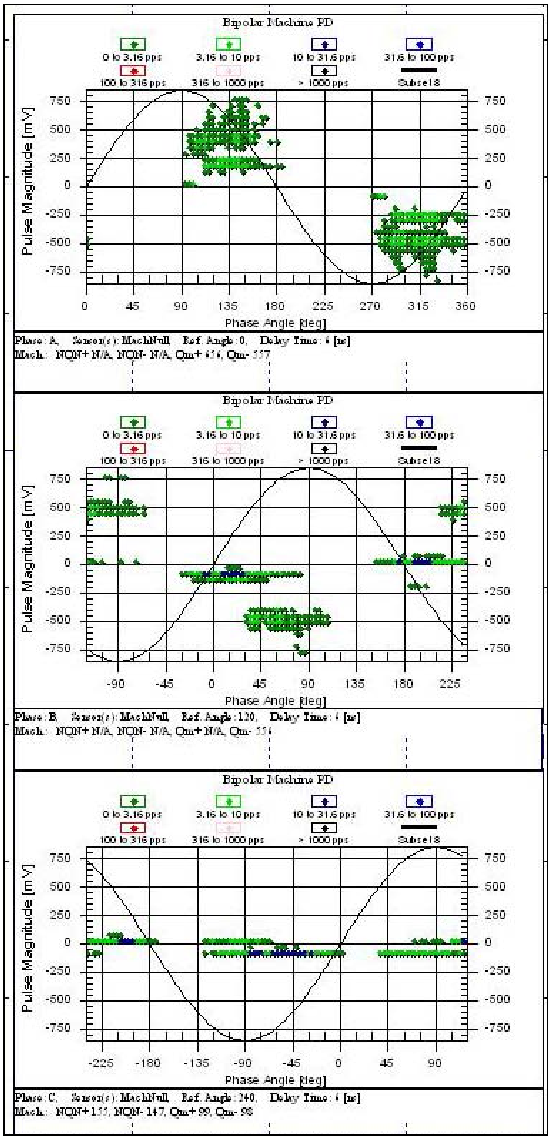


Figure 4-5
Marshall Unit #4 Phase Resolved PD Analysis. Tester B

PD Evaluation: Tester A

The second PD evaluation was conducted on February 2nd 2006 by Tester A when the load was 680MW (60 MVAr). The stator temperature was recorded at 55°C and the H_2 pressure at 0.41 MPa (59 psi). Since the same tester evaluated Unit #4 in June 2005,a direct comparison can be made, although it must be recognized that the reactive power delivered in the 2005 test was much higher, resulting in a higher winding temperature; presumably as a result of the associated cross flux. Such a comparison is made in Figure 4-6 on the basis of a pulse height analysis applied to Phase A. This illustrates both that the method appears reproducible and that the machine is stable with no significant change in condition over the intervening period.
A similar conclusion could be drawn for the other two phases (not pictured here).

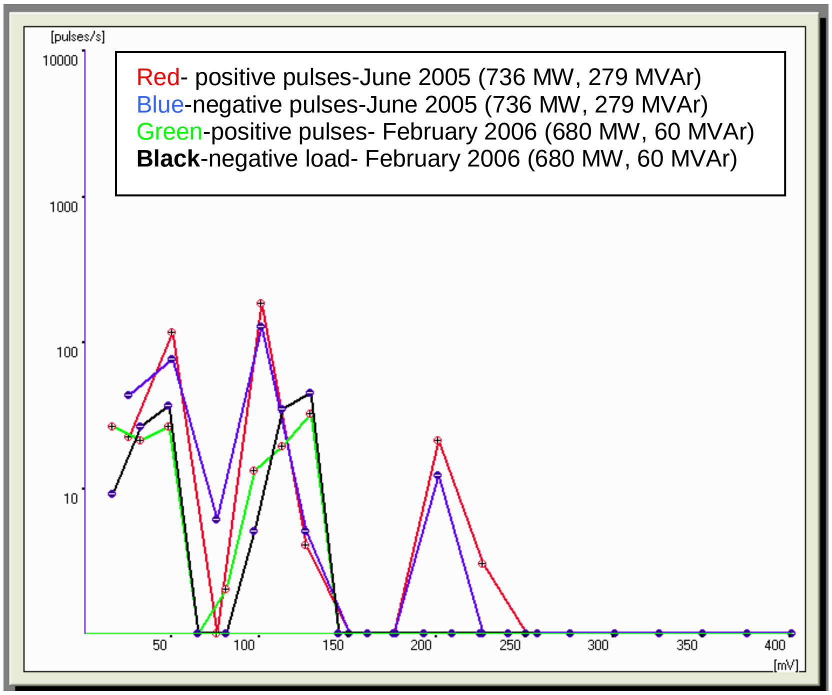


Figure 4-6
PD Pulse Height Analysis for Phase A of Marshall Unit #4. Tester A Comparison Over a 7 Month Period

Figure 4-6 also provides an important additional perspective since the power factor angle has changed significantly between the two readings without any obvious change in the PD characteristics. The import (or export) of reactive power has been shown to be a means of determining whether the slot area of the machine is tight and the groundwall well consolidated. [4]. This comes about due to the change of forces resulting from the interaction of the slot leakage flux and the conductor current. The absence of any meaningful change would tend to confirm that the slot portion of the winding was still in good condition for a machine of this age.

EMI Evaluation Tester E

An EMI analysis was conducted on Unit #4 on February 9th 2006 at a load of 703 MW, and hydrogen pressure of 0.40 MPa (58.7 psi). The signals were captured using a split-core RFCT placed around a ground connection to the generator neutral grounding transformer. Previous measurements made by Tester E have used an Electro-metrics™ EMI3115A EMI Analyzer/Receiver, but these measurements were taken with a new instrument - Agilent E7405A EMC Analyzer coupled to a PC to provide the necessary data processing. The mobile set-up is illustrated in Figure 4-7. In addition Tester E also derived measurements from the installed 9 nF couplers on the isophase bus at the line end for comparison.

Figure 4-7
EMI Measurements in Progress at Marshall

It is instructive to compare this measurement with a previous assessment made by the same tester. This is illustrated in Figure 4-8 where is can be seen that, although there has been some change since 2003, the unit appears stable which confirms the PD assessments. The somewhat higher levels in the results taken in 2004 (see Ref [2]) probably result from the fact that the RF current transformer used was placed on the high side of the neutral grounding transformer for those measurements. Tester E concludes that the slight increase in activity around 1 MHz is indicative of both slot and endwinding discharge.

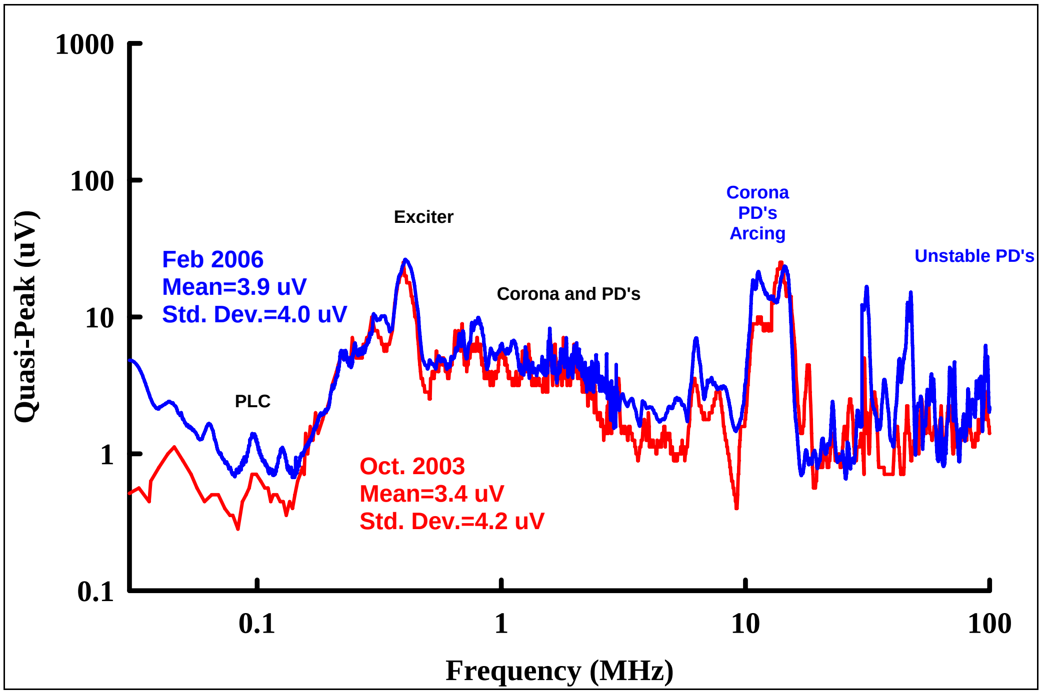


Figure 4-8
Comparison of EMI Signatures for Marshall Unit #4 between 2003 and 2006 using CT Neutral Connection. Tester E

The activity seen between 2 and 4 MHz is identified with the stator winding, while that above about 20 MHz likely originates from the buswork external to the generator. It is also speculated, on the basis of this result, that there may be some core edge discharges as the result of stator bar movement. Figure 4-9 documents the same result, taken on a phase-by-phase basis, from the line-end bus couplers. As would be expected, the sensitivity is greater since the sensors are closer to the top end of the winding where most of the discharge is expected. Figure 4-6 would indicate that the T3 coupler (Phase C) is registering significantly more activity than Phases A and B. Measurements taken with a portable EMI detector [2] at the lower frequency range were identified with slot related deterioration, particularly at the core edges. In comparing the characteristics of Figures 4-5 and 4-6 using different sensors on the same machine, it is also clear that the marked peaks shown in Figure 4-9 are the result of resonances which are excited to a much greater extent than is visible for the neutral CT connection.

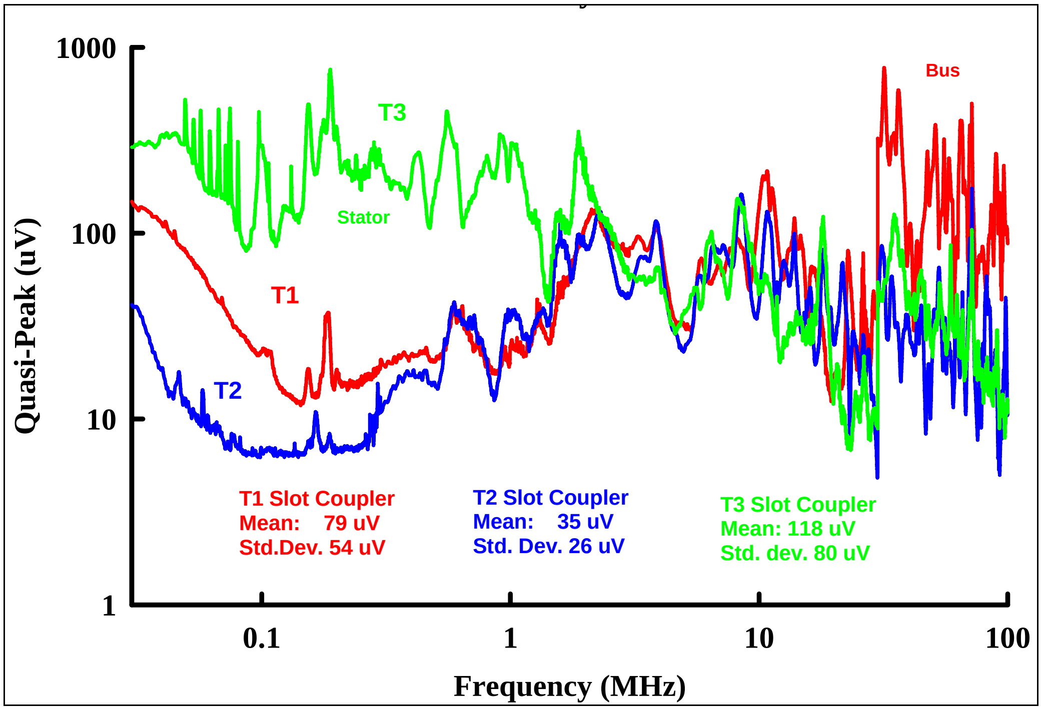


Figure 4-9
EMI Signatures from the 3 Bus Couplers on Marshall Unit #4. Tester E

It is important to recognize [2] that the assignment of the extent and location of deterioration through the EMI technique also relies on time domain observation of the signals when conditioned by band-pass filters. For example, Figure 4-10 depicts a time sequence of discharges at 35 MHz derived from phase C from the bus coupler. The single high-amplitude gap discharges, seen almost every half cycle, suggest that a broken or cracked insulator may be present in the C phase structure.

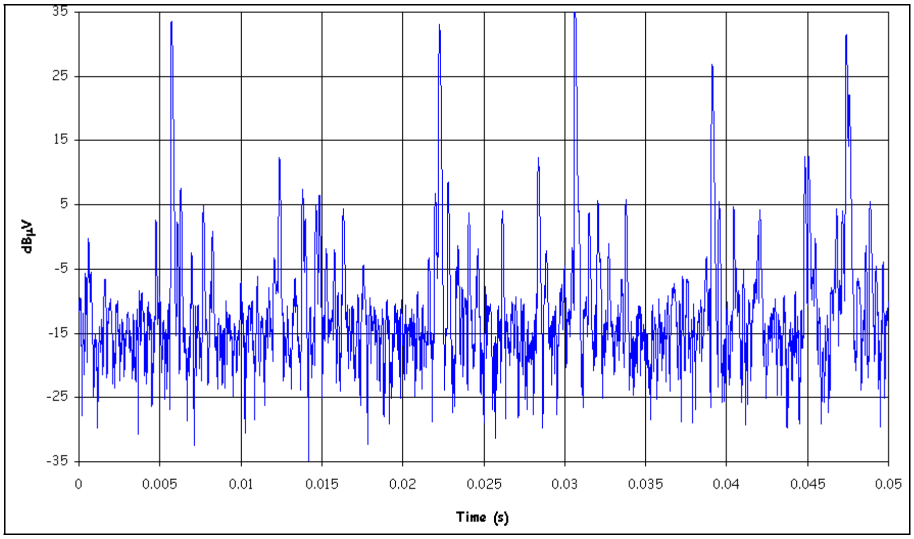


Figure 4-10
Marshall Unit #4 Time Domain Signal taken by Tester E at 35 MHz

Marshall Unit #4 Visual Inspection

The March 3rd 2006 inspection of this unit revealed that, overall, this 30-year-old winding appeared to be in good condition despite the fact that this is a very large GE unit with high electromagnetic bar forces. Figure 4-11 shows an overall view of the end-winding region, and there were no indications of discharges at the phase breaks. The close-up shown in Figure 4-12 indicated that the machine was only slightly oily. This winding was in stark contrast to the SW Sammis #6 winding which was the age of this generator when first inspected in 1998 as part of the EPRI PD project. A comparison may be made by looking at Figure 2-7 in Chapter 2. Wedges were generally tight. With the exception of very minor greasing at the ends of a few slots, there were no indications of bar vibration, either in the slots or, more particularly, at the ends of the core – see Figure 4-12. There were no visible deposits relating to partial-discharge at the line-to-line voltage phase breaks on the top bars at either end of the winding. We were unable to find any evidence of partial discharge occurring anywhere on the endwinding of this machine. The conductors are set very deep in the slot, thus it was not possible to examine for partial discharge without use of a borescope. Since the winding was about to be removed, the Duke Energy personnel were requested to examine the bars as they were removed from the slots and to record and photograph any indications found.

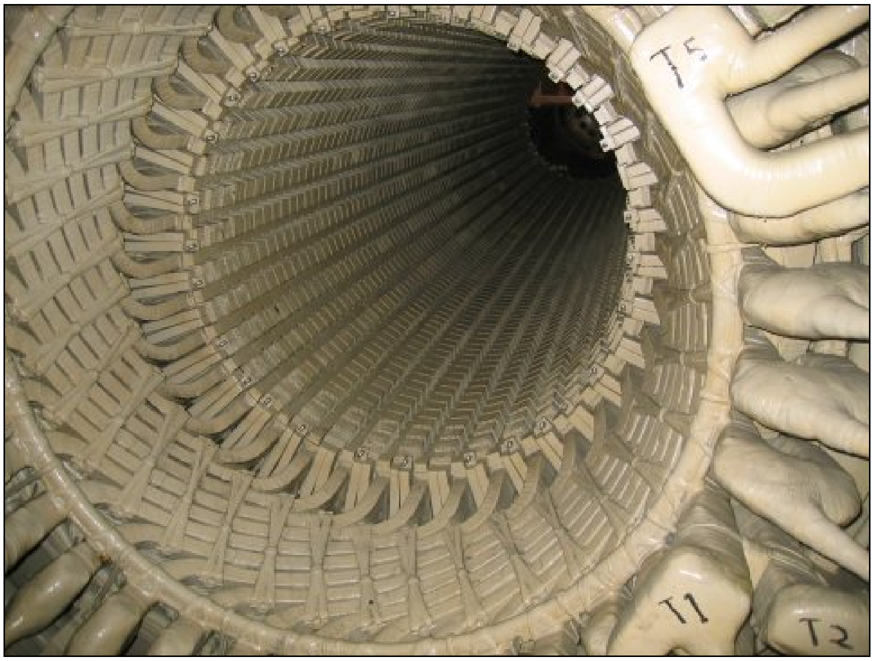


Figure 4-11
Overall View of the End-Winding Region of Marshall Unit #4

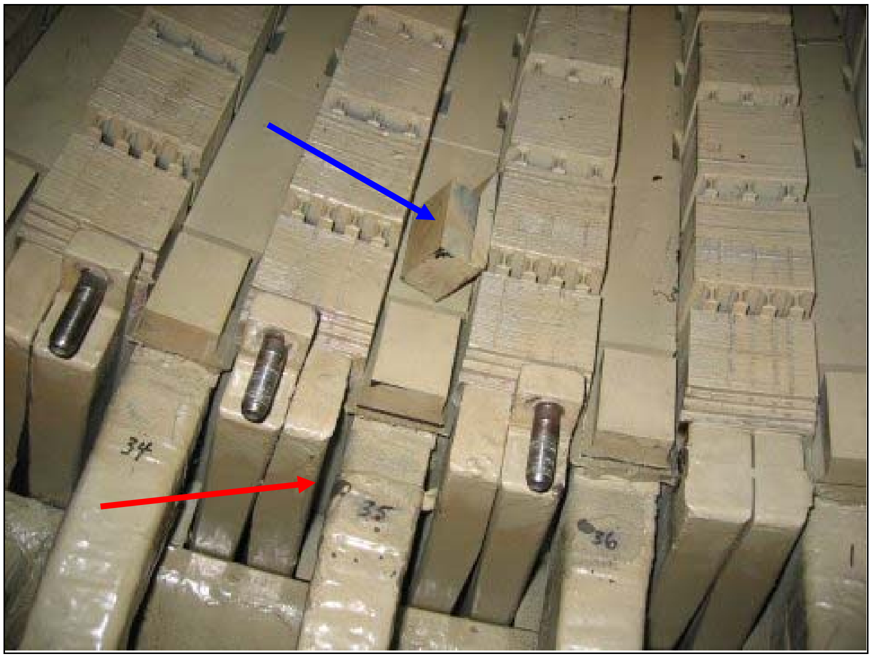


Figure 4-12
Minor Greasing on a Few Bars (Red Arrow). Loose End Ventilation Block (Blue Arrow)

The Duke engineers have also asked the GE winders to watch for indications of PD as the bars are removed from the slots. In talking with Duke personnel after all bars were removed, they state that they were able to find no indications of PD on the surfaces of any of the bars, and in particular the phase bars.

It would have been instructive to examine the insulation internally. However, the bars are armored with asbestos, and arrangements could not be made to obtain sections of the bars for internal inspection.

Generator Iso-Phase Bus

The EMI readings, and many of the PD assessments, have strongly indicated high PD associated with the iso-phase bus duct. Accessible bus areas were therefore examined. In particular, the flexible leads (flex-links) below the high-voltage bushings which connect to the iso-phase bus were examined. Evidence of overheating was readily visible on some of the tangs. A typical lead is shown in Figure 4-13.

The lead shown in Figure 4-13 was microscopically examined by the M&P Laboratory in Schenectady, New York. Arc damage, with pitting and solidified molten copper, was clearly visible in the area identified by the enlargement. Professional pictures of this lead were taken by the Laboratory and are depicted in Figure 4-14.

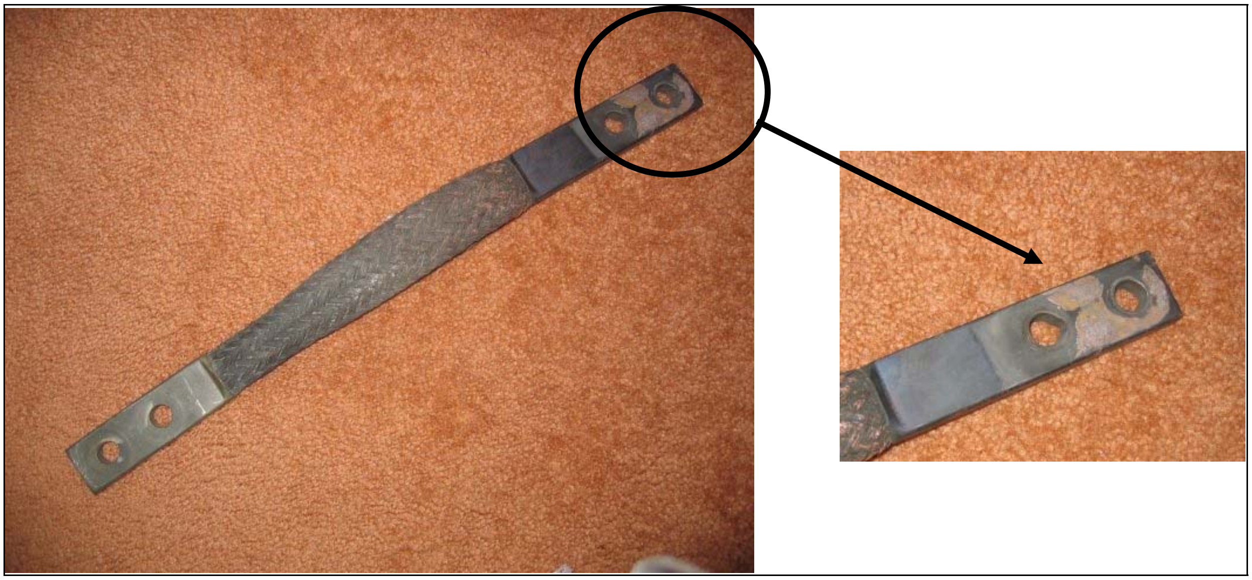


Figure 4-13
Overheating of a Generator Flexlink (Insert Shows Close-Up on Overheated Tang)

In addition to the pitting, severe overheating is visible under the bolt clamping areas. The mini-arcs associated with the condition of these leads would be expected to generate strong arc voltages, easily sensed by PD and EMI methods. These leads from Marshall #4 are almost identical in appearance to leads from Marshall #3 shown in Figure 4-15 which were found to be a problem in 2002 and replaced at an outage. This is clearly not an uncommon issue and has also been seen elsewhere.

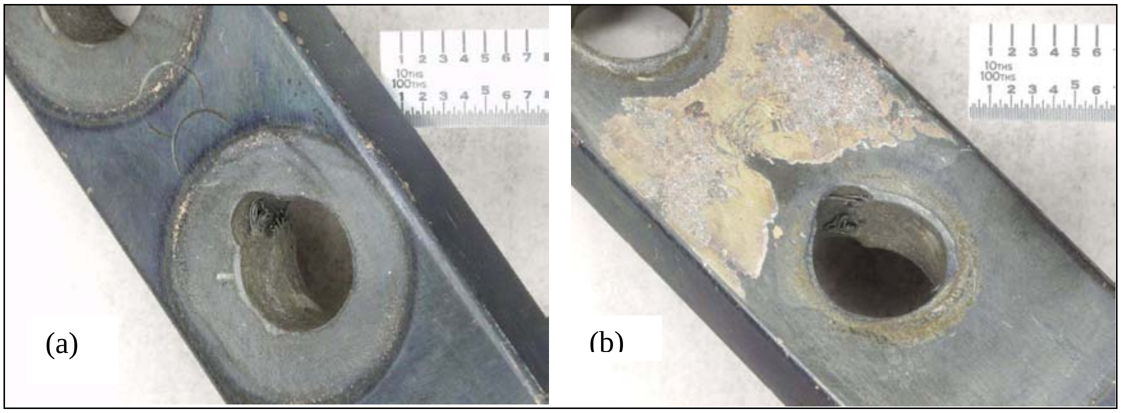


Figure 4-14
Photomicrographs Showing (a) Bolt Hole Burning, and (b) Arc Pitting on the Tang

Figure 4-15
Two Levels of Overheating Previously Observed on Leads from Marshall #3

Marshall Unit #4 Reconciliation

From a partial discharge perspective, the stator winding on Marshall #4 appeared, by visual inspection, to be in good condition. It is remarkable that no PD indications would be observed on the bar external surfaces of a 30-year old winding, but the results are in line with the information reported by many, but not all, of the assessments made. Marshall #4 has generally shown lower discharge activity with both PD and EMI than the sister unit #3. The inspection was consistent with the instrumentation assessment in that there was no indication of significant partial discharge on this winding.

It is instructive to revisit the diagnostic predictions made by the various methods used over the period over which the unit has been under EPRI surveillance. This may conveniently be done by examining the summary tables provided in References [2,3,5]. Since there has been considerable confusion at the Marshall site over the phase references provided, it is perhaps appropriate to remove the identification of the phase from the comparison. One also has to be somewhat careful to recognize that, in some instances, Duke Energy undertook remedial work on the bus duct and instrument transformers between assessments which does not always allow a direct comparison of *external* problems.

The first observation that has to be made is that many of the methods used have been able to detect the ongoing external busbar problems which have been a feature of this site. This is perhaps a positive, if non surprising, finding. The Marshall station is equipped with only one set of 9 nF couplers per phase. This implies that time-of-flight methods cannot be used to differentiate between discharge activity within the machine envelope and external problems. In this situation other intuition had to be employed. Sometimes this was based on the character of the discharges, but more often, the rationalization was based on the high levels of activity seen which, it was reasoned, could not reasonably be sustained in a hydrogen-cooled machine. In this context, it is appropriate to mention that EMI, in the hands of experts, has shown itself well able to identify external problems. However, in many cases this has also relied on other supplementary attendant evidence.

The results of the study on this machine would indicate, however, that EMI was not as effective at predicting problems within the stator insulation system. Reviewing the record, core edge discharges and end-winding activity have been consistently cited as problems for several years. The March 2006 inspection found no evidence for this at all. Both HF and LF Partial Discharge assessments on this unit were mixed, but, in general, the assessment was that some low level activity was discernible, but the machine was judged as serviceable and in good condition. Since the inspection was unable to do any bar sectioning, the extent of the internal groundwall PD was not evaluated, but clearly the machine was found to be in acceptable condition.

5

LAKE ROAD GENERATING UNIT #3

Unit #3 at Lake Road Generating (Dayville, CT) has been equipped with two sets of couplers, and thus high-frequency techniques which can take advantage of time-of-flight methods can be employed to discriminate activity within the stator from that originating externally. However, this plant is a combined-cycle peaking station and it has been quite difficult to schedule testing at this site on account of the unknown availability of the units. In particular, it has proved impossible recently to arrange for an EMI test since the transit time for the testing unit from its base in the mid west is greater than the advance notice of availability that the station can provide. However, the unit is important to the program since it represents the only large air-cooled generator (ABB, 340 MVA, 21 kV, put in service in 2001).

2005 Assessments

In 2005, PD tests were conducted at Lake Road by both high- and low- frequency methods (testers B and C respectively). However, only the high-frequency results are presented here since the lower-frequency data was withheld by the tester due to concerns about Intellectual Property aspects.

HF PD Evaluation: Tester B

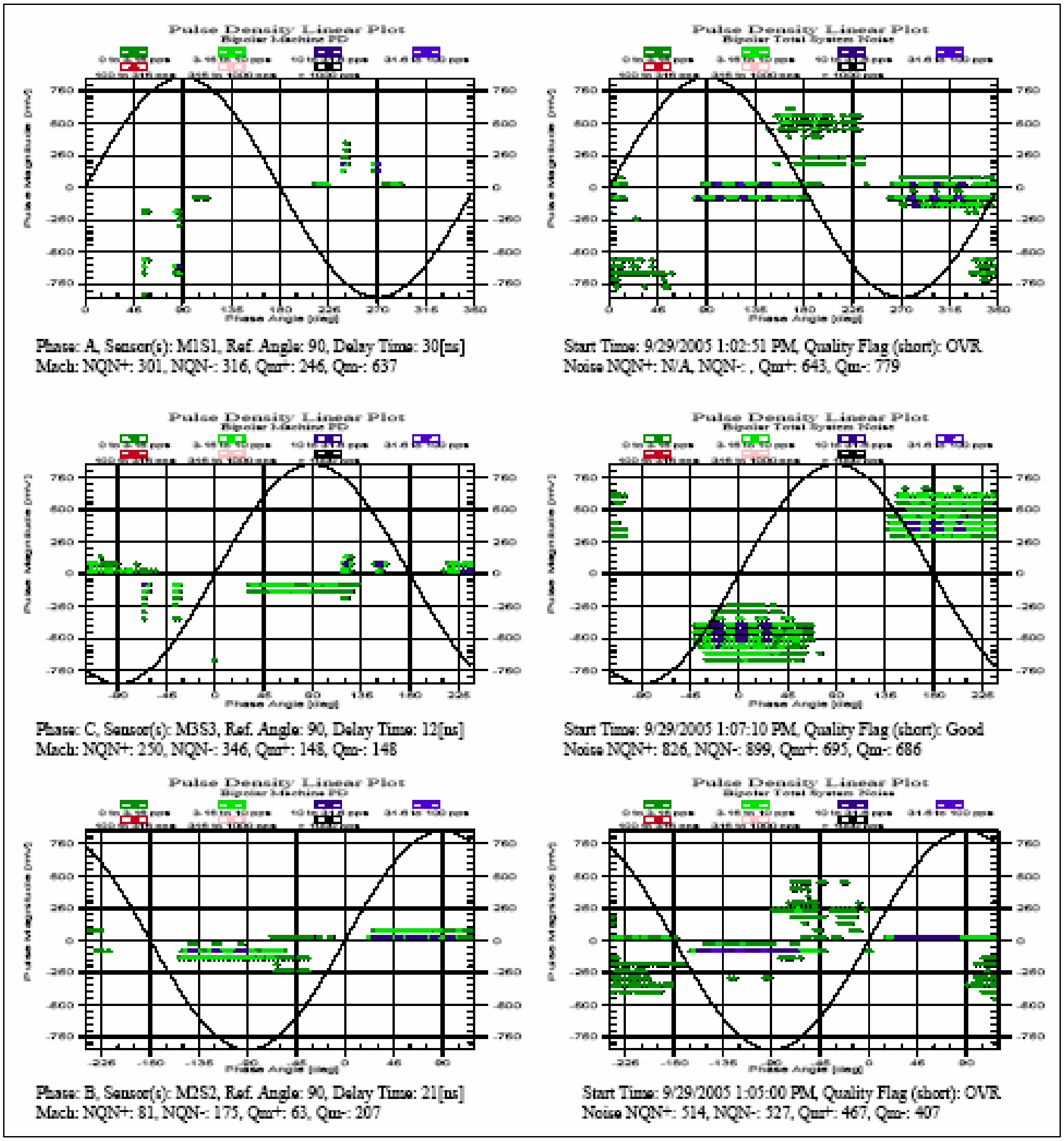
Tester B undertook PD tests on Unit #3 at Lake Road on September 29th 2005 when the unit was operating at a load of 245 MW (101 MVAr) and had a winding temperature of 80°C. Tester B relies both on the features of a phase-resolved PD plot, and also on polarity discriminated maximum pulse magnitude (Q_m+ and Q_m-) and integrated measures (NQN+ and NQN-).

These indices are shown in Table 5-1 for tests conducted in 2005 in comparison with similar evaluations completed in September 2003.

Table 5-1
Maximum Discharge Magnitudes (Q_m) and Integrated Measure (NQN) for Lake Road Unit #3 Over a Two-Year Period. Tester B

Date ↓	**Phase A**		**Phase B**		**Phase C**	
	Q_m+	**Q_m-**	**Q_m+**	**Q_m-**	**Q_m+**	**Q_m-**
Sept 03	664	671	336	288	257	332
Sept 05	246	637	63	207	148	148
	NQN+	**NQN-**	**NQN+**	**NQN-**	**NQN+**	**NQN-**
Sept 03	Ph.A unavailable		364	329	435	448
Sept 05	301	316	81	175	250	346

It is evident that discharge activity, as measured both by the maximum magnitude and integrated measure, is substantially reduced over the 2 year period. By comparison of the values in Table 5-1 with those which are typical of machines of the same type (cooling) and voltage, the overall condition of a unit may be gauged with respect to its peers. Of course, this only applies if the same test method is used with the same coupler configuration. With the exception of Phase A which continues to exhibit high levels of discharge, the levels (magnitudes here expressed in mV) of the other phases have declined to more typical levels for a high-voltage air-cooled machine. The reason for this decline is not clear.



Phase: A, Sensor(s): M1S1, Ref. Angle: 90, Delay Time: 30[ns]
Mach: NQN+: 301, NQN-: 316, Qm+: 246, Qm-: 637

Start Time: 9/29/2005 1:02:51 PM, Quality Flag (short): OVR
Noise NQN+: N/A, NQN-: , Qm+: 643, Qm-: 779

Phase: C, Sensor(s): M3S3, Ref. Angle: 90, Delay Time: 12[ns]
Mach: NQN+: 230, NQN-: 346, Qm+: 148, Qm-: 148

Start Time: 9/29/2005 1:07:10 PM, Quality Flag (short): Good
Noise NQN+: 826, NQN-: 899, Qm+: 695, Qm-: 686

Phase: B, Sensor(s): M2S2, Ref. Angle: 90, Delay Time: 21[ns]
Mach: NQN+: 81, NQN-: 175, Qm+: 63, Qm-: 207

Start Time: 9/29/2005 1:05:00 PM, Quality Flag (short): OVR
Noise NQN+: 514, NQN-: 527, Qm+: 467, Qm-: 407

Figure 5-1
Directional Phase-Resolved Discharge Patterns for Lake Road Unit #3. Top to Bottom: Phases A, C and B. Left: from the Machine. Right: from External Sources. Tester B

The phase resolved data shown in Figure 5-1 can be useful in trying to pinpoint the underlying cause(s) of the activity. The discharges which appear on the left-hand panel in Figure 5-1 are not classical (i.e. appearing at the 45° and 225° positions on the power frequency line-to-ground waveform – see Reference [3]). It is thus likely that the groundwall insulation is in good condition. The discharges seen are most likely to result from surface discharges occurring at a few locations on the surface of the stator bars or perhaps in the endwinding.

The right-hand panel in Figure 5-1 portrays activity which emanates from outside the stator and is generally very high indeed on Phases A and B, although not all shown in Figure 5-1 since it is off scale. Since much of the activity occurs near the AC voltage zero crossings, Tester B speculates that it may be due to a poorly torqued bolt or perhaps oxidized flexlink connections.

2006 Assessments

HF PD Evaluation: Tester A

An evaluation was made on June 2nd 2006 utilizing the installed 80 pF couplers when the active/reactive power was 256 MW/38 MVAr. At the time of the test, the stator temperature of Unit #3 was recorded as 74°C.

The high frequency PD technique usually capitalizes on the application of time-of-flight methods to differentiate between disturbances emanating from within the machine envelope and those reaching the coupler from outside. However, despite the fact that two couplers are installed on Unit #3 to allow this, manufacturers have different protocols for dealing with the arrival time delays due to the surge propagation on the bus. The hardware and software used by Tester A did not permit the use of uncompensated cable runs. As a result, it is understood that a single ended measurement was taken, utilizing the three phase couplers in the plenum above the machine (i.e. closest to the machine terminals). As a result of this, there has to be some doubt about whether the signals are originating wholly inside the machine.

Figure 5-2 provides a composite view of the activity recorded on Phase A. The upper two plots are phase-resolved 3-D representations of the activity recorded in 2004 (left) and 2006 (right) and an increase in activity is clearly present. This is quantified in the lower pulse height analysis which shows the pulse magnitudes at the two dates plotted so that the polarities can be clearly seen. It is clear that there has been a very substantial increase in activity since the readings were last taken by this tester in 2004. The fourfold increase in magnitude should be of some concern if it really is the result of discharges within the stator winding – *see commentary in previous paragraph.* One common yardstick used in the industry is that a doubling of activity over a six month period should be a cause for further investigation. Although these results are much further apart than 6 months, nevertheless the increase would appear anomalous and the owner was informed as soon as the data was available. Having said that, it is also instructive to compare these results with those of Tester B taken in September 2005 (9 months previously). In the case depicted in Figure 5-1, it is clear that there is a substantial contribution to the activity on Phases A and B which time-of-flight discrimination would indicate has its origins outside the machine (right hand panels). It may thus be that Figure 5-2 paints an unduly pessimistic picture.

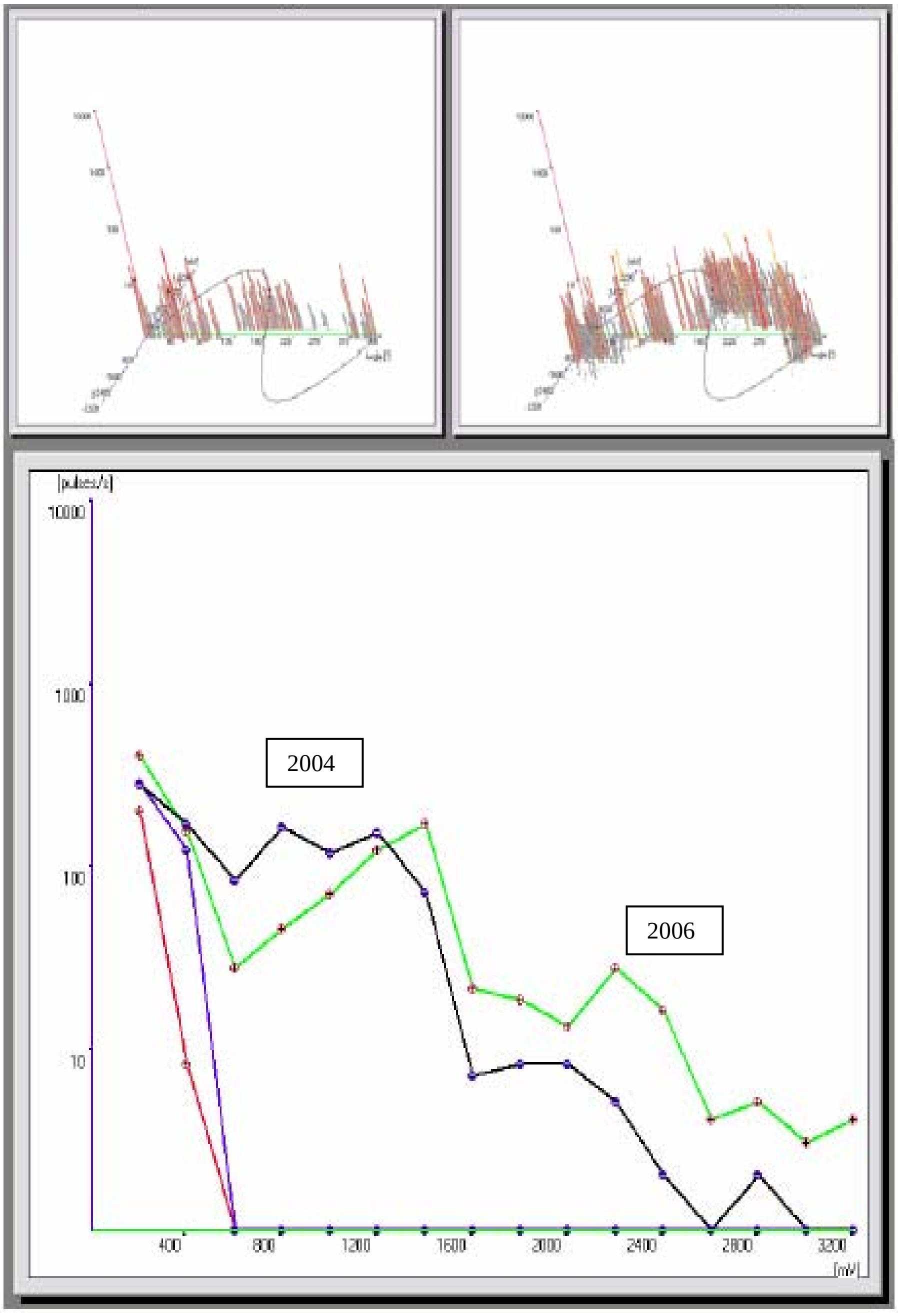


Figure 5-2
Lake Road Generating Unit #3. PD Analysis by Tester A. Top Left 2004, Top Right 2006

Results for Phase B (not shown here) were similar to those for Phase A and also indicate a substantial increase in activity in comparison with the 2004 data. Comparison of the phase-resolved data for Phases A and B would also indicate that cross-coupling between the phases is taking place as indicated by a 120° shift. Tester A clearly recognizes the possibility of corruption by outside sources to create multiple sources, and cites isophase bus duct issues as a possible origin of some of this signal. However, it is difficult to interpret polarity effects relating to classical groundwall PD activity in such circumstances.

In contrast, Phase C showed no significant increase in activity and indicated no polarity predominance. This is in general agreement with the findings of Tester B.

LF PD Evaluation (2 Frequency): Tester F

In late August 2006, Tester F undertook a PD evaluation of the air-cooled Units 1, 2 and 3 at Lake Road Generating. However, only Unit #3 is currently equipped with couplers of both high and low capacitance types. As a consequence, only the results of Unit #3 are reviewed here in some detail, since they can then be compared with data obtained from Testers A and B using higher frequencies. However, the overall findings for the other two units are included in Table 6-3 from which it can be seen that they are behaving in a broadly similar way. However, the levels of activity in units 1 and 2 are still modest, whereas Unit #3 has seen some increase.

Unit #3 was running at 156 MW (15 MVAr) when the evaluation was conducted. This represents a little less than half of full load. Tester F utilized the installed 9 nF capacitive couplers and used a 60 s period for the acquisition of discharge data which is typical. Phase resolved plots are depicted in Figure 5-3 for two different frequency ranges. Although unspecified, it is believed that the upper plots used a frequency range of 40 – 800 kHz (bipolar) and the lower ones use the higher frequency interval of 2 – 20 MHz. (monopolar). However, both of these frequency bands would be regarded as “low” frequency when compared with the measurements normally made by Testers A and B. The reader should also be cautioned that Figure 5-3 also expresses the discharge magnitude in terms of nC which is not directly comparable with the voltage scales used by some others, and these differences have been discussed previously [5]. The discharges seen in the lower frequency band are dominated by signals due to cross coupling of the high frequency components from the generator excitation to the measurement circuit. These can be readily identified since they appear regularly with a phase shift of 60°.

The patterns appearing in the higher frequency measurements in Figure 5-3 are more interesting. Firstly if this data is compared with the equivalent data taken by this Tester in 2004 at almost the same load, it will be seen that there has been a significant increase in the magnitude of the activity. The extensive phase spread of the activity seen in Figure 5-3 might suggest that some contamination was involved. However the ongoing development of some separated “clouds” also points to an ongoing development of some surface discharges in the area of the end windings as suggested by Tester F. The characteristic pattern seen in Phase C is often also associated with delamination or slot discharges. However, in this case the phase angle at which it appears does not support this interpretation (assuming that Tester F is using the correct phase reference).

The increase in activity chronicled by the 2-frequency LF method of Tester F provides some confirmation of the tests conducted using an HF technique about 3 months earlier in 2006 by Tester A. Neither Tester A or F used means to discriminate against external interference, although there is nothing to indicate that external interference is an issue other than an indication in 2005 from another tester that significant signal was being picked up from outside the machine [3].

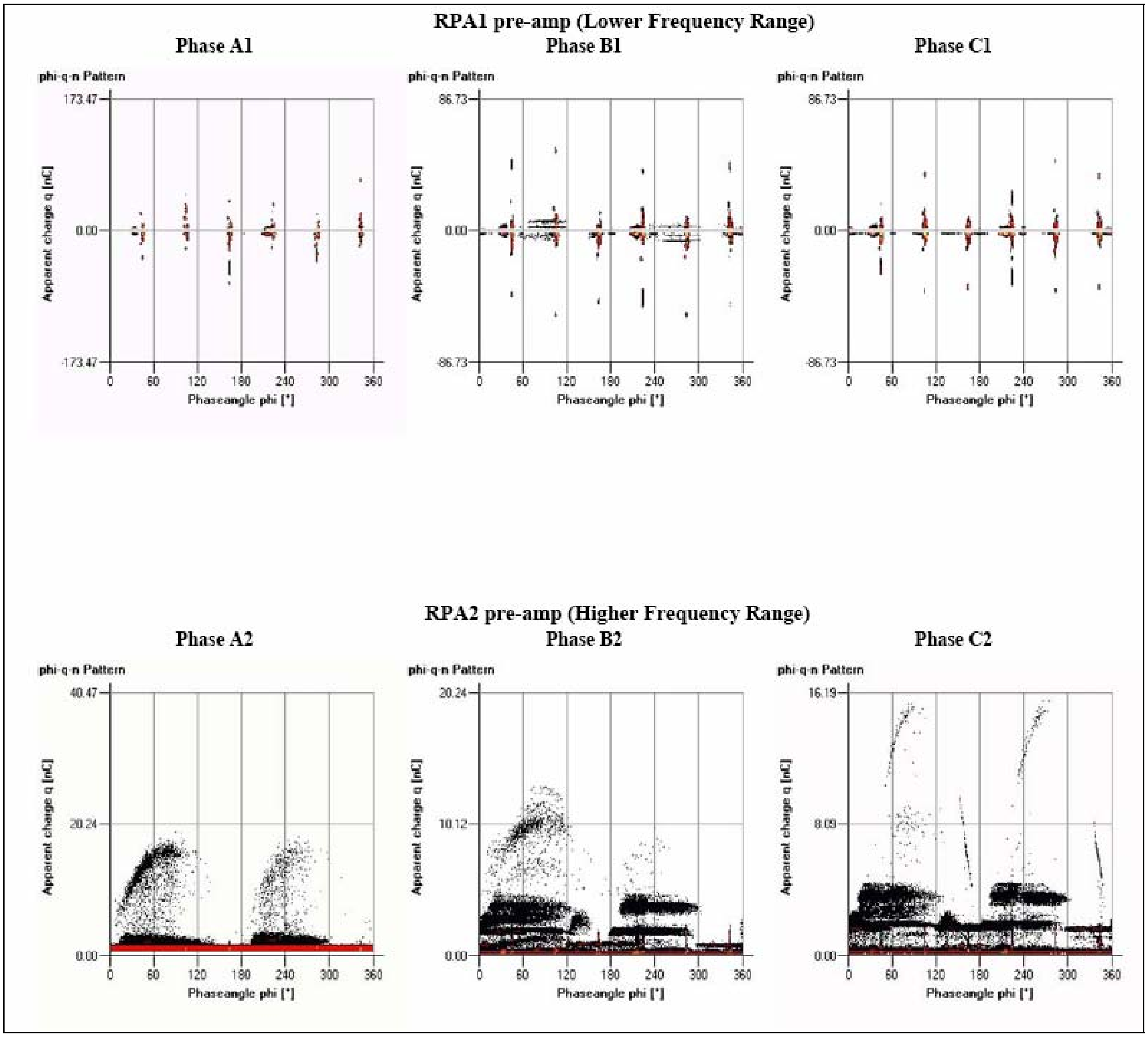


Figure 5-3
Phase Resolved PD Analysis for Lake Road Generating Unit #3. Upper: Low Frequency Analysis, Lower: High Frequency Analysis. Tester F

6

APPRAISAL AND PERSPECTIVE

Recent (2005/2006) Test Results

As in previous reports, this section seeks both to provide a discussion of the findings of the testing reported in 2005/6, but, perhaps more importantly, to examine the impact of the multi-year effort from the perspective of the user. This report has documented the results of condition assessments made by Mr. Clyde Maughan during major outages (where the rotors have been removed to allow access to the stator bore) for three of the machines in the program. This has allowed some measure of corroboration (or otherwise) for the predictions of machine condition made through the various methods employed. It will be seen that the issue is often clouded by the fact that problems outside the machine have often predominated, and this, somewhat philosophical, issue will be discussed.

It is perhaps instructive to look at the conclusions recently drawn from the various techniques on a machine-by-machine basis. This recent data is important since it can both be related to that available from prior years, and it also represents the most recent assessment for comparison to the actual condition as determined from a machine internal inspection. For reasons of clarity, the main findings are presented below on a tabular basis.

Sammis #6

For the last few years, this unit has shown a considerable degree of stability. As a consequence only a limited amount of testing has been undertaken. The most recent EMI and PD conclusions are provided in Table 6-1.

Table 6-1
Abbreviated Findings and Recommended Action for the Sammis #6 Unit

Tester		**B**	**D**
Method		**PD (HF)**	**EMI**
Sammis #6	**1st Finding**	Only modest discharge levels which are within the norms expected for machines of this type	No alarming slot or end-winding activity
	2nd Finding	Trending indicates stability with no noticeable deterioration	Little change since 2003, & trending since 2001 shows stability
	Action	None. Machine serviceable without restriction	None

Both the assessments carried out came to the conclusion that the machine was in good condition, stable and with discharge levels that were considered modest. This unit has been in the program for the longest time and the value of trending is clearly evident from figures such as Figure 2-3 and 2-4.

Marshall Units #3 and #4

It is useful to consider both the units in the program at the Marshall station of Duke Energy together since they are sister units. A summary of the findings using the various techniques may be found in Table 6-2.

Table 6-2
Abbreviated Findings and Recommended Action for the Marshall #3 and #4 Units

Tester		A	A	B	C	C	E
Method		PD HF	PD LF	PD HF	PD LF (2 Frequency)	EMI	EMI
Marshall #3	1st Finding	Indications of "external" activity. Phase B predominant	Confirmed HF Results indicating Phase B as dominant source	Indications of "external" activity. Phase C predominant	External "gap type" discharge activity evident	Substantial changes seen in the last 3 years	Major external activity previously detected has been rectified but some bus-related discharge remains
	2nd Finding	*Reduction* in activity between 05 and 06		Significant *increase* in activity between 04 and 06	No abnormal PD within the generator		Some stator related slot discharge activity
	Action	Inspect iso-phase bus Replace/ relocate couplers Continue PD monitoring		Visual inspection of Phase C bus duct. Repeat PD testing in 3 months	Continue monitoring on an annual basis for trending	Continue monitoring on an annual basis for trending	Inspect iso-phase bus at next outage
Marshall #4	1st Finding	Unit stable and in acceptable condition	Consistency between HF and LF methods demonstrated	"Gap-type" discharge activity	External "gap type" discharge activity evident		Stator bar deterioration in slots and core edges; particularly in Phase C
	2nd Finding	Consistent readings in 2005 and 2006		Low level internal PD			Some end-winding deterioration
	Action	Continue PD monitoring	Continue PD monitoring	Visual inspection of external components. Annual PD testing			None in view of impending rewind

There are some significant issues raised by Table 6-2 since it points to some very obvious differences in addition to the welcome confirmations:

- For Unit #3, Testers A, B and E are all agreed that the probable major source of activity is outside the machine, but the phase identification is different. The issue of phase identification has arisen previously and continues to be a weakness of the current methodology.
- For Unit #3, the 2006 measurements taken by Tester A show a reduction in PD activity, whereas Tester B sees quite a dramatic increase over previous measurements. Despite the caveat provided in 2006 assessment, such a clear contradiction is worrying. However, if the source is, indeed, outside the unit (as seems likely) and of an intermittent nature, the observation could still be rationalized. However, findings such as this do not instill much confidence in the user.
- While tests conducted on a machine at different times always raises issues of the influence of external "interference", Tester A undertook both HF and LF PD measurements at Marshall at the same time on Unit #3. The entries in Table 6-2 indicating that the two techniques is not always good; even when taken by the same Tester at the same time using time-honored assessment methods, are able to identify the phase having predominant activity. The identification of the major activity in Phase B was made by Testers A, C, and E, but Tester B found Phase C to be predominant.

Lake Road Generating Unit #3

Although it would appear again from the summary information in Table 6-3 that Testers A and B have come to different conclusions even though utilizing essentially the same technique, the trending period is different. Consequently, it cannot be said with certainty that they are inconsistent. What is certain from both sets of results is that the levels of activity are unusually high, even taking into account that this is an air-cooled machine.

Reconciliation

Since this report contains details of inspections of three of the units in the program, it is perhaps appropriate to make some sort of assessment of the various techniques on an overall basis. This has been done in Table 6-4 in which a comparison is made of the findings which were derived from the various methods and the condition actually observed when the rotor was removed. Since the program has been ongoing for several years, an attempt has been made in Table 6-4 to provide a consensus opinion to compare with the visual findings. Although this has been done using the data garnered for several years, a greater weight is placed on the more recent assessments. The crude and subjective nature of this assessment only warrants the coarse three-step reconciliation used in Table 6-4.

Table 6-3
Abbreviated Findings and Recommended Action for the Lake Road Generating Units

Tester		A	B	F
Method		**PD HF**	**PD HF**	**PD LF 2 Freq**
Lake Rd #1	1st Finding	Unit not tested	Unit not tested	Discharges in the bar overhang area
	2nd Finding			Low levels provide no concern
	Action			Retest :< 6 months, at 2 loads Visual inspection at next overhaul
Lake Rd #2	1st Finding	Unit not tested	Unit not tested	Surface discharges in end-arms
	2nd Finding			Trending shows only a small increase in activity. Machine serviceable
	Action			Retest in 6 months, at 2 loads
Lake Rd #3	1st Finding	Significant increase in activity on Phases A & B between 04 and 06	Somewhat reduced activity between 03 and 05	Significant increase in activity on all phases between 04 and 06
	2nd Finding	Groundwall discharges seen in Phases A and B	Surface or end-winding discharges indicated. Some bus-duct sparking	Surface tracking indicated
	Action	Visual inspection of leads, busbars, etc. Retest in 3 months	Nothing specific	Retest :< 6 months, at 2 loads Visual inspection at next overhaul

Table 6-4
Reconciliation of PD and EMI Test Results with Inspections of Sammis #6 and Marshall #3 and #4 Units

Number of Testers	**2**	**2**	**2**	**1**
Method	**PD HF**	**PD LF**	**PD LF {2 Freq}**	**EMI**
Sammis #6 (Machine only)	*substantially correct assessment*	*substantially correct assessment*	*no opportunity to check*	*substantially correct assessment*
Marshall #3 (Machine only)	*partially correct assessment*	*partially correct assessment*	*substantially correct assessment*	*partially correct assessment*
Marshall #3 (External sources)	*substantially correct assessment*	*substantially correct assessment*	*substantially correct assessment*	*substantially correct assessment*
Marshall #4 (Machine only)	*substantially correct assessment*	*substantially correct assessment*	*partially correct assessment*	*little or no correlation*
Marshall #4 (External sources)	*partially correct assessment*	*substantially correct assessment*	*substantially correct assessment*	*partially correct assessment*

Of particular interest is the fact that most of the methods were able to correctly detect external discharge problems, even if they have no inherent means to differentiate. In most cases this was accomplished since the external discharge magnitudes at the Marshall site were so large that, if emanating from within the machines, they would have been substantially greater than normally encountered. It is not clear that more modest external sources would have been correctly identified. There is also another caveat that should be made clear in viewing Table 6-4. The inspection schedule has meant that the reconciliation undertaken here is heavily dependent on the units at Marshall. The couplers installed at this site are not well matched to the high-frequency technique. As a consequence, the apparent marginally better performance of the LF techniques should not be interpreted as significant.

A Global Perspective of Discharge Analysis Applied to Large Utility Generators

On the basis of this study, there is no doubt that both PD and EMI can be effective techniques for the assessment of machine condition. This statement is made on the basis that predictions made through the use of a variety of methods could be verified though eventual inspection of the machine at a major outage. However, inspection of Tables 6-1 through 6-3 in this report and similar tables drawn up in earlier reports [2,3,5] make it very clear that tests are not always in agreement. This is sometimes as a result of the technique used, but also sometimes due to errors either of measurement or, more usually, of interpretation.

While both the EMI and PD techniques are essentially attempting to measure the same signal disturbances, the two windows on the same event do provide somewhat different perspectives. However, these two views are also colored by the different frequency bands often being used. For example, comparison of the EMI signatures in Figure 4-8 for Marshall #4 with the PD signatures depicted in Figure 4-5 for the same unit is difficult since the majority of the spectrum depicted in Figure 4-8 is below the limits of the high-frequency PD technique. This study has not shown that the routine use of *both* EMI and PD techniques provides enough additional information to justify the cost for either air-cooled or hydrogen-cooled units.

The most common error of measurement has been the mistaken use of an incorrect phase reference. However, this can be readily remedied by the simple expedient of deriving a reference voltage from the coupler being used for the measurement. Errors of interpretation are more problematical. If is often very difficult indeed even for a seasoned professional to provide unambiguous interpretation of signatures which are either not classical or complicated by the presence of a plurality of different discharge sites. This is further complicated when significant cross-talk between phases is present. These issues have often led to a differing diagnosis being given by testers using a variety of different techniques. However, it must be said that most of these differences have occurred when attempts have been made to provide a detailed, and sometime subtle, diagnosis. When gross problems existed (in this study, usually outside the units) there was much better agreement. However, we have been privileged in this study to have the participation of some of the industry's most experienced and professional practitioners. Moving forward, the vision is to develop this technology to the point at which it can be used effectively by technicians who do not necessarily have that level of experience.

The techniques used in this study to examine complete generators (i.e. eliminating local detection by the use of stator slot couplers or RTD elements) can broadly be divided into categories:

- Partial Discharge utilizing a high-frequency band
- Partial Discharge utilizing a low-frequency band
- EMI with neutral or line-end coupling

There are, of course, some variations of these. For example, it is possible to undertake PD detection with a signal conditioned with a pass-band frequency filter. However, this study has shown that, although they are all essentially detecting the same discharge sources, they do not always provide the same window on the event. The reasons for this are explained in some detail in Appendix A and will not be repeated here. However, it does mean that, to some extent, the techniques may be regarded as complimentary. However, it is unrealistic to think that a machine owner would use *all* these techniques to assess a machine. Consequently, it would seem as though the industry needs a compromise PD specification. A first attempt at this has been provided in Appendix A.

Central to the issue of an "ideal" specification for use with large generators is the question of the discrimination, i.e. the determination of what originates from within the machine and what comes from outside the machine envelope. It is believed that the time-of-flight method is, today, the best way of undertaking this which dictates against low frequency systems. However, recent experimentation with clustering techniques [6] has been applied to the recognition of discharges with good effect. This approach is outlined in Appendix B and could lead to computer-based methods for discrimination that may approach the performance of the classical methods, but represent significant cost savings.

Computer-Based Interpretation

While on-line PD and EMI tests on generators have traditionally been made by attaching detectors to installed couplers and taking measurements on, say, an annual basis, there is an increasing demand to permanently install equipment for continuous surveillance. This unattended PD testing has fuelled unpublished initiatives by several entities to develop software that has the ability to provide some measure of automated recognition of anomalous discharge activity and also, in principle, to detect unacceptable deterioration. Much of this work which has been published does not relate specifically to generator structures and thus is only of general applicability. However, Appendix B provides some insight into the computer-based intelligence which has been both published and also holds the promise of having applicability to large generators. There can be little doubt going forward that this is the direction in which the industry will move.

Appendix B makes it clear that the diagnosis of anomalous problems can most readily be accomplished through the distillation of the incoming signal into meaningful indices which can be either tracked in time or compared with a database of values for a similar class of machine [voltage, cooling method, insulation type, etc]. However, in principle, parametric analysis can also be automated to substantially improve the detection capability. For example the PD (or EMI) signatures can be measured as the load, or reactive power, is changed to detect loose bars. Similarly, excursions in temperature, ozone levels (for air-cooled machines) or H2 pressure may be correlated with PD characteristics to reveal underlying behavior.

Conclusions and Recommendations

While the results obtained from this multi-year program have been variable, a global perspective permits some overall conclusions to be distilled from the results based on the demonstrated condition of 3 hydrogen-cooled generators all having stator windings in excess of 35 years old. Although Project Conclusions 1 and 2 below are clearly tied to the demonstrated condition of the hydrogen-cooled generators inspected, many of the other Conclusions and Recommendations are more widely applicable. The absence of a visual inspection at Lake Road Generating and the problems associated with testing a peaking unit has made it difficult to drawn any conclusions which are specific to air-cooled units.

Project Conclusion 1

PD and/or EMI monitoring of hydrogen-cooled generators having tight windings, with or without contamination, does not generally yield additional information on the insulation condition.

Project Conclusion 2

EMI indications of core-edge and end-winding discharges could not be confirmed by inspection

Project Conclusion 3

EMI is effective in identifying problems outside the winding; such as those relating to the iso-phase bus duct components or the exciter, but is also often reliant on supplementary information in the time domain and from other sources.

Project Conclusion 4

Currently, the interpretation of both PD and EMI signatures requires the skill of a trained insulation expert particularly where the signals indicate “non-classical” behavior or are derived from a plurality of sources.

Project Conclusion 5

The routine use of both EMI and PD techniques provides insufficient additional information to justify the cost for either air-cooled or hydrogen-cooled units.

During the progress of this investigation, it has also become clear that, from the user’s perspective, there are some actions that vendors could take which might lead to a greater applicability of these techniques:

Vendor Recommendation 1

Currently vendors have somewhat entrenched positions which are not necessarily always in the best interest of the user. There is currently no interchangeability of couplers and the instrumentation used by various PD vendors. Furthermore, there is no agreement on the units of measurement (pC or mV). While there are technical issues involved here, there is no doubt that users would greatly benefit from some standardization and interchangeability. This applies both to the measurements and to the means of reporting the results.

Vendor Recommendation 2

The user would greatly benefit from explicit vendor statements on how “outside” discharges are identified. While it may not be necessarily representative, this program has probably found more problems external to the generators than stator winding issues. Such external problems are often identified by some PD methods with low confidence.

Vendor Recommendation 3

The misidentification of phases appears to be very common indeed. Vendors should take steps to eliminate this problem through hardware modifications (e.g. deriving a synchronizing signal from the coupler being used for the PD measurement), or through establishing the necessary "checks and balances" to identify the problem.

Recommendations for Further Work

The recent introduction of commercial PD measuring equipment capable of a much higher degree of interpretation of discharge signatures (particularly for multiple sources) offers, for the first time, the exciting possibility of automatic machine diagnostics. This technology needs assessment so that the industry can have some confidence before the traditional interpretation by an insulation expert is circumnavigated.

A

SPECIFICATIONS FOR PARTIAL DISCHARGE DETECTION IN LARGE GENERATORS

Background

One of the original objectives of this project was to identify the methods and “best practices” which show the most promise for the assessment of utility generators based on Partial Discharge and Electromagnetic Interference monitoring. Experience gained over the last few years utilizing a variety of methods has provided some basis for evaluating the various techniques that have been used. Previous reports [2,3,5] on this program have attempted to identify the positive and negative aspects displayed, and this Appendix is an attempt to consolidate that experience in the form of a specification for PD detection in the generator environment (and should not be used in another context where the conditions may be very different). It should, however, be made clear from the start that it is the intention that the results obtained using different methods on this program were to be verified through confirmatory inspections of the monitored generators. In some cases, the opportunity for inspection has not yet been made available. Consequently, in such cases, the predicted condition has not totally been verified, but nevertheless enough tests have been conducted to establish a consensus view of the condition.

It is fully recognized that this is a contentious issue which is interwoven with commercial interests. Many of the vendors have established and entrenched technology preferences which have led to a variety of coupler systems permanently connected to generators that tend to lock a user into a particular technology. In addition, it has been emphasized previously that the only really reliable measurement is one that can be meaningfully compared with other similar data (a previous baseline, another phase, industry experience, etc.) This need has tended to stifle change since technology advances yield data which may not be readily compared with prior experience. A good example of this is the use of a neutral CT coupler with the EMI method highlighted in reference [2]. There is no good technical reason why the EMI method should not employ line couplers. Indeed, tests have shown the EMI method can also collect data from existing line couplers (and thus benefit from phase identification) in the same way as used in PD detection. The main reason why this is not done is the associated inability to compare the results with previous experience.

From the user’s perspective, some form of common specification would both provide needed flexibility and interchangeability in the application of these methods and also provide a common basis for the interpretation of the results. This has not been possible in the last 20 years since the technology has been in development, but perhaps now there is some justification for moving in that direction. Even when the same technology is being employed, variations in implementation create significant limitations. A good example of the problem is seen in the Lake Road 2006 assessment. Testers A and B are essentially using the same time-of-flight discrimination method, but because of the different means for handling the delay times involved, the hardware configuration could not be utilized readily by both testers despite the fact that the couplers were quite compatible with the high-frequency technique being used by both testers.

At the outset of this project, it was indicated that the objective was to evaluate methodology and not rank testing companies. In that spirit, an attempt has been made here to develop a specification in a logical way based on the perceived scientific merits rather than on the basis of entrenched commercial interests. To this end, the Hardware, and Data Interpretation Sections provide the technical rationale for the specification developed. However, the situation is changing quite fast as a result of the increasing use of computer-based intelligence, both for interference discrimination and for data interpretation. It is thus perceived that the industry will need to remain open-minded on this issue since software enhancements may change the slope of the playing field in the coming decade.

As a non-commercial assessment, no account has been taken of the ownership of relevant intellectual property. Furthermore, the development of this specification is limited to the overall determination of a generator using line-end couplers and does not address local diagnostics using slot couplers, antennae or other means of local PD pick-up.

Hardware

Interference Discrimination

It is universally agreed that, in the generator environment, it is very desirable to be able to discriminate between discharges emanating from the machine being tested and those whose origin is outside the machine. Furthermore, although early work in this arena tended to regard the external noise as “interference” which needed to be removed as it was corrupting the desired signal from the generator, it is now evident that the noise may contain information relating to external incipient problems. It is thus very desirable that the noise should be separated, but not discarded as might be assumed on the basis of interference elimination.

There are two primary means to discriminate between generator PD and external noise:

1. the use of time-of-flight methods to determine the origin of the signal.
2. the use of software to identify the origin of the pulses based on their shape and other characteristics.

The time-of-flight method is illustrated in Figure A-1. Unfortunately, for turbo machines it requires the provision *two* sets of couplers on each phase with the concomitant expense. One set is usually installed (during a scheduled outage) close to the generator terminals and the other a few 10s of meters away. There will be a pulse transit time between the two sets of sensors (associated approximately with the speed of light assuming the path is a bus duct). Further, assuming that the cables from the couplers to the recording equipment are the same length (or have been appropriately compensated for) then the arrival times of the PD pulses at the two sets of couplers permit a determination to be made as to origin of the signal – Figure A-1 shows a pulse from the external circuit which will clearly arrive at the outer coupler before the inner one. Clearly, the electronics can be programmed to capture either the signal emanating from the generator or from the outside world (or both). This is well developed technology, which was originally explored in hydro machines using dual couplers attached on either side of the ring bus [8] used to make the transit time discrimination.

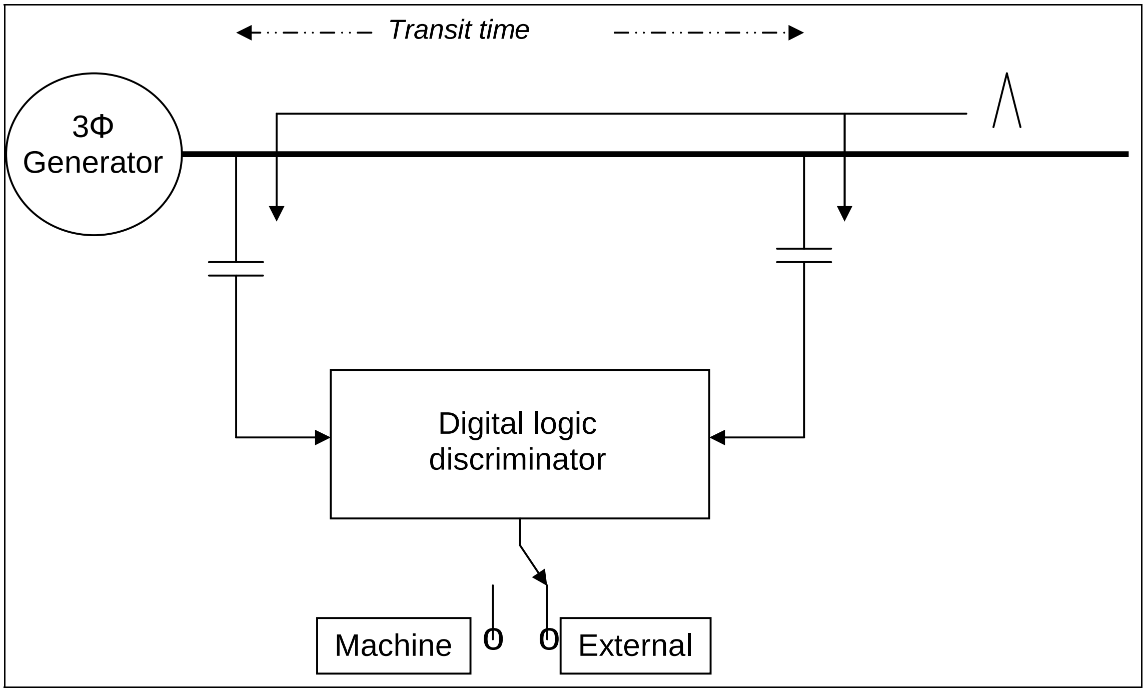


Figure A-1
Schematic of Discriminator Circuit for Differentiating Between Machine-Related PD and External Signals

The use of the time-of-flight methodology clearly can only be effective if the bandwidth of the measuring system is large enough to resolve time differences of the order of a few tens of ns. As a consequence, the adoption of such a system thus favors the use of wide bandwidth detectors and the associated implications for the couplers.

It has to be said that the use of artificial intelligence methods to provide the noise discrimination needed are not so advanced as the time-of-flight method; at least in the generator context. This would seem to favor detection at higher frequencies, although the identification of external interference is not the only factor involved with the choice as discussed in following Section.

Sensitivity

The choice of the frequency band for the detection of discharges is not only dependent on the effective rejection of interference, but also on the extent of the signal captured. As a result, the sensitivity of high-frequency detection systems is inherently low. The PD phenomenon also requires instrumentation with a wide dynamic range. Typical threshold levels are a few mV and discharges can produce pulses at the terminals of several V.

It is sometimes argued that computer-based intelligence can enable a low frequency system to exhibit both a high sensitivity and the discrimination typical of a high-frequency time-of-flight system. Nevertheless, the commercial state-of-the-art today really does not support that contention. However, it is likely that artificial intelligence applied to this area will evolve rapidly, and so this may not be the situation indefinitely.

Couplers

Coupling a PD detection system externally in the machine environment may be achieved in a number of ways:

1. A high-frequency current transformer (CT) placed around the neutral connection.
2. A set (usually 2 per phase to allow for discrimination) of low capacitance couplers, typically about 100 pF (the industry has "standardized" on 80 pF), placed at the terminals of the generator suitable for detection in the frequency range 40 -500 MHz
3. A set of high capacitance couplers, typically 1000 – 10,000 pF, placed close to the machine terminals suitable for systems working in the frequency range 10 kHz to 50 MHz.
4. Antenna systems.

While it is recognized that sensors may also be built into a machine either in the form of purpose made stator slot couplers or by utilizing existing built-in RTD temperature sensors, these provide a local measurement and are not considered here since the interest is in overall machine monitoring.

An RFCT (Radio Frequency Current Transformer) on the neutral has the advantage that it can be connected without a shut-down. The bandwidth of the RFCT is very broad and flatter than capacitor couplers. But there are drawbacks. These are principally that it does not provide any information on which phase(s) is(are) generating the signal, and this can be important for defect location. Even though most of the PD is in the top 1/3 of the winding, it is claimed that there is sufficient sensitivity to detect deterioration throughout the entire stator. Signals are also present from defects originating from other sources such as the isolated phase bus as well as the generator stator. As a result, isolating this "noise" can be very challenging. Similarly, any fixed antenna system is both very vulnerable to external interference and difficult to interpret and quantify. Options (2) and (3) above (capacitance couplers placed at, or near, the terminals) have shown themselves to be reliable and effective. The value of the capacitance will be dictated by the frequency band employed.

Some systems employ a combination of CT and capacitance coupler – see Figure A-2. This has the advantage that the detection equipment is not directly connected to the power system, but has the drawback for high-frequency detection that the CT may limit the bandwidth (with an upper limit of about 100 MHz). This can be avoided if the capacitance coupler is fed directly, for example, to a 50 Ω impedance. For the proper interpretation and display of the resulting signatures, it is imperative that a known phase reference is provided. Figure A-2 shows this being derived from a metering potential transformer.

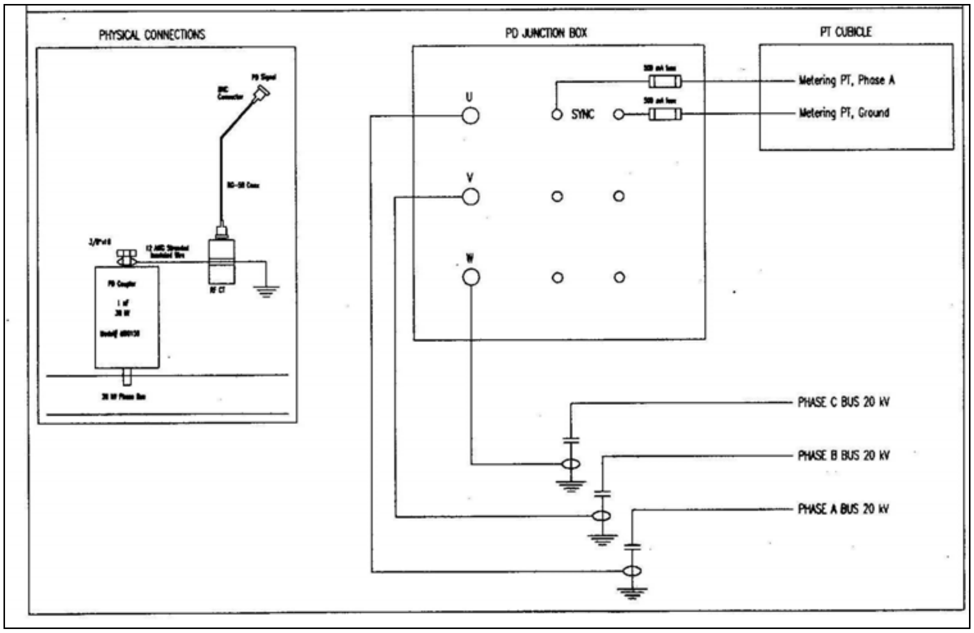


Figure A-2
3-Phase Coupler Arrangement Showing the Incorporation of High-Frequency Current Transformers in the Ground Path

The choice of coupler capacitance is a complex issue. If time-of-flight methods are to be used a high-frequency is dictated, and large coupling capacitance not appropriate. However, the results of this program have indicated that PD acquisition in the high frequency band does, in fact, miss some problems which can only be seen at lower frequencies. Analysis based on the frequency considerations shows that there is advantage indicated in using a coupler capacitance of 500 pF from the viewpoint of encompassing signal. There are also some less obvious factors which come into play in the selection of coupler capacitance:

- The early introduction of 80 pF couplers has established a considerable inventory of couplers which are not likely to be changed out.
- In 6-coupler installations, the space to accommodate the couplers is often at a premium, and thus a larger coupler may present some difficulties.
- A larger coupler may have a higher parasitic inductance (and, perhaps more importantly, a higher lead inductance) which would not be desirable for time-of-flight discrimination.
- There is a paucity of experience with 500 pF couplers.
- As a result, it is felt that some comparative field experience is needed. This could perhaps be obtained by fitting 80 pF and 500 pF couplers on sister machines.

Data Handling

Modern partial discharge detection systems employ analog-to-digital (A/D) conversion in order to capture the discharge pulses. This clearly requires conversion rates which permit capture of pulses which may have rise times of a few 10s of ns without aliasing. Clearly, the memory and access time requirements for the storage of extended pulse sequences are prohibitive, and so it is usual to undertake some processing of the data. This can range from simply recording the magnitude and number of the pulses received over a set period of time (to generate a pulse height analysis) to much more sophisticated systems which attempt to extract more information from the character of the pulses or their sequencing. The D/A conversion will involve some deadtime. However, since it is typical that the interval between pulses is a few μs, this is not disqualifying.

Frequency Band

The factors outlined in preceding Sections all have a bearing on the choice of frequency band(s) for discharge detection in machines. The dilemma can be perhaps understood with reference to Figure A-3 which depicts the low frequency attenuation experienced with systems equipped with three different couplers. The measurement gain curves are plotted together with a typical PD spectral analysis. Taken at its face value it would seem as though a high capacitance coupler used with a detection system operating below 50 MHz would result in the capture of a major proportion of the PD energy. Indeed, some commercial systems employ couplers as large as 9 nF which provides a bandwidth extending down to 20 kHz. However, the issue is not as straightforward as depicted in Figure A-3 since the region below 50 MHz is also the band in which all the unwanted interference exists. Use of this part of the spectrum is thus characterized by an abundant signal, but a severe problem of identifying the salient machine signatures buried in noise.

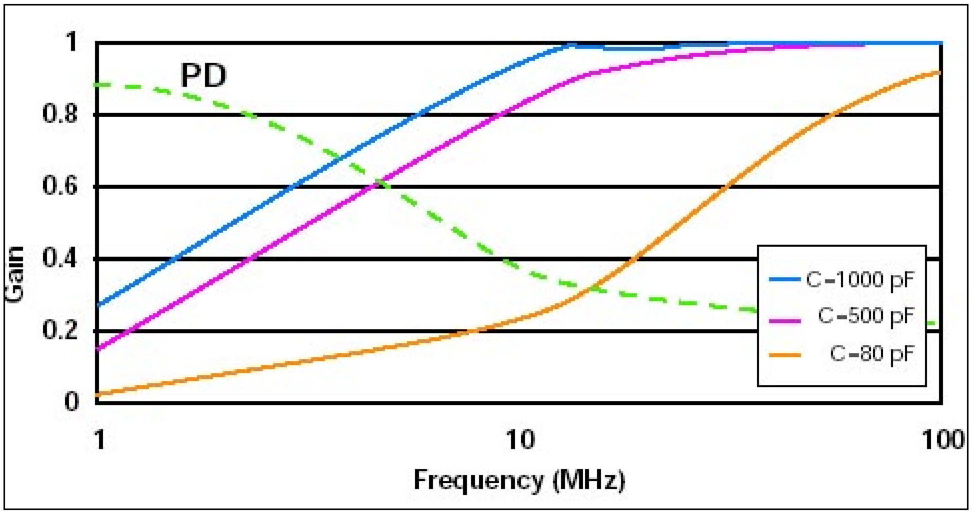


Figure A-3
Typical Frequency Transmission Characteristics in Comparison with PD Signal. [Courtesy: Adwel International with Permission]

Since the disruptive event caused by discharges generates pulses that have risetimes in the range 1 – 5 ns, there will be some energy also in the frequency range 50 – 250 MHz. Figure A-3 indicates that the signal at these frequencies is perhaps less than 20 % of that existing at 1 MHz. It should also be recognized that propagation through the windings will produce an increase in risetime and a concomitant extension of the frequencies seen at the terminals in the downward direction. Furthermore, the attenuation of the discharge signals is very much enhanced for the high frequency components making systems working above 50 MHz very insensitive to problems far from the line end terminal. Furthermore, it has been found during this program that those who utilize the higher frequency band sometimes will miss issues, such as exciter noise, which typically occur in the kHz range.

Data Interpretation

Basic Methods

Post processing of the captured data is a necessity if reliable interpretation is to be successful. Most of the current methods in use in the field rely heavily on a number-magnitude-phase display such as those depicted in the body of this report. Although there is no standard format for the three-dimensional format that is needed to display this data, in the hands of an experienced professional patterns discerned from such plots can be associated with particular kinds of activity in machines both in the stator slots and in the end-windings. The reader may find examples both in the CIGRE guide [9] and a recent contribution by Hudon and Bélec [10]. This is further enhanced if polarity discrimination is also incorporated. Since the deterioration experienced in machine windings subject to discharges is related to the energy dissipated, some measure of the energy has also been found useful such as the integrated Normalized Quantity Number (NQN) parameter defined in Reference [3]. The time-honored basic methods will certainly still form the backbone of future diagnostic systems. However, it is anticipated that they would be augmented by more advanced techniques which hold the promise of permitting a more automated interpretation.

Advanced Methods

The basic methods have served the industry well. If the discharge signals are distilled into meaningful indices (such as the maximum pulse magnitude), then a basis for (relative) comparison can be established. However, the industry is understandably demanding much more detail on the location and nature of the perceived source of elevated activity. Some of this is currently available from a study of the phase-resolved discharge activity plots. However, this requires interpretation by a skilled and experienced operator, and study of the previous reports in this series clearly demonstrates that even experience does not guarantee a unique diagnosis.

The availability of cheap computing power makes it attractive to examine the use of computer-based intelligence to provide unbiased estimates of insulation condition, and also a numerical assessment of the confidence of the diagnosis. There is a considerable body of literature in the recent past in this arena, but, unfortunately most of it relates to specimens unrealistic of the machine environment, and in laboratory conditions. Notwithstanding that, it is very clear that this is the way the technology is progressing, and it is likely that aspects of this will appear to tackle the complex problems associated with detailed diagnostics in the machine environment. Indeed, inference engines were developed over 10 years ago [11] to permit differentiation of certain forms of machine insulation defects, and the recent commercial introduction of a system that employs more sophisticated techniques for interpretation [12] is clearly a harbinger of the way the industry will move.

Perhaps the most innovative technique which has been introduced and shown to be effective is the use of a clustering technique based on the time and frequency characteristics of the pulses appearing at the coupler. This method is outlined in Appendix B and provides a means to separate discharges of different characteristics. By this means, pulses coming from different sources can be clustered and analyzed separately. An example of this clustering in a Cartesian plane is shown in Figure B-1 (in Appendix B) taken during a test on a large air-cooled machine. The separation of pulse type is clearly seen.

It is perhaps instructive to tabulate the techniques that have been advanced to characterize discharge signatures with a view to extracting more data from PD tests. It has to be said that, in some cases, the utility of the methods has not been demonstrated in the machine context where the pulses are distorted during their passage to the coupler or in the field environment. Candidate techniques include:

New indices describing the activity such as those derived from statistical analysis (e.g. skewness and kurtosis[13]) or from phase analysis (e.g. discharge stagnation voltage[14]).

- The use of fractal theory to describe the events
- Cluster analysis to characterize phenomena occurring in the stator windings
- Pulse sequence analysis to characterize the activity on the basis of discharge history
- The use of neural networks to associate signatures with known defects
- Fuzzy logic to characterize mechanisms

This is by no means an exhaustive list, and it is not clear which of these is the most effective for generator diagnostics. However, there is widespread agreement that no single measure or technique is effective in providing a diagnosis. It is thus likely that future systems will rely on a plurality of such techniques for interpretation and this may have implication for the way in which data is captured and handled. The use of several measures then lends itself to the use of inference engines and fuzzy classifiers for diagnosis.

Partial Discharge Specification for Large Turbogenerators

Preamble

It has already been inferred that this is an area of endeavor in which signal processing and pattern recognition are playing an increased role in shaping the methodology. However, it is perceived that TODAY such techniques are not as good as the time-of-flight method for the elimination of external noise and the identification of internal vs. external signals. If the time-of- flight method is employed, then the frequency band utilized (and hence the digitization rates) must be high enough to properly resolve pulses with a 5 ns rise time. This is the primary rationale for the specification which attempts to both outline hardware needs and methodology without prejudice to entrenched methods.

PD Measurement Specifications

Couplers (Line-End)

Capacitive Couplers

PD free to 2 x phase voltage

Withstand voltage to at least the machine high potential test level

Detector

Input channels: 6, 50 Ω impedance

Polarity: Dual

Dynamic Range: ± 5mV - ± 5 V

Noise rejection: Time-of-flight discrimination

Bandwidth: 1 MHz – 250 MHz with switch-in high-pass filter

Synchronization: Zero-crossing from coupler signal

Communication: RS232

Processing/Interpretation

Discriminator: Switchable internal/external

Platform: MS Windows

Phase Analysis: 3° phase windows; 16 magnitude channels

Data reduction: Calculation of descriptive indices

Classifier: Interactive with parametric capability

Output: Selectable displays, tables, interpretation and confidence limits

B

USE OF COMPUTER-BASED INTELLIGENCE IN THE INTERPRETATION OF DISCHARGE SIGNATURES

The PD signal may be derived from a variety of sources, but for large generators would usually be obtained from unspecified line couplers at the line end of the generator in common with many other PD monitoring systems. The input signal is fed to a single channel A/D converter with a sampling rate of 100 MS/s. The digitized signal is displayed with the option to magnify and select a time window. The input is characterized on a pulse-by-pulse basis by extracting five descriptors which are:

a. Peak magnitude and polarity
b. Phase (in relation to the applied power frequency voltage)
c. Time of occurrence
d. Equivalent time duration
e. Equivalent bandwidth (frequency)

These attributes of the incoming pulses are stored as descriptive of each pulse.

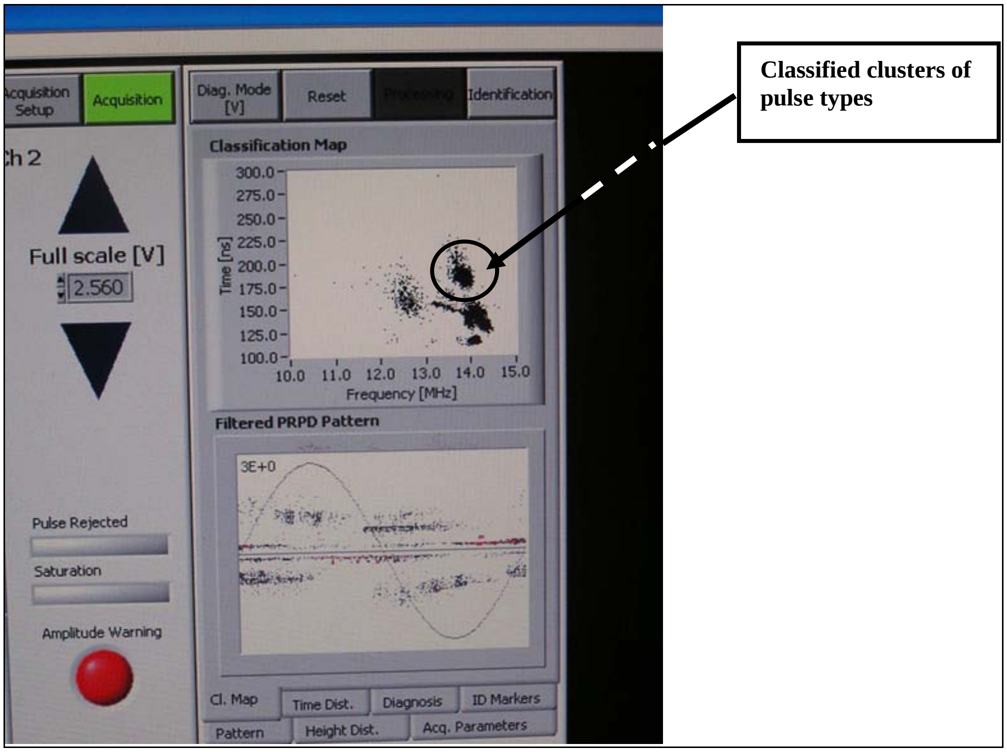
Perhaps the most innovative initiative that has been introduced and shown to be effective is the use of a clustering technique based on the time and frequency characteristics of the pulses appearing at the coupler. This is a method borrowed from the communications industry [15] in which each incoming pulse is characterized to generate attributes (d) and (e) above. Following Cavallini et al. [16], the equivalent width of the signal in the time and frequency domain, σ_T and σf, respectively, are given by:

$$\sigma_T = \sqrt{\int_0^T (t - t_0)^2 \tilde{s}(t)^2 \, dt}$$

$$\sigma_f = \sqrt{\int^{\infty} f^2 \left|\tilde{S}(f)\right|^2 df}$$

where $\tilde{S}(f)$ is the Fourier transform of $\tilde{s}(t)$, and t_0 is the time averaged center of the normalized signal. By arranging the incoming pulses in $[\sigma_T - \sigma_f]$ space, the pulses may be sorted dependent on the characteristic shapes. An example of this clustering in a Cartesian plane is shown in Figure B-1 taken during a test on a large air-cooled machine. The separation of pulse types is clearly seen.

Since this system (as currently configured) is unable to take advantage of time-of- flight methods for discriminating between PD emanating from the generator and noise (or other discharge activity) entering from the *external* environment, discrimination is accomplished using the two indices cited above [(d) and (e)] to sort the incoming pulses in a time/frequency plane so that pulses of a similar type (based on this categorization) are grouped together. Indices (d) and (e) are defined in such way that they are independent of polarity and amplitude. By this means, incoming pulses which exhibit similar values of these two attributes originate from the same source (either inside or outside the generator). The operator is then able to select a particular cluster of PD events from the display for further analysis. In this way, each category of event can clusters of events can be identified and displayed, as shown in Figure B-1. The assumption is that be analyzed separately so that generators exhibiting more than one source of discharge can, in principle, have a plurality of problems identified.



Classified clusters of pulse types

Figure B-1
Classification of Captured Pulses on the Basis of Duration and Bandwidth Attributes

After the clusters of pulses have been identified and selected, the first three attributes [(a) - (c) above] are used to further characterize the nature of the selected subset of discharges into one of three basic types:

1. Corona (partial discharge at point of field intensification in a free gaseous environment)
2. Surface discharge (creep discharge and/or discharges at interfaces driven by tangential electrical field)
3. Internal discharge (usually within cavities or delaminated areas within a solid insulating structure).

This determination is made by using markers extracted from the distributions of the relevant indices [(a) - (c) above, mainly the Phase Resolved PD pattern] to formulate descriptions of the pulse characteristics which are then used in an inference engine to interpret the signals attributes captured for the feature selected. While this is not a new approach and has been used before [11], fuzzy logic is being used for the inference which permits a probability (or confidence) to be assigned to the process which will clearly depend on how close the descriptors match the classical case with which a comparison is being made. Five fuzzy sets are used to describe each identification marker, while fuzzy identification is carried out by means of rules expressed in linguistic terms.

With reference to defect identification in rotating machines, identification markers that are used to infer the nature of PD sources include:

- Discharge pulse asymmetry
- Pulse phase inception
- Pulse phase interval
- Amplitude distribution Weibull (shape) parameter
- Amplitude distribution skewness
- Pulse number
- Cluster descriptors

At face value, it would seem that the phase information [(b) above] and the time of occurrence [(c) above] would contain the same information. However, it is claimed that the two attributes are necessary in order to describe precisely the discharge time and phase behavior. By detecting the time of occurrence of each discharge it is not possible to derive the relevant phase of occurrence because of the fluctuation of the 50/60 Hz reference. On the other hand, by measuring the phase, the actual time of occurrence is not recorded, and, as a result, the number of periods between two discharges remains unknown. Phase information is used to build up the Phase Resolved PD Pattern, while the time of occurrence is used to evaluate the time-between-discharge behavior of the PD activity (see, for example, van Brunt [17]). The established theory requires that discharges emanate from the same site, which cannot be determined in these circumstances making the method essentially an ensemble analysis. Once a separation of the original dataset into clusters is obtained, both the pattern, and also a histogram of the time between discharges are estimated to achieve the distributions relevant to the separated clusters of pulses. While the classical PD detection method places, understandably, a large emphasis on discharge magnitude, the emerging more sophisticated identification algorithms attempt to extract information from the PD character. The features used for identification, are descriptors of the shape of the PD pattern. Robustness to propagation path means that the selected identification features are only slightly affected by absolute values of PD magnitude (since patterns that differ by a scale factor can, nevertheless, exhibit the same shape). Magnitude independence is an important feature, since PD amplitude calibration in inductive apparatus is problematical due to the attenuation associated with the long propagation paths.

Experiments undertaken in a laboratory environment [18] would suggest that at least some of these descriptors are insensitive to the propagation path which is, of course, a substantial asset. However, this is not altogether consistent with the need to differentiate between signals emanating from the machine and those coming from the external environment.

It is also understood from the work of Cavallini *et* al [18] that further levels of sophistication are being used to permit some differentiation beyond that given by the three basic processes (surface, corona and internal discharge). This is very specific to the apparatus involved, and detailed information on the means for achieving this is sketchy.

Clearly, in the case of machines, a more detailed identification of the defect generating the PD activity is the basis for automatic recognition processes. However, some information can be obtained by examining the polarity of the discharges and by examining the detailed pattern of the ensuing phase resolved measurements through the examination, for example, of the higher order moments. A typical inference engine for making these determinations is shown in Figure B-2.

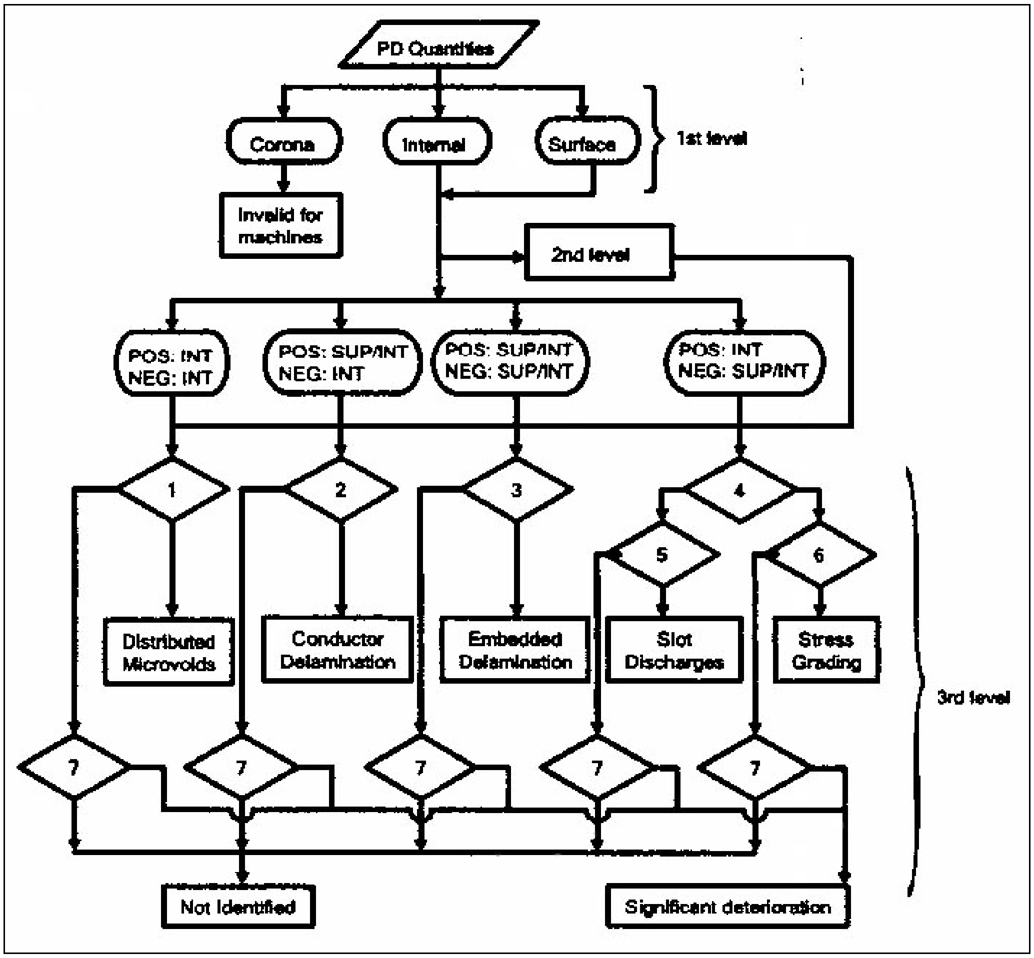


Figure B-2
Inference Engine for Interpretation of Generator Discharges [18]. Blocks 1 – 6 Evaluate the Membership of a Data Set to a Defect Type; Blocks 7 Exist to Flag Cases which Cannot be Identified

It also has to be assumed that the phase of the discharge pulses is used to identify cross coupling between phases since this is clearly not available from a simultaneous phase comparison, although it could be inferred from sequential measurements.

C
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