Partial Discharge Signal Interpretation for Generator Diagnostics

Claude Hudon and Mario Bélec
Institut de Recherche Hydro-Québec IREQ,
1800 Boul. Lionel Boulet, Varennes,
Québec, Canada J3X 1S1

ABSTRACT

Several common sources of discharges activity occurring on generators have been replicated in the laboratory under well-controlled conditions. Each source was evaluated individually and recorded with a phase resolved acquisition system and with a spectrum analyzer. The dominant features of each respective phase resolved partial discharge (PRPD) pattern are presented. The frequency content of the discharge signal at the detection coupler was also investigated. The association of each well-defined type of discharge source, with its specific PRPD pattern, constitutes the basis of our database used for the discharge source recognition during generator diagnostics. The comparison of laboratory results with actual field measurements gathered over the last decade is summarized in this paper.

Index Terms — **Partial discharge, PRPD patterns, discharges sources recognition, generator diagnostics.**

1 INTRODUCTION

PARTIAL discharge (PD) measurements have been performed on generators as far back as 1951 [1], but there is still today no unique procedure or standard rules on how to carry out PD diagnostic on generators. However, there has been considerable effort over time to correlate PD pulses detected from the generator stator winding to its specific condition. Multiple means of detection have been used over the years, and are still in use today. They include the detection of electro-magnetic signal with an antenna [2] or a simple AM radio, with an antenna in front of stator slots [3, 4], the use of a high frequency current transformer connected around the neutral point of a stator winding [5, 6] or on the ground straps of surge capacitors [7, 8], and probably the most widespread on-line coupling method is to connect a capacitive coupler directly on the line-end terminals of a machine or on individual parallel circuits [7, 9, 10]. Depending on the coupling method and on the measurement instruments, different frequency ranges are used for detection. Moreover, measurements can be made on-line under actual operating stresses but at a fixed voltage under prevailing temperature and humidity conditions, or off-line without any vibration or higher temperature, but with the flexibility of gradually increasing the voltage to determine such quantities as the corona inception and extinction voltages (CIV and CEV). An exhaustive document has been put together to summarize all of these applications, the different frequency ranges, and the most common detection methods [11]. This document is a consensus in which a large number of available tests methods are discussed and advantages and disadvantages are outlined. However, this excellent compilation does not recommend any practice as being the best one. This is in part due to the fact that no one as yet clearly demonstrated on the best way of providing an exact diagnosis of the condition of a generator based on PD measurements.

In spite of this, it has to be pointed out that PD measurement is one of the most important tools for use in generator diagnostics, but it is by no means a perfect technique. To obtain the best diagnosis of the generator, PD measurements usually have to be used together with other techniques such as visual inspection, insulation resistance, core loss and wedge tightness measurements, just to name a few. However, PD measurements have the advantage of providing information while the generator is on-line, and once couplers are installed, periodic or continuous measurements do not require any down time to make a diagnosis. It is thus possible to get a preliminary indication on the condition of the generator or to know if further testing is needed without affecting operation.

Most failures on generators are eventually of electrical nature, even when the initial cause is not. For instance,

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wedge looseness, which is typically a mechanical problem, can result in semi-conductive coating erosion on stator bars, causing slot PD, and eventually a phase-to-ground or phase-to-phase failure. The combined effect of vibrations and electrical erosion of the groundwall insulation can eventually lead to a condition where the electrical stress cannot be supported anymore by the bar insulation system, at which point a failure will occur. In such a case, the PD signal can be measured during the entire degradation process, which is usually evolving slowly on generators, and the results can be used to plan proper maintenance or to decide if a rewind is necessary.

However, in order to come up with the correct diagnosis, one has to be able to interpret the PD signals. The application of PD measurements can basically be divided in three stages:

- the first one being the detection,
- the second one being the interpretation of the signals,
- and the last one is the diagnosis of the condition of the generator.

The detection of PD signal is relatively simple and anyone with a basic understanding in electronics can do it. In contrast, the interpretation of PD signal requires significant knowledge of generator construction, insulation design, signals propagation and attenuation, failure modes, and a good understanding of the measurement equipment. Thus the interpretation stage basically consists in identifying the problems affecting a generator. The final stage: the knowledge about the exact condition of generators based on PD measurements, relies on rate of degradation of each type of degradation mechanism, their maximum acceptable levels, and the cumulative time for which a generator can be exposed to these mechanisms. This diagnostic method has improved substantially over the past decades, but it is not straightforward and different experts do not always agree on critical and acceptable PD levels or even on the most significant parameters to characterize PD quantities to use.

The authors believe that global parameters (such as maximum amplitude or total apparent current) can be used as preliminary indicators but have limited capability to support the identification of active PD sources. We believe that every type of discharge has its own degradation rate and its own critical level. Before one can establish these levels or rates of degradation, which is included in the third stage of the overall PD diagnostic process, one first has to recognize each type of defect to study them separately, and this identification of PD sources is the main focus of the current paper.

In order to eventually come up with a more systematic generator diagnostic procedure, based on generally accepted PD parameters and critical levels, more work will be needed. Several techniques of PD measurements practices are in use today. Measurements are carried out over different frequency ranges. Some people use pulse shape analysis while others consider PD pulse count or maximum PD amplitudes, making it difficult to quantitatively compare results from one instrument to the other or from one expert team to an other. In spite of these differences, some techniques have become more popular over the last decade. For instance, the phased resolved partial discharges (PRPD) representation proposed in the late 70's [12, 13] is now considered as one of the most powerful tools for PD source identification and is being incorporated into most modern PD equipment. This technique has proven its strength over the years to support specialists in carrying out better generator diagnostics. However, as long as there is no common database associating each discharge source with its own specific PRPD pattern, the results are difficult to interpret. Further, in the case of PD measurements on generators, multiple PD sources can be present simultaneously and each of their characteristic signatures will superimpose on the global PRPD pattern, resulting in a complex pattern. For a non-PD expert, it is very difficult to distinguish if this signature comes from a unique source or from multiple sources.

Over the last ten years, Hydro-Quebec has been working toward building a database of PRPD patterns from various PD sources. This work has been carried out partially in the laboratory and on actual generators in the field. The laboratory contribution was essential to unequivocally isolate individual defects and to determine their corresponding PRPD patterns under well-controlled conditions. In addition, field measurements were used to make sure that simulations evaluated in the laboratory were also representative of actual generator problems.

To investigate different types of discharge sources, the laboratory study was divided in four parts.

1) The first part was aimed at studying three of the most common types of end-winding defects: surface tracking, bar-to-bar discharges and corona discharge at the junction of the field grading system.

2) The second part of our study consisted in simulating and measuring slot discharge activity, occurring between the bar and the iron core surface.

3) The third type of discharge source characterized was internal discharges, occurring within the ground-wall insulation, and always present at voltage above 6.0 kV in modern rotating machine insulation.

4) Finally, discharge activity from delamination of the groundwall insulation at the copper conductor interface was characterized.

The advantage of the laboratory investigation was that an ultra-sonic probe, an ultra-violet camera and a blackout test could be used to ascertain without any doubt the presence or the absence of PD activity. For each specific type of PD activity, electrical detection was used when a specific activity initiated, to compare the PRPD patterns before and after PD inception. On generator such observations may not be possible. However, in the case of discharges external to the core, degradation products can be observed during visual inspection to confirm if external activity has been active or not on a generator. Based on our preliminary laboratory database some end-winding discharges have been identified and later confirmed during generator visual inspections.

In addition to the PRPD analysis, wideband spectrum analyses were carried out both in the laboratory and in the field to determine the frequency content detected at the coupler for every type of PD activity. It is generally accepted that different discharge sources will generate PD signals with varying frequency content. In addition to PD signal generation, transmission and attenuation also need to be considered. The signal transfer function associated with propagation and attenuation will depend on the type of machine, the winding design and the detection coupler used. Moreover, it should be pointed out that at least two modes of signal propagation exists as was reported by others [14]: one portion of the PD signal can be conducted along the stator winding conductors, whereas another portion can propagate electro magnetically in the air. This portion of the signals is responsible for cross-coupling which can be detected between phases. Generally, discharges external to the core will generate a more intense electro-magnetic signal, whereas internal discharges will mainly propagate in the conductor out to the coupler. Finally, the measurement instrument also has an influence on the frequency response of the recorded signal. Usually, the detection bandwidth of the instruments is the combination of the response of both the coupler and the acquisition system. Thus, spectrum analyses presented herein were used to recognize over which frequency range each type of activity was detected with a unique type of coupler. This information was further used to make sure that the PRPD analysis, carried out over narrower frequency ranges, was not biased by the choice of frequency range.

The scope of this paper mainly focuses on the detailed investigation of the interpretation of PRPD patterns. The identification stage is the only one treated here in detail. The rate of degradation of each type of activity, with relation to signal evolution and failure history, is not part of the current investigation. In addition, the severity of each PD source raises the question of PD quantification (pC. mV, μA. . .) and the necessity or validity of performing signal calibration. Although these aspects are discussed briefly in the paper, the main emphasis of this work is in pattern recognition. No attempts have been made to establish critical PD limits. Although the authors recognize the importance of these aspects they have been deferred, because one first has to know what to look for, before thinking of quantifying it. For instance, a PD activity from surface tracking will most probably not represent the same risk than a slot discharge activity of the same amplitude. The capability of recognizing several different PD sources is thus a precursor to its quantification.

2 EXPERIMENTAL DESCRIPTION

The discharge sources studied herein were classified in four groups: internal discharges, slot discharges, discharges external to the iron core (end-winding discharges), and discharges from delamination of the groundwall insulation from the inner conductor. Obviously, such investigation required each its own laboratory set-up as defined below. Almost all Hydro-Québec's generators operate at a nominal voltage of 13.8 kV, thus the following investigation applies to such a construction, and phase-to-ground nominal voltage in the present document is always of 8.0 kV, unless otherwise specified.

2.1 INTERNAL DISCHARGES

At nominal voltage (13.8 kV), most Roebel bars and coils will give rise to internal discharge activity. This is usually not a problem because modern epoxy-mica insulation systems are manufactured to withstand this normal discharge activity for more than 40 years without any dramatic degradation. However, internal PD may, under some conditions, show abnormal progression, leading to excessive insulation degradation and thus should be differentiated from other discharge sources. This type of activity was the easiest one to characterize in the laboratory because it is always present on all the bars tested at nominal voltage in the laboratory. It was not necessary to modified new bars in any way to have internal discharge activity. The CIV were generally between 3.5 and 6.0 kV. This activity was studied either on single stator bars (out of core), subjected to high voltage with two 15 cm copper plates as ground electrodes, or on undamaged bars installed in a mock-up stator core, also used for the slot discharge investigation.

2.2 SLOT DISCHARGES

A full height section of a stator core has been assembled in our laboratory. Six stator bars were installed in three of the slots with three different side clearances, characterized as: loose: 1.00 mm, intermediate: 0.50 mm and tight: 0.25 mm), as depicted in the diagram of Figure 1. Initially, all bars were installed without any armor defect and were subjected to voltage in order to get a baseline PRPD measurement of the internal PD activity. After characterization of each individual bar at voltages up to 10 kV, they were removed from the stator section, and localized artificial defects were introduced by abrading the semi-conductive coating down to the bare insulation on the right side of each bar. Two rectangular defects were made on each bar in locations to coincide with to consecutive stacks of laminations, as illustrated in Figure 2.

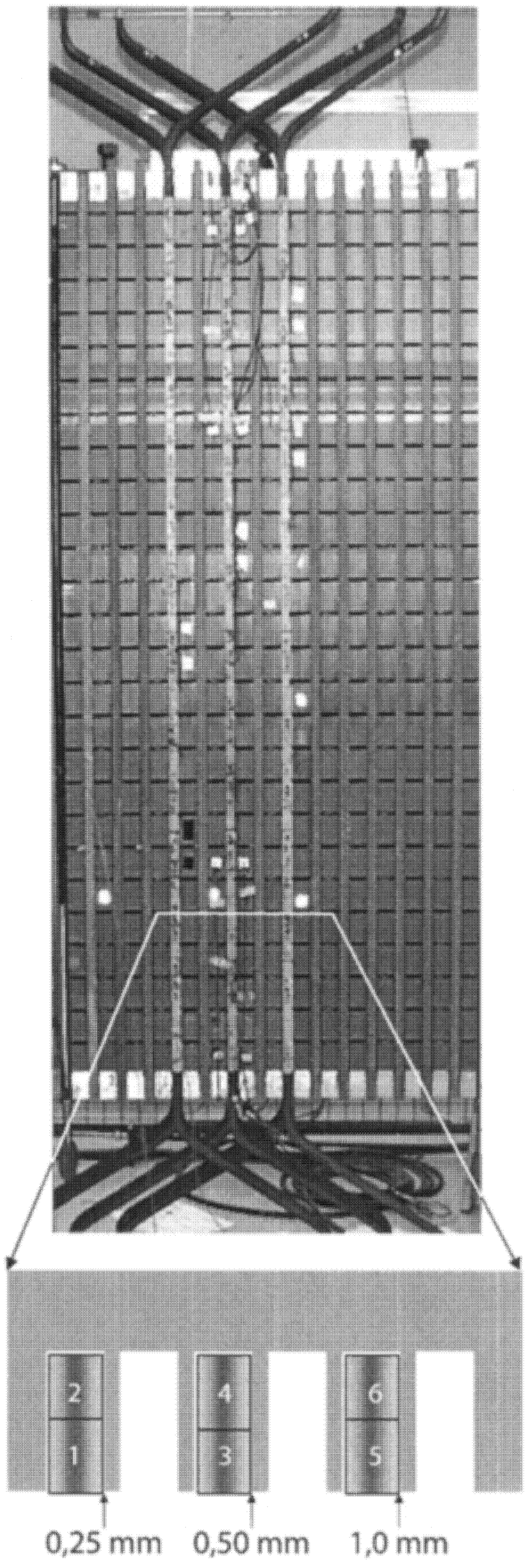

Figure 1. Stator core mockup (top) and diagram of a cross-section of the 6 bars in the core showing the 3 levels of side clearance.

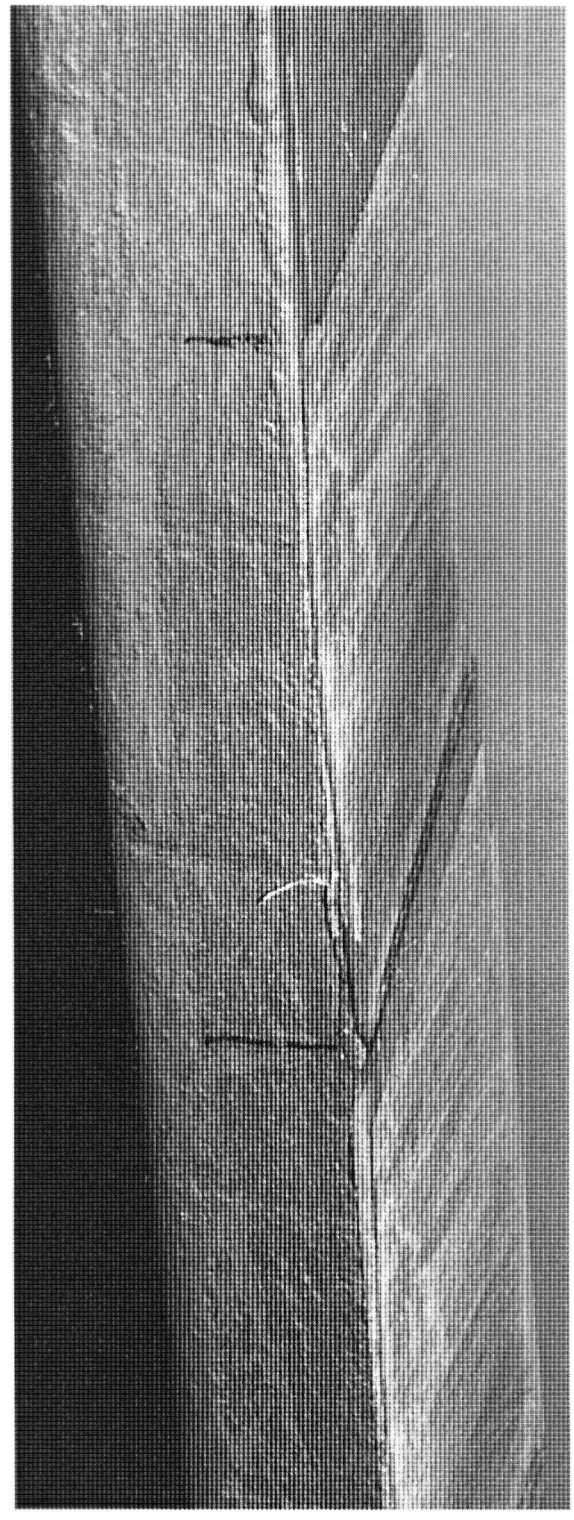

Figure 2. Simulated defect on the surface of stator bars.

Thereafter, the bars were installed a second time in the same slots as before, with the same degree of side packing as before. It should be pointed out that the side clearance indicated in Figure 1 was only controlled at and around the location of the defects (or at the same location before the defects were made).

The discharge patterns were once again measured with the PRPD acquisition system at different voltage levels.

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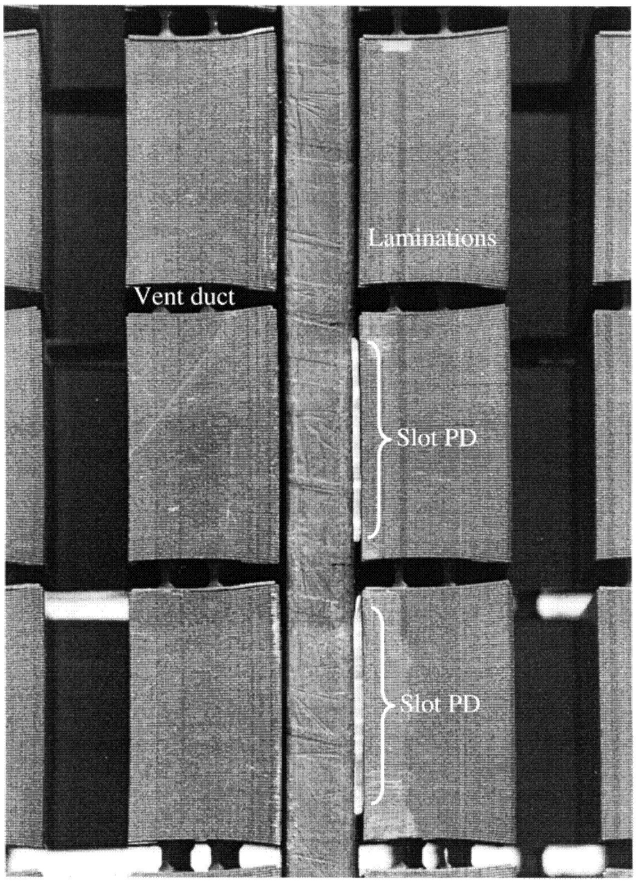

Figure 3. Visual manifestation of slot discharge activity at location of armor defect.

Measurements were first made immediately after voltage application, then one hour after continuous voltage application, and finally 24 hours later. This revealed that there was an initial rapid change in PRPD patterns, which stabilized over time. In order to obtain reproducible results, a conditioning time of 24 h, at 8 kV, was thereafter always used before carrying out slot PD measurements.

Before installing the radial wedges on the three slots with bars, the voltage was first applied to the bars to make sure that there was slot PD at the location of the artificially created surface defects, and that there was no slot PD where the armor had not been modified. The PD activity was monitored as a function of voltage, in conjunction with visual observation using a UV camera. A picture of this slot activity shows the light emission at the bar/core interface as presented in Figure 3 (the light associated with the slot discharges created two white band on the picture as a result of 20 minutes of exposure to this activity). The slot PD can be observed at the two locations where the armor had been abraded away on the right side of the bar. Notice that no other portion of the bar was discharging between the side of the bar and the slot (left side of the bar or elsewhere on the right side). After it was made sure, upon voltage application, which specific features on the PRPD pattern were associated to slot discharge activity, the radial wedges were installed for the rest of the test. Acoustic measurement confirmed that the localized slot PD was still present after wedging the bar in place.

2.3 END-WINDING DISCHARGES

The end arms of standard production Roebel stator bars have been modified to force the occurrence of three of the most common types of end winding discharge activity, each surface defect being active individually on separate end-arms. The three setups were duplicated in order to have two setups showing surface tracking, two others showing corona type discharges at the semi-conductor/grading paint junction, and finally there was two setups with bar-to-bar type discharges. Copper plates were pressed against the side of the bars, one or two centimeters from the end of the semiconductor coating, and grounded to simulate the iron core. These plates did not extend over the entire length of the straight portion, but rather over the first fifteen centimeters. The setup illustrating each type of source is shown in Figure 4. An oil and carbon dust mixture was used as a contaminant, to induce the surface tracking. Figure 5 clearly shows the presence of tracking around the contaminated area. After many tests it was established that surface tracking did not occur in our laboratory setup up to voltages of 30 kV as long as the grading paint was of good quality, even if it was severely contaminated with oil and carbon particles. The only modification resulting in significant surface tracking consisted of a combination of grading paint having an abnormally high resistivity contaminated by an oil and carbon dust mixture. Under such condition, the inception voltage of this type of activity was always above the operating voltage, but more severe stress enhancement conditions may exist on generators than what was simulated in our laboratory. Moreover, it should be pointed out that the temperature might enhance this type of activity, possibly triggering it even at nominal voltage. Here, all tests were carried out at room temperature.

Corona discharge activity can occur around the bars a few centimeters out of the stator core, at the junction between semi-conductive paint, used in slot, and stress grading paint (or tape), used in the end-arm for electrical stress control. In the laboratory, the corona discharges activity at the junction of the stress control grading were easy to induce, simply by abrading away the junction of semi-conductor/grading paint. Corona at this location was observed at, and above, operating voltage. A visual manifestation of this type of activity is illustrated in the picture of Figure 6. This picture was taken in our laboratory, with a long exposure time on a bar modified as described above.

Each setup of the third type of end-winding activity, namely bar-to-bar defect was composed of two bars, one at high voltage and the other one at ground. The air gap

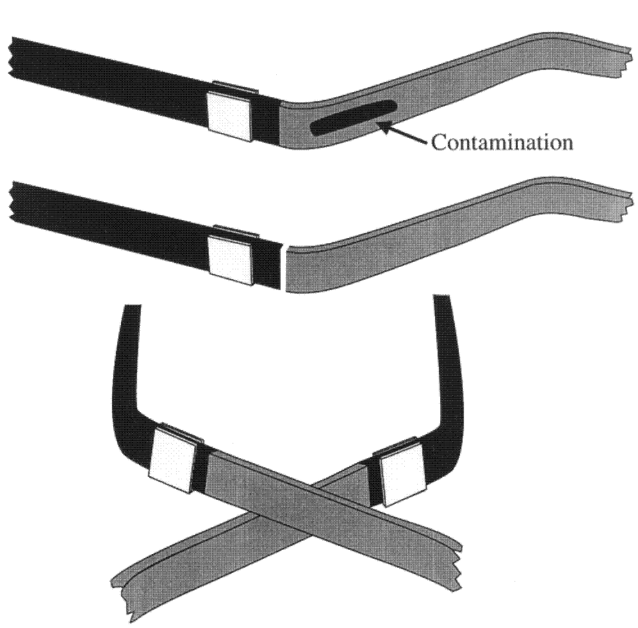

Figure 4. Setup used to recreate end-winding discharges: surface tracking (top), corona at the junction of the grading paint (center) and bar-to-bar discharges (bottom).

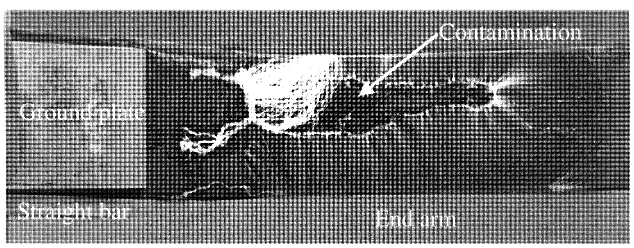

Figure 5. Surface tracking activity on a contaminated end arm of a stator bar subjected to a voltage of 20 kV.

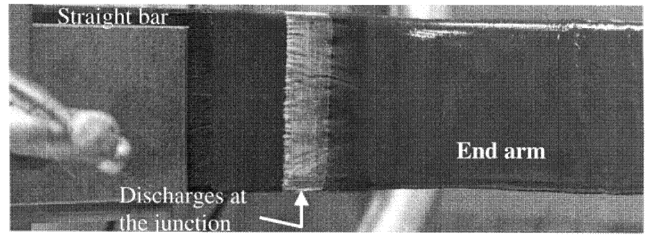

Figure 6. Corona discharge activity at the semi-conductive and stress grading paint junction.

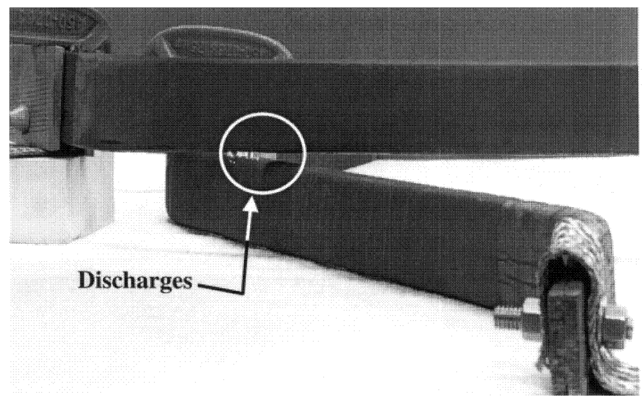

Figure 7. Bar-to-bar discharge activity on an experimental setup at 20 kV.

at the crossover of the end-arms was adjusted in order to get discharges from one bar to the other. The gap could be adjusted to get bar-to-bar discharges at nominal voltage, in which case the gap was abnormally small, or the gap could be increased to a more usual spacing, but it was then necessary to apply higher voltage to get bar-to-bar discharges. The picture of Figure 7 taken in our lab, illustrates the manifestation of bar-to-bar discharge at 20 kV.

2.4 DELAMINATION DISCHARGES

Two types of delamination exist. The first one pertains to delamination of the groundwall insulating tape itself, whereas the other one is related to delamination of the insulation close to the inner conductor strands. Several trials have been made to induce delamination on new Roebel bars either by mechanical impact or flexural stress cycles, but it was found that when this construction is well made, they do not delaminate readily. Over the years, bars extracted from the field have shown that Roebel bars with epoxy-mica insulation are seldom affected by internal delamination and delamination at the conductor. The only exception found was for Roebel bars with the first generation of polyester-mica flakes, which was more prone to delaminate internally. It appears that delamination is a more widespread problem on multi-turn coils. The only case tested in the lab was made using coils extracted from a generator on which PRPD measurement had been previously made. The dissection of one of the legs of a reference coil and of other coils has shown that this machine had extensive delamination of its groundwall insulation and of some portion of its turn insulation. In order to detect PD signal coming from delamination with the conductor, a section of the second leg of the reference coil was cut and its central conductor was easily extracted with the turn insulation, which was removed from the copper package. Thereafter, the central conductor was reinserted, as illustrated in Figure 8, and PRPD measurements were made on this test specimen.

2.5 DETECTION COUPLER AND FREQUENCY BANDWIDTH

The detection coupler used throughout the investigation, both in the lab and in the field, was an 80 pF capacitor in series with a 50 Ω resistor, which gave a high pass response with a first order cut-off frequency of 40 MHz. Since the phase winding of generators acts as a low pass filters, the low frequency component of the signal coming out of the machine will be less attenuated with propagation than the higher frequency components. A similar

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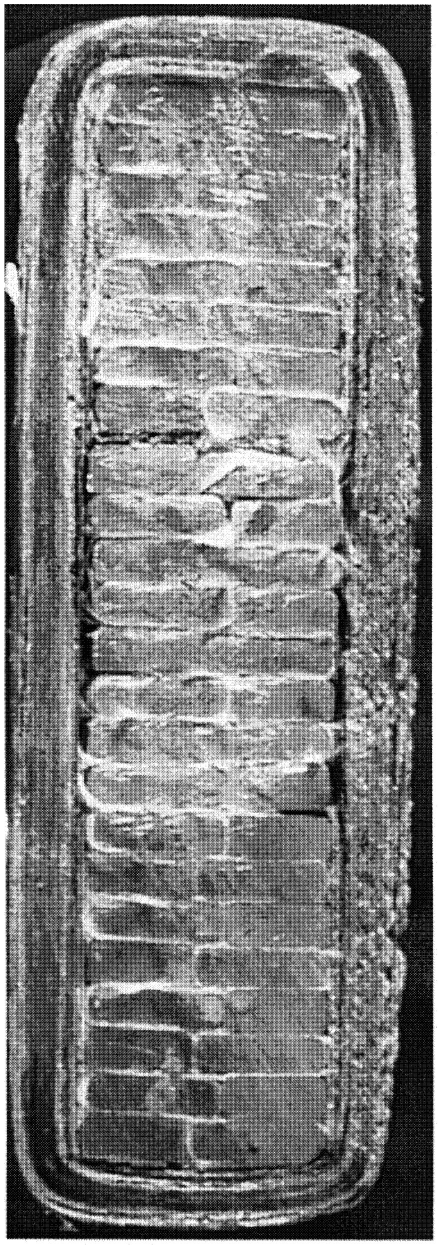

Figure 8. Turn insulation removed form the central strand package of a three-turn delaminated coil.

phenomenon also takes place when measuring PD signals from individual stator bars in the lab, but because of their smaller distributed capacitance, a single bar is expected to have a low pass characteristic with higher cutoff frequency than an entire phase winding. In contrast, the coupler attenuates more low frequency signal than the high frequency contribution.

The PRPD measuring system used here was operating in three distinctive detection bandwidths: 40-800 kHz, 2-20 MHz and 200-1000 MHz. For these measurements, all detected signals within the bandwidth would accumulate to form the overall PRPD pattern during the entire acquisition time. This time can be adjusted, but was fixed at 30 seconds for all measurements. In addition to these measurements over these fixed bandwidths, a wideband spectrum analysis was also made in every condition (lab or field measurements) from 10 kHz up to several hundreds of megahertz. The spectrum analyzer could be used up to 1.8 GHz but in most cases the detected signals were limited to hundreds of megahertz if not tens of megahertz.

The authors usually use maximum pulse amplitudes calibrated in pC, however it is not the intent of this paper to suggest typical or acceptable pC values for each defect types. Nevertheless, some quantitative units are still needed such as maximum PD amplitudes during the positive and negative cycles of the 60 Hz on individual pattern for comparison. In order to keep the focus of this work on pattern recognition, all units used for amplitude (Q_{max}), which is the peak value measured during the entire integration time, will be expressed in relative amplitude units (a.u.). These units should not be used for absolute comparison, but only relative comparison. When using unique equipment with a single type of coupler, regardless if measurements were made in pC or mV, every signal can be normalized and these units become arbitrary units. This approach was adopted here because or intent was the analysis of the shape of the patterns and not to fix critical amplitude values.

In addition to the maximum amplitude the number of discharges pulses (N) are also used to quantify symmetry. Finally, a value proportional to the overall discharge energy, coming from the integration of all discharge pulses measured during the acquisition time, is also used herein for PD quantification and is referred to as NQS. This NQS, given in relative energy unit (e.u.) is proportional to a weighted area under each PRPD pattern. This NQS values is based on the total number of pulses detected during the integration time multiplied by the amplitude of each pulse and divided by the integration time.

3 RESULTS

Over the past decade, Hydro-Québec has accumulated an extensive PRPD database obtained from field measurements. Many characteristic patterns have been measured from several generators. Initially, most of those signatures could not be associated with their corresponding causes, because PRPD pattern recordings are not absolute. However, based on the results presented in the current section, such an association between characteristic patterns and specific cause of PD activity now becomes possible. For each type of discharge source studied in the lab, you will find in the following section one of the many examples of PRPD pattern also recorded from actual generators, and showing the features characteristic of this PD source.

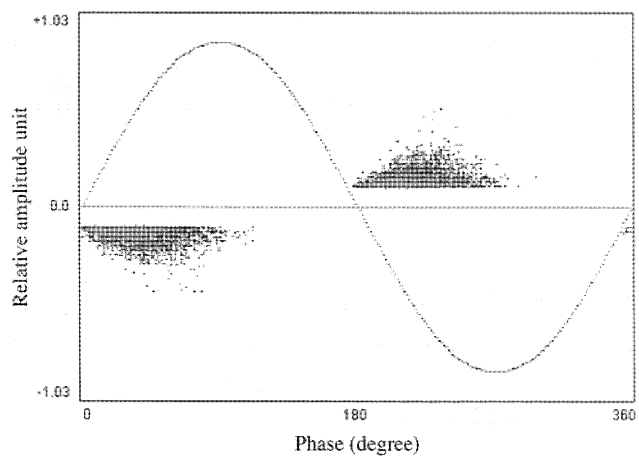

Figure 9. PRPD pattern (40-800 kHz) of internal discharge activity, measured on a self standing bar in the laboratory at 8.0 kV.

3.1 PRPD PATTERNS

3.1.1 INTERNAL DISCHARGES

Internal discharges occur within the insulation groundwall, inside small voids. Internal discharge activity is always present on 13.8 kV generators under normal operating conditions. During off-line tests, it will normally be the activity appearing at the lowest voltage, except in the presence of severe problems such as slot discharge activity, or with severely deteriorated stress grading paint. If such problems are present, the ensuing PD activity can occur at a voltage lower than the internal PD inception level. This will usually yield signals larger than internal discharge, and thus mask the contribution of the internal partial discharge. If such problems are not present at nominal voltage, or just below, only internal discharge will be active.

Internal partial discharge activity is characterized by symmetry in the maximum amplitude and in the number of discharge pulses, when the activity occurring in both voltage half cycles is compared. The relative amplitude of internal discharge detected for all lab and field conditions ranged from 0.1 to 5.0 a.u. In the laboratory and during off-line generator tests, it was observed that this PD activity normally started a few kilovolts below the nominal voltage. Figure 9 shows a typical PRPD pattern of internal discharge activity, recorded in our lab on a single bar without added artificial defect. It can be observed from this pattern that the maximum amplitude of this internal PD was of about 0.25 a.u. In addition, this PRPD pattern also shows symmetry of the positive discharges (occurring during the negative half cycle of the voltage) and the negatives discharges (occurring during the positive half cycle of the voltage), which has long been recognized as characteristic of internal discharges [15, 16].

The previous results were obtained when energizing a single bar with two 15 cm ground plates placed each side of the armor at the center of the strait portion of the leg. When bars were mounted inside the slots of a full height section of a stator core and energized, there was no basic difference of behavior with regard to CIV, amplitude and shape of the PRPD pattern as depicted in Figure 10. The same symmetry is present, and maximum amplitude was again in the range of 0.25 a.u. This PRPD pattern was recorded at 7.0 kV, on a bar without surface defect in the slot section. During off-line tests, it is usually possible to determine that the CIV of internal PD activity is less than the line-to-ground operating voltage.

The PRPD pattern illustrated in Figure 11 was recorded on-line on a 30 MVA / 13.8 kV generator. This generator was in good condition, as suggested by the low maximum amplitude of the internal PD, which did not exceed 0.4 a.u. Such symmetrical patterns, with small maximum amplitude, are characteristic of generators in good condition.

3.1.2 SLOT DISCHARGE ACTIVITY

It is well recognized that the presence of slot discharge activity increases the risk of in-service failure. Those dis-

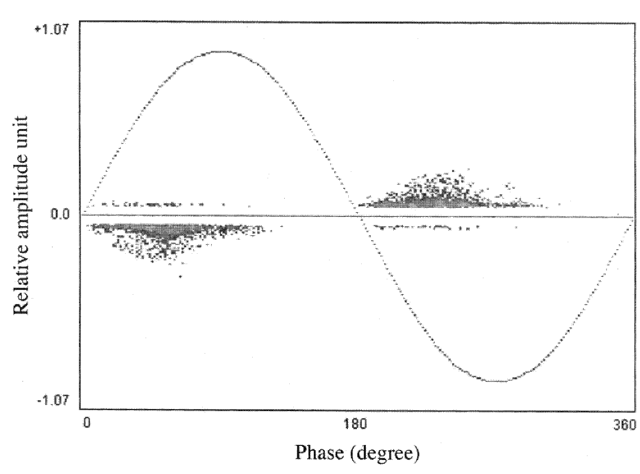

Figure 10. Internal PD measured on a bar in the slot of a magnetic core in the laboratory at 7.0 kV.

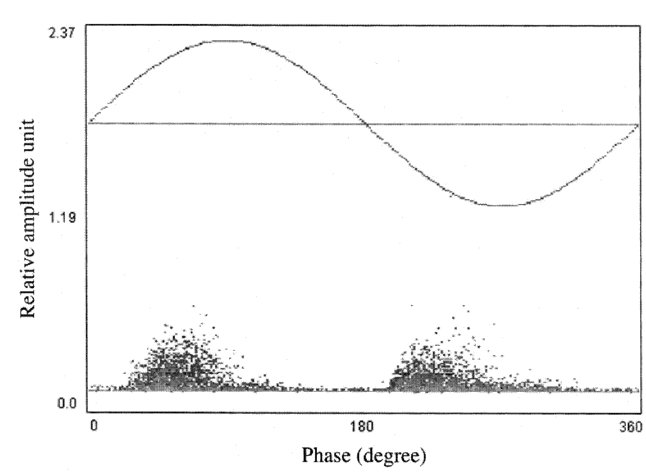

Figure 11. PRPD pattern (2−20 MHz) of internal discharge activity, measured on-line on a 30 MVA/13.8 kV generator.

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Table 1. Change of PD characteristic of slot discharge at 8.0 kV with voltage application time (40−800 kHz).

V time	Qmax+ (a.u.)	Qmax- (a.u.)	N+ (Thousand)	N− (Thousand)	NQS+ (e.u.)	NQS- (e.u.)	Q+/Q−	N+/N−	NQS+/NQS−
0	9.7	9.7	150.9	120.7	9.61	7.66	1	1.25	1.25
24	6	1.6	214.5	5.3	8.47	0.115	3.75	40.5	73.6

charges occur in the air gap, between the magnetic core and the side of stator bars. This activity will manifest itself when the semi-conductive coating of the bar is too resistive, or when, as a result of bar vibration, the erosion of the coating will leave bare insulation at high voltage facing the metallic grounded core. To simulate this in the lab, the semi-conductive paint on one side of the bar (see Figure 2) was abraded away, before it was introduced inside the slot.

When voltage was first applied to these modified bars mounted in their slots, it was observed that the maximum amplitudes were larger than internal discharges with maximum in the range of 5 to 20 a.u. Out of the six bars tested, there was not always a marked asymmetry in the discharge pattern. However, after one hour of voltage application, some of the patterns changed significantly, and after conditioning, all PRPD patterns were asymmetric. The PD parameters revealed the formation of a marked asymmetry after one hour of voltage exposure, which was maintained thereafter until 24 h of conditioning time, as depicted in Table 1 for one of the six bars.

Such a behavior could be explained by a conditioning of the surfaces at the discharge site. Initially, the availability of initiatory electrons was large because of the bare metallic surface of the lamination. This favors the presence of sufficient free electrons in the air gap to start an avalanche, regardless of the voltage polarity. After some time, this intense slot discharges, together with ozone generated, starts to attack both the insulation and the core. Bar removal has revealed that this activity has caused rapid oxidation of the surface of the laminations. Bars subjected to significant slot discharge and removed from the core after only 24 h of voltage have revealed noticeable oxidation of the core. This can affect the availability of free electrons.

In the presence of slot discharge activity, the PRPD pattern was completely different from what was seen with internal PD. A typical PRPD pattern resulting from slot discharges measured in the lower frequency range (40-800 kHz) is shown in Figure 12. This PRPD pattern was recorded on the same bar as the one in Figure 10 (PRPD pattern with internal discharge alone), at the same voltage (7.0 kV), but after a surface defect was made to the armor coating. In comparison to the internal PD, a significant asymmetry with regard to discharge amplitude was observed, but also in the discharge count. Moreover, another feature of this PRPD pattern, which is typical of slot discharge, was the very sharp slope at the onset of the positive discharge pattern (during the negative half cycle of the voltage) and marked by a solid line triangle in Figure 12.

As the applied voltage was gradually increased, the PRPD pattern gave rise to some changes as depicted in Figure 13. At low voltage, the activity started later in the voltage cycle, namely after the voltage zero crossing, and this for both half cycles (around 20° and 200° of phase angle). With increasing voltage, the activity started earlier, shifting the PRPD pattern to the left in Figure 13. The reason for this is that the positive slot discharge occurred when the local field reached the inception field (E_{inc}) for this slot activity. This field (E_{inc}), at the defect location, is caused by the addition of the applied voltage and of the local voltage due to the surface charge deposited by previous discharges, with respect to the gap size at this location. By increasing the applied voltage, this E_{inc} is reached earlier in the high voltage cycle, thus the activity will start earlier in the cycle. In fact, this is true for any other type of PD source.

It can be recognized that some generic features were present in the four PRPD patterns of slot PD in Figure 13, for one of the six tested bars, but there were some variations between these patterns. The typical PD parameters (Q_{max}, N, NQS) extracted from all PRPD patterns, recorded between 5 and 10 kV in 1 kV steps and presented in Table II, also highlighted these differences.

From those parameters, it can be seen that the ratio of N+/N− was constantly increasing with voltage, but it was not always greater than 1. At low voltage, near the incep-

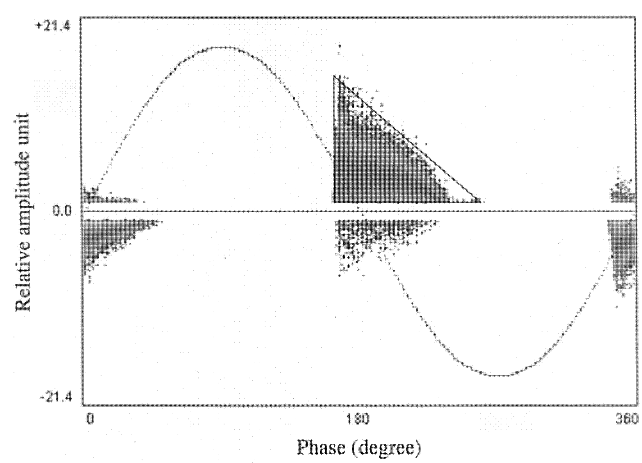

Figure 12. PRPD pattern of slot discharge activity, measured at 7.0 kV on a laboratory setup with a known slot defect.

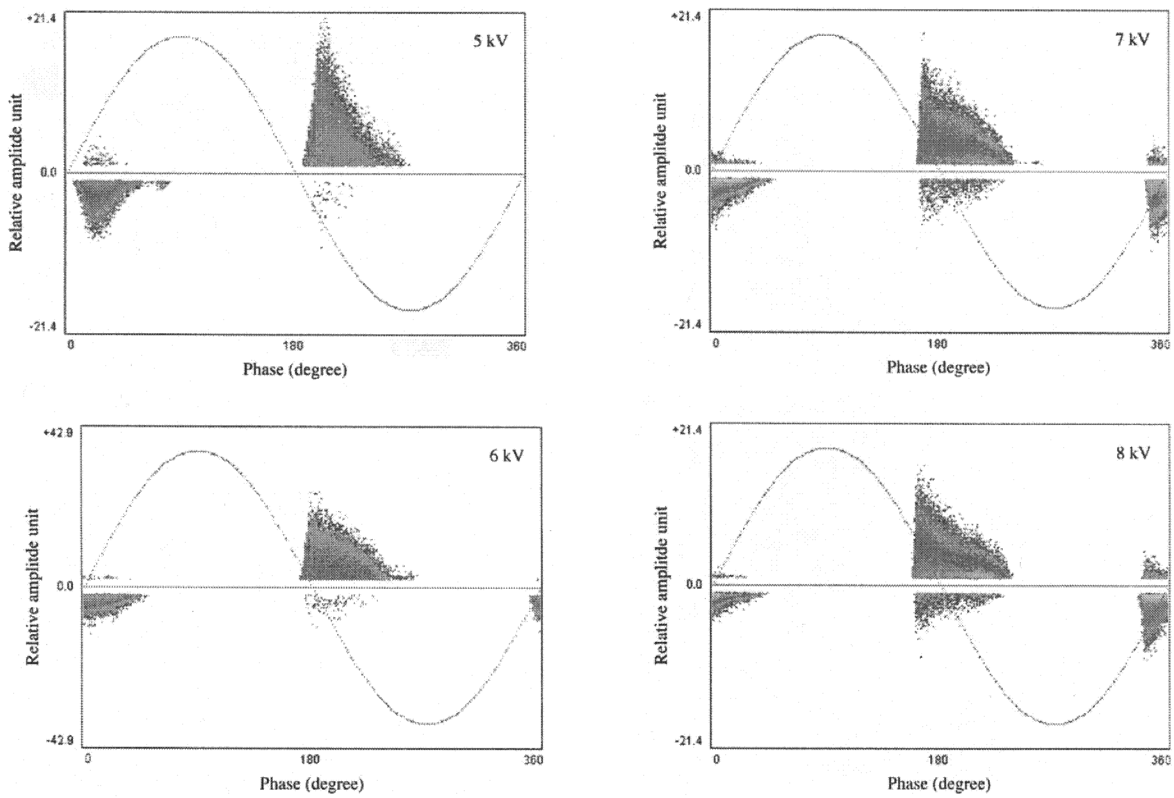

Figure 13. PRPD patterns of slot PD, measured at different voltages, on experimental setup with slot defect.

tion voltage of slot discharge activity, this ratio was of 0.7. In contradistinction, the ratio Q+/Q− was for this laboratory specimen a better indicator of the asymmetry observed in the PRPD pattern, because it was always larger than 1, actually most of the time it was closer to two.

It is also interesting to note that although there was an asymmetry reflected by the ratio of Q+/Q−, there was no increase of the maximum slot discharge amplitude with voltage. In fact, there was a general decrease of $Q_{max}+$ and $Q_{max}-$ when voltage was increased from 6.0 to 10.0 kV, as depicted in Table 2. Apparently, the maximum amplitude was not the best indicator of the severity of the slot discharge activity, because in contrast with this Q_{max}, as the voltage was increased there was in fact an increase of the slot activity as indicated in Figure 13. The gray scale coding in this figure is associated to the number of discharges. The only parameters in Table II reflecting the increase with the voltage are the number of detected pulses and to a lesser extent the relative overall energy NQS. For both of those parameters the increase with voltage was more pronounced for their positive contribution (N+, NQS+). The NQS+/NQS− ratio was always between 1.6 and 3.2, but was not constantly increasing, with the applied voltage. To a different extent, these three ratios can be used to reflect pattern asymmetry, but have limitations with respect to the quantification of severity as it was the case for the maximum discharge amplitude.

It is easy from the phase resolved representation to differentiate slot from internal PD, and over the last decade it has supplanted other types of representation such as the common representation of the rate of discharge versus amplitude (RA). The RA representation also reflects the asymmetry typical of slot discharges, as shown in Figure 14 (note that the vertical scale of 13 b is not the same as

Table 2. PD parameters extracted from PRPD patterns of slot discharge activity as a function of voltage increase (40−800 kHz).

V	Qmax+ (a.u.)	Qmax− (a.u.)	N+ (Thousand)	N− (Thousand)	NQS+ (e.u.)	NQS− (e.u.)	Q+/Q−	N+/N−	NQS+/NQS−
5	19.8	8.7	18.5	26.3	3.3	2.1	2.3	0.7	1.6
6	21.7	9.9	32.5	22.9	7.3	2.7	2.2	1.4	2.7
7	14.7	8.8	85.1	60.0	8.7	3.9	1.7	1.4	2.2
8	14.0	8.3	109	57.8	9.9	3.7	1.7	1.9	2.7
9	12.7	6.8	108	46.7	8.4	2.7	1.9	2.3	3.1
10	11.5	5.8	110	49.0	8.6	2.7	2.0	2.3	3.2

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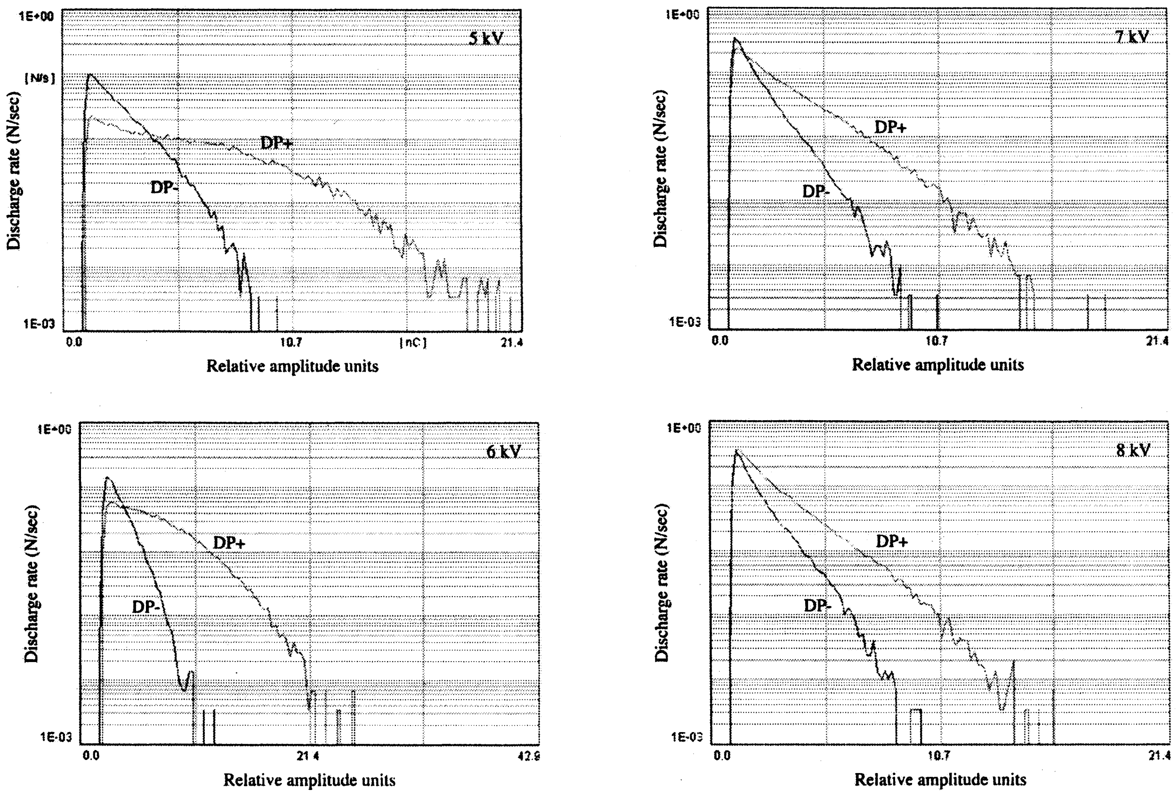

Figure 14. Pulse rate versus amplitude representation of slot PD activity at different voltage.

the other graphs), compared to the activity corresponding to the PRPD patterns shown in Figure 13. However, it is interesting to observe that even though all PRPD patterns were of similar shape, forming triangles during the negative half cycle of the voltage, they gave different RA distributions. At low voltage, with low-level slot activity, the shape of the distribution in Figure 14 is non-linear and more rounded, while a more pronounced slot activity results in a linear decrease (on the logarithmic scale). This highlights the fact that a single known source measured in the laboratory can be analyzed by several means, which makes it difficult for different teams to compare their results. The measurement of a single discharge source should be straightforward, easy to identify and should be the same for everyone. Here, the RA representation cannot conclude, based on the shape of the four curves in Figure 14, that there was only one PD phenomenon. The asymmetry would suggest the presence of slot PD, but as we will see later, other types of defects can also generate similar asymmetric RA distribution.

On generators, this triangular shape in PRPD pattern is also commonly observed. Figure 15 depicts such a pattern, recorded on-line on a 805 MVA/18 kV generator. This pattern clearly shows a marked asymmetry, in favor of positives discharges (occurring during the negative half cycle of the voltage), highlighted by a triangle. The largest partial discharges on this pattern (marked by ellipses) in Figure 15 were coming from another phase and were cross-coupling to the measured phase. Those discharges were caused, as we will see later, by bar-to-bar discharge activity. The pattern of Figure 15 illustrates well that field conditions, often reveal more than one PD source on a single pattern, which makes identification more difficult. This is why it is so important to make proper identification on distinctive patterns, and build a database.

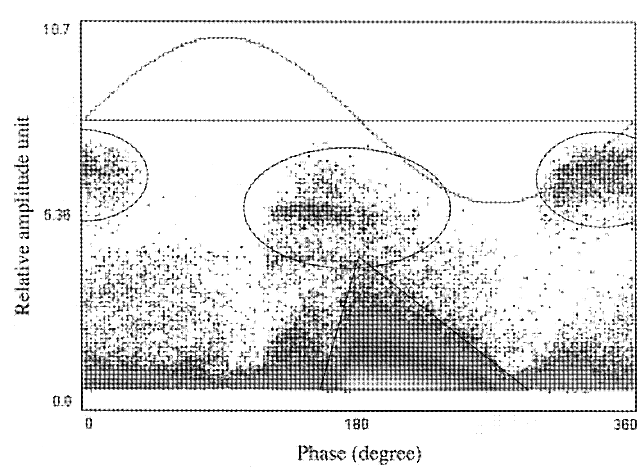

Figure 15. PRPD pattern (2–20 MHz) of slot discharge activity, measured on a 805 MVA / 18 kV hydro generator.

3.1.3 END-WINDING DISCHARGES

3.1.3.1 SURFACE TRACKING

Surface tracking are discharges forming along the end arms, at the air/insulation interface. It is normally caused by dust or other contaminants, or is enhanced by a bad performance of the stress grading paint or abnormally high temperatures. Surface tracking also gives asymmetric PRPD patterns. However, its predominant feature is that it gives rise to a few very large negative discharges with a maximum sometimes reaching amplitude as high as a few tens to hundreds of a.u., in the 40−800 kHz frequency range. These very large discharges generally occur around 30° of phase angle, which create an equal vertical cluster of discharges, such as the one shown in Figure 16. This well defined cluster of activity (shown inside the ellipse) only extends over a limited phase angle window, which we found to be the predominant characteristic of surface tracking. Although, sometimes when this activity is very intense, a few large discharges can be detected as well in the other half cycle, around 210° of phase angle. The smaller positive and negative discharges observed on the same PRPD pattern in Figure 16 were caused by corona discharge activity at the junction of the semi-conductive and grading paints. This second contribution in the PRPD pattern revealed a limitation of our laboratory setup, since in the lab conditions the voltage had to be increased to 20 kV to generate surface tracking. Thus, the surface tracking was always accompanied by small corona discharges at the stress-grading junction. The presence of both of those activities was visually confirmed with a UV camera. From what was observed in the lab, and noticed during field measurements, surface tracking was always a sporadic phenomenon, which was very dependent on the ambient conditions (humidity, temperature, end-arm contamination). On the contrary, corona activity at the junction was observed to be a more permanent phenomenon. Moreover, the surface tracking generated in the lab a distinctive short sparking noise completely different to the continuous hissing sound of the corona at the junction, thus they could also be differentiated only by sound. When the characteristic cluster of surface tracking was present on the PRPD pattern, it was always accompanied by a sparking noise, which was always combined with a streamer tree like discharge as shown in Figure 5. Such discharges usually leave on the surface of the end arms a carbonized channel, forming a tree like structure.

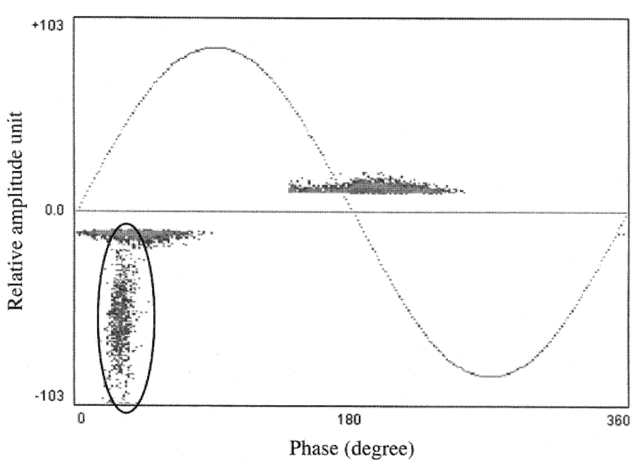

Figure 16. PRPD pattern (40−800 kHz) of surface tracking recorded in the lab at 20 kV.

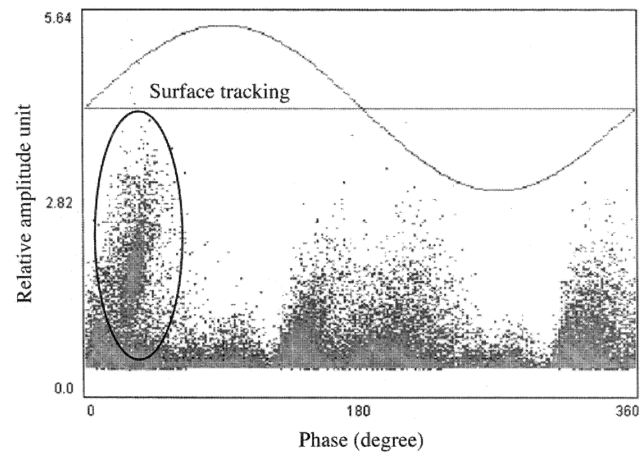

Figure 17. PRPD pattern (2−20 MHz) of surface tracking, recorded on a 80 MVA / 13.8 kV.

The amplitude of surface tracking discharges was generally the largest in the lab, reaching levels larger than 100 a.u. In the field, the corresponding signal mostly propagating electro-magnetically can also give rise to signal of tens of a.u., but depending on the source location, these signals can also give smaller signal such as in Figure 17.

The surface-tracking phenomenon is not unique to laboratory conditions. The PRPD pattern illustrated in Figure 17 shows a similar cluster recorded on a 80 MVA / 13.8 kV. This vertical cluster marked by an ellipse in Figure 17, and detected around 30°C of phase angle was superimposed on other discharge sources.

3.1.3.2 CORONA ACTIVITY AT THE STRESS GRADING JUNCTION

From what was observed at Hydro-Québec for the last decade, the corona discharge activity at the junction of the semi-conductive and stress grading paints, is a very common phenomenon. Without having specific statistics about this phenomenon, an estimated 50% of our generators are affected, to different extent, by this type of activity.

Our field experience is that this activity evolves slowly over the years, and can be easily trended with PD measurements. As it directly attacks the overlap portion of the semi-conductive and stress grading material, as illus-

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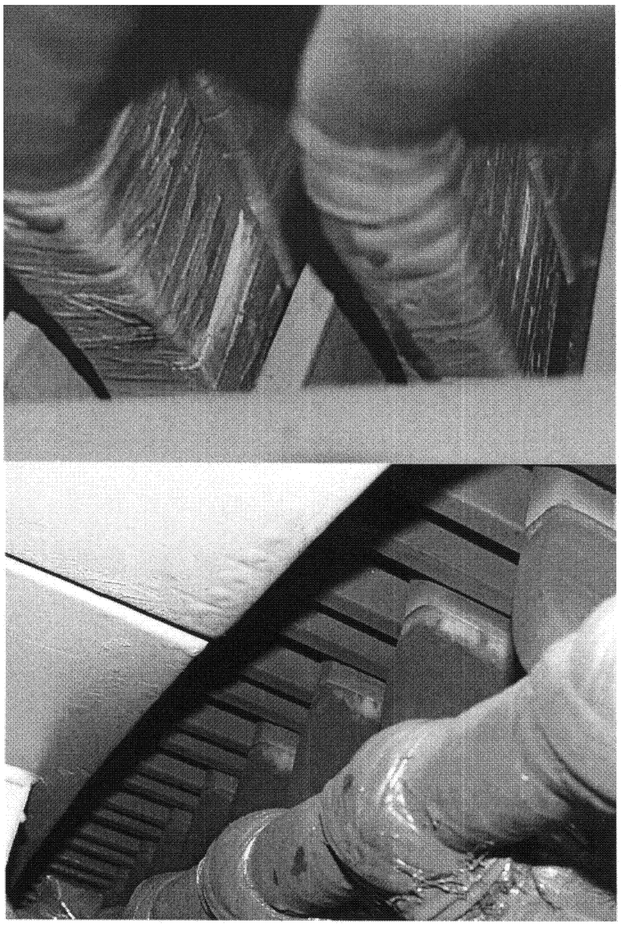

Figure 18. Degradation at the semi-conductor / field grading junction, caused by sustained corona discharge activity (top: grading tape, bottom: grading paint).

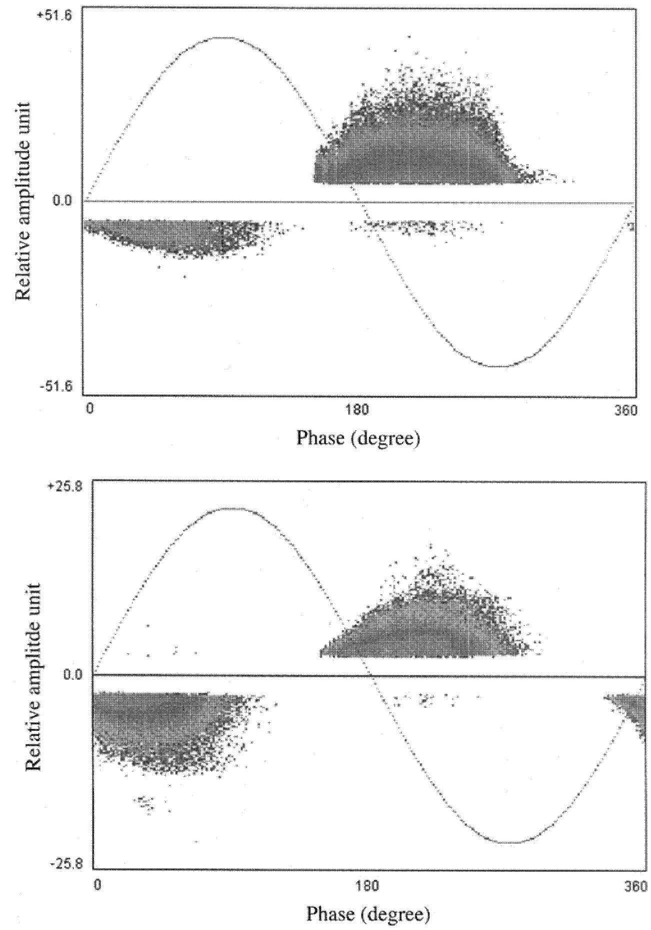

Figure 19. PRPD patterns (40–800 kHz) of corona discharge activity at the junction of the field grading paint on the experimental setup.

trated in Figure 6, this type of activity causes degradation directly at the junction, leaving a deposit of white powder at this location, as illustrated in the pictures of Figure 18. With time, this will eventually break the electrical contact of the paint junction, resulting in an abnormally high electrical stress at the junction.

Typical PRPD patterns corresponding to this type of activity are shown in Figure 19. They are characterized by an asymmetry from one voltage half cycle to the next, with positive discharges being much larger in number, and generally also in magnitude, then negative ones. The asymmetry with respect to polarity is the same as for slot PD. However, the shape of the pattern is much more rounded than what was observed for slot discharges (see Figures 12 and 13). It should be pointed out that under applied voltage in the laboratory, the asymmetry regarding the maximum amplitude tended to disappear when the corona activity was more intense, either when increasing the voltage or after the degradation of the junction gave more discharges. Nevertheless, even when the pattern was almost symmetric with regard to the PD amplitude, there was usually still an asymmetry in the number of pulses, as shown in the PRPD pattern in the lower portion of the Figure 19, always giving a larger number of positive than negative discharges. In the lab the Q_{max} of this type of discharge was in the range of 5 a.u. $< Q_{max} <$ 50 a.u. in the 40–800 kHz frequency range.

On rotating machines, degradation products such as those in Figure 18 are often observed, in such cases the PRPD pattern usually shows contribution similar to the ones in Figure 19. For example, Figure 20 shows such a pattern recorded during normal operation on a 680 MVA / 24 kV turbo generator. The discharge amplitudes in the PRPD pattern were here very low (around 0.2 a.u.), because the measurement was performed from the phase terminals of a hydrogen cooled turbo generator. The low magnitudes were due to the location of the couplers and/or the hydrogen pressure. The six vertical peaks separated by 60 degrees were not partial discharges and came from commutation of the excitation circuit.

These results show that the asymmetry with regard to the ratio of positive and negative discharges is not only observed in the lab and moreover is not exclusive to slot discharge. Because of the similitude in asymmetry, corona

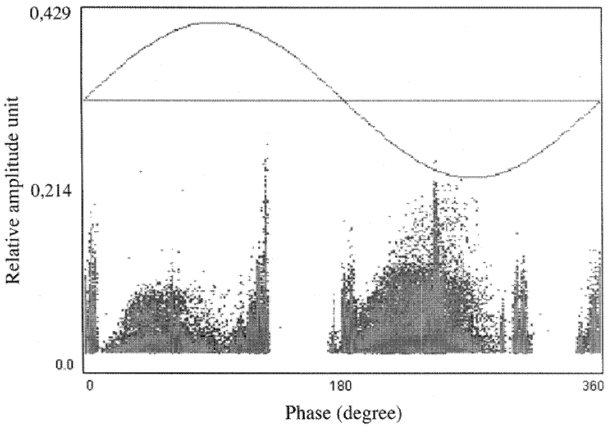

Figure 20. PRPD pattern (2–20 MHz) of corona discharge activity, measured on a 680 MVA / 24 kV turbo generator, with six exciter pulses.

discharges at the junction of the field grading system cannot be distinguished solely on the basis of the ratios of $Q_{max}+/Q_{max}-$, N+/N− nor NQS+/NQS−. Table III shows the differences in PD parameters for two distinctive lab specimens. The ratios found in this table are always larger than unity, but can be as large as 16 and as small as 1.09. Thus, only based on these parameters it is not possible to distinguish the discharges at the junction from slot discharges.

It should be pointed out that using a two dimensional RA representation of the PD activity also reduces the source recognition capabilities in comparison to PRPD analysis. In fact, when the corona activity of the PRPD patterns of Figure 19 are represented with the same RA mode as before for slot PD activity, we get the corresponding two graphs illustrated in Figure 21. This two dimensional distribution of corona at the grading junction again shows similar curves as for slot discharges. However, it is much more difficult to differentiate slot PD from corona discharge at the junction of the field grading with the RA representation, because there is no distinctive feature differentiating this phenomenon from the other one. The differentiation between these two sources is as much based on distribution of the PD pulse with respect to phase angle, than it is on the pulse polarity. Thus only PRPD can confirm which source is active. In addition, a simple comparison of discharge ratio can be less significant for on-line generator measurements, because most of the time multiple sources can superimpose, reducing the overall count asymmetry. The additional dimension (third axis giving by the gray shade coding) in the PRPD representation makes it easier to see if there is superposition of multiple sources.

3.1.3.3 BAR-TO-BAR DISCHARGE ACTIVITY

Bar-to-bar discharge activity is also a common phenomenon on high voltage generators. This type of activity takes place in the end-arm portion of the winding between two bars. It occurs when the air gap between the bars is too small to support the electrical stress. This activity will also cause insulation degradation leaving a white powder on the surface of the bars, noticeable during visual inspection. These discharges can occur between bars from different phases, or between a high voltage and a neutral-end bar of the same phase. It can also be observed between bars of the same plane, or at the crossover of the end-arm between top and bottom bars, as simulated in our laboratory and illustrated in Figure 7.

Bar-to-bar discharge activity gives a characteristic PRPD pattern, typical of gap discharges with much larger air gap spacing than for internal discharges occurring in minute voids or even in the slot. It is characterized by a signal at almost constant amplitude on the PRPD representation. Most of the time PD are recorded during both half cycles of the applied voltage, as illustrated in Figure 22 for a measurement made in the laboratory at a voltage of 20 kV. The discharge magnitude is very much related to the local field, and to the dimension of the air gap. At nominal voltage (here 8.0 kV), this activity was also present, but much less pronounced. Thus, a higher voltage (20 kV) was used for a better illustration. The drawback was that it caused simultaneously the formation of corona activity at the junction that partially masked some of the bar-to-bar features. It should be pointed out that the grading paint was not designed to operate at such a voltage, thus the corona activity at the junction was always present at this higher voltage. Observation with UV camera confirmed the presence of both bar-to-bar PD and corona at the grading junction.

This activity was observed on a number of generators during field measurements. The PRPD pattern shown in Figure 23 illustrates bar-to-bar activity, recorded on a 120 MVA / 13.8 kV generator. In this case, two distinctive levels of activity were observed. The larger one (source 1) was in phase with the phase-to-ground voltage, while the one at smaller amplitude (source 2) was shifted by 30° and was probably occurring between bars of different phases. During the visual inspection on this generator, many dis-

Table 3. Change of PD characteristic of corona activity at the junction at 20 kV (40–800 kHz).

Qmax+ (a.u.)	Qmax− (a.u.)	N+ (Thousand)	N− (Thousand)	NQS+ (e.u.)	NQS− (e.u.)	Q+/Q−	N+/N−	NQS+/NQS−
35.4	14.8	108.5	8.16	36.96	2.29	2.39	13.3	16.1
14.5	13.3	55.7	46.6	8.72	7.38	1.09	1.20	1.18

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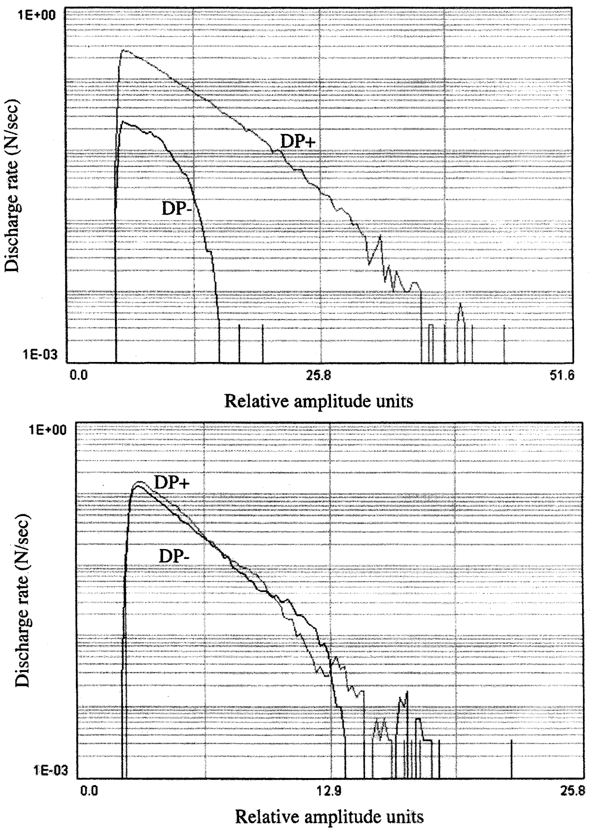

Figure 21. Pulse Rate versus Amplitude (RA) representation of the corona activity at the field grading system for the same PRPD patterns than in Figure 19.

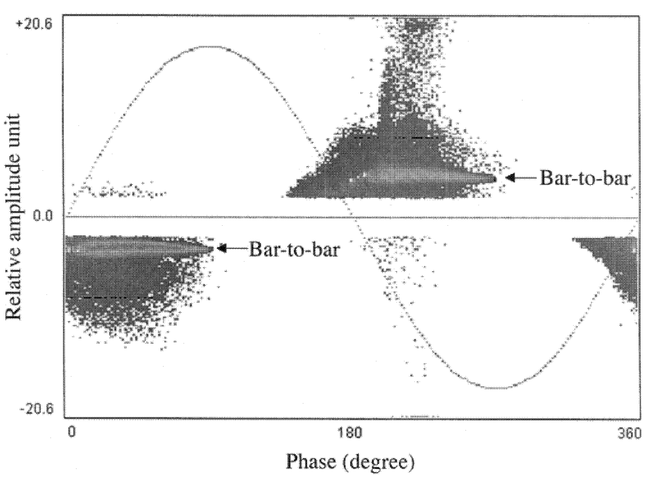

Figure 22. PRPD pattern (40–800 kHz) of bar-to-bar activity, measured at 20 kV.

charge sites were showing deposit of white powder, which was a consequence of bar-to-bar discharge attack on the insulation, as shown in Figure 24.

3.1.4 DELAMINATION DISCHARGE ACTIVITY

Result from the coil modified in the laboratory as described above gave PRPD patterns that were symmetric at

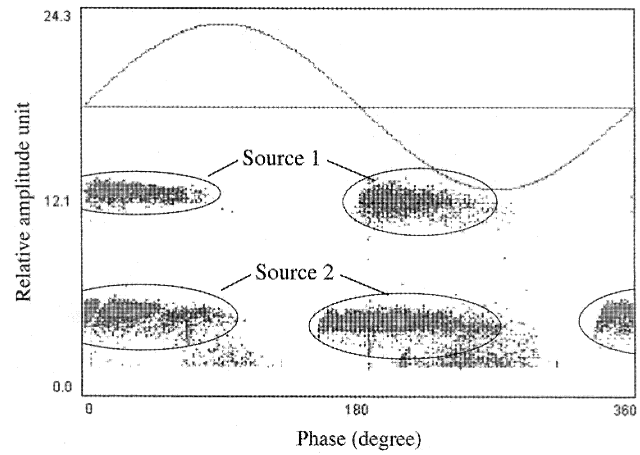

Figure 23. PRPD pattern (2–20 MHz) of bar-to-bar activity, measured on a 120 MVA / 13.8 kV generator.

Figure 24. Picture of bar-to-bar degradation products between end arms of the same plane, corresponding to the signature of Figure 23.

CIV and at voltages up to 6.4 kV. Above this voltage, some asymmetry in the pattern appeared to favor of negative discharges occurring during the positive half cycle of the voltage as depicted in Figure 25. The maximum amplitude of negative discharges was of 9.0 a.u, compare to 6.3 a.u. for positive discharges, for a $Q_{max}+/Q_{max}-$ ratio of 0.7, but the ratio $Nb+/Nb-$ is larger than unity, at 1.2, probably caused by another active source. It is suspected that at lower voltages only internal delamination between layers of tape was active. The CIV of the delamination at the interface with copper was higher because of the unusually large gap left by the full removal of the turn insulation.

Although a distinctive asymmetry was recorded for this type of defect, it disappeared after a short exposure time to high voltage. This behavior was possibly associated with the fact that the large contribution of the discharges within the delaminated ground-wall eventually dominated the pattern. A larger number of test specimens should be studied to establish the exact behavior of this discharge

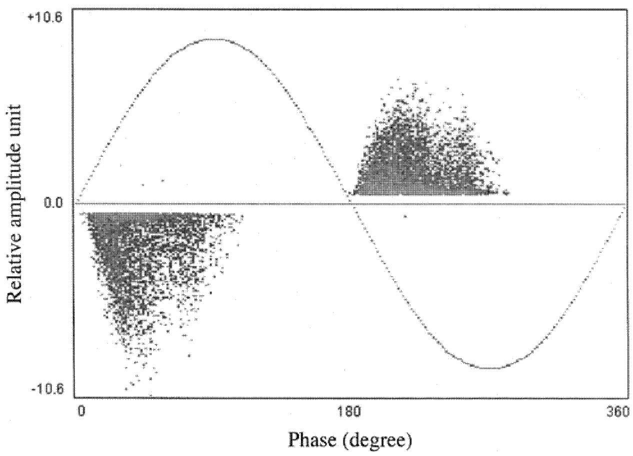

Figure 25. PRPD pattern from discharges at delamination between insulation and internal copper conductor.

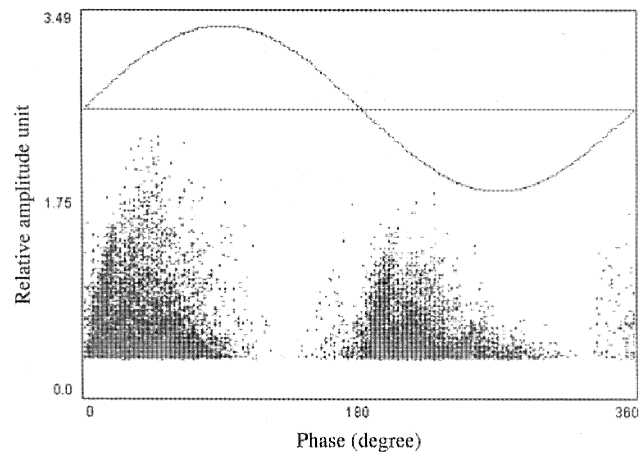

Figure 26. PRPD pattern (2–20 MHz) of delamination PD activity, measured on a 65 MVA/13.8 kV hydro generator.

source and its progression over time. For the time being, this specific signature is the only one showing the same asymmetry as the one observed on the generator from which the lab coils were extracted, as illustrated in the pattern of Figure 26.

This pattern was recorded only a few months before the unit was rewound. The observed asymmetry, in favor of negative discharges during the positive voltage half cycle, gave a positive Q_{max} of about 1.5 a.u., while the negative Q_{max} was of 2.2 a.u., for a ratio $Q_{max}+/Q_{max}-$ of 0.68. The ratio regarding the number of discharges (Nb+/Nb −) was similar with 0.7. These ratios reflect the expected asymmetry resulting from delamination. This asymmetry is of opposite polarity compared to the one of slot discharges, which gave ratios in the vicinity of 2.0. A ratio of positive to negative discharges smaller than unity suggests that discharges are occurring close to the high voltage conductor. The dissection of several coils extracted from this generator, showed significant delamination throughout the groundwall insulation, between the layers of tape, but also on the turn insulation directly in contact with the high voltage conductor.

3.2 SPECTRUM ANALYSIS

One advantage of using PRPD representation for the identification of the discharge sources is that the shape of each characteristic pattern is almost independent on the chosen measurement frequency. Depending on the selected frequency, either the source is detected or not. However, the measured amplitude will be very dependent on the choice of frequency. The same activity measured in different frequency ranges could result in differences in amplitude, as large as one order of magnitude. Signal calibration can somewhat compensate for this, but the correction or compensation will never be perfect. Moreover, the relative amplitude of two different sources can change dramatically over different frequency ranges. It is thus essential to have good understanding of the effect of the frequency range selected for measurement. For all lab measurements, but also for recording from every field measurement, frequency spectra were recorded to recognize the different types of discharges. The spectrum analyses presented below were measured using a single type of coupler. The resulting spectra are obviously affected in part by this choice, but always in the same way for all measurements. The results in the current section will clarify some questions with regard to expected frequency content as a function of the type of discharge activity.

It was found that specific discharge sources manifested over some specific frequency ranges. These ranges were the combination of the actual frequencies at the generation site, of the transfer function along the propagation path, and of the natural high pass response of the coupler used. The spectrum analyzer could be use to detect from 10 kHz up to 1.8 GHz at the detection point. For internal discharges measured in the lab on a single bar or portion of a bar, the PD pulses propagate along the end-arm directly out to the detection coupler. Because of the distributed capacitance of the straight portion of the bar, higher frequencies were more attenuated than the lower frequency components of the signal. A similar phenomenon occurs in generators, but when multiple bars are connected in series, the pulses from the first bar will be the ones giving the higher frequency content at the detection point and resulting in higher magnitude because of lower attenuation. Pulses coming from further down the phase winding will have a larger portion of the high frequency signal filtered due to a larger distributed capacitance. Thus, generator measurements will give, at best, conducted signals with maximum frequencies equal to, or lower than what was measured in the lab on single bar. The low pass response of a bar was responsible for the fact that internal discharges, detected at 8.0 kV, were in the lab always recorded at frequencies lower than 50 MHz, as depicted in Figure 27 (curve 1) for measurement on a single bar.

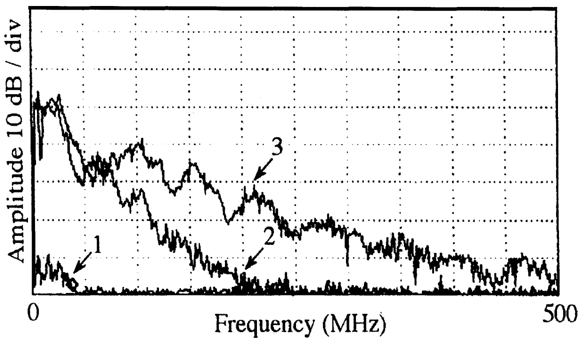

Figure 27. Typical frequency spectra of internal PD (1) at 8 kV, surface tracking (2) and corona discharges (3), both at 20 kV.

On generators, internal discharges occurring further from the detection point are expected to attenuate even more than what is reported here. On the contrary, external discharges signals were not restricted to conducted propagation along the stator bars and the high frequencies generated at the discharge site could irradiate in the air, out to the detection coupler. This supports the theory that two modes of propagation exist [14, 17, 18]: conducted signal and irradiated electro-magnetic signals. Because they were all external to the bar, and occurring in the air around it, all three types of end-winding defects generated intense electro-magnetic signals that were found to give rise to spectrum extending up to a few hundreds of megahertz, at the detection coupler. In the laboratory, it was generally observed that, out of the three end-winding defects, corona discharges at the grading junction gave signals of highest maximum frequency, reaching up to 500 MHz (see Figure 27, curve 3). On the contrary, signals from surface tracking were more limited in frequency, and normally did not exceed 250 MHz (see Figure 27, curve 2). Bar-to-bar discharges were much more variable, and their spectra were normally bounded by curves 2 and 3 in Figure 27.

Similar frequency spectra were recorded from bars installed in the core section. Figure 28 shows the frequency spectra for measurements with only internal PD activity (top trace), and with slot activity (bottom trace). Both spectra were recorded at 7.0 kV on the same bar, first without the slot defect and then, after the surface defect was made on the semi-conductive coating. The internal discharge activity, corresponding to the PRPD pattern of Figure 10, was only detected at frequencies lower than 35 MHz, which is comparable to the out of core measurement, while slot PD activity was detected up to 100 MHz. Compared with end-winding activity, the slot discharge gave smaller magnitude and stopped at lower frequencies. Even if slot activity can be detrimental to the integrity of the insulation, the resulting PD magnitude and frequency content are generally small compared to corona activity at the stress grading paint junction or surface tracking, which are less deleterious [19].

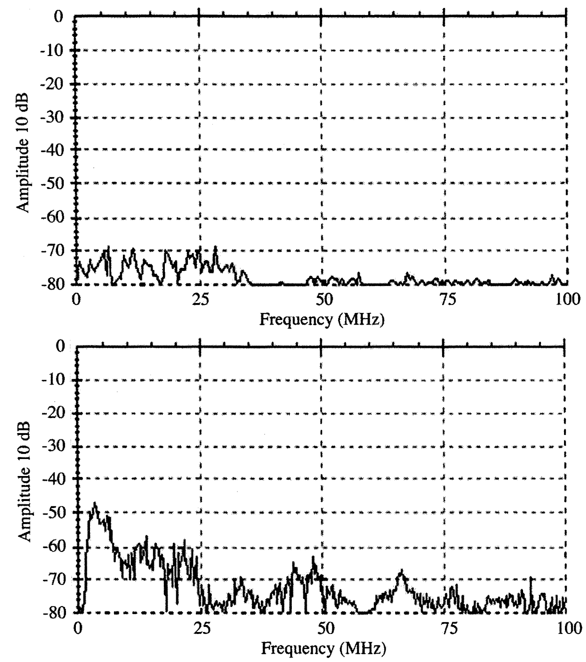

Figure 28. Frequency spectra of internal PD activity (top), and slot discharge activity (bottom), recorded at 7.0 kV from a bar in a stator core.

The frequency spectrum recorded in the laboratory closely match what was detected on generators throughout the years. The main difference in frequency ranges appears to be related to the propagation mechanism rather than to the frequencies generated during discharge manifestation. Conducted signals always give lower signal frequency at the detection point than signal propagating electro-magnetically. Moreover, as conducted signals propagate, they will further attenuate and this is always more pronounced for higher frequencies. On the contrary, irradiated signals attenuate less at higher frequencies and their amplitude at the detection coupler are more related to physical distance between this point and the discharge site and to intermediate objects than to its electrical position in the phase winding.

4 DISCUSSION

Partial discharge signal analysis with the PRPD representation is currently one of the most powerful methods to carry out discharge source recognition, even in cases where multiple sources are superimposed. For the untrained eye, these PRPD signatures are not easy to interpret. Even for experts, characteristic signatures are not easily associated with their generating sources. In this sense, the signatures are not absolute in nature, and they have to be translated or decoded with a proper database. We have presented herein the PRPD patterns for several types of discharge sources that were investigated over the last ten years in our laboratory. The diagnosis of partial discharges is not perfect and in some cases two distinctive sources could give similar patterns, but based on what was presented above, the authors believe that this is the exception rather than the general rule.

This laboratory investigation has allowed us to make specific association of known discharge sources with their corresponding PRPD patterns. In some cases, such as for internal discharges, our PRPD identification corroborates results reported by others namely with regard to the symmetry of pulse amplitudes during both voltage half cycles [15, 16, 23]. In other cases, such as for slot PD, the asymmetry in discharge polarity reported here has been observed in the past by others using a RA approach [16, 23]. However, as it was shown here the use of discharge polarity alone can lead to misinterpretation. The PRPD has proven to be a much more reliable tool as it offers one additional dimension in its representation which can be used to do signature shape recognition. In the current document all forms of recognition were done by a human expert, but once this association can be achieved with a high degree of confidence, and only then, will it be possible to come up with an adequate automatic recognition process. Such work has already given promising results [13, 24–27].

Asymmetry in the PRPD pattern of slot discharges has also been reported by others [23, 28–31], but in some cases these identifications were only based on circumstantial evidence. For instance, when the specific asymmetry of slot PD is observed in the pattern from a generator, this generator can only be suspected to suffer from slot PD activity. This identification alone is not yet sufficient to plan a rewind or even corrective actions. Nevertheless, this information can be used to target the small percentage of generators potentially affected by slot PD and perform on them additional tests to evaluate the extent of the degradation. Since these tests, normally being performed off-line, are now done on a limited number of machines the availability of generation is maximized. Amongst possible corroborating tests, bars selected with electromagnetic sensor or based on *in-situ* armor coating resistivity measurements, can be removed from the generator. If they show the characteristic formation of a ladder of white powder on their side, the probability is high that slot PD was causing the recorded pattern asymmetry, but was slot PD active at the time of the measurements or was the recorded pattern associated with another active source meaning that the surface damage dated from a prior epoch? In order to eliminate such uncertainty, laboratory simulation had to be performed individually for every studied defect. In the lab, it was possible to increase or reduce the voltage at will in order to trigger or to quench a specific discharge activity. Under such conditions, the UV camera, acoustic detection and audible sound were used to match the presence of a source with its formation on the recorded PRPD pattern. It is only under such conditions that it becomes possible to effectively associate

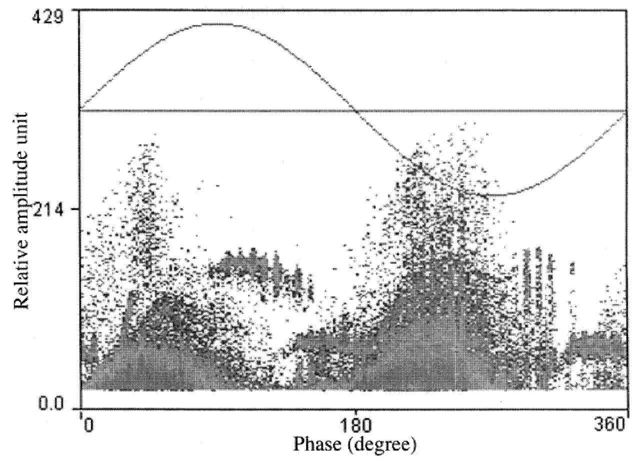

Figure 29. Complex PRPD pattern (2–20 MHz range) from a turbo-generator showing multiple discharge sources.

specific patterns with their source. A lab experiment on slot PD by Zondervan et al. [31] and similar to ours, has revealed identical asymmetry with a typical triangular shape pattern during the negative voltage half cycle. Usually such associations are not straightforward and a simple PRPD measurement on a generator may reveal a characteristic feature, which can only be linked to its source by means of a proper recognition database.

In addition to internal and slot PD, it has also been reported in the past that discharges attributed to delamination of the groundwall insulation on the conductor gives rise to some asymmetry when comparing pulses of different polarity, but this asymmetry being of opposite polarity to the one for slot discharges [23, 28]. In the past, delamination was identified by means of a two dimensional RA representation [16] and evidence of delamination using a PRPD representation has seldom been reported. Some exceptions are the ones presented by Warren et al. [23] and Stone et al. [28] which revealed, as was the case for us, that the asymmetry associated with delamination of the insulation on the copper strands is much less pronounced than what is generally found for slot discharges. The asymmetry of opposite polarity was expected because here the gap was against the high voltage electrode, but one explanation for observing only minor asymmetry for delamination, is that usually delamination at the copper strands does not come alone. It is generally accompanied by internal delamination within the groundwall insulation. It was observed that such internal delamination does not usually give rise to asymmetry in the discharge pattern as was also reported independently by others [30, 32], but it does however contribute significantly to the overall pattern reducing the asymmetry from the contribution of the discharges against the inner conductor. The discharges occurring within the delaminated tape are subjected to symmetrical field conditions, because both sides of internal voids are bounded by insulating surfaces. This is why

PD at this location are more similar to internal PD than to PD in delamination with the conductor.

In the case of surface tracking, like with discharge from delamination, an asymmetric pulses are also associated with larger negative discharges, but the shape of the signatures is completely different when comparing their PRPD patterns. For those two sources, the RA representation could be sufficient to recognize each source because of these differences.

Discharge occurring around the junction of the field grading system gave asymmetry in the pattern, which were similar to those of slot PD on a two-dimensional RA representation, but were different in the PRPD pattern. This type of activity was not triangular in shape. It was much more rounded at the onset of the pattern during the negative half cycle of the voltage. However, as depicted in Table III, the ratios of positive/negative discharges could be very large or close to unity. It was found that as voltage was increased much above the CIV, the pattern tended to become more symmetric. Thus, for this particular source, asymmetry can suggest the presence of corona at the junction of the grading system, but the absence of asymmetry does not necessarily imply the absence of discharges at the junction. Results from a similar laboratory simulation has revealed the same asymmetry as the one presented herein [31], but the patterns recorded by Zondervan et al. did not have identical shape to ours. Under some conditions their PRPD pattern even had more than one hump. These differences should be further investigated. When there is no asymmetry in the pattern, the frequency at which the measurement is made can also be helpful in identifying this source, because external corona at the junction will propagate electro magnetically at higher frequencies than conducted signal.

The bar-to-bar type discharges simulated in our lab were typical of a large gap discharging in the air. The characteristic patterns presented above and consisting of equal magnitude clusters are often detected on generators but also on other high voltage apparatus. The main feature of this pattern is that discharges are occurring at almost constant amplitude and always over the same voltage phase angle. Such PRPD patterns have been observed in the past to be caused by metallic parts at floating potential discharging periodically and completely to ground as reported by Gross [9]. Our experience is that bar-to-bar discharges between planes of top and bottom bars or in the same plane, give exactly the same signature of clusters at almost constant amplitudes. This confirms the results of Stone et al. [28]. Sometimes, when more than one gap spacing exists, several clusters can be observed at different amplitude levels. In addition to bar-to-bar discharges, Gross has also reported that strong discharges between the side of a bar and the stator pressure finger of a generator, can lead to a similar pattern [9]. As mentioned earlier, it is possible that different types of discharge sources may lead to similar PRPD patterns but every identification should be validated. Previously the same author had reported that an almost identical signature was caused by slot discharges [21]. In order not to discredit the field of PD diagnosis what should be avoided more than everything, is that everyone makes different contradictory claims all stated as the unqualified truth, only resulting in confusion for non-experts. From what we have seen in the lab, slot discharges, perhaps because of the small gap size involved, never resulted in PRPD patterns with equal magnitude clusters, such as those associated with larger gaps. This does not mean that the association of horizontal cluster, on the PRPD pattern, to slot discharges is incorrect, but it should be validated under well-controlled conditions. At some point, every expert should work to reach a general agreement as to the specific PRPD pattern association with their corresponding source.

Discharges between the side of the bar and the pressure finger have recently been associated with a generator failure at Hydro-Québec. Discharge measurements made prior to the failure had revealed the presence of equal magnitude clusters in the PRPD representation (see Figure 30 top) and visual observation made during the post mortem inspection confirmed the presence of degradation products at this location (see Figure 30 bottom). Because this circumstantial evidence was corroborating the previ-

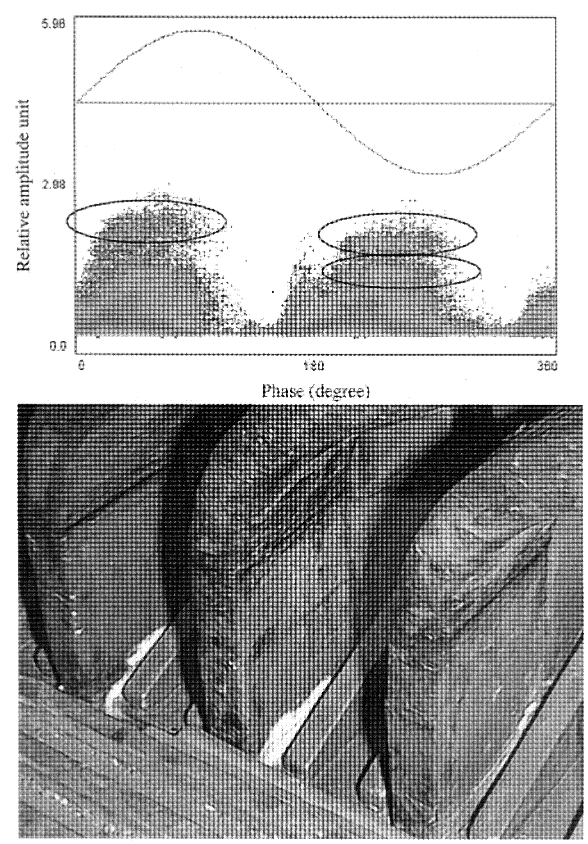

Figure 30. PRPD pattern of large gap discharges (top) and the corresponding degradation products (bottom).

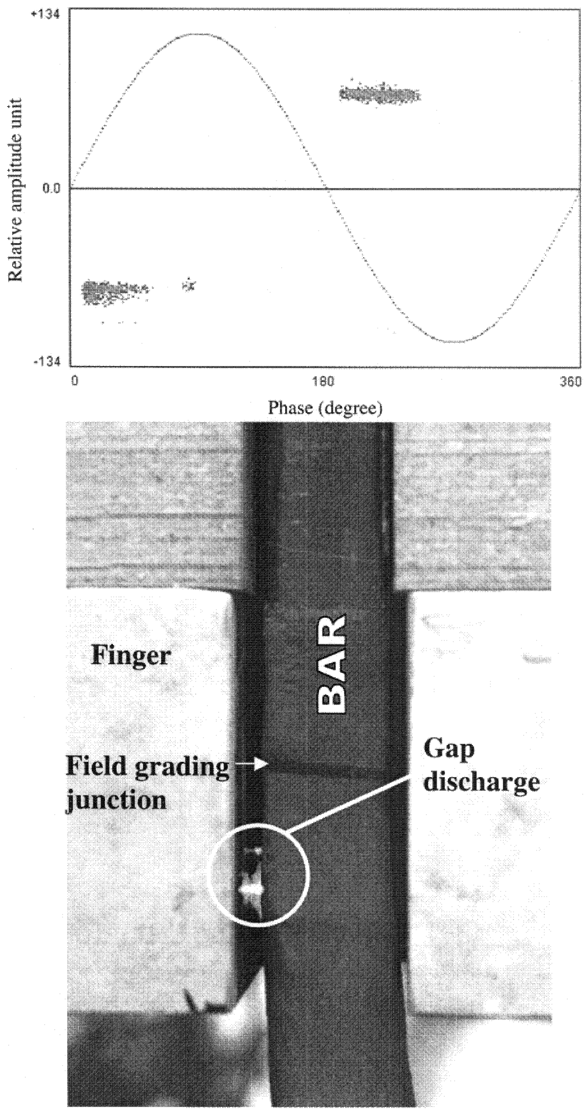

Figure 31. PRPD pattern of gap discharges to the pressure finger (top) and the corresponding visual manifestation (bottom).

ous hypothesis of Gross, a modification was made to our laboratory setup in order to reproduce similar discharges between the side of a bar and the pressure finger. The laboratory simulation did in fact show the clear formation of horizontal clusters on the PRPD pattern and a visual observation with the UV camera confirmed that this activity was in fact occurring between the side of the bar and the finger. This evidence is depicted in Figure 31, showing a picture of the discharge manifestation and the corresponding PRPD pattern. It appears that this equal magnitude cluster formation is more characteristic of the air gap size and to the local field conditions in the gas, than it is to the type of surfaces on each side of the gap (insulating, grading or conductive). Even when the similarity of such a pattern for different discharge sources cannot be resolved by PD measurements alone, the identification can at least point out to areas of the generator where complementary tests or visual inspection can be used to resolve the issue.

All the results presented herein form the preliminary PRPD database, which is use at Hydro-Quebec to carry out adequate on-line diagnosis of problems that may affect its generators. All the patterns currently recognized are summarized in Figure 32. More than 90% of Hydro-Quebec's generators are in good condition and detailed diagnosis or preventive inspections are, in most cases, unnecessary. For the rest of them, PD measurements are a preliminary step used to plan the need for further investigation or testing and eventually the need for maintenance. However, an even greater task awaits us, because recognizing the discharge sources is only the first step. Our research team is now working on determining the rate of change for every one of these sources, for which individual critical limits will have to be established. This obviously will bring up the contentious issue of calibration and quantification. One of the most important things before starting to evaluate these rates of change and possibly changes in the shapes of the patterns with degradation, was to make sure that a specific pattern was in fact associated with the studied source. As it was shown, in some cases a characteristic PRPD pattern (such as an equal magnitude cluster) could be attributed to more than a single source. It is suspected that other types of sources could give similar pattern redundancy and although our database is not yet perfect, it serves as a basis to support diagnostic specialists with their PD identification. We hope that with time this database can evolve with other contributions, confirmation and refinement to make it a tool that can benefit all diagnostic specialists in their work.

In addition to the PRPD analysis, it was observed that it is of primary importance to understand the process of signal propagation and attenuation at different frequencies if ones wants to compare PD results with those of others because the selection of the frequency range for the measurement will have a major impact on the discharge sources detected. The signal detected is greatly affected by the bandwidth of the detection equipment of which the coupler is one component. Detection at high frequency will tend to favor external discharges, which are not necessarily the most dangerous ones. At lower frequencies, the detection may be affected by the presence of noise which can in some cases be large enough to impede detection of the PD signal. Although of importance, the subject of noise discrimination exceeds the scope of our investigation and the reader is referred to other publications treating this problem in detail [10, 11, 20, 21]. Usually, the choice of frequency does not alter very much the shape of the PRPD pattern or of distinctive asymmetry, but it will have a significant impact on the detected amplitudes. Moreover, in some frequency ranges some discharge sources may remain undetected. For instance, internal discharges give no or very little signal at frequen-

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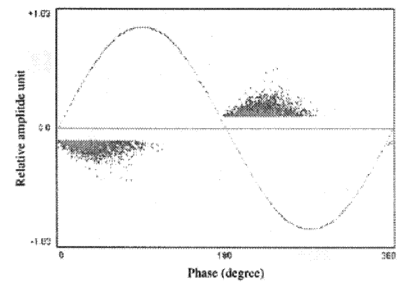
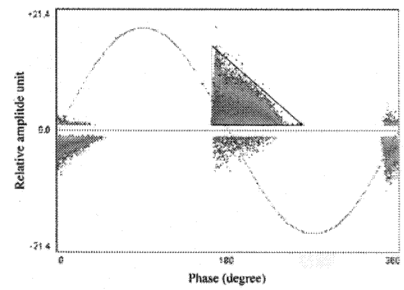
<table>
<tr><td>Internal discharges</td><td>
</td></tr>
<tr><td>Slot discharges</td><td>
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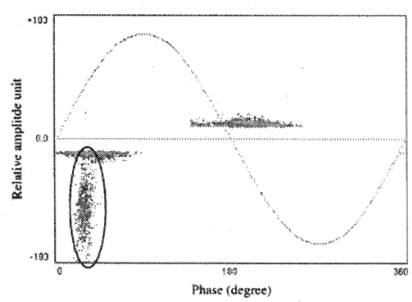
<tr><td>Surface tracking</td><td>
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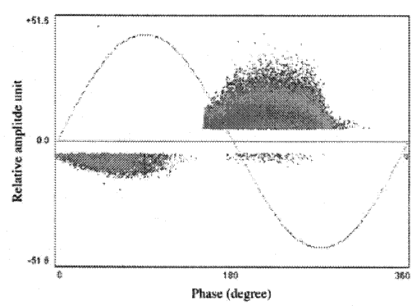
<tr><td>Corona discharges at the field grading junction with semi-conductive coating</td><td>
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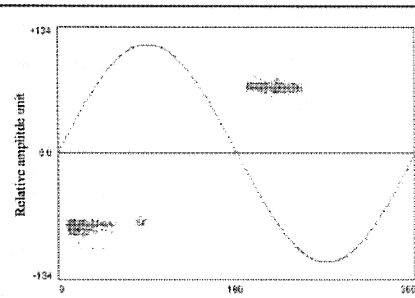
<tr><td>Gap type discharges Between bars or between a bar and the pressure finger of the core</td><td>
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Figure 32. Current database developed by Hydro-Quebec for PRPD shape recognition.

cies above 50 megahertz. Based on our experience this was true for all purely conducted signals. Another problem often manifesting while performing PD measurements on generators is the superposition of multiple sources. Using different measurement frequencies, in conjunction with the PRPD approach, can help to identify all sources present. In specific frequency ranges, such as 2−20 MHz, the pattern can be complex as shown in Figure 29 where multiple discharge sources were detected simultaneously on one of Hydro-Québec's turbo-generators. In this specific case, continuous PD monitoring over a two months period revealed that under different operating conditions not all sources were constantly present. It was thus easier to sort out individual contribution [22]. However, PRPD performed at different frequencies could also help to sort out conducted signals from signals external to the core, which mainly propagate electromagnetic radiation. The use of a combination of PD measurement tools can significantly enhance source identification, but one has to have an in depth knowledge of discharge processes to know which combination may give the best results. For example, for untrained personal it would be impossible to determine the cause of each source that resulted in the pattern in Figure 29, or even to separate the different contributions. It should also be pointed out that the analysis of such a pattern with the two-dimensional RA approach would make it impossible to give an acceptable diagnosis. Warren et al. [23] also recognized the limitation of the two-dimensional RA approach when dealing with complex patterns.

Another difficult task of PD analysis is to identify all sources present specially when larger signals mask smaller ones. For example, if large discharges associated with surface tracking are recorded without signal saturation, smaller slot discharges can be missed, if they fall below the lower level discriminator of the instrument. The best option to give a proper diagnosis would be to carry out measurements with different gain settings in every frequency range to get the best recognition capability possible, but this is clearly time consuming. Thus, the selection of a few gain settings and a few selected frequency ranges can offer sufficient information to recognize and evaluate both conducted signals and electro-magnetically radiated signals. Spectrum analysis is a good complementary approach, but it is more limited than PRPD analysis when it comes time to recognize the origin of discharge sources.

5 CONCLUSION

AN extensive investigation was made in the laboratory in order to determine, under well-controlled conditions, the exact PRPD patterns of several types of discharge sources. It was shown that the use of this preliminary database of PRPD patterns already serves to allow a better diagnosis of the generator with minimal impact on operation because it can be carried out on-line.

Our work has demonstrated the usefulness and the strength of the phase resolved representation compared to other types of analyses when carrying out discharge source recognition. To our knowledge this is the most general PRPD database published yet and although some of the discharge parameters associated with specific sources presented herein, corroborate what others have found, some new characteristic features have been published here for the first time. In other instances, differences with what was found in the literature would deserve further investigation. Some explanation for these differences were proposed to clarify why direct quantitative comparison of PD results is not always a straightforward task. However, the association of a specific PRPD signature with its source should be well defined and independent of the measurement equipment. Thus, based on solid evidence every expert should contribute to improve what has been presented here so that a more generally accepted PRPD database can be adopted. The current investigation will now have to be complemented with additional source identification, but more importantly with a detailed investigation of the changes in pattern shape with degradation of the insulation and finally by setting sets of critical limits or rates of change for each discharge source.

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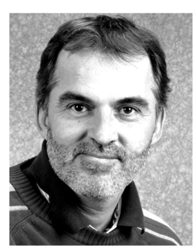
Claude Hudon was born in Montreal, Canada on 21 December 1963. He received the Ph.D. degree in engineering physics from École Polytechnique de Montréal in 1993. He has worked for two years at the Corporate Research and Development center of General Electric, after which he joined the Research Institute of Hydro-Québec "IREQ", where he is now employed as a senior researcher. His fields of interest are generators and motors diagnostics, the development of diagnostic tools and the measurement and analysis of partial discharges. He is the author of about 40 scientific papers.



Mario Bélec was born in Ste-Anne-du-Lac, Québec, Canada on 20 March 1962. He received the B.Ing. degree in electrical engineering from École Polytechnique de Montréal in 1987. He joined the Research Institute of Hydro-Québec "IREQ" in 1987 as a researcher. He is a generator diagnostic specialist, and has been involved in partial discharge recognition activity, and development of new diagnostic tools and correction methods for high voltage rotating machines. He is the author of more than 30 scientific papers.