Title: **Understanding ozone distribution inside stator core and measurements inside air-cooled generators to assess partial discharges problems**

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It is well known that electrical discharges in air produce ozone. High ozone concentration in air-cooled generators has been reported in a number of high voltage generators and was always associated with the presence of partial discharges (PD), most often slot discharges. In addition, this highly aggressive gas may chemically attack the semi-conductive coating and subsequently ground insulation, as well as exposed metallic or rubber components. However, its high reactivity and inherent instability, besides other physical factors such as air velocity, temperature or humidity, may intervene to favor the elimination of the ozone generated by PD.

Laboratory experiments were conducted in an effort to understand the distribution and behavior of ozone close to the stator winding and inside generator core. We have recorded ozone concentration profiles generated by artificially-made slot PD inside a small scale section of stator core, while varying air flow velocity. Finally, ozone measurements were performed with a truly portable UV-based ozone monitor on many electric generators in normal operation. In all cases where ozone was detected above ambient level, the presence of PD (mainly slot discharges) was correlated by PD measurements, and in one case by visual inspection. In one particular case, mapping the ozone concentration surrounding the stator core enabled us to pinpoint the source of a localized slot discharges activity within a very small section of the stator core. These results show that ozone measurements could be an interesting tool to detect and locate partial discharges on electric generators, for diagnostic purposes, during normal operation.

General facts about ozone

Ozone (O_3) is a gas which exists naturally in the upper atmosphere (stratosphere) where it is formed by irradiation of oxygen (O_2) by the UV rays of the sun. It is also found naturally at ground level, at concentrations of approximately 20-35 ppb (parts per billion), which constitutes the basic natural level apart from the great urban centers. The human activity can also generate ozone, particularly in urban environment, by chemical reaction between nitrogen oxides (NO_x) and some volatile organic compounds (VOC). Thus, it is the principal ingredient of the urban "smog" and a major element of the air quality index.

Electric discharges and intense UV radiation have sufficient energy to transform the oxygen into ozone. It is for example what explains the characteristic odor and the tingling that one immediately feels after a violent thunderstorm. Electric motors or generators are also potential sources of ozone when partial discharges (PD) occur. When it happens, we have the following reaction:

$$O_2 + e^- \rightarrow 2O^*$$

followed by $$O^* + O_2 \rightarrow O_3$$

However, this molecule is relatively unstable with an intrinsic half-life of a few days and will return naturally to its original oxygen form after a certain time by the opposite reaction

$$O_3 \rightarrow O_2 + O^*$$

In ambient air, we are thus naturally in the presence of following equilibrium:

$$3\ O_2 + e^- \leftrightarrow 2O_3$$

As ozone is one of the most oxidizing powerful reagents, the presence of certain oxidizable materials (ferrous metal, polymeric materials, etc) can catalyze the reaction of destruction and favors the decrease of the ozone concentration. Reactions with different contaminants in air also consume ozone by oxidation reaction. It was also reported that the temperature and moisture can facilitate this reaction.[1] In practice, the half-life of indoor ozone is usually less than 30 minutes. It is what explains why the ozone levels inside buildings where no ozone is produced are normally lower than the natural content measured outdoor. Typically, indoor background ozone levels range from 5 to 20 ppb.

Reported cases of ozone in generators from the literature

Some authors have reported the presence of ozone in generators of hydroelectric power stations. Among these, the worst case we have seen was reported at the Davis Dam power plant in Colorado,[2] where the ozone level was so acute that a blue haze was reportedly visible in the generator room. Generator #2 was identified as the source of the problem and measurements taken inside the enclosure showed a steady-state ozone concentration of 40 ppm (40 000 ppb). They were able to reduce it to 2 ppm by recirculating enclosure air through a 230 m^3/min (8100 ft^3/min) carbon filtration system. Visual inspection revealed widespread deterioration of the stator winding semi-conductive slot paint. Substantial corrosion of ferrous parts and deterioration of rubber components, caused by high ozone attack, were also reported.

In Central Europe, the measurements of ozone made over a 3-years period showed an upward trend on a generator which, after measurements of partial discharges and a visual inspection, revealed problems of corona discharges at the junction of semi-conductive coating and stress grading paint.[1]

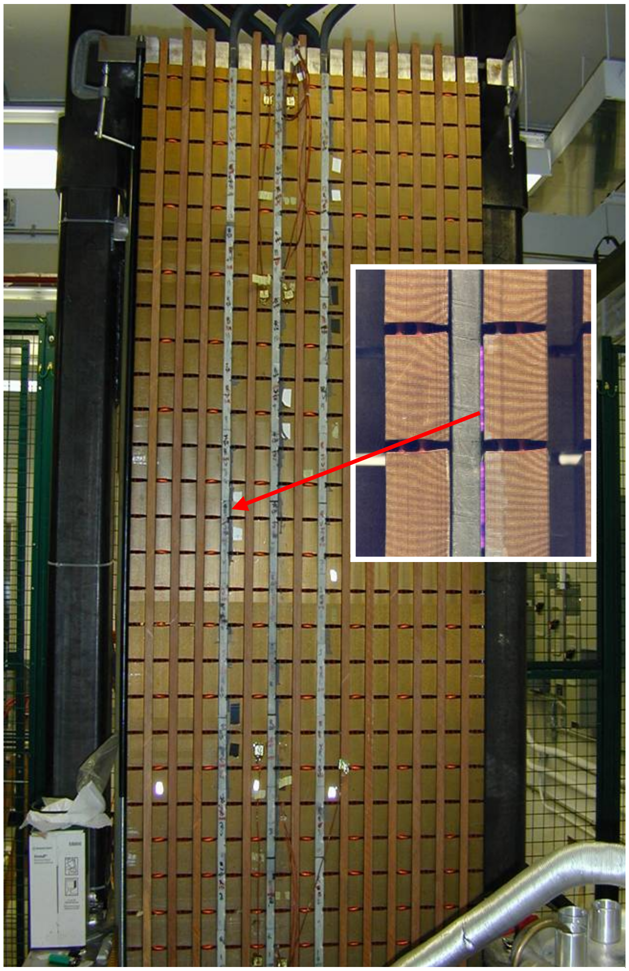
Measurements taken in March 1993 at Peace Canyon generating station, in British Columbia, Canada, as part of a CEA research project,[3] show ozone levels varying from 100 to 500 ppb inside the generator enclosure of the four generators. Accelerated corrosion and deterioration of rubber and polymer o-rings were also reported. These generators have been running under high ozone for many years and are just undergoing a winding replacement program of one machine per year which started in 2006.

In Hydro-Quebec power plants, ozone concentration from 30 to 60 ppb were measured in 2002 at the louvres exhaust of six air-cooled 48MW generators of one power plant for which the presence of partial discharges had already been diagnosed in one of them.[5] Recent measurements in 2007 showed that the ozone level has more than double the 2002 values in all of these cases, indicating an evolution of the partial discharges activity.

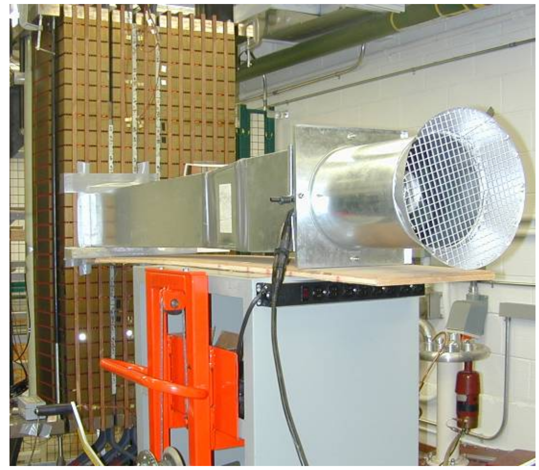
Experimental laboratory work

We have used in our laboratory a scale model of stator core to study the distribution profile of ozone, inside and at the exit of a ventilation duct, in the presence of a slot partial discharges activity. The discharge defect was created by removing the semi-conducting coating on one side of a bar, over the length of two consecutive core stackings. This bar was placed in the front position into the slot. Figure 1a) shows the section of stator core, composed of a full-height stacking core, with an enlarged picture of the slot discharges activity taken with a long time exposure.

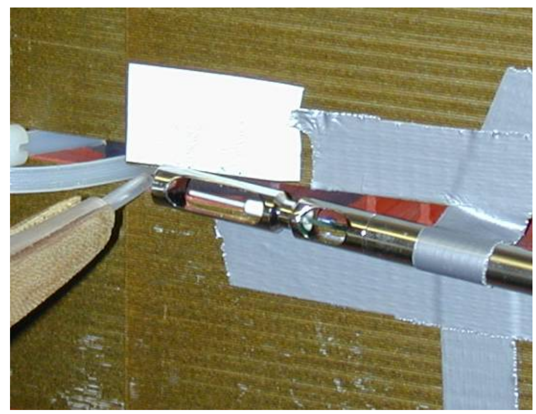
Figure 1b) shows the linear-flow blower placed in front of the stacking exactly at the discharges level. Figure 1c) shows the back of the stacking with the heated mass flow sensor used to measure air flow velocity coming out of the ventilation duct. It also shows the Teflon 1/8" sampling tube at the ventilation duct exit. This tube was inserted inside the ventilation channel located in the middle of the two stackings at the default location.



a) Slot discharge



b) Linear-flow blower



c) Back view: flow sensor and sampling tube

Figure 1: Stator section scale model.

Ozone measurements are made by an API 400A UV-based ozone monitor, connected at the other end of the sampling tube. A phenolic guide is also used to move the tubing linearly at the back of the duct, to acquire the ozone profile coming out of the duct.

Figure 2 shows the profile recorded inside the ventilation channel in a static mode, without ventilation, with 8kV and 12 kV applied to the bar. As expected, the maximum concentration of ozone is recorded right next to the discharges source. It then decreases although very slowly as we move behind the bars inside the duct. Finally, it drops very rapidly as we approach the channel end, and no significant ozone is measured outside the stator core. Similar profiles were recorded at the two voltage levels, with the 12kV experiment generating slightly more ozone.

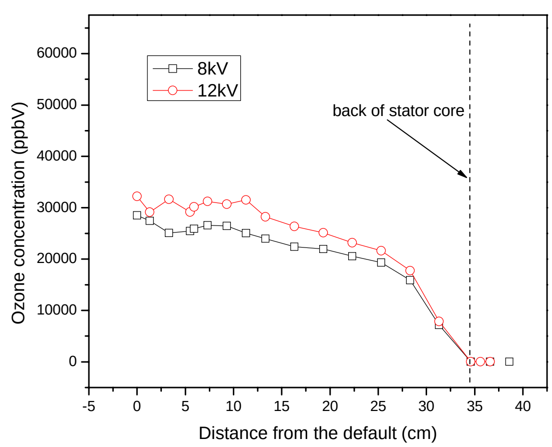


Figure 2: Ozone profile inside and out of the stator core without ventilation.

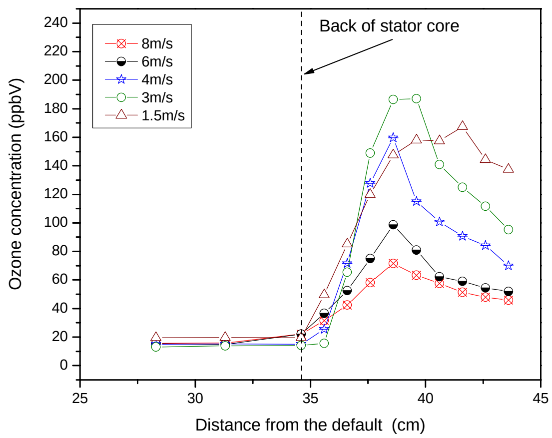


Figure 3: Ozone profile inside and out of the stator core at 8kV and varying air flow.

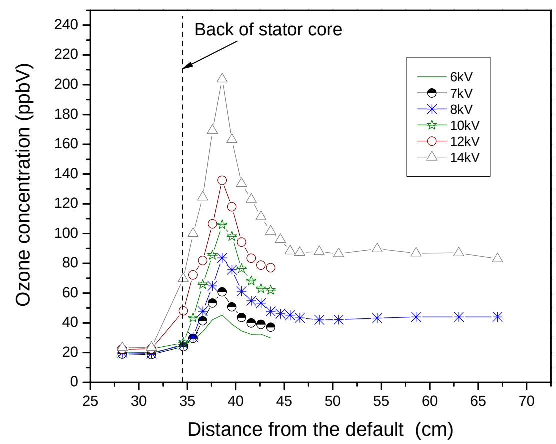


Figure 4: Ozone profile inside and out of the stator core with an 8m/s air flow and varying tension applied to the front bar.

The situation is completely different in presence of ventilation, as shown on Figure 3 and 4, where we vary respectively the air velocity and the voltage applied to the bar. At first, with a fixed 8kV applied to the bar (Figure 3), we observe that the ozone generated by the discharges is swept away by the ventilation towards the back of the stator and has its maximum at approximately 5 cm away from the core. Also, even at the lowest air speed of 1.5 m/s, the maximum concentration of ozone is 2 orders of magnitude lower than without ventilation. This maximum also decreases further as we increase the air speed.

If we fix the air speed at a typical value of 8 m/s and vary the voltage applied to the bar, we can see at first that the maximum concentration of ozone is obtained again at approximately 5 cm away from the stator core. As expected, the concentration of ozone coming out of the ventilation channel increases with the voltage applied to the bar (and of course the intensity of the partial discharges activity). Also, we can see from Figure 4 that the concentration of ozone tends to stabilize at distance greater than 12cm outside the core and stays constant as far as we could measure.

These results indicate that it should be possible to measure the ozone generated by slot partial discharges at some points behind the stator core, and that the amount of ozone should be indicative of the PD activity.

Ozone measuring instrument

The most commonly used ozone monitors are based on the UV absorption principle. They measure the absorption by ozone of a UV radiation at 254 nm which is governed by the Beer-Lambert law

$$\text{Absorbance} = \ln\left(I_0/I\right) = \varepsilon\,\ell\,C$$

where I and I_0 respectively represent the intensity of the light which crosses the measuring cell filled by the sample and that when the cell contains an ozone-free gas, ε is the molar extinction coefficient specific to ozone, ℓ the optical length of the measuring cell and C the concentration. For a given system, ε and ℓ are constant and the concentration is directly proportional to the measured absorbance. An absolute measurement is thus obtained, which to some extent does not require standards calibration. This measurement is however dependent on the temperature and pressure of the gas sample in the cell and measurements are generally corrected for these two parameters and reported at normal temperature and pressure (NTP), that is to say 20°C and one atmosphere.

These detectors offer a more than adequate detection limit of about 1 ppb with a precision generally better than ±2%.

Most commercially available ozone monitors are mainly used for measurements of ozone in the urban environments and are designed for fixed stations. However, the company 2B Tech in Colorado [4] have introduced few years ago a truly portable UV ozone monitor that could be powered by a 12V battery. It was originally design for ozone profiling in the atmosphere. With its compact, lightweight and low power consumption, it is a truly portable and standalone UV-based ozone monitor.

We have used the 2B Tech ozone monitor, model 202, as a diagnostic tool for more than three years inside and around electric generators to measure ozone generated by partial discharges. The exact reading locations are specifically chosen for each generator considering its ventilation pattern and accessibility. The idea is to monitor cooling air as close as possible to the source of discharges which would be, in the case of slot discharges, directly at the back of the stator core. On generators with water coolers, the closest accessible spot in operation is generally behind those coolers.

Case study

We present here few examples of ozone monitoring on generators of two power plants operated by Alcan, which the latter was kind enough to give us access to their producing facilities located on the Saguenay River in Québec. One of them, Shipshaw, has eight 75 MW, 13.2 kV, water-cooled generators with coolers in the corners of the generator enclosure, as shown in Figure 5. Access to the stator core and the upstream side of the coolers is provided by access doors on the sides of the enclosure. Measurements on these generators were performed by fixing the end of the Teflon sampling tube in the center of each cooler, on the upstream side, with the instrument outside the enclosure. These sampling points are indicated on Figure 5 by numbers 1 to 8. The other plant, Isle Maligne, has 12 air-cooled 30 MW generators, shown on figure 6. In this case, the open architecture of the generator enabled us to take ozone reading through openings on the outside shell, directly behind the core stacking all around the machines. Measurements were performed in the middle ventilation opening, at each of the 36 section of the stator core (see the red arrow on Figure 6).

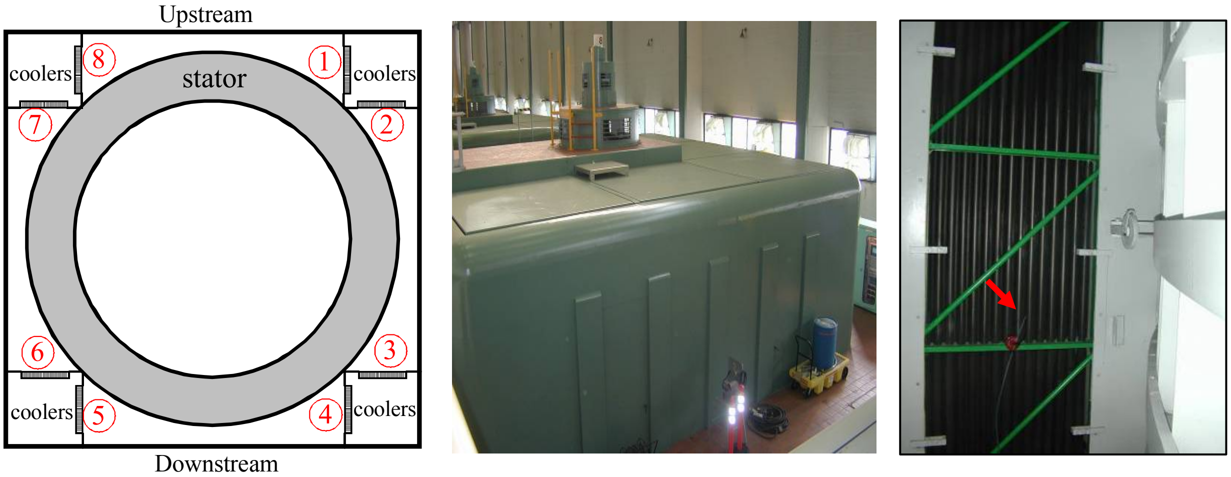


Figure 5: Ozone monitoring location inside Shipshaw generators enclosure.

Figure 6: Sampling location on Isle Maligne generators.

Figure 7 portrays the most interesting cases selected from these power plants investigation. The distribution of ozone data is shown in radial coordinates, each point representing a sector of the generator. The first case, Shipshaw unit 2, shows ambient ozone level at about 20 ppb, which does not indicate the presence of slot discharges. It is an example of what one can expect when no PD activity is active. Unit 5 from the same plant have slightly higher general ozone level in a non-uniform pattern, with a maximum in sector 1, and decreasing in sectors 2 to 4. This is indicative of slot discharges activity on this side of the generator, predominantly in sector 1. The last case from Shipshaw, unit 10, shows high ozone level on all of the coolers, with values between 60 and 90 ppb, the highest point being in sector 4. These data have been acquired twice and the two sets of data demonstrate a good reproducibility of results. Fortunately, a six month shutdown was scheduled on this unit few months later for the replacement of the waterwheel. With the ozone data in hand, plant personnel performed a visual inspection on the stator from the inner side and found evidence of white powder in different places around the machine, most predominantly in sector 4 where the ozone was the highest (see Figure 8).

The next three cases present generators from Isle Maligne power plant. Units 1 and 5 reveal ozone levels between 30 to 40 ppb all around the stator core, which is slightly above the expected ambient level. This is indicative of a low to moderate general PD activity. Although unit 1 has a somewhat symmetrical pattern, with the exception of one area, unit 5 presents significantly higher values in three distinct areas. The wiring diagram of this generator indicates that these specific areas contains the first bars of some parallel circuits of the three phases, which are at higher potential and most likely to generate partial discharges. Finally, unit 11 represents a very interesting case. The general value all around the generator is comparable to ambient ozone, between 20 to 30 ppb, with the exception of two consecutive openings (15 and 16) where ozone concentration jump to above 50 ppb. This location contains the first bars of one parallel circuit of the three phases, which again are the most likely to give slot PD because of their higher potential. This suggests that the winding on this unit is in good general condition, with the exception of a very localized default. This may be a case of loose or deficient wedge in only or few slots.

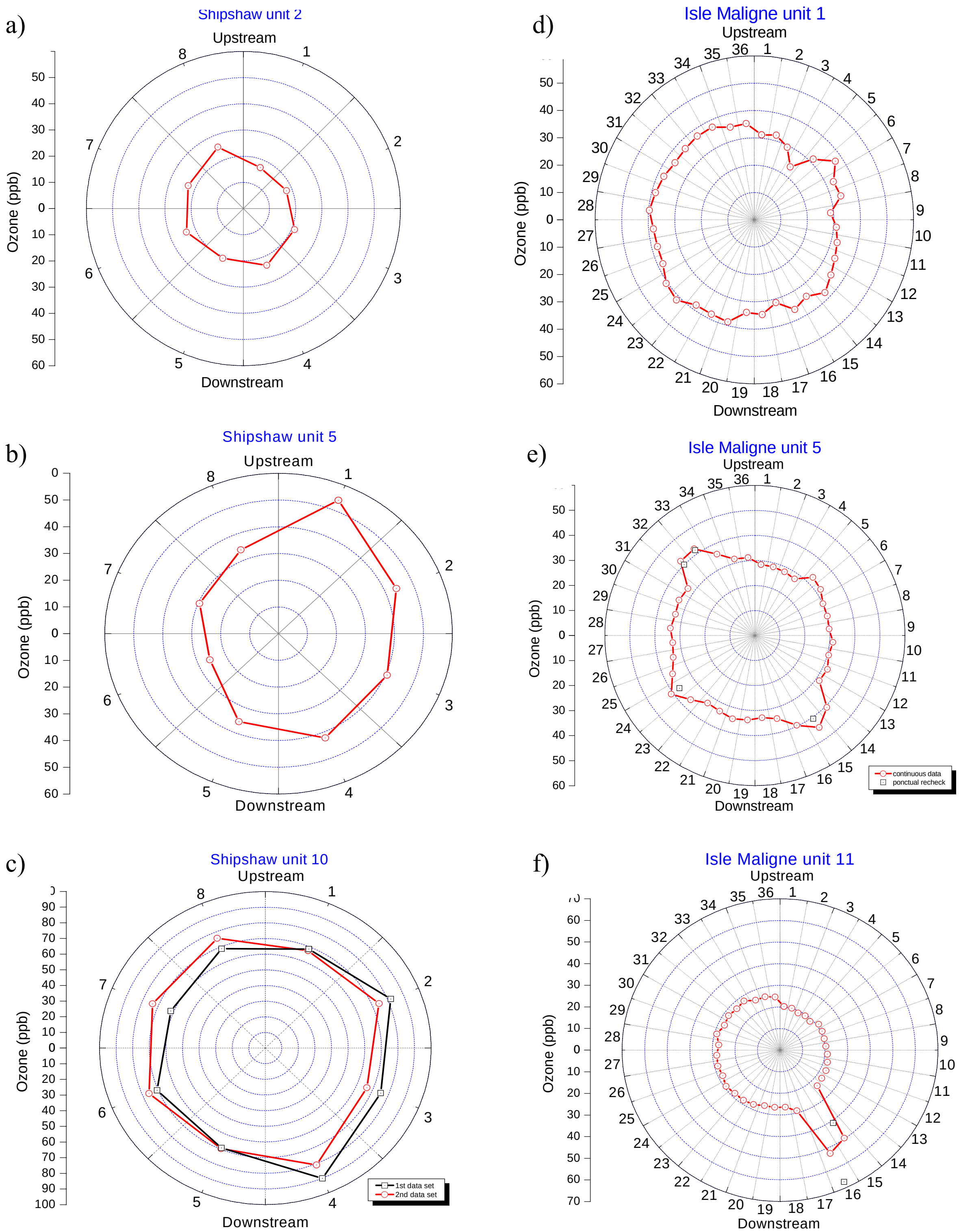


Figure 7: Examples of ozone distribution around generators.

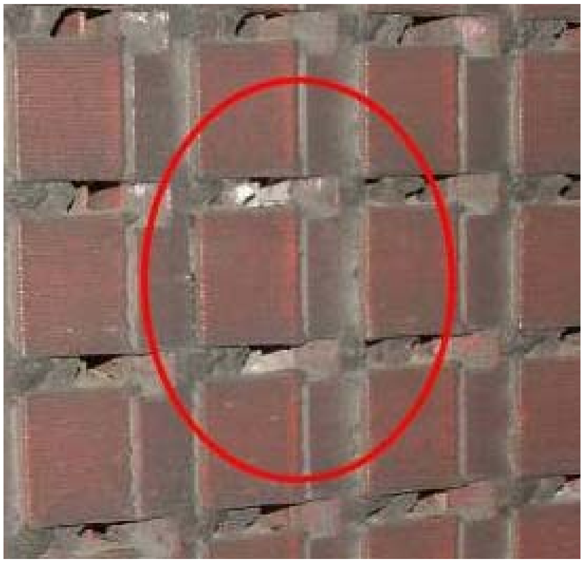


Figure 8: White powder from slot discharge, Shipshaw unit 10, position 5 o'clock.

PRPD measurements

In both power plants, permanent capacitive couplers are installed (6 per generator) so partial discharges measurements are possible. Phase Resolved Partial Discharges (PRPD) technique was chosen, because of its capability to recognize different PD sources. Measurements were performed on the six generators presented in Figure 7 to confirm the presence of PD activity and to identify the type of partial discharges that were active. As an example, Figure 9 illustrates the PRPD pattern recorded on generator #5 of Shipshaw power plant. This pattern is very characteristic of slot partial discharges activity, with an asymmetry in favor of positives discharges with regards of discharges amplitudes and also in the discharges count. Another feature of this PRPD pattern, which is typical of slot discharges activity, is the very sharp slope at the onset of the positive discharges pattern, during the negative half cycle of the voltage, combined with a triangular shape [6, 7].

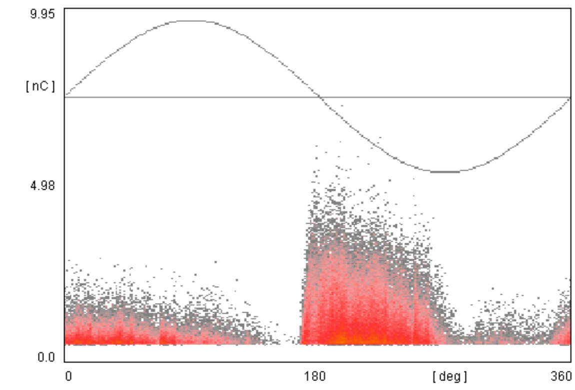


Figure 9 : PRPD pattern recorded on generator 5 of Shipshaw.

Results interpretation

The interpretation of the results obtained by Ozone and PRPD measurements at Shipshaw and Isle Maligne power plants are summarized in Table 1. It shows a very good correlation between the diagnostics obtained by these two completely different techniques on all of the six cases. For example, on Shipshaw unit 2, PRPD detected only a very small PD activity in one of the phase, while we did not measured any significant ozone produced. On the other end, unit 10 of the same power plant gave the highest level of ozone all around the generator while PRPD also detected a high incidence of slot discharges on all circuits. In this particular case, this diagnostic was also confirmed by visual inspection (Figure 8). Finally, the results on generator 11 of Isle Maligne demonstrate not only the correlation between the two techniques, but also their complementarity to identify the site of a localized default. By cross-referencing the electric circuit on which PRPD has detected the default with the specific location where the ozone was detected, one could narrow the search to only few selected slots. A limited inspection or measurements could be scheduled on these slots in a convenient time to find the problem, which could be easily corrected by semi-conductive paint or CRTV injection.

Table 1: Comparison of diagnostic by Ozone and PRPD

Plant	Unit	Ozone measurements	Partial discharges (PRPD) Type and importance	Diagnostic
Shipshaw	2	No significant ozone (ambient level). Symmetrical distribution.	Few slot PD on phase C. Weak gap discharges on phase A.	Slow degradation process at an early stage.
Shipshaw	5	Low-to-moderate ozone concentration. Most intense in sector 1, decreasing from sectors 2 to 4.	Important slot-PD on circuits A2, B2, C1, C2. Lower slot-PD on A1, B1. Less important Corona discharges on B1.	Relatively advanced degradation process on 4 of the 6 half-phases.
Shipshaw	10	Generalized moderate-to-high ozone level. Maximum on sector 4.	Numerous slot PD on all of the circuits. Weak corona activity possible.	Degradation process active on all circuits.
Isle Maligne	1	Low ozone concentration. Symmetrical distribution.	Important PD activity on phase B. Normal activity on phase A and C.	Important degradation, but limited to phase B.
Isle Maligne	5	Low-to-moderate ozone concentration. Asymmetrical, more intense in sectors 14-16, 24 et 32-33.	Corona discharges over the 3 phases. Moderate slot PD on C1, low on B2 and C2.	Moderate degradation in progress.
Isle Maligne	11	No significant ozone in general (ambient level). Moderate-to-high ozone locally in sectors 15-16.	High slot PD on A1. Low activities on phases B et C.	Important degradation in process but limited to a very localized area (half-phase A1, position 5h).

Conclusion

We have presented in this paper the direct relation between the presence of partial discharges, specifically slot discharges, and the production of ozone inside generators. While the ozone is produced inside the slot in the air gap surrounding the bar, the massive air flow blows it away at the back of the stator core through the ventilation ducts. The maximum concentration of ozone is measured outside the stator core, at the back of the stator.

Measurements of ozone on real generators in operation, as presented here in the cases studied, demonstrated a good correlation in the diagnostic given by this technique and PD monitoring through capacitive couplers. Moreover, it has shown in one particular case of a localized default, the complementarity of the two techniques to pinpoint the location of the default.

Consequently, ozone monitoring could be an interesting technique to detect slot-PD activity inside generators. This technique is simple, easy to perform in normal operation and requires no downtime of the generator. It can be very useful as a first line of diagnostic on generators where no capacitive couplers are installed.

Acknowledgements

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