Using Ozone Measurements to Diagnose Partial Discharge in Generators

When partial discharge occurs in electric motors or generators, the chemical reaction can produce ozone. Researchers from Canadian utility Hydro-Québec measured ozone in generators and then correlated the measurements with partial discharge activity. The higher the ozone, the greater the partial discharge. These results show that ozone measurement in generators can be a tool for pinpointing areas where partial discharge is occurring.

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In 2001, we set out to better understand the distribution and behavior of ozone close to the stator winding and inside the generator core, in order to correlate the production of ozone with the presence of partial discharge (PD). First, we performed laboratory work using a small-scale section of a stator core. We recorded profiles of ozone concentration generated by artificially-made slot PD. Second, we took ozone measurements on electric generators in working hydro facilities during normal operation. Then we performed measurements to identify PD activity.

In all cases where ozone was detected in concentrations greater than the ambient level, we correlated the presence of PD (mainly slot discharges). In one case, determining where the ozone concentration was greatest allowed us to pinpoint the source of the ozone from localized slot discharge activity within a small section of the stator core. Overall, these results show that ozone measurements can be a tool for detecting, locating, and estimating PD on electric generators during normal operation.

How ozone is produced

Ozone (O3) gas exists naturally in the upper atmosphere (stratosphere), where it is formed when the sun’s ultraviolet (UV) rays irradiate oxygen (O2). Naturally occurring electrical discharges (lightning) also can transform oxygen into ozone.

Ozone is found naturally at ground level, in concentrations of 20 to 35 parts per billion (ppb). Human activity also can generate ozone due to a chemical reaction between nitrogen oxides and some volatile organic compounds. Ozone is the principal ingredient of urban “smog” and is a major element of the air quality index.

Electric discharges have sufficient energy to transform oxygen into ozone. Consequently, electric motors or generators are potential sources of ozone when PD occurs. When this happens, the chemical reaction is:

O2 + e   -2O* + e-

The free radical O* then reacts with another oxygen molecule to give:

O* + O2 O3

Once formed, ozone is a relatively unstable molecule, with an intrinsic half-life of about three days.

Because ozone is one of the most powerful oxidizing agents, its reaction with certain oxidizable materials (e.g., ferrous metal and polymeric materials) favors the decrease of ozone concentration. Reactions with other contaminants in air also consume ozone through oxidation. Higher temperatures and moisture can facilitate these reactions[1]. The practical half-life of ozone indoors usually is less than 30 minutes, thus the ozone level inside buildings (where no ozone is produced) is typically 5 to 20 ppb.

There have been several reports regarding ozone in generators at hydroelectric stations. For example, at the 255-MW Davis Dam power plant in Arizona, the ozone level was so high that a blue haze was visible in the generator room[2]. The U.S. Department of the Interior's Bureau of Reclamation identified the Unit 2 generator as the source of the ozone. Measurements taken inside the enclosure for this generator showed a steady-state concentration of 40,000 ppb. Reclamation reduced the ozone level to 2,000 ppb by recirculating air in the enclosure through a carbon filtration system. Visual inspection of this generator revealed widespread deterioration of the stator winding semi-conductive slot paint. Substantial corrosion of ferrous parts and deterioration of rubber components also were reported.

In March 1993, ozone measurements were taken at Peace Canyon generating station in British Columbia, Canada, as part of a Canadian Electricity Association research project[3]. These measurements showed ozone levels of 100 to 500 ppb inside the enclosures of the four generators. Accelerated corrosion and deterioration of rubber and polymer O-rings also were reported. These generators have been running with high ozone levels for many years and are undergoing a complete stator replacement program of one generator per year, which began in 2006. When some of the bars were removed from the first generator to be refurbished, personnel discovered widespread deterioration of the semiconducting paint, causing slot discharge[4].

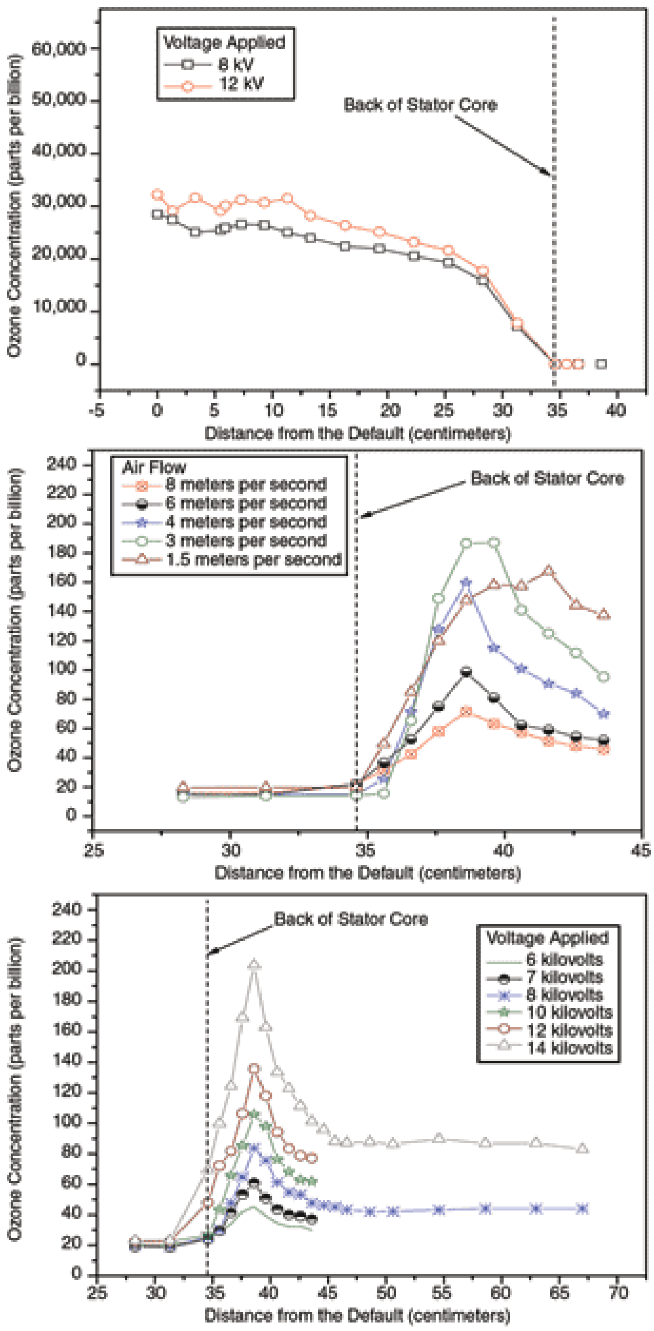

Figure 1: Profiles of ozone concentration were developed with no ventilation (top), with varying air flow at 8 kilovolts (middle), and with varying voltages at a constant air flow of 8 meters per second (bottom). Results show that ventilation moves ozone toward the back of the stator.

At one of Hydro-Québec's plants, ozone concentrations of 30 to 60 ppb were measured in 2002 at the exhaust louvres of six air-cooled 48-MW generators. The presence of PD already had been reported in at least one unit at this plant[5]. Measurements taken in 2007 showed that the ozone level has more than doubled since 2002, indicating an evolution of the PD activity.

Performing lab experiments

In our laboratory, we used a stator core mockup to study the distribution of ozone inside and at the exit of the ventilation ducts in the presence of slot PD activity. The mockup was composed of a full-height, 14-slot section of a stator core. The PD was created by removing the semi-conducting coating on one side of a bar, over the length of two consecutive core packets. This bar was placed in the front position in the slot.

We built a linear-flow blower and placed it in front of the core packets at the discharge level. At the back of the core, we used a model 8455 heated mass flow transducer from TSI to measure air flow velocity. We also inserted a 1/8-inch Teflon sampling tube at the ventilation duct exit. This tube was inserted inside the ventilation channel in the middle of the two packets at the fault location.

We performed ozone measurements using a model 400A UV-based ozone monitor from Teledyne API, connected at the end of the sampling tube. We used a phenolic guide to move the tubing linearly at the back of the stator, to acquire the ozone profile coming out of the duct. We performed measurements with two voltage levels applied to the bar, including some with the ventilation channel in a static mode (e.g., no forced ventilation) and others with ventilation.

The top image in Figure 1 shows the profile recorded inside the ventilation channel in a static mode with 8 kilovolts (kV) and 12 kV applied to the bar. As expected, the maximum ozone concentration is recorded right next to the discharge source. The level decreases, although very slowly, as sampling is performed behind the bars inside the duct. Finally, the level drops rapidly near the rear channel end, and no significant ozone is measured outside the stator core. The 12-kV experiment generated slightly more ozone.

The results are completely different with ventilation (see center image in Figure 1). Even at the lowest air speed of 1.5 meters per second, the maximum concentration of ozone is less than 180 ppb, compared with about 30,000 ppb in the static mode. This maximum concentration decreases further as air speed is increased. In addition, the voltage applied to the bar affects the ozone levels (see bottom image in Figure 1). With 8 kV applied to the bar, the ozone generated by the discharge is swept toward the back of the stator and is at its maximum about 5 centimeters from the core.

If air speed is 8 meters per second and voltage applied to the bar is varied, the maximum concentration of ozone is about 5 centimeters from the back of the stator core. As expected, the concentration of ozone coming out of the ventilation channel increases with the voltage applied (and of course the intensity of the PD activity). Also, the bottom image in Figure 1 shows that the ozone concentration tends to stabilize at a distance greater than 12 centimeters outside the core and stays constant thereafter.

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

Case studies at operating facilities

We have used 2B Technologies' model 202 ozone monitor for more than three years inside and around electric generators. It is a portable and stand-alone UV-based ozone monitor, powered by a 12-volt battery.

The exact measurement locations are specifically chosen for each generator considering its ventilation configuration and accessibility. The objective is to monitor the cooling air as close as possible to the source of discharge. In the case of slot discharges, this would be directly at the back of the stator core. On water-cooled generators, the closest accessible spot during operation is generally behind the coolers.

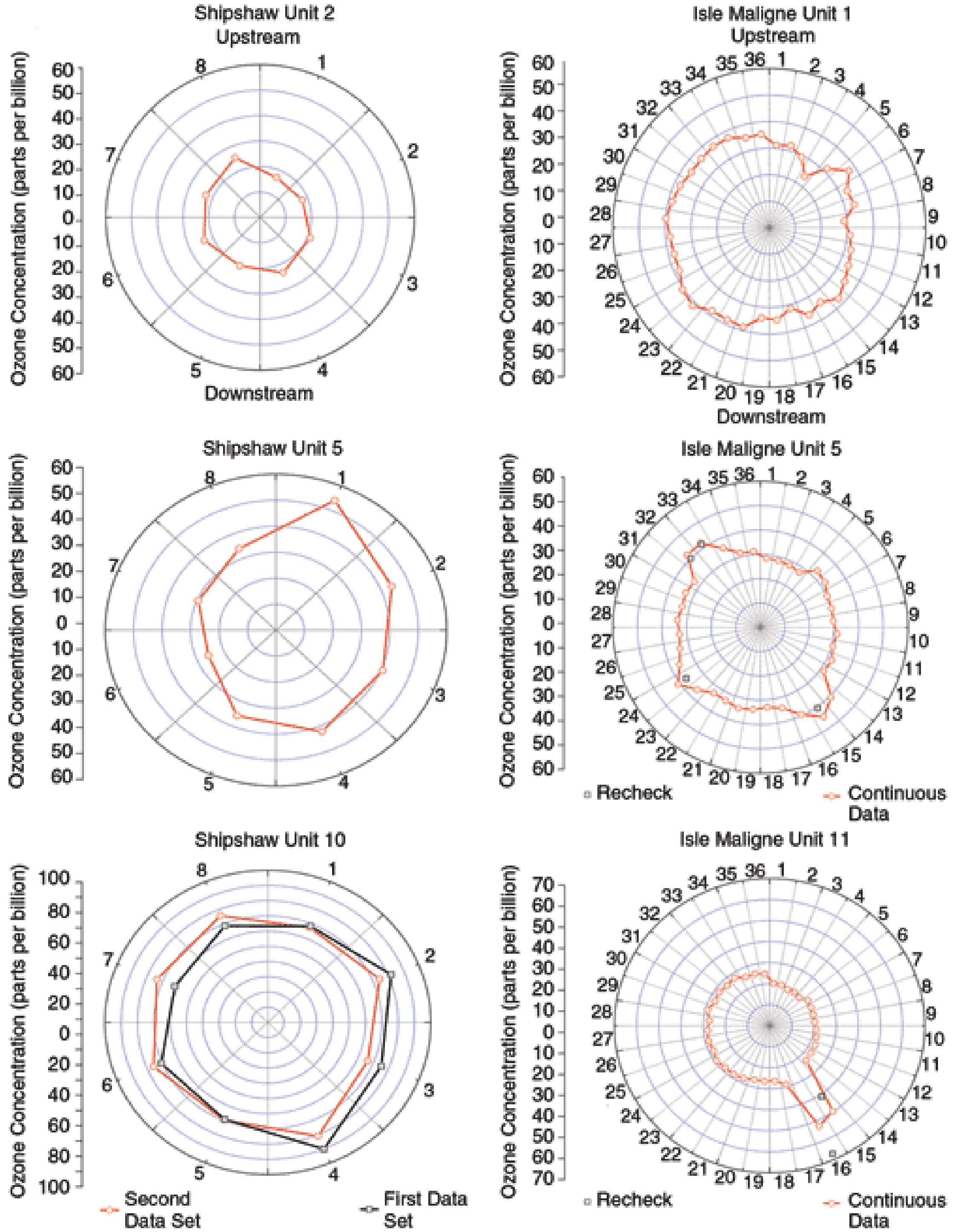

Figure 2: Ozone measurements from three units at Shipshaw and three at Isle Maligne are represented in radial coordinates. Unit 10 at Shipshaw (bottom left) and Unit 11 at Isle Maligne (bottom right) showed the most interesting results, with the former showing partial discharge activity distributed all around the stator and the latter representing a very localized default.

We performed ozone monitoring on generators at two hydro plants owned by Alcan on the Saguenay River in Québec. One of these facilities, Shipshaw, is equipped with 12 water-cooled, 75 MW, 13.2 kV generators with the coolers in the corners of the generator enclosure. Doors on the sides of the enclosure provide access to the stator core and the upstream side of the coolers.

Measurements were performed by fixing the end of the Teflon sampling tube in the center of each cooler, on the upstream side.

Another plant, Isle Maligne, is equipped with 12 air-cooled 30 MW generators. In this case, the open structure of the generator enabled us to take ozone reading through openings on the outside frame, directly behind the core all around the machines. Measurements were performed in the middle ventilation opening, at each of the 36 sections of the stator core.

Figure 2 shows the most interesting data from these investigations. The ozone distribution is shown in radial coordinates, each point representing a measuring point for the generator. The first case, Shipshaw Unit 2, shows an ambient ozone level of about 20 ppb, which is about what to expect when there is no PD. Shipshaw Unit 5 has a slightly higher general ozone level in a non-uniform pattern, with a maximum in sector 1, and decreasing from sectors 2 to 4. This indicates slot discharge activity on one side of the generator, predominantly in sector 1.

The third case is Shipshaw Unit 10. It shows high ozone levels on all of the coolers, with values of 60 to 90 ppb, the highest point being in sector 4. These data were acquired twice, and the two sets of data are very similar. Fortunately, a six-month shutdown was scheduled to replace the turbine runner a few months after the ozone measurement campaign. Plant personnel visually inspected the stator from the rotor side and found a white powder in different places around the stator, most predominantly in sector 4 where the ozone was the highest.

The next three cases are from Isle Maligne. Units 1 and 5 had ozone levels of 30 to 40 ppb all around the stator core, which is slightly above the expected ambient level. This indicates 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 areas. The wiring diagram of this generator indicates that these areas contain the first bars of some parallel circuits of the three phases, which are at higher voltage and most likely to generate PD.

Isle Maligne Unit 11 is an interesting case. The ozone level all around the generator is comparable to ambient ozone, 20 to 30 ppb, with the exception of two adjacent openings (sectors 15 and 16) where the ozone concentration jumped to above 50 ppb. This area contains the first bars of one parallel circuit of the three phases, which again are the most likely to give PD. This suggests that the winding on this unit is in good general condition, with the exception of a localized default. This may be a case of loose or deteriorated bars or coils in a few slots.

PRPD measurements

To confirm the presence of PD activity on the six units where ozone was found, and to identify the type of PD activity, we performed PD measurements at both plants. Both plants have permanent capacitive couplers installed (six per generator) to perform PD measurements. The phase resolved partial discharge (PRPD) technique was chosen for this situation for its ability to recognize different PD sources, such as internal, slot, bar-to-bar, corona, and delamination.

Unit	Ozone Measurements	Partial Discharges (PD)	Diagnosis
Shipshaw 2	No significant ozone, symmetrical distribution	Few slot PDs 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 and decreasing from sec-tors 2 to 4	Important slot PD on circuits A2, B2, C1, and C2; lower slot PD on A1 and B1; less important corona discharges on B1	Relatively advanced degradation process on four of the six half-phases
Shipshaw 10	Generalized moderate to high ozone level, maximum on sector 4	Numerous slot PDs on all 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 to 16 and 24 to 33	Corona discharge over three phases; moder-ate slot PD on C1, low on B2 and C2	Moderate degradation in process

Table 1: Comparison of Ozone and Partial Discharge Measurements

Interpreting the results

Table 1 summarizes the results obtained from ozone and PRPD measurements at the Shipshaw and Isle Maligne plants. For all six cases, there is a good correlation between the ozone and PRPD measurements. For Shipshaw Unit 2, PRPD detected only a small PD activity in one of the phases, while no significant ozone was produced. Shipshaw Unit 10 gave the highest level of ozone all around the generator, and PRPD detected a high incidence of slot discharges on all circuits.

The results on Unit 11 of Isle Maligne demonstrated 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 where PRPD detected the default with the location where ozone was detected, the plant owner could narrow the search to a few slots. A limited inspection or measurements then could be scheduled on these slots to find the problem, which might be easily corrected using semi-conductive paint or CRTV injection.

Conclusion

We have demonstrated the direct relationship between PD and the production of ozone inside generators. While the ozone is produced inside the slot in the gap surrounding the bar, the cooling air discharges it to the back of the stator core through the ventilation ducts. The maximum concentration of ozone measured is outside the stator core, at the back of the stator.

Measurements of ozone on operating generators demonstrate a good correlation in the diagnosis given by this technique and PD monitoring through capacitive couplers (sensors to detect on-line PD activity). In the case of one localized default, the capability of the two techniques to pinpoint the location of the fault has been demonstrated.

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

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Notes

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Acknowledgments

The authors are grateful to Alcan, which gave us access to its hydro plants. Special thanks go to Mr. Denis Bussières, from Alcan electric division, who coordinated and facilitated work at the facilities.

Louis Lépine, PhD, and Mario Bélec are research scientists and Denise Lessard-Déziel and Calogero Guddemi are technicians at Hydro-Québec's research institute (IREQ). Duc Nguyen, P.E, is a research project manager with Hydro-Québec Production.