



UNIVERSIDADE
ESTADUAL de LONDRINA

MARTIM FELIPE FERNANDES

INVESTIGATION AND METHODOLOGY FOR OZONE CONCENTRATION
ANALYSIS IN HYDROGENERATORS AS A PREDICTIVE MAINTENANCE
TOOL

LONDRINA
2025

MARTIM FELIPE FERNANDES

**INVESTIGATION AND METHODOLOGY FOR OZONE CONCENTRATION
ANALYSIS IN HYDROGENERATORS AS A PREDICTIVE MAINTENANCE
TOOL**

Doctoral Thesis presented to the Doctorate Program
of Universidade Estadual de Londrina for obtaining
the degree of Doctor of Science in Electrical Engineering.

Supervisor: Prof. Dr. José Alexandre de
França

**LONDRINA
2025**

Ficha de identificação da obra elaborada pelo autor, através do Programa de Geração Automática do Sistema de Bibliotecas da UEL

F363i Fernandes, Martim Felipe.
Investigation and methodology for ozone concentration analysis in hydrogenerators as a predictive maintenance tool / Martim Felipe Fernandes. - Londrina, 2027.
140 f. : il.

Orientador: José Alexandre de França.
Tese (Doutorado em Engenharia Elétrica) - Universidade Estadual de Londrina, Centro de Tecnologia e Urbanismo, Programa de Pós-Graduação em Engenharia Elétrica, 2027.
Inclui bibliografia.

1. Máquinas Elétricas - Tese. 2. Manutenção Preditiva - Tese. 3. Descargas Parciais - Tese. 4. Ozônio - Tese. I. de França, José Alexandre. II. Universidade Estadual de Londrina. Centro de Tecnologia e Urbanismo. Programa de Pós-Graduação em Engenharia Elétrica. III. Título.

CDU 62

MARTIM FELIPE FERNANDES

**INVESTIGATION AND METHODOLOGY FOR OZONE CONCENTRATION
ANALYSIS IN HYDROGENERATORS AS A PREDICTIVE MAINTENANCE
TOOL**

Doctoral Thesis presented to the Doctorate Program
of Universidade Estadual de Londrina for obtaining
the degree of Doctor of Science in Electrical Engineering.

EXAMINATION COMMITTEE

Supervisor: Prof. Dr. José Alexandre de França
Universidade Estadual de Londrina

Dr. Greg Stone
Stone Dielectrics

Prof. Dr. Hédio Tatizawa
Universidade de São Paulo – USP

Prof. Dr. Marcelo Tosin
Universidade Estadual de Londrina – UEL

Prof. Dr. Leonimer Flávio de Melo
Universidade Estadual de Londrina – UEL

Londrina, July 7th, 2025.

*“In a world where everything could be done by
machinery, everything would be done by
machinery.”*

George Orwell

FERNANDES, M. F.. **Investigação e metodologia de análise de concentração de ozônio em hidrogeradores como ferramenta de manutenção preditiva**. 2025. 129f. Tese de Doutorado em Engenharia Elétrica – Universidade Estadual de Londrina, Londrina, 2025.

RESUMO

O hidrogerador é um ativo de importância central para a geração de energia em muitos países, especialmente no Brasil, onde mais de 60% da eletricidade gerada vem de usinas hidrelétricas (2023). Danos permanentes, falhas na operação ou até paradas não planejadas geralmente resultam em altos custos para as empresas de geração. A avaliação regular da condição da máquina, que está fortemente relacionada à qualidade de seu sistema isolante, permite a minimização dessas perdas e a redução do risco operacional. Durante a operação, a distribuição desigual do gradiente de campo elétrico dentro do gerador pode causar descargas em pequenos espaços ou vazios no isolamento, conhecidas como Descargas Parciais (DP). Além disso, o envelhecimento, a vibração mecânica e muitos outros fatores deterioram o sistema de isolamento, aumentando a intensidade das descargas. A medição de descargas parciais é uma ferramenta de manutenção preditiva bem estabelecida para máquinas rotativas de alta tensão, permitindo a avaliação da condição do isolamento não apenas durante as paradas da máquina, mas também continuamente durante a operação regular, possibilitando um planejamento mais eficiente de grandes revisões ou possíveis reparos. Alguns tipos de descargas parciais têm como consequência a produção de ozônio em máquinas resfriadas a ar, mas o monitoramento de ozônio não tem sido amplamente usado comercialmente para essa aplicação, talvez com uma exceção que utiliza um sistema complexo de tubos e válvulas para direcionar amostras de ar para uma câmara de medição, usando o princípio de absorção de luz ultra-violeta (UV). No entanto, avanços em sensores eletroquímicos permitiram medições mais confiáveis a um custo muito mais baixo. Neste trabalho, um protótipo de sistema de monitoramento completo é desenvolvido com base em sensores eletroquímicos de baixo custo e instalado em dois hidrogeradores de 311 MVA, junto a monitores contínuos de descargas parciais. Métodos para mitigar uma das principais desvantagens dos sensores eletroquímicos, que é a sensibilidade a variações de umidade e temperatura, são apresentados, permitindo uma redução consistente de até 75% no erro quadrático médio, quando comparado com medições não corrigidas. Os dados coletados das duas máquinas, uma das quais tinha problemas de DPs na superfície, foram avaliados para determinar qualitativamente a utilidade geral do monitoramento contínuo da concentração de ozônio como uma ferramenta de manutenção preditiva para hidrogeradores e para propor recomendações objetivas para a aplicação prática desta técnica. Em uma das máquinas, o monitoramento de ozônio permitiu identificar um potencial problema que não seria detectado apenas com a análise tradicional de pulsos de descargas parciais.

Palavras-chave: Hidrogeradores, Descargas Parciais, Ozônio, Máquinas Rotativas, Manutenção Preditiva, Alta Tensão, Sensores Eletroquímicos.

FERNANDES, M. F.. **Investigation and methodology for ozone concentration analysis in hydrogenerators as a predictive maintenance tool**. 2025. 129p. Doctoral Thesis in Electrical Engineering – State University of Londrina, Londrina, 2025.

ABSTRACT

The hydroelectric generator is an asset of central importance for power generation in many countries, especially in Brazil where over 60% of the total electricity generated comes from hydro plants (2023). Permanent damage, failure in operation or even unplanned halts usually incur in high costs to generation companies. Regular assessment of the machine condition, which is strongly related to the quality of its insulation system, allows for minimization of such losses and reduced operational risk. During operation, the uneven electric field distribution inside the generator can cause discharges to happen across small gaps or voids in the insulation, which are known as Partial Discharges (PD). Moreover, aging, mechanical vibration and many other factors deteriorate the isolation system, increasing the intensity of PD. Partial discharge measurement is a well-established predictive maintenance tool for high-voltage rotating machines, allowing the condition of the insulation to be assessed not only during machine outages, but also continuously monitored during regular operation, enabling a more efficient planning of major overhauls or possible repairs. Some types of partial discharges are known to produce ozone in air-cooled machines, but ozone monitoring has not been widely available commercially for this application, perhaps with one exception which uses a complex system of tubes and valves to direct air samples to a measuring chamber, based on ultra-violet (UV) light absorption. Advances in electrochemical sensors, however, have allowed for more reliable measurements at very low cost. In this work, a full monitoring system prototype is developed based on inexpensive electrochemical sensors and installed in two 311 MVA hydrogenerators, along continuous PD monitors. Methods to overcome one of the main disadvantages of electrochemical sensors, which is their sensitivity to humidity and temperature variations, are presented, allowing a consistent reduction of 75% in the Root Mean Square Error when compared to non-compensated measurements. The data collected from the two machines, one of which knowingly had surface PD problems, was evaluated in order to assess the overall value of continuous ozone concentration monitoring as a predictive maintenance tool for hydrogenerators and to propose objective recommendations for practical application of this technique. In one of the machines, ozone monitoring allowed the detection of a potential problem that would not have been detected only with traditional analysis of partial discharge pulses.

Keywords: Hydrogenerators, Partial Discharges, Ozone, Rotating Machines, Predictive Maintenance, High Voltage, Electrochemical Sensors.

LIST OF FIGURES

Figure 1 – Brazilian electricity mix.	14
Figure 2 – Root causes of hydrogenerator failures.	15
Figure 3 – Failure causes at electrical insulation system.	16
Figure 4 – Ozone absorption cross-section for $200\text{ nm} < \lambda < 1100\text{ nm}$	22
Figure 5 – Ozone levels at <i>Peace Canyon</i>	23
Figure 6 – General structure of an electrochemical gas sensor.	27
Figure 7 – Diagram of a photometric ozone sensor.	28
Figure 8 – Diagram of the commercially available ozone monitoring system for hydrogenerators.	29
Figure 9 – UV absorption ozone sensor with fiber optics.	29
Figure 10 – Diagram showing the different types of insulation in stator bars.	33
Figure 11 – Electric field distribution with/without stress-grading tape.	34
Figure 12 – Paschen’s law plotted using parameters for air.	35
Figure 13 – Typical locations for occurrence of PD.	36
Figure 14 – Model of the groundwall capacitance.	37
Figure 15 – Types of capacitive coupler installation for PD measurement.	39
Figure 16 – Example of Pulse Phase Analysis graph.	40
Figure 17 – Example of Pulse Height Analysis graph.	40
Figure 18 – Lab setup for model validation.	44
Figure 19 – Power house of the Enercan hydro plant.	47
Figure 20 – Active and reactive power for UG3 throughout 2020.	47
Figure 21 – Temperature histogram for UG3 throughout 2020.	48
Figure 22 – Example of PDA installation.	49
Figure 23 – Coupler installation at Enercan, with radiators numbered 1 through 8.	50
Figure 24 – Detail of couplers installation.	51
Figure 25 – Environmental conditions near machine radiators.	52
Figure 26 – SGP41 NO_x signal sensitivity.	53
Figure 27 – Protections and 12 V DC regulation for the module board.	53
Figure 28 – 5 V DC regulation for the module board.	54
Figure 29 – Onboard humidity and temperature sensor.	54
Figure 30 – Digital-to-analog converter used in the design.	54
Figure 31 – Analog amplification of signals using operational amplifier.	55
Figure 32 – Final assembly of the board.	55
Figure 33 – Drawing of the generator and position of one of the modules installed.	56
Figure 34 – One of the sensing modules installed at the power plant.	56
Figure 35 – Electrical cabinet of the ozone monitoring system.	57
Figure 36 – System topology.	57
Figure 37 – Experimental setup for sensor evaluation.	59
Figure 38 – Reference instrument.	60
Figure 39 – Electrochemical sensor measurements compared to reference UV absorption method.	60
Figure 40 – Tests comparing electrochemical sensors to reference UV absorption method.	61
Figure 41 – Comparison of SGP41 MO_x sensor outputs and ozone concentration.	63
Figure 42 – SGP41 calibration attempt.	63
Figure 43 – Humidity variation and effect on Winsen electrochemical sensor.	64

Figure 44 – Humidity variation and effect on Sensirion MOx sensor.	65
Figure 45 – Recursive filter parameters with varying β	66
Figure 46 – Filter response during a humidity peak.	67
Figure 47 – LSTM performance for various batch sizes and number of epochs.	69
Figure 48 – LSTM method for estimation of ozone concentration under humidity variations.	69
Figure 49 – Winsen sensor corrected with LSTM during extreme humidity variation.	70
Figure 50 – Sensor 3 after LSTM correction.	70
Figure 51 – Sensor 1 after LSTM correction using NOx signal.	71
Figure 52 – Sensor 3 after LSTM correction using NOx signal.	71
Figure 53 – PRPD graph showing pulses measured in couplers B3-B6 and C3-C6.	73
Figure 54 – Values of Q_{m+} and Q_{m-} for UG2 from July 2022 to March 2025 (phase A).	74
Figure 55 – Values of Q_{m+} and Q_{m-} for UG2 from July 2022 to March 2025 (phase B).	75
Figure 56 – Values of Q_{m+} and Q_{m-} for UG2 from July 2022 to March 2025 (phase C).	76
Figure 57 – Values of Q_{m+} and Q_{m-} for UG3 from July 2022 to March 2025 (phase A).	77
Figure 58 – Values of Q_{m+} and Q_{m-} for UG3 from July 2022 to March 2025 (phase B).	78
Figure 59 – Values of Q_{m+} and Q_{m-} for UG3 from July 2022 to March 2025 (phase C).	79
Figure 60 – Ozone concentrations for all 8 sensors around UG2.	80
Figure 61 – Ozone concentrations for all 8 sensors around UG3.	81
Figure 62 – Ozone measurements in UG2 after outlier removal.	83
Figure 63 – Ozone measurements in UG3 after outlier removal.	84
Figure 64 – Correlation between ozone sensors in UG3.	85
Figure 65 – Pair plots of adjacent ozone sensors in UG3.	86
Figure 66 – Temperatures measured around UG3.	87
Figure 67 – Humidity measured around UG3.	88
Figure 68 – Humidity and temperature recorded by the modules during anomaly.	88
Figure 69 – Temperatures measured around UG2.	89
Figure 70 – Humidity measured around UG2.	89
Figure 71 – Ozone measurements from sensor 4 in UG2 compared to PD data.	90
Figure 72 – Ozone concentrations for each radiator in UG3, compared to PD coupler location.	91
Figure 73 – Data available for UG3.	92
Figure 74 – UG3 ozone measurement with PD and operational data.	93
Figure 75 – Corona spots identified in UG3 in 2019.	94
Figure 76 – Corona repair process in UG3 in 2019.	95
Figure 77 – Location of corona repairs in the top endwindings (2023).	96
Figure 78 – Location of corona repairs in the bottom endwindings (2023).	97
Figure 79 – Corona spots prior to repair, slot 36.	98
Figure 80 – Corona spots prior to repair, slot 37.	98
Figure 81 – Corona spots prior to repair, slot 298.	99

LIST OF TABLES

Table 1 – Overview of ozone sensor types.	26
Table 2 – Failure mechanisms and characteristics.	41
Table 3 – Generator information.	48
Table 4 – Continuous PD monitoring system.	49
Table 5 – Comparison of commercially available ozone sensors.	52
Table 6 – Signal comparison for electrochemical sensors.	61
Table 7 – Correlation benchmarks for VOC and NO _x with respect to UV reference.	64
Table 8 – Performance metrics for LSTM predictions.	72
Table 9 – Statistical distribution of Q _m measurements for 13.8 kV machines (PDA).	72
Table 10 – Q _m + / Q _m - values (mV) measured on UG3 (June 30th 2022).	73
Table 11 – Mean and Coefficient of Variation (CV) for each sensor in UG3.	83
Table 12 – Covariance matrix between humidity and temperature.	87
Table 13 – Corona repairs done on UG3 (September 2023).	99

LIST OF ABBREVIATIONS AND ACRONYMS

ANN	Artificial Neural Network
ANEEL	National Agency of Electrical Energy
au	Arbitrary Units
BIBO	Bounded Input, Bounded Output
CFD	Computational Fluid Dynamics
CNT	Carbon Nanotube
DAC	Digital-Analog Converter
DBD	Dielectric Barrier Discharge
EB-PVD	Electron Beam Physical Vapor Deposition
FIR	Finite Impulse Response
GE	General Electric
HFCT	High Frequency Current Transformer
HMOS	Heated Metal Oxide Semiconductor
HV	High Voltage
IEEE	Institute of Electrical and Electronics Engineers
IEC	International Electrotechnical Commission
IIR	Infinite Impulse Response
LSTM	Long Short-Term Memory
MOS	Metal Oxide Sensor
MOx	Metal Oxide
NIST	National Institute of Standards and Technology
NQN	Normalized Quantity Number
PD	Partial Discharge
PHA	Pulse Height Analysis
PdM	Predictive Maintenance
PLC	Programmable Logic Controller
ppb	Parts per billion
ppm	Parts per million
PPA	Pulse Phase Analysis

PRPD	Phase-Resolved Partial Discharge
Q _m	Maximum PD magnitude at 10 pulses per second
RF	Radio Frequency
RMSE	Root Mean Square Error
RNN	Recurrent Neural Network
SAW	Surface Acoustic Waves
SHP	Small Hydropower Plants
UART	Universal Asynchronous Receiver/Transmitter
UFPA	Federal University of Pará
PCB	Printed Circuit Board
UHF	Ultra High Frequency
UV	Ultra-Violet

CONTENTS

1	INTRODUCTION	14
2	LITERATURE REVIEW	19
2.1	History of ozone inside rotating machines	19
2.2	Recent works on ozone and electrical machines	22
2.3	Ozone sensing	24
2.3.1	Electrochemical sensors	25
2.3.1.1	Amperometric sensors	25
2.3.1.2	Impedimetric sensors	27
2.3.2	Optical sensors	28
2.3.2.1	Optical absorption sensors	28
2.3.2.2	Chemiluminescent sensors	30
2.3.2.3	Photoacoustic spectroscopy and surface acoustic waves	30
2.3.3	Solid state sensors	30
2.3.4	Ozone sensor calibration	31
2.4	Industry standards and ozone	32
3	THEORETICAL FOUNDATION	33
3.1	Typical high-voltage rotating machine design	33
3.2	PD in electrical machines	35
3.2.1	PD detection in rotating machines	37
3.2.2	PD analysis	39
3.3	PD and ozone	41
3.4	Ozone fluid dynamics	43
4	METHODOLOGY	45
4.1	Objectives	45
4.2	Methods	45
4.2.1	Generator and power plant information	46
4.2.2	PD monitoring	48
4.2.2.1	Differential coupler installation	48
4.2.3	Ozone sensor module design	51
4.2.3.1	Electrochemical ozone sensor requirements	52
4.2.3.2	Circuit design	53
4.3	Installation at the power plant and system topology	54
4.4	Restrictions	57
5	RESULTS	59
5.1	Validation of the electrochemical sensors	59
5.2	Temperature and humidity compensation	64
5.2.1	Recursive filter	65
5.2.2	Recurrent Neural Network	66
5.3	Partial discharge measurements	72
5.4	Ozone measurements	80

5.5	Temperature and humidity measurements	87
5.6	Comparison of PD and ozone concentrations	90
5.7	Repairs made in UG3	94
6	CONCLUSIONS	100
	REFERENCES	103
	APPENDIX	109
	APPENDIX A – DEVELOPMENT OF A LOW-COST OZONE MONITORING MODULE FOR CONTINUOUS PARTIAL DISCHARGE DETECTION IN HYDROGENERATORS . .	110
	APPENDIX B – PARTIAL DISCHARGES IN HYDROELECTRIC GENERATORS: DETECTION, PROCESSING, CLASSIFICATION, AND PINPOINTING	112
	APPENDIX C – FAULT DETECTION IN COMPONENTS OF SYNCHRONOUS MOTORS THROUGH ONLINE PARTIAL DISCHARGE MEASUREMENTS	115
	APPENDIX D – (SUBMITTED PATENT) MÓDULO DE MONITORAMENTO DE OZÔNIO PARA MÁQUINAS ELÉTRICAS DE ALTA TENSÃO	117
	APPENDIX E – DIMENSIONALITY REDUCTION AND CLUSTERING STRATEGIES FOR LABEL PROPAGATION IN PARTIAL DISCHARGE DATA SETS	119
	ANNEX	121
	ANNEX A – PHASE-RESOLVED PARTIAL DISCHARGE PLOTS FOR UG2	122
	ANNEX B – PHASE-RESOLVED PARTIAL DISCHARGE PLOTS FOR UG3	126

1 INTRODUCTION

Hydropower plays a critical role in Brazil’s energy matrix, serving as the cornerstone of the country’s electricity generation system. With approximately 60% of its total electricity capacity derived from hydroelectric sources, as shown in Figure 1, Brazil is among the world’s leaders in renewable energy production from water resources. The country operates over 1,300 hydropower plants, ranging from small-scale hydroelectric generation centrals to large-scale hydroelectric power plants, which collectively represent more than 101 GW of installed capacity. The prominence of hydroelectricity in Brazil is not only a reflection of its abundant river systems but also of decades-long infrastructure investments aimed at harnessing this renewable resource efficiently. Alongside countries like China, Canada, and the United States, Brazil is one of the top five producers of hydroelectricity worldwide. Landmark projects such as the Itaipu Dam, which generates 14,000 MW, and the Belo Monte complex, with a capacity of over 11,000 MW, underscore the country’s technical capability. Recent large-scale hydroelectric projects in Brazil, such as Belo Monte, Jirau, and Santo Antônio, have predominantly adopted the run-of-the-river configuration, which inherently limits their energy storage capacity. In contrast, the country’s extensive reservoir system is capable of storing energy equivalent to several months of national consumption. However, this storage capacity has diminished in recent years, driven by increasing demand and climate-related challenges [1].

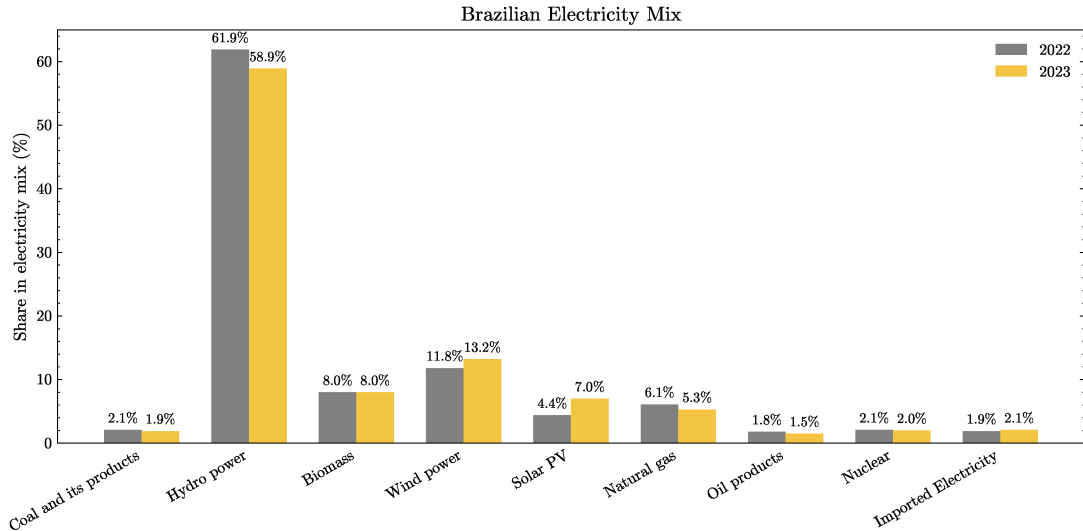


Figure 1 – Brazilian electricity mix, adapted from [2].

Despite the advantages of hydropower, including its low carbon footprint and renewable nature, Brazil faces several challenges that threaten the sustainability of this sector. Climate change, characterized by altered precipitation patterns, higher temperatures, and extreme hydrological events, poses direct risks to water availability and reservoir operation. These environmental stressors may reduce the flow in major river basins, particularly in the Amazon and Northeast regions, undermining energy security. Additionally, socio-environmental concerns such as biodiversity loss, greenhouse gas emissions from flooded biomass, and the displacement of local communities further complicate the development of new hydropower projects.

In response to these issues, Brazil is increasingly turning to complementary strategies, including the development of small hydropower plants (SHPs) with lower environmental footprints and the integra-

tion of alternative renewable sources such as wind, solar, and biomass. However, it is imperative that the hydro plants that already exist can continue operating reliably. For that, power plants have been using sophisticated maintenance methods to identify and even predict potential problems.

Predictive maintenance (PdM) represents an important strategy in the realm of industrial asset management, offering the potential to significantly reduce unplanned downtimes and extend the useful life of machinery. Unlike traditional corrective or preventive approaches, PdM relies on continuous monitoring of equipment conditions through sensor data and advanced analytics, allowing for interventions to be scheduled precisely when needed. This shift has been accelerated by real-time data acquisition from all sorts of parameters that can vary according to the type of asset in question [3].

When evaluating PdM technologies applied to hydrogenerators, there is a multitude of parameters that can be measured and analyzed to identify potential problems with the machine (electrical, thermal, mechanical, environmental, etc). However, the weakest part of the generator is the insulation system, since it is made, at least in part, of organic compounds that can age and degrade relatively quickly through the action of various failure mechanisms.

A detailed survey of hydrogenerator failures [4] shows that 56% of the problems happen in the insulation, as shown in Figure 2. Within the insulation issues, ageing represents the largest fraction of failures, followed by contamination and internal Partial Discharges (PD), as shown in Figure 3. This distribution underscores that insulation deterioration is not attributable to a single mechanism, but rather a combination of electrical, thermal, mechanical, and environmental stresses. Therefore, comprehensive monitoring strategies are essential to detect early signs of insulation degradation, with a focus on mitigating ageing and contamination effects, which together represent over half of all observed insulation failures.

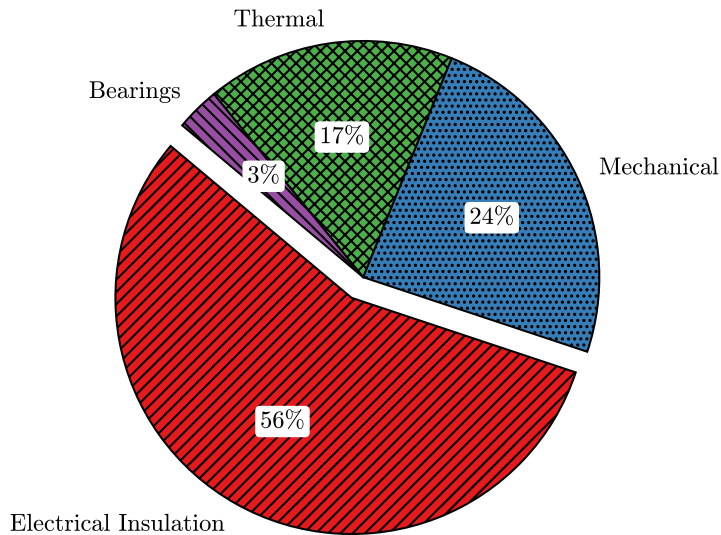


Figure 2 – Root causes of hydrogenerator failures, adapted from [4].

PD monitoring in stator windings is a well-known tool for the diagnostics of the insulating material condition in rotating machines with nominal voltages above 4 kV. These systems are based on high-frequency pulse measurements (50-350 MHz), generated by the occurrence of PD in the insulation of the stator. Typically, the measurements are done through capacitive couplers permanently installed on the machine terminals, although other methods exist, such as the use of UHF antennas or High Frequency Current Transformers (HFCTs).

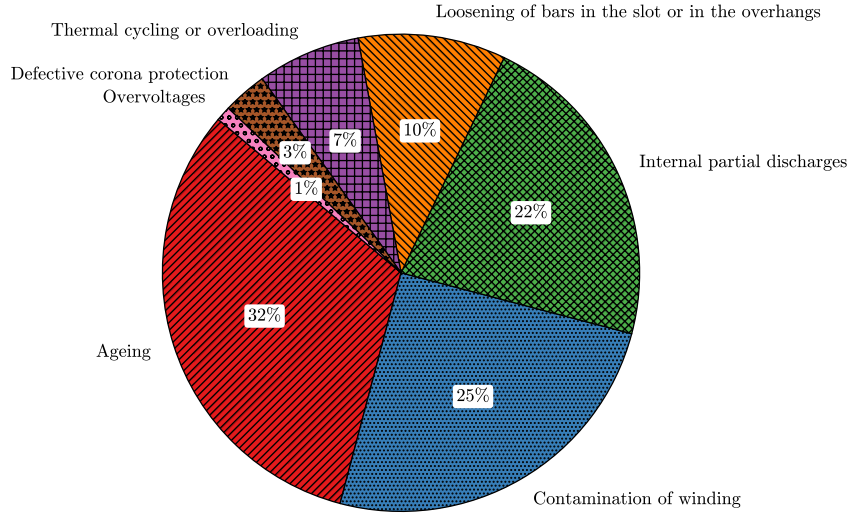


Figure 3 – Failure causes at electrical insulation system, adapted from [4].

In the frequency of PD pulses (dozens or hundreds of MHz), the couplers, which have a capacitance between 80 pF and 3 nF, act as a short circuit, filtering the high frequency signal content. In online monitoring, with the machine in operation, an external interface is used to collect these signals through a portable or permanently installed instrument.

When studying the PD pulses of a given machine, information is usually represented in two main graphs: Pulse Height Analysis (PHA) and Phase-Resolved Partial Discharge (PRPD), which provide useful information about the PD occurring in the insulation, namely:

- PD magnitude: Related to the size or volume of the voids in the insulation, represented by Q_{m+} and Q_{m-} .
- PD pulse rate: Related to the total number of voids or defects in the insulating material.
- PD polarity: Indication of the place where the voids are, whether closer to the copper conductors or the insulator surface.
- PD pulse position compared to phase-ground voltage: An indication of the PD having phase-phase or phase-ground dependence.

This information allows, in many cases, a general evaluation of the insulation condition. A rigorous analysis of the data can provide the severity of the deterioration and the approximate locations of occurrence, for instance if the voids are within the insulation, in the copper/insulation interface or in the surface of the insulation. The ability to assess the condition of the stator through a non-invasive method, with the machine in operation, is extremely valuable because it allows plant managers to make better informed decisions regarding the generator maintenance, such as whether or not a machine needs to be taken offline and inspected or even prevent potential catastrophic failures.

In air-cooled machines, some types of PD are known to produce ozone. Recent works have shown a correspondence between surface PDs and ozone formation [5] [6]. However, ozone is not yet widely used as a diagnostic tool for possible problems in the stator insulation. Ozone measurements reported in literature in the context of rotating machine PD detection have always been discrete, but continuous measurements are much more valuable from a maintenance point of view, since they allow for trends to

be observed and compared. One such comparison would be to traditional PD monitoring, but also with the operational parameters of the machines, which can bring additional insight into their condition.

There is one commercially available solution [7] for continuous ozone monitoring for hydrogenerators, which makes use of several tubes distributed throughout the generator and a pump to bring sequential air samples to a measuring chamber that uses UV absorption method to determine ozone concentration. This method is very expensive and has drawbacks such as the use of moving parts (valves/manifold), the sequential sampling and, possibly, the distance between the sampling location and the measuring equipment, which means the ozone concentration can change.

The present study is guided by the following objectives:

- To develop a cost-effective methodology for online monitoring of ozone concentrations in hydrogenerators.
- To implement the proposed monitoring system in operational units of a hydropower plant, in conjunction with conventional PD monitoring equipment, and to evaluate potential correlations between the respective time-series data.
- To investigate the relationship between ozone concentrations and PD activity through continuous measurements, incorporating additional operational parameters of the machine in order to identify possible interdependencies.
- To present and validate the results of the developed method within the context of the research project funded by the National Agency of Electrical Energy (ANEEL), under the code *PD-00642-2905/2020*, entitled “*Investigation and methodology of ozone concentration analysis in hydrogenerators as a predictive maintenance tool*”.

In order to maintain the low-cost nature of the ozone monitoring modules, electrochemical sensors were employed. These sensors, while economically advantageous, present certain drawbacks, notably their sensitivity to environmental variables such as temperature and humidity. Consequently, specific techniques were developed and implemented to mitigate these potential sources of measurement error and to enhance the reliability of the monitoring system. The ozone monitoring systems were deployed in two 311-MVA hydrogenerators, one of which exhibited known surface PD issues, while the other unit, with no reported insulation problems, served as a form of control group. The decision to utilize only two machines for this investigation was mandated by practical constraints, as it was not feasible to install such systems across a larger number of generators.

While ozone measurements alone are not intended to replace conventional PD monitoring techniques, the results of this study demonstrate that such measurements can serve as valuable indicators of the presence or progression of surface PD over time. Furthermore, ozone monitoring may reveal insulation problems that are not readily detectable through traditional continuous PD monitoring approaches. Given the low cost of the developed system, it can be readily implemented in electrical machines that currently lack any form of continuous PD monitoring due to budgetary limitations. Moreover, the potential applications of this technology are not confined to hydrogenerators; the modules can be adapted for use in electric motors and even in certain types of static electrical equipment.

The research project was executed through a collaboration involving Eurovolt Energy Service and the Federal University of Pará (UFPA), with financial support provided by the Barra Grande and Campos Novos hydropower plants, both of which are partially owned by CPFL Energia. The prototype

monitoring system was specifically installed at the Campos Novos facility (Enercan), in generating units UG2 and UG3.

The structure of this work is as follows: Chapter 2 presents a comprehensive literature review concerning ozone generation in electrical machines and its relationship with partial discharges; Chapter 3 establishes the theoretical basis for employing ozone monitoring as a potential predictive maintenance tool; Chapter 4 details the methodology used for laboratory testing and specifies the requirements for ozone sensing, describing the development of the ozone sensing module and field installation; Chapter 5 presents the data collected with respective analyses; finally, Chapter 6 summarizes the main conclusions derived from this research.

2 LITERATURE REVIEW

2.1 History of ozone inside rotating machines

The discovery of ozone is directly linked to electricity. In 1785, Martin van Marum observed that his static electricity machine produced a very particular odor, also noticing the oxidation of mercury contained in the Leyden bottles (early type of capacitor) of the apparatus and the reduction of the oxygen volume. In his opinion, that was the smell of electricity.

Five decades later, Schoenbein [8] proposed that the smell related to electric discharges in air or water hydrolysis would be a new substance and called it ozone, from the greek *ozein*, which means to “smell”. Many studies were done trying to characterize ozone and Schoenbein himself described the three main methods of formation: by electric arcs in air or oxygen, through water electrolysis in acid solutions and exposing phosphorous to humid atmosphere.

In 1857, Ernst Werner von Siemens proposed a more efficient method to produce ozone, using “silent discharges”, or a Dielectric Barrier Discharge (DBD) device. The novelty of this configuration was that electrodes were placed outside of the discharge chamber, without contact with the plasma. Curiously, Siemens never tried to patent this design, even though he considered it one of his most important inventions.

At this point, no one yet knew what ozone actually was. Many theories were put forth until 1865, when Soret [9] showed in a study of volumetric proportions that ozone would be an allotrope of oxygen, a molecule with three atoms (O_3).

Schoenbein kept researching ozone until the end of his life in 1868, having published over 200 papers on the subject. By then, the broad scientific community already accepted that ozone was in fact O_3 and the research on its potential applications and properties spread quickly. Not long after, it was noticed that ozone could be used in water treatment and that was the main push on studies to produce ozone in high quantities very efficiently.

In 1870, the first patent of an ozone generator using electrical discharges was granted [10]. By 1920, many cities around the world had water treatment plants using ozone, including large capitals.

The early twentieth century was also when electricity generation expanded incredibly quickly. The total generation capacity in the United States was around 100 MW in 1900 and grew by one order of magnitude every two decades until 1960 [11]. Many scientists and engineers started to notice that high voltage machines could sometimes produce ozone in their interiors and that could be related to certain failure modes.

In 1905, J. S. Highfield published a paper describing the observation of nitric acid inside a 3 MVA, 11 kV generator [12]. His hypothesis was that ozone created by electrical discharges was the cause for the subsequent formation of nitric acid, which was corroding the stator. This generator worked for a year before breaking down, and its insulation was of the highest quality (for the time, of course). Upon further inspection of the windings, it was observed that the turn insulation, made with cotton and resin, had been destroyed and replaced by a green substance. Also, the surface of the conductors had become rough. Some quantities of sulphuric acid, nitric acid and copper nitrate were found, giving more evidence that a chemical process had taken place. Highfield attributed this to the high humidity and performed laboratory experiments with the copper gauze wrapped in paper under a 10 kV potential difference. In 3

days, the paper was completely degraded and the copper was green, similar in appearance to the defective generator winding. He predicted that no generator in England could work effectively above 18 kV, due to the chemical degradation.

An independent work in 1907 [13] confirms that nitric acid was present in cotton interturn insulation, suggesting that for machines operating above 10 kV (phase voltage), precautions should be taken with respect to acid formation. A. P. Fleming [14] argues against this, saying that the insulation degradation occurred exclusively through the action of electrical discharges and not by chemical attack, adding that ozone could never be formed in measurable quantities at the working temperature of the generators.

Clearly, there was very little consensus about what exactly damaged the insulation of generators. It was only in 1911 that a detailed investigation on this subject was published. The paper *Chemical action in the windings of high-voltage machines* [15] should be read in full by all those who have an interest in rotating machines and partial discharges. It is the first work that clearly distinguishes between chemical degradation and the insulation wear caused by the constant action of electrical discharges (now called partial discharges). Giving a detailed explanation of the electric field gradients in the insulation, this work presents important conclusions:

- Chemical degradation is not perceived in machines operating below 6 kV (line voltage).
- Chemical degradation happens only in places exposed to air.
- Although ozone formation occurs in interfaces with air, chemical damage can happen in other regions of the machine, because the gas can move freely.
- The results of the chemical action in the insulation (whether by ozone, nitrous oxide or nitric acid) are oxidations.
- A failure by chemical degradation is almost always a short between turns.
- When the electric stress is too great, the degradation is not necessarily chemical. If there are two materials in the insulation with different values of permittivity, the material with smaller permittivity can be compromised by a large electrical stress without a full insulation breakdown.

In the following year, it was shown that electrical discharges also ionize the nitrogen gas present in air (N_2), which produces molecules of NO_2 [16]. This reaction is actually much more efficient if the oxidant is ozone. At that time, it was not known that another product of the same group of reactions is NO . The set of NO and NO_2 is commonly referred to as NO_x , and used as one of the main indicators of atmospheric pollution. Their reaction with the humidity of the air leads to the formation of nitric acid (HNO_3) and acid rain.

Despite the strides towards a clearer comprehension of what happens inside a generator, until the 1940s there was still a lot of confusion around all these concepts. In 1943, it was shown by Von Cron that dielectric breakdown can happen after repeated discharges of small magnitude under constant electrical stress. This was an important result that helped understand how generators actually fail. A compendium on electrical insulation materials from 1949 [17] states that “Voids must not be formed; for if the voltage gradient is high, corona may occur. The ozone and nitric oxide formed by corona may have destructive effects on the windings.”

After this, research on ozone inside electrical machines seemed to focus more on environmental and health implications - possibly because insulating materials used in the manufacture of stator coils

became much more reliable and durable. In 1951, the first publications mention equipment and methods to detect slot discharges in generators, both with the machine offline [18] and online [19]. Interestingly, the first mention of a continuous ozone monitoring system is probably from 1993 [20], so there is a very large temporal gap in research on the subject.

A 1972 report [21] approaches the problem that transmission lines may pose to public health, considering the air quality standard of 0.08 ppm of ozone. The report determines that the ozone produced by corona is negligible considering the lowest detection limit of the equipment then used (2 ppm). A transmission line, however, is generally placed in open spaces, exposed to wind. For rotating machines, such as hydrogenerators, or even electrical cubicles, the situation is very different, as the gas can accumulate, leading to high concentrations.

The ozone formation through electrical discharges is not a simple process and its rate or efficiency depends on many variables. Two main parameters are mainly used: β which represent the number of molecules formed per unit charge transported and η which is the “energy efficiency” or the number of reactant molecules chemically changed per unit energy supplied to maintain the discharge [22]. The relationship between the two empirical rate coefficients for discharge reaction, β and η , can be traced in terms of the gas pressure, p , the electrode spacing, d , and the corresponding potential difference between the electrodes maintaining the discharge. Of course, the partial discharges happening in a machine stator during operation have a more complex behavior, since the discharge path is not well defined and there are interfaces between different materials (mica, epoxy, steel, air, etc), not to mention the influence of the cooling air flow which has patterns that are far from trivial and will affect directly the rate coefficients.

Just as an example of this complexity, a simple experiment where an electrode discharged a DC current on two hollow needles separated by an equal distance shows that the current at constant voltage (or the total energy of the discharge) is not linearly proportional to the amount of ozone formed. This happens because if the energy is too high, thermal effects accelerate the destruction of ozone [23]. At the same time, it is possible to expect that greater electric fields tend to generate more ozone for a constant discharge current.

The relative concentrations and proportions of ozone (O_3) and nitrogen oxides (NO_x), such as nitric oxide (NO) and nitrogen dioxide (NO_2), produced during corona discharges are influenced by multiple parameters. In laboratory experiments described by Chen et al, key factors include the linear current density, electrode geometry, gas temperature, and airflow velocity [24]. Higher current densities lead to an increased number of energetic electrons within the plasma region, thereby enhancing the rate of ozone and NO_x production. The electrode wire radius also plays a significant role: larger radii result in thicker plasma regions and higher electron populations, although with slightly reduced mean electron energy due to lower electric field intensities near the electrode surface. Increasing the wire radius from 10 μm to 1000 μm , while maintaining a constant surface current density of 0.406 A/m², increased the maximum ozone concentration from approximately 89 ppb to over 110 ppm. Gas temperature inversely affects ozone production: as temperature rises from 300 K to 800 K, the ozone production rate decreases by approximately 80%. This reduction is attributed to the combined effects of lower gas density, increased diffusion, and shifts in the kinetics of key reactions.

Moreover, while the airflow velocity significantly alters the spatial distribution of ozone downstream from the discharge region, it has minimal influence on the overall production rate within practical ranges (0.05–2 m/s). This insensitivity arises because the characteristic times for ozone formation are much shorter (on the order of 0.01–0.1 ms) than typical residence times in corona devices evaluated (10–20 ms). In contrast, ozone destruction, primarily through reactions with NO and other nitrogen oxides, occurs on much longer timescales, often exceeding several hundred milliseconds. Consequently,

despite simultaneous NO_x generation, relatively high ozone concentrations persist near the discharge zone, with NO concentrations typically representing only about 2% of the ozone concentration under standard operating conditions [24].

2.2 Recent works on ozone and electrical machines

The work “Hydro-Electric Generator Ozone Monitoring” [20] presents ozone measurements in 4 generators from Peace Canyon plant, in Canada, with concentrations between 168 and 260 ppb. The authors also compared 3 types of sensors available commercially in 1993:

1. Membrane (or electrochemical), where a current is generated when ozone reacts chemically with an electrode.
2. Luminescent, where the light spectrum is measured when ozone reacts with a different substance, in this case, ethylene.
3. UV absorption, which measures the amount of light absorbed by the sample at the wavelength of 254 nm. This wavelength is the absorption peak for ozone, known as Hartley band, which is the largest peak in Figure 4.

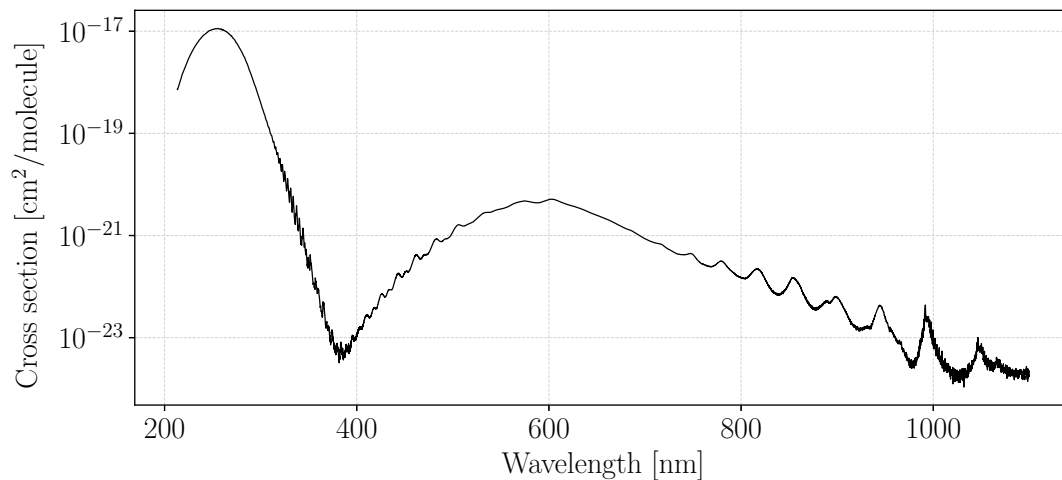


Figure 4 – Ozone absorption cross-section for $200 \text{ nm} < \lambda < 1100 \text{ nm}$, plotted with data from [25]. The peak at 253.7 nm is the Hartley band.

To create a prototype, they chose the UV absorption sensor, due to its high dynamic range and repeatability. The disadvantage is that oil particles in the air and dust, for example, can also absorb light in the same wavelength. To reduce this effect, they suggest a baseline measurement after running the local air through an ozone catalyst, so the ozone is completely eliminated. This method would work if the baseline conditions didn’t change too much. The proposed system is centralized, which means air samples from the generator were taken by Teflon tubes spread throughout the machine and taken to the measurement chamber. The authors tested the sample transport through 60 m of tubing and temperatures up to 20 °C above ambient, with ozone losses in the order of 2%. A system of valves controlled by a computer was used to send each air sample to the measurement chamber sequentially. The paper claims the system was to be installed in two of the Peace Canyon generators with eight measurement spots in each.

A very similar system is commercialized today as part of a larger package of monitoring systems for hydrogenerators [7]. They also use Teflon tubes and offer up to 8 sampling points throughout the machine.

In 2007, a comparison was made between ozone and PD measurements in the same Peace Canyon plant [26]. The high ozone concentrations of up to 250 ppb the PD patterns suggested damage to the semiconductive layer of the insulation, which was visually verified when the machine was taken offline. The same authors show in a subsequent paper [27] that ozone measurements taken around a hydrogenerators have direct correlation with the PD severity in the respective areas of the stator. They also test the influence of voltage, sensor distance and air flow in the ozone concentrations.

Figure 5 shows the results of such measurements in the top and bottom sections of each of the 16 radiators. The concentrations are very high, and possibly some of the worst reported in literature. The general distribution around all radiators indicate that PD activity is present around all the stator.

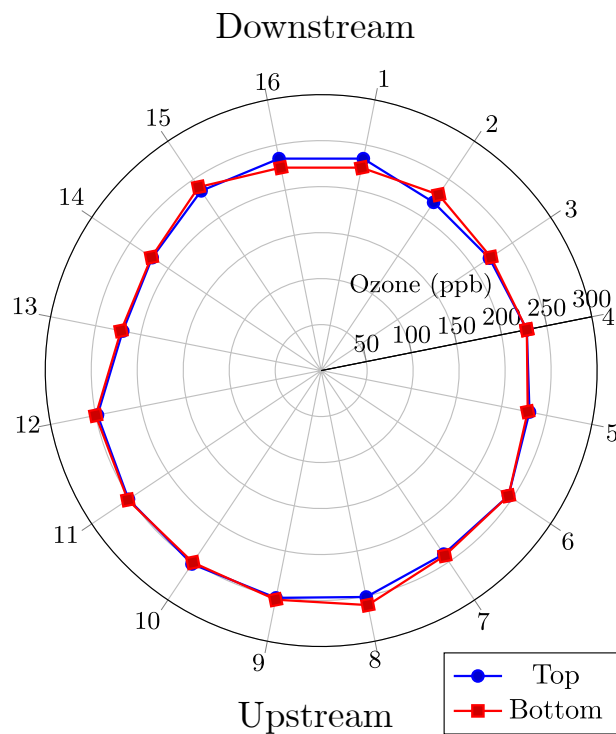


Figure 5 – Ozone levels around generator 4 at *Peace Canyon* (adapted from [28]).

A paper from 2009 [29] reports ozone concentrations done in a hydroelectric plant from Hydro Québec. Measurements were taken around all 6 generators with a portable UV absorption instrument. High concentrations were found and became a concern for the health and safety of the plant personnel. Actions to reduce ozone concentrations were taken, such as improving air circulation and a phase-neutral inversion in one of the machines that contributed to a 34% reduction in ozone levels.

In 2006, a strategic plan was formulated to install PD couplers at the hydroelectric plants of Porto Primavera, Jupiá, and Ilha Solteira, with the objective of monitoring the condition and aging of the generators. Subsequently, in 2010, the utility company Companhia Energética de São Paulo (CESP) acquired a portable ozone monitor based on ultraviolet (UV) absorption (Thermo-Environmental, Model 49C) to measure ozone concentrations in the vicinity of the generators and to correlate these levels with PD measurements [30].

At the Jupiá plant, generators with insulation classes B and F were systematically compared.

Thermal classes of insulation define the maximum continuous temperatures that materials can withstand over a long operational life (20,000 hours, according to IEC60085). Class B is rated at 130 °C and class F at 150 °C.

Class B machines exhibited ozone concentrations of up to 80 ppb, notably in Unit UG06. This unit, characterized by asphaltic insulation, along with UG01 and UG02, experienced the most frequent stator failures over their operational lifespans. The authors observed that Class B machines generally present fewer problems related to bar vibration within the stator slots when compared to Class F machines operating under similar conditions. Conversely, Class F machines at Jupiá demonstrated very low ozone concentrations, with correspondingly minimal PD activity.

At the Ilha Solteira plant, all assessed generators were of insulation class F and had been in operation for over 40 years, with some units having undergone repairs. The highest ozone concentration, reaching 180 ppb, was recorded near UG15, a unit that had neither been rewound nor subjected to major repairs. Other machines exhibiting elevated ozone levels shared the same design characteristics and, at the time of the study, had been in operation for 37 years. In contrast, the lowest ozone concentrations were observed in two machines that had been rewound in 2001 and 2002.

In summary, that study identified significant correlations between machine age, insulation type, repair history, and ozone concentrations. Older machines exhibited a greater propensity for PD activity, particularly surface PD, which in turn tends to generate increased levels of ozone.

Ozone measurements have also been used as part of a “health index” of generators [31]. This concept has been applied widely in the power generation, transmission and distribution sectors, not only for generators. It consists of selecting certain metrics considered relevant to a given asset, such as a generator or power transformer, which are aggregated in a single number, usually through some kind of weighted sum. This number helps stakeholders make decisions, for example to prioritize maintenance or invest in new equipment.

A work from 2017 [5] compares partial discharge levels and ozone concentrations using a 6.6 kV motor stator as test object inside an acrylic enclosure with a fan. In two of the phases, intentional defects were inserted by removing semiconductive coating. the measurements show very good correlation between ozone concentrations and the PD severity. It’s worth noting, however, that this is a very small test object, when compared to a typical hydrogenerator.

No publications were found about continuous ozone measurements in hydrogenerators using electrochemical sensors (or solid state / HMOS). Although the NO_2 concentration has a direct influence in the output signal of ozone electrochemical sensors, some research has shown that the proportion of O_3 generated by discharges tends to be higher - sometimes 1-2 orders of magnitude higher, depending on the conditions [32].

2.3 Ozone sensing

There are many ways to measure concentration of ozone in the air. Table 1 gives a general, non-exhaustive review of the main technologies in use. Each one has its own advantages and disadvantages, some of which will be discussed below.

For applications in electrical motors or generators, there are basically two main options:

1. Electro-chemical sensors, which are cheap but typically have smaller detection ranges and a life of 2-3 years (although there are manufacturers claiming up to 10 years [33]).

2. Optical spectroscopy, which have large detection ranges, good precision and long life span but are very expensive. This technology is also more sensitive to dust or other contaminants.

2.3.1 Electrochemical sensors

Electrochemical sensors are a class of sensors where an electrode acts as transducer element, as shown in Figure 6. This type of sensor first appeared in the 1950s, applied to industrial oxygen monitoring. Health and safety regulations started to establish limits for exposure to hazardous substances and Leland C. Clark proposed a concept for oxygen sensing consisting of two electrodes inside a cell with a membrane permeable to oxygen [37]. Upon chemical reduction in one electrode, an electrical current appears, which is proportional to the oxygen concentration in the sample. The same principle was applied to other types of gases. Since they rely on a chemical reaction, the sensor has a limited lifetime. Nowadays, there is usually a third electrode for reference purposes, improving signal-to-noise ratio, response time and stability.

Electrochemical sensors are very cheap and versatile, since their electrical output can immediately be sent into signal conditioners, PLCs and similar equipment. The main limitation of this type of sensor is their dynamic range. Common values are 0-10 ppm or 0-20 ppm. For comparison purposes, optical sensors can easily measure 0-200 ppm with accuracy of 2%.

For the purpose of monitoring the condition of a hydrogenerator, however, the range 0-20 ppm is acceptable, since typical values recorded in peer-reviewed literature are below 1 ppm. Note that the sensor, in particular of the electrochemical type, will not be installed on the stator itself, but rather somewhere near it, for example in cooling air ducts, near the radiators around the machine, etc. Therefore, the ozone concentration at the measurement point is typically much lower than at the discharge source, due to dilution and air movement. A big advantage of this type of sensor is that the signal generated is intrinsically electrical, which facilitates its conditioning and amplification. Other highlights are the possibility of miniaturization, relative low cost and fairly short response time. Electrochemical sensors can be classified by the electrical parameter that is changed in presence of the analyte.

The physical sensing principle of a given electrochemical sensor can be one of the following:

1. Potentiometric (electric potential V).
2. Conductometric or impedimetric (resistance or impedance Ω).
3. Amperometric (current I).
4. Coulometric (electric charge Q).
5. Capacitance (C).

With regards to ozone electrochemical sensors commercially available, the large majority are amperometric or impedimetric.

2.3.1.1 Amperometric sensors

In its most basic configuration, amperometric sensors have 2 electrodes: one functional electrode and a counter-electrode. A constant reference voltage is applied between them and the presence of O_3 causes a reduction reaction in the surface of the functional electrode, at the same time that an oxidation occurs in the counter-electrode. This generates an electrical current that is proportional to the number of molecules of analyte that are present.

Table 1 – Overview of ozone sensor types [34] [35] [36].

Sensor Type	Advantages and Features	Disadvantages and Limitations
Electrochemical (EC)	- Widely used in commercial low-cost ozone monitors. - Compact, low power consumption, and suitable for portable and distributed networks. - Operates based on redox reactions between ozone and the electrode material. - Moderate to high selectivity to ozone when NO₂ cross-sensitivity is addressed.	- Sensitive to temperature and humidity variations, requiring compensation circuits or models. - Limited lifespan (typically 1–2 years). - Possible drift and aging effects over time. - Reduced accuracy at low ppb concentrations or in harsh outdoor environments.
Metal Oxide Semiconductor (MOS or MOx)	- Cost-effective and easily miniaturizable. - High sensitivity and fast response to ozone in the ppb–ppm range. - Operates through changes in electrical resistance when exposed to ozone gas. - Suitable for compact, integrated devices and IoT applications.	- Requires high operating temperatures (200–500°C), increasing power consumption. - Strongly affected by humidity and ambient temperature. - Poor selectivity without functional material coatings or filters. - Long warm-up time and potential aging of the sensing layer.
Optical (UV Absorption)	- High precision and stability, based on Beer-Lambert law. - Capable of continuous measurements with low detection limits (down to 1 ppb). - Not influenced by temperature or humidity. - Gold standard for regulatory monitoring stations.	- Bulky and expensive setup due to the need for UV sources (lamps or LEDs), optical cells, and photodetectors. - Requires regular calibration and maintenance. - Power intensive and not suitable for portable systems without significant miniaturization.
Conducting Polymer	- Operates at room temperature with low power requirements. - Can be printed on flexible substrates (e.g., for wearable devices). - Tunable electrical properties depending on polymer composition. - Promising for disposable or low-cost monitoring.	- Susceptible to environmental factors (humidity, ozone degradation). - Limited long-term stability and reproducibility. - Aging effects and poor baseline stability over time.
Carbon-based (CNTs, Graphene)	- High surface-to-volume ratio allows detection at very low ozone levels. - Enables flexible and transparent sensor designs. - Promising for wearable, mobile, or implantable sensors. - Functionalization can improve selectivity.	- Complex and costly fabrication processes. - Susceptibility to ambient humidity and temperature. - Drift and baseline shifts require recalibration or signal processing.
Photoacoustic	- Operates by converting absorbed light energy into an acoustic signal. - High sensitivity and specificity due to wavelength selection. - Less affected by ambient light or humidity.	- Still largely in research phase with few commercial implementations. - Requires precise acoustic components and gas cells. - Calibration is non-trivial and may drift with temperature.
Surface Acoustic Wave (SAW)	- Detects gas adsorption via changes in surface wave velocity. - High sensitivity and rapid response times. - Can be miniaturized for integrated electronics.	- Complex fabrication using piezoelectric substrates. - Temperature-sensitive and may require compensation. - Limited real-world deployment for ozone sensing.

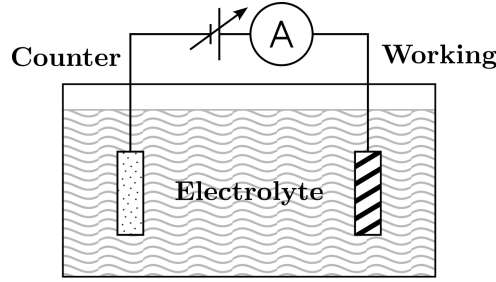


Figure 6 – General structure of an electrochemical gas sensor. The analyte diffuses through the electrolyte and reaches the electrodes, where a chemical reaction occurs.

Modern amperometric sensors also have a third reference electrode, whose function is to keep the functional electrode at an electrochemical potential as constant as possible, even with changes in temperature, pressure, humidity or presence of contaminants.

Considering an ideal linear amperometric sensor, the gas concentration can be modeled by:

$$\text{Gas concentration (ppb)} = \frac{(WE_i - WE_0) - (RE_i - RE_0)}{\text{Sensitivity}}, \quad (2.1)$$

where WE and RE are, respectively, the changes in voltage at the **W**orking and **R**eference electrodes. Sensitivity, in this case, would have as unit V/ppb , even though the original signal is an electrical current. Common materials for the electrodes are silver, gold and platinum, which can be manufactured in various substrates, such as silicon [38] or even polymers [39].

One of the major advantages of amperometric sensors is the ability to operate at room temperature, with low energy consumption (typically in the order of tens of mW) and reduced sizes, allowing for battery operation, for example. Common measuring ranges for ozone are between 50 ppb to a few hundred ppm.

This type of sensor, however, is subject to quick degradation, usually lasting 1-2 years. This is due to the measuring process itself. For this reason, amperometric sensors are less suitable for measuring high concentrations of ozone (>50 ppm). Also, amperometric sensors can have high cross-sensitivity with NO_2 [40]. In some applications, this characteristic can invalidate O_3 measurements altogether.

2.3.1.2 Impedimetric sensors

Impedimetric or resistive sensors have a sensitive area whose resistance (or impedance) changes in contact with the analyte. In the same way as amperometric sensors, this change can be caused by redox reactions. In the case of ozone, these sensors are mostly made of metal oxides. For the reaction with ozone to occur, the material must be activated, which means reaching specific thresholds of conductivity, electrical mobility, charge carriers and chemical kinetics. This can be achieved with heat or light.

In the case of heated sensors, there is a resistive element that keeps the sensitive electrode at high temperatures (100-500 °C). There is some confusion regarding how these sensors are named, because some of them are labeled as HMOS (heated metal oxide sensors), as if they were not electrochemical sensors. This is likely a marketing strategy, because the broader definition still applies. Even in peer-reviewed works, some authors place HMOS sensors in a separate category. Their main disadvantage is the high power consumption, and they also have limited life spans.

Due to the high working temperatures, these sensors may be subject to instabilities and they can't be used in some places, such as areas with explosion risks. Measurements may also be affected by

humidity present in the sample.

When light is used to activate the sensitive material (either visible or UV light), the sensor is often called photo reductive or photostimulated. It is also possible to find them labeled as “room temperature metal oxide sensors”. Even with light excitation, some of these sensors may also require a minimal operation temperature.

A study with 143 amperometric and metal oxide sensors continuously collecting data for 5 months mentions that HMOS sensors are not as effective for measuring concentration peaks [41]. Although HMOS sensors can be more selective and have lower detection limits, they are also slower [42].

2.3.2 Optical sensors

There are two main types of optical sensors: optical absorption (or photometric) and chemiluminescent (or photoluminescent). The photometric type is more widely used to measure ozone concentrations, especially when precision is a priority.

2.3.2.1 Optical absorption sensors

The O_3 molecule has a peak of absorption in the UV region, called Hartley band. This peak occurs at $\lambda = 253.7nm$, as shown in Figure 4. This peak can be used to determine the ozone concentration in a very precise way, using the Beer-Lambert law[43]:

$$A = \log_{10} \frac{I_0}{I} = L\epsilon c. \quad (2.2)$$

The absorbance (A) is given by the logarithmic ratio between the intensity of incident light (I_0) and the light intensity after crossing a medium (I). This is equivalent to the length of the medium multiplied by the molar absorbance (ϵ) and concentration (c).

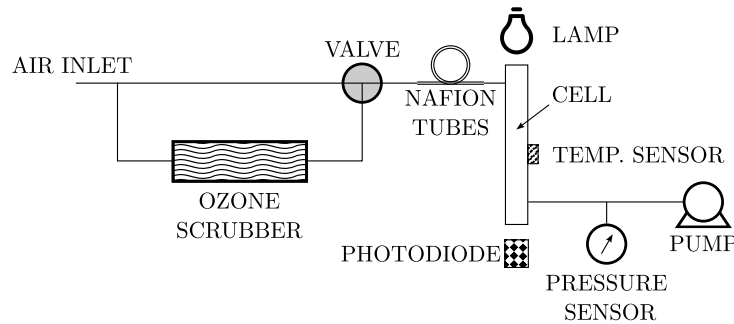


Figure 7 – Diagram of a photometric ozone sensor. Source: adapted from [44].

Typically, photometric sensors have a scrubber system that allows all ozone to be eliminated from a sample. The sample first goes through the scrubber and has its absorbance measured. Then, a new sample is routed to the measuring cell without going through the scrubber. The measurements are compared and the real O_3 concentration can be determined. Figure 7 shows this process. In this device, there is also a Nafion tube for moisture removal, as well as pressure and temperature sensors that allow for a more precise volumetric concentration measurement.

This technology has a series of advantages, such as precision and stability. With an adequate design, ozone sensors of this type can detect levels below 10 ppb with small margins of error. The most noticeable downside of UV absorption technology is price, since it is more expensive than heated metal oxide, solid-state or electrochemical technologies. For some applications, the reliability of UV absorption can be worth it, especially when using a portable unit to take regular measurements across many machines.

Specifically, for hydrogenators, there are systems provided by manufacturers that can measure ozone concentrations around the stator in real time continuously. This is done by placing tubes at each measurement point which suck in air to a manifold. The manifold sequentially directs the sampled gas of each tube to a measurement chamber where the concentration of ozone is evaluated and logged into the monitoring device [7].

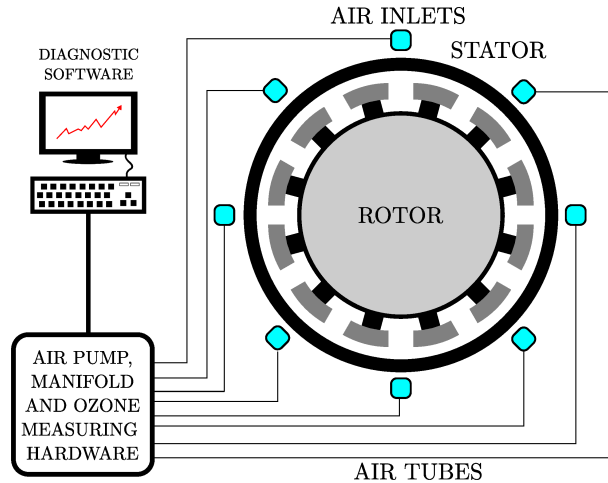


Figure 8 – Diagram of the commercially available ozone monitoring system for hydrogenators.

The setup shown on Figure 8 has a few disadvantages, for instance the sampled air must travel a considerable distance to reach the measurement chamber, which means that changes in the O_3 concentrations can happen. Also, the manifold has valves that open and close to switch between the different air inlets. These mechanical moving parts are more subject to maintenance issues and replacements.

Another type of optical sensor uses the same technology (UV absorption), but instead of bringing the air to a measurement chamber, it sends light through fiber optics, which then bounces off of a mirror inside an enclosure where the sampled air is. The light then comes back through another fiber into the spectrometer, where the UV absorption is measured and further correlated with the ozone concentration.

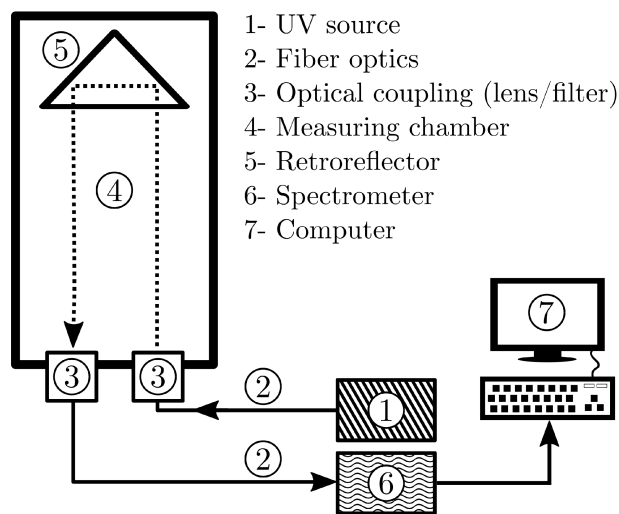


Figure 9 – UV absorption ozone sensor with fiber optics. Source: adapted from [45].

In the example from Figure 9, the sensor described had a measurement range of 0.1-10 ppm and was intended for MV cubicles, but the same principle would apply for rotating machines. The advantages are that the air being sampled finds itself closer to the source of ozone (discharge). Also, the design of this

sensor can be completely dielectric (fiber optics, lenses and mirrors), which means it could theoretically be placed as close to the stator as desired, or even glued to the endwindings, for example, similar to optical endwinding vibration sensors commercially available. The fiber optics would then be connected to an optical multiplexer or multi-channel spectrometer that would give the ozone concentration, eliminating the need for moving parts.

2.3.2.2 Chemiluminescent sensors

Chemiluminescence is light emission caused by a chemical reaction. This technique uses a known reagent which is placed in contact with the analyte. The light emitted goes through a photomultiplier, and the signal amplitude is proportional to the analyte concentration. This method is used in laboratories, because it has extraordinary sensitivity and dynamic range. At the same time, it demands stable conditions, has very high costs and slow response times (20-30 mins). Common uses are automobile emission certifications, combustion efficiency evaluation and atmospheric pollution monitoring [46].

2.3.2.3 Photoacoustic spectroscopy and surface acoustic waves

Photoacoustic spectroscopy (PAS) is a substance identification technique which relies on the illumination of a sample with specific wavelengths absorbed by the analyte. Part of the electromagnetic energy absorbed is transformed into heat, which translates into a physical expansion of the molecules and a subsequent pressure wave, which is measured with a microphone. The amplitude of this wave is proportional to the quantity of molecules that absorbed the initial electromagnetic energy, which also gives us the concentration.

In general, it is possible to obtain good measurement performance, even though selectivity is not high. Especially for ozone, sensitivity is not as high as photometric sensors. There are recent works using PAS to detect ozone through the application of visible light [47]. In literature, most works mention a minimum detection limit of 1-2 ppm [48, 49, 50], which narrows the scope of possible practical applications.

A recent technology that has shown promising results to measure gas concentrations in air, including ozone, is the use of surface acoustic waves (SAW). This is a type of sensor that benefited from the advances in nanotechnology. The physical principle of detection consists on the electro-mechanical coupling between resonating piezoelectric structures. The presence of an analyte changes the characteristics of this structure, such as mass or conductivity, also changing the propagation parameters of the acoustic wave [51]. It is common to represent sensitivity of this type of sensor with unit Hz/ppm when the resonant frequency is the parameter measured, or deg/ppm when phase is measured instead.

One of the biggest advantages of this type of sensor is the possibility of making passive RFID sensors. A sensor of this type with detection limit in the order of 60 ppb is reported in [52], although the objective was dosimetry and not instantaneous ozone concentration.

2.3.3 Solid state sensors

Although many electrochemical sensors may also be considered *solid-state*, this term is usually reserved for sensors that use thin films as sensitive elements, with thickness in the order of tens or hundreds of nanometers, often deposited through electron-beam physical vapor deposition (EB-PVD) [53].

This type of sensor has great potential, since thin films can be tuned in their physical structure or composition to favor gas detection for specific conditions and concentrations. Recent works mention capability of detection in the order of ppt (parts per trillion) [54] [38].

It is important to highlight that solid state sensors mentioned in literature are often impedimetric, where the relationship between the resistance of the sensitive element exposed to the measured gas and the resistance of the same element when exposed to air gives a sensitivity parameter.

Similarly to HMOS, solid state sensors usually need activation, also done with heat [53] or light [55]. There are thin film sensors being developed for room temperature operation, although not yet commercially available [56].

An interesting solid state sensor was produced in a small TO encapsulation, with a light source (LED) embedded in the sensitive structure itself. The authors claim to have measured ozone concentrations between 10 ppb and 200 ppm, which is an extremely high dynamic range, with low power requirements (50 mW) [57]. Unfortunately, this sensor does not seem to be commercially available.

2.3.4 Ozone sensor calibration

Even sensors with favorable technical specifications may yield unreliable data if not properly calibrated. Photometric sensors, in part due to their higher value and precision, usually come with a calibration certificate, which is valid for a given period of time.

Electrochemical sensors, including MOS, are much cheaper and, despite having good linearity, must be calibrated with a reference equipment - usually a photometric sensor. Few electrochemical sensor manufacturers provide factory calibration as an optional service and, when available, can cost more than the sensor itself.

The linearity of electrochemical sensors makes calibration fairly easy, since in theory you only need two data points to find the angular coefficient α :

$$C = \alpha V_{gas} + V_0, \quad (2.3)$$

where C is concentration of the measured gas, V_{gas} is the voltage at a given concentration and V_0 is the voltage at concentration zero. The use of a voltage signal assumes that the original signal has already been amplified, often through electronic circuits embedded in the same board as the sensor itself. However, this linearity is never ideal and this technique ignores the influence of temperature and humidity, for example. It does not take into consideration the cross-sensitivity with other gases as well. That is why more complex calibration methods have been developed.

A large study done in the European Union (MACPoll - Metrology of Chemical Pollutants in Air) evaluated many ozone sensors available commercially. The results are very interesting, because they show technical characteristics that are not supplied by the manufacturers, such as correlations between different variables, hysteresis, drift, etc [58]. Some of the most important conclusions of this study are:

- Amperometric and metal-oxide sensors are affected by changes in ambient temperature and humidity, but the change in behavior for amperometric sensors involves hysteresis, which is much difficult to compensate. In general, the influence of humidity changes (40-80%) tends to have a larger impact than temperature changes (12-32 °C).
- The cross-sensitivity of NO_2 in electrochemical ozone sensors is high, with a coefficient close to 1. Metal oxide sensors do not suffer as much from this problem.
- The long term stability (60-200 days) of electrochemical sensors was satisfactory, while metal oxide sensors showed significant drift in the same period of time.

To each commercial sensor evaluated, the researchers suggested a multivariate calibration model, taking into account the main factors that interfere with the measurements. That would allow for better estimates of the real ozone concentrations, assuming that the other interfering variables are also being measured. For one of the sensors evaluated, the suggested calibration model is [59]:

$$O_3 = \frac{R_s - bNO_2 - cNO_2 \cdot H_2O - d}{a}. \quad (2.4)$$

The parameters a , b , c and d can be obtained from the linear regression of reference measurements taken during the calibration stage and R_s is the ozone sensor response.

A more sophisticated method for ozone sensor calibration consists in the use of artificial neural networks (ANNs). In [40], neural networks are compared to linear regression and multivariate linear regression. The best results are achieved by the neural networks, using O_3 , NO_2 and CO sensors simultaneously. Curiously, humidity and temperature effects were also compensated by the neural networks, even though they were not being measured directly. This can be a result of the different way these parameters affect each of the three sensors.

Most of the inexpensive sensors available commercially are not calibrated by the manufacturer. Some manufacturers offer a calibration service, but in some cases the calibration price is a multiple of the sensor price itself.

2.4 Industry standards and ozone

There is a notable lack of information on ozone in the most common standards about machine monitoring and partial discharges. Most descriptions are brief and without any real guidance.

The IEEE 1129 guide for the monitoring of synchronous machines above 10 MVA has one paragraph about ozone, mentioning that its presence is an indicative of partial discharges, while also accelerating the degradation of the insulating materials (chemical attack).

The IEEE 1434 guide for partial discharge measurements in AC machines also has a similar paragraph, adding that the sample source is critical, since the ozone concentration is affected by environmental conditions. It also mentions that ozone monitoring can be done in an offline machine, but the greatest benefit is measuring ozone with the machine in operation.

The IEEE 492 guide for operation and maintenance of hydrogenerators mentions briefly that the amount of ozone present inside the generator or around it can be an indicative of surface partial discharges.

No standard gives more objective information about how to actually measure ozone concentrations or how to compare it with other variables.

3 THEORETICAL FOUNDATION

To better assess the potential for ozone monitoring in hydrogenerators, it's important to understand the basic structure of the stator insulation system and how partial discharges can happen in different parts. Moreover, the way ozone is dispersed around the machine can be a limiting factor for the correct condition assessment.

3.1 Typical high-voltage rotating machine design

Machine windings provide a path for the electric current, while the stator core allows for the efficient magnetic coupling between rotor and stator as well as providing heat dissipation. Since there is a potential difference between the conductors and the core, an insulating material must exist between them. Modern insulation materials are generally reliable, but they are by far the weakest component of an electrical machine and the part that ages the quickest.

High voltage (HV) stator windings are usually separated into two categories: bars, generally used in larger machines with long axial dimensions (such as 2-pole turbogenerators) and full coils, typically used in smaller machines or with a high number of poles.

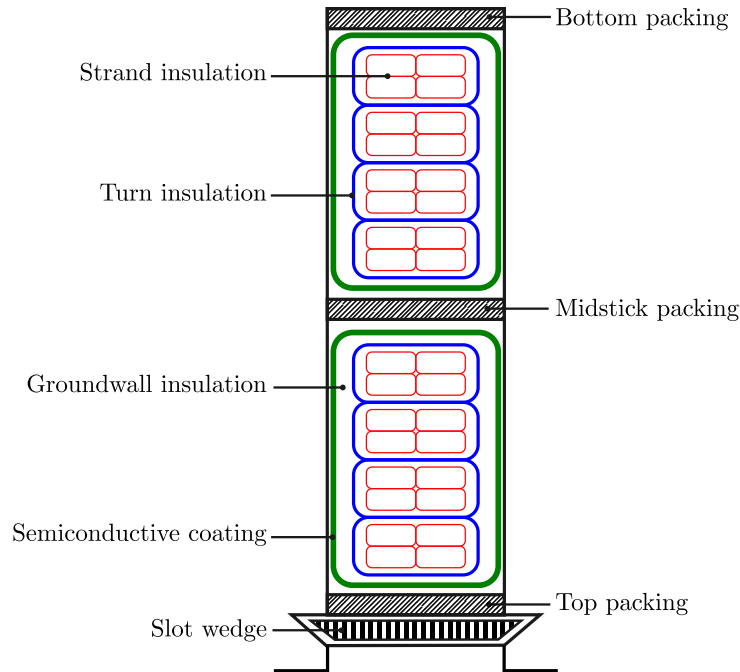


Figure 10 – Diagram showing the different types of insulation and placement of the bars inside the slot.

Figure 10 shows the different insulating components of a bar. Each of these elements has a role in the final purpose of electric insulation, with different requirements:

- **Strand insulation:** Provides individual insulation for each conductor strand, which typically have a potential difference of less than 1 V. A fault in this insulation is not usually a significant problem, but in some situations can lead to permanent damage to the bar or coil. Main materials used for this are mica sheets, polyamide and others.

- Turn insulation: More commonly found in multi-turn coils, this layer provides insulation between different turns, which can have a potential difference in the range of 10-300 V. A fault in this layer may cause large current circulation with intense thermal stress, possibly damaging the groundwall insulation in the process. Main materials used are mica sheets, polyester and others.
- Groundwall: Provides insulation between the conductors and the grounded core. The thickness of this layer depends on the material properties and design constraints. The thicker this layer, the less conductive material can fit in the same space, resulting in increased thermal stress. The thinner it gets, this layer will be subject to more electric field stress and higher risk of failure. A failure in this insulation generally means a short to ground and catastrophic damage to the machine.
- Semiconductive layer: A paint or tape around the coils which prevents high electric field gradients to develop in the interface between the groundwall insulation and the stator core. If not present or damaged, small gaps can cause sparking which would damage both the core and the insulation layer with time.
- Stress-relief layer: When looking at a stator core with HV coils, it is possible to see two distinct regions, the straight part that is tightly embedded inside the stator core and a “floating” part that is not in direct contact with the core, called end-winding. Since the part inside the stator slot is grounded with the semiconductive layer, the end-winding is subject to a dramatic electric stress, as shown in Figure 11. The stress-relief layer, which can be a paint or a silicon carbide (SiC) tape, aims to provide a smooth resistive gradient between the semiconductive layer and the end-winding.

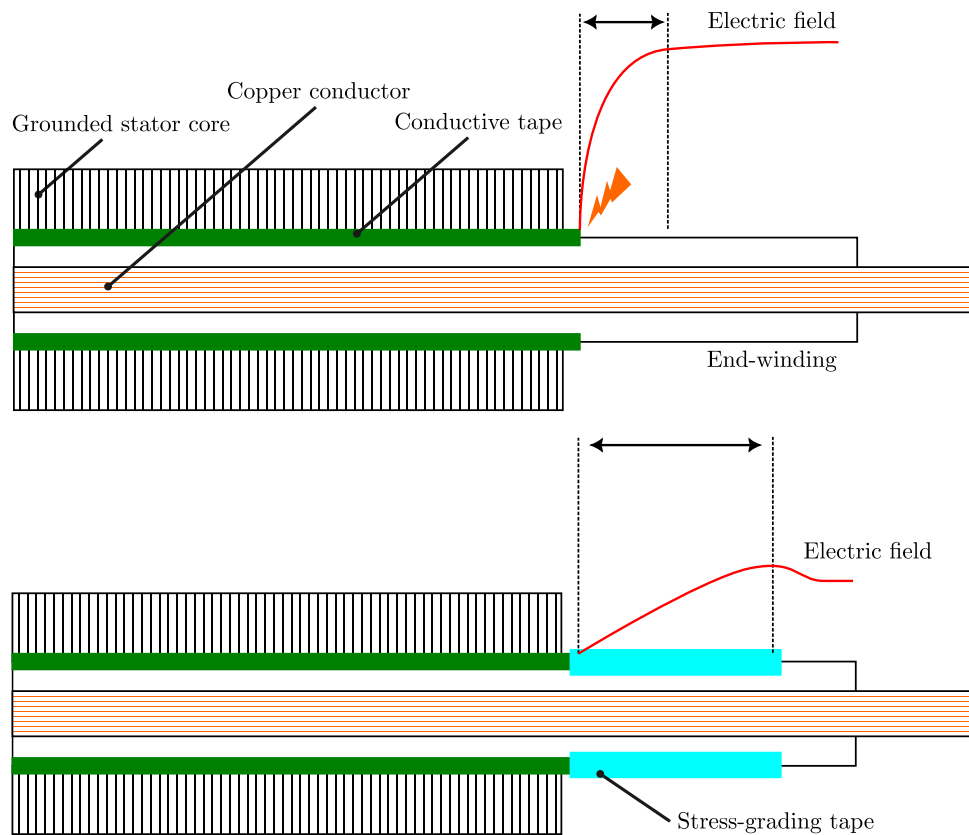


Figure 11 – Electric field distribution without stress-grading tape (top) and with stress-grading tape (bottom). The tape reduces the occurrence of PDs by creating a smoother electric field gradient in the end-windings.

3.2 PD in electrical machines

Partial Discharges (PDs) are small electric discharges that occur in voids or gaps when these regions are subject to high electric fields that surpass the dielectric strength of air (around 3 kV/mm). In electrical machines, these gaps can be present in the insulation due to a number of reasons, such as manufacturing defects, the relative movement and vibration of insulating materials during operation, thermal stresses and even inadequate assembly.

The electric discharges happen when the electric field is high enough to break down the gas molecules adjacent to the solid insulation. Another term used for this type of discharge is *corona*. The strength of the electric field (V_B) necessary to break down different types of gases is given by Paschen's law [60]:

$$V_B = \frac{Bpd}{\ln\left[\frac{Apd}{\ln(1/\gamma)}\right]}. \quad (3.1)$$

The parameters p and d are pressure and distance between the electrodes, respectively. Notice that what matters is their product, while A , B and γ are material properties of any given gas. In Figure 12, from left to right, the breakdown voltage decreases as the pd product increases. This is because there are more molecules present to be ionised, freeing electrons to ionise other molecules, which will in turn ionise others, creating a self-sustained process which is the breakdown itself. However, after a certain minimum, the quantity of molecules starts to hinder this process because electrons are colliding too frequently and therefore a larger voltage is necessary for the breakdown.

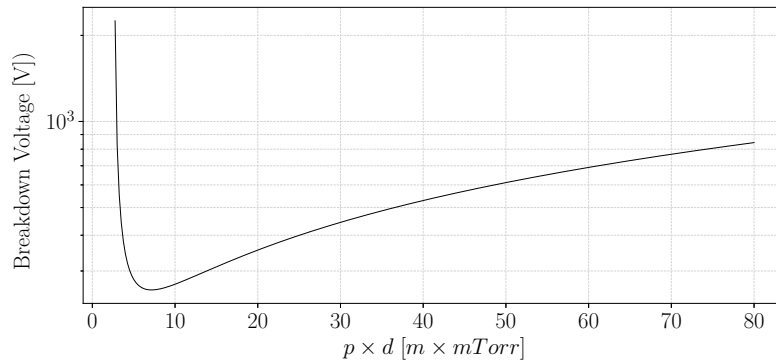


Figure 12 – Paschen's law plotted using parameters for air.

These discharges slowly damage the insulating materials and, once the insulation starts to degrade, the collective number of discharges, as well as their intensity, tend to increase. Although PD pulse magnitude is not directly related to the remaining life of the insulation, a rapid rise in PD measurements can indicate severe degradation of the insulation.

Figure 13 shows common spots where PDs happen in a stator bar. It is important to notice that PDs can also happen in the end-windings, for example between bars when spacing is too tight, through contaminants or even due to bad assembly of support structures.

According to [61], the main causes of PDs in the stator insulation are:

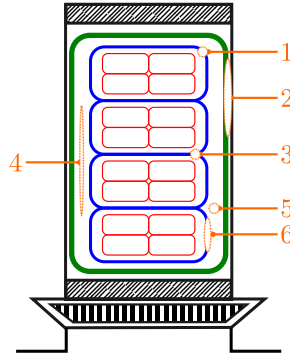


Figure 13 – Typical locations for occurrence of PD. 1- Early PD on corners due to high field strength; 2- Erosion of corona protection, slot discharges; 3- Degradation of turn insulation; 4- Delamination between layers in the groundwall; 5- Voids from impregnation process; 6- Delamination from copper (short-term overheating, thermal cycling).

- **Bad impregnation:** Problems in manufacturing processes such as incomplete cure of resins, issues when applying vacuum to the bars, incorrect application of insulating tapes or even the presence of contaminants can result in a defective bar or coil.
- **Thermal degradation:** When subject to thermal overloads, the insulation can lose its mechanical properties and begin to delaminate. Of course, this depends on the temperature class of the insulation. When delamination occurs, the conductors may begin to vibrate because they would not be tightly held by the insulation.
- **Load cycling:** More likely to happen in machines with long stator cores (> 2 m) when they experience frequent start-stop cycles or rapidly changing loads. Different components of the machines will have different thermal expansion coefficients, and these rapid changes can weaken the bond between the copper and the insulation. In some cases, this can lead to damage in the semiconductive layer, creating yet another source of PDs.
- **Semiconductive layer degradation:** This can be caused by high contact resistance, for example when the gap between the bar and the slot is filled with an insulating material or an impregnation problem. When PDs appear in this location, the degradation of the insulating material may cause the bars to become loose. Another common problem is the looseness of bars due to bad assembly, which leads to vibrations and deterioration of the semiconductive layer. It is not trivial to define if vibrations caused PDs or vice-versa.
- **Stress relief layer degradation:** PDs in this region are caused by bad design or inadequate manufacturing. Currents flow between the HV conductors and the stress relief layer through capacitive coupling, and then to the grounded stator core through an overlap between the stress relief layer and the semiconductive layer, as seen in Figure 14. If the connection resistance between these two layers is too high, there will be high I^2R losses and local heating, increasing the resistance even more through oxidation. This condition facilitates the appearance of discharges and, since the region is exposed to air, also promotes ozone formation. For machines connected to frequency inverters, this can be an even bigger issue, since the current will have high-frequency components that are more easily coupled.
- **Inadequate spacing:** If the spacing between end-windings is too small, PDs can appear in this region of the machine. This can happen in different ways, for example when the groundwall insulation is too thin and the spacing between bars is not taken into account to compensate for this, inconsistent shapes of the bars or coils after manufacturing or incorrect assembly.

- Contamination: Can be caused by oil vapors, dust, dirt, condensation, humidity, wear of parts of the machine or even tools inadvertently left during maintenance works. Contamination provides a “bridge” between regions with different potentials (phase-to-phase or phase-to-ground). It can also have other implications, such as blocking ventilation paths. Depending on the type of contamination, the insulation can be chemically attacked. Other signs of contamination are electric tracking.

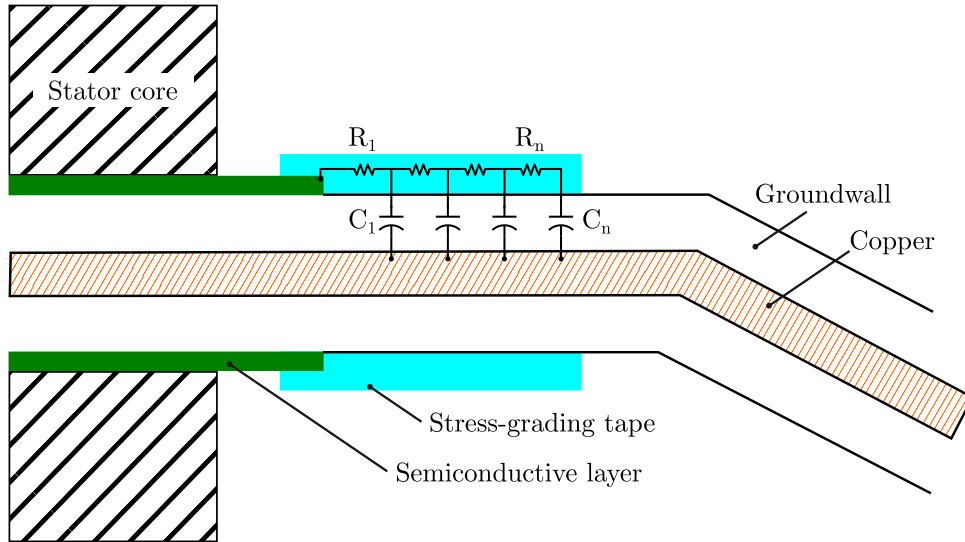


Figure 14 – Model of the groundwall capacitance and the SiC coating.

3.2.1 PD detection in rotating machines

PD signals in high-voltage rotating machines propagate through complex electrical and physical pathways that significantly affect their detection and interpretation. The stator windings act as multi-conductor transmission lines, where both the geometry of the winding and the surrounding electromagnetic environment influence the signal’s attenuation, dispersion, and arrival time at measuring terminals. These effects mean that the recorded PD signal may differ considerably from the original discharge event, both in waveform and amplitude, depending on the location of the source and the frequency content of the signal. Understanding the propagation behavior is therefore essential for reliable PD diagnostics, especially in large machines where the travel distances are long and losses are more pronounced.

An important aspect of PD propagation is the existence of multiple modes through which energy can reach the terminals. Low-frequency components tend to follow the physical layout of the windings, resulting in delayed, damped signals, while higher-frequency components can couple capacitively or inductively to nearby conductors, producing rapid but often weaker transients [62]. These coupling mechanisms can cause signals to appear in phases other than the one in which the discharge occurred, leading to ambiguities in phase identification and localization. Consequently, inter-phase crosstalk must be considered in any reliable PD interpretation methodology.

External components such as bus ducts, transformers, and grounding configurations further shape the observed signals through reflections, resonance, and parasitic paths. This can make the electrical environment outside the machine as relevant as the internal winding structure for PD signal propagation. As a result, measurement systems must be carefully designed with broadband capability and high temporal resolution and signal processing techniques must account for the dispersive and coupled nature of PD propagation. Only by incorporating this broader understanding can practitioners develop robust

PD monitoring systems capable of distinguishing true insulation defects from artifacts introduced by the propagation path.

Practical PD measurements on generators rely mostly on electrical pulses. Optical detection with UV cameras is a fairly common offline test, but it only allows the detection of surface discharges and, for better results, the rotor has to be pulled to allow for a full field of view of the stator. Acoustic sensors are more often used for static machines, like power transformers [63].

The main international standards cite three types of sensors for PD measurement: capacitive, current transformers and antennae. There is a predominance of the capacitive type in literature and they also have the largest installed base. The IEC standard 60034-27-2, which is widely used as reference for online PD measurement, gives more emphasis to capacitive couplers.

There are many possible configurations for installing capacitive sensors on a machine, starting with the point where the detection is done, which can be in the neutral or HV terminals. The HV terminal technique is more widely adopted and has more product options commercially available [64].

When considering the different configurations of capacitive sensors installed on HV terminals of a given machine, three main alternatives exist [65], which are shown in Figure 15:

1. Single-ended: with just one coupler per phase, making it more sensitive to noise, as it does not allow common-mode noise cancellation.
2. Directional: uses two sensors per phase, with one sensor closer to the phase terminal and the other on the machine's output bus. In this format, the external noise is separated from the PD signal based on the PD pulse arrival time.
3. Differential: recommended for machine designs with multiple circuits per phase and circuit rings, usually adopted in hydro generators, where couplers are installed at the stator circuit ring. If the noise comes from the external environment, it will enter the circuit rings, split, and propagate in both directions. If the circuit ring has the same length on both the left and right of the terminals, the pulse will arrive at the couplers at the same time, and if the conductors connecting the couplers to the analyzer are the same length, the signals will arrive simultaneously. In this case, the analyzer will interpret the signal as noise and not as a PD pulse. In the case of asymmetric circuit rings, it is possible to calibrate the cable lengths of the capacitive couplers to compensate for the different travel times in the different circuit rings. With this methodology, the pulse arrival time can be used to separate the noise from the PD signal.

There is also a difference between the recommended frequency ranges when performing online or offline measurements. IEC 60034-27-1 [66] recommends that the offline PD measurements must be below 3 MHz, due to the capacitive and inductive nature of the winding. For online tests (IEC 60034-27-2), the ranges are broader, from below 3 MHz up to 3000 MHz [67]. Higher frequencies tend to be used (> 30MHz) due to reduced noise presence in those bands [68]. The downside is that high-frequency signals are attenuated more easily throughout the winding, so the PD detection is much more effective when the pulses happen closer to the HV terminals. In practice, this is a more complex problem, because the winding impedance is a non-trivial curve and pulses originating from different points will be subject to different degrees of attenuation which are not linearly dependent on how far they are from the HV terminals.

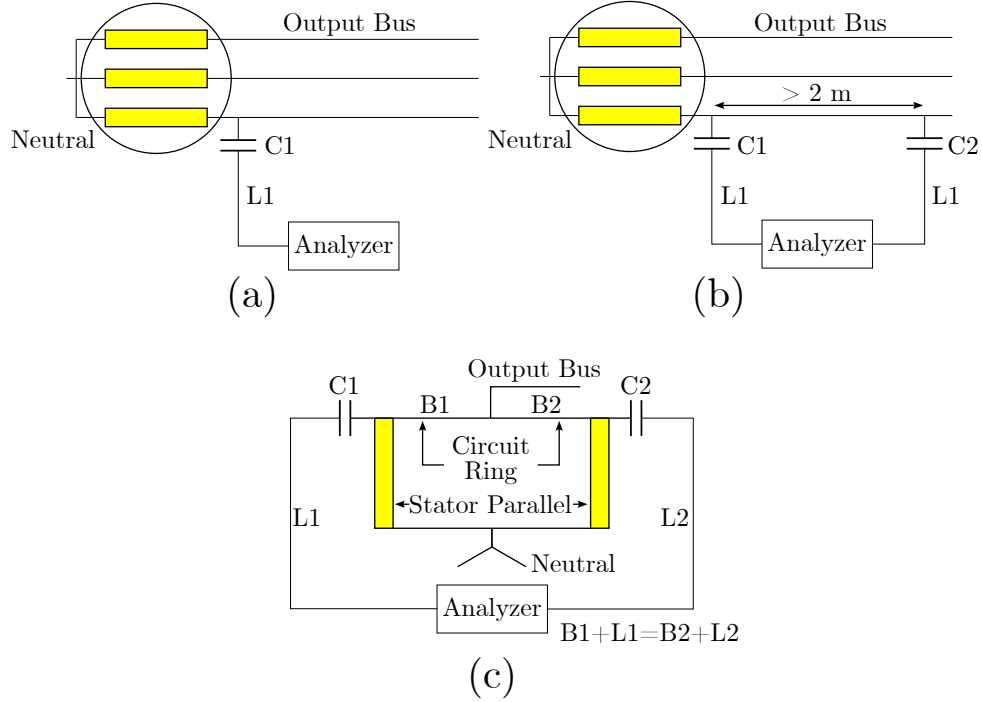


Figure 15 – Types of capacitive coupler installation for PD measurement (adapted from [65]).

3.2.2 PD analysis

Interpreting PD measurements in rotating machines, particularly hydrogenerators, requires a comprehensive approach that goes beyond simple amplitude thresholds or one-time observations. PD activity is inherently stochastic and affected by many variables including insulation design, operational conditions, machine geometry, and environmental noise. As such, reliable interpretation depends on recognizing trends over time, comparing data between similar units, and identifying shifts in discharge characteristics that may signal insulation deterioration. A single high PD level is not necessarily indicative of a fault unless it deviates significantly from established historical baselines or is accompanied by changes in phase-resolved patterns.

One of the central principles in PD interpretation is the distinction between relevant and non-relevant signals. Discharges from external sources and other noise-like phenomena can easily contaminate measurement data. Therefore, the detected PD pulses must be separated from noise, especially in online measurements where the machine is connected to the power system. If noise cannot be adequately suppressed or accurately separated from PD pulses, it can be misidentified as PD, reducing the reliability of the measurement.

There are denoising techniques that are implemented via hardware and software. Hardware denoising mostly rely on pulse shape recognition and time of arrival comparison, as mentioned previously in the directional and differential capacitive coupler configurations. Based on the specific location of two sensors, it's possible to identify signals coming from the machine itself or from outside (system). To use this method, the measurement system must operate in HF or VHF band to capture the pulse waveform with reasonable fidelity, and yet cannot remove disturbances originating from the machine itself, such as those from excitation systems, connections, etc.

Software denoising relies on the fact that noise pulses will have different characteristics than PD pulses in the time domain, frequency domain or time-frequency domain. In the time-domain, waveform analysis and pattern recognition can be used [69]. In the frequency domain, different types of filters can

be used to suppress noise, such as the infinite impulse response (IIR) filter, finite impulse response (FIR) filter, notch filter [70] and adaptive filter [71]. Time-frequency domain denoising can also be done using the wavelet transform, which involves a sequence of three steps: decomposition, thresholding and reconstruction [72] [73].

Once noise has been successfully suppressed, the information conveyed by the high frequency signals is usually shown in a graph where the pulses are placed over the AC system sine wave for that specific phase, where the pulse repetition rate is denoted by different colors, as shown in Figure 16. This representation is often referred to as Phase-Resolved Partial Discharge (PRPD) graph. The same graph can sometimes be represented in 3D, where pulse repetition rate becomes a height in the Z-axis. When viewing all three phases at the same time, it is best to have the sine wave shifted in each phase to keep their respective positions in time, so possible phase-to-phase activity can be more easily identified.

An equivalent representation is shown in Figure 17, where negative pulses are represented by a green line and positive ones by a red line, often called Pulse Height Analysis (PHA) graph. This representation gives more insight into the predominance of positive or negative pulses, but doesn't bring any information regarding the phase position of the pulses.

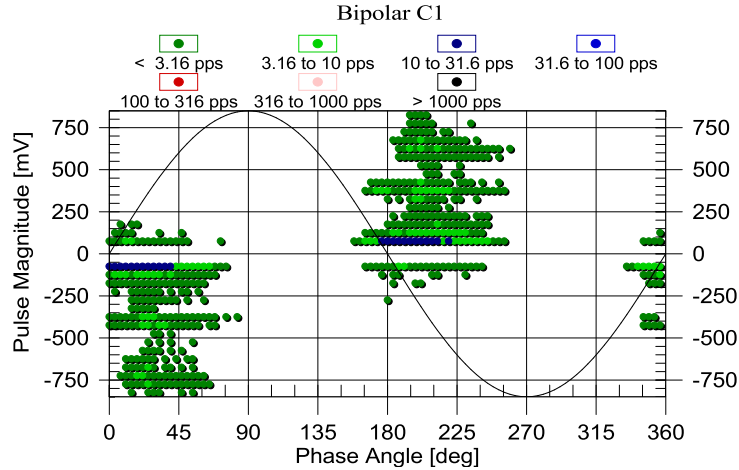


Figure 16 – Example of Pulse Phase Analysis graph.

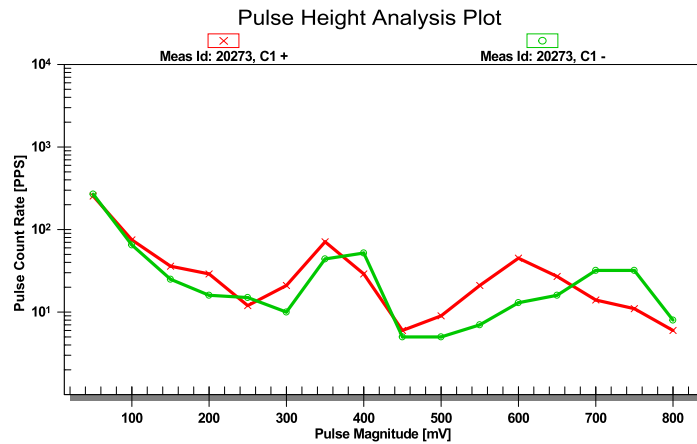


Figure 17 – Example of Pulse Height Analysis graph.

The magnitude at a repetition rate of exactly 10 pulses per second is often called Q_m . This definition is somewhat arbitrary, but it was found empirically that it summarizes well the severity of the PD activity. Since there are positive and negative pulses, there are Q_{m+} and Q_{m-} .

Another metric that is used as a summary of PD activity is the Normalized Quantity Number (NQN). It is calculated by the expression below:

$$NQN = \Delta v \sum \log N_i \quad (3.2)$$

where Δv is the size of the amplitude resolution measured and N_i is the number of pulses per second for each magnitude window. Like Qm, NQN will have a positive and negative variant (NQN+ and NQN-). NQN serves as an indication of all the pulses reaching a given sensor.

A predominance of positive values (Qm+/NQN+ magnitudes larger than Qm-/NQN-) can indicate that PD is happening at the insulation surface or close to it.

Different patterns of pulses can be associated with different types of PD. There is a high number of research work about methods to recognize these patterns automatically and diagnose potential problems without the need of human assessment. However, the patterns alone are not enough to determine with certainty which failure mechanisms are happening and having more context on the maintenance history, visual inspections, knowledge of how the machine is operated, etc, are much more important pieces of information that will actually improve the chances of a correct diagnostic. For reference, the most typical patterns and their respective failure mechanisms are shown in Table 2.

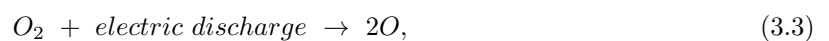
Table 2 – Failure mechanisms and characteristics.

Failure mechanism	Polarity	Load Effect	Temperature Effect	Phase Location
Internal delamination	No predominance	None	Inverse	45° and 225°
Thermal cycling	Negative	None	Inverse	45°
Manufacturing defect	No or negative predominance	None	Inverse	45° and 225°
Bar/coil movements	Positive	Direct	Inverse	225°
Electrical slot discharge	Positive	None	Direct	225°
Contamination or Electrical tracking	No predominance	None	Unpredictable	15°, 75°, 195°, 255°, can be erratic
Interface problem	Mostly positive	None	Direct	225°, can be 0°/180°
Gap-type discharge (Open air)	No predominance	Unknown	Unknown	0° - 90°, 180° - 270°
Vibration sparking *	No predominance	Direct	Inverse	Erratic
Broken strands *	No predominance	Direct	Unknown	Sometimes 0°/180°, can be erratic

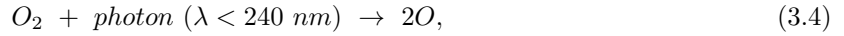
* Will only be seen in PD measurements if it is occurring at or near the phase line ends or it is near the neutral connection and an EMC is installed there.

3.3 PD and ozone

Ozone is formed when an oxygen molecule (O_2) is broken into single oxygen atoms by the action of light or an electrical discharge, which then react with other oxygen molecules.



or



then:



It should be noted that the reactions shown above are a simplified representation of the complex chain of events that occur at the molecular level, because the electrical discharges excite O_2 molecules in various ways and the dissociation can be quickly followed by the recombination into O_2 instead of O_3 . This is also not taking into account the vast amount of intermediate reactions that occur [74]. The actual rate of ozone formation is a parameter that is not easily calculated, especially outside of laboratory conditions.

Ozone is highly reactive and, for that reason, it is currently used in many kinds of applications, such as water treatment, sanitizing, food processing, etc. The main method to produce ozone commercially relies on corona discharges, which allow for concentrations of 3-6% to be produced using nothing but atmospheric air. Other techniques exist, such as UV radiation (concentrations of up to 0.5%), electrolysis and even through radioactive rays, but none of them are nearly as efficient.

In the interior of high-voltage machines, the ozone is formed by PD in the following manner:



Stone et al [61] state that “semiconductive coating deterioration tends to produce the most ozone”. The presence of ozone, nitrogen from the atmosphere and water (humidity), can trigger the formation of nitric acid (HNO_3), which is very corrosive. Thus, in sealed machines, where the internal atmosphere is not constantly renovated and which have high levels of PD in the stator, there is a higher chance of formation of nitric acid and corrosion”. The same work also mentions that nitric acid “attacks many substances, including epoxy, polyester, rubber compounds, lubricating oil and steel. In particular, the production of the nitric acid facilitates the spread of the semiconductive coating deterioration to adjacent areas. High levels of ozone are thus possible with this process, as experience shows that most coils/bars operating at a high voltage will eventually deteriorate due to the nitric acid attack, creating a large number of locations for the PD and thus more ozone to occur. In totally enclosed machines, the ozone concentration can reach over 10 parts per million (ppm)” [61]. Epoxy degradation by PD has been studied in a laboratory environment and the formation of acids in its surface is well known - not only nitric acid, but also formic, oxalic and glycoxalic acids [75].

A major challenge when using ozone concentrations to determine the approximate location of partial discharges is ventilation. Air flow severely affects concentrations. For instance, a lab experiment in a stator scale model showed that concentrations of ozone of 30,000 ppb produced by a defect with static conditions and measured behind the stator core quickly dropped to 180 ppb at an air flow rate of 1.5 m/s. The higher the flow rate, the smaller the concentration. Moreover, single localized PD sites are

unlikely to produce measurable quantities of ozone, especially if these sites are distant from the sensors or downwind with respect to cooling air flow.

Hence, the absolute levels of ozone inside a stator are probably not very meaningful (unless they are exceptionally high), but the comparison of measurements at different points as well as the determination of a baseline can be very useful to detect and confirm failure mechanisms that may be in action. Comparing the ozone concentrations with PD levels, machine load, voltage and temperature will certainly allow for a better diagnostic. If PD levels are increasing but ozone concentration remains stable, this could be an indication that PD is happening inside the insulation, for example.

There is another case where ozone measurements can help diagnosing surface PD. It is known that humidity severely affects the PD levels measured. In particular, high humidity levels tend to reduce the surface PD pulses measured through capacitive couplers [76]. This can be a bigger problem for off-line PD tests, when the machine is cool and exposed to higher humidity. In these cases, ozone measurements should be done as a complement to the traditional PD tests and will increase the reliability of the diagnostic. It is a good practice to record the temperature and humidity for every electrical test, since they usually influence heavily on the results.

In general, the ozone concentration can mostly be an indicative of surface discharges, such as:

1. Slot discharges.
2. Partial discharges due to vibration or displacement of bars.
3. Partial discharges due to contamination or tracking.
4. Partial discharges in the endwindings.
5. Partial discharges in the semiconductive / stress grading coatings.

For hydrogen-cooled machines, on-line ozone monitoring is not relevant since the quantities of oxygen are too small to form significant concentrations of ozone. If off-line tests are being done with the machine exposed to air, then it could be beneficial to record ozone concentrations with a portable equipment.

3.4 Ozone fluid dynamics

To better assess the viability of ozone as a predictive maintenance tool, it is important to understand its spatial distribution inside a hydrogenerator. Therefore, part of the ANEEL research project focused on the fluid dynamics theory and simulations, a work led by Prof. Rodrigo M. S. de Oliveira at UFPA [77].

The Navier-Stokes equations for incompressible viscous flow and the convection-diffusion equation for reactive gas species were implemented using COMSOL Multiphysics 5.5 in a detailed three-dimensional model of the hydrogenerator stator, based on technical drawings sent by the Enercan power plant. The model included 378 coil bars, air directors, rotor and radiators, with precise physical dimensions and material parameters. Ozone generation was introduced through localized cuboid sources, simulating PD emissions with a reaction rate derived from empirical discharge power data. Surface deposition losses were accounted for via accommodation coefficients specific to concrete, steel, epoxy, and semiconducting coatings.

The computational fluid dynamics (CFD) simulations produced nuanced ozone concentration maps across radiator surfaces. The most important conclusions of the simulations were that:

1. Ozone concentration in a given measurement spot is highly dependent on the source of the discharges and the configuration of stator bars, air inlets and rotor speed.
2. The top and bottom of the generator have a less obstructed airflow path, so higher azimuthal and vertical air velocity components are seen there, which means that ozone can be transported to an adjacent radiator, where it will have higher concentrations. Conversely, sources placed in lower-flow zones yielded more localized ozone signatures.
3. If several sensors are placed on each radiator, the simulations can help locate the source(s) of discharges. This would require, of course, a model of the specific machine, which is usually not readily available.
4. Using only one sensor in each radiator for ozone measurements can mean that localized sources of ozone can be completely missed, because the diffusion is far from uniform.

The simulation results were validated by a laboratory experiment using a stator bar in an acrylic chamber, as shown in Figure 18, with a normalized spatial prediction error of 10%. Although a single coil is very different from a full stator with a spinning rotor, the measurements helped calibrate the parameters considered in the CFD model.

The principal advantage of this approach lies in its ability to spatially resolve ozone emission patterns, allowing the exploration of sensor placement strategies and diagnostic optimization, providing a virtual testbed for system design. The simulations show that there could be very high differences of concentration depending on the exact position of the sensors. Therefore, a higher number of sensors would allow for more coverage of potential “hot spots”, while at the same time allowing for a more precise localization of the PD sources.

However, many limitations exist. The models assume steady-state conditions, which may not reflect transient PD behavior or fluctuating airflow. Computational demands are significant: each simulation required up to 14 hours and 124 GB of RAM. The simplification of ozone sources to cubic volumes and the absence of real-time data integration constrain the model’s real-world responsiveness. Real-life machines rarely present extremely localized discharges. The insulation ages as a whole, and therefore discharges happen in larger areas of the insulating material - even when considering a specific problem like semiconductive layer degradation or endwinding phase-to-phase discharges. This is verified by a real example in Chapter 5, where corona spots are found in multiple locations.

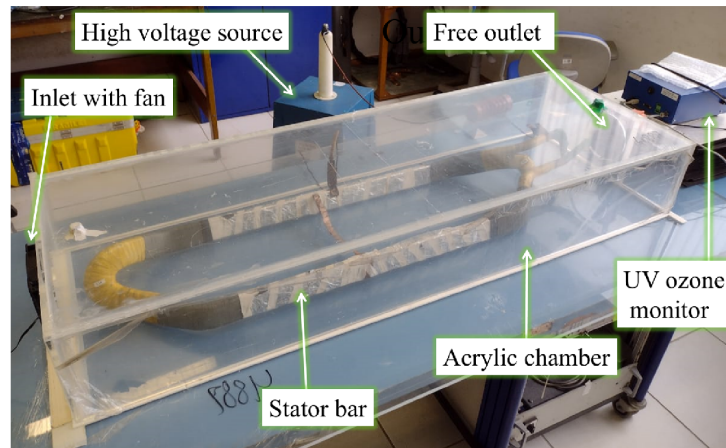


Figure 18 – Lab setup for model validation [77].

4 METHODOLOGY

4.1 Objectives

This work aims to evaluate continuous ozone monitoring as a predictive maintenance tool for hydrogenerators. Since continuous PD monitoring is the benchmark for online condition assessment of the stator insulation, one of the objectives is to compare ozone concentration data with partial discharge levels during a significant period of time, of at least a few months. This comparison can indicate possible correlations, limitations of the method or even reveal problems that would not be identified only with PD monitoring/testing.

Another objective is to source the best possible sensors and develop the ozone monitoring system at a cost that would allow it to be installed in machines where the viability of continuous PD monitoring is questionable, taking into account that the only commercially available alternative is imported and very expensive, probably costing about the same as a full-fledged online PD monitoring system.

A secondary objective is to secure the intellectual property of the ozone monitoring system developed so it can be commercialized as a product tailored for application in high voltage machines in the future.

4.2 Methods

In the previous chapter, the relationship between surface PD and ozone was presented and discussed with simulations and experiments that demonstrated the potential usefulness as a predictive maintenance tool. However, the practical implementation in a real power plant has its own challenges.

The research method can be separated in two major parts:

1. Ozone module development: this phase encompassed the selection and characterization of appropriate electrochemical sensors capable of reliably detecting low concentrations of ozone under varying environmental conditions found near the generator heat exchangers. The development process also involved the validation of sensor performance through laboratory-based experiments designed to replicate relevant operational scenarios. Furthermore, this phase included the complete design and fabrication of the sensor circuitry, ensuring compatibility with the onboard microcontroller for data acquisition, signal conditioning, and subsequent processing. Special attention was given to aspects of sensor calibration, environmental compensation (temperature and humidity), and mechanical robustness to ensure reliable long-term operation within the harsh conditions of a power plant.
2. Field evaluation: the second phase entailed the deployment and evaluation of the developed ozone monitoring modules within a real-world operational context. Specifically, the modules were installed in two 311-MVA hydrogenerators, in conjunction with existing continuous partial discharge monitoring systems, to facilitate comparative analysis and data validation. The field evaluation was designed to collect a comprehensive set of data, encompassing both ozone concentrations and key operational parameters such as voltage, current, stator temperature, and other relevant machine metrics. This integration enabled the assessment of correlations between ozone levels, PD activity, and machine operating conditions, thereby providing critical insights into the practical applicability and diagnostic effectiveness of the developed monitoring system in supporting condition-based maintenance strategies.

In an ideal research and operational scenario, a large number of similar machines, each potentially exhibiting different types and severities of insulation-related issues, would be equipped with both PD and ozone monitoring systems. Such a comprehensive deployment would facilitate extensive comparative analyses, allowing for a more nuanced understanding of the relationships between different failure mechanisms, operational conditions, and diagnostic indicators. The availability of diverse datasets from multiple machines would enhance the generalization of the findings. However, this luxury can't be afforded due to budget constraints and also because the power plant in the study has only three generators.

In the context of the present study, these limitations were further compounded by the specific operational characteristics of the power plant under investigation, which comprises only three generating units. Consequently, the scope of the study was necessarily constrained, and a strategic decision was made to select two of the three available machines at the Campos Novos Hydropower Plant - specifically UG2 and UG3 - for the installation and evaluation of the monitoring systems. This selection enabled a focused yet meaningful assessment of the proposed methodologies within a real-world operational setting.

UG3 was selected as the primary candidate for this study due to its documented history of surface PD activity, particularly localized in the endwinding regions (top and bottom), as well as evident degradation of the stress relief coating. These specific insulation defects are well-recognized precursors to ozone generation within rotating electrical machines, as the corona activity associated with surface PD leads to the formation of reactive oxygen species, including ozone. Therefore, UG3 presented an ideal case study for evaluating the effectiveness of the proposed ozone monitoring system in detecting and correlating ozone presence with known insulation deterioration.

The second machine selected for the study was UG2, primarily due to its physical proximity to UG3 within the power plant layout, which significantly simplified the logistics of system installation, data acquisition, and subsequent maintenance. Notably, both UG1 and UG2 had no specific or documented issues related to insulation degradation or PD activity at the time of the study. As such, either unit could have been appropriately designated as a baseline or "control group" for comparative purposes. Ultimately, UG2 was chosen to fulfill this role, providing an opportunity to compare ozone monitoring data between a machine with known insulation defects and one operating under normal conditions. This comparative framework was essential for assessing the diagnostic sensitivity of the monitoring system and for validating its applicability in distinguishing between healthy and deteriorating stator insulation states.

4.2.1 Generator and power plant information

Campos Novos (Enercan) hydro power plant is located in the river Canoas, between the cities of Campos Novos and Celso Ramos, both in the southern state of Santa Catarina, Brazil. The plant has a generation capacity of 880 MW and a reservoir with 29 km² of area, which translates to one of the best ratios between capacity and flooded area in the whole country.

Vertical Francis turbines power three generators, each with the specifications listed in Table 3.

The machines operate as generators and also as synchronous condensers, sometimes switching between these modes of operation fairly quickly, as can be seen from the reactive power graph in Figure 20. In fact, it is easy to note that UG3 actually operated much more often as a synchronous condenser in 2020 by looking at the stator temperature histogram, in Figure 21.



Figure 19 – Power house of the Enercan hydro plant.

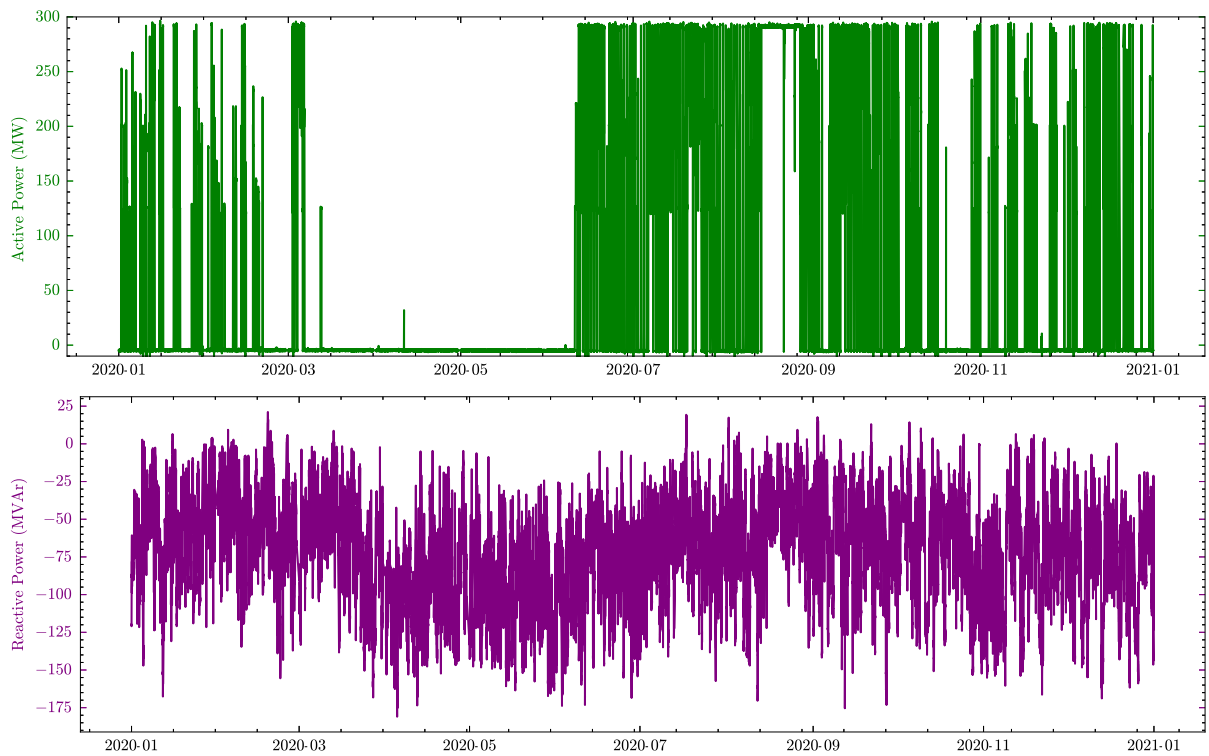


Figure 20 – Active power (top) and reactive power (bottom) for UG3 throughout the year of 2020.

Table 3 – Generator information.

Year of manufacture	2005
Manufacturer	GE
Type	Synchronous
Power	311 MVA
Power factor	0.95
Nominal Voltage	13.8 kV
Nominal Current	13011 A
Parallel circuits per phase	6
Poles	36
Speed	200 rpm
Number of slots	378
Thermal class	F

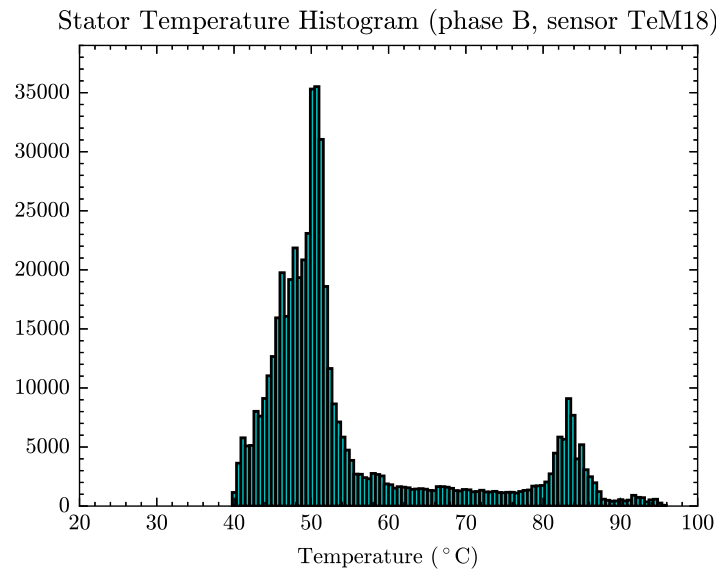


Figure 21 – Temperature histogram for UG3 throughout the year of 2020. The y-axis represents the sum in minutes.

4.2.2 PD monitoring

All three machines from Enercan had PD couplers (80 pF) already installed, but no continuous monitoring equipment. The PD monitor chosen for this research project was the GuardII+, manufactured by Iris Power LP (Canada), with the technical characteristics shown in Table 4.

4.2.2.1 Differential coupler installation

As shown in the previous chapter (Figure 15), a basic Differential PDA coupler installation consists of six couplers, two installed per phase. Couplers in a pair must be separated from each other by at least 2 m of conductor and circuit ring combined. The couplers should be connected as close as possible to the line-end coils of each parallel circuit on opposite ends of the circuit ring as shown in Figure 22, and within 1 m of where the line-end coil is jointed to the circuit ring. Each circuit ring is monitored individually.

In electrical machines equipped with multiple parallel circuits connected to a common circuit ring, it is possible to install several pairs of PD couplers per phase — typically one pair per parallel branch, although this configuration is not strictly required. The coaxial cables (designated L1 and L2)

Table 4 – Continuous PD monitoring system.

Manufacturer	Iris Power
Type of installation	Differential
Number of coupler inputs	18
Measurement cycle time	32 mins
Input sensitivities	2 mV-34 mV 5 mV-85 mV 10 mV-170 mV 20 mV-340 mV 50 mV-850 mV 100 mV-1700 mV 200 mV-3400 mV 500 mV-8500 mV 1 V-17 V 2 V-34 V
Input impedance	50 Ω
Analog bandwidth	350 MHz
Phase windows	100
Communication	Modbus over TCP/IP

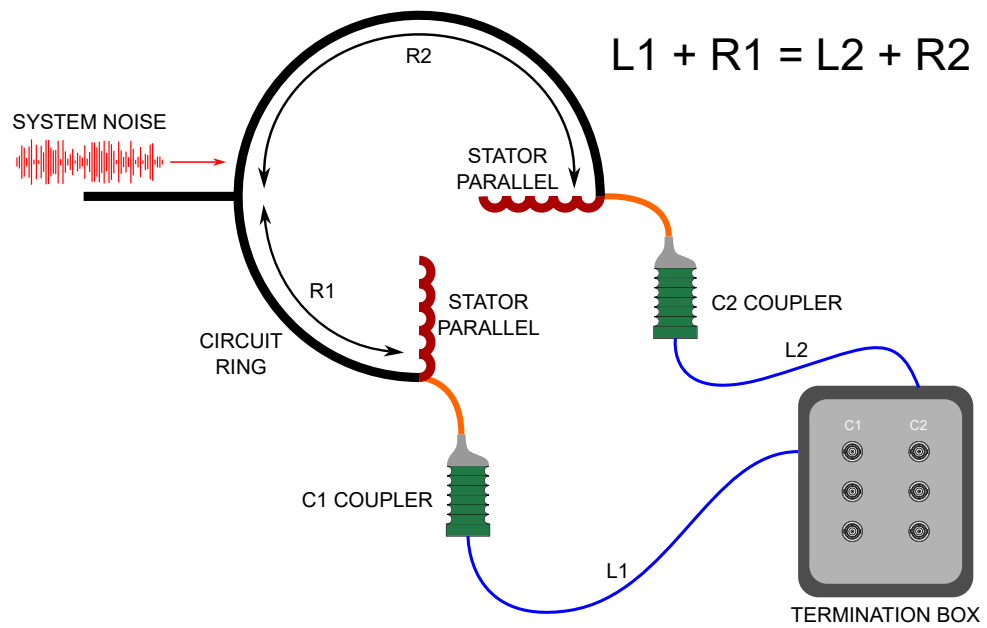


Figure 22 – Example of PDA installation.

that connect couplers C1 and C2 to the terminal box where measurements are acquired must be carefully trimmed to ensure equal electrical path lengths. This symmetry is essential to guarantee that external noise signals arriving simultaneously and with identical waveform characteristics can be reliably identified and discarded during analysis. For optimal performance, these coaxial cables should be installed along grounded surfaces to reduce electromagnetic interference.

The termination box, where the measurement instrument can be connected (either for periodic or continuous monitoring), is generally installed in a location that offers convenient access for routine data collection during normal machine operation. Additionally, this placement should minimize the overall length of the coaxial cables, thereby reducing signal attenuation and preserving signal fidelity. It is essential that the termination box be properly grounded to a reliable earth point within the plant's electrical grounding system.

At Enercan, there are 3 coupler pairs per phase, for a total of 18 couplers. The couplers were installed during the plant commissioning in 2005, according to the drawings seen in Figures 23 and 24.

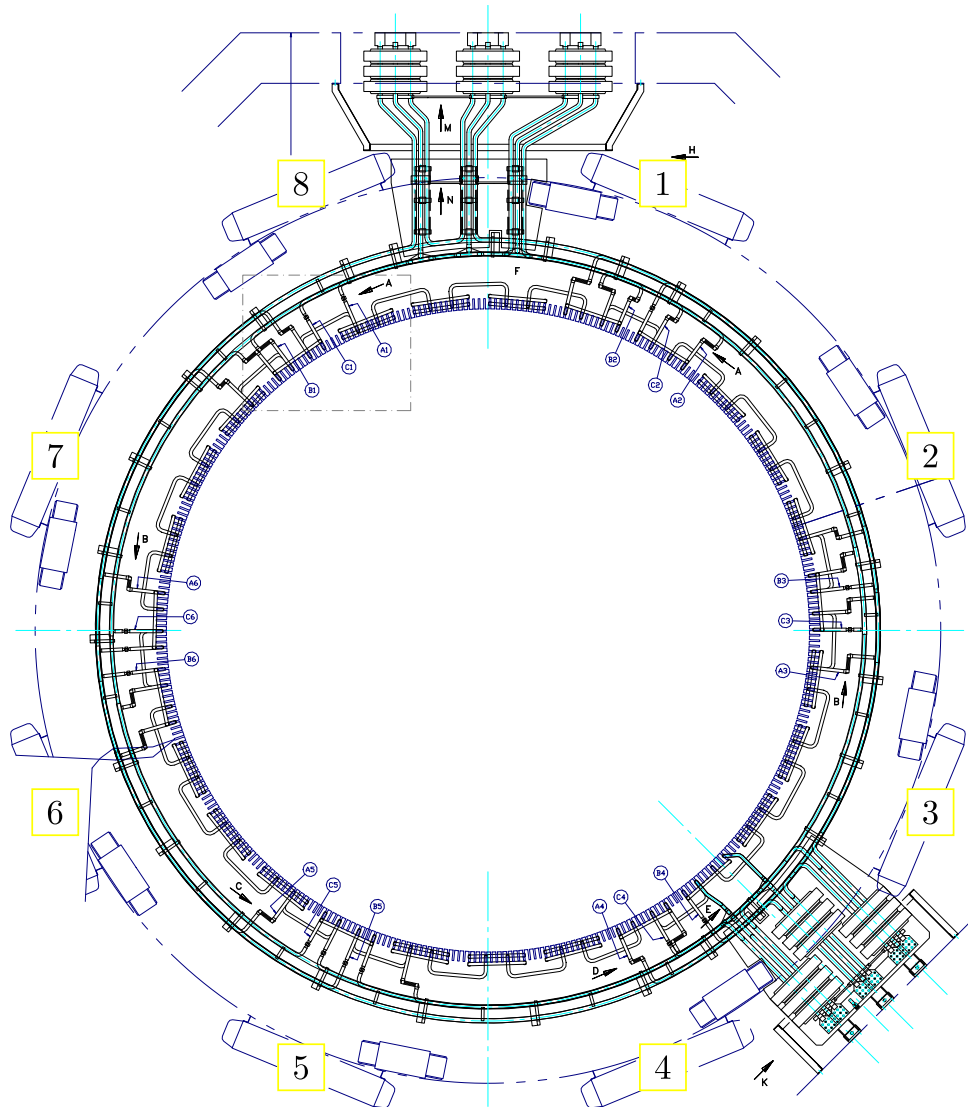


Figure 23 – Coupler installation at Enercan, with radiators numbered 1 through 8.



Figure 24 – Detail of couplers installation.

4.2.3 Ozone sensor module design

The design of a sensor module for application in hydrogenerators has several constraints. The first step was to define the design guidelines for this application.

One obstacle is the machine design itself and its cooling system, which can vary greatly. For this reason, the module should be compact enough to allow installation in air ducts, radiators, cubicles and similar structures, offering enough flexibility to be as close to the ozone sources as possible. The module should be easy to install, debug and maintain by power plant staff without bespoke tools.

The measured signals have to be transmitted in industrial environments, so the module output should comply with standard protocols. For analog signals, a 0-10 V output was chosen. The design also included relevant input protections (over-current, over-voltage, voltage spikes and polarity inversion).

The module must have the capability to process signals for filtering, calibration and alerting purposes. The initial prototype uses an Arduino Nano for these tasks.

Since the available literature quotes ozone concentrations of up to hundreds of ppb in hydrogenerators, the sensor range should be around 0-1000 ppb. The absolute values are not critical, but the trend information is important, so an exact accuracy requirement was not established in advance.

Air exiting the stator can have fairly high temperatures, compared to typical applications of electronic circuits. To evaluate this constraint, data from the 311 MVA hydrogenerator where the modules would be installed was assessed to verify the conditions right next to the radiators, as seen in Figure 25.

Another issue is the rate of change of temperature and humidity, which can affect the electrochemical sensor measurements. In this specific environment, especially due to alternation between operation modes (generator and synchronous condenser), humidity and temperature can vary up to 1.7 %/minute and 0.3 °C/minute, respectively. As a comparison, rates of change in humidity that would not affect electrochemical ozone sensors significantly are around 0.1%/minute [78]. This implies that using an electrochemical sensor for this application would require methods to compensate for possible errors caused by a rapidly changing environment. For this reason, a temperature and humidity sensor was included in the board design and integrated into the microcontroller.

Since the electromagnetic environment can also be a concern for this application, a model of the generator was evaluated in finite-element software to estimate worst cases [79]. A simplified model of the electrochemical sensor positioned at different distances from the stator showed induced voltages of 26-1671 μV , which could mean a 0.05 % error at full scale of 0-3.3 V. The simulations, however, did not account for the grounded metallic radiators themselves and the grounded steel case inside which the

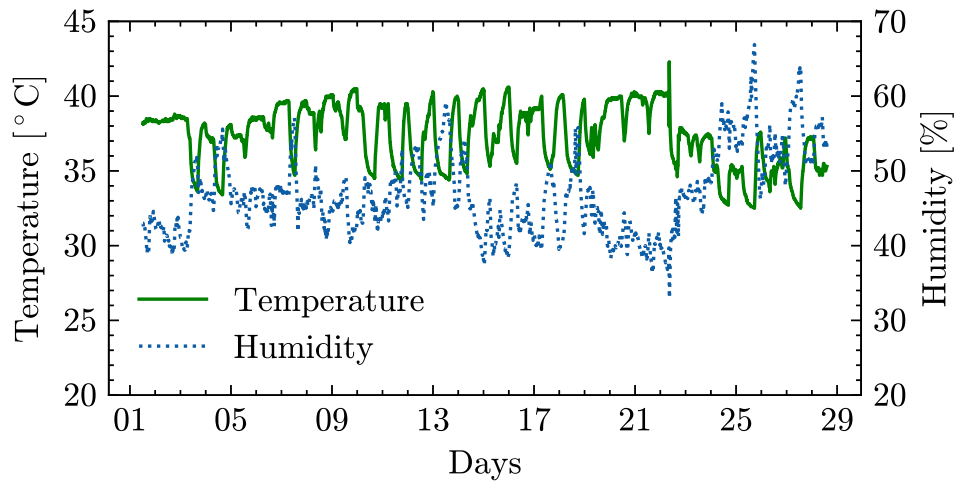


Figure 25 – Environmental conditions near machine radiators.

sensors would eventually be installed, which help further shield the sensor and its auxiliary circuit, so this potential source of errors was ignored for the remainder of the project, since its impact would not be relevant for the digital and/or analog signals, when compared to other sources of errors discussed in chapter 5.

4.2.3.1 Electrochemical ozone sensor requirements

Extensive research was done to find and quote the highest number of commercially available ozone sensors possible, in order to select the best option overall. The main sensors considered are shown in Table 5.

The first criterion for sensor selection was the range. Since the literature has examples ranging from tens of ppb to several hundreds and no data was available for the power plant where the modules would be installed, a 0-1 ppm range seemed like a safe choice.

Adding to this criterion the objective of developing a low cost monitoring system two models were initially considered: Winsen ZE25A-O3 and SPEC Sensors ULPSM-O3.

Table 5 – Comparison of commercially available ozone sensors.

Manufacturer	Winsen	Winsen	SPEC Sensors	Alphasense
Model	ZE25-O3	ZE25A-O3	ULPSM-O3	OX-B431
Technology	Amperometric	Amperometric	Amperometric	Amperometric
Range (ppm)	0-10	0-2	0-20	0-20
Minimum detection limit	?	?	<100 ppb	?
Resolution (ppb)	10	1	<100	15
Response time (s)	90	90	30	45
Operating temperature (°C)	-10 a 55	-10 a 55	-20 a 40	-30 a 40
Sensitivity to NO_2	1	1	1	1
Average price (USD)	50	50	50	80-170

Manufacturer	Membrapor	Citytech / Honeywell	Aeroqual	Aeroqual
Model	O3/S-5	O3 3E 1F	SM50	SM50
Technology	Amperometric	Amperometric	HMOS	HMOS
Range (ppm)	0-5	0-2	0-10	0-0.5
Minimum detection limit	?	?	10 ppb	1 ppb
Resolution (ppb)	30	30	10	1
Response time (s)	60	60	60	60
Operating temperature (°C)	-40 a 50	-20 a 40	-5 a 40	-5 a 40
Sensitivity to NO_2	1	0.6	0	0
Average price (USD)	100-300	>100	450	450

A third sensor model, Sensirion SGP-41, was also tested in later stages of the project. However, it is not an ozone sensor but rather an air quality sensor that has sensitivity to ozone, among other gases. This sensor has two signal outputs, VOC (volatile compounds) and NO_x . The manufacturer doesn't

specify the exact sensitivity for a comprehensive set of gases, but the datasheet has a graph for the NO_x signal with an individual curve for ozone, shown in Figure 26. The signal has arbitrary units, named “ticks”, and cannot be calibrated to a norm.

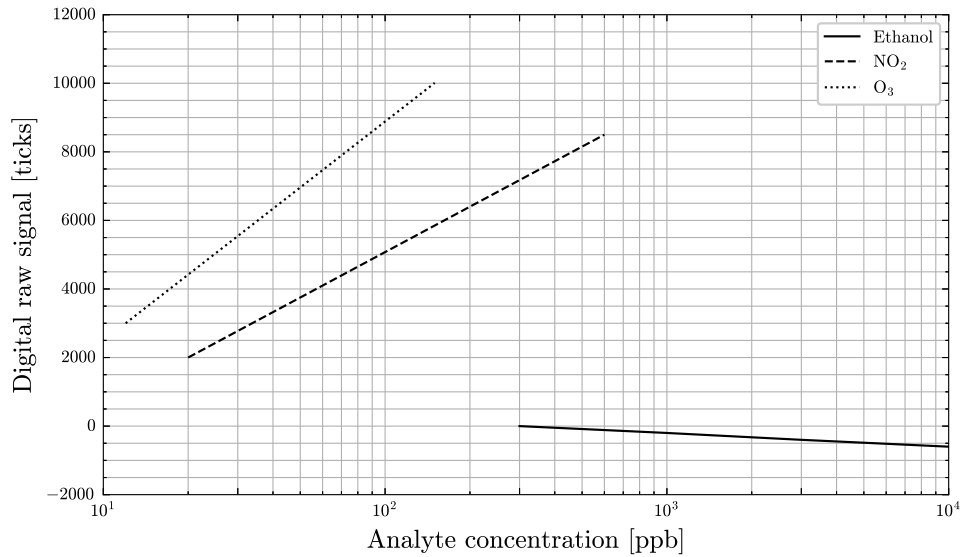


Figure 26 – SGP41 NO_x signal sensitivity [80].

4.2.3.2 Circuit design

Considering the sensor module will be used in industrial environments, a few initial constraints were defined. The power input was chosen as 24 V DC, a supply voltage common for automation and control equipment. Over-voltage, over-current, voltage surge and polarity inversion protections were added to the power input stage, which uses a 12 V DC linear regulator, as seen on Figure 27.

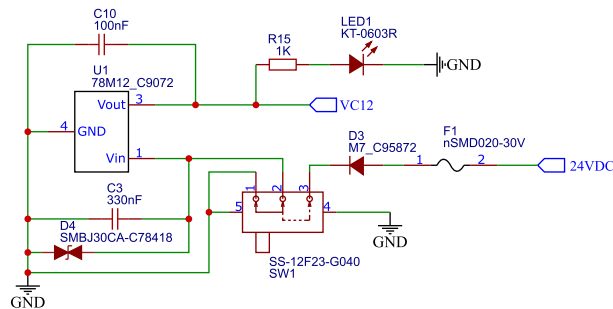


Figure 27 – Protections and 12 V DC regulation for the module board.

The UART output of the sensor must be read by a microcontroller, using a buffer and checksum to avoid errors. The microcontroller initially chosen was an Arduino Nano development board, which has a power supply voltage of 5 V DC. Therefore, a 5 V rail was added to the design, also linearly regulated, as seen on Figure 28.

With the knowledge acquired from the lab tests that temperature and humidity compensations will be needed, an analog humidity/temperature sensor is also present in the module, shown in Figure 29.

To send measurement data through the plant network, a separate digital-to-analog (DAC) integrated circuit is used to preserve signal accuracy (MCP4725). Figure 30 shows the DAC in the circuit.

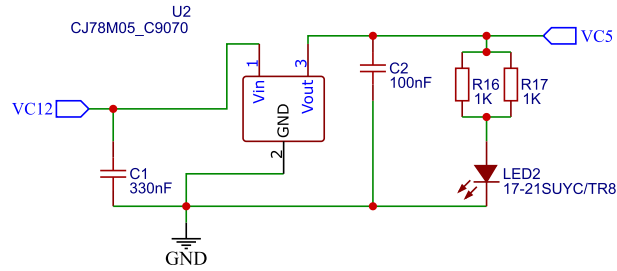


Figure 28 – 5 V DC regulation for the module board.

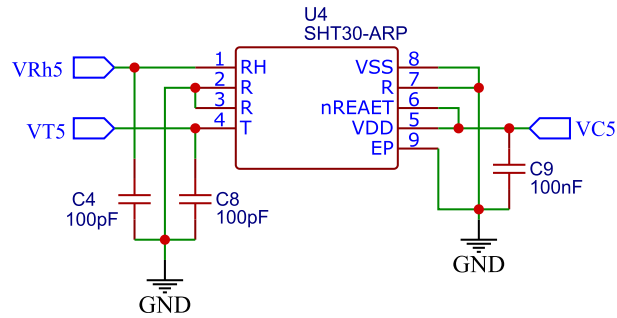


Figure 29 – Onboard humidity and temperature sensor.

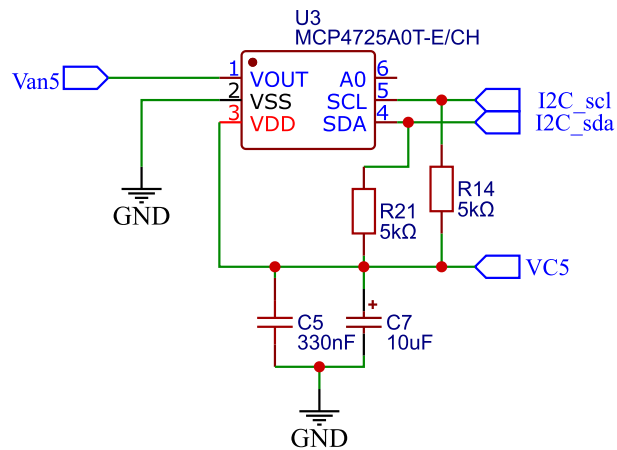


Figure 30 – Digital-to-analog converter used in the design.

The resulting 0-5 V analog signals from ozone, temperature and humidity is then amplified to 0-10 V using an LM324 operational amplifier, shown in 31. The 0-10 V signal can be read by common Programmable Logic Controller (PLC) inputs, and although not as resilient to noise as a 4-20 mA type of signal, it was easier to implement.

The whole circuit was then translated to a printed circuit board layout and manufactured, as seen on Figure 32. The first prototypes had minor issues corrected and a few improvements, so a second iteration was manufactured for the final installation at the power plant.

4.3 Installation at the power plant and system topology

The PD monitoring system was installed in UG2 and UG3 in June/2022 and started collecting data right away. During this period, the full infrastructure for power and data was also installed, which involved pulling cables from distant parts of the power plant, installing and wiring panels and electrical

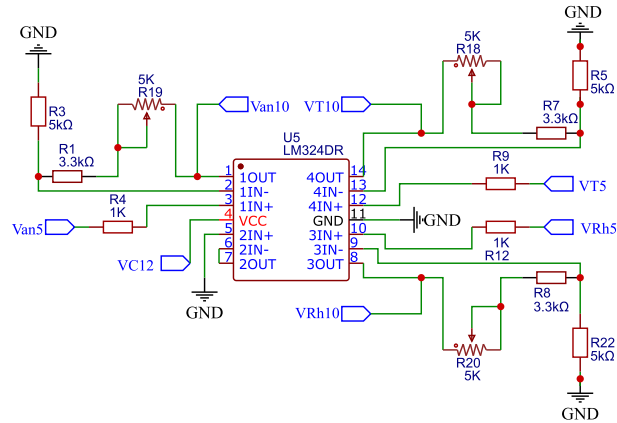


Figure 31 – Analog amplification of signals using operational amplifier.

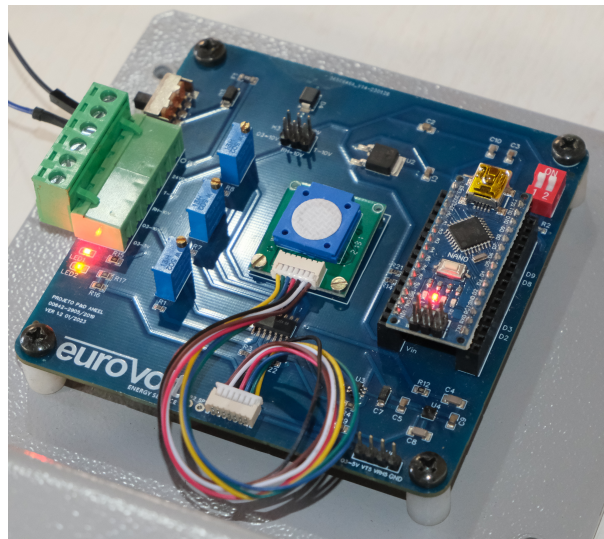


Figure 32 – Final assembly of the board.

equipment, such as a frequency converter, PLCs, Ethernet switches, etc. However, due to various reasons and many delays, the ozone sensing system, which was developed in this research project, could only be installed in UG3 in September/2023. For UG2, the installation happened in April/2024.

The modules were housed within custom-designed steel enclosures, which were powder-coated to enhance durability and conform to the established color standards of the power plant. Installation on the radiators was accomplished using a horizontally mounted bar, securely bolted to the radiator frames. Given that the radiators measured approximately 3 meters in height and 2 meters in width, the central position was selected for sensor placement. This choice was made despite simulation results indicating that ozone diffusion might occur at higher rates in other regions, contingent upon the specific locations of ozone sources and prevailing airflow patterns. A schematic representation of the generator's vertical cross-section is provided in Figure 33, wherein one radiator is highlighted to illustrate the positioning of a representative sensor.

During the installation of the ozone monitoring system, each module was individually tested to ensure proper functionality and the expected sensitivity to ozone. The sensors employed had been previously selected through laboratory experiments, based on their correlation with the reference UV measurement instrument. After each installation, the system was checked to make sure data was being correctly sent to the server and properly recorded in the database. The cabinet with the PLC where the

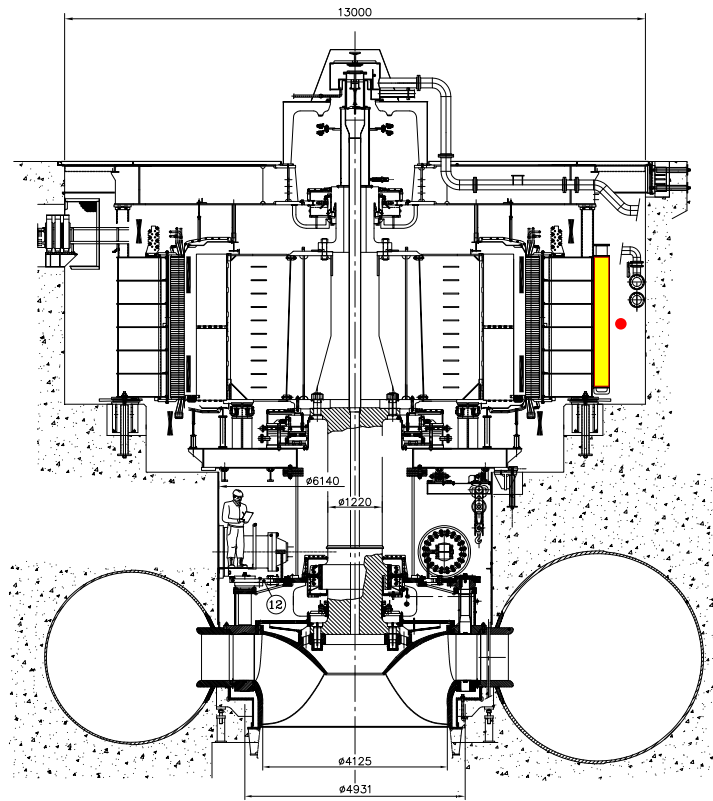


Figure 33 – Drawing of the generator and position of one of the modules installed (red dot). The radiator is highlighted in yellow.

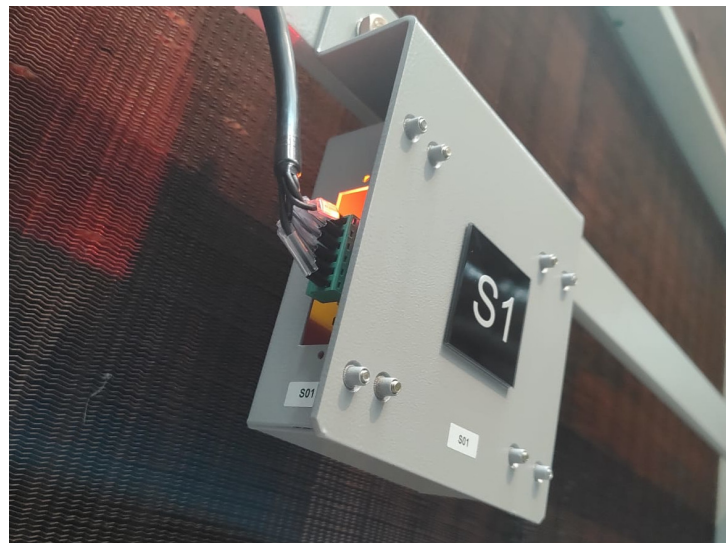


Figure 34 – One of the sensing modules installed at the power plant, in the center of the heat exchanger.

modules were connected is shown in Figure 35.

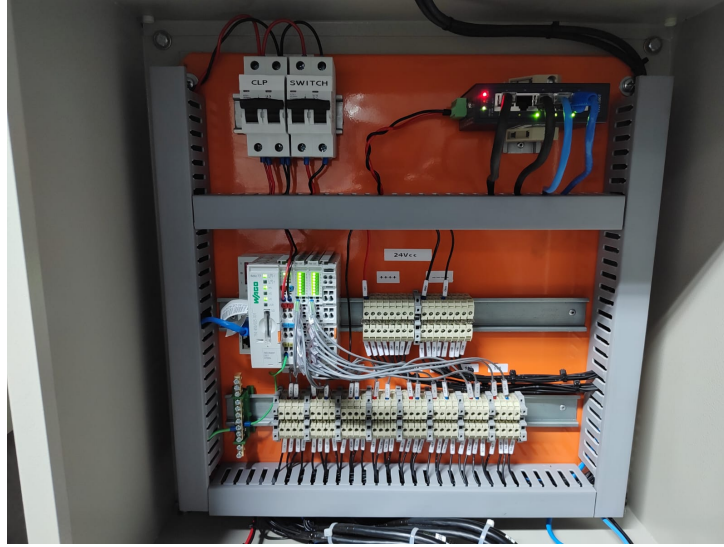


Figure 35 – Electrical cabinet of the ozone monitoring system.

The full system topology is shown in Figure 36, for one of the generators. Both UG2 and UG3 are connected via Ethernet to the same server in the control room of the power plant.

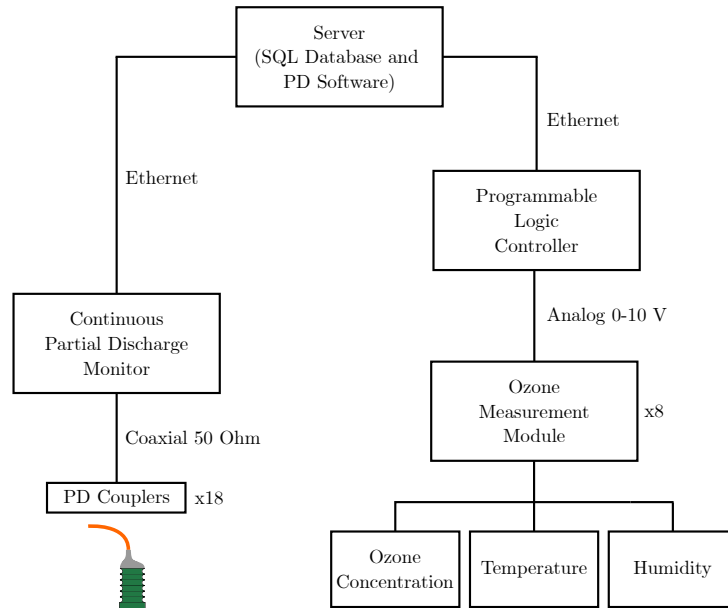


Figure 36 – System topology.

4.4 Restrictions

As discussed in the previous chapter, ozone measurements around the machine are influenced by several environmental and geometric factors, including airflow patterns, humidity, temperature, proximity to PD sources, and the physical layout of the generator. As a result, absolute ozone concentration values, when considered in isolation, have limited diagnostic significance. To address this limitation, the methodology of this project prioritizes continuous monitoring, which enables the identification of temporal trends and patterns that are more robust indicators of insulation condition and machine health.

It is also important to acknowledge the intrinsic limitations of ozone monitoring in the context of comprehensive insulation diagnostics. Specifically, PD activity that occurs internally within the insulation system (such as that arising from delamination, the formation of internal voids, or other subsurface defects) does not result in the production or release of ozone into the surrounding environment. Therefore, ozone monitoring is inherently incapable of detecting such forms of PD. As a result, it is neither intended nor recommended that ozone monitoring be viewed as a substitute for conventional PD monitoring techniques, which remain indispensable for the detection of both surface and internal discharge phenomena.

With respect to the instrumentation employed, electrochemical sensors present certain disadvantages that must be considered. Although advancements in sensor design and manufacturing processes have led to the development of more reliable and durable electrochemical sensors, the fundamental measurement principle involves a chemical reaction, whereby the sensor's active elements degrade over time. Consequently, sensor replacement is required after a finite operational lifespan, which varies depending on the specific model and manufacturer specifications. For instance, in the case of the Winsen ZE25-AO3 electrochemical ozone sensor utilized in this study, the manufacturer specifies a nominal service life of approximately two years under standard operating conditions.

Another notable limitation associated with the use of low-cost electrochemical sensors pertains to variability in manufacturing quality. Due to the economic constraints associated with producing affordable sensors, quality control measures may be less stringent, leading to inconsistencies in sensor performance. It is not uncommon to encounter sensors that exhibit systematic deviations from expected calibration behavior, thereby compromising the reliability of collected data. To mitigate this risk, it is essential to implement a secondary, post-purchase quality assurance protocol. Such measures ensure that only sensors meeting the required performance standards are deployed in the field, thereby safeguarding the integrity of the monitoring data and the validity of subsequent analyses.

Ideally, the ozone monitoring system would be deployed across a large number of machines, thereby enabling comprehensive comparative studies of various failure mechanisms and facilitating the identification of correlations between PD activity and ozone generation in various operational contexts. This would also allow for the collection of a sufficiently large dataset to support statistically significant conclusions regarding insulation degradation processes. However, as previously noted, the realization of such an extensive monitoring study is hindered by financial and logistical constraints.

5 RESULTS

5.1 Validation of the electrochemical sensors

Winsen ZE25A-O3 and SPEC ULPSM-O3 sensors were purchased and tested in laboratory. The experiment setup consists of an acrylic box of around 40 cm x 60 cm x 30 cm, inside of which the sensors are placed, along with a tube coming from an ozone generator, as seen in Figure 37. The ozone generator is controlled with an Arduino for repeatability. Inside the box, an incandescent light bulb, also controlled electronically, allows for variations of temperature and humidity, which are also measured continuously. A humidifier was added to the setup for specific tests to simulate more rapid humidity spikes.

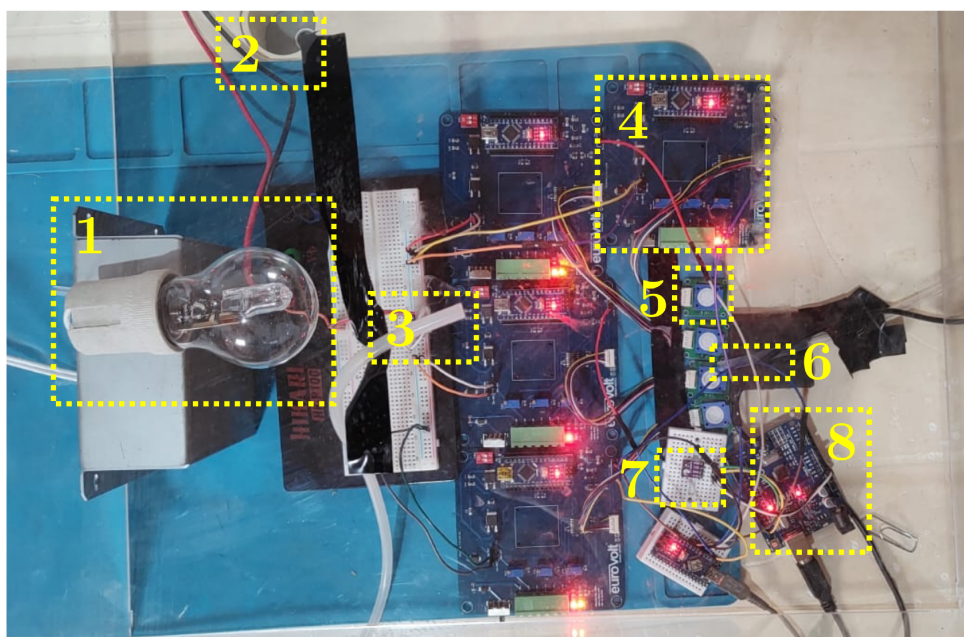


Figure 37 – Experimental setup for sensor evaluation. 1- Incandescent bulb for controlled heating. 2- Humidifier inlet. 3- Ozone generator tube (taped to the top of the acrylic box for more uniform gas distribution). 4- Signal processing board. 5- Winsen ZE25-AO3 electrochemical sensor. 6- Inlet tube of the reference Ozone monitor. 7- Sensirion SGP41 metal oxide sensor. 8- Microcontroller for data recording.

The reference for ozone concentration measurements is a 2B Tech 106-L NIST-certified monitor with 1.5 ppb (or 2%) precision, shown in Figure 38. This equipment uses the UV absorption principle to measure ozone concentration and the sample passes through an internal Nafion tube which removes humidity. It can measure 0-100 ppm with 0.1 ppb resolution. The ozone generator was an unbranded model commonly used in aquariums for disinfection purposes, which mainly consists of a small air pump, a high-voltage transformer and a Dielectric Barrier Discharge tube. It can generate up to 1,000 mg of ozone per hour, according to the manufacturer.

The ULPSM-O3 sensor did not yield usable results, with extreme noise content to the point where the manufacturer had to send new units, because there was suspicion of manufacturing defects. The new batch presented similar results, so this model was promptly abandoned.

The best performing electrochemical sensor model, Winsen ZE25-AO3, has a range of 20-2000 ppb and, according to the manufacturer, can withstand up to 50 °C in operation, with an estimated life



Figure 38 – Reference instrument.

span of 2 years. The sensor only outputs data via serial interface (UART) and has no analog outputs.

To evaluate multiple sensors at the same time, microcontrollers were used to read data and communicate with a computer for logging purposes. Around 60 units were purchased throughout the project for validation and destructive testing. In Figure 39, one of the tests is shown, where four units were tested simultaneously during 9 hours with 6 temperature variation cycles between 37-45 °C and compared to the reference instrument. Ozone generation cycles were programmed for every 10 minutes, reaching ≈ 700 ppb and returning to baseline before the cycle restarts. This test was performed to verify linearity under temperature conditions similar to those found near machine radiators and possible hysteresis effects. Figure 40 shows the scatter graphs of each electrochemical sensor, compared to the reference UV measurements.

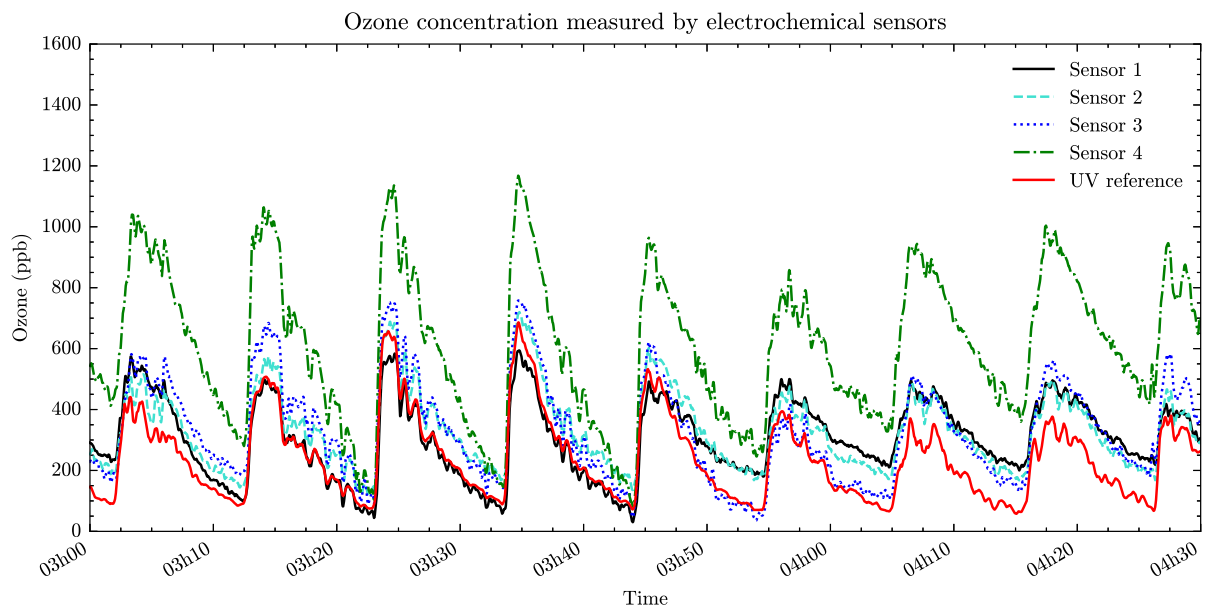


Figure 39 – Electrochemical sensor measurements compared to reference UV absorption method.

Four metrics were chosen to evaluate the sensors compared to the reference instrument (correlation coefficient, Spearman ρ , bias error and RMSE). The correlation coefficient is defined by:

$$r = \frac{\sum (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum (X_i - \bar{X})^2 \sum (Y_i - \bar{Y})^2}} \quad (5.1)$$

where X_i and Y_i represent, respectively, each measurement from the samples sets X (reference UV instrument) and Y (electrochemical sensor). A coefficient of 1 represents perfect linear correlation. The Spearman ρ uses the same basic equation, but substitutes $\mathcal{R}(X_i)$ and $\mathcal{R}(Y_i)$ for X_i and Y_i , where $\mathcal{R}(X_i)$ is the rank of measurement X_i and $\mathcal{R}(Y_i)$ is the rank of measurement Y_i [81]. Spearman's ρ was chosen because there was a possibility that low cost sensors could have a monotonic relationship with the reference measurements, but perhaps not very linear. This metric is also more robust to outliers, which can happen with certain low cost sensors. The bias error is simply the absolute value of the difference between the averages of all measurements $|\bar{X} - \bar{Y}|$ and, for this case, the RMSE for n samples is defined by:

$$RMSE = \sqrt{\frac{1}{n} \sum (X_i - Y_i)^2} \quad (5.2)$$

The results are listed in Table 6, showing good correlation, but also that individual calibration is needed.

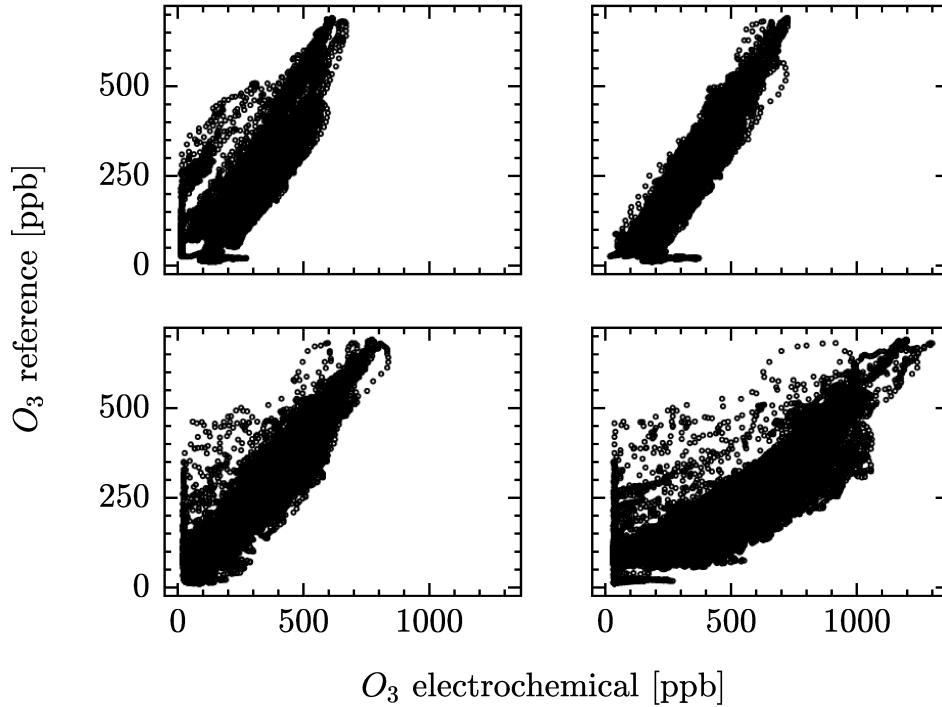


Figure 40 – Tests comparing electrochemical sensors to reference UV absorption method.

Table 6 – Signal comparison for electrochemical sensors.

Sensor	Corr. Coeff.	Spearman ρ	Bias error	RMSE	RMSE %
S1	0.8045	0.7949	54.69 ppb	103.14 ppb	15.44
S2	0.9316	0.9111	85.63 ppb	99.14 ppb	13.69
S3	0.9066	0.8926	59.89 ppb	93.34 ppb	11.17
S4	0.8318	0.8307	245.97 ppb	312.05 ppb	24.00

As mentioned in Chapter 4, a third type of sensor was also tested, the air quality sensor Sensirion SGP41. This sensor is a state-of-the-art digital gas sensor developed for accurate and robust indoor air quality monitoring, targeting volatile organic compounds (VOCs) and nitrogen oxides (NOx). Based on metal-oxide (MOx) sensing technology, the sensor offers a complete solution on a single chip, including temperature-controlled micro-hotplates and a digital I²C interface. It outputs both raw signals and processed VOC and NOx indices, which are humidity-compensated and mapped onto a standardized scale (1–500), facilitating straightforward interpretation in air quality applications. With a compact $2.44 \times 2.44 \times 0.85 \text{ mm}^3$ DFN package, low power consumption (3.0 mA at 3.3 V), and high resilience to contaminating gases, the SGP41 is marketed for integration into high-volume consumer products such as air purifiers and demand-controlled ventilation systems [80].

Figure 41 shows the two outputs of the sensor in arbitrary units. The datasheet only declares sensitivity to ozone for the NOx signal, but it's possible to notice some correlation in the VOC signal as well. Since these signals are in arbitrary units, using RMSE and bias errors as metrics makes no sense, so they were replaced by Kendall's Tau and Cosine Similarity for quantitative analysis.

Kendall's Tau (τ) is a non-parametric statistic used to measure the ordinal association between two variables. It quantifies the degree to which the relationship between two variables can be described by a monotonic function. Given two variables X and Y with n paired observations, Kendall's Tau is calculated based on the number of concordant (n_c) and discordant (n_d) pairs [82]:

$$\tau = \frac{n_c - n_d}{\frac{1}{2}n(n-1)}$$

A pair of observations (x_i, y_i) and (x_j, y_j) is said to be concordant if the ranks of both elements agree (both increase or both decrease), and discordant if they disagree. The value of τ lies in the interval $[-1, 1]$, where $+1$ indicates perfect agreement, -1 indicates perfect disagreement, and 0 indicates no association. Kendall's Tau is particularly useful in scenarios with many ties or non-linear relationships.

Cosine similarity is a metric that evaluates the angular similarity between two non-zero vectors, independent of their magnitude. It is especially appropriate for comparing variables measured in arbitrary units, as it focuses solely on the shape of the data [83]. Given two discrete data vectors $\mathbf{x} = [x_1, x_2, \dots, x_n]$ and $\mathbf{y} = [y_1, y_2, \dots, y_n]$, the cosine similarity is computed as:

$$\cos(\theta) = \frac{\mathbf{x} \cdot \mathbf{y}}{\|\mathbf{x}\| \cdot \|\mathbf{y}\|} = \frac{\sum_{i=1}^n x_i y_i}{\sqrt{\sum_{i=1}^n x_i^2} \cdot \sqrt{\sum_{i=1}^n y_i^2}}$$

The result ranges from 0 to 1 for non-negative data, where a value close to 1 indicates that the two vectors point in the same direction (in other words, have similar temporal behavior), while values closer to 0 indicate orthogonality or lack of similarity. Since cosine similarity is unaffected by the scale of the data, it is widely used in pattern recognition and signal comparison tasks.

The results can be seen in Table 7. As suspected, although not high, there is some correlation. One important caveat for these measurements is that the ozone sensitivity declared in the datasheet goes from approximately 10 to a little over 100 ppb. The test ranges are much higher, so maybe in lower ozone concentrations, the SGP41 sensor could perform better. Although the manufacturer clearly states that it is not possible to calibrate the sensor to specific concentrations, this was attempted anyways, using a simple linear regression to match ppb values from the reference instruments. As seen in Figure 42, the calibrated values have a noticeable drift. However, the result might be acceptable in certain contexts, with a RMSE of 129 ppb or about 12.4% (relative to the signal range). Since this sensor can be currently purchased for less than USD 10.00, the price/performance ratio is very interesting.

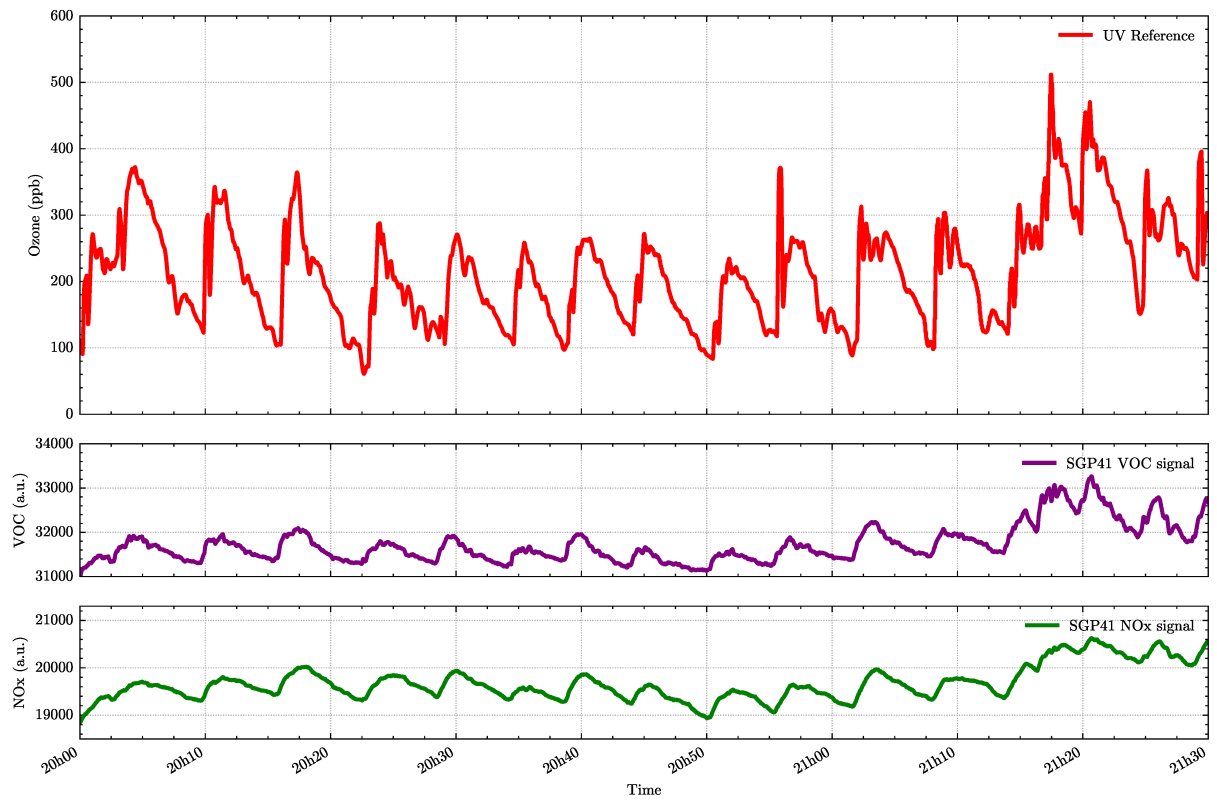


Figure 41 – Comparison of SGP41 MOx sensor outputs and ozone concentration.

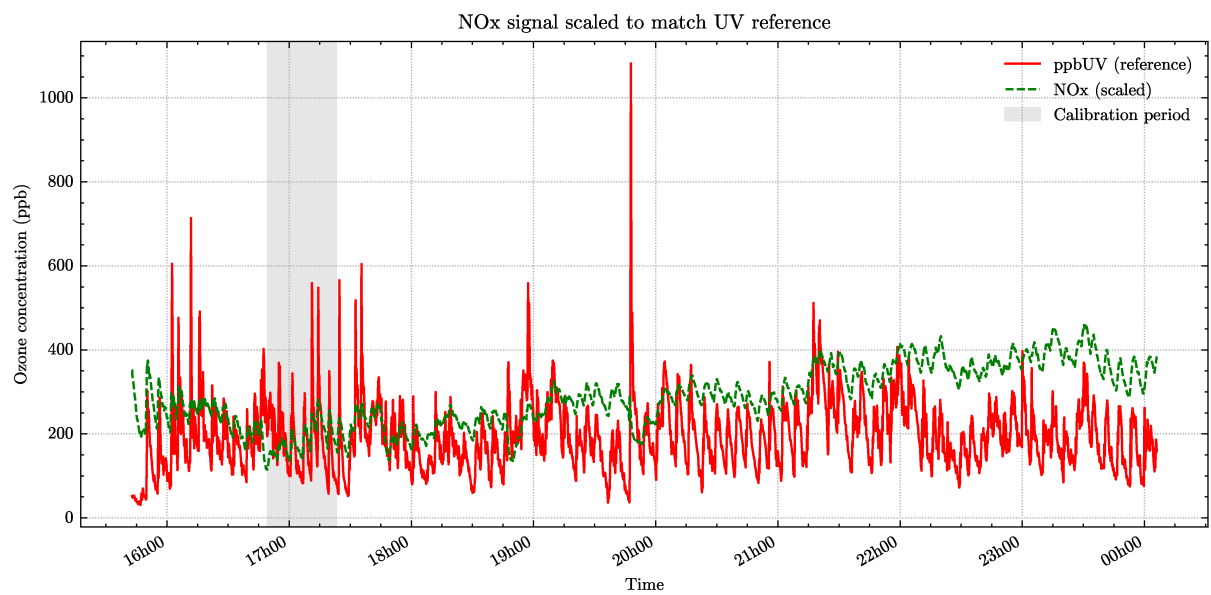


Figure 42 – SGP41 calibration attempt.

Table 7 – Correlation benchmarks for VOC and NOx with respect to UV reference.

Signal	Pearson	Spearman ρ	Kendall's τ	Cosine Sim.
VOC	0.2683	0.3483	0.2367	0.9267
NOx	0.2841	0.3270	0.2231	0.9285

One aspect of low cost electrochemical sensors that often has to be taken into consideration is the cross-sensitivity to other gases, which is usually non-negligible [84]. Ozone sensors can be sensitive to NO_2 , and the manufacturer of this specific model declares this information in the datasheet, but without quantifying the effect. From similar types of sensors, however, it can be expected that the cross-sensitivity factor is close to 1. Since PD in air also produces NO_x compounds [85], this is not an obstacle to the intended application, because the aim is to detect PD and track its trends. Alternatively, electrochemical NO_2 sensors could be used for the same objective, as they often have cross-sensitivity to ozone. Therefore, the orthogonality requirements for calibration are not so strict [84].

5.2 Temperature and humidity compensation

During rapid variations in humidity, electrochemical sensors become notoriously unreliable. Temperature variations also have an effect, but not as pronounced. Figure 43 shows a test where a humidifier was turned on for a few seconds to increase humidity inside the test chamber. Notice the signal from the Winsen electrochemical sensor saturates to 2000 ppb, while the real concentration was around 300 ppb.

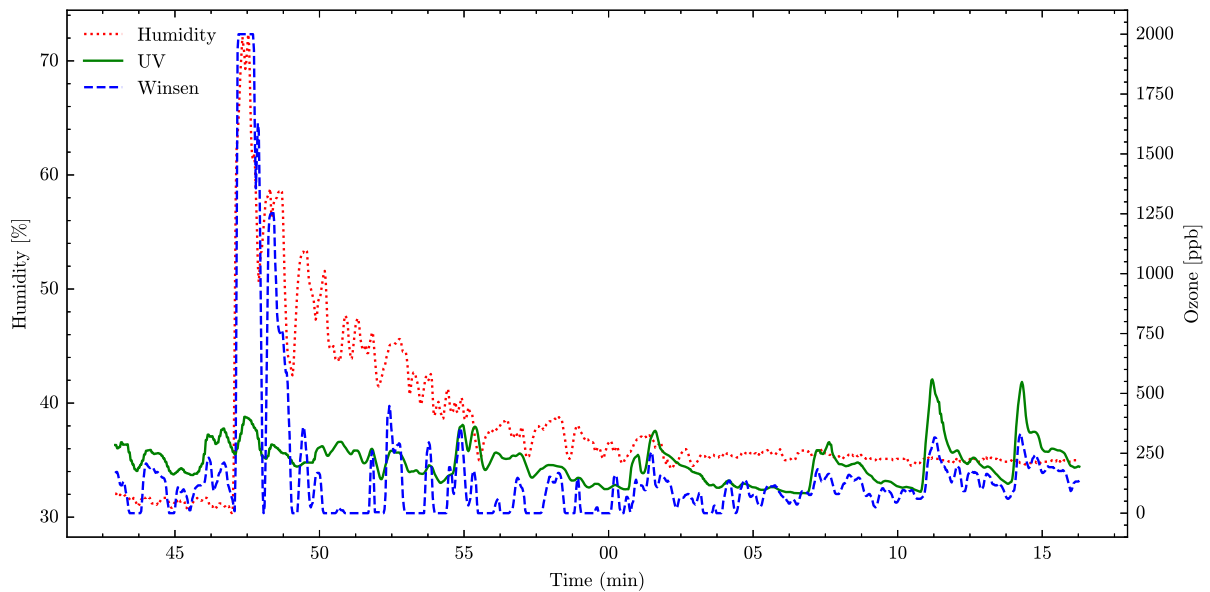


Figure 43 – Humidity variation and effect on electrochemical sensor. The Winsen electrochemical sensor (blue curve) saturates when humidity increases rapidly, while true concentration remains in the order of 300 ppb.

Interestingly, the SGP41 NOx signal seems to have a negative correlation with rapid humidity variations, as seen on Figure 44.

To mitigate this disadvantage, two methods were devised to be used in tandem. The first method aims at reducing errors during the changes in operation regime (generator $\Leftrightarrow$ condenser) with a recursive filter. The second method uses a recurrent neural network (RNN) to calibrate the electrochemical sensors by including humidity and temperature data as inputs.

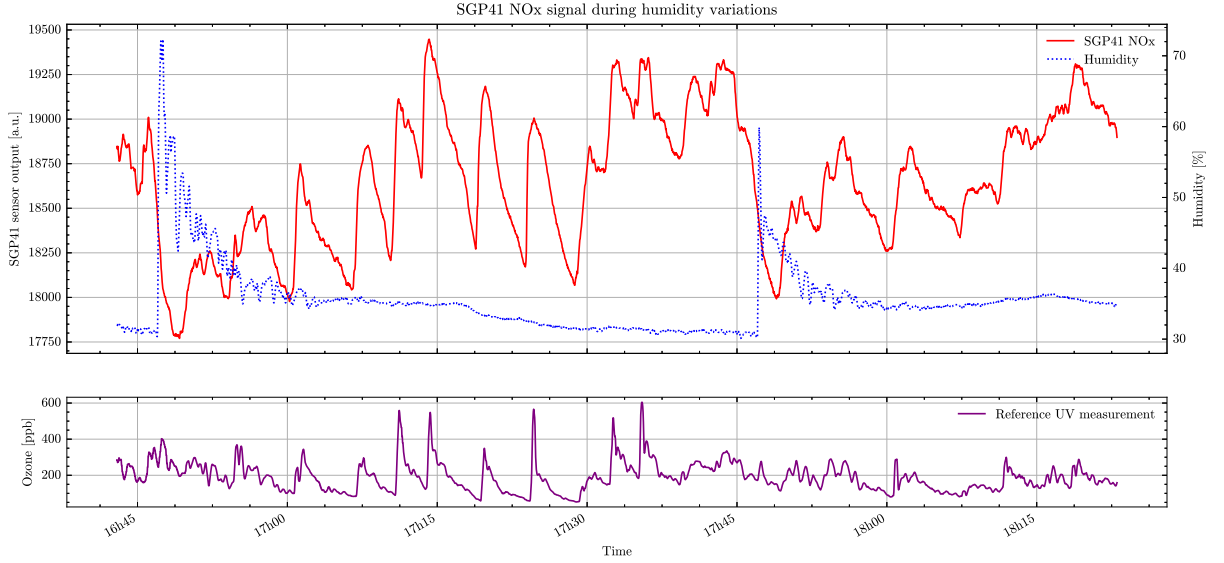


Figure 44 – Humidity variation and effect on Sensirion MOx sensor. The NOx values (arbitrary units) rapidly decrease with sharp humidity peaks.

5.2.1 Recursive filter

The first method to reduce errors in the electrochemical sensor measurements can be modeled with the differential equation shown in Eq. 5.3, where α is a scaling constant, H' is the humidity rate of change, y is the corrected ozone concentration, y' its rate of change and g is the measured ozone concentration. The discrete version is shown in Eq. 5.4, with k representing the index of the sample and dt the time interval between samples, but an arbitrary function $f(H')$ can be chosen with a better behavior and no instabilities (Eq. 5.5). One function that behaves predictably with bounded input, bounded output (BIBO) stability is a decreasing exponential, as shown in Eq. 5.6.

$$\alpha H' y' + y = g \quad (5.3)$$

$$\alpha H' (y[k+1] - y[k])/dt + y[k] = g[k] \quad (5.4)$$

$$y[k+1] = f(H')g[k] + (1 - f(H'))y[k] \quad (5.5)$$

$$y[k+1] = e^{-\beta|H'|}g[k] + (1 - e^{-\beta|H'|})y[k] \quad (5.6)$$

This filter, described by the first-order recurrence equation with varying coefficients, behaves in a way where present measurements are less “trusted” when humidity variations are large, adding more weight to the previous value, and vice-versa. The absolute value of the rate of change of humidity is used because the sensor is sensitive both to humidity increases and decreases. Figure 45 shows the characteristics of the filter for different values of β .

The rate of change is calculated with an algorithmic implementation of linear regression. For the experiments, a buffer of 10 measurements with period $T = 2$ s was used.

The same filter can be applied to temperature with a different β coefficient. In the end, two filtered ozone measurements exist, one for humidity variations and another for temperature variations.

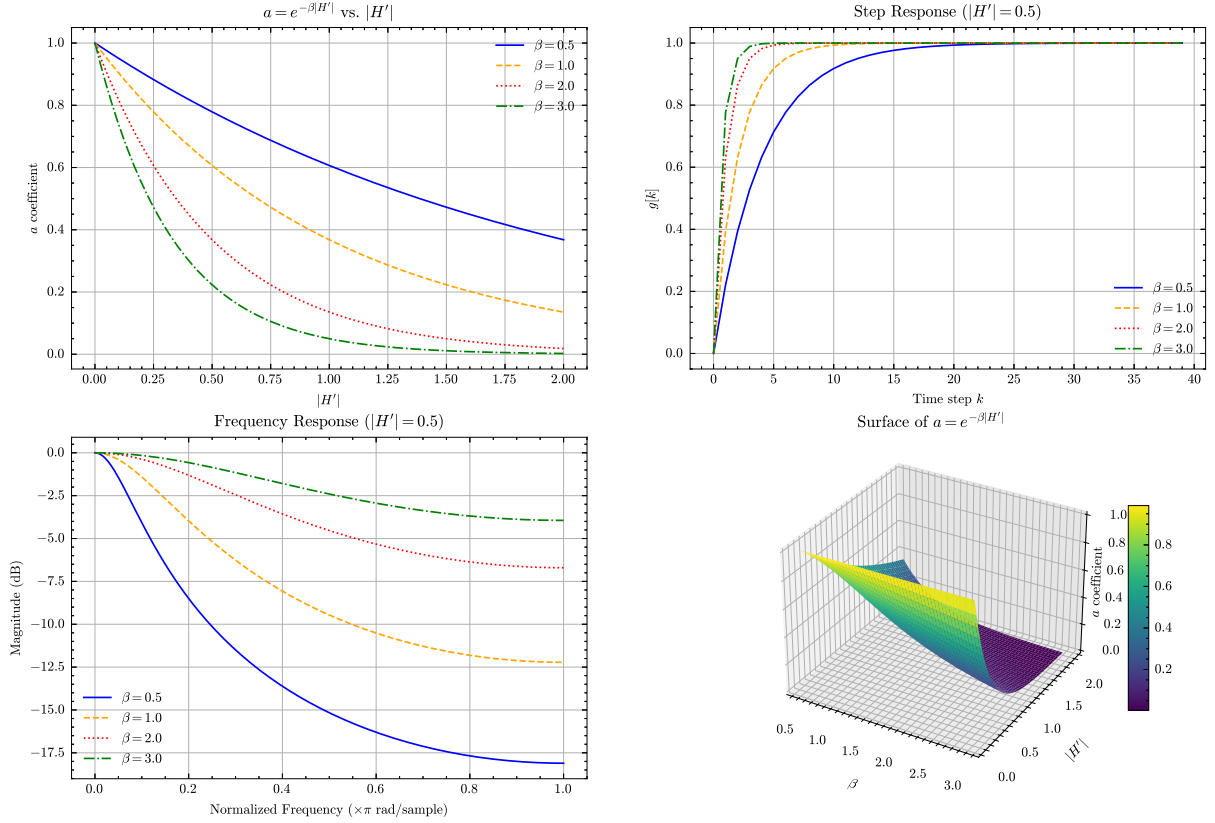


Figure 45 – Recursive filter parameters with varying β .

The final value chosen is the arithmetic mean of these two, although it is also possible to use a weighted average to fine-tune the responses and prioritize humidity variations, for example. The end result is that when the generator changes mode of operation, the ozone measurements are less affected by steep changes in temperature/humidity, until a minimum environmental stability is detected, as shown in Figure 46. In practice, it was observed that machine temperature changes are also accompanied by changes in humidity, as seen in Figure 25. These changes are negatively correlated and, since the behavior is very consistent, the same effect was used in laboratory experiments, ignoring the situations where both temperature and humidity increase at the same time or decrease at the same time.

5.2.2 Recurrent Neural Network

The second method for measurement compensation relies on the use of a Long Short-Term Memory (LSTM) recurrent neural network to predict the correct ozone concentration [86] based on an array of past ozone, temperature and humidity measurements. This approach has the benefit of taking into account the temporal order of measurements and has been used extensively to improve low-cost gas sensor measurement quality. Most reports in literature apply this method for measurement cycles that can vary throughout a full day or more. In this application, the variations are much quicker, so the array of past samples were in the span of 1-4 minutes.

LSTM networks are a specialized type of RNN architecture designed to model sequential data and overcome the limitations of traditional RNNs in learning long-term dependencies. Traditional RNNs often struggle with the vanishing and exploding gradient problems when learning patterns over long sequences. To address this, Hochreiter and Schmidhuber introduced the LSTM [87], characterized by a unique cell structure that includes gate mechanisms input, output, and forget gates that regulate the

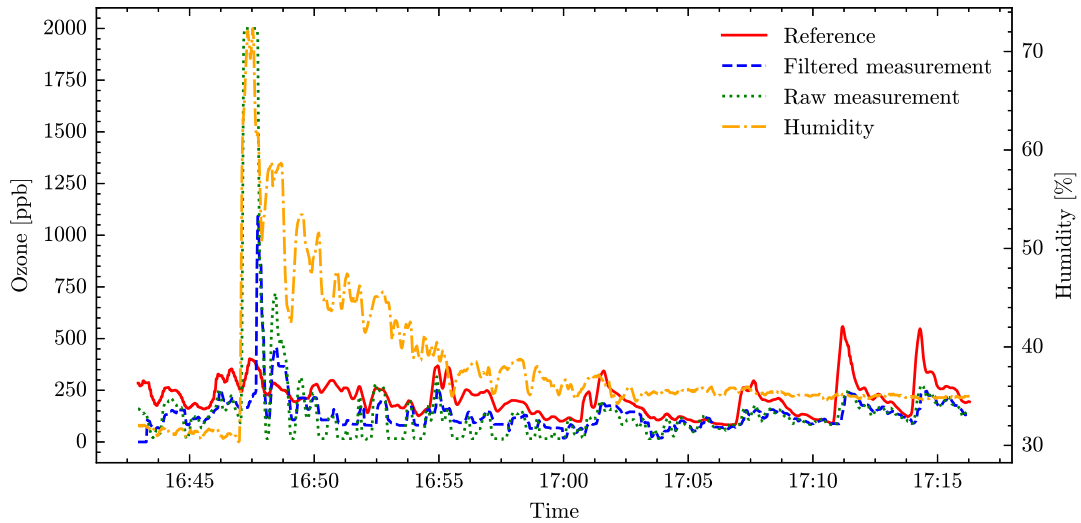


Figure 46 – Filter response during a humidity peak measured in a test bench, compared to real concentration.

flow of information through the network. These gates enable the LSTM to maintain, update, or discard information from the cell state, allowing it to capture dependencies over extended time horizons effectively. Since its introduction, the LSTM has become a foundational model in fields such as natural language processing, speech recognition, and time series forecasting [88].

The key advantages of LSTM networks stem from their ability to selectively remember or forget information through their gating mechanisms, making them highly effective for tasks involving long-term sequential dependencies. Unlike traditional feedforward networks or convolutional neural networks (CNNs), which lack inherent mechanisms to handle temporal dynamics, LSTMs excel in modeling sequential phenomena such as text, audio, or sensor data streams. Their versatility has led to successful applications in machine translation, handwriting recognition, and predictive maintenance. However, this enhanced capability comes at a cost: LSTM models are typically more computationally intensive due to their complex internal structure and the increased number of trainable parameters, which can make them slower to train and more prone to overfitting, particularly on smaller datasets.

For this case, three LSTM layers were used. The first one with 50 LSTM units, the second and third with 30 units each. A dropout parameter of 0.2 was added between the layers to reduce overfitting. This method reduced RMSE of the measurements by up to 75%, averaged throughout 10 cycles of training and validation, as seen in Figure 48, which only contains measurements not previously used to train the model. The same technique can be generalized to other types electrochemical sensors and applications where environmental changes can affect measurement reliability.

The batch size and number of epochs were chosen based on multiple tests run on the dataset, as shown in Figure 47. Smaller batches introduce gradient noise, which may improve generalization but slow convergence. Larger batches offer more stable updates and better hardware utilization but can lead to poorer generalization and require more memory.

The LSTM network structure can be seen in the code snippet below. The general topology was defined after several rounds of trial and error, trying to balance simplicity (and training speed) with consistent results and the overall ability to generalize, without overfitting. The datasets used were normalized using the min-max method, so all measurements were scaled to a value between 0 and 1. The learning rate parameter was set to the default from the Keras Adam optimizer (0.001), to avoid adding

more variables to the tuning process.

```

from keras.models import Sequential
from keras.layers import Dense
from keras.layers import LSTM
from keras.layers import Dropout

xtn=x_train.values
ytn=y_train.values

XT = []
YT = []
for i in range(120, a2-a1): #Window of 120 samples or 4 minutes was chosen
    XT.append(xtn[i-120:i, 0])
    YT.append(ytn[i, 0])
XT, YT = np.array(XT), np.array(YT)

XT = np.reshape(XT, (XT.shape[0], XT.shape[1], 1)) # Transforming data dimensions to be input
into LSTM

regressor = Sequential()

regressor.add(LSTM(units = 50, return_sequences = True, input_shape = (XT.shape[1], 1)))
regressor.add(Dropout(0.2))
regressor.add(LSTM(units = 30, return_sequences = True))
regressor.add(Dropout(0.2))
regressor.add(LSTM(units = 30, return_sequences = True))
regressor.add(Dropout(0.2))
regressor.add(Dense(units = 1))

regressor.compile(optimizer = 'adam', loss = 'mean_squared_error')

regressor.fit(XT, YT, epochs = 20, batch_size = 64) #Training parameters, can be further
optimized to reduce compute time

```

For drastic changes in humidity, it's possible to see that the LSTM “learns” that a fast-rising humidity peak should be “ignored”, and the model prediction remains very close to the behavior of the reference UV measurement, as shown in Figure 49.

It's important to highlight that the LSTM method was validated not only using a separate dataset from a different period of measurements unseen during the training stage, but it was simultaneously applied to a different sensor of the same model that was part of the same experiments, to make sure the technique would be scalable and not be dependent on the calibration of individual units. In Figure 50, the model was trained with data from sensor 1. Then, the trained model was applied to a different time period of the test, for data from sensor 3.

Since the Sensirion SGP41 sensor showed some correlation with ozone concentrations and is very compact/inexpensive, another variation of the LSTM was tested, using as inputs not only the Winsen sensor data with humidity and temperature, but also the NOx signal from the SGP41. The aim is to test if having both Winsen ZE25-AO3 and Sensirion SGP41 in the same board could eventually increase overall accuracy and robustness. Figure 51 shows the results with and without the NOx signal. Figure 52

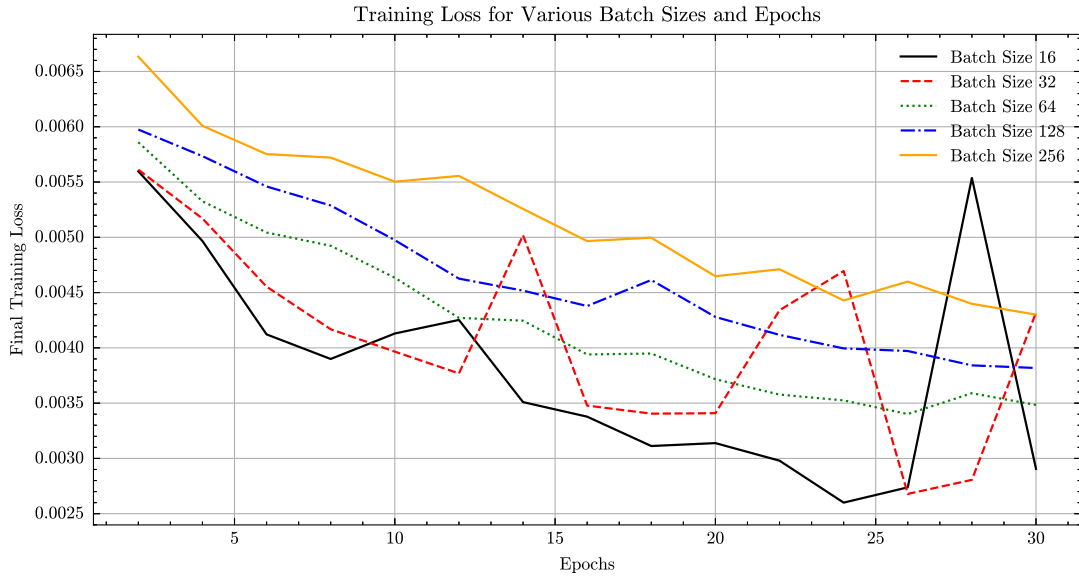


Figure 47 – LSTM performance for various batch sizes and number of epochs.

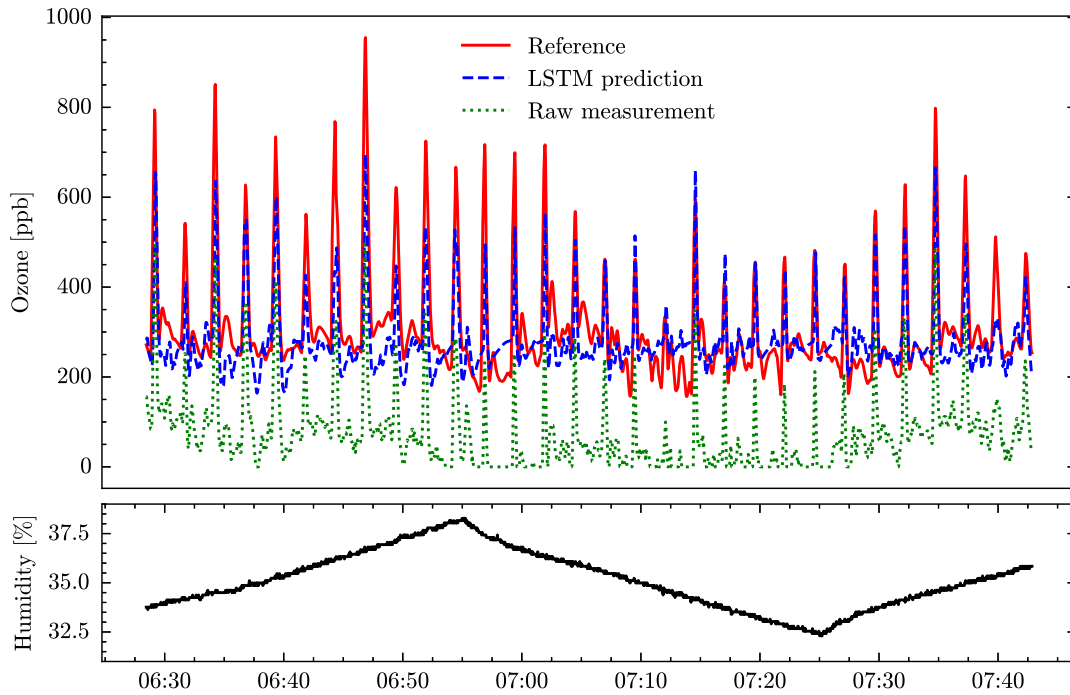


Figure 48 – LSTM method used for ozone concentration estimation in the span of 1 hour (validation set), with ozone generation cycles every 5 minutes under humidity variations. When humidity decreases, the raw signal average also drops, but the effect is corrected by the LSTM RNN.

shows the application of the model using sensor 1 data to correct sensor 3, to verify the robustness of the process. The results are summarized in Table 8. It seems the SGP41 offers an advantage when applying the model on sensor 1 itself (the metrics always refer to a validation dataset not included in training). However, when using the model trained with sensor 1 applied to sensor 3, the presence of the NO_x signal made no noticeable difference in performance.

Although the Sensirion SGP41 sensor is not specifically designed for applications involving single-gas measurement, the data it generates has been found to be sufficiently informative to serve as an

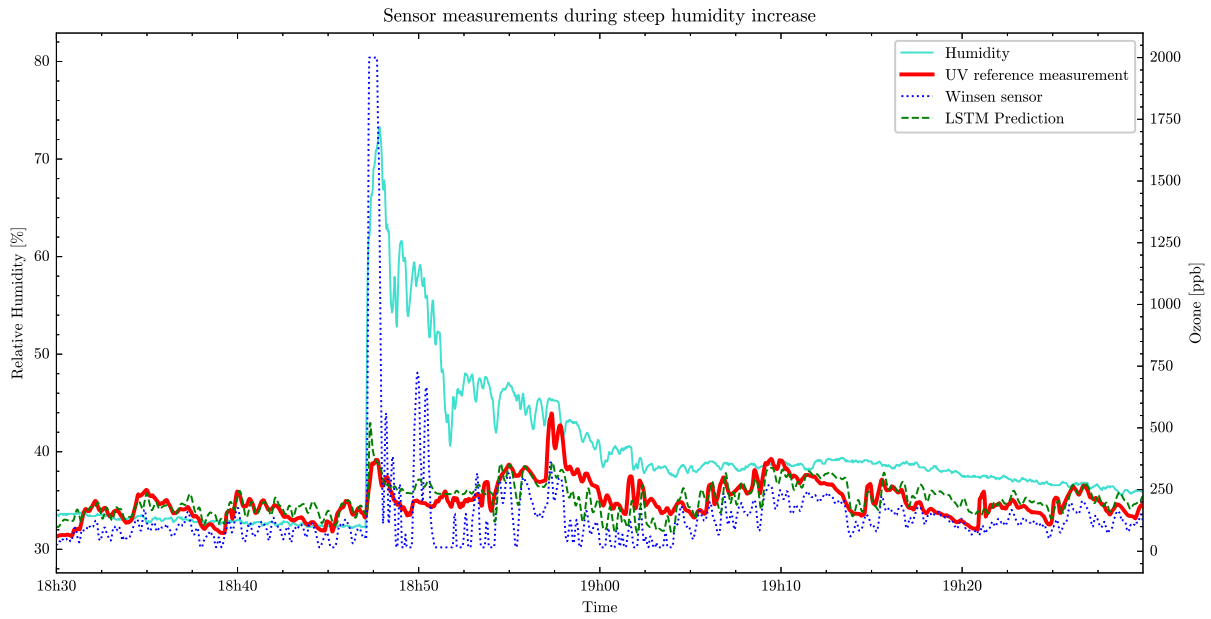


Figure 49 – Winsen sensor corrected with LSTM during extreme humidity variation. The saturation to maximum values (2000 ppb) is completely eliminated.

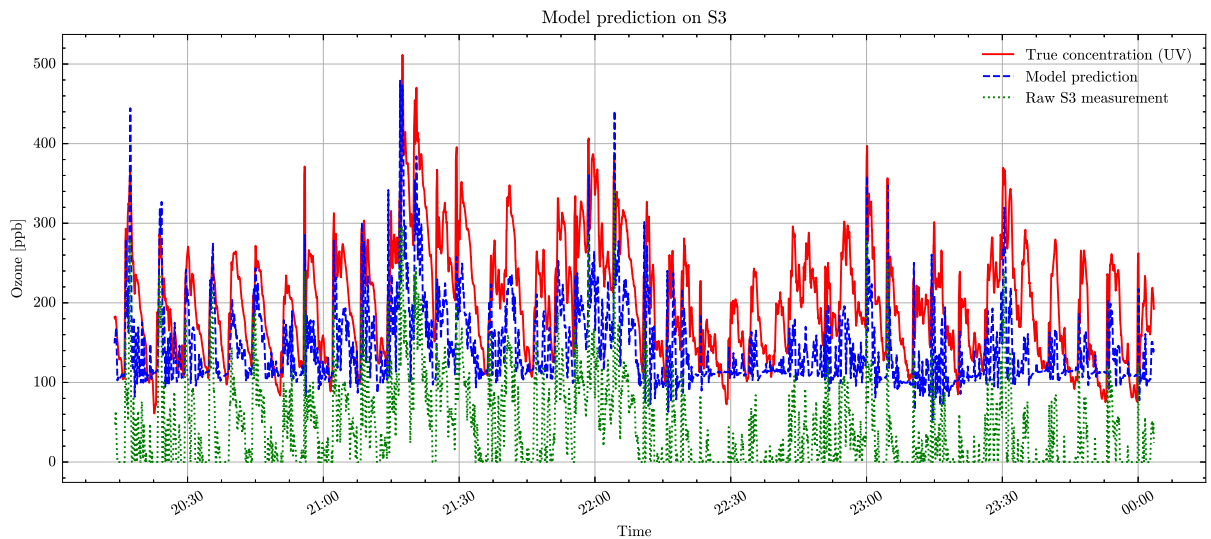


Figure 50 – Sensor 3 after LSTM correction. The model was trained with data from sensor 1, to demonstrate the robustness of the process. RMSE before the training was 167.03, which fell to 76.65, a reduction of 54%. Correlation coefficient decreased a little after application of the LSTM, from 0.809 to 0.769.

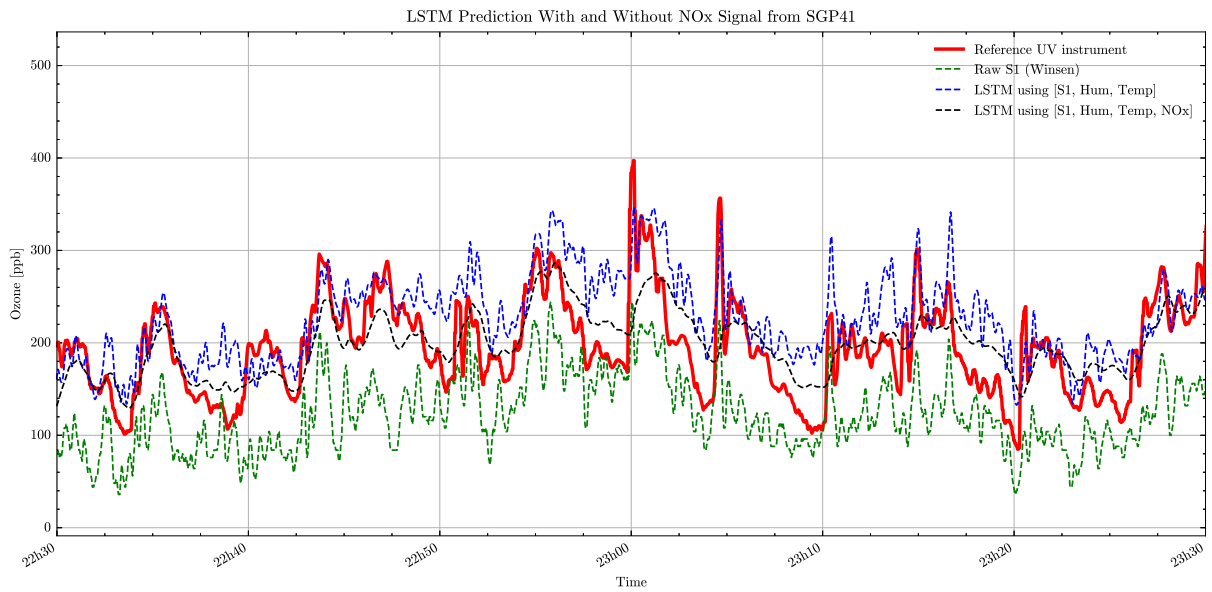


Figure 51 – Sensor 1 after LSTM correction using NOx signal.

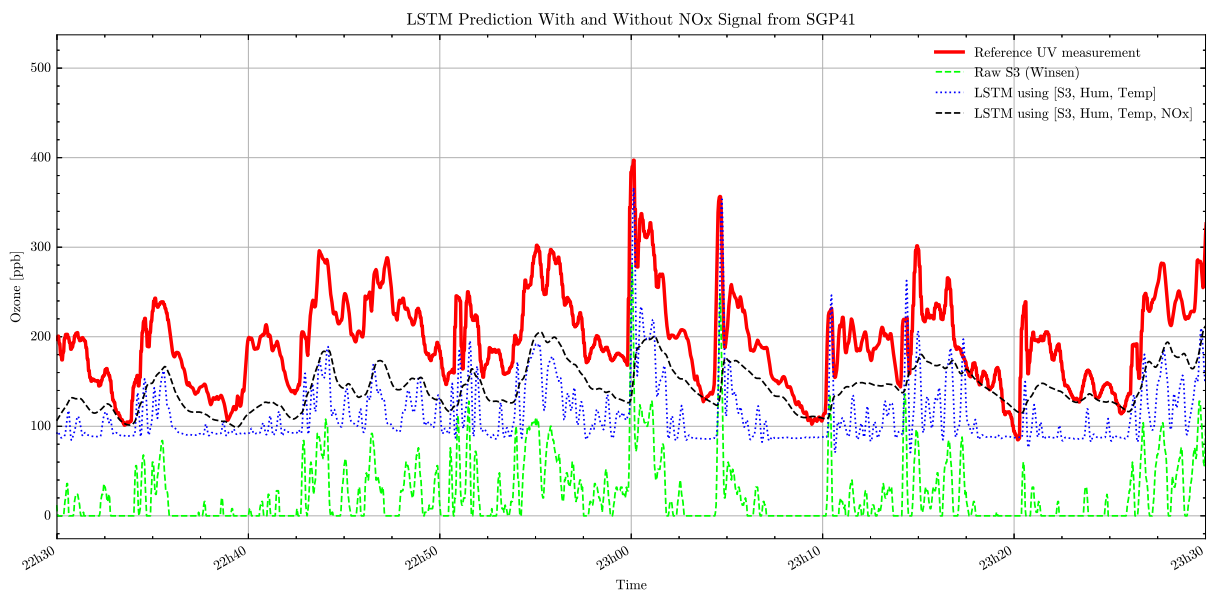


Figure 52 – Sensor 3 after LSTM correction using NOx signal. Once again, in this case the model was trained using sensor 1 data, which was after applied to sensor 3, to verify robustness.

Table 8 – Performance metrics for raw electrochemical sensor measurements and LSTM predictions compared to reference UV instrument.

Signal	Corr. Coeff.	Spearman ρ	Bias error	RMSE	RMSE %
Raw S1	0.8187	0.7960	62.97 ppb	73.76 ppb	16.37
LSTM S1	0.7175	0.7059	52.81 ppb	63.25 ppb	14.04
LSTM S1 + NO _x	0.8087	0.8266	31.66 ppb	41.86 ppb	9.29
Raw S3	0.8091	0.8089	161.79 ppb	167.03 ppb	37.07
LSTM S3	0.8259	0.8361	71.26 ppb	80.50 ppb	17.87
LSTM S3 + NO _x	0.7983	0.7936	70.62 ppb	83.12 ppb	18.45

auxiliary input for advanced signal processing techniques. In particular, the integration of SGP41 data into the LSTM model can enhance the accuracy of ozone concentration estimates obtained from the Winsen electrochemical sensor. This improvement is contingent upon the appropriate training of the LSTM model using sensor-specific datasets to account for the inherent response characteristics of each sensor type.

Additionally, an alternative and promising application of the SGP41 in this monitoring system lies in the implementation of sensor fusion strategies. Through such an approach, the distinct strengths of each sensor can be harnessed to improve overall system performance. For instance, the SGP41 may offer superior sensitivity and resolution at lower ozone concentration levels, particularly below the threshold of 100 ppb, where the signal-to-noise ratio of the Winsen sensor may be insufficient for reliable detection. Conversely, at higher concentration levels, the Winsen sensor can assume primary measurement responsibility, providing stable and robust readings where the performance of the SGP41 may not be so good. This hierarchical sensor fusion strategy would enable seamless measurement coverage across a wide dynamic range of ozone concentrations, thereby enhancing the versatility, accuracy, and reliability of the overall monitoring system. This approach was not explored in the present study, but could be applied to a future revision of the ozone monitoring module.

5.3 Partial discharge measurements

The manufacturer of the partial discharge (PD) monitoring equipment maintains a database comprising approximately 300,000 measurements from various types of machines. According to the manufacturer, these data serve as a preliminary benchmark for comparative evaluation in cases where no historical PD measurement records are available. Both machines under study, UG2 and UG3, fell into this category, as no prior PD measurements were known to exist or such records had been lost. Upon comparison with the reference database, it was noted shortly after system commissioning that the PD levels in UG3 were exceptionally high - exceeding, in some instances, the threshold for inclusion among the top 5% of highest values recorded in the database by as much as 50%. The statistical reference values for comparable machines, provided by the manufacturer, alongside the measured values for UG3, are presented in Tables 9 and 10.

Table 9 – Statistical distribution of Qm measurements for 13.8 kV machines (PDA).

Severity	Percentile of machines with lower values	Qm (mV)
Negligible	<25%	38
Low	<50%	97
Typical	<75%	202
Moderate	<90%	387
High	<95%	580

Table 10 – Qm+/Qm- values (mV) measured on UG3 (June 30th 2022).

Phase A			Phase B			Phase C		
Coupler	Qm+	Qm-	Coupler	Qm+	Qm-	Coupler	Qm+	Qm-
A1	230	-233	B1	77	-86	C1	180	-137
A2	0	0	B2	173	-187	C2	64	-73
A3	342	-339	B3	712	-733	C3	256	-700
A6	0	0	B6	0	0	C6	193	-375
A4	340	-184	B4	889	-881	C4	850	-843
A5	197	-190	B5	0	0	C5	125	-367

As discussed in Chapter 3, The values of Qm+ and Qm- represent a general magnitude of the PD in the stator and relate to the severity of the deterioration of the insulation. There is no clear predominance of positive Qm/NQN, which was initially expected in this machine, since it had known corona issues in the endwindings. However, this is common for phase-to-phase PD activity in the endwindings due to insufficient spacing [89].

The analysis of Qm (mV) and the pulse height / pulse phase graphs of the machine suggested high PD activity between phases B and C, especially between couplers B3 and C3, as seen on Figure 53, where the highlighted regions demonstrate two clusters of pulses with inverted polarity but same position in time. This is very likely a confirmation of the known corona problems in this machine.

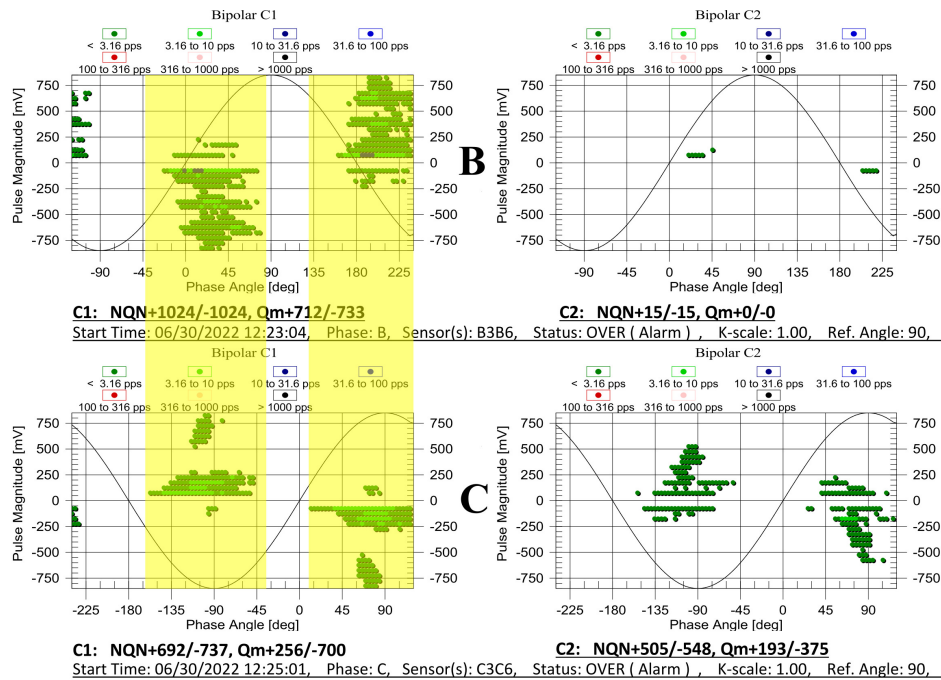


Figure 53 – PRPD graph showing pulses measured in couplers B3-B6 and C3-C6. The vast majority of pulses are concentrated in coupler B3, with phase-to-phase discharges between B3 and C3, as highlighted in yellow. Each color for the points represents different repetition rates for the PD pulses, and the Qm values are determined by the highest amplitudes at a rate of 10 pulses per second, both for positive (Qm+) and negative (Qm-) pulses. The lack of clear predominance of either positive or negative pulses and their patterns are consistent with PD happening between bars in the endwindings due to insufficient spacing [89].

In UG2, the highest Qm value measured soon after installation in July 2022 was around 300 mV in coupler C5, which by itself isn't concerning at all. Complete PRPD plots are available on Annex A for UG2 and Annex B for UG3.

While individual PD measurements are useful, more meaningful insights can be derived from analyzing long-term trends. For both machines, the Q_m values associated with each coupler pair are presented in Figures 54, 55 and 56 for UG2 and Figures 57, 58 and 59 for UG3, covering a monitoring period of nearly three years. To facilitate visual comparison across different couplers, the y-axis scale was standardized: for UG2, a maximum of 600 mV was applied, while for UG3, the scale extends to 1300 mV. Although the Q_m values serve as practical indicators of the general condition of the stator insulation, it is important to note that each data point in the time series corresponds to a complete PRPD plot. These full discharge patterns can be further examined using the proprietary software provided by the monitoring system manufacturer.

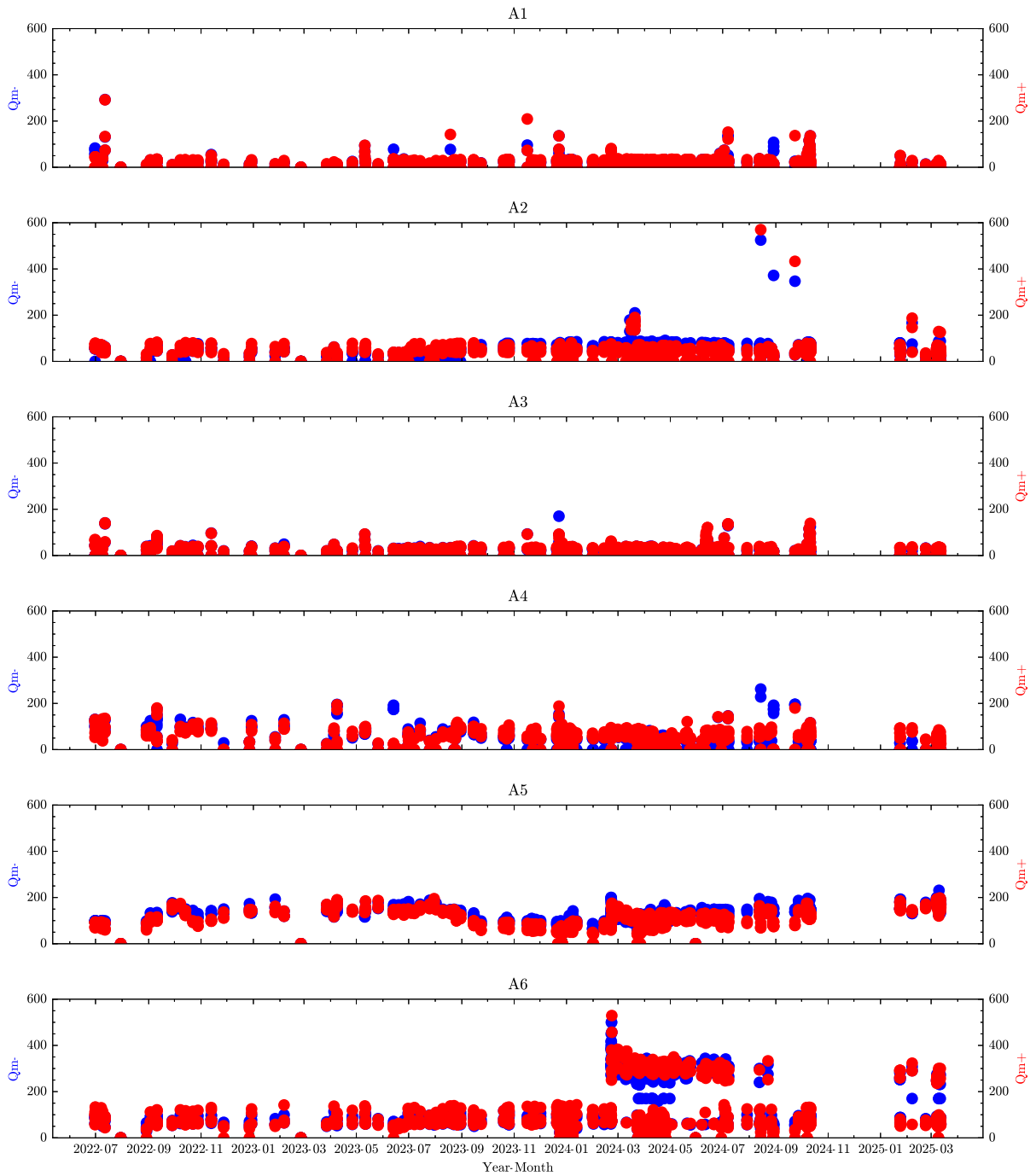


Figure 54 – Values of Q_m^+ and Q_m^- for UG2 from July 2022 to March 2025 (phase A).

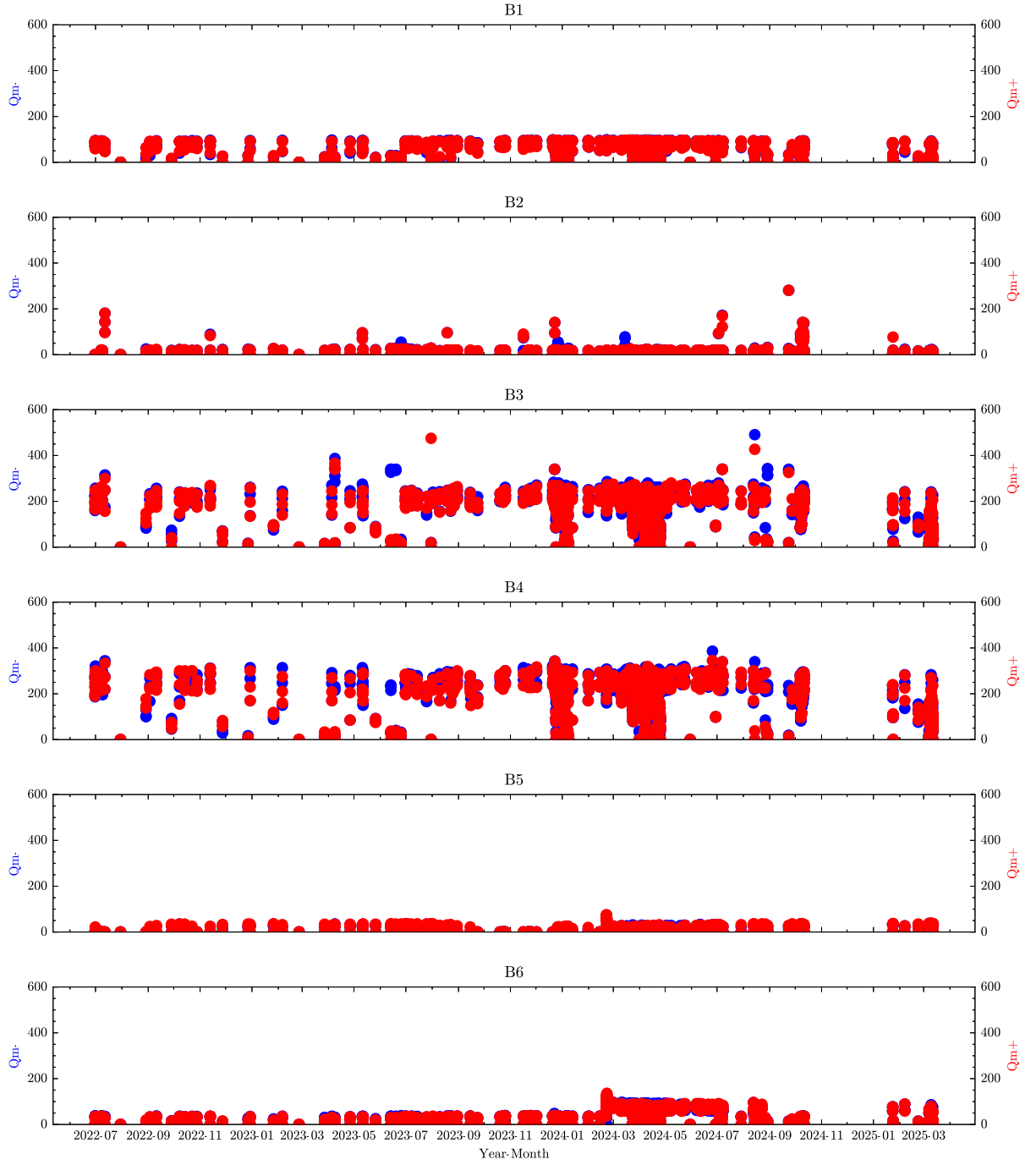


Figure 55 – Values of Q_{m+} and Q_{m-} for UG2 from July 2022 to March 2025 (phase B).

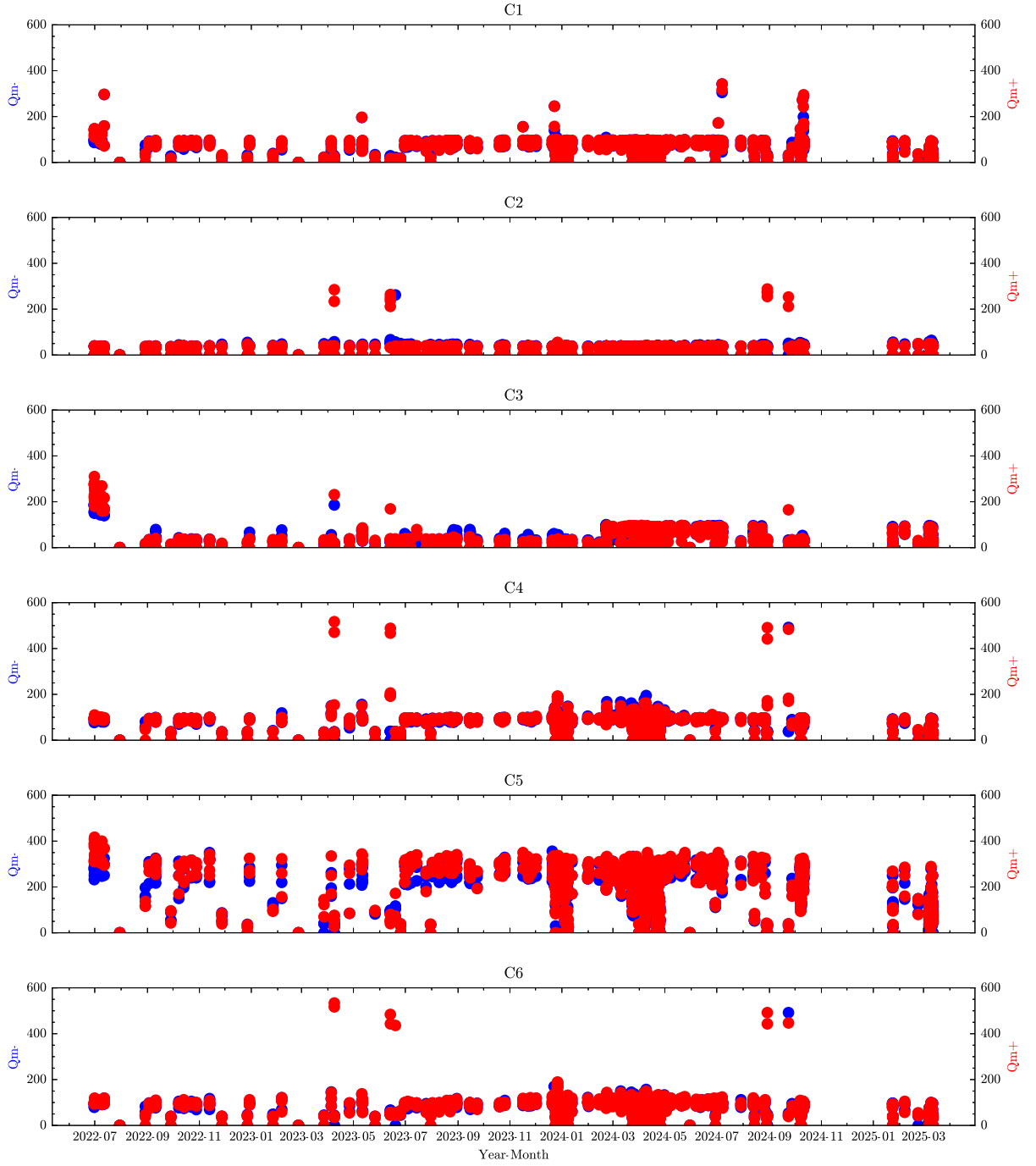


Figure 56 – Values of Q_{m+} and Q_{m-} for UG2 from July 2022 to March 2025 (phase C).

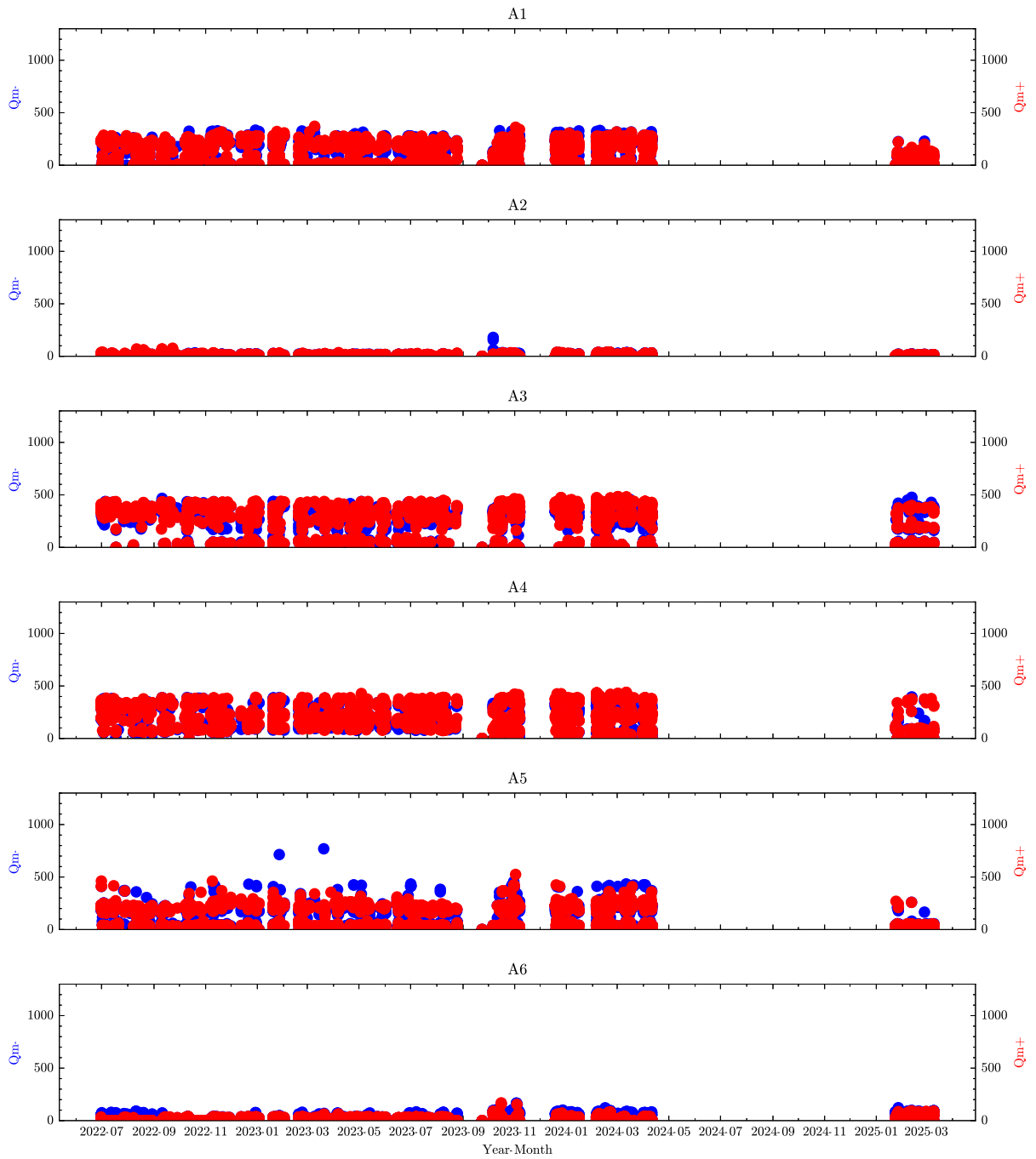


Figure 57 – Values of Q_{m+} and Q_{m-} for UG3 from July 2022 to March 2025 (phase A).

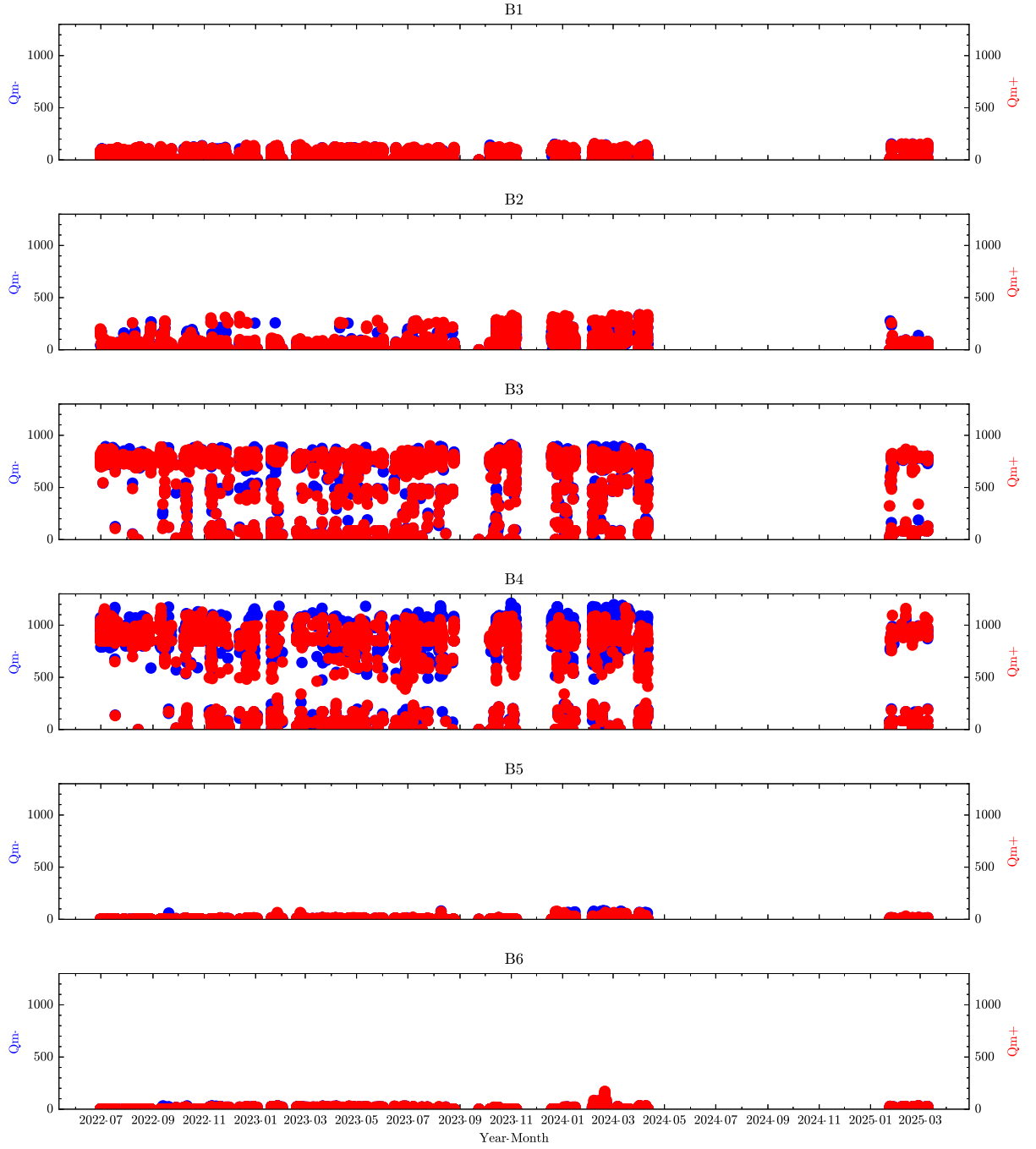


Figure 58 – Values of Q_{m+} and Q_{m-} for UG3 from July 2022 to March 2025 (phase B).

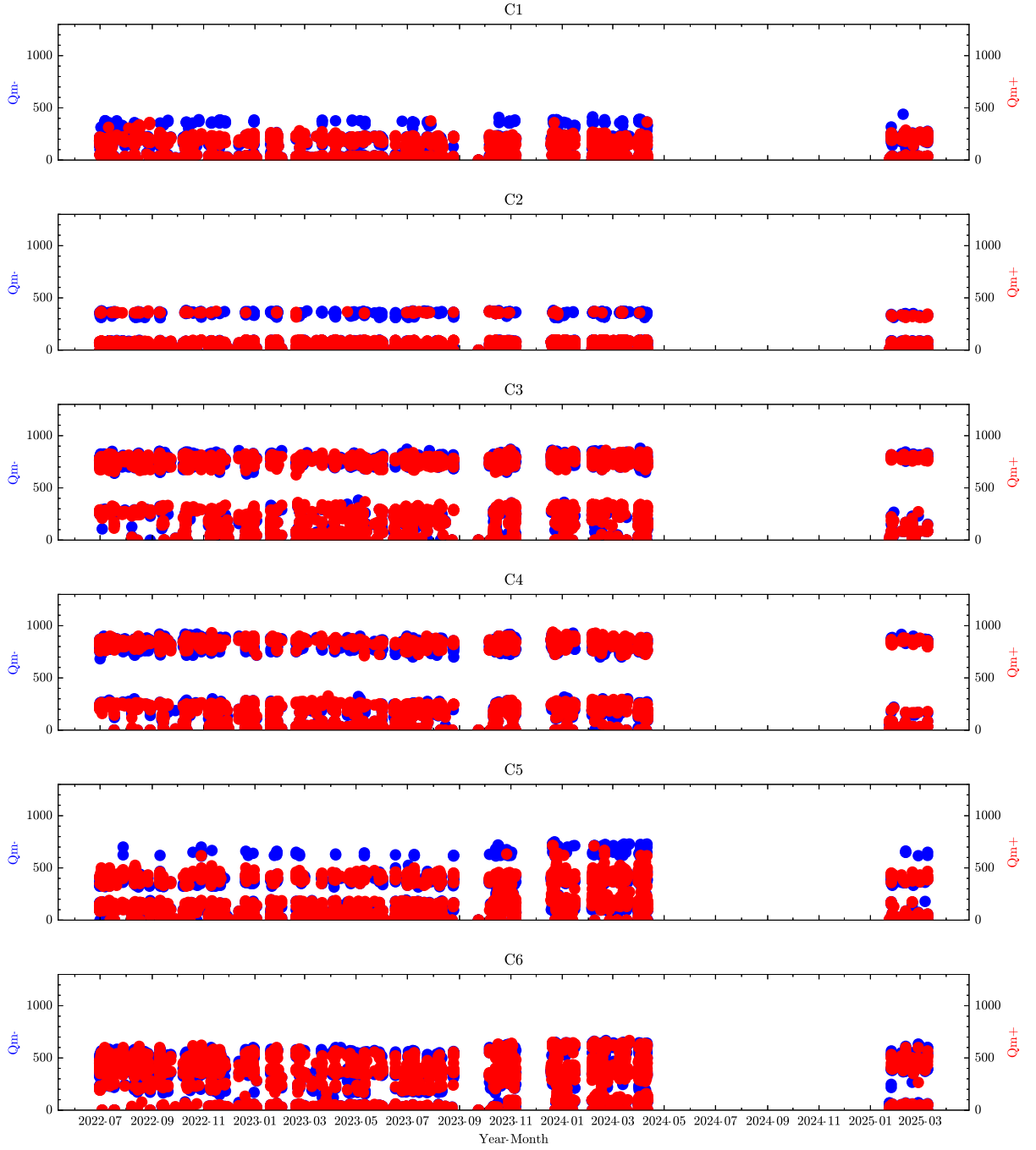


Figure 59 – Values of Q_{m+} and Q_{m-} for UG3 from July 2022 to March 2025 (phase C).

For both machines, there is no clear increase or decrease of Q_m values. The only exception is coupler A6 from UG2, which shows a steep increase in Q_m levels around March/2024 (Figure 54). The reason the values oscillate so much in all graphs is probably due to the fact that the machines operate as synchronous condensers very frequently. Unfortunately, the PD monitors are not receiving operational data from the industrial plant network to record the operational parameters at each measurement - this was a decision by the plant staff, who wanted the system in its own isolated network for security reasons.

Due to unforeseen technical malfunctions, the PD monitoring system installed on UG3 ceased data acquisition from May/2024 until January/2025. Despite multiple attempts by the equipment manufacturer to recover the missing data from the internal storage, these efforts were ultimately unsuccessful, resulting in an irretrievable loss of diagnostic information for this period. In response to the incident, corrective measures were implemented in January/2025, including the installation of a firmware update to correct the identified software issues, as well as a complete purge of the device's internal memory to mitigate the risk of similar data loss events in the future.

Despite this interruption in continuous data acquisition, it is noteworthy that the PD measurements recorded immediately prior to the malfunction, specifically in April/2024, were carefully analyzed and compared with the data collected after the system was restored to operational status. This comparative analysis revealed a high degree of consistency in both the patterns and amplitudes of the PD activity, indicating that no significant changes occurred in the insulation condition of the machine during the monitoring hiatus. Accordingly, it is reasonable to infer that the underlying insulation degradation processes remained relatively stable over the affected period, thereby preserving the validity of the overall diagnostic assessment despite the temporary absence of data.

5.4 Ozone measurements

The ozone concentrations were measured for the 8 radiators during a significant period of time, as shown in Figures 60 and 61. For UG2, the measurements begin in April/2024 and for UG3, October/2023. This is because the ozone sensors were installed on UG3 first.

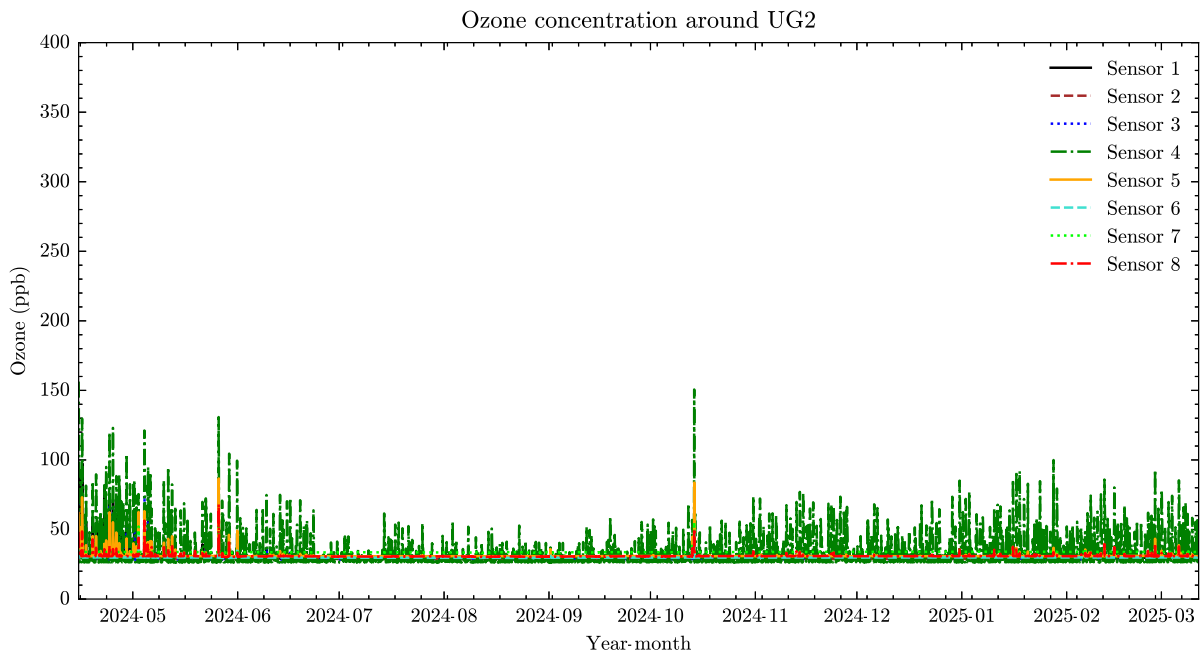


Figure 60 – Ozone concentrations for all 8 sensors around UG2.

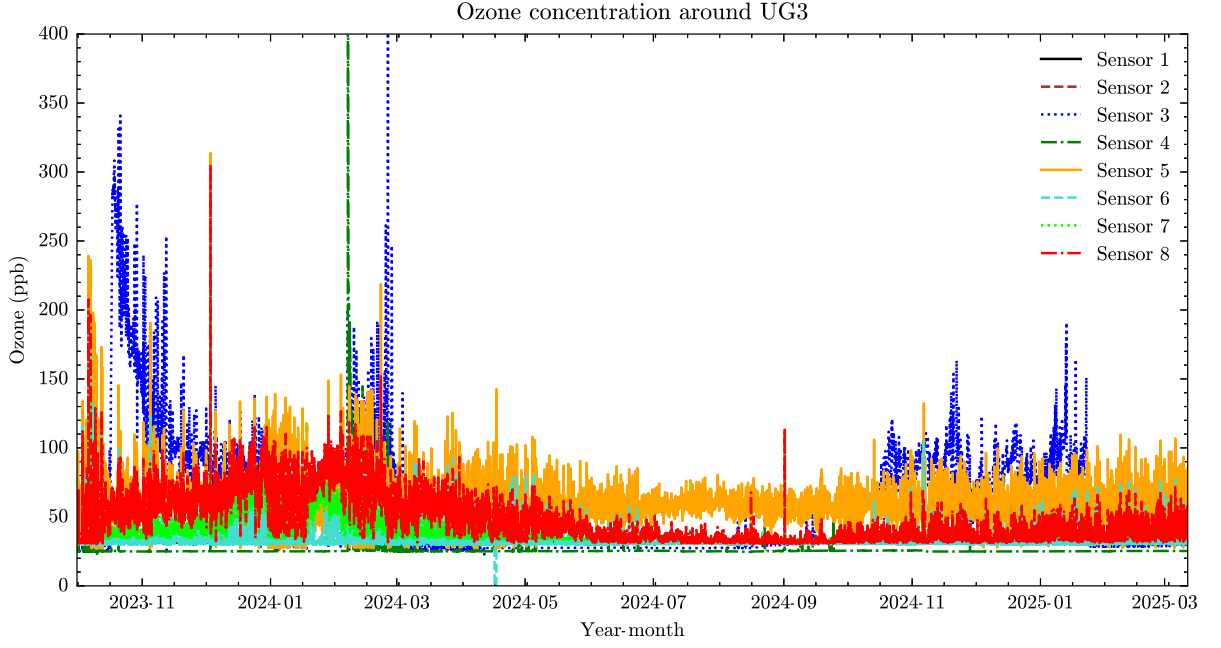


Figure 61 – Ozone concentrations for all 8 sensors around UG3.

During the analysis of the ozone concentration data, the presence of numerous outliers was observed, characterized by sporadic instances of sensor readings either momentarily saturating at the maximum measurable values or, conversely, dropping abruptly to zero. Such anomalies are physically implausible within the context of this application, given that the minimum detectable output of the sensor employed is specified at 20 ppb. These outliers are likely attributable to power-on/power-off cycles, switch between power supply sources and communication errors during data acquisition.

In order to enhance the interpretability and overall quality of the dataset, a preprocessing step was undertaken to mitigate the influence of these outliers, by using the Savitzky–Golay filter.

The Savitzky–Golay filter is a digital smoothing technique widely employed in signal processing and time series analysis to enhance data quality while preserving the essential shape and features of the signal, such as peak height and width. Unlike simple moving average filters, which tend to distort important features, the Savitzky–Golay filter fits a low-degree polynomial to a sliding window of consecutive data points using the method of least squares [90]. This local polynomial regression results in a smoothed version of the original signal that maintains the higher-order moments of the distribution, making it particularly suitable for applications requiring retention of fine-scale structure, such as spectroscopy, biomedical signals, and environmental sensor data.

To identify outliers, the filtered (smoothed) signal can be compared to the original time series by analyzing the residuals, defined as the pointwise difference between the observed and smoothed values. Residuals that deviate significantly from zero may indicate anomalous behavior, noise spikes, or sensor faults. A common approach is to compute the standard deviation of the residuals and then apply a thresholding rule, such as flagging or excluding points where the residual exceeds ± 3 standard deviations. This method combines the robustness of smoothing with a statistically grounded residual analysis, allowing for dynamic, context-aware outlier detection that adapts to local signal structure while minimizing the risk of discarding meaningful trends or natural variability.

Given a discrete time series $y = \{y_1, y_2, \dots, y_N\}$, the filter operates on a window of width $2k + 1$ centered at each point y_i , fitting a polynomial of degree $p \leq 2k$ via least squares. The smoothed value $\hat{y}_i$

is given by:

$$\hat{y}_i = \sum_{j=-k}^k c_j y_{i+j}$$

where c_j are the Savitzky–Golay convolution coefficients, precomputed based on the window size and polynomial order. These coefficients are derived by solving the normal equations of the least-squares problem:

$$\min_{\beta_0, \dots, \beta_p} \sum_{j=-k}^k \left(y_{i+j} - \sum_{m=0}^p \beta_m j^m \right)^2$$

The result is a set of weights that are applied to the input signal to produce a smoothed output while preserving important features such as peaks, slopes, and inflection points—characteristics often distorted by traditional moving average filters.

Once the smoothed signal $\hat{y}_i$ is obtained, *residual-based outlier detection* involves computing the residuals:

$$r_i = y_i - \hat{y}_i$$

These residuals represent the difference between the original data and the locally estimated trend. To detect outliers, a statistical threshold is typically applied:

$$\text{Flag as outlier if } |r_i| > \lambda \cdot \sigma_r$$

where σ_r is the standard deviation of the residuals, and λ is an arbitrary threshold multiplier (commonly $\lambda = 2$ or $\lambda = 3$). Points exceeding this threshold are considered anomalous and may be excluded or flagged for further analysis. This approach combines the structural preservation benefits of Savitzky–Golay filtering with a statistically grounded framework for anomaly detection, making it especially suitable for time series with transient noise, periodic structure, or nonstationary behavior.

Using $\lambda = 3$ and a filter window of 51 samples, the ozone concentrations can be better interpreted in Figure 62 for UG2 and Figure 63 for UG3.

UG2 did not show a lot of ozone activity, as expected, since there were no known surface PD issues. Sensor 4 has a few measurement peaks approaching 100 ppb, but those levels are not sustained for long periods of time.

In UG3, the ozone concentrations were worrying, especially in the module installed in radiator 3. The average ozone concentration above 200 ppb measured in this module in the first days of operation after installation - around October/2023 - is above the safe limits for continuous human exposure [29], and the peaks are higher than some of the worst cases recorded in literature for hydrogenerators [26].

Around November/2024, more ozone activity is seen on sensor 3 for a period of about 3 months. Sensors 5, 6, 7 and 8 also register continuous ozone presence above usual atmospheric levels, compared to sensors 1 and 2, for example. Table 11 shows the mean and coefficient of variation (CV), given by $CV = \frac{\sigma}{\mu} \times 100\%$, where σ is the standard deviation and μ is the mean, for all data recorded by the ozone sensors in UG3. Although sensor 3 shows the highest peaks, sensor 5 has a higher mean.

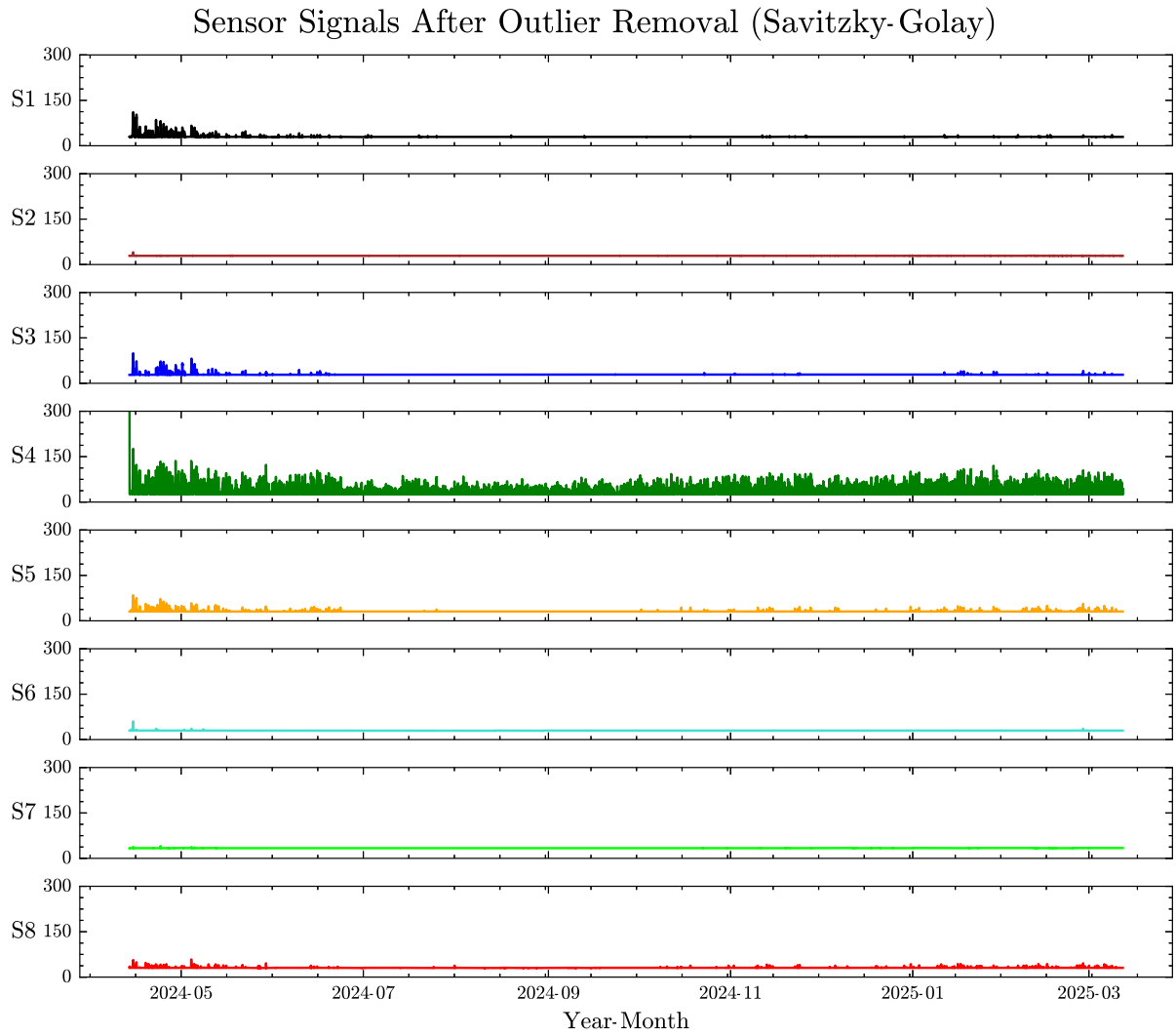


Figure 62 – Ozone measurements in UG2 after outlier removal.

Table 11 – Mean and Coefficient of Variation (CV) for each sensor in UG3.

Sensor	Mean	CV (%)
SENSOR 1	31.88	23.64
SENSOR 2	31.26	35.19
SENSOR 3	56.20	77.00
SENSOR 4	26.21	60.77
SENSOR 5	60.16	42.64
SENSOR 6	34.59	50.42
SENSOR 7	38.40	37.28
SENSOR 8	46.64	52.85

Figure 64 shows the correlation between all ozone measurements in UG3. Since the sensors are symmetrically placed around the generator, it's also possible to plot each sensor against its adjacent sensors, as seen in Figure 65. Some adjacent sensors have high correlation, but that's not valid for all of them.

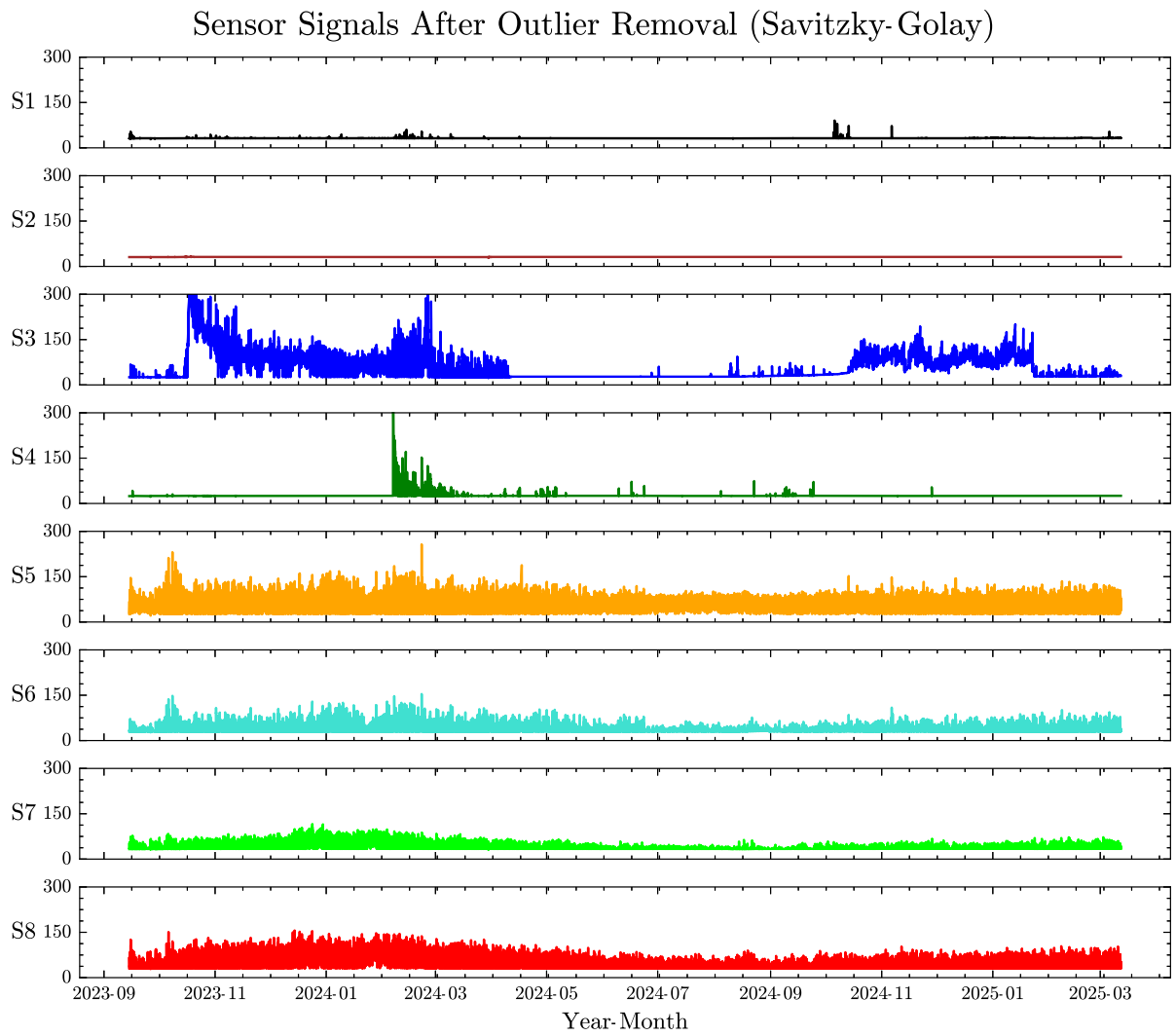


Figure 63 – Ozone measurements in UG3 after outlier removal.

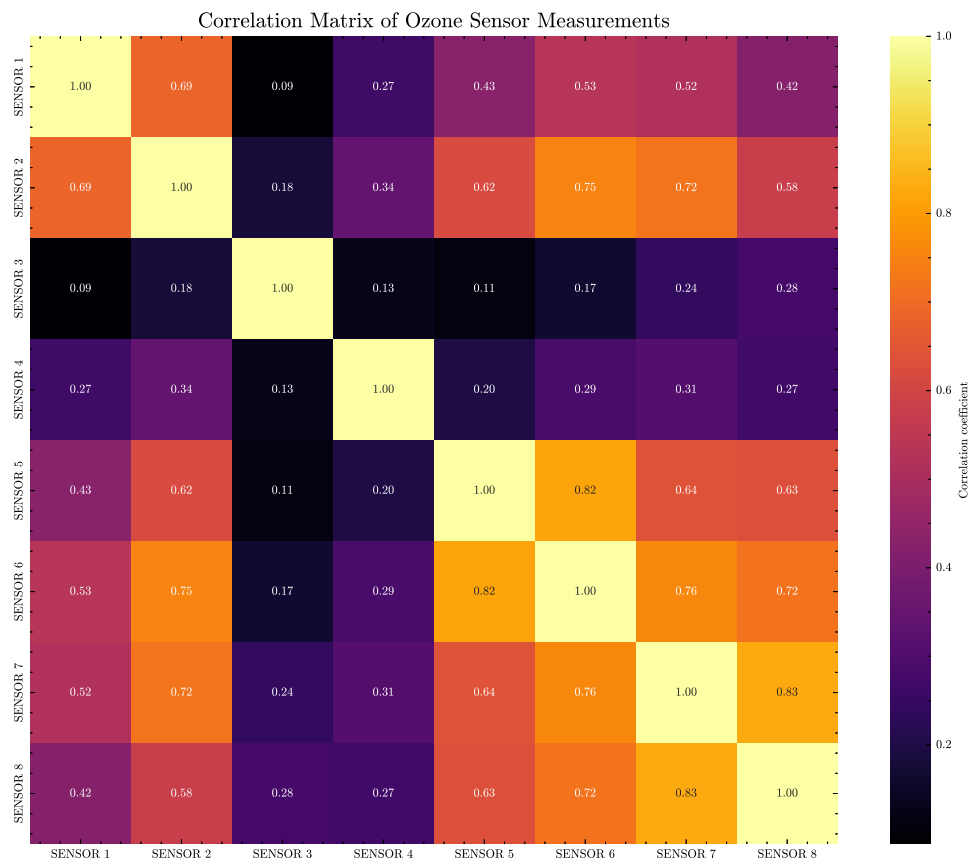


Figure 64 – Correlation between ozone sensors in UG3.

Scatter Plots of Adjacent Sensor Pairs

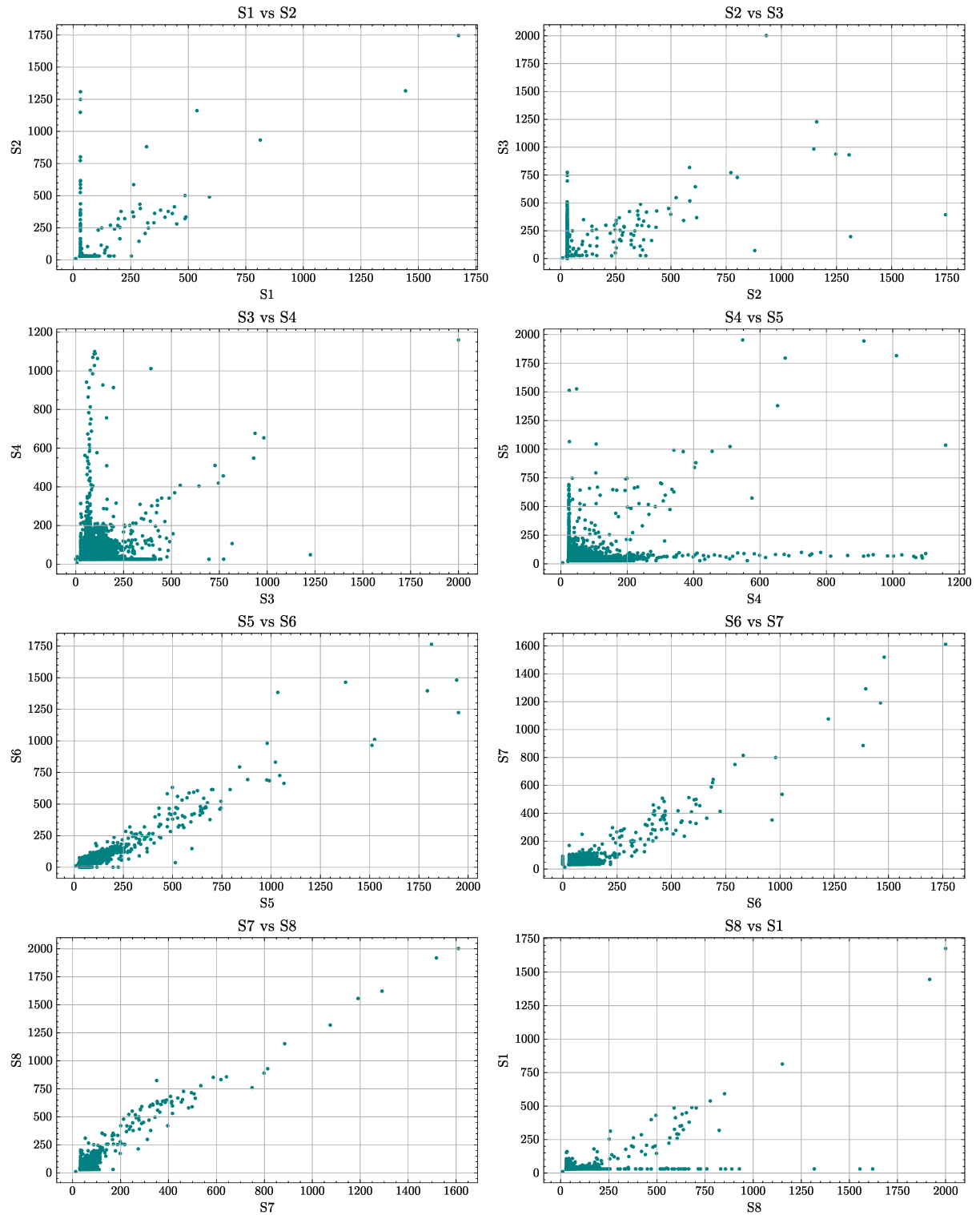


Figure 65 – Pair plots of adjacent ozone sensors in UG3.

5.5 Temperature and humidity measurements

Since the measurement modules have temperature and humidity sensors, those parameters were also evaluated, as seen in Figures 66 and 67 for UG3. Using sensor 1 for humidity and sensor 2 for temperature references, it's possible to confirm that the correlation is indeed negative, with a value of -0.342. Warmer air can hold more moisture, so relative humidity often drops when temperature rises (assuming constant moisture). Conversely, as temperature falls, relative humidity tends to increase (closer to saturation). This negative covariance is expected and the assumption made when testing the sensors during the laboratory experiments holds. The covariance matrix shows that variations in humidity are quite large (44.15) when compared to temperature (13.69).

Table 12 – Covariance matrix between humidity and temperature.

	Humidity	Temperature
Humidity	44.15	-8.41
Temperature	-8.41	13.69

An anomaly was detected in radiators 3 and 4, where humidity was much lower and temperature much higher than the rest for a period of a few weeks, as seen on Figure 68. At first, this seemed like a problem in the sensors or the circuit boards, but upon talking to the maintenance staff, those radiators had issues and had to be repaired. After the repairs, it's possible to see the values converging again, so in this case the ozone modules can also be helpful to monitor the heat exchangers themselves. The fact that these radiators are also the ones exposed to higher concentrations of ozone can be a coincidence, but it is known that ozone can form nitric acid when exposed to humidity, which can chemically attack metallic structures.

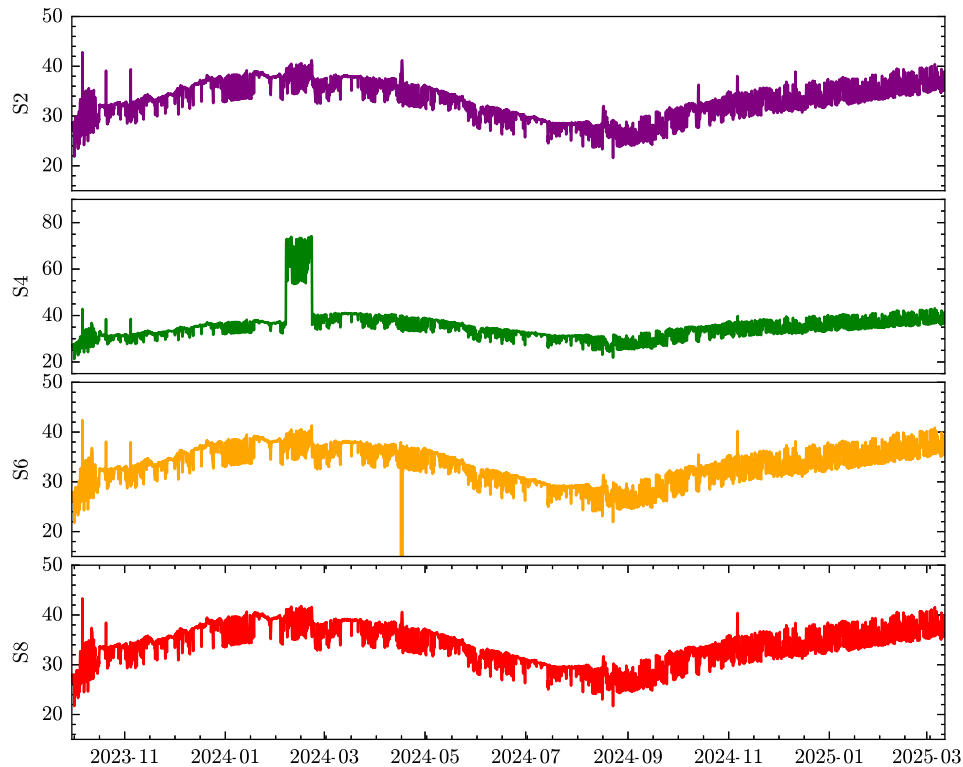


Figure 66 – Temperatures measured around UG3, in °C. Note the anomaly in sensor 4, around February 2024.

For UG2, no anomalies were recorded, as seen on Figures 69 and 70.

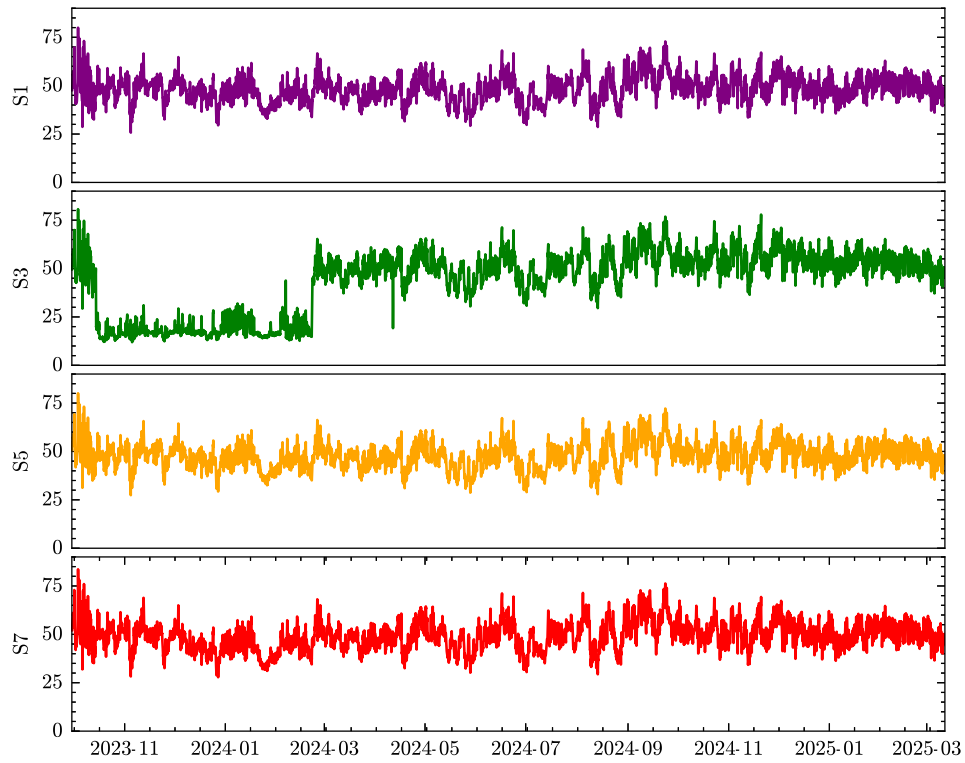


Figure 67 – Relative humidity measured around UG3, in %. Note the anomaly in sensor 3, between November/2023 and February/2024.

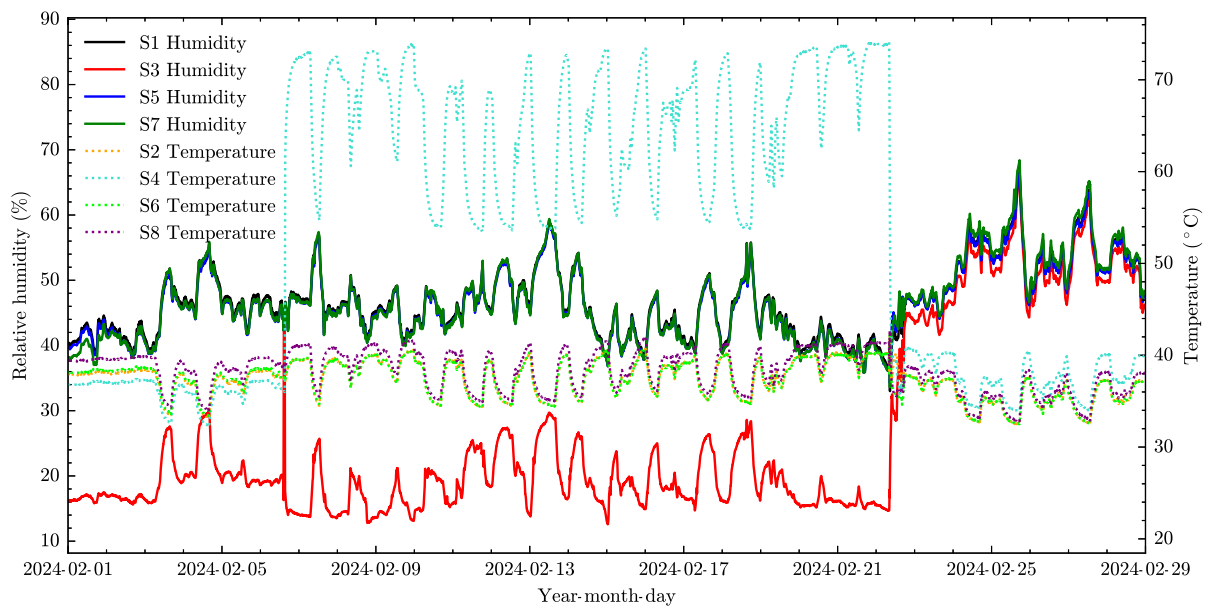


Figure 68 – Humidity and temperature recorded by the modules during anomaly.

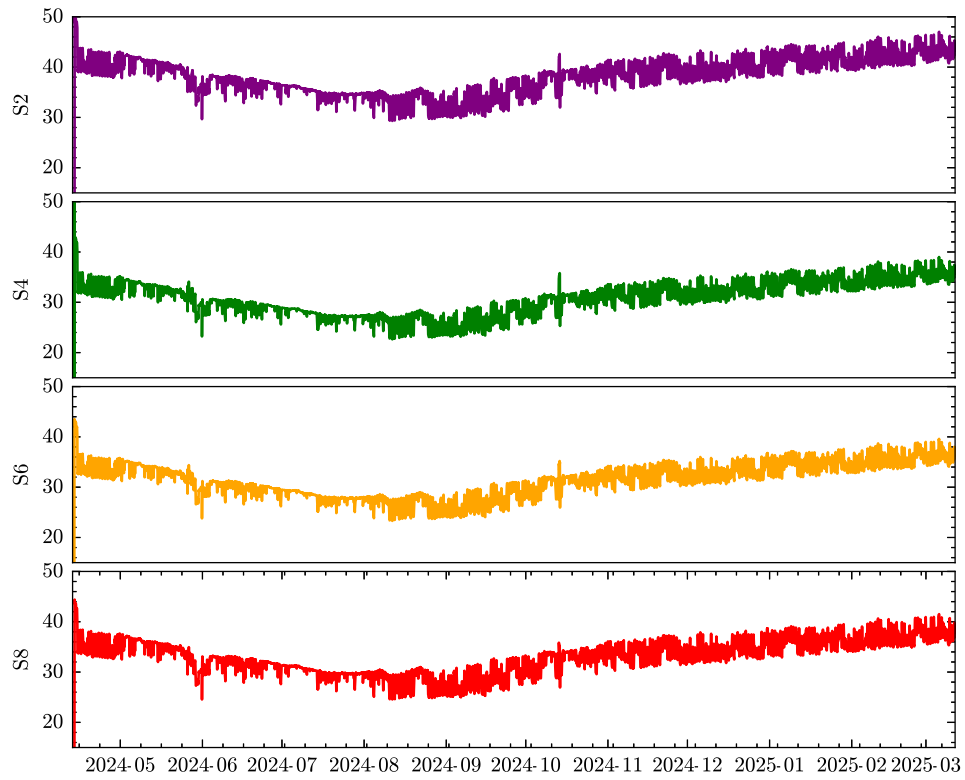


Figure 69 – Temperatures measured around UG2, in °C.

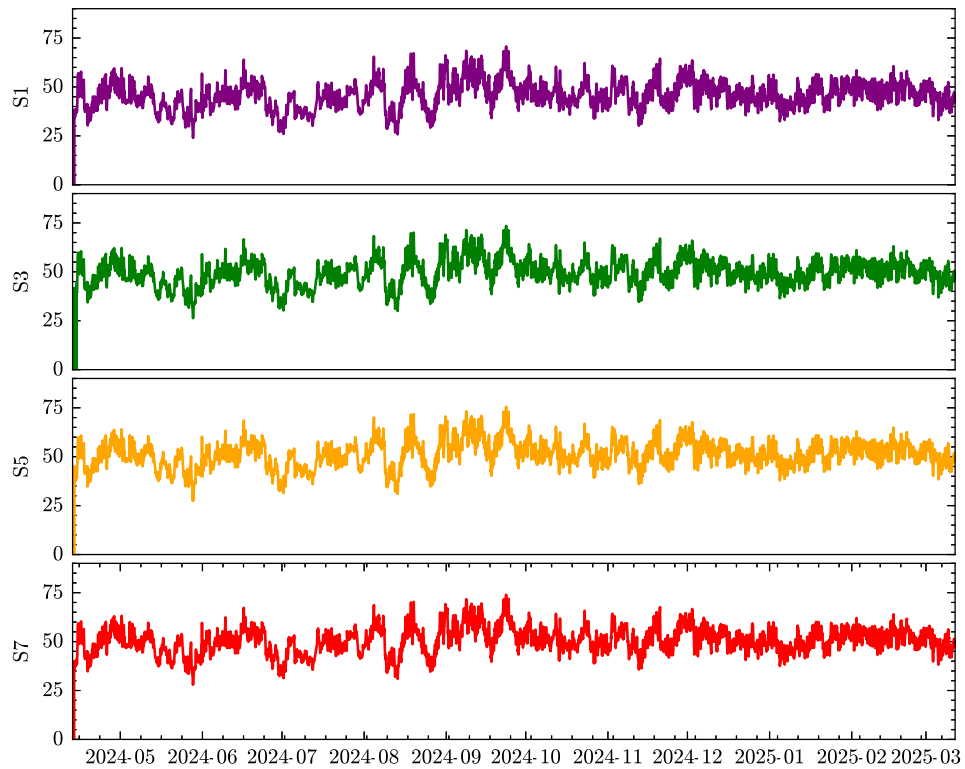


Figure 70 – Relative humidity measured around UG2, in %.

5.6 Comparison of PD and ozone concentrations

The ozone measurements from UG2 are not significant, perhaps with the exception of sensor 4. When comparing the values with PD data for the couplers with highest PD activity, as shown in Figure 71, there is no clear correlation. Also, the absolute ozone levels are not very high.

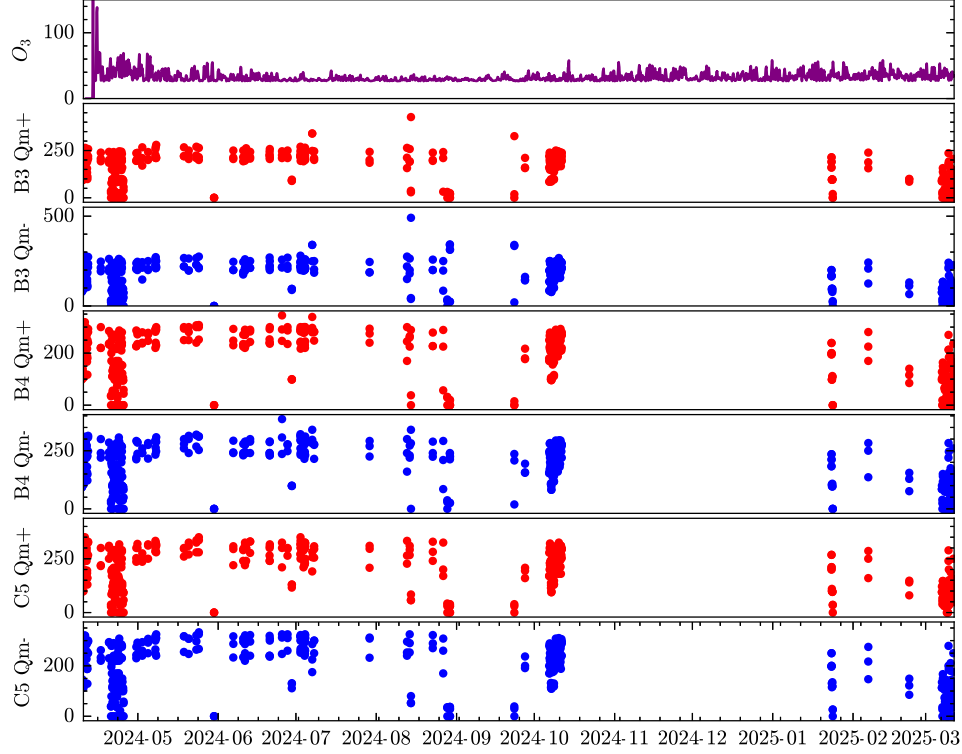


Figure 71 – Ozone measurements from sensor 4 in UG2 compared to PD data from the couplers with higher Qm values. Ozone concentrations are in ppb, all Qm values are in mV.

For UG3, the situation is different. The ozone levels in sensor 3 spiked to very high values right after the machine went back into operation after a planned overhaul in September/2023, when the ozone modules were installed. Figure 72 shows the average concentration in the first 10 days of operation. It is interesting to note that coupler B3, with the highest PD values, is installed near this radiator, which is evidence to support a localized problem in the stator insulation. Very high PD measurements were seen in coupler B4, which is also physically close to radiator 3.

The average ozone concentration above 200 ppb measured in this module in the first days after UG3 resumed operation is above the safe limits for continuous human exposure [29], and the peaks are on par with the worst cases recorded in literature for hydrogenerators [28].

As mentioned in Section 5.3, the PD monitor installed in UG3 had technical issues, so for a period of time, there are no measurements available. The operational data with voltage, current, stator temperature and active power was also restricted to a period of around 6 months, adding to the challenge of comparing all variables. The data available is summarized in Figure 73.

It is possible to analyze the relevant operational parameters during the period in which sensor 3 recorded an anomalous increase in ozone concentration. Figure 74 presents key machine parameters following the scheduled maintenance outage. Notably, once the generator resumed continuous full-load operation on approximately October 17th, ozone concentrations in radiator 3 rose sharply to around 280 ppb before gradually declining. Despite this variation, PD activity remained stable, as evidenced by

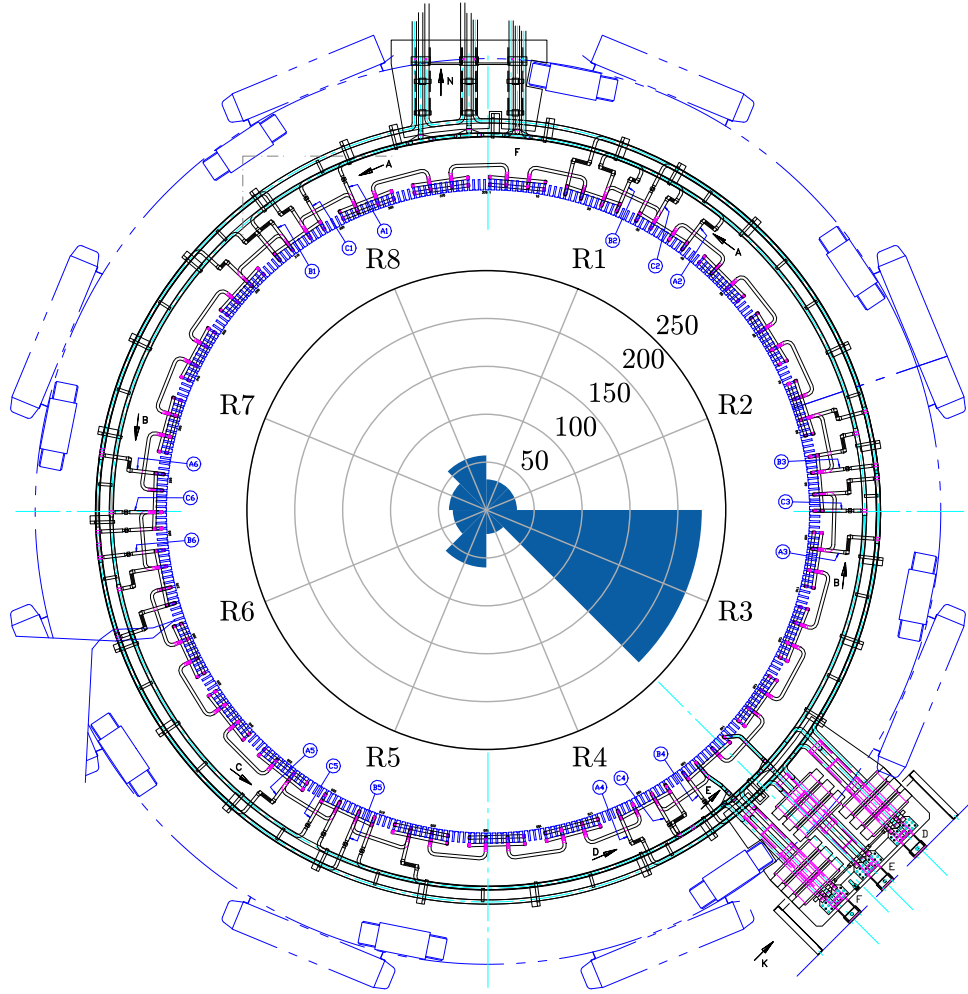


Figure 72 – Average ozone concentration (ppb) detected by the modules installed in each radiator (R1-R8) during 10 days of operation after the planned outage. The stator drawing is overlaid with the position of each PD coupler.

the Q_{m+} and Q_{m-} signals from coupler B3, which were comparable to pre-outage measurements. No significant variations were observed in the signals from the other coupler pairs during this interval.

Given that corona-related maintenance had recently been carried out on the stator, such elevated ozone levels would not be anticipated unless some regions of the stator were inadequately treated. In isolation, the available data does not fully account for the abrupt increase and subsequent slow decrease in ozone levels — particularly under the assumption of stable PD activity. However, subsequent information from plant personnel revealed that the corona repairs had not been entirely finalized when the unit was returned to service, and portions of the applied resin were required to cure while the generator was operating. This supports the hypothesis that residual corona discharges initially generated elevated ozone levels, which then progressively diminished as the resin completed its curing process under full-load conditions. After approximately six weeks of continuous operation, ozone concentrations measured by sensor 3 had decreased to below 100 ppb on average, although they remained slightly elevated compared to readings from the other sensors. Additional information regarding the maintenance activities performed during the outage is provided in Section 5.7.

Interestingly, sensor 3 once again recorded elevated ozone concentrations between November/2024 and February/2025. It is not possible to establish a direct correlation with PD measurements during this interval, as it coincides with the period in which the PD monitoring system experienced technical mal-

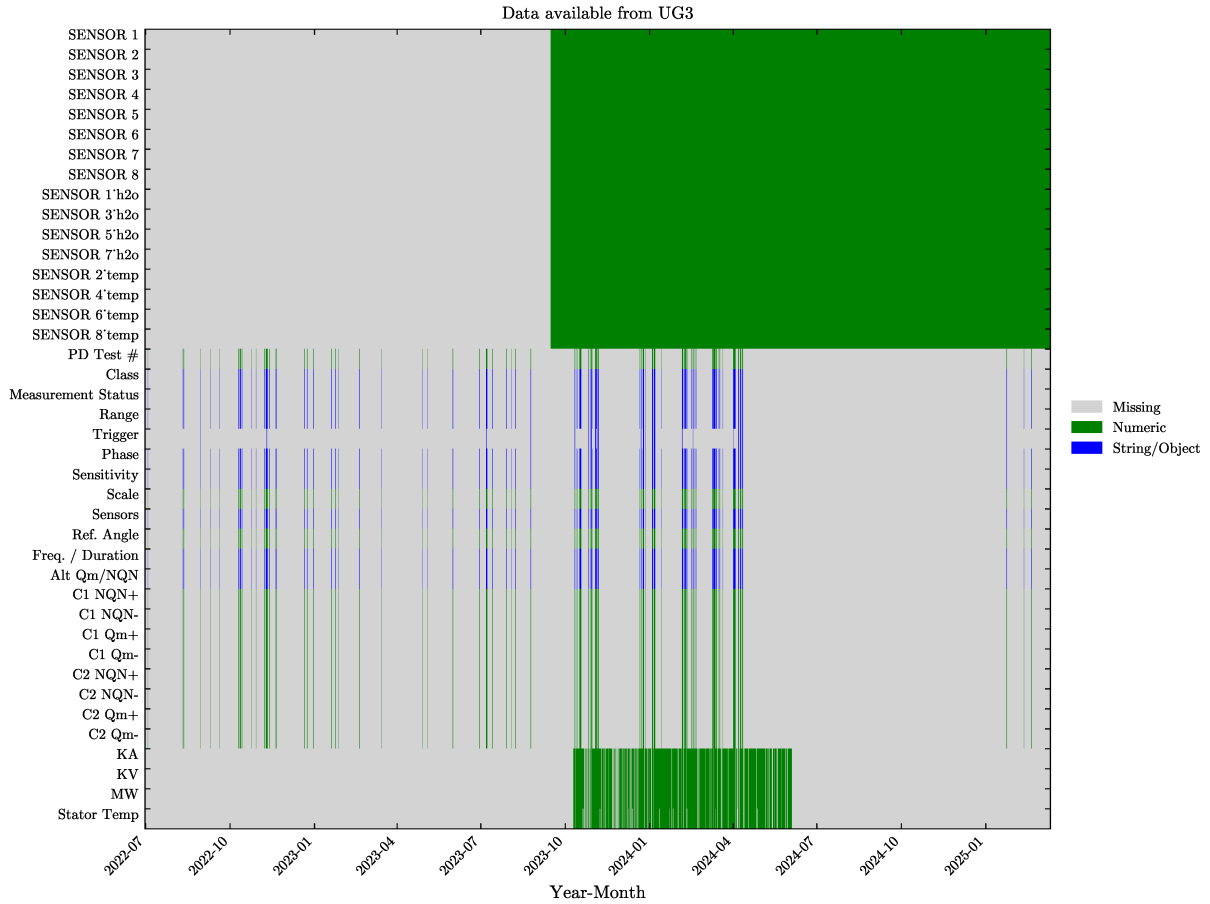


Figure 73 – Data available for UG3. From top to bottom: sensor 1-8 are data from the ozone modules; parameters from “PD Test #” to “C2 Qm-” are data from the PD monitor; “KA”, “KV”, “MW” and “Stator Temp” are operating parameters from the machine sourced from the process historian.

functions. Nevertheless, the ozone concentrations measured in January/2025 do not differ significantly from those observed in April/2024, when the monitoring system was functioning correctly. This observation suggests that the ozone sensor may be detecting underlying corona activity that is not captured by conventional PD measurement techniques.

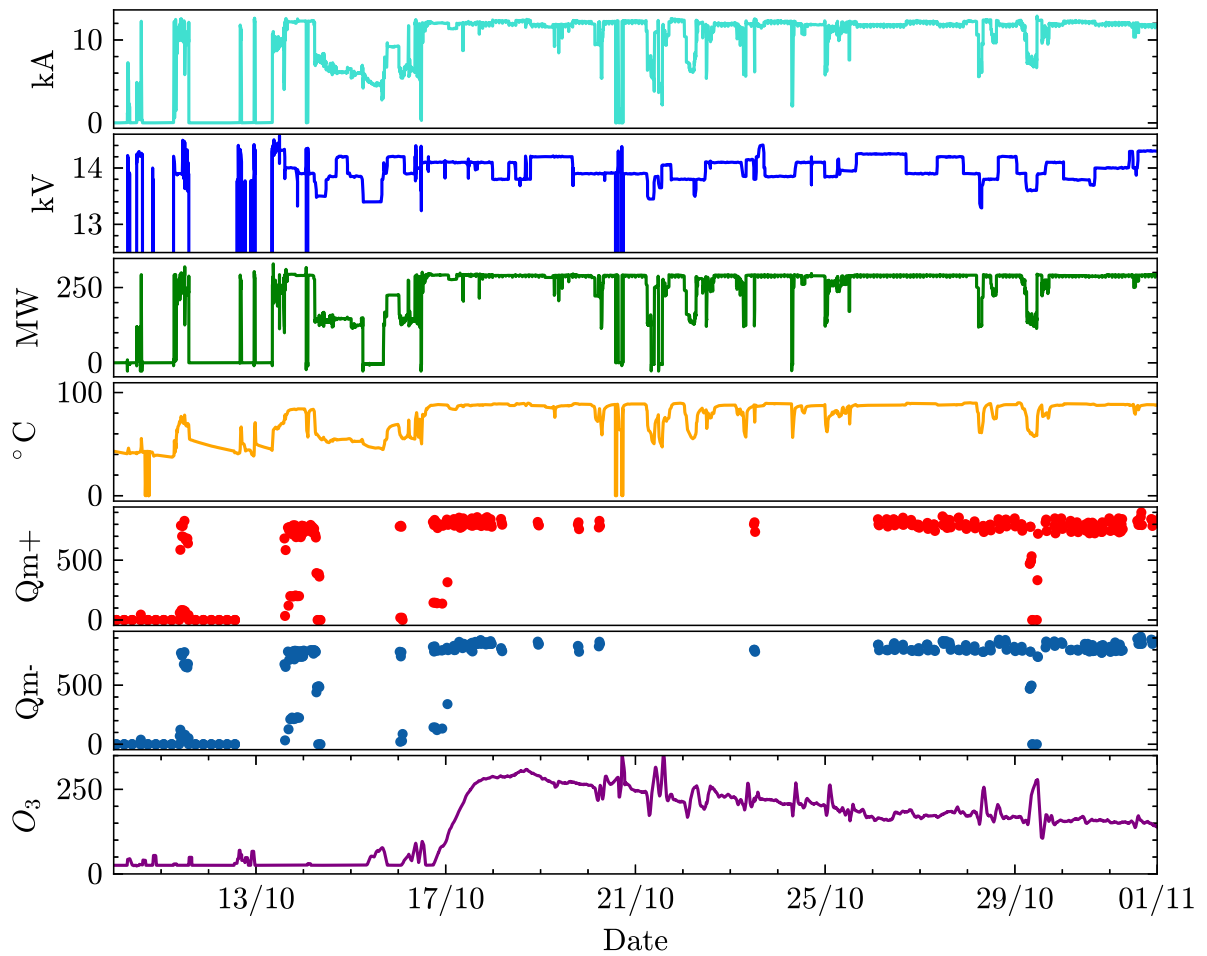


Figure 74 – Operational parameters of the hydrogenerator with PD data for coupler B3 and ozone concentrations in radiator 3. From top to bottom: stator current, voltage, active power, stator temperature, Qm+ in coupler B3 (mV), Qm- in coupler B3 (mV) and ozone concentration in radiator 3 (ppb).

5.7 Repairs made in UG3

UG3 began experiencing evidence of corona discharge phenomena in its stator bars after approximately a decade of operation, in 2017. In 2018, multiple corona points were identified through visual inspection, leading to a systematic mapping of affected areas. A total of 41 bars - comprising 8 in the top and 33 in the bottom endwindings - exhibited damage, primarily located approximately 20 mm from the stator slot exit, in the transitional zone between the main insulation and the stress grading layer.

In response, localized repairs were undertaken in accordance with the manufacturer's recommendations. These procedures included sanding of the damaged surface, cleaning with isopropyl alcohol, and the application of two layers of AstroChemical 3411 semiconductive paint. Due to material availability at the time, a protective varnish layer could not be applied during this intervention. Although these repairs were effective in mitigating the immediate issues, the recurrence of corona in previously treated areas highlighted the need for long-term monitoring and more robust intervention.

A subsequent maintenance intervention was carried out in July 2019, focusing on the stress grading coating of the stator bars. This service addressed 32 identified corona points, including 7 locations that had previously undergone repair but required retouching. The affected regions were found predominantly near the interface between the straight portion of the bars and the stress grading layer, as shown in Figures 75 and 76. The repair methodology involved surface sanding, cleaning, and the application of a semiconductive grading paint to restore the adequate electrical properties.



Figure 75 – Corona spots identified in UG3 in 2019.

The interventions revealed that even after over a decade of operation, UG3 exhibited signs of premature insulation aging, inconsistent with the expected service life of generators with Class F insulation. The recurrence and concentration of corona points in specific bar regions suggested potential flaws in assembly processes or material application during manufacturing.

During the installation of the ozone monitoring system in 2023, UG3 was under a major overhaul and, once again, repairs were performed to mitigate corona in the endwindings. Figures 77 and 78 show



Figure 76 – Corona repair process in UG3 in 2019.

the exact spots where corona was found and repaired during this time.

Photos of some of the corona spots prior to the repair activities are shown in Figures 79, 80 and 81. Table 13 gives detailed information regarding where the repairs were done, either in the top bar, bottom bar or interface between bars. Overall PD levels (Q_m/NQN) were not altered after the repairs.

Given the localized nature of the defects present in the stator insulation of UG3 and how they are progressing with time, requiring interventions every few years, there is a possibility that ozone monitoring can be a more effective way to detect their evolution than traditional PD measurements. This can also explain the transient nature of the ozone concentrations, for example the “reappearance” of high concentrations in sensor 3 between November/2024 and February/2025.

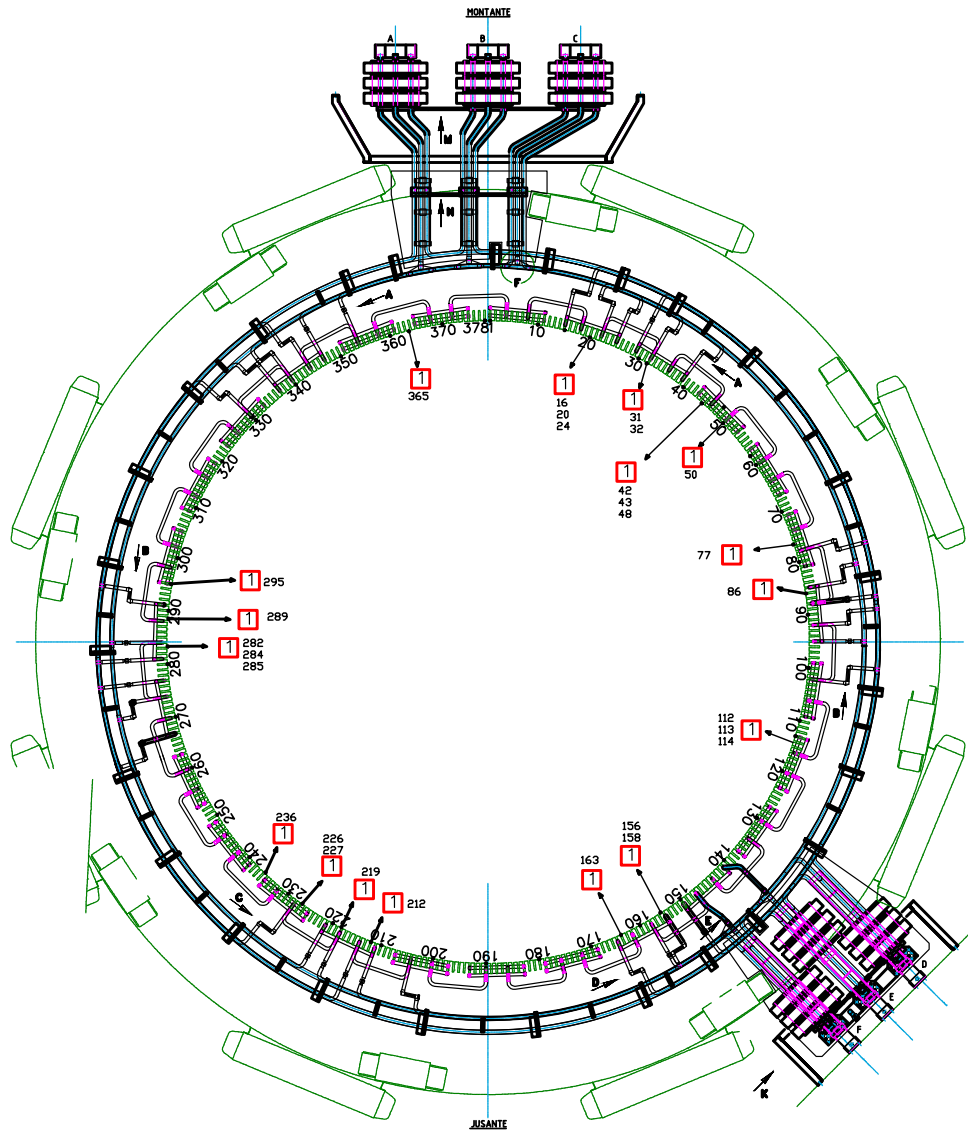


Figure 77 – Location of corona repairs in the top endwindings (2023).

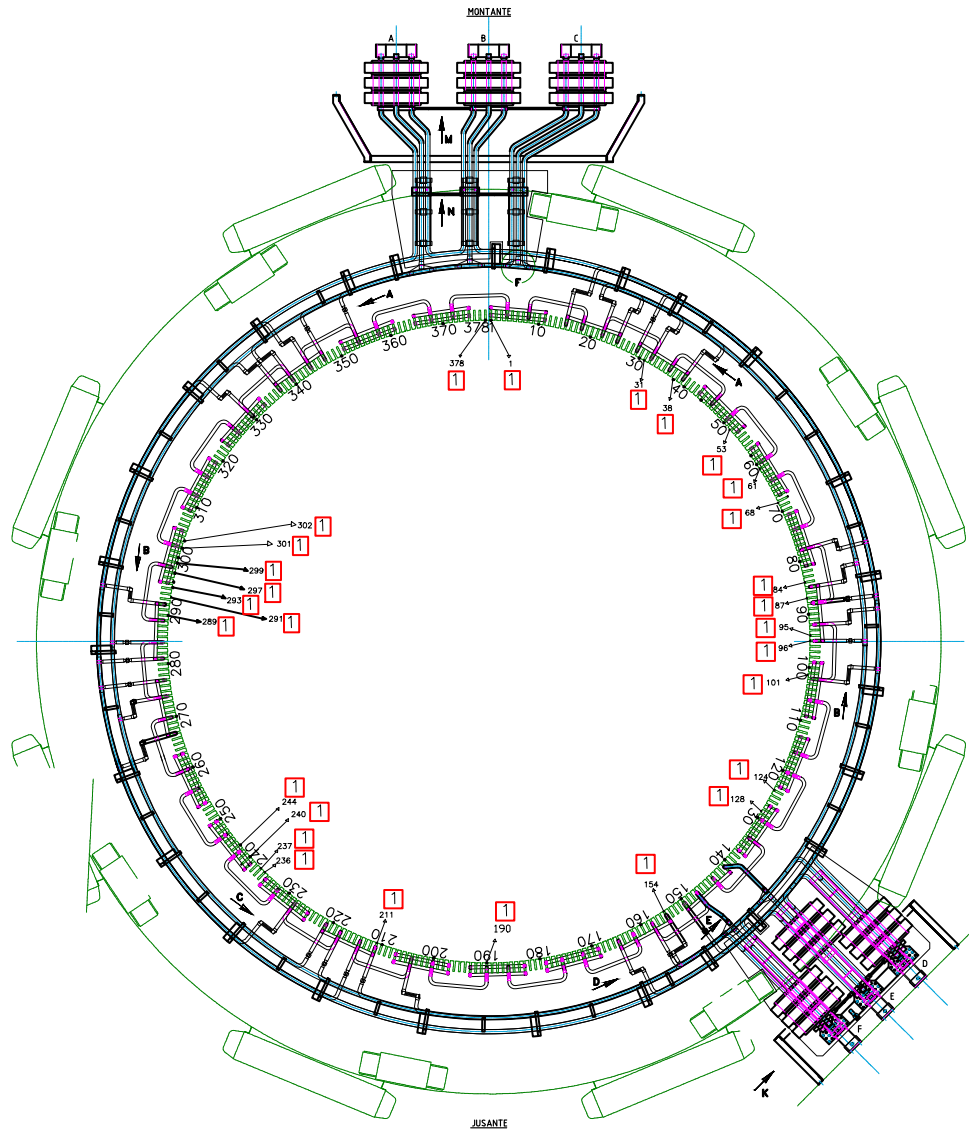


Figure 78 – Location of corona repairs in the bottom endwindings (2023).

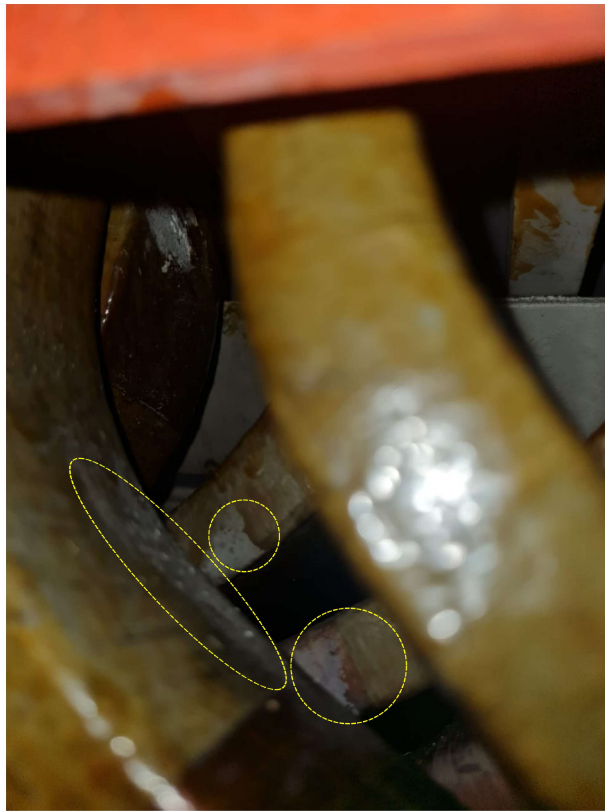


Figure 79 – Corona spots prior to repair, slot 36.



Figure 80 – Corona spots prior to repair, slot 37.



Figure 81 – Corona spots prior to repair, slot 298.

Table 13 – Corona repairs done on UG3 (September 2023).

CORONA TOP SIDE	CORONA BOTTOM SIDE
SLOT 163 top	SLOT 61 bottom
SLOT 158 top	SLOT 68 top
SLOT 156 top	SLOT 53 top
SLOT 114 top	SLOT 38 top
SLOT 113 top	SLOT 31 bottom
SLOT 112 top	SLOT 01 bottom
SLOT 86 bottom	SLOT 378 bottom
SLOT 77 top	SLOT 237 bottom
SLOT 32 top	SLOT 236 bottom
SLOT 31 top	SLOT 302 top
SLOT 24 between bars	SLOT 301 top
SLOT 20 top	SLOT 299 bottom
SLOT 16 top	SLOT 297 bottom
SLOT 42 top	SLOT 293 bottom
SLOT 43 top	SLOT 291 top
SLOT 48 between bars	SLOT 289 bottom
SLOT 50 between bars	SLOT 244 top
SLOT 212 bottom	SLOT 240 top
SLOT 219 top	SLOT 124 bottom
SLOT 226 between bars	SLOT 211 bottom
SLOT 227 between bars	SLOT 190 bottom
SLOT 236 top	SLOT 154 bottom
SLOT 284 top	SLOT 128 top
SLOT 285 top	SLOT 101 top
SLOT 282 between bars	SLOT 96 bottom
SLOT 289 top	SLOT 95 bottom
SLOT 295 between bars	SLOT 87 bottom
SLOT 365 top	SLOT 84 bottom

6 CONCLUSIONS

The objectives proposed at the beginning of the project were accomplished. Prototypes of a low-cost ozone concentration measurement module using electrochemical sensors were developed and installed in two hydrogenerators. Compared to the current state-of-the-art in hydrogenerator monitoring, these modules offer several advantages: they contain no moving parts, allow direct *in situ* measurement without pumps or tubing, can be easily installed and maintained without proprietary tools, and can be readily integrated into existing SCADA systems. A patent application was submitted to secure intellectual property rights for the design.

A key innovation of this work is the integration of an onboard microcontroller within the monitoring module, which offers a critical advantage by enabling real-time compensation of sensor readings in response to local variations in environmental parameters, specifically temperature and humidity. These factors represent significant sources of interference and measurement uncertainty when employing this class of sensors, particularly in industrial environments characterized by fluctuating ambient conditions. Addressing these environmental influences is essential for ensuring the accuracy and reliability of the sensor outputs, enhancing the overall efficacy of the monitoring system. To this end, two distinct compensation methodologies were developed and implemented to mitigate the effects of such variations. Both methods are adaptable and hold potential for broader application to a wide range of similar electrochemical sensors used in diverse monitoring contexts. However, it is important to note that while these approaches improve sensor reliability, their computational requirements differ substantially. Specifically, the application of long short-term memory (LSTM) neural networks for advanced signal processing and compensation demands greater processing power and memory resources, thus necessitating the use of more sophisticated microcontrollers for successful embedded implementation.

These compensation techniques are not limited to the specific sensors used in this study. Their adaptability positions them as valuable tools for broader applications, such as air quality monitoring, where accurate gas detection under variable environmental conditions is essential [91]. By enabling real-time corrections, the proposed methods contribute to the development of robust, distributed sensing networks for smart infrastructure, for example.

Unfortunately, the scope of the present study was constrained by the limited availability of critical operational parameters, which were exclusively accessible for UG3. Additionally, certain segments of the PD data exhibited corruption, further restricting the dataset's completeness and integrity. These limitations precluded the possibility of conducting a more comprehensive evaluation and establishing robust correlations among the full range of monitored variables over extended periods of time. Such analyses are often essential for uncovering deeper insights into the complex interactions between operational conditions, insulation aging mechanisms, and PD activity. Nevertheless, despite these constraints, the dataset that remained available was sufficiently extensive and of adequate quality to support solid and reliable conclusions. The findings obtained underscore the effectiveness of the proposed monitoring approaches and provide valuable empirical evidence that can inform future research and practical applications.

Compared to the PD data systematically recorded in the two hydrogenerators over an extended monitoring period of nearly three years, the prototypes installed as part of this study demonstrated the capability to detect potential localized insulation issues that would likely have remained undetected if relying solely on conventional PD monitoring techniques. These findings provide compelling evidence that the application of such monitoring can significantly enhance the machine condition assessment

practices. By enabling the detection of spatially confined anomalies, ozone monitoring facilitates more targeted maintenance interventions, thereby improving the overall reliability and operational efficiency of hydrogenerators. An added benefit of having temperature and humidity sensors embedded in the same module is the possibility of detecting problems with the heat exchangers, which was observed during the period of data collection.

It is also noteworthy that, despite the predominance of studies in the existing scientific literature focusing on isolated or discrete ozone measurements in hydrogenerators, the implementation of a low cost yet reliable continuous ozone monitoring represents a substantial advancement in the field. From the perspective of predictive maintenance, the ability to continuously evaluate ozone levels offers superior diagnostic value, as it enables the detection of temporal trends and the early identification of emerging issues. In contrast, isolated or sporadic measurements of ozone concentration may lack contextual relevance and diagnostic reliability, given that absolute ozone values can be influenced by transient environmental factors and may not consistently reflect the underlying state of insulation degradation. Therefore, the capacity for continuous monitoring not only enriches the dataset but also provides a more robust basis for predictive analytics, ultimately supporting more effective maintenance strategies.

Although certain types of partial discharges may not be directly associated with significant ozone production, the modular system developed in this study offers considerable practical advantages. The design facilitates rapid deployment in hydrogenerators currently lacking any form of diagnostic monitoring, thereby enabling the identification of potential insulation-related issues at a substantially lower cost compared to the implementation of comprehensive, continuous PD monitoring infrastructures. Furthermore, the integration of a microcontroller within the prototype enhances its versatility and operational independence. With minimal hardware modifications, the system could be configured for standalone operation, eliminating the necessity for ancillary equipment such as a PLC. This adaptation would, however, necessitate the incorporation of a suitable data storage medium, such as a memory card, to enable the logging and subsequent analysis of monitoring data. Such an autonomous configuration would further reduce installation complexity and operational costs, allowing a wider adoption of this monitoring solutions in hydrogenerators. The low current draw (around 42 mA at 24 V) expands the possibility of application with batteries in locations where cables cannot be installed, and a wireless communication protocol could be used to retrieve measurements, for example.

In addition to their application within hydrogenerators, continuous ozone monitoring systems hold significant potential for deployment in other classes of electrical machinery, particularly high-voltage motors that are operated in hazardous or chemically aggressive environments. In such applications, it is common for the internal atmosphere of the machine to be completely sealed in order to prevent the ingress of external contaminants. However, this sealing can inadvertently result in the accumulation of ozone generated by internal electrical discharges, creating conditions that lead to chemical degradation. The presence of ozone within the enclosed system can cause the formation of secondary reactive species, such as nitric acid, which pose a serious risk of chemical attack on various critical components, including insulation materials and metallic parts [92]. The resultant degradation can compromise the operational integrity of the machine and significantly reduce its service life. Given that the monitoring modules developed in this study are characterized by their low cost and ease of implementation, their application in such high-voltage motors presents a practical and economically viable solution for the early detection of ozone accumulation. Early identification of this condition can enable timely maintenance interventions, thereby mitigating the risk of unplanned outages and extending the operational reliability of the equipment.

An additional way to enhance the effectiveness and diagnostic capability of ozone monitoring systems would be the deployment of sensor arrays or grids, as opposed to relying solely on single-point

measurements. The utilization of multiple spatially distributed sensors would enable a more comprehensive characterization of the internal ozone concentration profile within the machine, providing valuable insights into the spatial distribution of ozone generation and accumulation. This, in turn, would allow a more precise localization of the sources of surface PD. For example, sensor grid data could reveal whether PD activity is predominantly concentrated in specific regions, such as the top or bottom endwindings. Such spatial resolution would greatly improve the ability to implement targeted maintenance actions, focusing on areas most susceptible to degradation, and thereby optimizing maintenance schedules and resource allocation. Furthermore, the application of sensor grids could contribute to the development of advanced diagnostic models and algorithms that leverage spatially resolved data to predict insulation aging patterns with higher accuracy.

While the monitoring approach proposed in this study demonstrates significant practical benefits, it is important to note that current international standards issued by organizations such as the IEC and IEEE provide limited guidance on the use of ozone monitoring in hydrogenerators and other high-voltage rotating machines. These standards primarily focus on traditional PD measurement techniques and do not adequately address alternative diagnostic tools such as ozone detection. Given the empirical evidence presented herein, continuous ozone monitoring should be considered as a complementary technique, particularly in machines exhibiting localized stator insulation degradation or constructive defects that may lead to surface PD. For instance, in units where stator bars have insufficient spacing or recurrent corona activity is observed, ozone monitoring may even surpass conventional PD detection in effectiveness by offering clearer, spatially resolved indications of insulation stress. Moreover, the placement of ozone sensors within the machine must be carefully planned: since ozone is highly reactive and disperses quickly, sensor positioning should prioritize areas near the most probable sources of surface PD - such as top or bottom endwindings - where ozone concentrations are more likely to remain detectable. In this context, the integration of ozone sensing into condition monitoring practices fills a critical gap left by current standards and presents an opportunity for future revisions of international guidelines to incorporate alternative and complementary monitoring methodologies.

Future research could explore the long-term behavior and degradation of electrochemical sensors under sustained exposure to high-voltage machine environments, with the aim of developing adaptive calibration protocols that account for sensor aging and drift. Additionally, the integration of ozone monitoring data with other diagnostic indicators — such as vibration, temperature and PD measurements — could support the development of multi-modal predictive maintenance algorithms, potentially employing machine learning for automated fault classification. Expanding field trials to a broader range of hydrogenerators and high-voltage motors, including those operating under diverse load and environmental conditions, would further validate the robustness of the proposed system. A new version of the sensing module could include both Winsen ZE25A-O3 and Sensirion SGP41, making use of sensor fusion for wider dynamic range. Lastly, future developments could focus on the implementation of sensor grids within rotating machines to enable the spatial mapping of ozone concentration gradients. Such configurations would enhance the ability to pinpoint localized PD activity with greater accuracy.

REFERENCES

- [1] DIAS, V. D. S. et al. An overview of hydropower reservoirs in brazil: Current situation, future perspectives and impacts of climate change. *Water*, MDPI AG, v. 10, n. 5, p. 592, maio 2018. ISSN 2073-4441. Disponível em: <<http://dx.doi.org/10.3390/w10050592>>.
- [2] Empresa de Pesquisa Energética - EPE (Ed.). *Brazilian Energy Balance Summary Report 2024*. [S.l.]: Ministry of Mines and Energy – MME, 2024.
- [3] NUNES, P.; SANTOS, J.; ROCHA, E. Challenges in predictive maintenance – a review. *CIRP Journal of Manufacturing Science and Technology*, Elsevier BV, v. 40, p. 53–67, fev. 2023. ISSN 1755-5817. Disponível em: <<http://dx.doi.org/10.1016/j.cirpj.2022.11.004>>.
- [4] CIGRE (Ed.). *Survey of Hydrogenerator Failures, EG11.02*. [S.l.]: CIGRE Study Committee SC11, 2003.
- [5] KONG, T.-s. Analysis of correlation among partial discharges, ozone emission, and ultraviolet radiation in high voltage motor stator windings. v. 6, n. 6, p. 113. Disponível em: <<http://www.sciencepublishinggroup.com/journal/paperinfo?journalid=165&doi=10.11648/j.epes.20170606.14>>.
- [6] HUDON, C.; BELEC, M.; LEVESQUE, M. Study of slot partial discharges in air-cooled generators. *IEEE Transactions on Dielectrics and Electrical Insulation*, Institute of Electrical and Electronics Engineers (IEEE), v. 15, n. 6, p. 1675–1690, dez. 2008. ISSN 1070-9878. Disponível em: <<http://dx.doi.org/10.1109/TDEI.2008.4712672>>.
- [7] ANDRITZ HYDRO. *Andritz Cooling Air analysis - DIA TECH CAA-O3 product brochure*. Vienna, Austria, 2018. <https://grzg.andritz.com/c/com2011/00/02/51/25190/1/1/0/228048199/hy-diatech-caa-03.pdf>.
- [8] SCHOENBEIN, C. F. On the odour accompanying electricity, and on the probability of its dependence on the presence of a new substance; by C. F. Schoenbein, Professor of Chemistry, Bâle, communicated in a letter to Michael Faraday. *Abstracts of the Papers Printed in the Philosophical Transactions of the Royal Society of London*, The Royal Society, v. 4, p. 226–226, 12 1843. Disponível em: <<https://doi.org/10.1098/rspl.1837.0114>>.
- [9] SORET, J. L. Recherches sur la densité de l’ozone. *C. R. Hebd. Seances Acad. Sci.*, v. 61, p. 941, 1865.
- [10] DUNDERDALE, C. P. *Apparatus for the production of ozone*. 1870. US Patent US100736A. Disponível em: <<https://patents.google.com/patent/US100736A>>.
- [11] FICHMAN, B. T. *Annual Energy Review 2011*. Office of Scientific and Technical Information (OSTI), 2012. Disponível em: <<http://dx.doi.org/10.2172/1212312>>.
- [12] HIGHFIELD, J. S. *The Electrician*, v. 54, p. 573, 1905.
- [13] EPSTEIN, J. Testing of electric machinery and of materials for its construction. *Journal of the Institution of Electrical Engineers*, Institution of Engineering and Technology (IET), v. 38, n. 181, p. 28–62, 1907. ISSN 2054-0612. Disponível em: <<http://dx.doi.org/10.1049/jiee-1.1907.0002>>.
- [14] GLAZEBROOK, R. et al. Discussion on testing of electric machinery and of materials for its construction. *Journal of the Institution of Electrical Engineers*, Institution of Engineering and Technology (IET), v. 38, n. 181, p. 62–103, 1907. Disponível em: <<https://doi.org/10.1049/jiee-1.1907.0003>>.
- [15] FLEMING, A.; JOHNSON, R. Chemical action in the windings of high-voltage machines. *Journal of the Institution of Electrical Engineers*, Institution of Engineering and Technology (IET), v. 47, n. 209, p. 530–551, 1911. ISSN 2054-0612. Disponível em: <<http://dx.doi.org/10.1049/jiee-1.1911.0050>>.
- [16] LOWRY, T. M. The oxidation of atmospheric nitrogen in presence of ozone. *Journal of the Chemical Society, Transactions*, Royal Society of Chemistry (RSC), v. 101, p. 1152–1158, 1912. Disponível em: <<https://doi.org/10.1039/ct9120101152>>.

- [17] FAUCETT, M. A.; HOUPIS, C.; LEIBINGER, G. E. A survey of electrical insulation practices. *University of Illinois Bulletin*, v. 47, n. 23, p. 11, 1949.
- [18] JOHNSON, J. S. Slot discharge detection coil surface and core of high-voltage stator windings. *Transactions of the American Institute of Electrical Engineers*, Institute of Electrical and Electronics Engineers (IEEE), v. 70, n. 2, p. 1993–1997, jul. 1951. ISSN 0096-3860. Disponível em: <<http://dx.doi.org/10.1109/T-AIEE.1951.5060663>>.
- [19] JOHNSON, J. S.; WARREN, M. Detection of slot discharges in high-voltage stator windings during operation. *Transactions of the American Institute of Electrical Engineers*, Institute of Electrical and Electronics Engineers (IEEE), v. 70, n. 2, p. 1998–2000, jul. 1951. ISSN 0096-3860. Disponível em: <<http://dx.doi.org/10.1109/t-aiee.1951.5060664>>.
- [20] FRANKLIN, D. E.; POLLOCK, B. C.; LAAKSO, J. Hydro-electric generator ozone monitoring. In: *Waterpower '93*. [S.l.: s.n.], 1993. p. 1767–1777.
- [21] JR, W. D. *Ozone formed by high-voltage transmission line coronas*. [S.l.], 1972.
- [22] LUNT, R. The mechanism of ozone formation in electrical discharges. *Advances in Chemistry*, p. 286–303, 1959.
- [23] PEKÁREK, S.; ROSENKRANZ, J.; KHUN, J. Ozone generation from two hollow needles to plate electrical discharges enhanced by an airflow. In: *12th International Congress on Plasma Physics*. Nice, France: [s.n.], 2004.
- [24] CHEN, J.; DAVIDSON, J. Ozone production in the positive dc corona discharge: Model and comparison to experiments. *Plasma Chemistry and Plasma Processing*, v. 22, p. 495–522, 12 2002.
- [25] GORSHELEV, V. et al. High spectral resolution ozone absorption cross-sections part 1: Measurements, data analysis and comparison with previous measurements around 293 k. *Atmospheric Measurement Techniques*, v. 7, n. 2, p. 609–624, 2014.
- [26] BELEC, M. et al. Investigation and diagnosis of a 184-mva air-cooled generator heavily affected by slot partial discharge activity. In: *2007 Electrical Insulation Conference and Electrical Manufacturing Expo*. IEEE, 2007. Disponível em: <<http://dx.doi.org/10.1109/EEIC.2007.4562594>>.
- [27] LÉPINE, L.; LESSARD-DÉZIEL, D.; BÉLEC, M. Understanding ozone distribution inside stator core and measurements inside air-cooled generators to assess partial discharges problems. In: *Iris Rotating Machine Conference*. [S.l.]: Iris Power, 2007.
- [28] BELEC, M. et al. Investigation and diagnosis of a 184-mva air-cooled generator heavily affected by slot partial discharge activity. In: *2007 Electrical Insulation Conference and Electrical Manufacturing Expo*. [S.l.: s.n.], 2007. p. 85–90.
- [29] MILLET, C. et al. Case study - high ozone concentration in hydro generators. In: *2009 IEEE Electrical Insulation Conference*. IEEE, 2009. p. 178–182. ISBN 978-1-4244-3915-7. Disponível em: <<http://ieeexplore.ieee.org/document/5166340/>>.
- [30] LIMA, A. A. et al. Medição da concentração de ozônio como ferramenta no diagnóstico de envelhecimento da isolamento por descargas parciais em hidrogeradores. In: *Décimo Quinto Encontro Regional Ibero-americano do CIGRÉ*. Foz do Iguaçu, Brasil: [s.n.], 2013. p. 1–8.
- [31] HUDON, C. et al. Using integrated generator diagnosis to perform condition based maintenance. In: *2015 IEEE Electrical Insulation Conference (EIC)*. IEEE, 2015. Disponível em: <<http://dx.doi.org/10.1109/icacact.2014.7223540>>.
- [32] LI, K.; JAVED, H.; ZHANG, G. Calculation of ozone and NOx production under AC corona discharge in dry air used for faults diagnostic. In: *Proceedings of the 2015 2nd International Conference on Machinery, Materials Engineering, Chemical Engineering and Biotechnology*. Atlantis Press, 2016. Disponível em: <<https://doi.org/10.2991/mmeceb-15.2016.91>>.
- [33] SPEC SENSORS, LLC. *SPEC Sensor Operation Overview*. Newark, CA, 2016. <https://www.spec-sensors.com/wp-content/uploads/2016/05/SPEC-Sensor-Operation-Overview.pdf>.

- [34] PARRINO, F.; CIRIMINNA, R.; PALMISANO, G. Ozone sensors for an informed exposure assessment: A review. *Micromachines*, MDPI, v. 11, n. 6, p. 624, 2020.
- [35] LEWIS, A. C. et al. Review of low-cost sensors for the measurement of atmospheric composition: capabilities and limitations. *Atmospheric Measurement Techniques*, Copernicus GmbH, v. 9, n. 10, p. 5503–5529, 2016.
- [36] CASTELL, N. et al. Real-time mobile monitoring of air pollution using low-cost sensors: An urban case study in barcelona. *Environmental Pollution*, Elsevier, v. 229, p. 579–588, 2017.
- [37] SIMÕES, F.; XAVIER, M. 6 - electrochemical sensors. In: Da Róz, A. L. et al. (Ed.). *Nanoscience and its Applications*. William Andrew Publishing, 2017, (Micro and Nano Technologies). p. 155–178. ISBN 978-0-323-49780-0. Disponível em: <<https://www.sciencedirect.com/science/article/pii/B9780323497800000065>>.
- [38] SRINIVES, S. et al. Potassium iodide-functionalized polyaniline nanothin film chemiresistor for ultrasensitive ozone gas sensing. *Polymers*, MDPI AG, v. 9, n. 12, p. 80, 2 2017. Disponível em: <<https://doi.org/10.3390/polym9030080>>.
- [39] SCHENCK, E. H.; BURKE, P. A.; CENTANNI, M. A. *US-10001455-B2*. 2018.
- [40] SPINELLE, L. et al. Field calibration of a cluster of low-cost available sensors for air quality monitoring. part a: Ozone and nitrogen dioxide. *Sensors and Actuators B: Chemical*, Elsevier BV, v. 215, p. 249–257, 8 2015. Disponível em: <<https://doi.org/10.1016/j.snb.2015.03.031>>.
- [41] RIPOLL, A. et al. Testing the performance of sensors for ozone pollution monitoring in a citizen science approach. *Science of The Total Environment*, Elsevier BV, v. 651, p. 1166–1179, fev. 2019. Disponível em: <<https://doi.org/10.1016/j.scitotenv.2018.09.257>>.
- [42] LEWIS, A.; PELTIER, W. R.; SCHNEIDEMESSER, E. von. *Low-cost sensors for the measurement of atmospheric composition: overview of topic and future applications*. Geneva, Switzerland, 2018.
- [43] MAYERHÖFER, T. G.; PAHLOW, S.; POPP, J. The bouguer-beer-lambert law: Shining light on the obscure. *ChemPhysChem*, Wiley, v. 21, n. 18, p. 2029–2046, 8 2020. Disponível em: <<https://doi.org/10.1002/cphc.202000464>>.
- [44] ANDERSEN, P. C.; WILLIFORD, C. J.; BIRKS, J. W. Miniature personal ozone monitor based on UV absorbance†. *Analytical Chemistry*, American Chemical Society (ACS), v. 82, n. 19, p. 7924–7928, out. 2010. Disponível em: <<https://doi.org/10.1021/ac1013578>>.
- [45] MARIA, L. D.; RIZZI, G. Ozone sensor for application in medium voltage switchboard. *Journal of Sensors*, v. 2009, p. 1–5, 2009.
- [46] RAY, J. D.; STEDMAN, D. H.; WENDEL, G. J. Fast chemiluminescent method for measurement of ambient ozone. *Analytical Chemistry*, American Chemical Society (ACS), v. 58, n. 3, p. 598–600, mar. 1986. Disponível em: <<https://doi.org/10.1021/ac00294a025>>.
- [47] KEERATIRAWEE, K.; HAUSER, P. C. Photoacoustic detection of ozone with a red laser diode. *Talanta*, Elsevier BV, v. 223, p. 121890, fev. 2021. Disponível em: <<https://doi.org/10.1016/j.talanta.2020.121890>>.
- [48] KÖHRING, M. et al. Fiber-coupled ozone sensor based on tuning fork-enhanced interferometric photoacoustic spectroscopy. *IEEE Journal of Selected Topics in Quantum Electronics*, Institute of Electrical and Electronics Engineers (IEEE), v. 18, n. 5, p. 1566–1572, set. 2012. Disponível em: <<https://doi.org/10.1109/jstqe.2012.2182761>>.
- [49] BÖTTGER, S. et al. Off-beam quartz-enhanced photoacoustic spectroscopy with LEDs. *Applied Physics B*, Springer Science and Business Media LLC, v. 113, n. 2, p. 227–232, maio 2013. Disponível em: <<https://doi.org/10.1007/s00340-013-5462-x>>.
- [50] CHIEN, H.-T. et al. Standoff detection of ozone in an open environment using photoacoustic spectroscopy technique. *Applied Physics Letters*, AIP Publishing, v. 100, n. 10, p. 104102, mar. 2012. Disponível em: <<https://doi.org/10.1063/1.3692595>>.

- [51] DEVKOTA, J.; OHODNICKI, P.; GREVE, D. SAW sensors for chemical vapors and gases. *Sensors*, MDPI AG, v. 17, n. 4, p. 801, abr. 2017. Disponível em: <<https://doi.org/10.3390/s17040801>>.
- [52] WESTAFER, R. S. et al. Detection of ppb ozone using a dispersive surface acoustic wave reflective delay line with integrated reference signal. *Sensors and Actuators B: Chemical*, Elsevier BV, v. 192, p. 406–413, mar. 2014. Disponível em: <<https://doi.org/10.1016/j.snb.2013.10.104>>.
- [53] MASTELARO, V. R. et al. Ozone gas sensor based on nanocrystalline SrTi_{1-x}FexO₃ thin films. *Sensors and Actuators B: Chemical*, Elsevier BV, v. 181, p. 919–924, maio 2013. Disponível em: <<https://doi.org/10.1016/j.snb.2013.02.068>>.
- [54] LIMA, B. de et al. Ozone detection in the ppt-level with rGO-ZnO based sensor. *Sensors and Actuators B: Chemical*, Elsevier BV, v. 338, p. 129779, 7 2021. Disponível em: <<https://doi.org/10.1016/j.snb.2021.129779>>.
- [55] WU, C.-H. et al. Analysis of the sensing properties of a highly stable and reproducible ozone gas sensor based on amorphous in-ga-zn-o thin film. *Sensors*, MDPI AG, v. 18, n. 2, p. 163, jan. 2018. Disponível em: <<https://doi.org/10.3390/s18010163>>.
- [56] SUI, Y. et al. Room-temperature ozone sensing capability of IGZO-decorated amorphous ga₂o₃ films. *ACS Applied Materials & Interfaces*, American Chemical Society (ACS), v. 12, n. 7, p. 8929–8934, jan. 2020. Disponível em: <<https://doi.org/10.1021/acsami.9b22400>>.
- [57] WANG, C. et al. Photon stimulated sensor based on indium oxide nanoparticles i: Wide-concentration-range ozone monitoring in air. *Sensors and Actuators B: Chemical*, Elsevier BV, v. 152, n. 2, p. 235–240, mar. 2011. Disponível em: <<https://doi.org/10.1016/j.snb.2010.12.014>>.
- [58] European Commission. *Protocol of evaluation and calibration of low-cost gas sensors for the monitoring of air pollution - Joint Research Centre - Institute for Environment and Sustainability*. European Union, 2013. Disponível em: <<https://data.europa.eu/doi/10.2788/9916>>.
- [59] European Commission. *Laboratory and in-situ validation of ozone microsensors, αSense, model B4 O3 sensors. Task 4.3, Testing protocol, procedures and testing of performances of sensors*. European Union, 2014. Disponível em: <<https://data.europa.eu/doi/10.2788/84725>>.
- [60] WADHWA, C. L. *High Voltage Engineering*". 2. ed. New Delhi, India: New Age International, 2006. 10-14 p.
- [61] STONE, G. C. et al. *Electrical Insulation for Rotating Machines: Design, Evaluation, Aging, Testing, and Repair*. Wiley, 2014. ISBN 9781118886663. Disponível em: <<http://dx.doi.org/10.1002/9781118886663>>.
- [62] PEMEN, A. J. M. et al. Propagation of partial discharge signals in stator windings of turbine generators. *IEEE Transactions on Energy Conversion*, IEEE, v. 21, n. 1, p. 135–143, 2006.
- [63] CASTRO, B. et al. Partial discharge monitoring in power transformers using low-cost piezoelectric sensors. *Sensors*, MDPI, v. 16, n. 8, p. 1266, 2016.
- [64] LUO, Y.; LI, Z.; WANG, H. A review of online partial discharge measurement of large generators. *Energies*, MDPI AG, v. 10, n. 11, p. 1694, out. 2017. ISSN 1996-1073. Disponível em: <<http://dx.doi.org/10.3390/en10111694>>.
- [65] CRUZ, J. d. S. et al. Partial discharges monitoring for electric machines diagnosis: A review. *Energies*, MDPI AG, v. 15, n. 21, p. 7966, out. 2022. ISSN 1996-1073. Disponível em: <<http://dx.doi.org/10.3390/en15217966>>.
- [66] International Electrotechnical Commission. *Rotating Electrical Machines-Part 27-1: Off-line partial discharge measurements on the winding insulation. IEC/TS 60034-27-1*. Geneva, Switzerland, 2017.
- [67] International Electrotechnical Commission. *Rotating Electrical Machines-Part 27-2: On-Line Partial Discharge Measurements on the Stator Winding Insulation of Rotating Electrical Machines. IEC/TS 60034-27-2*. Geneva, Switzerland, 2023.

- [68] STONE, G. C.; SEDDING, H. Comparison of low and high frequency partial discharge measurements on stator windings. In: *Proceedings of the Nordic Insulation Symposium*. [S.l.: s.n.], 2019. p. 134–138.
- [69] MOR, A. R.; HEREDIA, L. C.; MUÑOZ, F. New clustering techniques based on current peak value, charge and energy calculations for separation of partial discharge sources. *IEEE Transactions on Dielectrics and Electrical Insulation*, IEEE, v. 24, n. 1, p. 340–348, 2017.
- [70] NAGESH, V.; GURURAJ, B. Evaluation of digital filters for rejecting discrete spectral interference in on-site pd measurements. *IEEE Transactions on Electrical Insulation*, Institute of Electrical and Electronics Engineers (IEEE), v. 28, n. 1, p. 73–85, 1993. ISSN 0018-9367. Disponível em: <<http://dx.doi.org/10.1109/14.192242>>.
- [71] KHAN, S. Z. et al. A new adaptive technique for on-line partial discharge monitoring. *IEEE Transactions on Dielectrics and Electrical Insulation*, Institute of Electrical and Electronics Engineers (IEEE), v. 2, n. 4, p. 700–707, 1995. ISSN 1070-9878. Disponível em: <<http://dx.doi.org/10.1109/94.407034>>.
- [72] CARVALHO, A. T. et al. Identification of partial discharges immersed in noise in large hydro-generators based on improved wavelet selection methods. *Measurement*, Elsevier, v. 75, p. 122–133, 2015.
- [73] ALTAY, O.; KALENDERLI, O. Wavelet base selection for de-noising and extraction of partial discharge pulses in noisy environment. *IET Science, Measurement and Technology*, Institution of Engineering and Technology (IET), v. 9, n. 3, p. 276–284, 2015. ISSN 1751-8830. Disponível em: <<http://dx.doi.org/10.1049/iet-smt.2013.0114>>.
- [74] CHEN, J.; WANG, P. Effect of relative humidity on electron distribution and ozone production by DC coronas in air. *IEEE Transactions on Plasma Science*, Institute of Electrical and Electronics Engineers (IEEE), v. 33, n. 2, p. 808–812, 4 2005. Disponível em: <<https://doi.org/10.1109/tps.2005.844530>>.
- [75] HUDON, C.; BARTNIKAS, R.; WERTHEIMER, M. R. Effect of physico-chemical degradation of epoxy resin on partial discharge behavior. *IEEE Transactions on Dielectrics and Electrical Insulation*, Institute of Electrical and Electronics Engineers (IEEE), v. 2, n. 6, p. 1083–1094, dez. 1995. ISSN 1558-4135. Disponível em: <<http://dx.doi.org/10.1109/TDEI.1995.8881923>>.
- [76] BINDER, E. et al. Effects of air humidity and temperature to the activities of external partial discharges of stator windings. In: *1999 Eleventh International Symposium on High Voltage Engineering*. London, UK: [s.n.], 1999.
- [77] DMITRIEV, V. et al. Localization of partial discharges in hydrogenerators by ozone emission. *Energies*, MDPI AG, v. 17, n. 13, p. 3173, jun. 2024. ISSN 1996-1073. Disponível em: <<http://dx.doi.org/10.3390/en17133173>>.
- [78] PANG, X. et al. Electrochemical ozone sensors: A miniaturised alternative for ozone measurements in laboratory experiments and air-quality monitoring. *Sensors and Actuators B: Chemical*, Elsevier BV, v. 240, p. 829–837, mar. 2017. ISSN 0925-4005. Disponível em: <<http://dx.doi.org/10.1016/j.snb.2016.09.020>>.
- [79] LOPES, N. M. et al. Compatibilidade eletromagnética em hidrogerador: Cálculo de campos e de voltagens induzidas oscilando a 60 hz. In: SOCIEDADE BRASILEIRA DE MICROONDAS E OPTOELETRÔNICA. *Proceedings of the 20th Brazilian Symposium of Microwaves and Optoelectronics*. Natal, RN, Brazil, 2022. p. 428.
- [80] Sensirion AG. *SGP41 Datasheet: Air Quality Sensor for VOC and NOx Measurements*. 2021. <<https://www.sensirion.com>>. Version 1.0, December 2021.
- [81] ZAR, J. H. Spearman rank correlation: Overview. *Wiley StatsRef: Statistics Reference Online*, Wiley, set. 2014.
- [82] GIBBONS, J. *Nonparametric Measures of Association*. SAGE Publications, Inc., 1993. ISBN 9781412985291. Disponível em: <<http://dx.doi.org/10.4135/9781412985291>>.

- [83] MANNING, C. D.; RAGHAVAN, P.; SCHÜTZE, H. *Introduction to Information Retrieval*. Cambridge University Press, 2008. ISBN 9780511809071. Disponível em: <<http://dx.doi.org/10.1017/CBO9780511809071>>.
- [84] TANCEV, G. et al. Efficient and automated generation of orthogonal atmospheres for the characterization of low-cost gas sensor systems in air quality monitoring. *IEEE Transactions on Instrumentation and Measurement*, Institute of Electrical and Electronics Engineers (IEEE), v. 71, p. 1–10, 2022. ISSN 1557-9662.
- [85] LI, K. et al. Analysis of air decomposition by-products under four kinds of partial discharge defects. *IEEE Transactions on Dielectrics and Electrical Insulation*, Institute of Electrical and Electronics Engineers (IEEE), v. 24, n. 6, p. 3713–3721, dez. 2017. ISSN 1558-4135.
- [86] TONDINI, S.; SCILLA, R.; CASARI, P. Minimized training of machine learning-based calibration methods for low-cost o3 sensors. *IEEE Sensors Journal*, Institute of Electrical and Electronics Engineers (IEEE), v. 24, n. 3, p. 3973–3987, fev. 2024.
- [87] HOCHREITER, S.; SCHMIDHUBER, J. Long short-term memory. *Neural Computation*, MIT Press, v. 9, n. 8, p. 1735–1780, nov. 1997. ISSN 1530-888X. Disponível em: <<http://dx.doi.org/10.1162/neco.1997.9.8.1735>>.
- [88] YU, Y. et al. A review of recurrent neural networks: Lstm cells and network architectures. *Neural Computation*, MIT Press, v. 31, n. 7, p. 1235–1270, 2019.
- [89] HUDON, C.; BELEC, M. Partial discharge signal interpretation for generator diagnostics. *IEEE Transactions on Dielectrics and Electrical Insulation*, Institute of Electrical and Electronics Engineers (IEEE), v. 12, n. 2, p. 297–319, abr. 2005. ISSN 1070-9878.
- [90] SAVITZKY, A.; GOLAY, M. J. E. Smoothing and differentiation of data by simplified least squares procedures. *Analytical Chemistry*, American Chemical Society (ACS), v. 36, n. 8, p. 1627–1639, jul. 1964. ISSN 1520-6882. Disponível em: <<http://dx.doi.org/10.1021/ac60214a047>>.
- [91] THOMPSON, J. E. Crowd-sourced air quality studies: A review of the literature & portable sensors. *Trends in Environmental Analytical Chemistry*, Elsevier BV, v. 11, p. 23–34, jul. 2016. Disponível em: <<https://doi.org/10.1016/j.teac.2016.06.001>>.
- [92] CESTARO, G. L.; FERNANDES, M. F.; TEIXEIRA, M. Fault detection in components of synchronous motors through online partial discharge measurements. In: *2024 IEEE Petroleum and Chemical Industry Conference Brasil (PCIC Brasil)*. [S.l.]: IEEE, 2024. v. 101, p. 1–10.

Appendix

**APPENDIX A – DEVELOPMENT OF A LOW-COST OZONE
MONITORING MODULE FOR CONTINUOUS PARTIAL DISCHARGE
DETECTION IN HYDROGENERATORS**

- [A] **M. F. Fernandes**, I. P. Bordin, J. A. de França. *Development of a Low-Cost Ozone Monitoring Module for Continuous Partial Discharge Detection in Hydrogenerators*. IEEE Transactions on Instrumentation & Measurement, vol. 74, pp. 1–7, 2025, Art no. 3529507, DOI: 10.1109/TIM.2025.3557129. (IF=5.6, A1-Eng. IV in QUALIS-CAPES)

Development of a Low-Cost Ozone Monitoring Module for Continuous Partial Discharge Detection in Hydrogenerators

Martim F. Fernandes^{ID}, *Graduate Student Member, IEEE*, Ian P. Bordin^{ID}, and José Alexandre de França^{ID}

Abstract—Partial discharge (PD) measurement is a well-established predictive maintenance tool for high-voltage rotating machines, allowing the condition of the insulation to be assessed not only during machine outages, but also continuously monitored during regular operation, enabling a more efficient planning of major overhauls or possible repairs. Some types of PDs are known to produce ozone in air-cooled machines, but online ozone monitoring has not been widely available commercially for this application, perhaps with one exception which uses a complex system of tubes and valves to direct air samples to a measuring chamber, based on ultraviolet (UV) absorption. Advances in electrochemical sensors, however, have allowed for more reliable measurements at very low cost. In this article, we describe the development and prototype of an ozone monitoring module with embedded signal processing for specific application in rotating machines, using simultaneous temperature and humidity measurements to reduce the typical errors induced by the variations of these parameters. Prototypes were manufactured and installed in two 311 MVA hydrogenerators and the data collected indicates that continuous ozone monitoring can detect potential problems that may not be identified with traditional PD monitoring.

Index Terms—High-voltage machines, hydrogenerators, monitoring, ozone, partial discharge (PD), predictive maintenance, rotating machines.

I. INTRODUCTION

PARTIAL discharge (PD) monitoring in stator windings is a well-known tool for the diagnostics of the insulating material condition in high-voltage rotating machines. These systems are based on high-frequency pulse measurements generated by the occurrence of PD in the insulation of the stator. Several international standards define the different ways that these pulses can be measured, such as the IEEE 1434 [1].

PD can be detected with the machine in operation (online) or during an outage (offline). Offline detection methods require an ac supply to energize the windings to a voltage at least equal to the rated phase-to-ground. The PD pulses are filtered through a high voltage capacitor and measured in an oscilloscope or specialized PD equipment. Another method involves

using an ultraviolet (UV) camera to visually detect spots where PD is occurring [2], which is more common during a rotor pull, since line of sight is needed.

Online measurements, with the machine in operation, have the advantage of not needing an external power supply, since the machine is already energized and can help identify potential problems much earlier, when compared to tests only performed during outages. Online PD measurements are usually done through capacitive couplers permanently installed on the machine terminals [3], although other methods exist, such as the use of ultrahigh frequency (UHF) antennas [4] or high-frequency current transformers (HFCT) [5]. The amplitude, phase and quantity of pulses, as well as their trends over time, help estimate the condition of the insulating system, avoiding unexpected outages and improving availability of the generators. Specifically for online monitoring, an external interface is used to collect these signals through a portable or permanently installed instrument. The hardware used for data collection is often based on proprietary field-programmable gate array (FPGA) implementations that can quickly compare individual pulse shapes and timings with a precision of nanoseconds. These systems can be very costly and are sometimes economically prohibitive for smaller machines, for example, since the installation may require specialized professionals, machine downtime, and be fairly invasive.

Having a cheaper alternative, then, or at least a complementary monitoring method that helps detect PD in rotating machines can have significant impact on the reliability of power plants, especially when considering smaller machines that may not have any PD monitoring at all. Recent works have shown a correspondence between surface PDs and ozone formation in air-cooled machines [6], [7], and although exact localization of PD is not possible, if ozone concentration is measured in many different points around the stator, locations with higher surface PD tend to correlate with higher ozone concentrations [8].

In 1951, the first publications mention equipment and methods to detect slot discharges in generators, both with the machine offline [9] and online [10], a first glimpse of what eventually evolved to become the modern PD measurement techniques. Interestingly, the probable first mention of a continuous ozone monitoring system is from 1993 [11], but the presence of ozone inside electrical machines is a subject that has been discussed since the beginning of the

Received 26 February 2025; accepted 21 March 2025. Date of publication 2 April 2025; date of current version 17 April 2025. This work was supported by the Research Project P&D Brazilian National Agency of Electrical Energy (ANEEL) "Investigation and Methodology of Ozone Concentration Analysis in Hydrogenerators as a Predictive Maintenance Tool" under Grant PD-00642-2905/2020. The Associate Editor coordinating the review process was Dr. He Wen. (*Corresponding author: Martim F. Fernandes.*)

The authors are with the Department of Electrical Engineering, State University of Londrina, Londrina, Paraná, Brazil (e-mail: martim.fernandes@uel.br; ian.pena.bordin@uel.br; josealexandre@uel.br).

Digital Object Identifier 10.1109/TIM.2025.3557129

1557-9662 © 2025 IEEE. All rights reserved, including rights for text and data mining, and training of artificial intelligence and similar technologies. Personal use is permitted, but republication/redistribution requires IEEE permission.

See <https://www.ieee.org/publications/rights/index.html> for more information.

Authorized licensed use limited to: UEL - Universidade Estadual de Londrina. Downloaded on April 21, 2025 at 15:00:45 UTC from IEEE Xplore. Restrictions apply.

APPENDIX B – PARTIAL DISCHARGES IN HYDROELECTRIC GENERATORS: DETECTION, PROCESSING, CLASSIFICATION, AND PINPOINTING

- [B] V. Dmitriev, R. M. S. Oliveira, Ronaldo F. Zampolo, P. R. M de Vilhena, F. de Souza Brasil and **M. F. Fernandes**, *Partial Discharges in Hydroelectric Generators: Detection, Processing, Classification, and Pinpointing*, Springer International Publishing, 2024, DOI: 10.1007/978-3-031-36604-8, ISBN 9783031366048.

Power Systems

Victor Dmitriev

Rodrigo M. S. Oliveira

Ronaldo F. Zampolo

Paulo R. Moutinho de Vilhena

Fernando de Souza Brasil

Martim Felipe Fernandes

Partial Discharges in Hydroelectric Generators

Detection, Processing, Classification,
and Pinpointing

MOREMEDIA



 Springer

Victor Dmitriev
Faculty of Electrical and Biomedical
Engineering (FEEB)
Federal University of Pará (UFPA), Institute
of Technology (ITEC)
Belém, Pará, Brazil

Ronaldo F. Zampolo
Faculty of Computer Engineering and
Telecommunications (FCT)
Federal University of Pará (UFPA), Institute
of Technology (ITEC)
Belém, Pará, Brazil

Fernando de Souza Brasil
Eletronorte
Belém, Pará, Brazil

Rodrigo M. S. Oliveira
Faculty of Electrical and Biomedical
Engineering (FEEB)
Federal University of Pará (UFPA), Institute
of Technology (ITEC)
Belém, Pará, Brazil

Paulo R. Moutinho de Vilhena
Eletronorte
Macapá, Amapá, Brazil

Martim Felipe Fernandes
State University of Londrina (UEL)
Londrina, Paraná, Brazil

ISSN 1612-1287

Power Systems

ISBN 978-3-031-36603-1

<https://doi.org/10.1007/978-3-031-36604-8>

ISSN 1860-4676 (electronic)

ISBN 978-3-031-36604-8 (eBook)

© The Editor(s) (if applicable) and The Author(s), under exclusive license to Springer Nature Switzerland AG 2024

This work is subject to copyright. All rights are solely and exclusively licensed by the Publisher, whether the whole or part of the material is concerned, specifically the rights of translation, reprinting, reuse of illustrations, recitation, broadcasting, reproduction on microfilms or in any other physical way, and transmission or information storage and retrieval, electronic adaptation, computer software, or by similar or dissimilar methodology now known or hereafter developed.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors, and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

Paper in this product is recyclable.

APPENDIX C – FAULT DETECTION IN COMPONENTS OF SYNCHRONOUS MOTORS THROUGH ONLINE PARTIAL DISCHARGE MEASUREMENTS

- [C] G. L. Cestaro, **M. F. Fernandes** and M. Teixeira, *Fault Detection in Components of Synchronous Motors through Online Partial Discharge Measurements*, 2024 IEEE Petroleum and Chemical Industry Conference Brasil (PCIC Brasil), Rio de Janeiro, Brazil, 2024, pp. 1-10, DOI: 10.1109/PCICBrasil54376.2024.10553094.

FAULT DETECTION IN COMPONENTS OF SYNCHRONOUS MOTORS THROUGH ONLINE PARTIAL DISCHARGE MEASUREMENTS

Copyright IEEE
Trabalho nº PCIC BR 2024-21

Guilherme L. Cestaro
Petrobras
Brazil

Martim F. Fernandes
IEEE Member
State University of Londrina
Brazil

Milene Teixeira
Iris Power
Brazil
IEEE Member

glcestaro@petrobras.com.br

martim.fernandes@uel.br

mteixeira@qualitrolcorp.com

Abstract – Online Partial Discharge (PD) tests have been widely used in rotating machines over 4 kV since the late 1980s. PD monitoring is a powerful tool to provide evidence of deterioration of the winding insulation months or even years in advance, allowing for the planning of proper corrective maintenance actions, avoiding in this way unexpected failures in service. PD is usually the main symptom of fault mechanisms occurring in the stator winding. Through the analysis of these symptoms, it is possible to infer the root cause. There are situations, however, where the PD is the cause itself, for example when the discharges lead to the formation of ozone in the interior of a sealed machine. The presence of ozone can trigger the formation of nitric acid (HNO_3), a highly corrosive substance not only for insulating materials, but also for the metallic parts of the machine. This paper presents a case study of a synchronous motor where extremely high PD levels were detected, prompting an internal inspection and confirmation of damage, possibly by the chemical attack of nitric acid on various parts of the machine. The worst problem was observed in the rotor, with the appearance of cracks and fissures in the damper winding cage, which may have been caused or intensified by the action of this acid.

Index Terms — partial discharges, synchronous motors, ozone, nitric acid, damper winding, predictive maintenance, rotating machines.

I. INTRODUCTION

Partial Discharge (PD) monitoring in stator windings is a well-known tool for the diagnostics of the insulating material condition in machines with nominal voltage above 4 kV. The system is based on high-frequency pulse measurements (50-350 MHz), generated by the occurrence of PD in the insulation of the stator. Typically, this system consists of capacitive couplers (80 pF) permanently installed on the machine terminals.

In the frequency of PD pulses, the couplers act as a short circuit, filtering these pulses. In online monitoring (with the machine in operation), an external interface is used to collect these signals through a portable or permanently installed instrument.

The signal collector/analyzer generates two main graphs: Pulse Height Analysis (PHA) and Pulse Phase Analysis, which provide useful information about the PD occurring in the insulation, namely:

- PD magnitude: Related to the size or volume of the voids in the insulation, represented by Q_{m+} and Q_{m-} .
- PD pulse rate: Related to the total number of voids or defects in the insulating material.
- PD polarity: Indication of the place where the voids are, whether closer to the copper conductors or the insulator surface.
- PD pulse position compared to phase-ground voltage: An indication of the PD having phase-phase or phase-ground dependence.

This information allows, in many cases, a general evaluation of the insulation condition. A rigorous analysis of the data can provide the severity of the deterioration and the approximate locations of occurrence, for example if the voids are within the insulation, in the copper/insulation interface or in the surface of the insulation.

In this work, we report a case where PD analysis led to a maintenance outage and observation that the ozone generated by the discharges possibly caused the formation of nitric acid, which in turn chemically degraded the surface of the stator insulation. In the same machine, major problems were diagnosed in the rotor, which may have been intensified by the presence of this acid. We also present the records from the disassembly of the machine and removal of the old winding.

II. BASIC CONSTRUCTIVE FEATURES OF MACHINE INSULATION SYSTEMS

Machine windings provide a path for the electric current, while the stator core allows for the efficient magnetic coupling between rotor and stator as well as providing heat dissipation. Since there's a potential difference between the conductors and the core, an insulating material must exist between them. Modern insulation materials are generally reliable, but it is by far the weakest component of an electrical machine and the part that ages the quickest.

High voltage (HV) stator windings are usually separated into two categories: bars, generally used in larger machines with long axial dimensions (such as 2-pole turbogenerators) and full coils, typically used in smaller machines or with a high number of poles.

**APPENDIX D – (SUBMITTED PATENT) MÓDULO DE
MONITORAMENTO DE OZÔNIO PARA MÁQUINAS ELÉTRICAS DE ALTA
TENSÃO**

[D] M. F. Fernandes, I. P. Bordin, *Módulo de monitoramento de ozônio para máquinas elétricas de alta tensão*, processo BR 10 2024 020972 9 (INPI), 09/10/2024.



SERVIÇO PÚBLICO FEDERAL
MINISTÉRIO DO DESENVOLVIMENTO, INDÚSTRIA, COMÉRCIO E SERVIÇOS
INSTITUTO NACIONAL DA PROPRIEDADE INDUSTRIAL

EXAME FORMAL PRELIMINAR – PEDIDO CONSIDERADO DEPOSITADO

N.º do Pedido: BR102024020972-9 **N.º de Depósito PCT:**
Data de Depósito: 09/10/2024

O pedido atende às condições formais estabelecidas pelo INPI na Portaria nº 14/2024 conforme disposto no art.19 da Lei da Propriedade Industrial (LPI) e é considerado como depositado.

Condições do Pedido	S	N
Formulário de depósito com os campos obrigatórios preenchidos	X	
Idioma Português	X	
Relatório Descritivo	X	
Reivindicações	X	
PI e CA – Apresenta desenhos (quando citados). MU – Apresenta desenhos.	X	
Resumo	X	
Formatado no padrão exigido	X	
Valor correto de Recolhimento	X	

Rio de Janeiro, 10 de março de 2025.

Aline Aimée Carneiro de Oliveira
Mat. Nº 1326227
DIRPA / COSAP/SEFOR

APPENDIX E – DIMENSIONALITY REDUCTION AND CLUSTERING STRATEGIES FOR LABEL PROPAGATION IN PARTIAL DISCHARGE DATA SETS

- [E] R. F. Zampolo, F. Lopes, R. M. S. Oliveira, **M. F. Fernandes** and V. Dmitriev, *Dimensionality reduction and clustering strategies for label propagation in partial discharge data sets*, MDPI Energies, 2024, v. 17, no. 23: 5936, DOI: 10.3390/en17235936. (IF=3.0, A2-Eng. IV in QUALIS-CAPES)

Article

Dimensionality Reduction and Clustering Strategies for Label Propagation in Partial Discharge Data Sets

Ronaldo F. Zampolo ^{1,*}, Frederico H. R. Lopes ¹, Rodrigo M. S. de Oliveira ^{1,*}, Martim F. Fernandes ²
and Victor Dmitriev ¹

¹ Institute of Technology (ITEC), Federal University of Pará (UFPA), Belém 66075-110, PA, Brazil; frederico.lopes@itec.ufpa.br (F.H.R.L.); victor@ufpa.br (V.D.)

² Electrical Engineering Department, State University of Londrina, Londrina 86057-970, PR, Brazil; martim.fernandes@uel.br

* Correspondence: zampolo@ufpa.br (R.F.Z.); rmso@ufpa.br (R.M.S.d.O.)

Abstract: Deep learning approaches have been successfully applied to perform automatic classification of phase-resolved partial discharge (PRPD) diagrams. Under the supervised learning paradigm, however, the performance of classifiers strongly depends on the availability of large and previously labeled data sets. Labeling is an intensive and time-consuming labor, typically involving the manual annotation of a large number of data examples by an expert. In this work, we propose a label propagation algorithm applied to PRPD data sets, aiming to reduce the time necessary to manually label PRPDs. Our basic pipeline is composed of three phases: pre-processing, dimensionality reduction procedures, and clustering. Different configurations of the basic pipeline are tested by using PRPDs obtained from online measurements in hydrogenerators. The performance of each configuration is assessed by using the Silhouette, Caliński–Harabasz, and Davies–Bouldin scores. The clustering of the best three configurations is compared with annotated PRPDs by using the Fowlkes–Mallows index. Results suggest our strategy can substantially decrease the time for manual labeling.

Keywords: label propagation; Kernel-PCA; PaCMAP; k-means++; clustering



Citation: Zampolo, R.F.; Lopes, F.H.R.; de Oliveira, R.M.S.; Fernandes, M.F.; Dmitriev, V. Dimensionality Reduction and Clustering Strategies for Label Propagation in Partial Discharge Data Sets. *Energies* **2024**, *17*, 5936. <https://doi.org/10.3390/en17235936>

Academic Editor: Claus Leth Bak

Received: 12 October 2024

Revised: 4 November 2024

Accepted: 18 November 2024

Published: 26 November 2024



Copyright: © 2024 by the authors. Licensee MDPI, Basel, Switzerland. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY) license (<https://creativecommons.org/licenses/by/4.0/>).

1. Introduction

Partial discharge (PD) analysis is an effective approach to monitoring the condition of high-voltage (HV) equipment. Practical evidence indicates that insulation defects are the main cause of HV machine failures in 60% of the occurrences [1,2]. By monitoring the PD activity of HV equipment, an analyst can decide the better moment for starting a maintenance intervention, either to prevent unforeseen failures or to reduce downtime.

The PD shape is closely related to its originating event in a way that periodic PD analysis allows following the evolution and identifying the type of insulation defect [3]. Individual pulse shape analysis, however, does not seem to be feasible in the field due to the need to recover the original pulse shape, i.e., the pulse shape at the very PD site. Thus, practical PD monitoring uses phase-resolved partial discharge (PRPD) diagrams, in which amplitude and phase pairs from the detected PDs are counted. After measuring a high number of PD pulses during several powerline cycles, a PRPD pattern is formed. The technical specification IEC/TS 60034-27-2 [4] associates specific PRPD patterns with distinct insulation defects, most of them usually found in regular operation of hydroelectric generators.

As in other technical fields, first automatic PD classifiers were based on classical machine learning techniques—like hidden Markov models [5], fuzzy classifiers [6], and support vector machines [7]. Then, we saw the development of strategies based on shallow artificial neural networks [1,8]. Due to their superior results, however, deep learning approaches have dominated the scenario of machine learning applications, including the area of condition monitoring of HV equipment [9–11]. As illustrated by Mantach et al. [12],

Annex

ANNEX A – PHASE-RESOLVED PARTIAL DISCHARGE PLOTS FOR UG2

Pulse Phase Analysis (PRPD, Rotation:ABC)

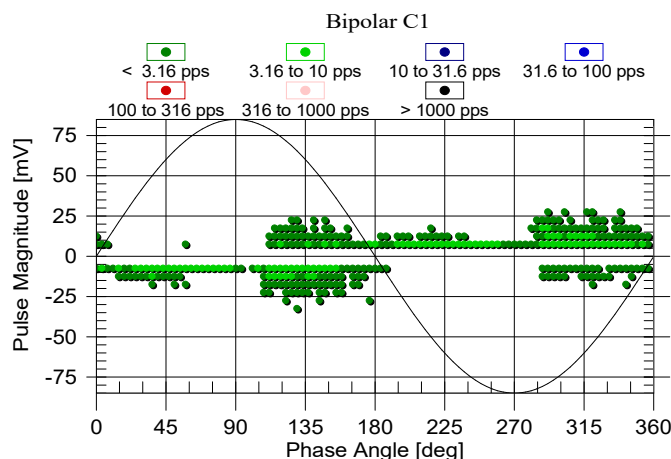
Asset Name: UG02

Folder: Campos Novos\, Asset Class: Hydro Generator, Serial Number:

Class: HydroGuard, Sensor Type: Epoxy Mica Capacitor (80pF)

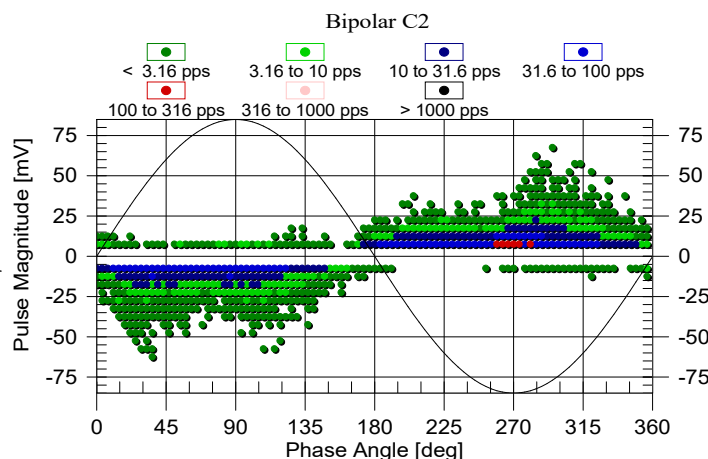
Operating Load: N/A, Reactive Load: N/A, Operating Asset Temp: N/A, Operating Voltage: N/A

Insulation Type: Epoxy Mica

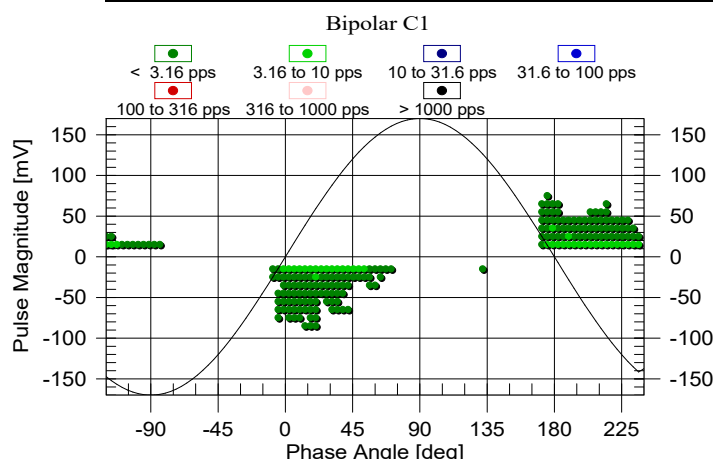


C1: NQN+35/-34, Qm+20/-19

Start Time: 10/28/2022 09:29:41, Phase: A, Sensor(s): A1A2, Status: Ok, K-scale: 1.00, Ref. Angle: 90, Delay Time: 6 ns

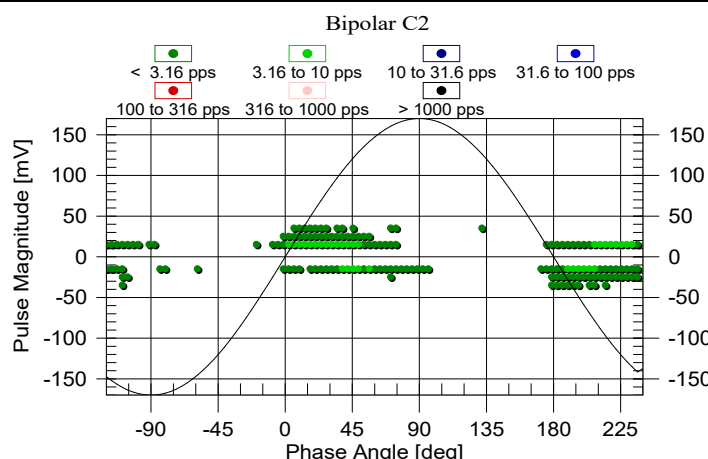


C2: NQN+95/-102, Qm+39/-47

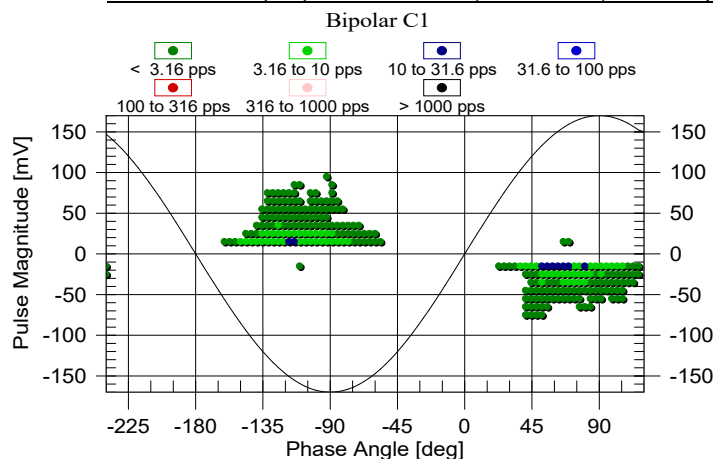


C1: NQN+105/-108, Qm+60/-67

Start Time: 10/28/2022 09:31:38, Phase: B, Sensor(s): B1B2, Status: Ok, K-scale: 1.00, Ref. Angle: 90, Delay Time: 6 ns

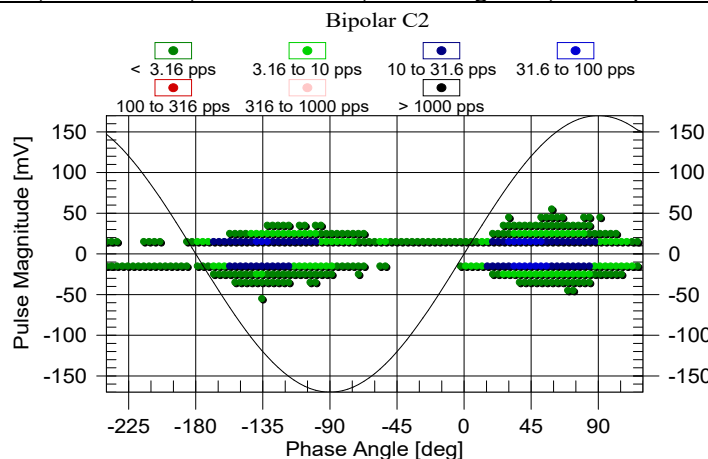


C2: NQN+23/-23, Qm+19/-19



C1: NQN+119/-117, Qm+72/-65

Start Time: 10/28/2022 09:33:36, Phase: C, Sensor(s): C1C2, Status: Ok, K-scale: 1.00, Ref. Angle: 90, Delay Time: 6 ns



C2: NQN+62/-66, Qm+30/-35

Pulse Phase Analysis (PRPD, Rotation:ABC)

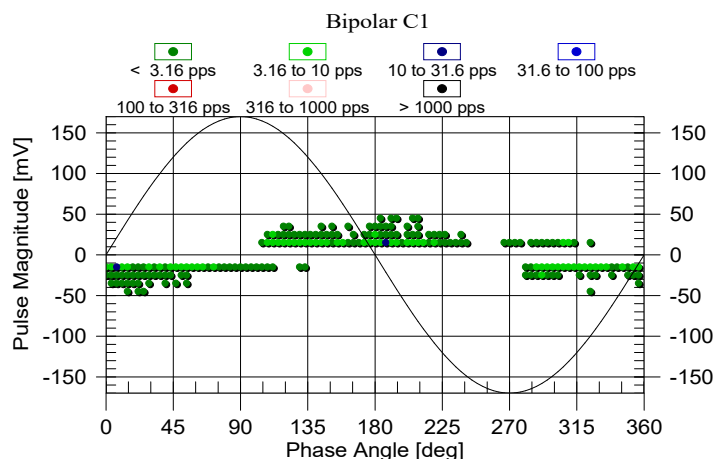
Asset Name: UG02

Folder: Campos Novos\, Asset Class: Hydro Generator, Serial Number:

Class: HydroGuard, Sensor Type: Epoxy Mica Capacitor (80pF)

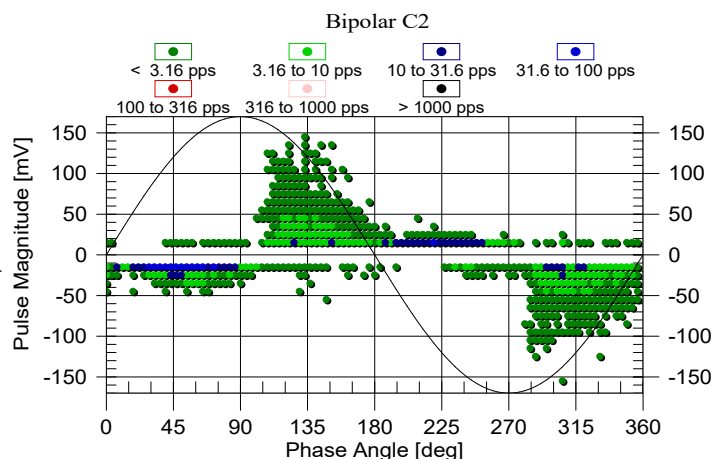
Operating Load: N/A, Reactive Load: N/A, Operating Asset Temp: N/A, Operating Voltage: N/A

Insulation Type: Epoxy Mica

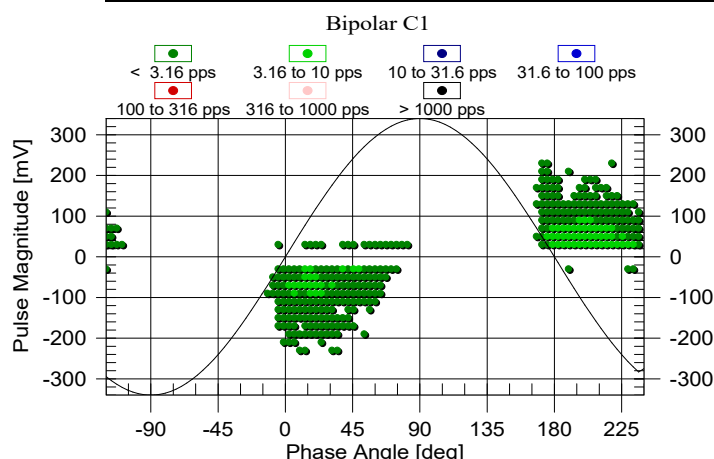


C1: NQN+59/-56, Qm+36/-33

Start Time: 10/28/2022 09:35:34, Phase: A, Sensor(s): A3A6, Status: Ok, K-scale: 1.00, Ref. Angle: 90, Delay Time: 6 ns

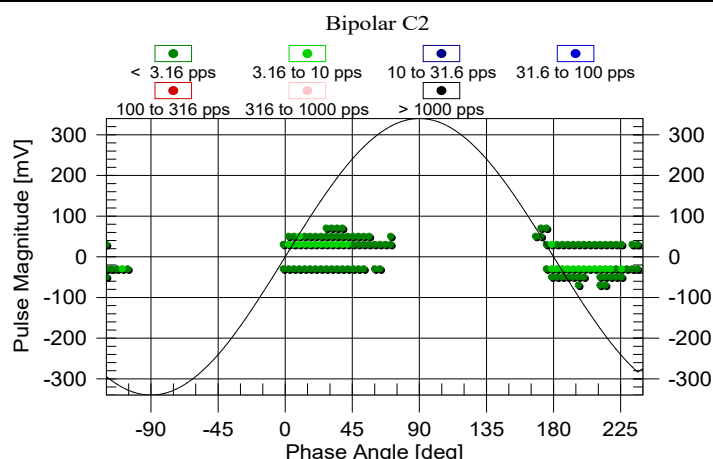


C2: NQN+131/-129, Qm+61/-64

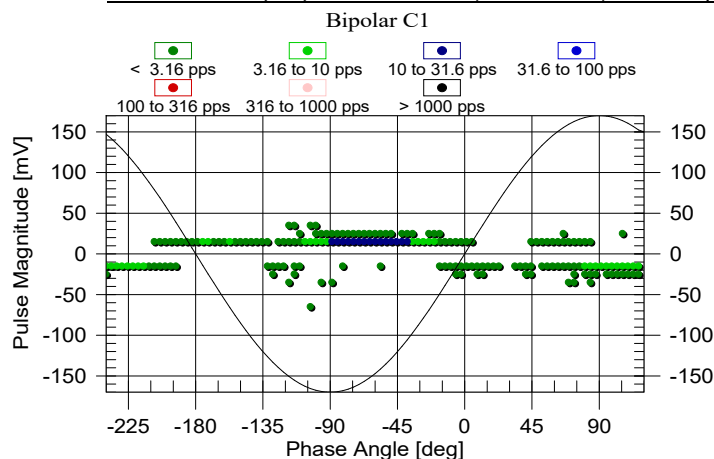


C1: NQN+313/-325, Qm+175/-188

Start Time: 10/28/2022 09:37:32, Phase: B, Sensor(s): B3B6, Status: Ok, K-scale: 1.00, Ref. Angle: 90, Delay Time: 6 ns

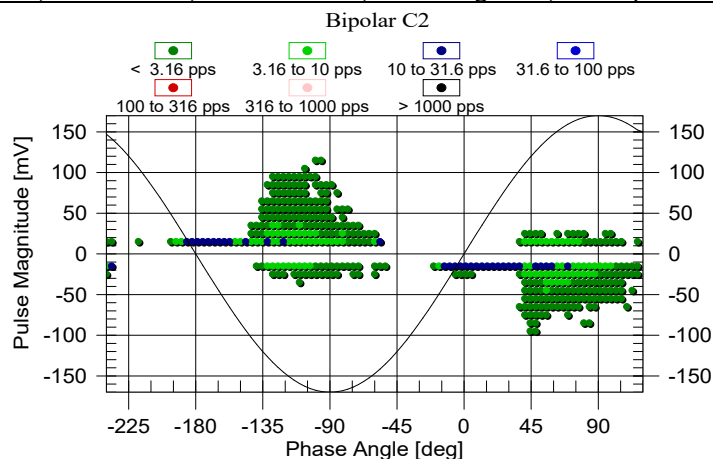


C2: NQN+42/-38, Qm+32/-33



C1: NQN+56/-56, Qm+27/-29

Start Time: 10/28/2022 09:39:29, Phase: C, Sensor(s): C3C6, Status: Ok, K-scale: 1.00, Ref. Angle: 90, Delay Time: 6 ns



C2: NQN+145/-131, Qm+85/-69

Pulse Phase Analysis (PRPD, Rotation:ABC)

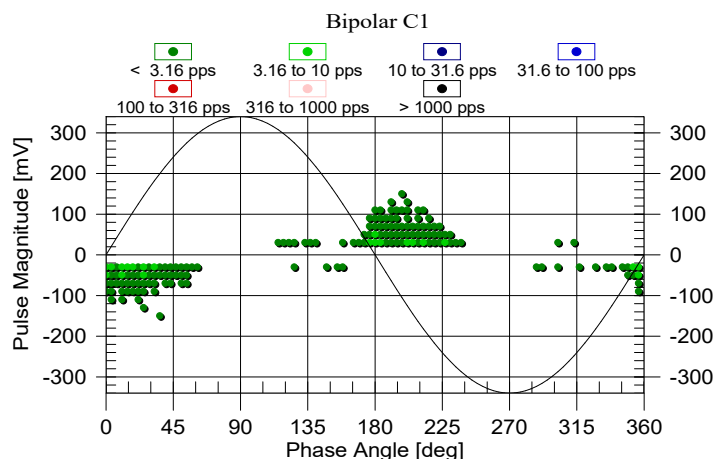
Asset Name: UG02

Folder: Campos Novos\, Asset Class: Hydro Generator, Serial Number:

Class: HydroGuard, Sensor Type: Epoxy Mica Capacitor (80pF)

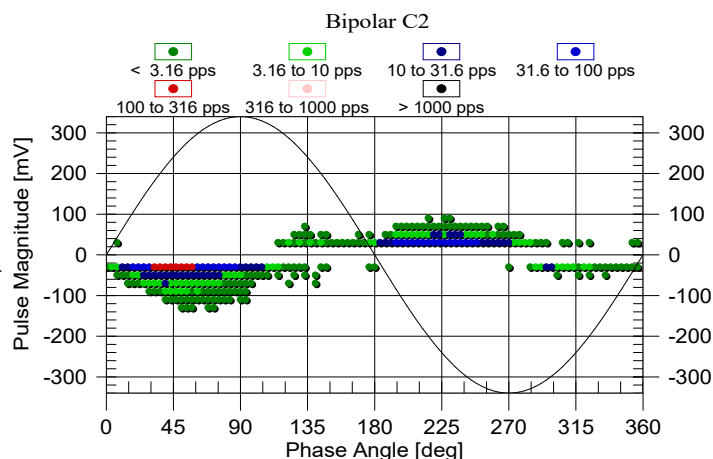
Operating Load: N/A, Reactive Load: N/A, Operating Asset Temp: N/A, Operating Voltage: N/A

Insulation Type: Epoxy Mica

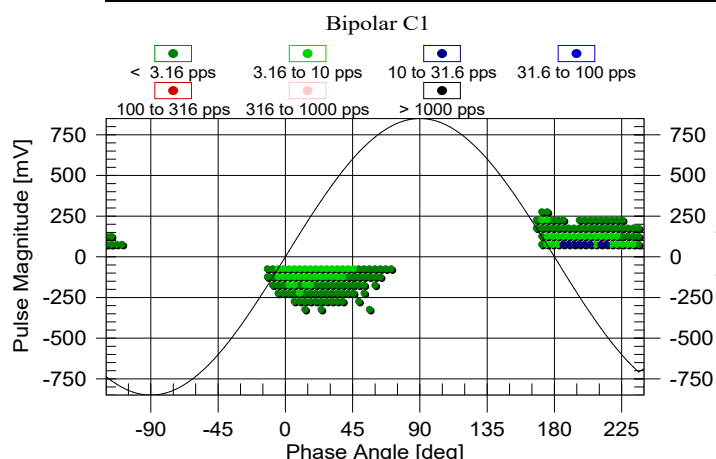


C1: NQN+151/-146, Qm+77/-86

Start Time: 10/28/2022 09:41:27, Phase: A, Sensor(s): A4A5, Status: Ok, K-scale: 1.00, Ref. Angle: 90, Delay Time: 6 ns

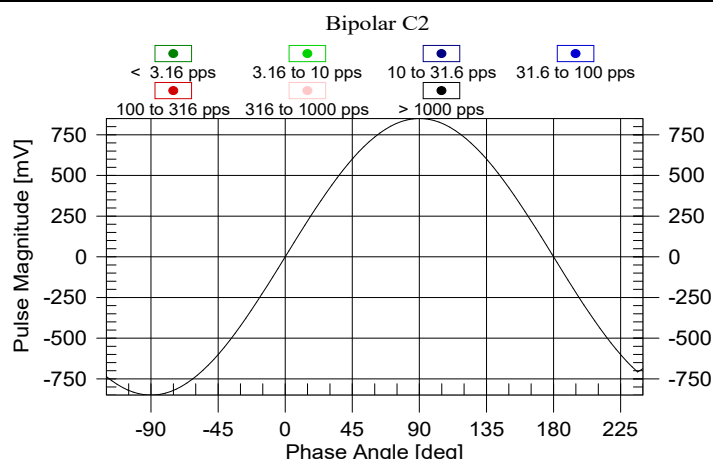


C2: NQN+149/-236, Qm+76/-115

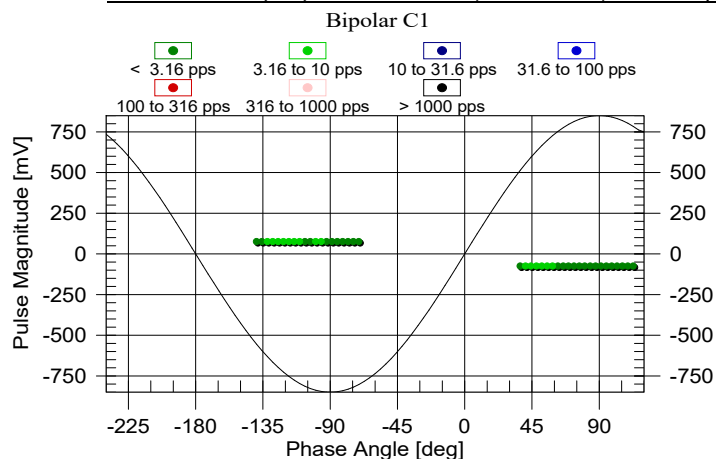


C1: NQN+453/-489, Qm+243/-260

Start Time: 10/28/2022 09:43:25, Phase: B, Sensor(s): B4B5, Status: Ok, K-scale: 1.00, Ref. Angle: 90, Delay Time: 6 ns

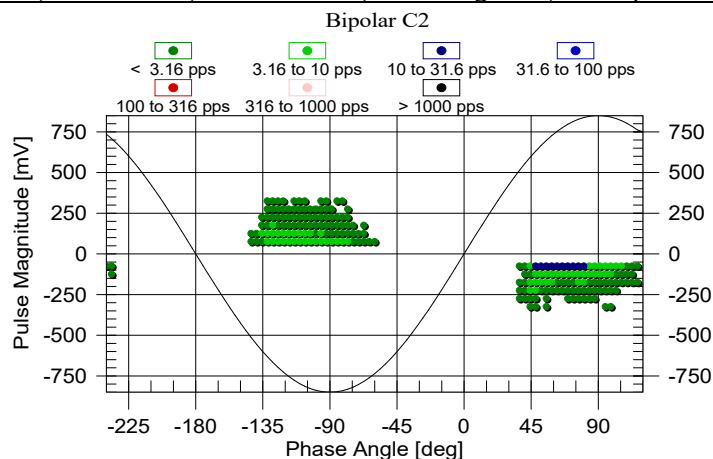


C2: NQN+0/-0, Qm+0/-0



C1: NQN+119/-102, Qm+95/-93

Start Time: 10/28/2022 09:45:23, Phase: C, Sensor(s): C4C5, Status: Ok, K-scale: 1.00, Ref. Angle: 90, Delay Time: 6 ns



C2: NQN+503/-494, Qm+306/-250

ANNEX B – PHASE-RESOLVED PARTIAL DISCHARGE PLOTS FOR UG3

Pulse Phase Analysis (PRPD, Rotation:ABC)

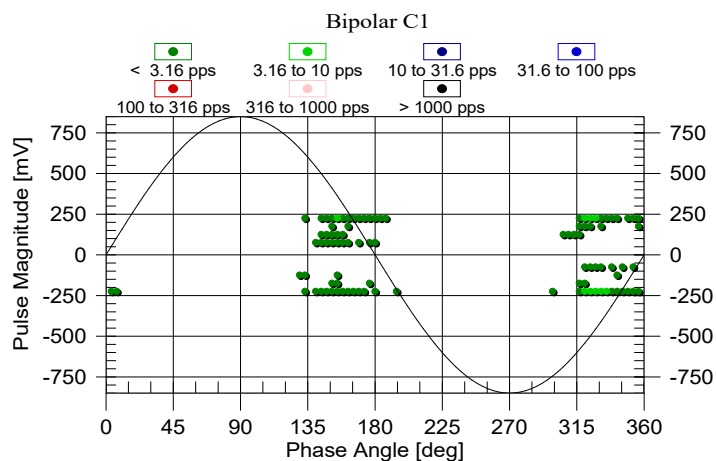
Asset Name: UG03

Folder: Campos Novos\, Asset Class: Hydro Generator, Serial Number:

Class: HydroGuard, Sensor Type: Epoxy Mica Capacitor (80pF)

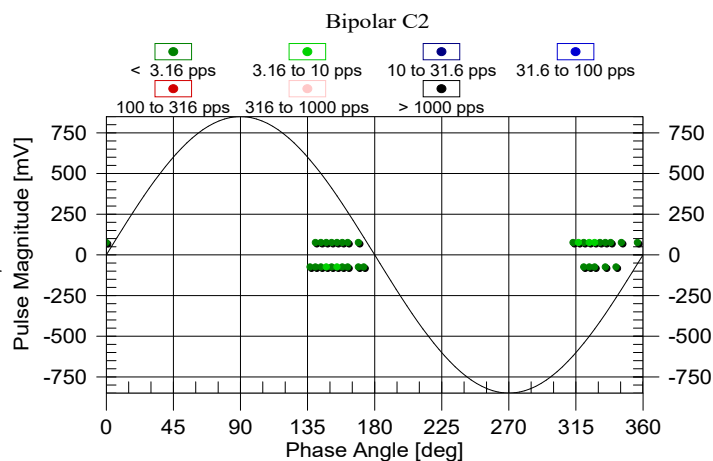
Operating Load: N/A, Reactive Load: N/A, Operating Asset Temp: N/A, Operating Voltage: N/A

Insulation Type: Epoxy Mica

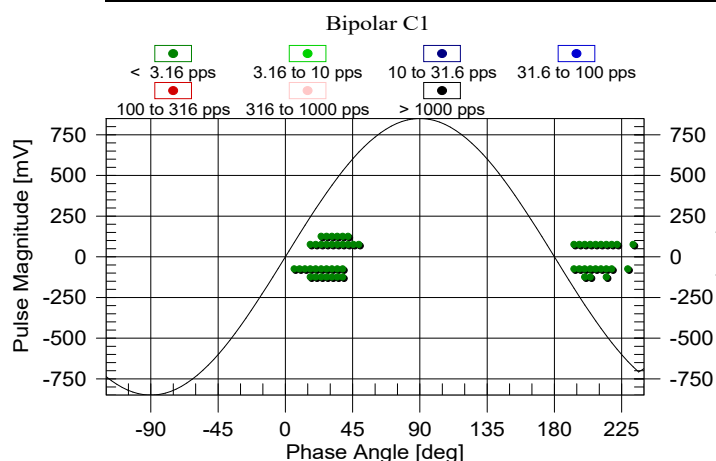


C1: NQN+199/-149, Qm+230/-233

Start Time: 06/30/2022 12:15:13, Phase: A, Sensor(s): A1A2, Status: Ok, K-scale: 1.00, Ref. Angle: 90, Delay Time: 6 ns

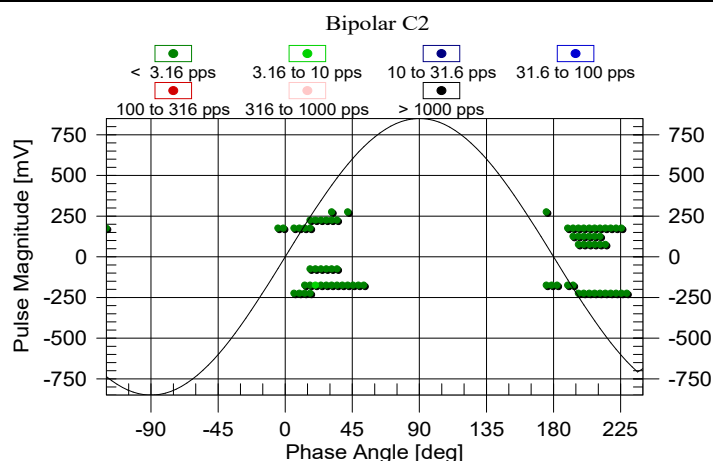


C2: NQN+45/-39, Qm+0/-0

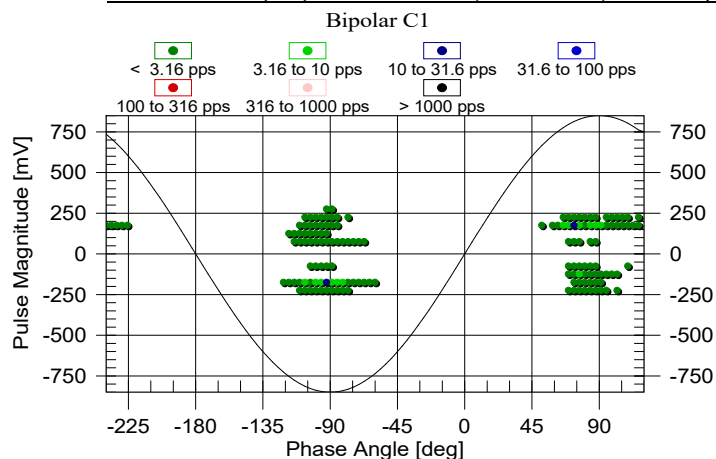


C1: NQN+95/-105, Qm+77/-86

Start Time: 06/30/2022 12:17:11, Phase: B, Sensor(s): B1B2, Status: Ok, K-scale: 1.00, Ref. Angle: 90, Delay Time: 6 ns

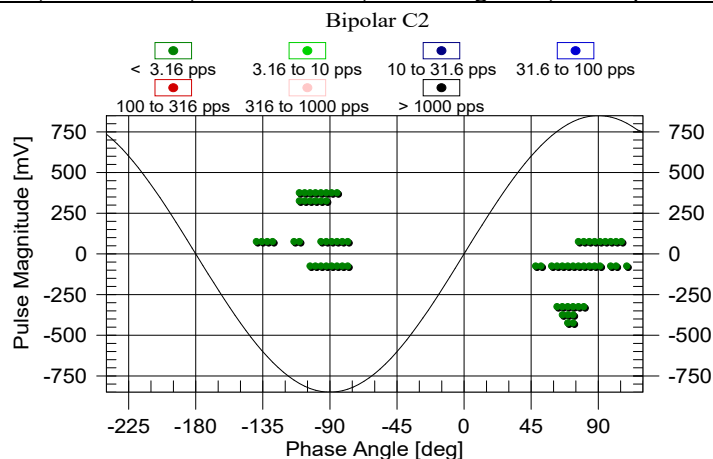


C2: NQN+189/-177, Qm+173/-187



C1: NQN+256/-245, Qm+180/-137

Start Time: 06/30/2022 12:19:08, Phase: C, Sensor(s): C1C2, Status: Ok, K-scale: 1.00, Ref. Angle: 90, Delay Time: 6 ns



C2: NQN+185/-178, Qm+64/-73

Pulse Phase Analysis (PRPD, Rotation:ABC)

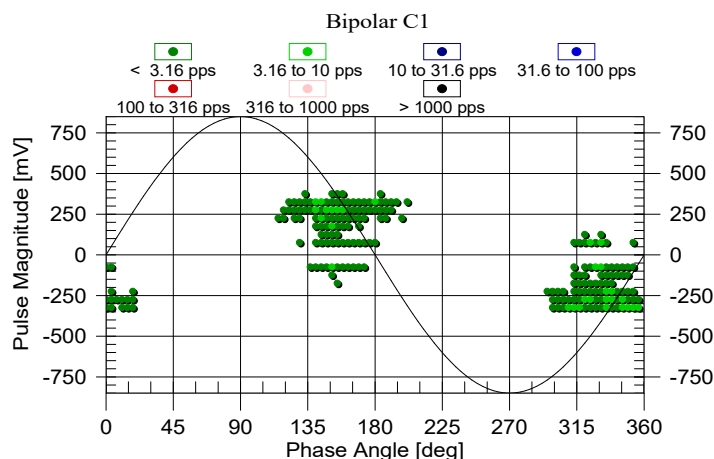
Asset Name: UG03

Folder: Campos Novos\, Asset Class: Hydro Generator, Serial Number:

Class: HydroGuard, Sensor Type: Epoxy Mica Capacitor (80pF)

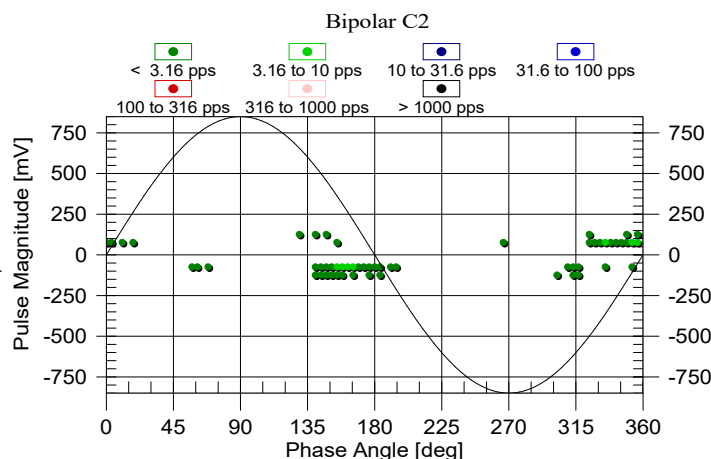
Operating Load: N/A, Reactive Load: N/A, Operating Asset Temp: N/A, Operating Voltage: N/A

Insulation Type: Epoxy Mica

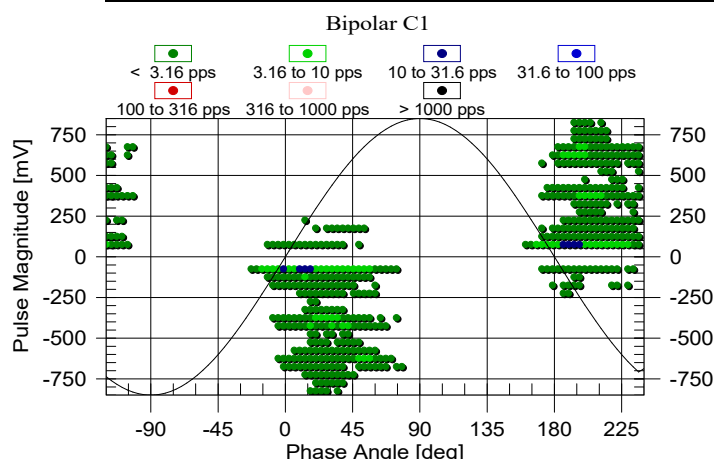


C1: NQN+412/-389, Qm+342/-339

Start Time: 06/30/2022 12:21:06, Phase: A, Sensor(s): A3A6, Status: Ok, K-scale: 1.00, Ref. Angle: 90, Delay Time: 6 ns

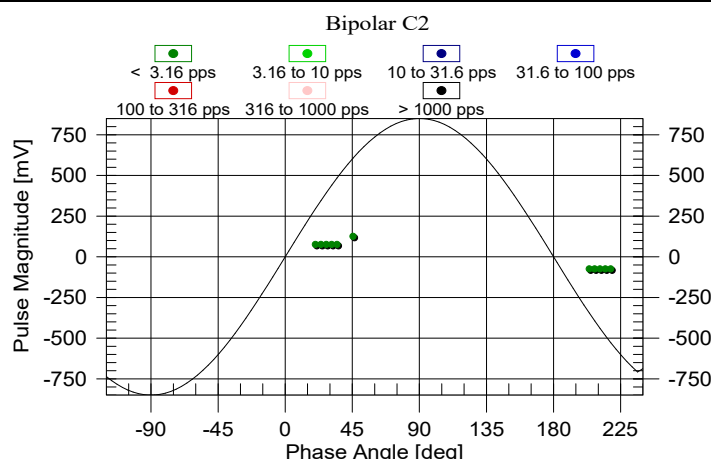


C2: NQN+30/-42, Qm+0/-0

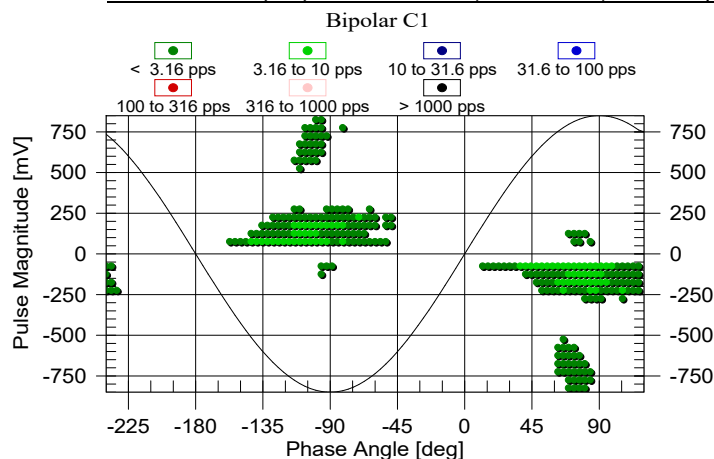


C1: NQN+1024/-1024, Qm+712/-733

Start Time: 06/30/2022 12:23:04, Phase: B, Sensor(s): B3B6, Status: OVER (Alarm), K-scale: 1.00, Ref. Angle: 90,

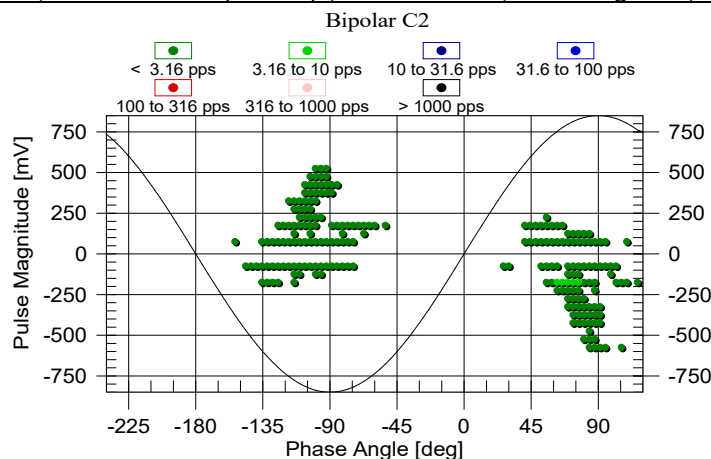


C2: NQN+15/-15, Qm+0/-0



C1: NQN+692/-737, Qm+256/-700

Start Time: 06/30/2022 12:25:01, Phase: C, Sensor(s): C3C6, Status: OVER (Alarm), K-scale: 1.00, Ref. Angle: 90,



C2: NQN+505/-548, Qm+193/-375

Pulse Phase Analysis (PRPD, Rotation:ABC)

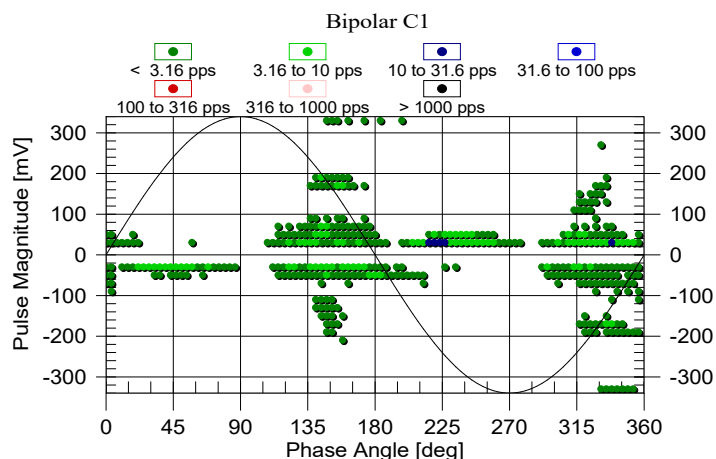
Asset Name: UG03

Folder: Campos Novos\, Asset Class: Hydro Generator, Serial Number:

Class: HydroGuard, Sensor Type: Epoxy Mica Capacitor (80pF)

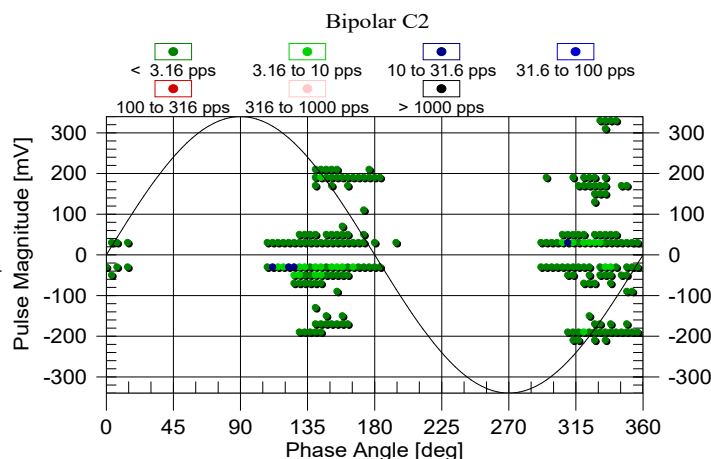
Operating Load: N/A, Reactive Load: N/A, Operating Asset Temp: N/A, Operating Voltage: N/A

Insulation Type: Epoxy Mica

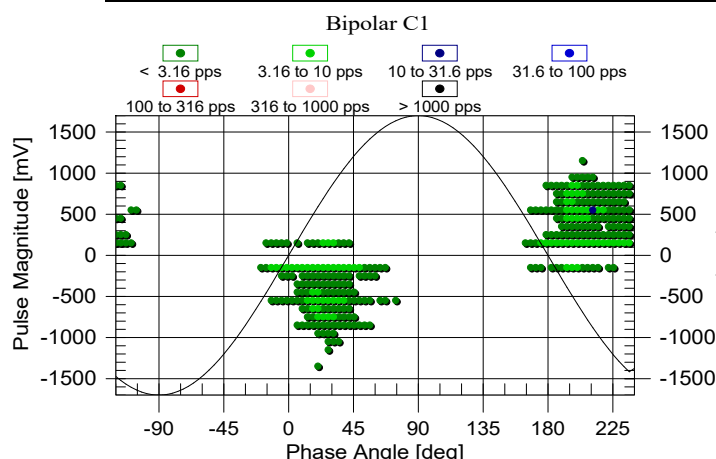


C1: NQN+203/-180, Qm+340/-184

Start Time: 06/30/2022 13:37:49, Phase: A, Sensor(s): A4A5, Status: OVER (QmE), K-scale: 1.00, Ref. Angle: 90,

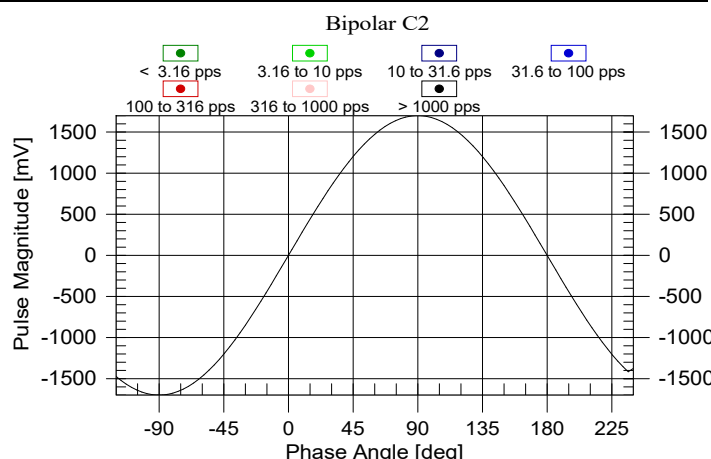


C2: NQN+127/-158, Qm+197/-190

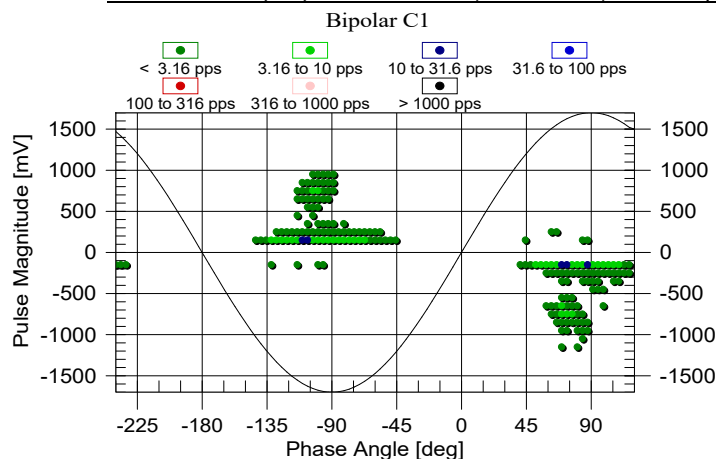


C1: NQN+1436/-1376, Qm+889/-881

Start Time: 06/30/2022 13:39:47, Phase: B, Sensor(s): B4B5, Status: Ok (Alarm), K-scale: 1.00, Ref. Angle: 90, Delay

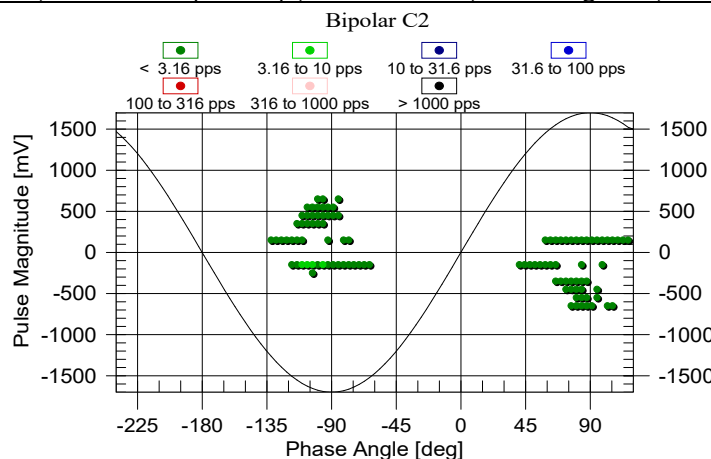


C2: NQN+30/-0, Qm+0/-0



C1: NQN+1079/-1142, Qm+850/-843

Start Time: 06/30/2022 13:41:45, Phase: C, Sensor(s): C4C5, Status: Ok (Alarm), K-scale: 1.00, Ref. Angle: 90, Delay



C2: NQN+589/-576, Qm+125/-367