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Digital Insights:

PARTIAL DISCHARGE MONITORING SYSTEM IN 230KV GAS-INSULATED SUBSTATIONS: IMPLEMENTATION, INSIGHTS, AND OPERATIONAL GUIDELINES

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ABSTRACT

Gas insulated switchgear (GIS) systems are widely used in high voltage power networks due to their compact design and reliability. However, insulation defects in GIS systems can lead to partial discharges, which can lead to catastrophic failures. There are several methods of detecting partial discharges. However, Acoustic methods are best suited as they offer a non-intrusive and effective way of monitoring GIS systems and hence reliability of the system due the nature of the GIS switchgear design.

This paper explores the detection and analysis of partial discharge in 230kV GIS system using acoustic methods. The study covers the fundamentals of partial discharge, types of PD's common in GIS systems, and the application of the IEC 60270 standard for acoustic measurements. The architecture and components of an acoustic PD measurement system are described along with the installation guidelines, calibration and sensitivity measurements. The paper also discusses the PD patterns, the use of pulse and phase resolved partial discharge (PRPD) methods for analysis. Lastly, a case study of a 230kV GIS substation installation is included to provide practical insights in and dissects the lessons learned.

INTRODUCTION

Gas insulated switchgear (GIS) systems are widely used in high voltage power networks due to their compact design and reliability. However, insulation defects in GIS systems can lead to partial discharges, which can lead to catastrophic failures. There are several methods of detecting partial discharges. However, Acoustic methods are best suited as they offer a non-intrusive and effective way of monitoring GIS systems and hence reliability of the system due the nature of the GIS switchgear design.

monitoring systems employed is the Partial Discharge (PD) monitoring system, known as PDMS. The PDMS is a critical diagnostic tool for ensuring the reliability and safety of high-voltage power systems, particularly in Gas-Insulated Substations (GIS). Partial Discharge (PD) is defined as a localized electrical discharge that partially bridges insulation and is a leading indicator of insulation degradation and potential failure. Early detection and analysis of PD phenomena enable timely maintenance interventions, significantly reducing the risk of catastrophic equipment failures. This paper focuses on the implementation of an advanced online PD monitoring system integrated into a 230kV GIS substation, designed to continuously detect and classify PD activities.

The system employs state-of-the-art Ultra High Frequency (UHF) detectors, which are seamlessly integrated with a robust Partial Discharge data acquisition and analysis software. By leveraging time-domain and frequency-domain techniques, the system can distinguish between different types of discharges, such as internal voids, surface discharges, and corona, providing actionable insights into insulation condition.

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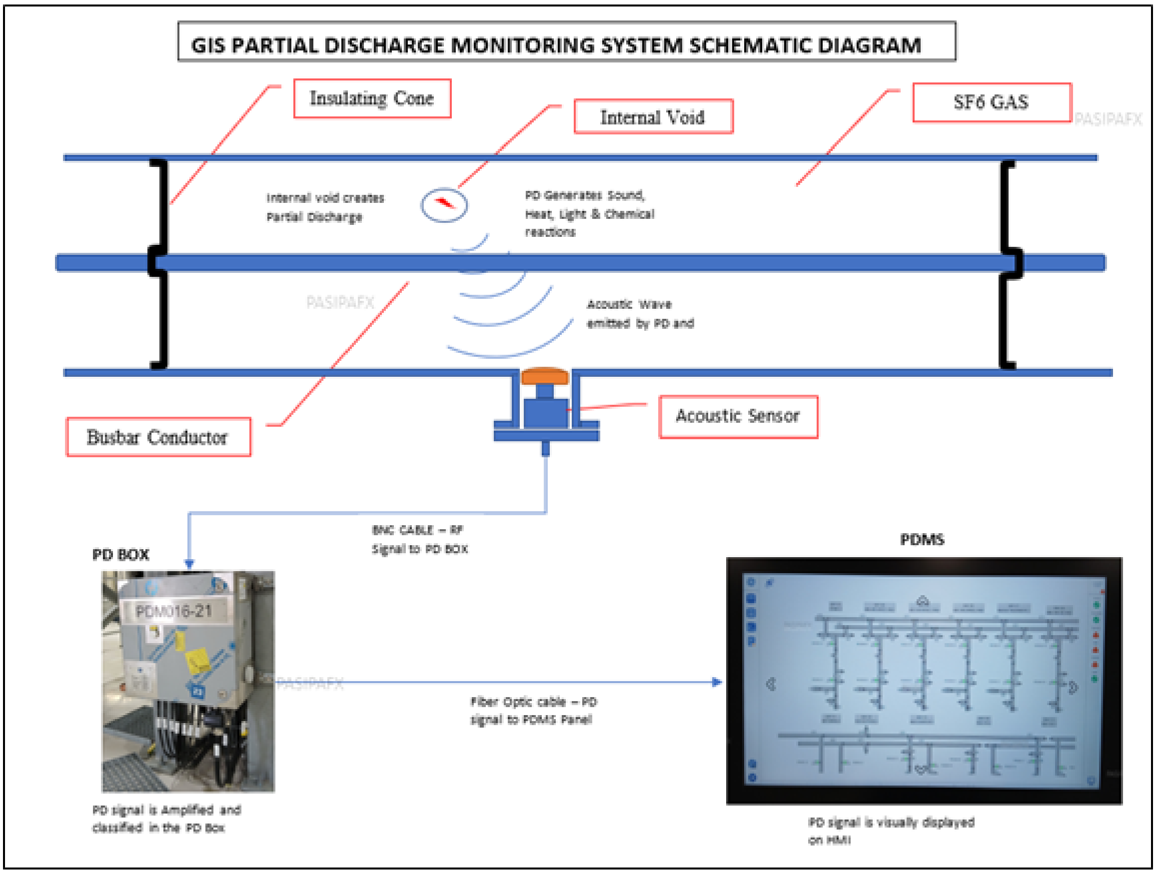
UNDERSTANDING PARTIAL DISCHARGE (PD) IN GIS SYSTEMS



Gas insulated substation consists of high voltage components enclosed in the middle of aluminium pipe or tube which are held centrally by use of epoxide resin insulating cones. The pipes are then filled with SF6 gas at a pressure of 6 bar. SF6 gas offers excellent insulation properties and this allows the system miniaturization.

WHAT IS PARTIAL DISCHARGE

Partial discharge is defined as a localized electrical discharge that only partially bridges the insulation between conductors, potentially leading to insulation breakdown over time.

As the name implies, partial discharge indicates partial bridging of the insulation which is a symptom of an impending insulation breakdown. Early detection of PD activities is key and will help preventing catastrophic and total insulation breakdown and failures. PD typically originates at imperfections in insulation, voids, or conducting surfaces. As the voltage stress increases, these weak points will initiate discharges which emits electromagnetic waves, heat and acoustic signals.

PD detection is key to ensuring asset lifespan by identifying faults and rectifying them before breakdown extending the equipment life. PDMS can be used as preventive maintenance tool, identifying early signs of PD activity, will signal maintenance requirements. PDMS therefore will help reduce costs because unplanned outages can be prevented and replacement of equipment will be avoided. Lastly, operational safety will be enhanced because PD can lead to explosions which possess a huge risk to the operational personnel.
Using UHF sensors, it is possible to detect these acoustic signals, analyse them and classify them according to the type of defect causing the discharge. There are several classifications and we will focus on the 5 below.

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TYPES OF PARTIAL DISCHARGES:

INTERNAL DISCHARGES:
Occur in voids within solid or liquid insulation material. They are caused due to manufacturing defects, improper curing or long-term degradation as gradual degradation of insulation material will lead to complete breakdown over time. Since internal discharge will emit Acoustic signals, the PD can be detected using Uhf sensors.

SURFACE DISCHARGES:
This type of discharge occurs along the surface of insulation in air or gas environments. This type is common in GIS systems and can be as a result of contamination, moisture within the system. Surface tracking can occur, carbonization as well as flashover. Below is an image that was taken from the one of the cones that experienced surface tracking during Hipot testing. In this particular case, there was surface contamination due to over application of grease and that contamination provided a path for surface tracking and flashover.

CORONA DISCHARGES:
The type is developed at sharp edges or protrusions in a gas-insulated environment. This is caused by the ionization of the insulating gas or fluid surrounding the conductor carrying high voltage electric charge. Usually the insulating gas undergoes electrical breakdown and becomes conductive and allows charge to continuously leak off through the gas to ground. The strength of the electric field or potential gradient around the sharp-edged conductor will be greater than the dielectric strength of the insulating gas. The gas near the sharp-edged conductor will become ionized and the charged particles will slowly find their way to the opposite charged outer GIS casing which is grounded.
Corona discharge generates gases such as ozone, Nitric oxide, Nitrogen Dioxide and over a long period can lead to surface degradation, like internal discharges, corona PD generates electromagnetic waves that can be detected using UHF sensors.

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PROTRUSION DISCHARGES:
Result from irregularities or defects on conductor surfaces.
Voids and Inclusions: Discharges in air gaps or inclusions within solid insulation.

COMMON CAUSES OF PARTIAL DISCHARGE IN GIS SYSTEMS

Contamination during Manufacturing
Contaminants such as dust, metal particles, or grease can inadvertently enter the GIS gas sections during manufacturing, assembly or installation. These contaminants create localized areas of high electrical stress, which can initiate partial discharges. Even the smallest of particles can act as nucleation points for PD activity, leading to insulation degradation over time.

Mechanical Stress or vibrations leading to cracks
Mechanical stress could be from incorrect handling, transportation, or installation which can generate micro cracks in solid insulation material such as insulating cones in GIS systems. Vibrations during operation or from mobile machinery can also initiate or accelerate the progression of cracks. Cracks in insulation create gaps or voids in insulation materials where electric fields will tend to concentrate, leading to partial discharges.

Moisture ingress or Gas decomposition
Moisture can enter the GIS through faulty seals, improper gas filling during maintenance activities. The SF6 gas can decompose under high energy discharges, producing by-products that degrade insulation. Moisture and SF6 by-products reduce the dielectric strength of insulation which increases the changes of PD to occur.

Aging of insulation

Over time, the insulation materials in GIS systems (such as epoxy resin insulators, spacers, barriers) can degrade due to thermal cycling, electric stress, and environmental factors. The aging process can lead to formation of Voids, cracks, or surface imperfections. Aged insulating materials are more prone to partial discharge which has a ripple effect of accelerating further degradation and ultimately lead to failure.

Design or Manufacturing defects

Imperfections in the design or manufacturing process such as sharp edges, uneven surfaces or improper material selection can create electric field concentrations. The points of high electric field stress can initiate points for corona discharges.

Environmental Factors

External environmental factors such as ambient temperature fluctuations, humidity, and pollution can affect the performance of GIS insulation. Extreme conditions can accelerate insulation aging process and increases the risk of PD. Therefore, it is important that the equipment is installed in a building under controlled conditions by use of an HVAC system.

IEC 60270 STANDARD AND ACOUSTIC MEASUREMENTS

IEC 60270 is the international standard for partial discharge measurements. It provides guidelines for the measurement of PD in high voltage equipment, including GIS systems. The standard defines PD measurement techniques, calibration procedures, sensitivity and accuracy requirements. The IEC standard focusses on the electric methods for partial discharge measurement but acknowledges acoustic techniques as supplementary tools, particularly in enclosed and pressurized GIS systems. Since IEC 60270 does not standardize acoustic techniques specific guidelines for acoustic instrumentation, calibration, and interpretation are not included in the standard, leaving their application to industry practices.

COMPONENTS OF THE PD MONITORING SYSTEM IN GIS

UHF SENSORS

Figure 2: Internal Sensor (1), External sensor (2)

The key components of the PDMS system are UHF sensors mounted inside the GIS gas filled chamber via a flange and the PD box with a data acquisition UHF module to process the PD signal from the sensor for transmission to the central HMI Panel (refer to Figure 1).

UHF sensors capture the sound waves emitted by PD activity within the GIS system and are essential for monitoring the health and performance of GIS system. These sensors detect partial discharge (PD) activities, which usually suggests imminent insulation failures or other faults within the GIS.
The UHF sensors, like any other antenna, operate by capturing electromagnetic waves emitted by partial discharges inside the GIS. A basic antenna can be used to transmit or receive an electromagnetic wave. When insulation materials are subjected to stress, they can generate high-frequency signals typically within the UHF range (300 MHz to 3 GHz). The UHF sensors are embedded into GIS structures, enabling real-time monitoring of PD activities. Captured UHF signals are processed (amplified) in the PD box by the UHF Module and analysed to assess the severity, type and location of discharge.

UHF sensors are compact, allowing seamless integration into existing GIS designs without notable modifications. Their reduced size is beneficial for installation in confined spaces often found in high voltage equipment.

CALIBRATION: SENSITIVITY VERIFICATION

Sensitivity verification is carried out by injecting an energy signal that emits an equivalent apparent charge of 10pC through one sensor and measuring the feedback through the adjacent sensor in the same bus duct.

The sensitivity is deemed successful if the signal is measured through the adjacent sensor. The process is then reversed for the same set of sensors and same apparent charge signal is injected and measured at the receiving sensor. If again the signal is measured the test is deemed successful.
The process is then repeated for all the yellow and blue phases per bay. (see below)

SENSITIVITY TEST

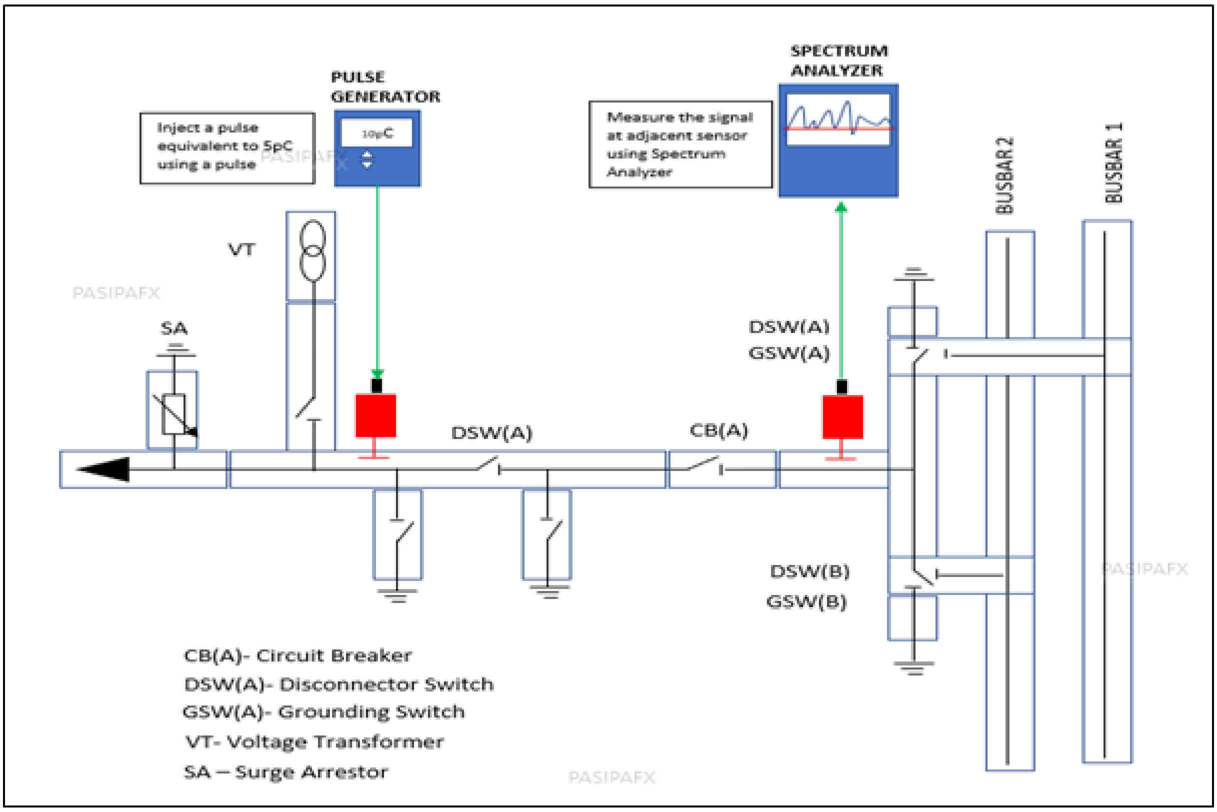

Figure 3: PDMS Sensor

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INSTALLATION AND INTEGRATION OF PD MONITORING SYSTEM

Each bay has 7 UHF sensors, 2 per phase located in gas compartments as shown on the diagram below adding up to 6 sensors and the 7th is an external sensor. The external sensor measures the external noise is used for filtering the unwanted noise generated externally from the systems but is being picked up by the internal PD sensor.

The PD box amplifies the PD signal from the UHF sensor and the module in the PD box will process and classify the signal in accordance with the PD profile and output will be sent to the PDMS panel where the signal will be displayed on an HMI panel.

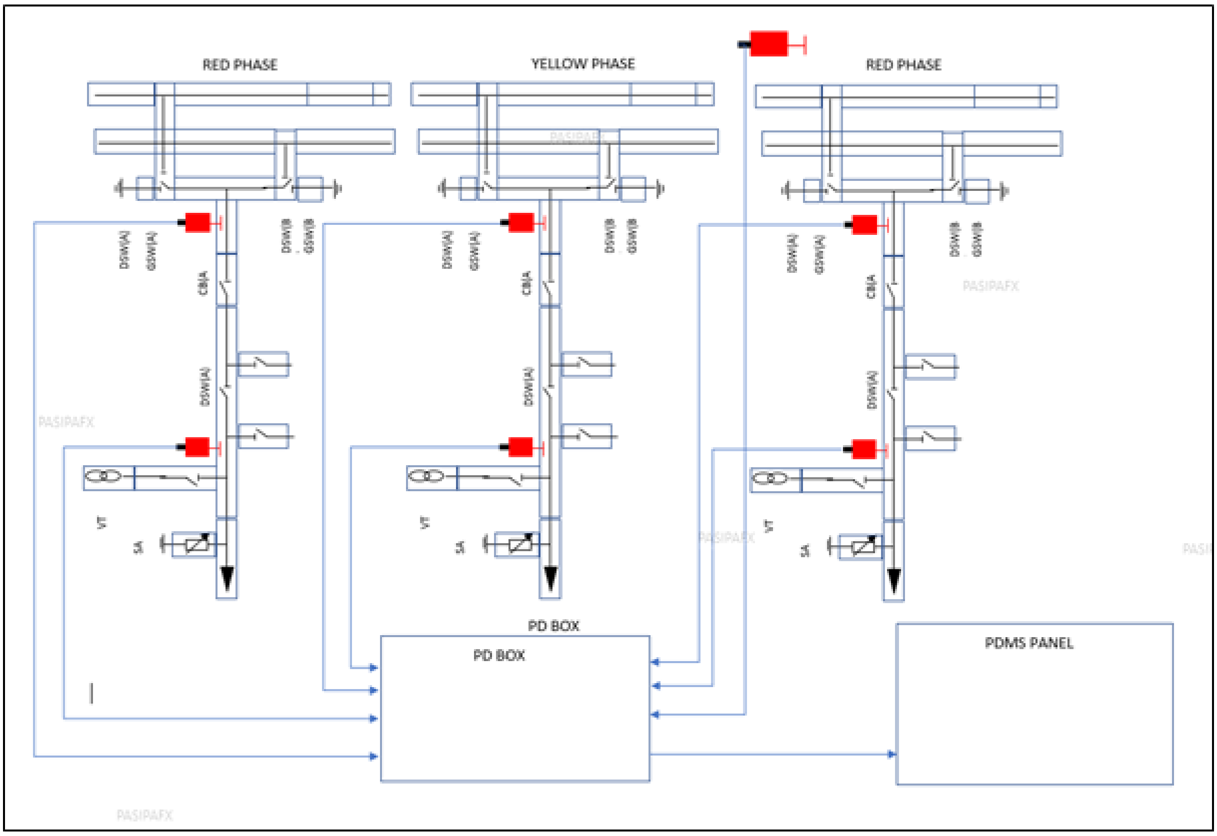

Figure 4: Installation Location of the PD sensors for 1 bay

DATA INTERPRETATION AND ANALYSIS

There are few ways of interpreting and analysing the partial discharge data. Each time a PD occurs, there is energy released in the form of heat, sound, and light. This energy can be measured and represented on a graph for analysis. There are several methods of capturing the data but we will focus on the sound energy since the GIS PDMS implementation make use of the UHF sensors.

There are basically two methods that we will look at:

1. Trend method
2. Phase Resolved Partial Discharge (PRPD)

1.TREND METHOD

The trend method basically is a plot of apparent charge released by a partial discharge, plotted against time. The charge (in Pico Coulombs) is derived by integrating the energy pulse released by a PD activity as shown below. Each time a charge is picked up by the measuring instrument, its integrated and the point is plotted on the graph. Over time, the plotted points create a pattern and the dots can be joined together to form a trend graph.

As explained above PD activity releases energy in the form of heat, light and sound. The UHF sensor inside the GIS chamber picks up the sound wave pulse. The pulse is integrated to derive the charge and the charge Is usually in picocoulombs (pC).

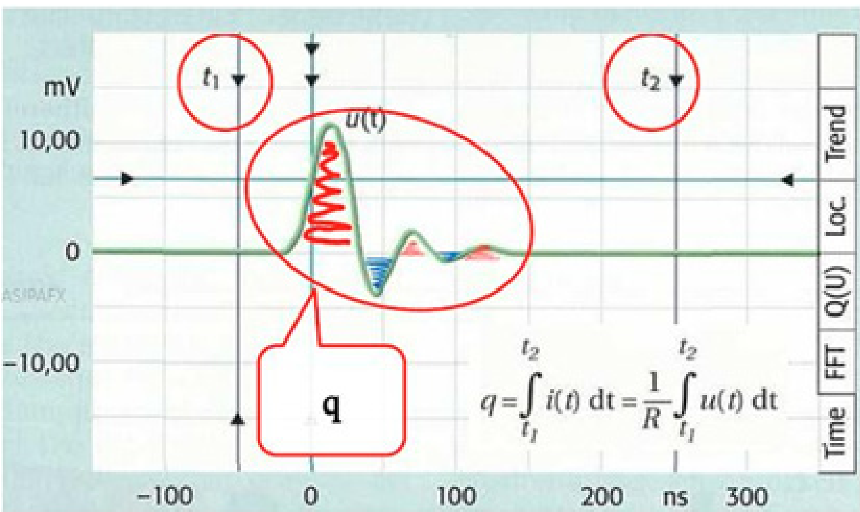

Figure 5; PD Pulse Integration

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To get the apparent charge Q, the area under the current pulse waveform is calculated by using integration. Since the measuring equipment passes the current through a resistive load which converts the current into a voltage signal, we integrate the voltage and divide by the resistance in the measuring instrument to determine the charge.

$$Q = \int_{t2}^{t1} i_t \, dt \qquad \text{but} \qquad i_t = \frac{V_t}{R} \qquad \text{Therefore } Q = \frac{1}{R}\int_{t2}^{t1} V_t \, dt$$

Below is an example of a trend graph, in the case, the apparent charge in DBm is plotted against the frequency at which is occurs. Only the Peak value is plotted for each frequency band and the result is a trend graph

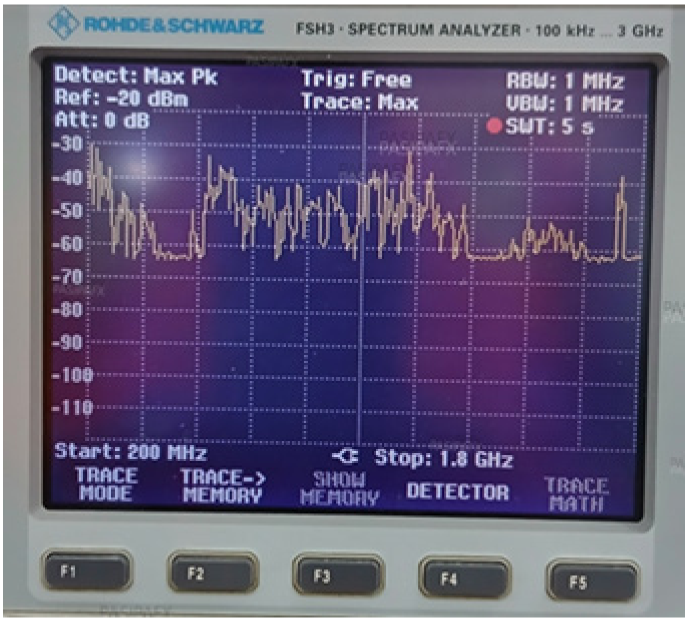
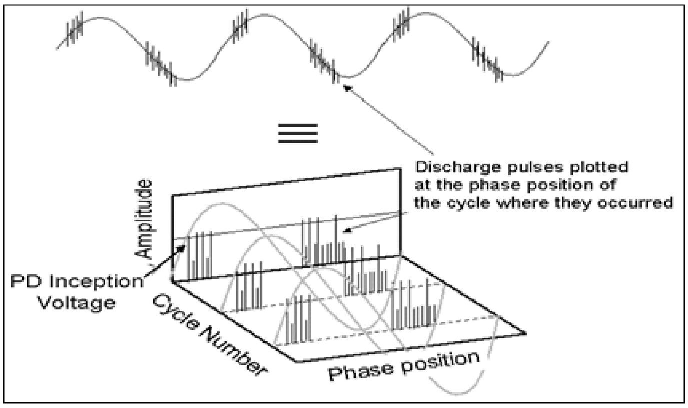


Figure 6: Trend Graph from FSH3 Spectrum Analyser

PHASE RESOLVED PARTIAL DISCHARGE – PRPD

PRPD is another way to represent partial discharge, in this method, the apparent charge from PD activity is monitored over a full 360° phase of the AC cycle. These energy charges are captured, processed into apparent charge and then plotted exactly at the same time they occur within the AC cycle.



The PRPD graph has voltage and charge (Q) on the vertical axis and phase angle on the horizontal axis. There is usually a correlation between the voltage level and the PD apparent charge, as the voltage increases, the apparent charges will also tend to increase and vice-versa. Therefore, in one cycle all the charges recorded will be plotted as dots on the graph and the sequence will continue for more cycles that follow until a pattern develops on the graph. The acquisition time should be long enough for a pattern to develop. Each type of discharge has a pattern and by using PRPD, it can be determined with certainty the type of discharge and its severity. As see below, each dot on the graph represent a PD event which has been converted into apparent charge and plotted exactly at the phase of the AC cycle when it occurred.

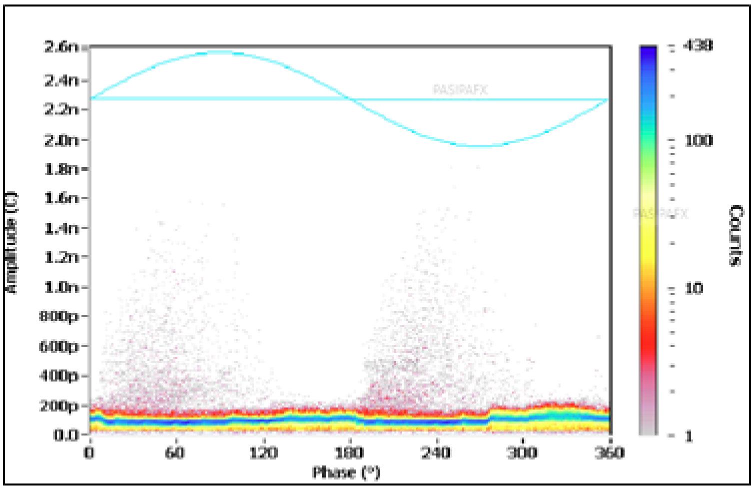


Figure 8: PRPD Plot

INTERNAL VOID

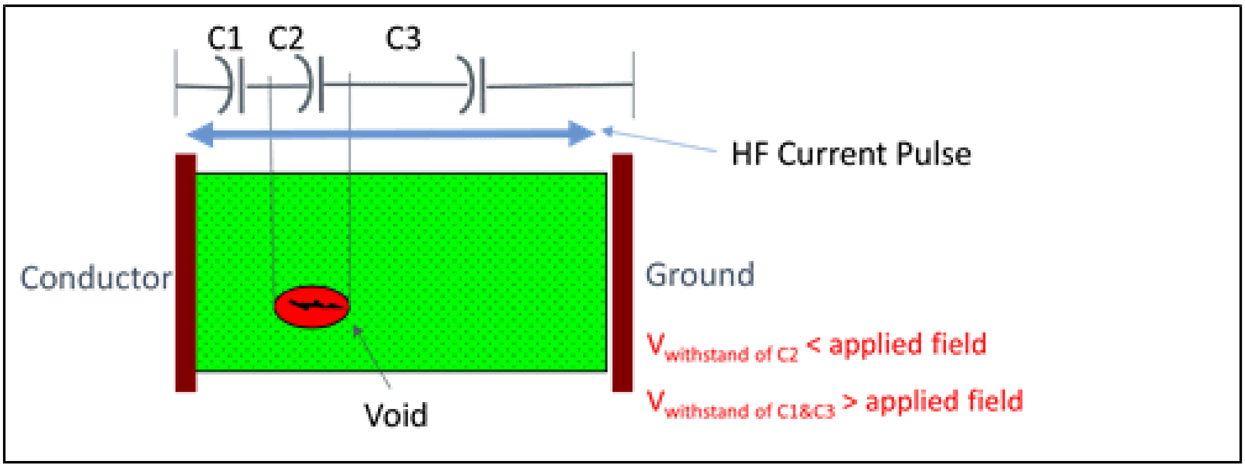


Figure 9: Internal Void (taken from EA Technology - Partial discharge Testing article)

In a SF6 gas filled GIS system, an internal void is a small pocket of air of gas bubble that gets trapped within the SF6 insulating gas. This void will create a defect in the insulation since the dielectric strength of air is different to the dielectric strength of SF6 Gas. When subjected to high electric field, the Void tends to ionize causing localized discharges.

On the diagram above, the dielectric strength of the gas contained within the void (C2) is less than the applied electric field, this will cause ionization and discharges will appear. However, the dielectric strength of the insulating gas represented by C1 and C3 is above applied voltage electric field strength and therefore total breakdown or flashover will not occur.

The diagram below shows a comparison of the dielectric strength of SF6 gas, oil and air at different pressure. As can be seen, the higher the SF6 gas pressure the better the dielectric strength, while there is a very change in insulating properties of air with increase in gas pressure. This explains why the compartment pressure for GIS systems is usually set at 6.3bar

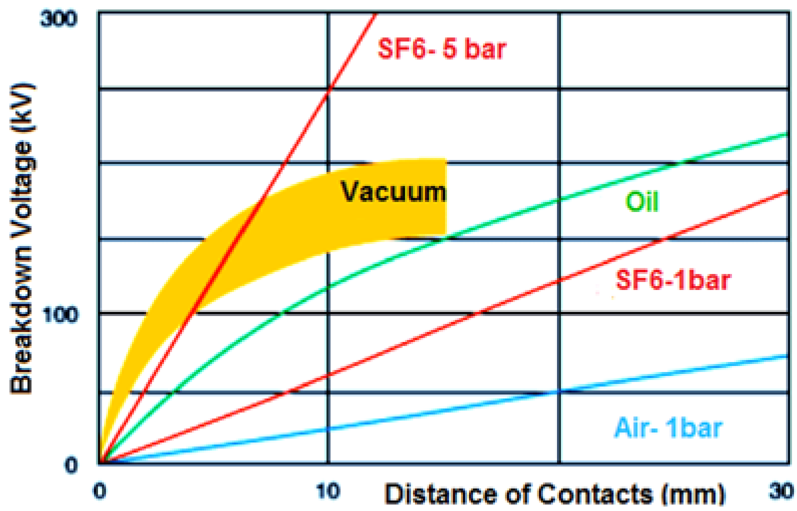


Figure 10: Dielectric Strength of Air, SF6 and oil in relation to pressure

The main cause of voids is improper vacuuming during the SF6 gas filling process, either because the procedures were not followed of the equipment did not perform sufficiently well to remove all air particles during vacuuming. Voids can also be as a result of manufacturing defects in the insulating cones within the GIS.

Partial discharge gas a tendency to cause SF6 gas degradation causing localized heating, further reduction in dielectric strength of the insulation gas and can lead to flashover.

There are distinct patterns for internal voids, the discharges always occur at or near the peak of the AC voltage waveform where the electric field strength is higher than the ionization threshold of the gas occupying the void. The pattern is symmetrical across the positive and negative half-cycles due to the similar nature of the field strength.

The PD pulses from the void have a broadband frequency spectrum but tend to be more concentrated towards the lower MHz range and the pulse magnitude increases with the electric field. Below are a couple of examples of void PD patterns.

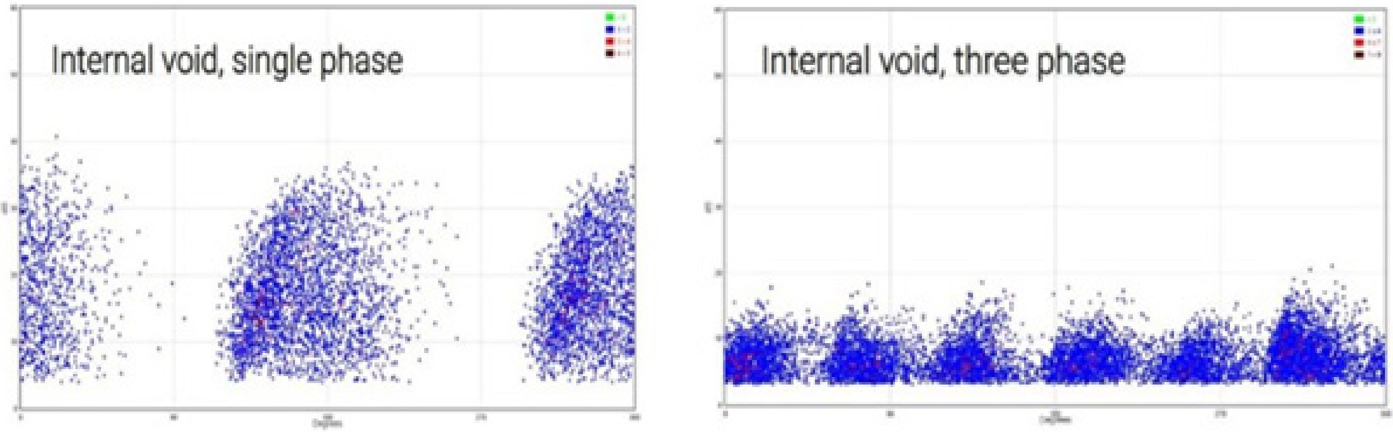


Figure 11: Internal Void

During the commissioning of the GIS, no void pattern was picked up as most of the patterns were pointing towards floating potential.

This is self-explanatory, the PD takes place along the surface of a solid insulating material. This type of discharge occurs when electric field near the insulation-gas interface exceeds the breakthrough strength of the gas thereby causing localized ionization.

The main cause is defects in insulating media, High electric field stress as well as contamination due to dust, moisture, grease or other particles deposited on the insulation distorting the electric field. Just like void discharge, the effects are the same and can cause insulating material erosion or breakdown, contaminant migration (Production of by-products such as Ozone, Nitric Oxides which can further accelerate surface degradation.

Surface discharge patterns are asymmetrical in nature due to their non-uniform field distribution at the interface. However, the PD will usually occur at the voltage peak and may persist across the broader phase range.

Surface discharge has a wider frequency spectrum range and extends into the higher MHz spectrum band. There are visual indicators of surface discharge as it leaves carbonized tracks. Below is the image of the insulating cone that suffered surface discharge during Hipot testing phase.

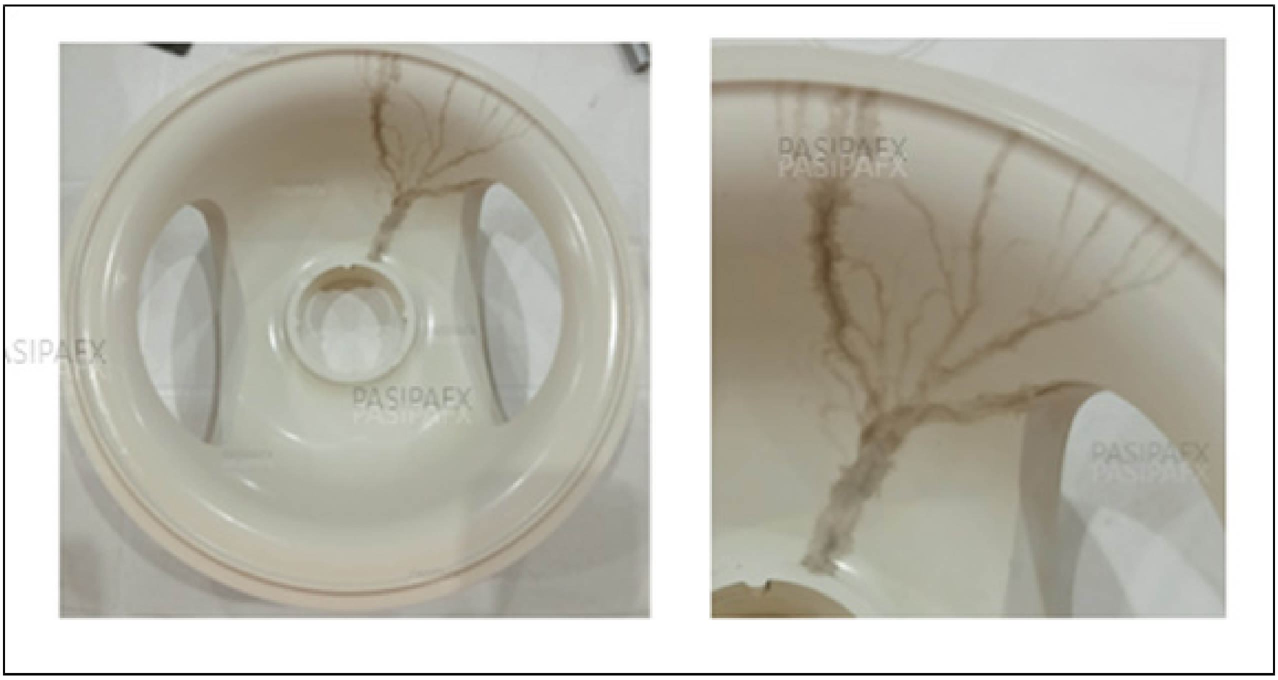


Figure 12: Surface Discharge on insulating cone during Hipot testing Phase

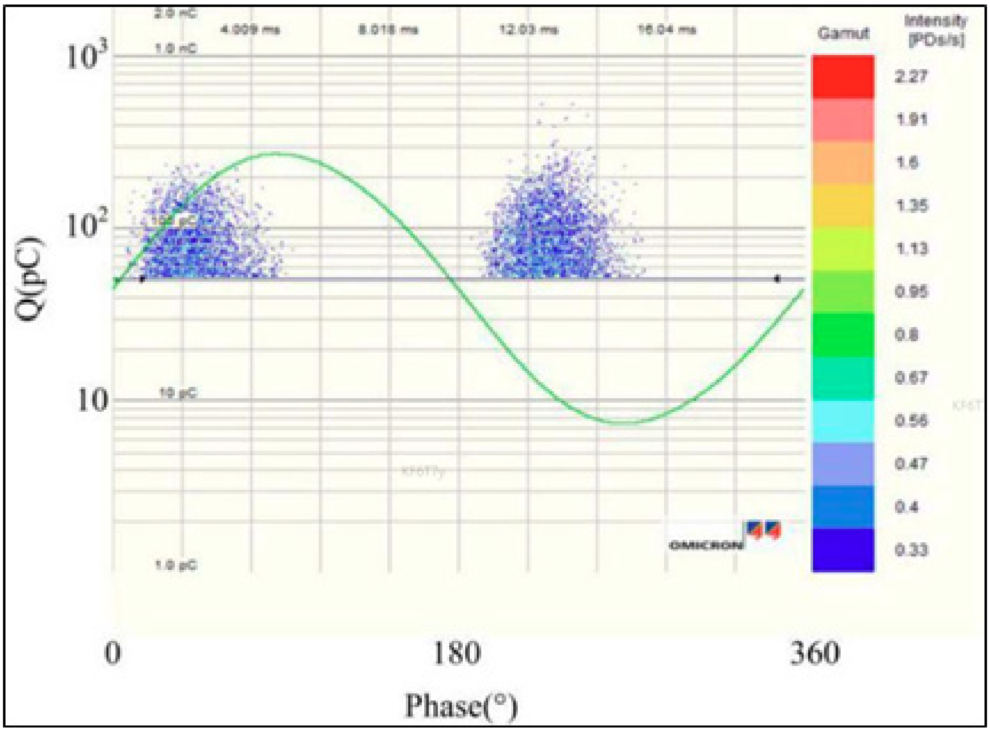


Figure 13: Surface Discharge during Hi-pot testing Phase

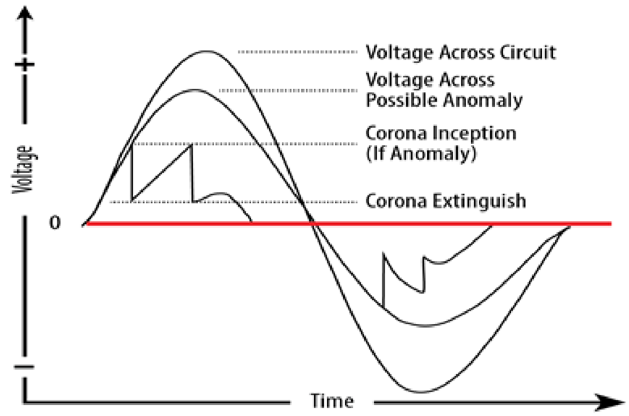
Corona Discharge Pattern

Corona discharge in GIS systems takes place when localized ionization of SF6 gas occurs in areas with high electric field concentrations such as sharp edges, protrusions or loose connections in the GIS components. Corona PD occurs mainly in Gas Phase (Air, Nitrogen or SF6 gas Medium).

The main cause of Corona PD is therefore sharp edges which can be due to design flaws or manufacturing imperfections, Loose connections creating poor electric contact which create high electric field stress, contaminants within the SF6 Gas such as metal objects creating localized high electric field strength.

Corona discharges cause degradation of SF6 gas into producer gas such as SO2, HF, S2F10. Increased activity can compromise result in accumulation of these by-products and further reduce the insulation strength of SF6 gas and can also initiate other forms of PD that can cause insulation breakdown.

Corona discharges produce consistent discharges near the Voltage peaks, with sharp and repetitive pulses. The acoustic noise emitted often extends into MHz spectrum band.



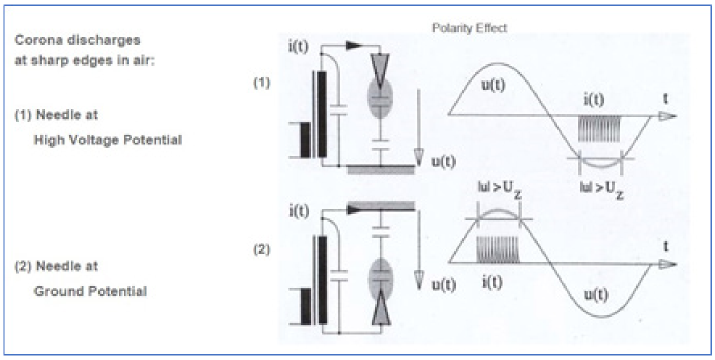


Figure 14: Corona PRPD Pattern (Image Taken from HV Technologies The Basics of Partial Discharge Testing)

FLOATING POTENTIAL

Floating potential partial discharge occurs when an ungrounded or improperly grounded conductive object, such as a loose component shield or particle within the GIS becomes electrically isolated. The object develops a floating potential which can lead irregular and unpredictable partial discharge activity when exposed to an electrical field.

The main cause of this pattern is loose connections, loose particles entrapped within the GIS (includes conductive micro-particles such iron fillings or shavings from grinding process). Isolated conductive surfaces such as objects not properly grounded, fasteners and free moving metallic debris. By-products of corrosion as well as mechanical vibration which can cause fixed components to become electrically isolated.

floating potential PD generates Pulses that are irregular and unpredictable in pattern. The pulses occur a various phase of the waveform and the discharges are less consistent when compared with corona and surface discharge. The activity may intensify when the floating object moves or shifts due to external forces or vibration.

The effective way to resolve this kind of PD is through cleaning. The gas compartment will be required to be emptied, a thorough inspection conducted and then cleaning, vacuuming and gas filling will be done before testing again for PD activity.

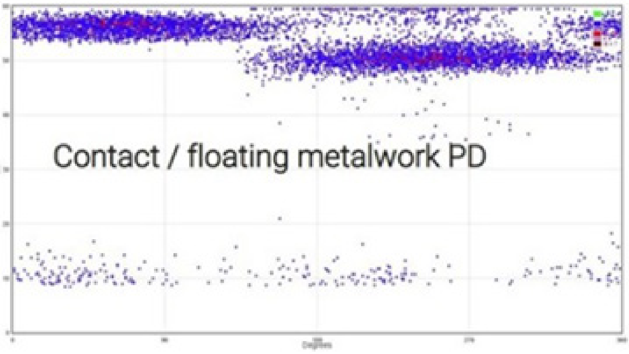


Figure 15: PRPD Pattern for Floating Potential

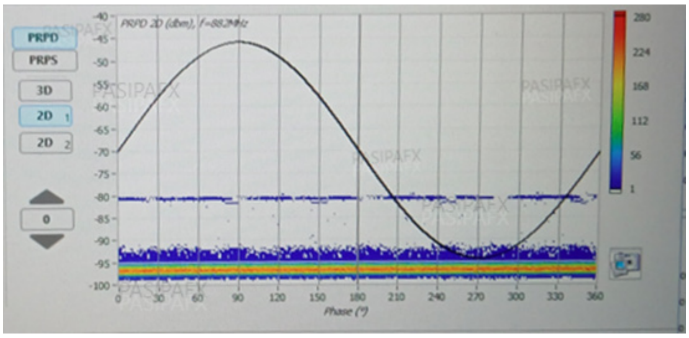


Figure 16: PRPD External Noise, + Floating Potential

Due to their nature floating potential is very difficult to resolve due to their unpredictable nature, irregular pattern which sometimes mimic

EXTERNAL NOISE

Noise is form of unwanted sGignal originating from outside the GIS that may or may not interfere with the data acquisition and process of the partial discharge signals. The noise can mimic or mask genuine partial discharge signals. Noise cancelling works by injecting a sound equal and opposite the sound to be cancelled, and so if the noise is equal and opposite the PD signal, that will have the same effect of cancelling the PD signal thereby masking it from detection by the PDMS.

The Acoustic method employed in GIS is prone to interference from a number of sources that generates, transmits or boosts electromagnetic waves. Noise comes from cell phone signals, vibration, two-way radios, LED lights, moving equipment, running fans, pumps, etc. All these produce sound waves and so when resolving PD using acoustic methods, it is important to note that there exists a certain level of noise. However, this noise exists at a certain threshold and when setting up the PD monitoring system, it is important to filter out this noise.

During testing, a charge of 10pC is usually injected into the PD sensor to determine the minimum acceptable noise level and any other noise above this threshold will be filtered and ignored during the PD measurement process. The filtered band should be as narrow as possible to ensure that the real PD signal will not be discarded during operation.

It is therefore of utmost importance that the PDMS must be setup when construction is finished and the conditions existing mimic the actual operating conditions.

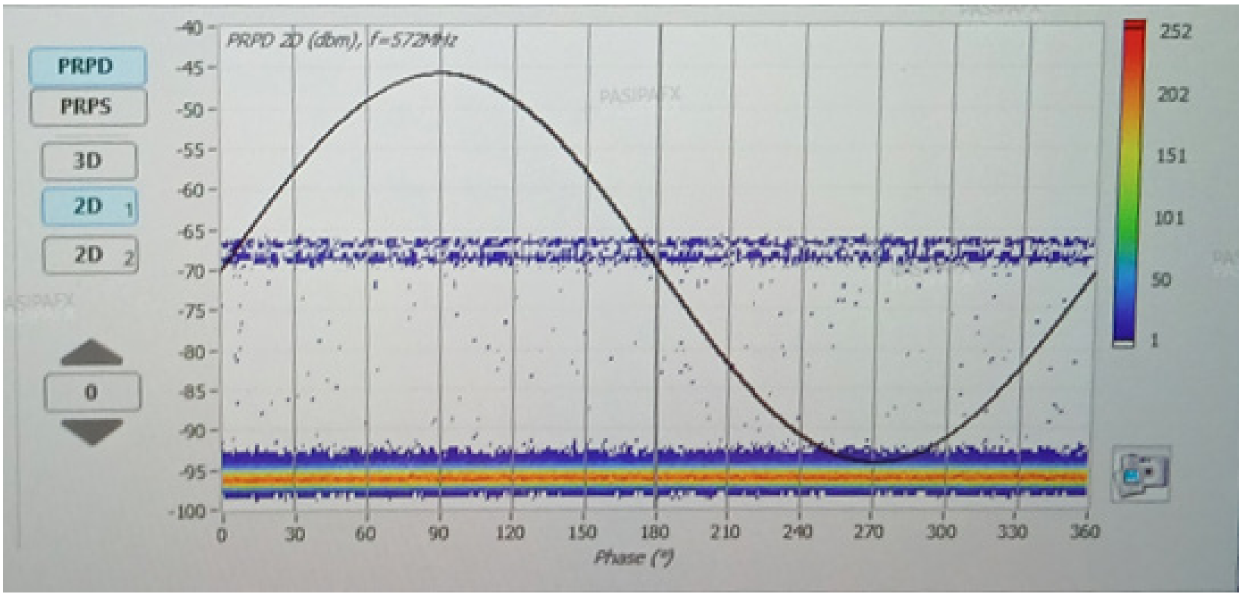
Below are two external noise PRPD patterns that were evaluated during the testing and commissioning phase.

Main cause of external noise is Electromagnetic interference from radio frequency, wireless communication signals or nearby electrical equipment such as VFD's, UPS systems, lighting, inverters. Noise can also come from Switching operations, mechanical vibrations from operating equipment such as transformers, pumps, fans as well as weather conditions such as lightning.

Noise must be effectively filtered as it is a source of false alarms and masking of genuine PD signals. Accuracy of the PD monitoring system, will therefore depend on the filtering techniques employed especially in high noise environments.

Noise PRPD pattern has an inconsistent correlation with the phase of the voltage AC waveform. The PD pulses are random and broadband and are unrelated to the actual operation of the GIS system. Noise usually has high-frequency broadband signals that overlap with genuine PD frequencies. Therefore, the signals are sporadic in nature and have no special characteristics tied to insulation defects.

In order to eliminate noise time synchronization techniques are used to differentiate between internal PD and external noises.



COMPARISON OF PD PATTERNS

PD Pattern	Internal void	Surface Discharge	Corona Discharge	Floating potential	External noise
Location	• Inside Solid insulation • Inside Gas filled Insulating media	• At Insulation Surface	• In Gas • Around Electrodes	• Near Isolated Conductive Objects	• Outside GIS (external Sources)
Cause	• Trapped Air/Gas in insulation	• Contaminants • Field Stress	• Sharp edges • Loose Connection	• Ungrounded Parts • Loose Parts	• EMI • Mechanical Vibration • Switch Operations
PD Bhavior	• Symmetric Pulses	• Asymmetric Pulses	• Sharp repetitive Pulses	• Irregular unpredictable Pulses	• Random Pulses • Unrelated to Voltage waveform
Main Effect	• Insulation Erotion	• Surface tracking • Erosion	• SF6 gas decomposition	• Insulation degratdation • Localized heating	False alarms Masking of PD signals
Frequency Spectum	• Narrow to Mid range	• Wide rande (Higher MHz)	• Broadband Higher (MHz)	• Broad • Irregular spectrum	• Broad • Overlapping with PD Spectrum
Resolution	• Improved Manufacturing Process	• Cleaning • Surface improvement • Field Grading	• Design Optimization • Gas Quality Control	• Grounding and securing of conductive parts	• Signal Filtering, • Shielding • Noise Siource mitigation

Table 1: PD Patterns

PHASE RESOLVED PARTIAL DISCHARGE – PRPD

This system is based on GE online PDMS system utilizing acoustic sensors. One of the key steps in the pre-commissioning is the segmentation of the GIS into smaller segments called circuits.

Optimal segregation has to be achieved to ensure proper operation of the Hipot test kit. Several bays in a single circuit increase the load impedance and the Hi-pot Kit will fail to synchronize and inject. At the same time, few bays in a circuit, reduces the load impedance below the required threshold and the Hi-pot test kit will fail to synchronize

[redacted]							
Circuit 1	C1-R	C1 - Y	C1 - B	**Circuit 6**	C1-R	C1 - Y	C1 - B
Circuit 2	C2-R	C2 - Y	C2 - B	**Circuit 7**	C2-R	C2 - Y	C2 - B
Circuit 3	C3-R	C3 - Y	C3 - B	**Circuit 8**	C3-R	C3 - Y	C3 - B
Circuit 4	C4-R	C4 - Y	C4 - B	**Circuit 9**	C4-R	C4 - Y	C4 - B
Circuit 5	C5-R	C5 - Y	C5 - B	**Circuit 10**	C5-R	C5 - Y	C5 - B

Total Circuits = 30

pot Circuit table

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The breakdown of the 10 circuits will be shown below for both bus section A and B

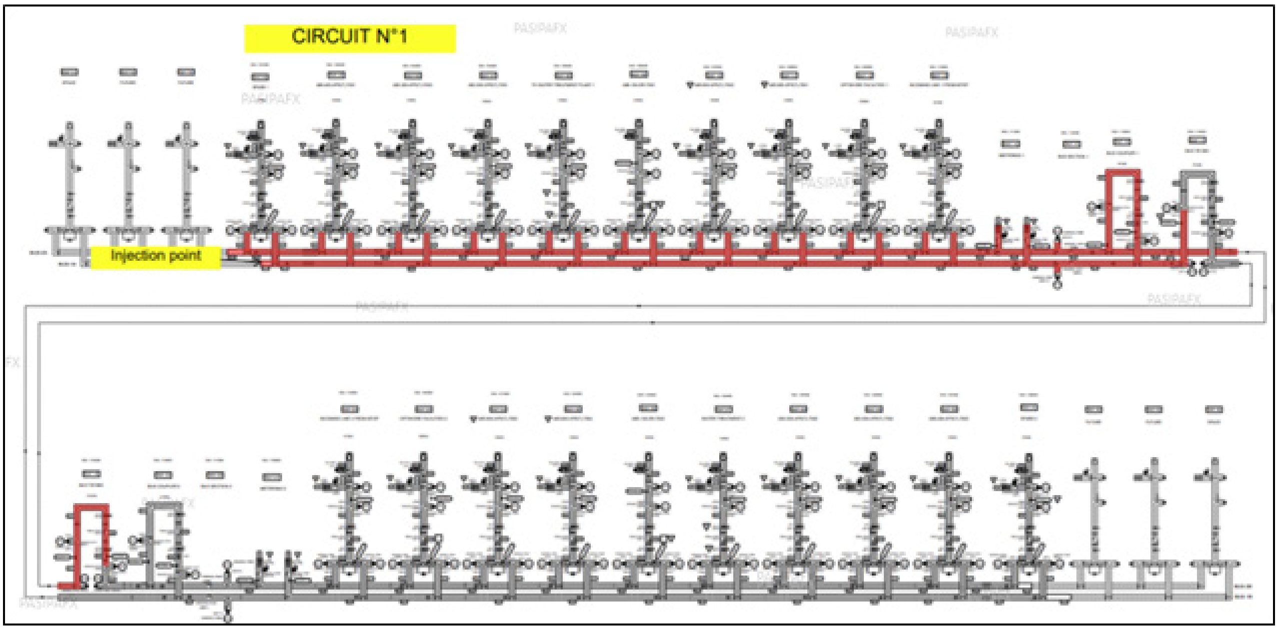

Figure 18: Hi-pot Circuit 1

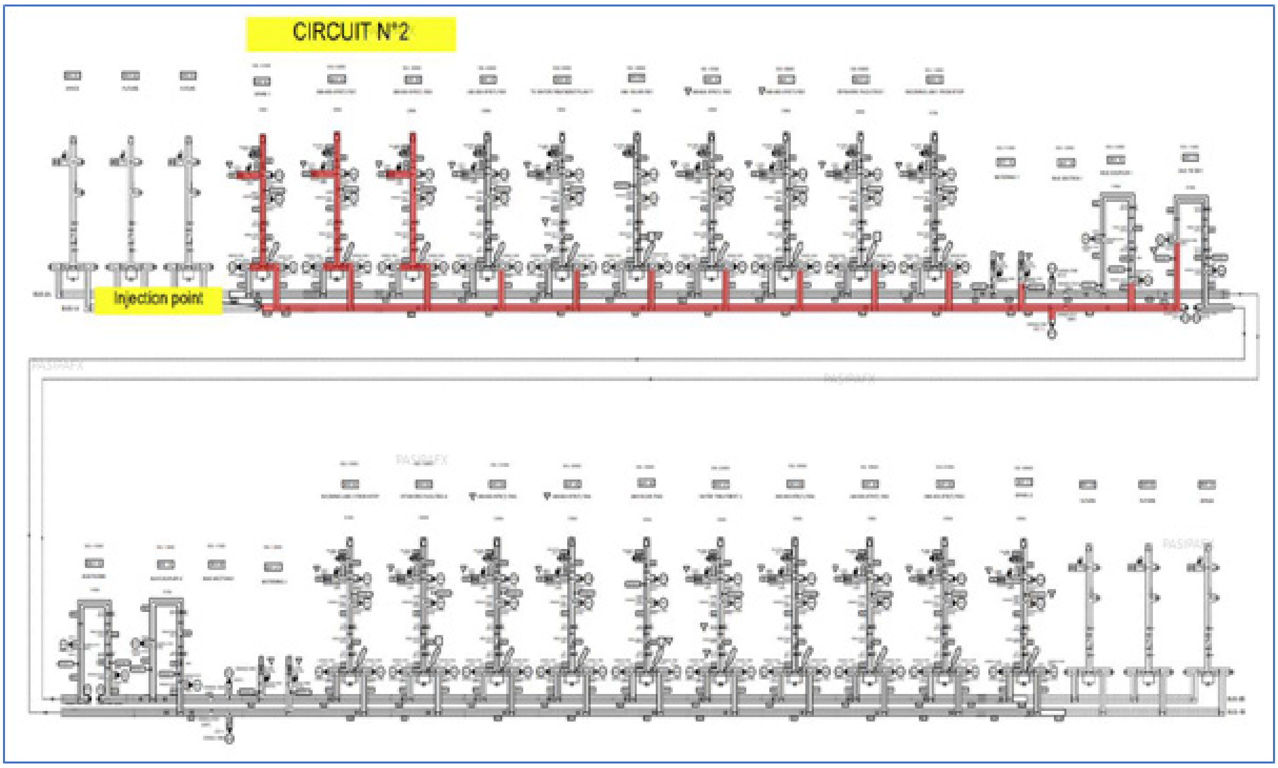

Figure 19: Hi-pot Circuit 2

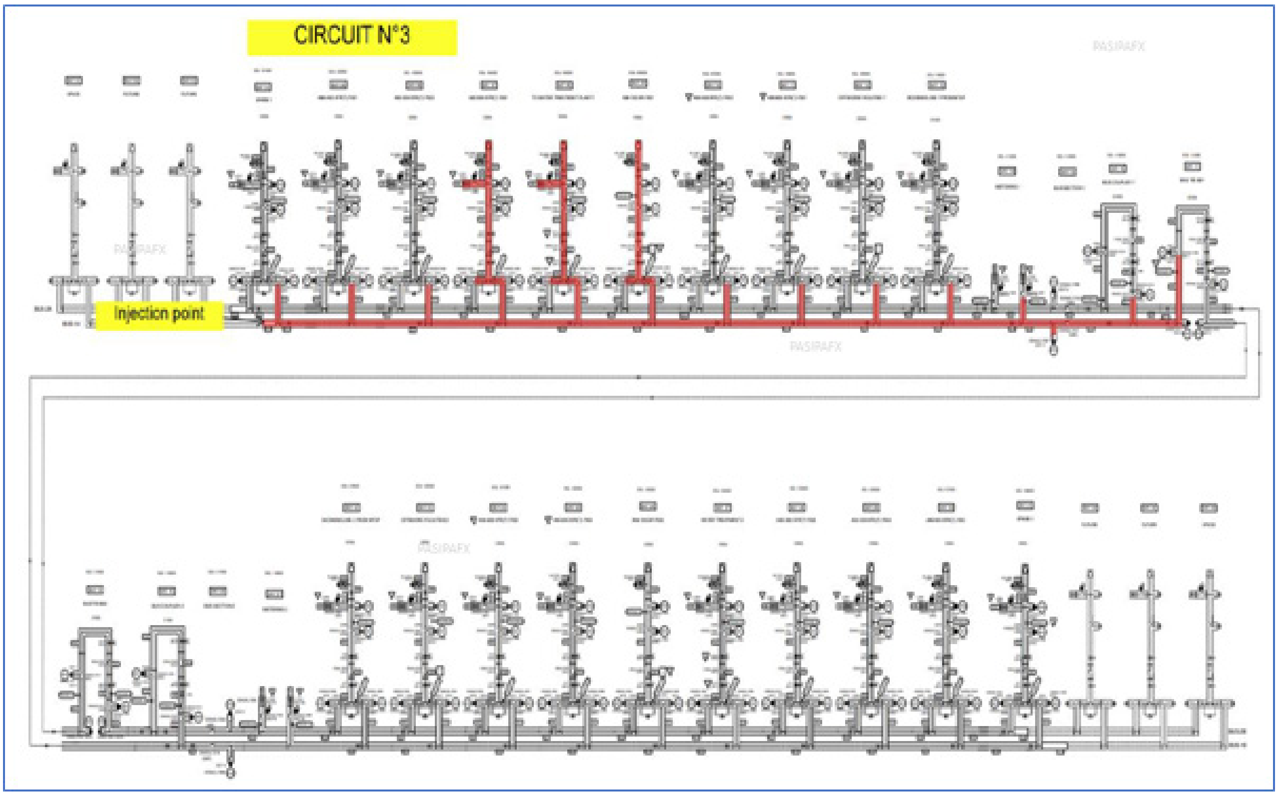

Figure 20: Hi-pot Circuit 3

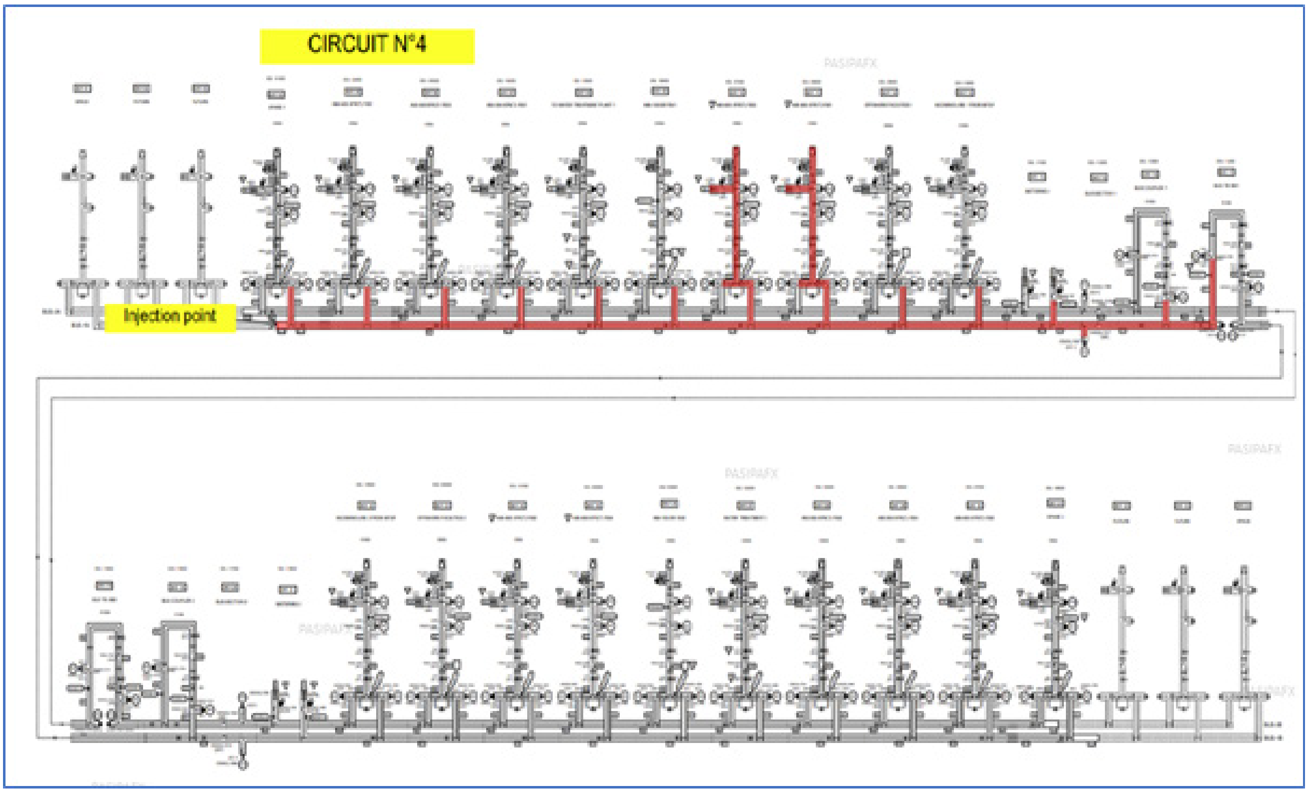

Figure 21: Hi-pot Circuit 4

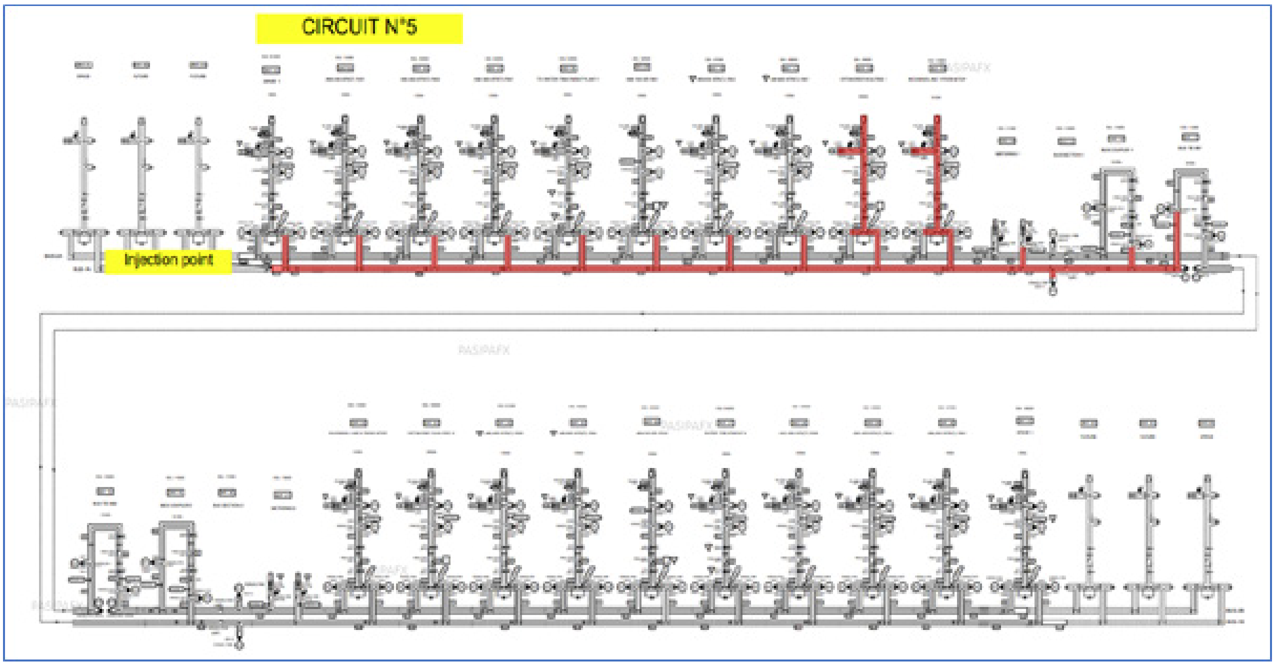

Figure 22: Hi-pot Circuit 5

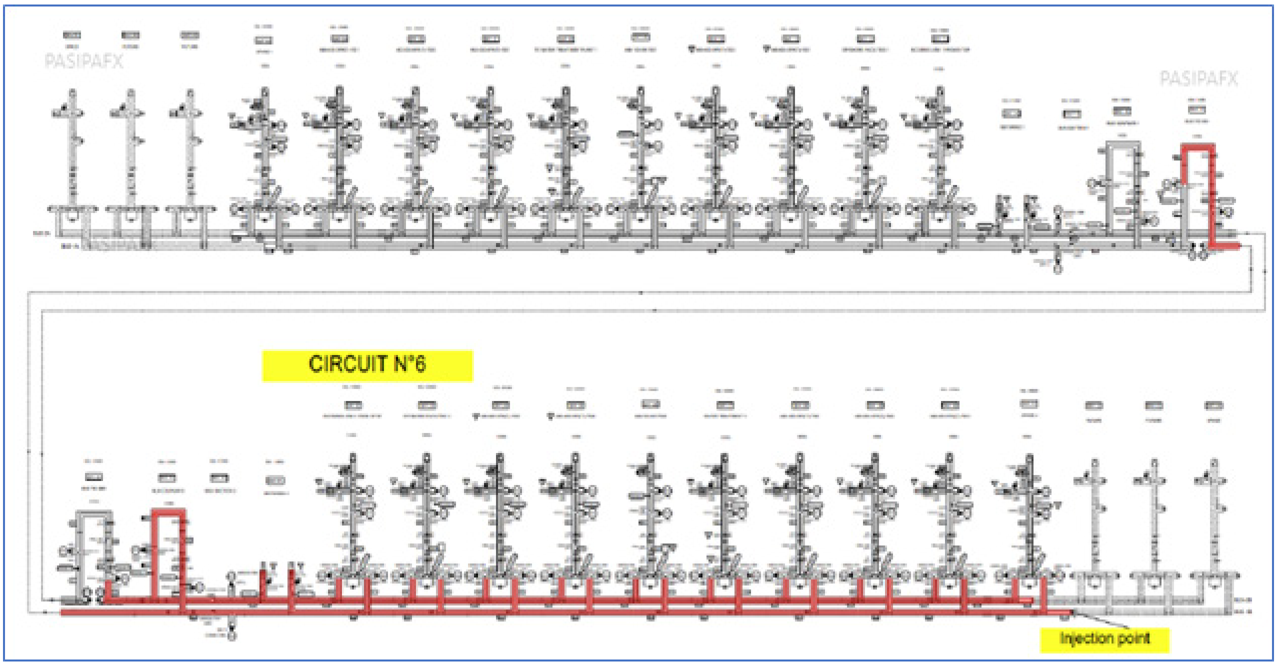

Figure 23: Hi-pot Circuit 6

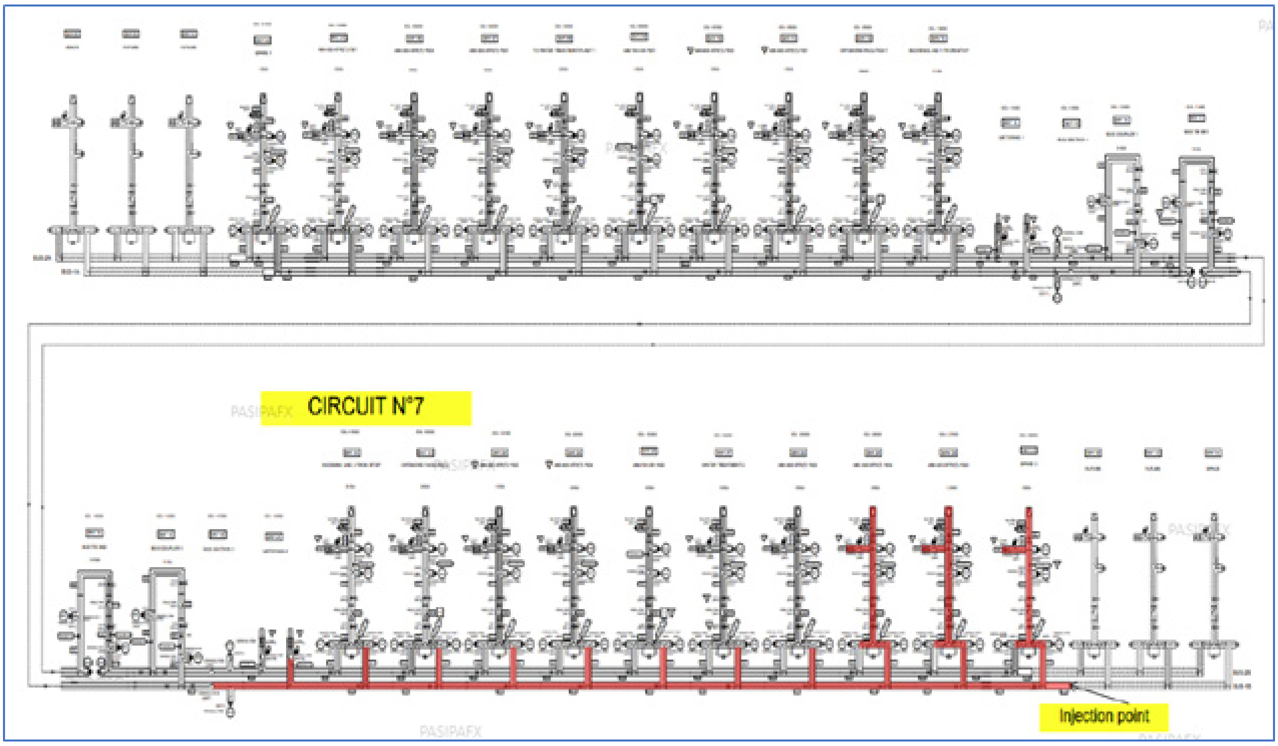

Figure 24: Hi-pot Circuit 7

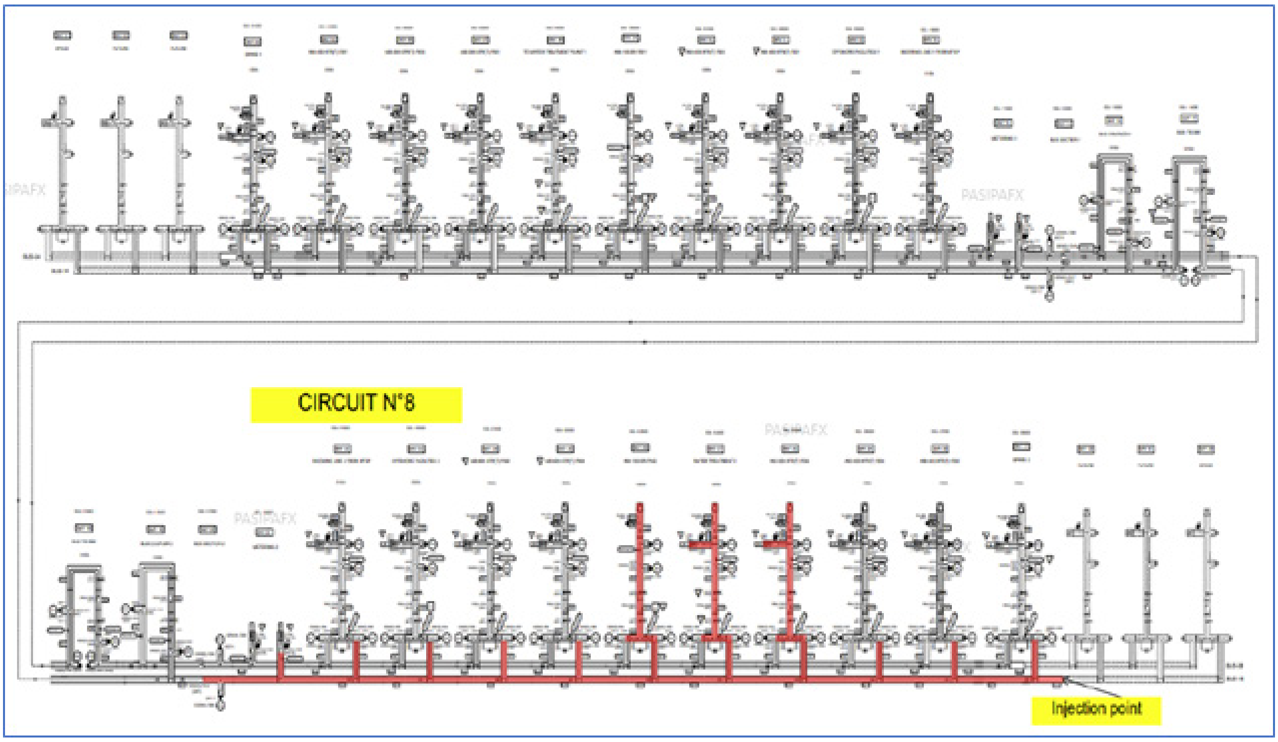

Figure 25: Hi-pot Circuit 8

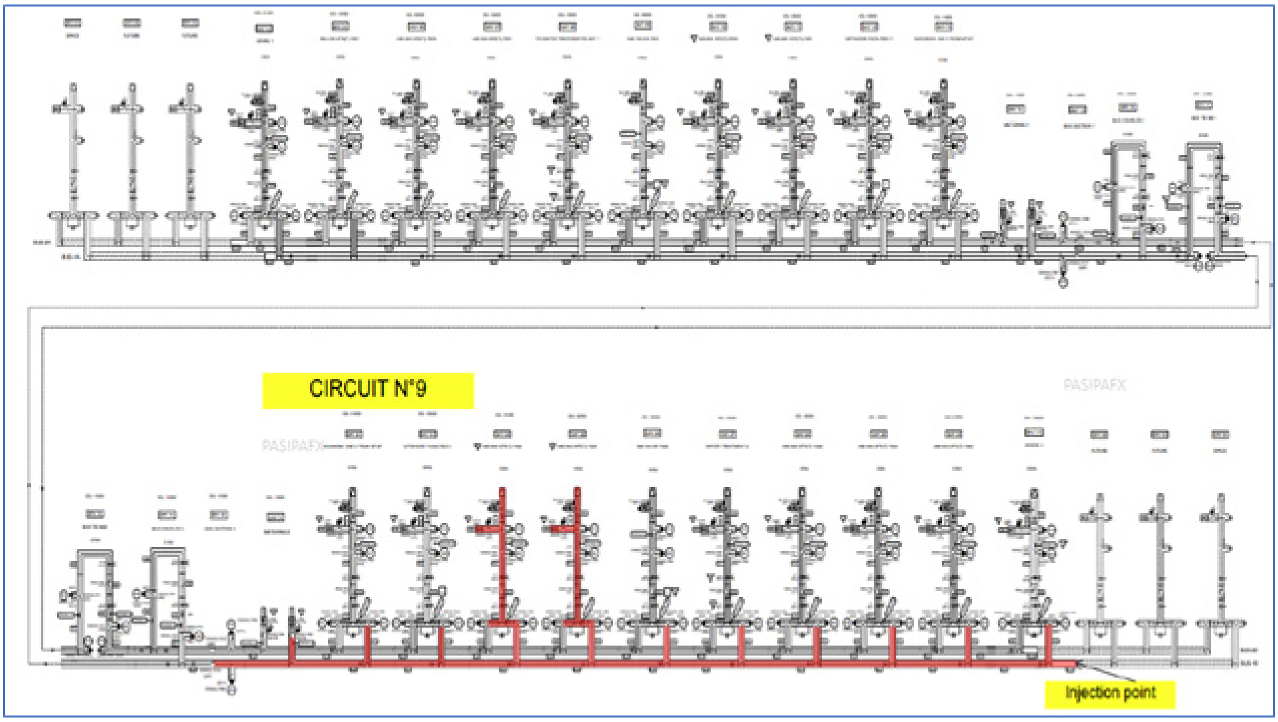

Figure 26: Hi-pot Circuit 9

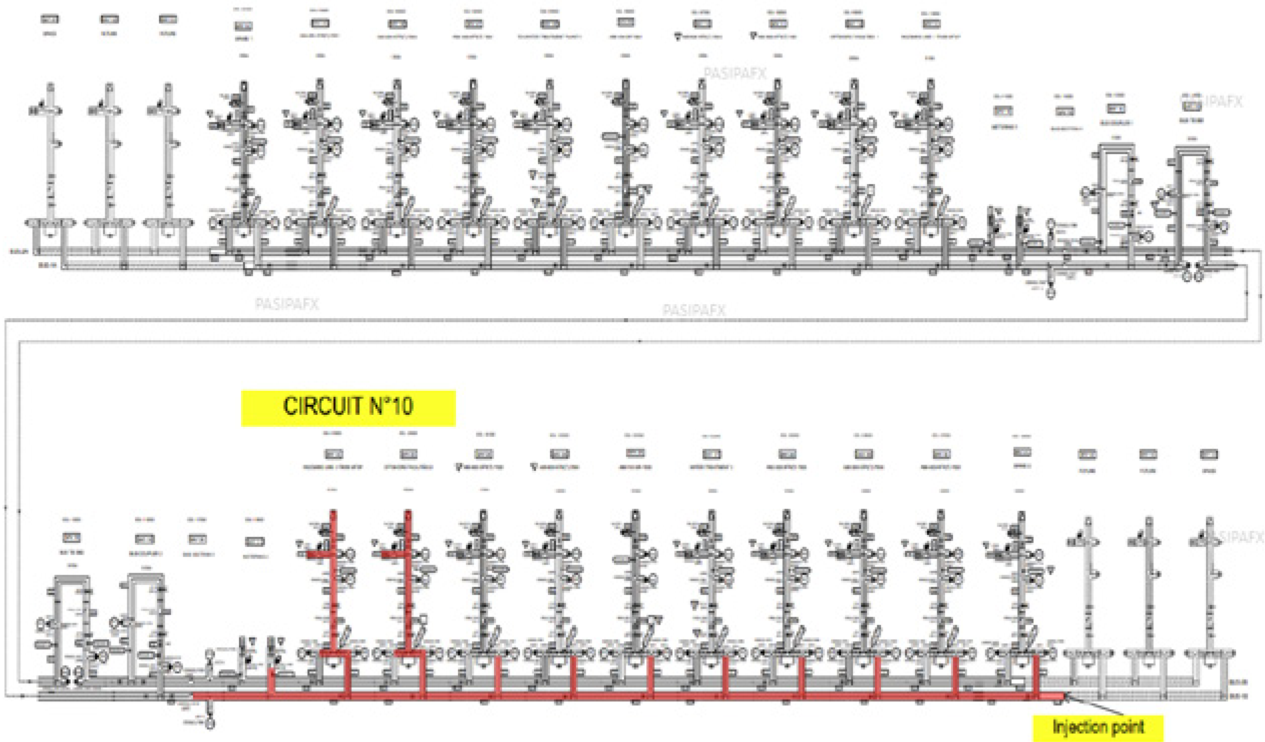

Figure 27: Hi-pot Circuit 10

HIPOT TESTING PROCEDURE

The procedure for the Hipot test involves setting up the test Kit and switching the GIS equipment according to the circuit arrangement.

1. Setup Hipot Test Kit – including connecting to the injection point.
2. Switching operation – Opening and closes breaker, isolators, earth switches to mimic the circuit arrangement. A checklist will be competed to ensure the circuit arrangement has been followed.
3. Synchronize and inject the test voltage to the circuit under test.
4. Increase the voltage as per the test curve to Conditioning voltage of 304kV
5. Hold the voltage at 304 for 180s
6. Increase the phase voltage to the test Voltage of 380kV (Line Voltage = 658kV)
7. Hold the Voltage at 380kV for 60s
8. Decrease the phase Voltage to the PD measurement level of 170kV (Line Voltage = 294kV)
9. Perform PD measurements
10. Shutdown the Hipot kit and proceed to the next circuit.

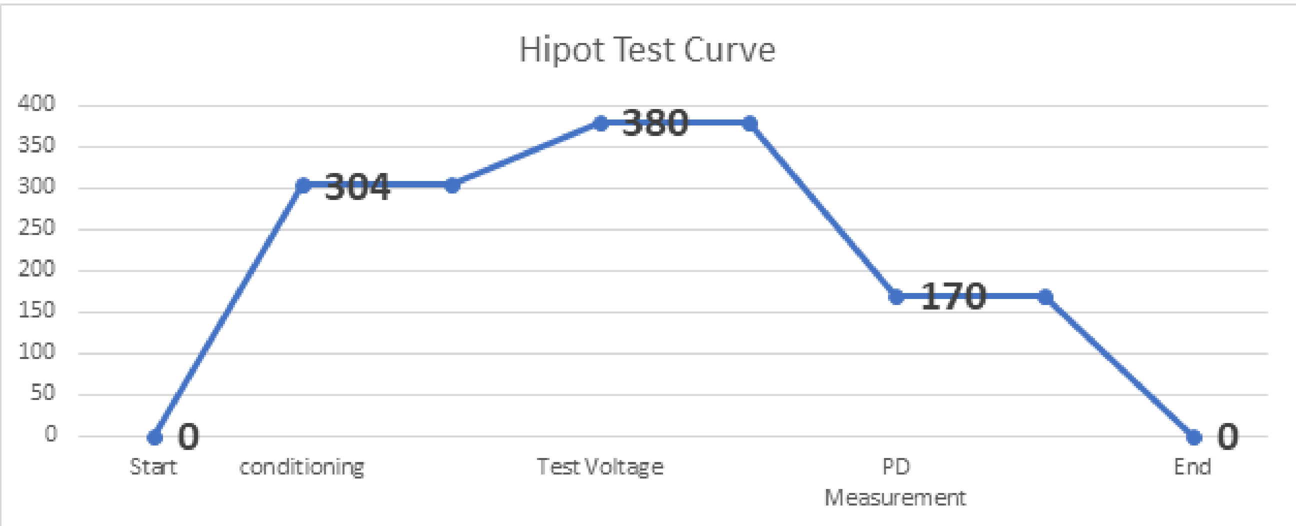

Figure 28: Hi-pot Testing Curve

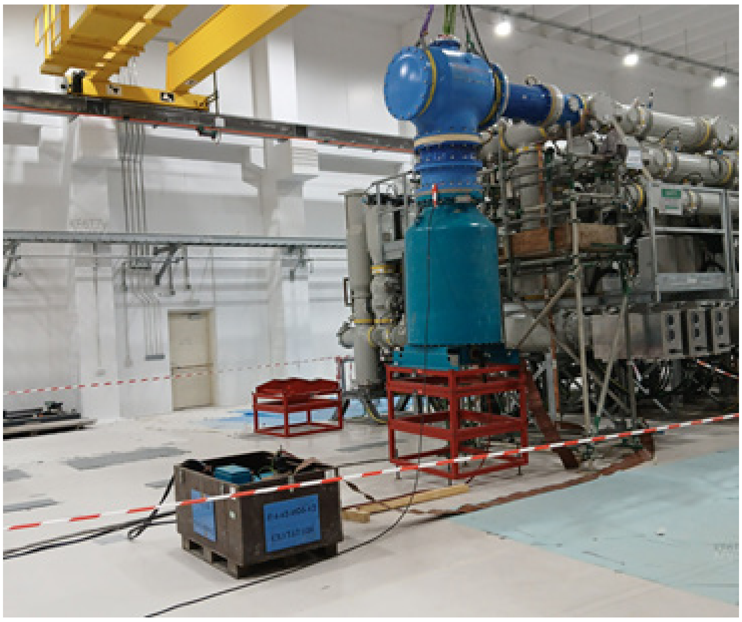

Figure 29: Hi-pot Test kit installed on Bus Section A, Red Phase

MEASURING INSTRUMENT USED

During the initial phases of the Hipot testing, the PDMS system had not been commissioned and therefore, a portable spectrum analyser was utilized for the measurement of Partial discharge. The analyser was connected to the individual measurement points using a BNC cable and connected in series with a Rf signal amplifier.

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MONITORING RESULTS: SUMMARY OF FINDINGS

BUS SECTION A: RESULTS

The Table below is a summary of the findings during the Hipot testing of the bus section A

Circuit 1	C1-R	PD Signal on Bus VT's Bay 15	C1 - Y	Hipot @380 and PD @170kV Pass	C1 - B	PD Signal on VT's Bay 15
Circuit 2	C2-R	Hipot @380 and PD @170kV Pass	C2 - Y	Hipot @380 and PD @170kV Pass	C2 - B	Hipot @380 and PD @170kV Pass
Circuit 3	C3-R	Hipot @380 and PD @170kV Pass	C3 - Y	PD Signal on PDC 08 Bay 6	C3 - B	Breakdown - Bay 8, PD Signal bay 09
Circuit 4	C4-R	Hipot @380 and PD @170kV Pass	C4 - Y	Hipot @380 and PD @170kV Pass	C4 - B	Hipot @380 and PD @170kV Pass
Circuit 5	C5-R	Hipot @380 and PD @170kV Pass	C5 - Y	PD Signal on PDC 11/12 Bay 13	C5 - B	Hipot @380 and PD @170kV Pass

Table 3: Bus A Result Analysis

BUS SECTION B: RESULTS

The Table below is a summary of the findings during the Hipot testing of the bus section B

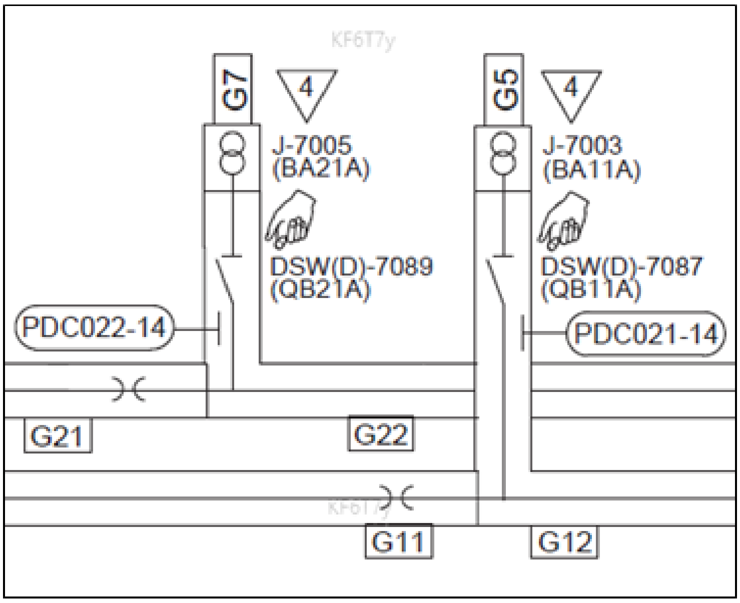
Circuit 6	C6-R	PD on Bus VT's	C6 - Y	Pass	C6 - B	PD on VT's
Circuit 7	C7-R	Pass	C7 - Y	Pass	C7 - B	Pass
Circuit 8	C8-R	Pass	C8 - Y	PD on PDC 08 Bay 6	C8 - B	Flashover - Bay 9 Cable Box
Circuit 9	C9-R	Pass	C9 - Y	Pass	C9 - B	Pass
Circuit 10	C10-R	Pass	C10 - Y	PD on PDC 11/12 Bay 13	C10 - B	Pass

Table 4: Bus B Result Analysis

BUS SECTION A: COMMON PD PATTERNS OBSERVED:

Bus section A had 5 PD activities detected during the testing process.

PD SIGNAL ON BUS SECTION 2A VT'S BAY 14R



The Insulating cone located on gas section G22 had surface discharge and was failing Hipot test, tripping at 300kV

The Hi-pot for circuit 1 was injected and as the test voltage was increased, there was breakdown around 300kV. As a standard procedure initial breakdown could be as result of a cleaning flash and so to confirm, a second injection has to be done. The circuit was injected again after external inspection was conducted and the circuit Hipot was completed successfully at 380kV without any breakdown. However, when the PD watch was performed at 170kV, PD signals were detected on Bay 14 VT compartment.

In order to zone-in to the source of the fault, some sections are usually isolated and test re-done to confirm source of PD. To achieve this, the VT disconnector switch DSW(D)-7089 was opened and another Hipot injection was performed successfully without any PD Signal. The source of the PD was therefore confirmed to be coming from the VT compartment section. An inspection was performed on the VT compartment checking for any loose connections, tightening all terminals on the VT secondary side, again retested the circuit and still the PD signals were detected in this section.

SF6 gas was removed from the compartment G22 (as shown in figure above) and an internal inspection was done, to identify if there were any foreign objects, debris of defects in the insulation materials. Upon opening the Elbow on the VT section, it was found that the insulating cone (as shown above: right image) had suffered surface discharge and this had occurred during the first phase of Hipot injection which produced the breakdown. The cone was replaced, the gas compartments cleaned and refilled again with SF6 gas.

The VT disconnector switch was closed and the circuit 1 was retested. This time, there was no PD signals on all sensors in circuit 1. As can be seen on the images on the next page, the signal level is running on the ambient noise level around -65dB and the small peaks that are recorded in the trends are background noise that exists in the environment.

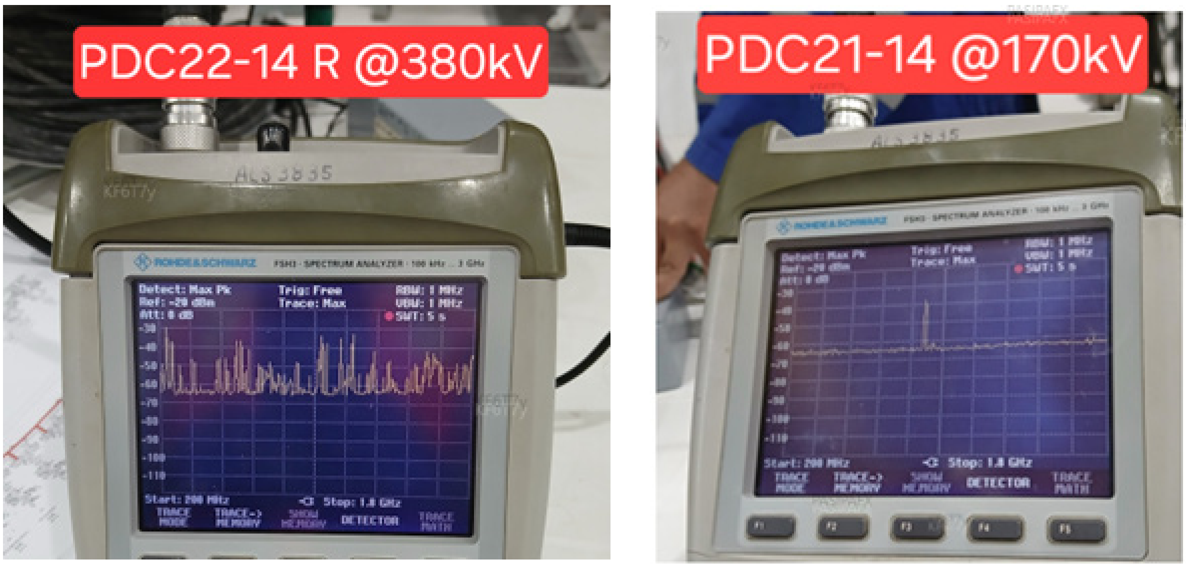


Figure 31: PDC14-022 Before and after cone replacement

ROOT CAUSE: Over application of grease creating a path for surface discharge to occur over the insulation cone bridging the insulation.

PD SIGNAL ON PDC08Y-07 BAY 07

On the Yellow phase there the Hipot test was successful at 380kV but failed the PD test at 170kV. Below is the trend graph of the PD signal. The entire bay was checked for loose connections and some loose connections were found and rectified. The circuit was again retested and no PD signal was detected or recorded on bay 07.

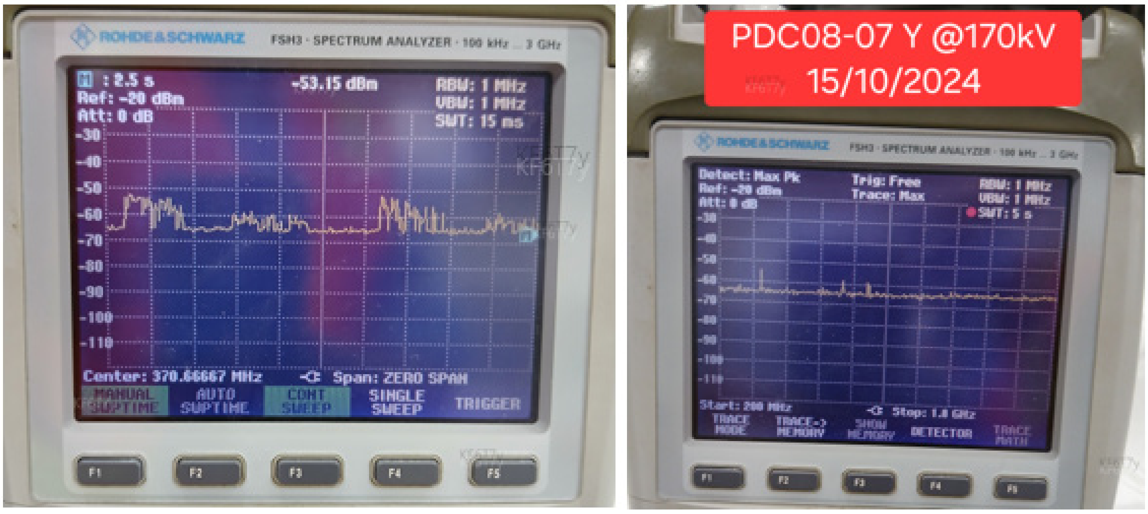


Figure 32:PDC07-08Y Before and after repair

ROOT CAUSE: Loose parts and connections on the GIS compartments.

PD SIGNAL ON PDC 12/11R BAY 13

Circuit 5 for bus section A was tested as per the PD Testing procedure diagram provided above. The Hipot was successful without any flashover but as can be seen on the trends below, the PD signals were detected on both PDC19 and PDC20. Looking at the two trends it could be deduced that the signal was much stronger on PDC20 since the peaks were much larger compared to PDC19 and so the gas section G4 was opened and cleaned.

Figure 33: Bay 13 PDC20/19R before Cleaning

Figure 34: PDC20/19R - 13 After cleaning the gas compartment

BUS SECTION B: COMMON PD PATTERNS OBSERVED:

There were 3 main PD patterns observed.

1. Floating Potential
2. Surface Discharge
3. External Noise

CORRECTIVE MEASURES TAKEN:

1. Floating potential was mainly due to foreign particles inside the GIS system and this required vacuuming and cleaning which resolved this type of PD pattern.

2. There was only one encounter with Surface discharge and the Insulating cone had to be replaced to resolve this PD pattern.

3. External noise was filtered out during the setup and calibration process, all external noises we identified and a filter was applied at the frequency band that contained the external noise signal. Prior to the commissioning of the PDMS it was almost impossible to classify the difference between a true PD signal and external noise. The Testing of Bus section B had to be delayed to allow the commissioning of the PDMS system before proceeding with Bus Section B Hipot.

CHALLENGES FACED DURING HIPOT TESTING:

There were several challenges faced during the Hi-pot testing. Initially the testing has been projected to take 15 days but due to unforeseen circumstances, requirements for repair work, delays in commissioning of the PDMS

1. PDMS system not commissioned during the initial testing of Bus section A, this made it difficult to classify the PD pattern as the Spectrum analyser on displays trend graph.

2. Pressurized system made Repair work complicated, to inspect a gas section required SF6 gas to be removed.

3. Limited access, since the Components are enclosed inside Aluminium Pipe, access to these components was very limited and had to rely on the use of an endoscopic camera to assess internal components.

4. Lifting operations – Almost all components repair require the use of crane

LESSONS LEARNED DURING THE INSTALLATION AND PRE-COMMISSIONING:

The Analysis of partial discharge activity in the 230kV GIS system revealed several critical insights for improving testing and operational practices. The most commonly observed PD pattern was floating potential, which was largely attributed to contaminants such as dust, particles and overapplication of grease on insulation cones. These findings underscore the importance of maintaining very strict hygiene standards and controlled application of lubricants during the assembly and installation process.

External noise interference was also prevalent particularly from other operating equipment as well as construction equipment and mobile machinery working around the GIS substation. To mitigate this, it is advisable to perform the Hipot test only after all construction activities are completed and under conditions that closely resemble actual operating ambient conditions.

Another key lesson in the necessity of commissioning the Partial discharge Monitoring system (PDMS) well in advance before starting the Hipot testing. This allows for precise classification of PD patterns using phase resolved partial discharge (PRPD) techniques, improving diagnostic efficiency and accuracy. One other aspect was the substation building status at the time of equipment installation. The installation was started before the HVAC system was functional and also doors not installed, which required temporary doors and HVAC systems to be installed before installation of equipment could commence. Dust storms were rampant during the installation phase and this led to ingress of dust into the building, a situation which was undesirable and could result in contamination during assembly.

The time allocated for the Hipot was inadequate and was based on assumption that the testing would be smooth, which was not the case. For each circuit tested, there was PD activity observed in some sections and this required rectification or repair. The repair process is time consuming since the section in question has to be depressurized and disassembled for inspection, cleaning or repair. Future consideration needs to consider the requirement for inspection and review when planning.

Finally, an endoscope camera should be readily available before testing cab commence since its critical for inspecting areas that may otherwise require disassembly, which significantly reduces the time required for inspection and repair.

Summary of lessons learned
1. Floating potential PD pattern was common due to contaminants such as dust, particles, and overapplication of grease
2. External Noise from construction activities introduced noise impacting PD measurement accuracy
3. Hipot testing should be performed as near operating conditions as possible

4. It is necessary to commission the PDMS before Hipot testing for PRPD classification
5. The GIS Building should be completed or pressurized to prevent dust contamination during installation
6. Allocate sufficient time in the testing plan for repairs if PD is detected, as disassembly may be required.
7. An endoscope camera should be readily available for inspection to avoid unnecessary disassembly.

CONCLUSIONS

Partial discharge Monitoring and mitigation are essential for ensuring the safety and performance of the GIS substation. The technical paper reviewed fundamental aspects of partial discharge, including its definition, common types (such as internal, surface, corona, void, and protrusion discharges), as well as their specific relevance to GIS systems. It also explored the components of a partial discharge monitoring system, the importance of calibration and sensitivity measurements. These insights provide a comprehensive understanding of PD behaviour and its implications for GIS operation and maintenance.

The review of a case study of a GIS installation highlighted practical challenges, such as floating potential PD patterns due to contamination, noise interference from construction activities, and the need for detailed planning and preparation during the Hipot testing. The key takeaways and recommendations include performing testing under controlled conditions, commissioning the PD monitoring system prior to Hipot, and ensuring adequate time allocation for repairs during Hipot testing. By applying these strategies, along with thorough understanding of PD types and detection techniques, operators, can enhance the reliability of the GIS substations

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3. IEEE Guide for Partial Discharge Measurement in Power Equipment

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5.https://eatechnology.com/australia/resources/blogs/high-voltage/what-is-a-partial-discharge-phase-plot-telling-you/

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7. Research gate – Development and pattern identification of End-winding discharge under effect of Relative humidity and temperature for HV motors

APPENDIX A: GLOSSARY OF TERMS

Acoustic Emission: The generation of transient ultrasonic waves caused by the rapid release of energy from localized sources such as partial discharges, within a material.

Acoustic Sensor: A device (piezoelectric or capacitive sensor) used to detect ultrasonic waves generated by partial discharge.

Calibration: The process of adjusting and verifying the accuracy of a measurement, such as an acoustic PD monitoring system, by comparing its output with a known reference signal.

Corona Discharge: A type of partial discharge that occurs in gaseous insulation around sharp edges or protrusions, characterized by continuous low-amplitude pulses.

Contamination: The presence of foreign substances (e.g. dust, particles, or grease) in a GIS system, which can lead to insulation defects and partial discharge.

Data Acquisition System: A system that converts analog signals from sensors into digital data for analysis, often used in PD monitoring systems to capture and process acoustic signals.
Endoscope Camera: A tool Used for visual inspection in GIS systems, often employed to inspect areas where PD is detected without requiring disassembly.

Floating Discharge: A type of partial discharge caused by floating components or loose connections within a GIS system, which is characterized by intermittent high-amplitude pulses.

Frequency Range: The range of frequencies over which an acoustic PD monitoring system operates to detect ultrasonic signals
Gas Insulated Switchgear (GIS): A compact, High-voltage electrical substation that uses SF6 gas as an insulating medium to enclose its components.

High Potential (Hipot) test: A high Voltage test performed on electrical equipment to verify the integrity of its insulation and detect potential defects.

IEC 60270: the international standard for partial discharge measurements, providing guidelines for PD detection techniques, calibration, and sensitivity requirements.

Internal Discharge: A type of partial discharge that occurs within solid or liquid insulation due to voids or impurities, characterized with consistent amplitude.

Localization: The process of determining the exact location of partial discharge source within a GIS system, often achieved using multiple sensors and advanced algorithms.

Noise Interference: Unwanted signals or disturbances (e.g. from transformers, construction activities) that mask or interfere with the detection of partial discharge signals.
Partial Discharge: A localized Electrical discharge that partially bridges the insulation between conductors, often occurring in regions of high electric stress.

Phase resolved Partial Discharge (**PRPD**)**:** A method of analysing PD Patterns by plotting PD Pulses against the phase of the applied voltage, providing insights into the discharge mechanism.
Piezoelectric Sensor: A type of acoustic sensor that generates and electric signal in response to mechanical stress, commonly used for PD detection in GIS systems.

Pulse Method: A technique for analysing individual PD Pulses to determine their amplitude, phase and frequency.
Real-time monitoring: The continuous measurement and analysis of partial discharge activity in GIS system, enabling immediate detection and response to PD events.

Signal Conditioning Unit: A component for the PD monitoring system that amplifies and filters sensor signals to enhance their quality for analysis.

Surface Discharge: A type of partial discharge that occurs along the surface of insulation, often due to contamination or moisture, characterized by irregular pulses with varying amplitudes.
Threshold: A predetermined level of PD activity set in the Partial Discharge Monitoring system (PDMS), above which an alarm is triggered to alert operators.

Ultrasonic Waves: High frequency sound waves (typically above 20kHz) generated by partial discharges and detected by acoustic sensors in PD monitoring systems.

Void: A small cavity or gap within solid insulation that can lead to internal discharges due to high electric stress.

Wavelet Transform: A signal processing technique used to analyse transient signals, such as those generated by partial discharges, by decomposing them into different frequency components.