PD ANALYSIS OF GAS INSULATED MEDIUM VOLTAGE SWITCHGEAR DURING FACTORY ASSEMBLY AND SITE COMMISSIONING

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INTRODUCTION

The Partial Discharge (PD) measurement of medium voltage (MV) gas insulated switchgear as a routine test is according to the standard IEC 62271-200 [1] a subject to agreement between manufacturer and user. However, more and more manufacturers of MV gas insulated switchgears are going to introduce this measurement as a factory test for quality assurance to qualify the proper insulation of the switchgear. Furthermore in the last years the user of MV gas insulated switchgears stated more and more the requirement for PD measurements after erection at site. The main reason is, that despite the current situation of high cost pressure the user has to maintain the reliability of the electricity distribution systems. The important role of medium voltage switchgear to guarantee a high service quality especially in HV-substations led to an increased application of gas insulated switchgears in the last 20 years. Due to the hermetical sealed design gas insulated switchgears have a lot of advantages and show a high reliability.

To achieve or even exceed the expected lifetime of 30 years a proper insulating system is of great importance. PD measurements give an indication of the degradation of the insulation. Low PD values at the factory ensure that the switchgear has left the factory not defective. Low PD values after erection on site confirm, that no damages have occurred during the shipment and the installation of the switchgear. The PD measurement is applied at all stages of the life cycle during the service may help to increase the service life of the switchgear [4].

Test circuits and procedures

The possible test circuits to measure the apparent charge described in IEC 62271-200 [1] consist of single-phase and three-phase arrangements. However, the only practicable method for MV gas insulated switchgear is the single phase testing. This test method can be used at the factory as well as at site. For measuring the partial discharge quantities, each phase shall be connected to the test voltage source successively, the other two phases and all the parts earthed in service being earthed. Thereby a sufficient sensitivity for the detection of defects from phase to phase and from phase to ground is reached [5].

According to the standard the neutral point treatment (with or without solidly earthed neutral) determines the test voltage. Most of the MV networks use resonant grounding of the neutral point (Petersen coil). In any case the MV GIS have to be designed and tested for a phase to ground PD test voltage of \( U_r \) and in fact the users don’t differentiate. Therefore the following test procedure is become customary: First, the applied power-frequency voltage is raised to a pre-stress value of 1,3 \( U_r \), and maintained at this value for 10 s. Partial discharges occurring during this period are disregarded. The voltage is then decreased without interruption to 1,1 \( U_r \), and maintained at this value a specified time, usually 60 s (no time limit is mentioned in the standard [1]). In this time period the partial discharge quantity has to be determined.

To ensure a proper insulation system of MV gas insulated switchgear a permissible PD value below 20 pC at the test voltage of 1,1 \( U_r \) is acceptable. In case of connected voltage transformers (VTs) the permissible PD value can’t be lower.
than that according to the IEC standard of VTs thus 50 pC. For additional information the PD inception and extinction voltages can be recorded, but always with respect to the actual background noise level. Normally the extinction voltage is the voltage when the PD disappears in the background noise. In some sites the background noise level can be very low (e.g. in metal housings lower than 1 pC) and the extinction voltage can decrease to very low values. Therefore the sole fixing of a permissible voltage level (acceptance criterion) for the PD inception and extinction voltages makes no sense. More practicable is the fixing of a second voltage level below the test voltage connected with a second permissible PD value, e.g. at \( U_i / \sqrt{3} \) lower than 5 pC. It is well known that PD values lower than 5 pC have a negligible impact on MV GIS.

**Requirements on test equipment**

The most usual method for detecting PD in MV gas insulated switchgear utilises a coupling capacitor (\( C_C \)) that is place in parallel with the test object. The PD signals are measured via a coupling device (CD) connected between test object and ground, see figure 1. The extraction of the test voltage signal out of the measuring impedance is of great advantage, as it saves an additional voltage divider.

![Figure 1 Usual test set up for MV switchgear](Image)

The test voltage source should be a 100-kV-transformer as an isolated vessel type (weight, size). The transformer has to be PD free up to 60 kV and its power supply should be filtered. The entire needed equipment described is easily transportable and can be used at factory as well as at site, figure 3.

For recording and analysis of the PD impulses a computerised measuring equipment, see figure 2 is of great advantage. Three important measuring possibilities can be realised:

- A meter for the weighted apparent charge according to IEC 60270 [2]
- An oscilloscope to display the single PD pulses in relation to the phase
- A graph of the phase resolved PD pattern

Additionally, certain device functions for the suppression of external PD disturbances, like windowing and gating should be available to reach a sufficient background noise level.

**ROUTINE TESTS AT FACTORY**

According to the standard [1], PD measurements as a routine test on assemblies or subassemblies should be made with the switching devices of the concerning primary parts in the closed position. Only in some exceptional cases, where the deterioration of the insulation by PD is conceivable, e.g. disconnectors or stand-by incoming feeder (energised in open position), an additional PD measurement could be performed with the device in open position.

The PD test on parts of the switchgear panel, which are already tested at the supplier like cast resin voltage transformer (VT), is not necessary. Therefore the VTs remain switched off during the test. If the user requires the test, it has to be considered that at power frequency the VT cannot be loaded with the test voltage. Above a design dependant voltage the iron core goes in saturation and an admissible high current flow, which can damage the VT windings. Normally applied voltages at power frequency above 1.0 \( U_i \) are not permissible. To be sure the VT supplier should be inquired.

For an advanced PD analysis a digital PD measuring system with the ability of phase resolved PD pattern was introduced at the factory test areas, see figure 2. To ensure a sufficient background noise level, which in most of the factories heavily is affected by spurious crane movements, the gating method has proved of value. For that purpose the antenna input is directly connected to the metallic fence of the test area.

For a normal PD measurement the oscilloscope function is sufficient for the testing staff and the people witnessing, if the measured charge and the applied voltage is displayed simultaneously. To avoid confusion it is important that in this function mode the weighted IEC value [2] and not the peak value is displayed. In the case of PD values, which exceed the maximum limit quantities, immediately the phase resolved PD pattern could be recorded and for a PD analysis considered. The best way is to record PD pattern at the fixed test voltage. At the inception or extinction voltages the PD activity is stochastic which leads to large variations of the patterns. For analysis the found PD pattern is compared with a catalogue of possible PD pattern. With this the testing staff can initiate first measures without consultation with the laboratory. If the failure cannot be cleared and investigations in the laboratory are necessary, the PD pattern recorded in the routine test areas is the guideline for the search for the defect.

**LOCALISATION OF DEFECTS**

If the PD measurement shows an admissible insulation defect the source of PD has to be localised. Switching operations leads to a first rough localisation of the parts concerned. A more detailed localisation can be performed by means of modern digital PD measuring systems with voltage indication.
These systems can store over a certain period of time the parameters amplitude, phase position and time of every single impulse. After the recording the PD analysis is done off-line. The analysis tool can generate interesting 3D diagrams like pulse number over phase and charge, charge over phase and time or charge over phase and voltage. However, it was found that the phase resolved PD pattern (figure 3 a) is the most suitable one for a fast PD analysis at factory and at site. Additional information can be delivered by the diagram charge over voltage (figure 3 b), out of which the inception and the extinction voltage can be also determined.

These diagrams are normally sufficient to find out the type of PD source. Together with the known design of the MV GIS in most of the cases the PD producing part can be identified. If not, there are unconventional methods, which support the localisation of PD source, like ultra sonic detection or the recording of ultra violet light emission, which are well known at air insulated equipment.

For this type of localisation the gas insulated switchgear has to be opened. Then an ultra sonic detector (microphone), which can normally detect PD down to 30 pC, is used to determine precisely the PD source. In some cases, e.g. loosen bolt or sharp edges, it was found, that a similar PD pattern could be reproduced in air, figures 4 and 5. This is important, because in air corona discharges could be initiated at other parts.

Therefore the PD pattern recorded in air has to be comparable to the PD pattern recorded in gas to ensure the right PD source is detected. It is remarkably that for the loosen bolt the inception voltage in air is the same like in gas and lays at 10 kV. For the sharp tip the inception voltage decreases from 18 kV in gas to 14 kV in air (- 20 %).

In both cases can be stated, that the PD values in air are much higher than in gas.

If the concerned area is too complicated or too compact, there is no other way, as part for part has to be removed until the PD disappears. Here it is important likewise, that at each step the recorded PD pattern is compared with the pattern in gas.

SITE TESTS AFTER COMMISSIONING

In general primary MV GIS are shipped at site in pre-assembled modules. These modules are subjected to the above-described routine tests in the factory, but it is almost impossible to perform the partial discharge routine test at the complete assembled switchgear. The size of such assemblies can be from a width of some meters to some tens of meters. According to IEC 62271-200 no partial discharge measurements neither in the factory nor at site are required. However from time to time customers are asking for this type of test after the assembly work at site. As the PD test is subject of agreement between manufacturer and user the test procedure and the acceptance criterions have to be agreed before the test. The environment of the test has to be taken into account when criterions are fixed. When speaking about environment both parties should have the physics in mind:

- At site there is no shielded laboratory.
- The background noise level is heavily affected by electromagnetic noise.
- This noise can be of permanent nature (radio transmitters) or random (cell phones).
- Partial discharges from other equipment in the switchyard may be interpreted as PD from the test object.
- The free space around the switchgear is limited (see figure 6).

The biggest difficulty is to judge on the expected background noise level. The accepted PD level at test voltage should be at least 2 times higher than the expected background noise level. Otherwise is almost impossible to make a clear distinction between PD and noise. After successful commissioning of the switchgear the test equipment has to be completed in the switchgear room.
Before running the acceptance test the representatives of the manufacturer and the end user have to be sure, that the test equipment itself is free of any discharges. This should be verified by increasing the voltage to at least 1.3 times the test voltage. The same procedure should be applied when the test cables are connected. Most the problems during site tests are caused by improperly connected high voltage cables. Once it is secured, that the connections and the test equipment are free of any disturbing discharges the applied test procedure is identical to the test procedure during the routine test in the factory. When the test is performed it is very important, that all PD impulses are recorded. Especially all impulses, which occur after switching on the test circuit without the presence of high voltage, are of importance. These impulses are an indicator for the background noise, which is picked up by the overall test arrangement. When the test voltage is reached it should be kept for the specified time. During this time period the reading of the PD-meter takes place (figure 7). According to the definitions of IEC 60270 a partial discharge occurs during every cycle of the voltage. That means pulses occurring randomly during the specified reading time have to be neglected and should not be considered as PD coming from the object under test. This point leads to the biggest discussions at site almost because of the poor preparation/knowledge of some people witnessing. A partial discharge measurement cannot be compared with a measurement of the resistance of the main circuit, where a reading can be reproduced at almost any time. To measure a partial discharge means to integrate the current of some $10^9$ Amperes and to calculate the apparent charge of some $10^{12}$ Coulombs. Further is has to be considered that the overall uncertainty of such measurements is in the range of some tens of percents and are highly dependant on the bandwidth and the quality of the PD-detector.

Another important factor of influence is the ratio of the coupling capacitor to the capacitance of the main circuit. It has to be considered that the sensitivity of the PD measurement is limited due to electrical length (total capacitance) of the main circuit tested. IEC 60270 gives sufficient indications how to avoid such problems, but unfortunately most of the content is not properly known. The measurement will be done normally on all parts of the switchgear, which were not tested in the factory. This means the bus bar and bus bar joints are subjected to the test voltage. All other parts of the switchgear modules, like circuit breaker compartments are already tested. The test results of this test sections should be taken into account when the overall PD-level of the switchgear is determined. As the measurement of PD-impulses is a single impulse measurement, no superposition of impulses takes place. That means 20 pC in one panel and another 20 pC in a second panel will not result in 40 pC for the measurement of the panels, when they are tested together.

The above experiences shall not have the character of a school, but should sensate all people who are specifying PD tests at site and who are witnessing these tests.

**IDENTIFIED CHARACTERISTIC DEFECTS**

**Defects in gas**

During the assembly small impurities, like conducting particles can get into the GIS compartment. Free particles as well as fixed particles at spacers can drastically reduce the ac breakdown voltage of the gas insulation [3]. Floating components, like not bonded shields or loosen bolts (see figure 4) cause generally high PD intensities, which are normally high enough to decompose $SF_6$ in huge amounts. The PD pattern is very characteristic with the small gap after the voltage maximum and the occurrence of PD values only in a certain range. In case of sharp protrusions or tips (see figure 5) the PD intensities are small, however, the lightning impulse breakdown voltage is seriously reduced. So all described defects in gas can be serious and should be located.

**Defects at interface areas**

Defects at interface areas like surfaces of spacers and cable joints cause high PD intensities up to several hundreds of pC. These creeping discharges can only start at high electrical stress. Contamination or air bubbles can cause continuous discharges along the surface or joint and these the burning of the organic material. The result is an electrical tree and the breakdown of the insulation along the creeping track. Figure 8 illustrates the PD pattern of a creeping discharge on the surface of an insulating spacer. The PD pattern is symmetrically in both half waves. PD occurs before and after...
the voltage maximum with the highest values short before. The PD pattern of a defect in a dummy plug (see figure 9) shows only PD impulses in the positive half wave of the voltage, but the shape is very similar to that of figure 8.

![Figure 9 PD pattern of discharges in the joint between silicon rubber of a dummy plug and the cast resin cable socket](image)

**Defects inside insulating parts**

PD values higher than 20 pC could cause the deterioration of solid insulations in the course of time. If the PD intensity is increasing, it may lead to the same development of damage like creeping defects. Figure 10 shows the very characteristic PD pattern of a longitudinal void, which lays in parallel to the electric field lines, of a 52-kV-spacer. The PD magnitudes are direct proportional to the instantaneous value of the voltage starting with the passing through of voltage. The PD pattern is identical in both half waves and has a small variance along the slope. In the PD pattern of a separation between an insert and the cast resin of an insulating spacer a linear slope of the PD values is indicated also, see figure 11. However, the variance along the slope is much higher and the characteristic is more diffuse. The clarification of this failure mode was difficult. Only then at a second spacer the inserts were pulled out by a mechanical appliance for 0.6 mm a similar PD pattern could be generated. This shape was surprisingly very close to that of figure 11.

![Figure 10 PD pattern of a longitudinal void of a 52-kV-spacer](image)

**CONCLUSION**

If factory or site tests of MV GIS are witnessed, it is of great importance that the test procedure and the acceptance criterions have to be agreed before the test. The agreement should include the test arrangement, the maximum permissible limits at which test voltage and the establishment of the PD reading. It was presented some practicable fixings. If admissible failures have to be localized inside the GIS compartment digital and computerized measuring systems are very helpful. Especially the phase resolved PD pattern has proved of value. The presented failures including free potential effects in gas, defects of interface areas and voids in insulating parts show surprisingly characteristic shapes of the PD pattern. These allow the classification to types of PD sources and support the identification of the part concerned.

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**REFERENCES**

[1] IEC 62271-200, 2002, "AC metal-enclosed switchgear and controlgear for rated voltages above 1 kV and up to and including 52 kV "


