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Partial discharge in Gas Insulated Substations (GIS): Effects, Mitigation & Analysis

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Abstract— Gas insulated substations (GIS) have made their entry into the Indian power sector and are now operating nationwide with a high degree of reliability. Gas insulated substation (GIS) are mixture of technologies with interfaces between components providing mechanical, dielectric and current carrying functions. An adequate quality assuring testing process therefore has to be developed which will ensure fulfillment of these requirements during the complete GIS life cycle. It is observed that certain defects in GIS systems generate partial discharge activity prior to complete breakdown of the GIS module. Therefore, partial discharge detection is required for dielectric diagnostics in GIS. This phenomenon thus requires a special attention from the GIS manufacturers worldwide. This paper discusses the analysis of the various available techniques for PD detection. Also the various techniques available for the partial discharge detection in GIS like UHF, Acoustic and standard process as per IEC 60270 are discussed. The prescribed procedure for partial discharge monitoring as per IEC 62271-203 is also discussed. A study for the partial discharge analysis techniques and its applications to different production stages Gas Insulated substations (GIS) from initial production to on-site testing has been conducted is also discussed. Finally this paper helps to conclude upon the most effective technique for PD detection considering the different parameters like cost, engineering and design parameters.

Index Terms— Partial discharge, dielectric diagnostics, UHF technique, Acoustic technique, IEC 60270, IEC 62271-203

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1 INTRODUCTION

Very early in the development of GIS technology, it became clear that there are certain phenomena unique to GIS as compared to air insulated substations. The processes of manufacture, assembly, transportation, erection and operation, generate metallic particle contamination in a GIS leading to the impairment of dielectric strength. Sharp points and protrusions on the electrode surfaces contribute for reduced dielectric strength. Support insulating spacers, which are essential to a gas insulated coaxial bus bar, are exposed to the deleterious effects of free moving metallic particles. Although SF_6 is an inert and stable gas, prolonged sparking and are discharges in the gas, particularly under high moisture content produces corrosive and toxic byproducts that will contribute to corrosion of metallic and insulating components and to the risk of personnel safety. These parameters contribute highly to the increased partial discharge activity in the Gas insulated Substation (GIS). Today, the manufacturers and users of GIS take into account all the above special phenomena to provide GIS equipment with a high degree of reliability and safety in operation. Partial discharge (PD) is a localized dielectric breakdown of a small portion of a solid or fluid electrical insulation system under high voltage stress, which does not bridge the space between two conductors. PD can occur in all the different medias (viz. solid, liquid or gaseous). It often starts in voids in solid epoxy insulation (Epoxy resin insulators of GIS spacers) or due to the impurities in GIS modules.

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2 INCEPTION OF DISCHARGES

Internal discharges occur in the areas of low dielectric strength along the GIS assemblies. Usually the areas are the gas-filled cavities and certain voids in the epoxy resin insulators, these regions of low dielectric strength can break down and cause gaseous discharges afterwards. Analysis shows that majority of PD activity initiates at the interfaces between two dielectrics (viz. gas to solid interface). It is also observed that certain impurities in the SF_6 gas, improper quality of casted conductors and enclosures or even in the voids of the cast epoxy insulators show significant contribution to PD activity in GIS.

The breakdown strength of the cavity depends upon the cavity dimensions and the overall gas pressure in the cavity. According to experiments made by several investigators, the discharge in a cavity in GIS bound by insulating material occurs at approximately the same voltage as between equally spaced metal electrodes. This voltage is for a certain gas given by the Paschen curve. It is obsereved that several factors may cause the breakdown voltage to be lower than predicted. The walls of the cavity may be covered by static charges, either produced when the cavity was formed or left after previous discharges; this may cause up to 20-30% variation in observed results for GIS. Semiconducting layers may occur on the walls of the cavity, more or less short- circuiting the cavity. This may cause a considerable increase of the stress at which the cavity breaks down [7].

2.1 Surface discharge under Sulphur Hexafluoride gas

Surface discharges do not occur only at the edges of electrodes, they may occur as well on insulation surfaces halfway between electrodes (viz. fractures or voids in the conductors or insulators). Insulator surfaces under sulphur hexafluoride gas pressure are sensitive to small particles it is generally seen that contamination on a dielectric surface causes a severe decrease of the flashover voltage and initiates partial discharges. Three important areas of interest for PD analysis are roughness of the surface, semiconducting areas and contaminating particles [7].

3 Partial discharge concept and recurrence of discharges in GIS

A model of GIS, gas filled module for dielectric analysis is shown in figure 1. Study shows that high voltage across the dielectric is V_a, and the voltage across the cavity is V_e. When voltage V_c reaches the breakdown voltage U+, a discharge occurs in the cavity. The voltage then drops to V+ (usually drop takes place in less than 10^{-7} seconds which is an extremely short period compared with the duration of a 50 c/s sine wave, so the voltage drop may be regarded as a step function. After the discharge has been extinguished, the voltage over the cavity increases again. This voltage is given by the superposition of the main electric field and the field of the surface charges at the cavity walls left after the last discharge. The fields counteract one another. When the voltage over the void reaches U+, a new discharge occurs. This happens several times, after which the high voltage V_a over the sample decreases and the voltage V_c drops to U- before a new discharge occurs. In this way, groups of regularly recurrent discharges are observed.

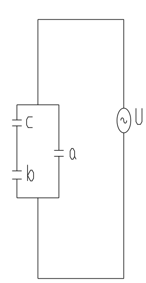

Fig 1: Partial discharge initiation equivalent circuit

4 Diagnostic techniques for PD detection in GIS

The statistics of GIS reliability show that the most common cause of electrical failure is a free metallic particle infusion. Other causes of failure are discharges from any protrusion around which field enhancement occurs, capacitive sparking from an electrode which is not properly bounded to the HV conductor or ground ,voids and cavities in the conductors and insulators etc. It is obsereved that all these defects generate PD activity prior to complete failure. Thus PD analysis holds high importance in insulation diagnostics for GIS.

PD usually takes place locally in gas over a small distance of usually less than 1 mm. In the case of protrusions i.e. Presence of burrs or sharp edges on the assembles, the discharge takes the form of corona streamers, which gives rise to current pulses with very short rise times of the order of 1 ns. In case of voids and poor contacts or movement of conducting particles ,high rates of change of current are observed. In all these cases, the very fast rise time of the PD pulse causes electromagnetic energy to be coupled into the GIS chamber, and the energy dissipated in the discharge is replaced through a pulse of current in the EHV supply circuit. In the case of micro sparks and intense coronas, the discharge is followed by rapid expansion of the ionized gas channel and an acoustic pressure wave is generated. PD is also accompanied by the emission of light from excited molecules and by the chemical decomposition of the gas. The PD, therefore, has many effects, chemical, acoustic, visual etc. and in principle any one of them could be used to detect the presence of the discharge [3].

The different byproducts of partial discharge activity are enlisted below:

1. Emission of light
2. Gas decomposition

This approach initially appears attractive because the chemical decomposition of gas is immune to the electrical interference, which is inevitably present in the GIS and with any steady-state discharge. The concentration of the diagnostic gas should rise in time to a level where it can be detected. The main decomposition product of SF_6 is SF_4, which is a highly reactive gas. It reacts further, typically with traces of water vapor, to form the more stable compounds-thionyl fluoride (SOF_2) and sulfurly fluoride (SO_2F_2). These are the two most common diagnostic gases, and by using a gas chromatograph and mass spectrometer, they can be detected with sensitivities down to 1 ppmv. A simpler but less sensitive alternative is to use chemical detection tubes as discussed in the earlier section. However, in a GIS the diagnostic gases would be greatly diluted by the large volume of SF_6 gas in which they occur, and therefore much longer times would be needed to detect the PD. Therefore, it appears that this approach is not very sensitive to be considered for PD monitoring.

3. Acoustic emission

5 Detection of Partial Discharge as per IEC 60270

In the figure 2 the following are the terminologies used:

U: high voltage supply
Zml: input impedance of measuring system
CC: connecting cable

OL: Optical link
Ca: test object (GIS)
Ck coupling capacitor
CD: coupling device
MI: Measuring instrument

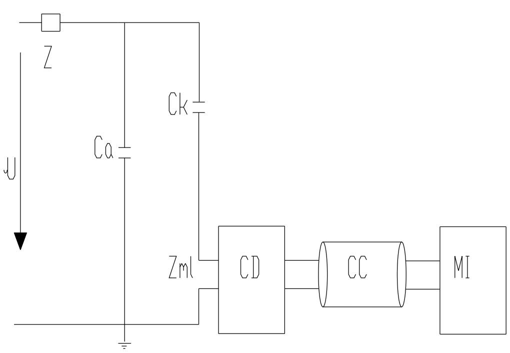

Fig 2: Partial discharge detection test setup as per IEC 60270:2000

For measurement of PD as per IEC 60270, the applied power-frequency voltage is raised to a pre-stress value which is identical to the power-frequency withstand voltage test and maintained at that value for 1 min. Partial discharges occurring during this period are disregarded. Then, the voltage is decreased to a specific value depending on the configuration of equipment and system neutral for partial discharge measurement. The extinction voltage is recorded [6].

6 NON ELECTRICAL TECHINIQUES FOR PD DETECTION

Nonelectrical methods can also be used for detecting the presence of discharges in GIS assemblies. Nonelectrical detection methods cannot be used for measuring the discharge magnitude. Two of the nonelectrical methods, however, are useful expedients for locating discharges. The nonelectrical phenomena used for discharge detection are, in order of increasing importance:

- Chemical transformation.
- Gas pressure.
- Heat.
- Sound.
- Light.

Only the last two are of practical importance for measurements of PD activity practically in GIS.

6.1 ACOUSTIC EMISSION

It is seen that pressure waves are caused by particles bouncing on the GIS enclosure floor. These signals in GIS have a broad bandwidth and travel from the source to the detector by multiple paths [1]. The signals originating at the enclosure wall propagate as flexural waves at velocities, which increase with the square of the signal frequency to a maximum of about 3000 m/s. Propagation through the gas is at the much lower velocity of 150 m/s, and the higher frequencies in the signal are absorbed quite strongly. The different propagation velocities of the waves as it passes through various materials and the reflections it experiences at boundaries between them; give rise to a complex signal pattern. The acoustic emission sensors attached to the outside of the chamber can pick this up. The acoustic signal from a particle bouncing on the chamber floor is characterized by a signal not correlated with the power frequency cycle. It also has other features, such as the crest factor (ratio of the peak to rms value) the impact rate and the ratio of the lift off/fall down voltages, from which the particle shape and its movement pattern can be inferred. Other sources of discharge may be identified in a similar way from their own characteristics. One advantage of acoustic measurements is that they are made non-intrusively using external sensors, which may be moved from place to place on the GIS. Because of the rather high attenuation of the signals, the sensors should preferably be on the chamber containing the source. This is itself gives the approximate location of the defect, but a more accurate position can be found within 1 cm using a second sensor and a time of flight detection method [1].

6.2 VISUAL DETECTION

The human eye is very sensitive to light after being in the dark for about a quarter of an hour. Nevertheless, the smallest detectable discharge is more easily found in the region of 500 to 1000 pC than at 1 pC.This technique however usually not applied in case of GIS.

6.3 PHOTOGRAPHY

Surface discharges may be detected very well by photography. The sample is placed in a dark room, and the shutter of the camera is opened for some time during which high voltage is applied to the sample. In addition, the sample is illuminated for a short time so that a photograph is obtained on which a picture of the discharges is superimposed on the sample. The first surface discharges that appear are smaller than 3 pC. At higher voltages discharges increase.

It follows from these tests that small discharges of about 1 pC may be detected. The required exposure time varies with the discharge magnitude, and an exposure time of several hours is required for small discharges below 10 pC. The exposure time depends also on the concentration of the discharges, e.g. corona discharges concentrated around the point of a needle in the order of 20 pC could be recorded in a few minutes. A relationship between discharge magnitude and brightness or size of the picture is difficult to establish. The concentration of the discharges, their repetition frequency and possible motion, affect this relationship.

The location of discharges in this way is excellent better than can sometimes be obtained with any other method. When doing research and development work in high-voltage engineering it may be fruitful to devise experiments in such a way that discharges can be photographed [7].

6.4 PHOTOGRAPHY

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6.5 THE PHOTOMULTIPLIER

The sensitivity of light detection can be improved appreciably by using a photomultiplier. As the radiation emitted by a discharge originates mainly from the ultraviolet part of the spectrum, a photomultiplier is a suitable detector, because of its high gain and good sensitivity in the ultraviolet region [7].

6.6 PRINTOUTS

After noise suppression, the number of pulses is printed out as for a small surface discharge.The PD activity is then analysed based upon this printed data.

7 DETECTION OF PARTIAL DISCHARGE BY UHF METHOD

The current along the PD path rises in about 1 ns and contains frequency components which range from 0 to 1000 MHz. They excite the GIS chambers into various modes of electrical resonance, which because of the low losses in these chambers may persist for about 3 μs. The resonances are indicative of PD activity and are picked up by sensors installed in the GIS. A spectrum analyzer is used to measure the frequency components of the picked up signals. Before a PD measurement is carried out, a spectrum of the background noise is scanned as a reference spectrum. The disturbances are therefore known and can be generated from the PD signals during PD measurement. The main advantages of the UHF method are its high sensitivity and the ability to locate discharges accurately by the time of flight measurements. It can be used readily in continuous and remotely operated monitoring systems[8].

7.1 UHF signals due to partial discharge

A GIS installation consists of a network of coaxial transmission lines, which act as a waveguide for UHF signals, with an inherently low loss. In the absence of barriers and discontinuities, attenuation at 1 GHz in a waveguide of this size (typically 0.5m diameter) would be only 3 to 5 dB/km. In practice, multiple reflections at discontinuities within the GIS chamber cause a reduction in signal strength, which has been observed to be in the region of 2 dB/m. This reflection can cause resonance to appear, such as that setup between dielectric barriers [2].

The usual mode of signal propagation associated with the coaxial line is the TEM mode, in which the electric and magnetic field components are transverse to the direction of propagation. In normal applications, the frequency of operation is kept below the region of the cutoff frequencies at which higher order TE and TM modes begin to propagate. This prevents leakage to other modes, which could be caused by asymmetries in the line, thus ensuring non-dispersive propagation, a normal requirement for the maintenance of signal fidelity.

In the case of a GIS, the coaxial structure is a consequence of the need to contain the gaseous insulation, and its dimensions are accordingly defined by the voltage requirements. At UHF (300 to 3000 MHz), the GIS dimensions are such that the TE and TM modes of propagation cannot be neglected. Excitation of a purely TEM mode signal would require symmetrical excitation of the waveguide, whereas the location of a PD current pulse is always asymmetrical with respect to the coaxial cross-section and therefore couples strongly with higher order modes. These modes are closely related to those of the hollow cylindrical waveguide, and are therefore capable of propagating across gaps in the HV busbar, which would block TEM signals, for these reasons, it is necessary to account for all modes of propagation within the measurement bandwidth to adequately describe the UHF signal resulting from a PD.

Experience in interpreting UHF data shows that although the point on wave of the discharge pulses remains the basis for interpretation, displaying only the peak discharge magnitudes given only a limited amount of information. This is also the case when studying the breakdown caused by a free particle, where an increase in the time interval between bounces indicates that the particle may be moving closer to the HV conductor and is approaching the condition where breakdown can occur[8].

7.2 PD measurements by UHF method

In general, it is stated that the UHF method possesses a high sensitivity for PD in GIS. Measurements have been made with fixed protrusions, moving particles, particles on spacers, gas filled cavities and floating electrodes as defects shows the location of each defect and the fully enclosed test set-up. The test set-up consists of a metal clad 325kV test transformer, which is connecte4d to commercial GIS components for 362 kV rated voltage (conductor radii 66 mm/commercial GIS compartments are filled with SF_6 gas at a rated pressure of 197 mm). The GIS compartments are filled with SF_6 gas at a rated pressure of 420 kPa. The peak values of the rated in-service field strength for this apparatus En is equal to 40.8 kV/cm at the inner conductor and equal to 13.67 kV/cm at the outer enclosure. For the IEC 270 method, a 60 pF coupling capacitor was built into one compartment. The coaxial coupling capacitor was connected to a standard PD detector (40….499 kHz) providing a reference with a noise level equivalent to less than 1 pC. A 10- cm diameter UHF sensor mounted in an earthed switch flange picked up the UHF PD signals. The equipment for the UHF method consists of a spectrum analyzer and a preamplifier with a gain of 35 dB [2]. The spectrum analyzer scans the spectrum of a signal continuously Partial discharge activity is indicated by peaks in the measured spectrum.

8 PD DETECTION LOCATIONS

8.1 During Design and Development

Most of the quality assurance activities take place during the design and development procedure. Initial testing is applied for design verification and later for type testing. These tests are conducted in well equipped laboratories using sensitive and sophisticated measuring systems. All kinds of PD measurement methods are used during design and development depending on the specific problem.

8.2 During Factory Testing.

The purpose of routine tests in the factory is to confirm that the GIS have been manufactured in accordance with the specification established during the development phase. The aim of routine testing is to detect as many faults as possible since test and repair costs increase substantially during erection or in serviced. Besides visual inspection and cleanliness checks, PD measurement according to IEC 60270 is done for each shipping unit. Fault location poses no problems since only a relatively small number of units are tested. The faulty component of the GIS can be identified easily by a few switching operations. Occasionally, acoustic measurement is used to identify mechanically loose components.

8.3 During On-site Testing

On-site tests should confirm that no failures have been introduced after factory testing. Vibration, shocks and pollution may slightly damage the insulation during transport and erection. Two methods are recommended for on-site testing, namely the acoustic method and the UHF method. The advantages of the UHF method have been discussed in the earlier section.

8.4 Periodic Checking and Condition Monitoring

Fault statistics prove that the modern GIS are highly reliable, 30 years of experience has shown that C IS requires negligible maintenance. In the case of an actual in-service fault, PD intensity may rise very fast that measures to prevent a flashover may not be possible during that short time. Therefore, continuous PD monitoring systems are used. Faults in GIS normally occur during the first few years of service. Thus, periodic PD checking during this period can increase reliability. Acoustic PD measurement is fast and relatively cheap; PD sensors together with general measurement techniques also offer a rapid and convenient option, when used in conjunction with other tests

9 APPLICABILTY OF TECHNIQUES AND TECHNIQUES TO REDUCE PD ACTIVITY IN GIS

Majority of the GIS manufactures around the globe are now opting for UHF based PD analyzers due to their compactness and fair degree of accuracy in output. The application of Acoustic techniques also hold good for GIS but the amount of accuracy obtained from this technique for measurement is lower than UHF technique. Both UHF and Acoustic techniques are finding a good applicability in on site partial discharge testing for GIS due to low cost of apparatus. The following pi chart represents the applicability of various techniques for PD analysis in terms of their percentage use.

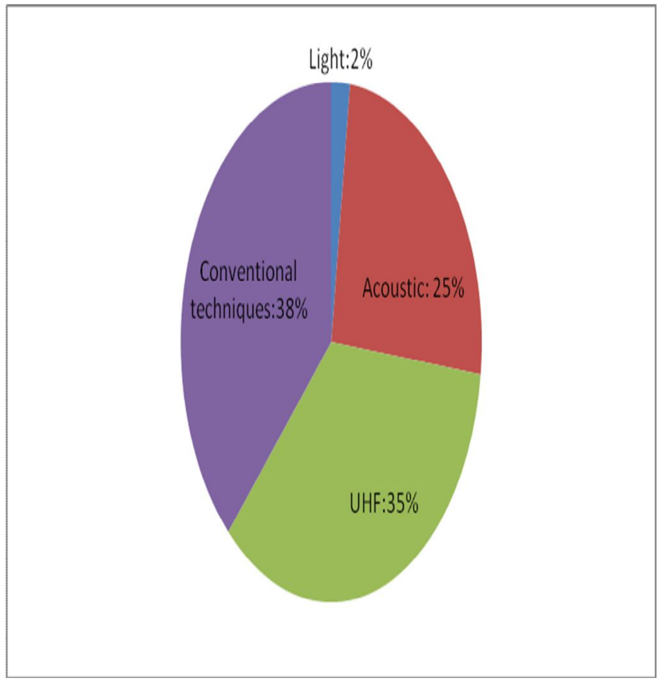

Fig 3: Analysis of applicability of PD detection techniques
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The PD activity in GIS can be considerably reduced by improving the overall process of assembly of modules. It has been observed that majority of occurrences take place due to contamination present in the SF_6 gas itself. Also the defects in castings of conductors and epoxy resin insulators are prime locations of PD activity. It is thus required that the insulation should be the prime focus for reducing the overall failures due to the PD activity.

10 CONCLUSION

The GIS technology application is gaining huge momentum in Indian power market gradually. High precautions are thus needed to be taken during the material selection, assembly, testing and erection of the GIS. The PD activity should be analyzed and reduced considerably in order to improve the life cycle and the reliability of the existing Gas Insulated substations.

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