

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. A common feature of all defects in GIS systems is that they generate partial discharge activity prior to complete breakdown. Therefore, partial discharge detection is the basis of all 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.

Keywords— Acoustic technique, dielectric diagnostics, Partial discharge, UHF technique, IEC60270, IEC 62271-203.

I. 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 SF₆ 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. In electrical engineering, 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. While a corona discharge is usually revealed by a relatively steady glow or brush discharge in air, partial discharges within solid insulation system are not visible. PD can occur in a gaseous, liquid or solid insulating medium. It often starts within gas voids, such as voids in solid epoxy insulation or bubbles in transformer oil. Protracted partial discharge can erode solid insulation and eventually lead to breakdown of insulation.

II. INCEPTION OF DISCHARGES

Internal discharges occur in inclusions of low dielectric strength. Usually these are gas-filled cavities, but oil-filled cavities, but oil-filled cavities also can break down and cause gaseous discharges afterwards.

Analysis shows that majority of PD activity initiates at the interfaces between two dielectrics. It is also observed that certain impurities in the SF₆ gas, improper quality of casted conductors and enclosures or even in the voids of the cast epoxy insulators.

The breakdown strength of the cavity depends on its dimensions and is governed by the type of gas and the gas pressure in the cavity. According to experiments made by several investigators, the discharge in a cavity bounded 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. The Paschen curve shows the breakdown voltage of a gap as a function of electrode spacing times gas density. Although the gas and the gas pressure may be unknown at the start of the cavity, in the long run it will adopt the gas and the gas pressure of the surrounding medium. This is caused by diffusion, so that, for example, cavities in epoxy insulators in sulphur hexafluoride gas systems in the long run will contain sulphur hexafluoride under pressure and cavities in polyethylene-insulated cables will contain air at 1 atmosphere.

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% variation. 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].

3.1 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. Insulator surfaces under sulphur hexafluoride gas pressure are sensitive to small particles it is generally known that contamination of a dielectric surface causes a severe decrease of the flashover voltage and initiates partial discharges. Brockman et al. has made an extensive study of these phenomena. Three variables are of interest here roughness of the surface, semiconducting areas and particles [7].

III. PARTIAL DISCHARGE CONCEPT AND RECURRENCE OF DISCHARGES IN GIS

A model of GIS gas filled modules is shown in figure 1. Study shows that high voltage across the dielectric is V_a , and the voltage across the cavity is V_c . 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} 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 found.

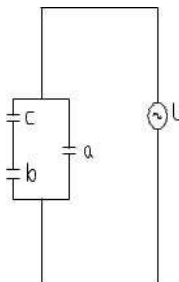


FIG 1: Partial discharge initiation equivalent circuit [Source: Reference 7]

IV. 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. 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, etc. The common feature of all these defects is that they generate PD activity prior to complete breakdown. Therefore, PD detection is the basis of all dielectric diagnostics in GIS.

A PD is the localized breakdown of gas over a small distance of usually less than 1 mm. In the case of protrusions, 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. Discharges in voids and micro sparks associated with poor contacts or with the movement of conducting particles, are also characterized by high rates of change of current. 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 SF₆ is SF₄, which is a highly reactive gas. It reacts further, typically with traces of water vapor, to form the more stable compounds-thionyl fluoride (SOF₂) and sulfurly fluoride (SO₂F₂). 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 SF₆ 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

V. DETECTION OF PARTIAL DISCHARGE AS PER IEC 60270

In the figure 2 the following are the terminologies used:

- U: high voltage supply
- Z_{ml}: input impedance of measuring system
- CC: connecting cable OL: Optical link Ca: test object
- C_k coupling capacitor CD: coupling device MI: Measuring instrument

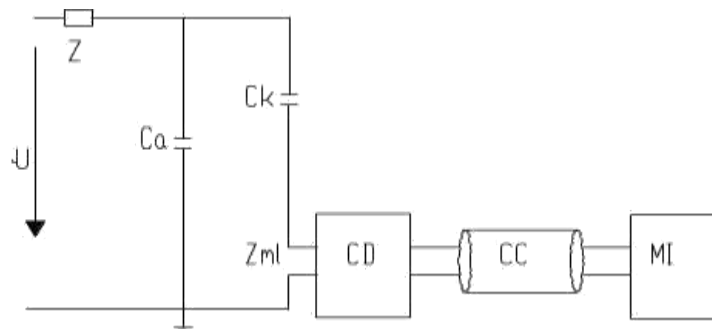


FIG 2: Partial discharge detection test setup as per IEC 60270:2000

VI. NON ELECTRICAL TECHNIQUES FOR PD DETECTION

Nonelectrical methods can be used for detecting the presence of discharges. 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.

6.1 Acoustic emission

Acoustic signals arise both from pressure waves caused by particles bouncing on the chamber floor. The signals in GIS have a broad bandwidth and travel from the source to the detector by multiple paths [1]. Those originating at the chamber 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 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

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.

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 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. A pulse sampling device is used, after the amplifier, to distinguish between wanted and unwanted signals. There are two types of unwanted pulses:

Noise pulses from the photocathode Those from the dynodes.

Dynode pulses are smaller than those caused by discharge pulses and can easily be eliminated by using a pulse height discriminator.

Cathode-originated noise pulses can be recognized, as there is no correlation between these pulses and the phase of the test voltage. On the other hand, there exists a distinct correlation between the phase of the wanted photo pulses and the phase of the test voltage, although the correlation factor is smaller than unity. A digital counting system can achieve this noise suppression using a flow scheme [7].

VII. DETECTION OF PARTIAL DISCHARGE PER IEC 62271-203 FOR GAS INSULATED SUBSTATIONS (GIS)

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 defined in Table 8.1 depending on the configuration of equipment and system neutral for partial discharge measurement. The extinction voltage is recorded [6].

VIII. 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 μ s. 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.

8.1 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.

8.2 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 connected to commercial GIS components for 362 kV rated voltage (conductor radii 66 mm/commercial GIS compartments are filled with SF₆ gas at a rated pressure of 197 mm). The GIS compartments are filled with SF₆ gas at a rated pressure of 420 kPa. The peak values of the rated in-service field strength for this apparatus E_n 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.

IX. 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.

REFERENCES

- [1] G.Eason, B.Noble, and I.N.Sneddon, "Uncertain integrals of Lipschitz-Hankel type involving products of Bessel functions," *Phil. Trans. Roy. Soc. London*, vol. A247, pp.529-551, April 1955. (references)
- [2] J.Clerk Maxwell, a Treatise on Electricity and Magnetism, 3rd ed., vol.2. Oxford: Clarendon, 1892, pp.68-73.
- [3] I.S.Jacobs and C.P.Bean, "Fine particles, thin films and exchange anisotropy," in *Magnetism*, vol. III, G.T.Rado and H.Suhl, Eds. New York: Academic, 1963, pp.271-350.