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Study on Effect of Metallic Particle Contamination on the Break Down Voltage in Air Insulated System

Sreenath K[1] and B. Rajesh Kamath[2]
[1]*Assistant Professor, Department of Electrical and Electronics Engineering, Sri Siddhartha Institute of Technology, Tumkur, Karnataka, India*
[2]*Professor, Department of Electrical and Electronics Engineering, Sri Siddhartha Academy of Higher Education, Tumkur, Karnataka, India*

[1]*Corresponding Author: sreenathk@ssit.edu.in*

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ABSTARCT
The development of compressed gas insulated switchgear (GIS) and gas insulated transmission line (GITL) have progressed rapidly worldwide because of the excellent insulating and arc quenching properties of Sulphur Hexa Fluoride (SF_6) gas. However, free conducting particles lower the corona onset and breakdown voltage of these systems. Under the action of the applied electric field in a coaxial geometry, conducting particles acquire charge and lift off from the outer enclosure when the electrostatic force from the electric field becomes equal or larger than the force due to gravity. Metallic particles move randomly in gas insulated systems under the action of electric field. The particle may remain in mid-gap or stay around the central conductor for several voltage cycles. Particle movement therefore plays a crucial role in determining the voltages withstand capability of GIS/GITL systems.

Metallic conductors in gas insulated system are protected with a dielectric covering to mitigate the problem of particle initiated breakdown. Dielectric covering reduces the effect of surface roughness of conductors/duct and also increases the dielectric strength of the insulation system. Several researchers have developed computational models for particle movement in co-axial electrode system. These models however make assumptions about the particle charging process and charge exchange mechanism when a moving particle returns to the dielectric coated enclosure. Many experimental techniques have been proposed by researchers to explain the movement of particles in a co-axial bus-duct system. The experimental observations are also compared with the computational model. However, particle contamination in GIS is not fully understood and explained satisfactorily. Though SF_6 is accepted universally as the best gaseous dielectric, it is considered to be a Greenhouse Gas. Hence research worldwide focuses on alternatives to SF_6 gas without making much compromise on dielectric and other properties. In this context, use of SF_6-N_2 gas mixtures, containing less than 10% of SF_6 gas is seen as a viable alternative for GITL. Hence the present study was taken up with this motivation.

Keywords: *SF_6-N_2 gas mixtures, breakdown voltage, metallic particles, computational models*

I. INTRODUCTION

Background

The Economic development of any Country depends upon availability of electrical power at an affordable price. Availability of power is the foundation of Industrial growth which in turn contributes to the Economy of the Country. India is one of the faster growing economies of the world and ranks sixth in the power consumption after USA, China, Russia, Japan and Germany (Kumarappa and Monishaa 2009). As per the Ministry of Power, Government of India, India has been able to achieve an economic growth rate of 8% per annum during last few years and is poised to achieve double digit growth rate. At the same time Industrial growth rate has been recorded over 9% rate consistently in last few years. The power sector at a glance "ALL INDIA" (Source CEA, July 2009) shows that the total installed capacity from different sources is 1,51,073.41 MW, of which 65% is from Thermal, 25% from Hydro, 3% from Nuclear and 8% from Renewable Energy Sources. The Indian government has set an ambitious target to add approximately 78,000 MW of installed generation capacity by 2012 (Kumar 2007). The total demand for electricity in India is expected to cross 950,000 MW by 2030. The Government of India also has an ambitious mission of POWER FOR ALL BY 2012. This mission would require that our installed generation capacity would be at least 200,000 MW by 2012 from the present level of 151,073.41 MW. Power requirement will double by 2020 to 400,000MW. (Electricity Sector in India, Wikipedia).

II. RECENT DEVELOPMENTS IN POWER SECTOR

In the present day context, with the advent of many technical developments, the transmission of large amount of power over long distances is best accomplished by using Extra High Voltage and Ultra High Voltage transmission. In recent years significant advances have been made in the design and development of high voltage transmission and distribution systems. Transmission voltages of 1200 kV ac and ±800 kV dc transmission are planned in India for this purpose. Higher voltages are also required for basic research in physics and other branches of Engineering. In industrial and consumer equipment, as well as in military applications and in medicine, high voltages or high electric fields are extensively used. For both energy security and climate change policy reasons, developing countries including India, are increasingly emphasizing the need to undertake major and rapid restructuring of their energy system. The combustion of fossil fuels for electricity generation has been identified as one of the major contributors to Greenhouse gas (GHG) emissions (CO2 - 10.9 Gt). Hence, replacing thermal generation by renewable alternatives is considered to provide a significant contribution towards reducing the CO2 emission (Page et al. 2009). Hence with threat of global climate change, policy makers all over the world have made regulations which promote renewable energy technologies.

III. GAS INSULATED SYSTEMS – EMERGING TECHNOLOGY IN INDIA

Gas insulated substations have been a major innovation in Power Transmission and Distribution with proven reliability and maintenance free operation. The ever-increasing demand for electrical power and the need for upgrading power transmission systems have led to rapid development in GIS (Gas Insulated Systems). GIS have become a major component of the power systems network at all high and extra high voltage levels with a broad range of applications. The application of GIS has increased rapidly over the past few decades all over the world for their advantages of reduced weight, size, volume and higher operating stresses. GIS have also performed successfully 29 under adverse service conditions and are protected from pollution. Compared to air insulated systems, GIS have many inbuilt advantages like (1) significant savings in land due to compact construction (2) enhanced personnel and operational safety (3) high reliability and (4) reduction in man power requirements for maintenance. Sulphur Hexa Fluoride (SF6) gas exhibits many properties that make it suitable for equipment and apparatus utilized in the transmission and distribution of electric power. Presently SF6 gas is widely used in equipment ranging from GIS, GCB and GITL (CIGRE TF01 2003). SF6 gas is one of the most extensively used gases in GIS. It is also more comprehensively studied molecular gases to date, largely because of the superior electrical insulation properties. It is a man made gas that became commercially available in 1947 (L. G. Christophorou et al. 1997). SF6 gas has been regarded as ideal gaseous insulation for electrical power equipment since the 1960’s due to its basic physical and chemical properties such as inertness, non-toxicity, non-flammability, non explosive nature and thermal stability. SF6 gas is a strong electronegative gas both at room temperature and at temperatures above ambient, which principally accounts for its relatively high dielectric strength. SF6 is non-ignitable and non-flammable gas which is self healing after electrical breakdown and no conducting decomposition products such as amorphous Carbon are deposited as a result of continuous arcing (Christophorou 1982). Due to its excellent physical and chemical properties SF6 has become the most favorite insulation gas used in GIS. SF6 is a chemically inert gas (ICF consulting 2002) and has dielectric strength of about three times that of air at atmospheric pressure (Brunt and Herron 1990). It has good heat transfer properties and it readily recombines itself when dissociated under high gas pressure conditions in an electrical discharge or an arc. Most of its stable decomposition byproducts do not significantly degrade its dielectric strength and are removable by filtering. Besides its good insulating and heat transfer properties, SF6 when contained has a relatively high pressure at room temperature. It is easily liquefied under pressure at room temperature, allowing storage in metal cylinders.

Greenhouse Effect

The Greenhouse Effect is the process in which the emission of infrared radiation by the atmosphere warms a planet's surface. The name comes from an incorrect analogy with the warming of air inside a greenhouse compared to the air outside the greenhouse. The greenhouse effect was discovered by Joseph Fourier in 1824 and first investigated quantitatively by Svante Arrhenius in 1896. Scientists and researchers at a meeting reported (Bangladesh news paper ‘Daily Star’ on 09.09.2009) that the industrial and richer nations are responsible for the climate change and they should take effective decisions right now or face the adverse impact of climate changes and other environmental degradations. Atmospheric measurements show that the Carbon dioxide concentration in the atmosphere is currently 385 parts per million (ppm) and is rising at a rapid rate (Melinda and Pieter 2008). As per the report from Nature Interactions (weekly journal, U.K, April 2009), more than 100 countries have adopted a global warming limit of 20 C or below (relative to pre-industrial levels) as a guiding principle for mitigation efforts to reduce climate change risks, impacts and damages. However, the green house gas emissions corresponding to a specified maximum warming are poorly known owing to uncertainties in carbon cycle and the climate response. In spite of its good electrical insulation properties, questions regarding use of SF6 gas and its impact on global atmosphere have been intensely debated and discussed all over the world. The environmentalists and power Engineers have seriously considered the contribution of SF6 gas to ozone depletion and the global green house effect. SF6 is believed to form highly toxic and corrosive compounds when subjected to electrical discharges. Non polar contaminants like air, CF4, are not easily removed from it. The breakdown voltage of SF6 is sensitive to water vapor, conducting particles and conductor surface roughness and it exhibits a non ideal gas behavior at low temperatures that can be encountered in environment, i.e., in cold climatic conditions (about -500C), SF6 becomes partially liquefied. SF6 is also an efficient infrared absorber and due to its chemical inertness is not rapidly removed from the earth's atmosphere. SF6 is reported to be one of the strongest man made greenhouse gases (Christophorou and Van Brunt 1995, Piemontesi et al. 1998 and Piemontesi et al. 1999). 31 SF6 has been found to be an efficient absorber of infrared radiation at wavelengths near 10.5 µm (Edelson and McAffe 1951). Unlike most other naturally occurring green house gases, SF6 is largely immune to chemical and photolytic degradation and therefore its contribution to global warming is expected to be cumulative and virtually permanent. Increasing commercial use of SF6 has resulted in its increased concentration in the atmosphere. The environmental problem of SF6 gas has been regarded as the key issue in the field of HV engineering since the meeting of the Inter-Government Panel on climate change/ Conference of parties 3 (IPCC/COP3) in 1997. Rinsland et al. (1993) have shown that the amount of SF6 in the atmosphere has been rising at a rate of approximately 0.9% per year.

Need for Gas Mixtures

Due to the various drawbacks of SF6, there is a strong urge worldwide that users actively pursue means to minimize the release of SF6 into the environment. The fear is about excessive release of SF6 gas into atmosphere and the Power Industry inherently bases its possible contribution to the greenhouse effect on the projections about the future consumption of SF6 gas. Since 1980s intensive research efforts had been made to find a new gas as a substitute for SF6 in overall evaluations that rated items such as insulation characteristics, boiling point and toxicity etc. (Tukama 1981 and Christophorou et al. 1997). Though many studies have been carried out to search new insulation gases or gas mixtures (Okabe et al. 2001) as alternative to SF6 gas, the results of investigations by Baumgartner (1974), clearly shows that nitrogen at high pressure is one of the most pollution free insulating gases for technological use in high voltage equipment. The dielectric strength of nitrogen could be increased by the addition of a small amount of electronegative gas. As a further advantage, the N2/SF6 gas mixtures, with small amounts of SF6, have lower boiling temperatures than pure SF6. Sabot (1999) is also of the opinion that SF6/N2 gas mixtures are expected to be possible candidates in place of pure SF6 gas. As reported by Neumann (1998), diluted SF6 mixtures promise a reduction of the environmental impact and are therefore of particular interest. Due to the particularly high insulation synergism, already 10% of SF6 leads to a doubling of insulation performance 32 of pure N2 in a defect free homogeneous field (Chakravorti 1997). Various aspects of the insulation performance of SF6/N2 mixtures have been published. As per Hunter and Christophorou (1984), SF6/N2 gas mixtures have excellent physical and chemical properties as well as much less global warming potential, lower cost and lower liquification temperature, compared with pure SF6 gas, while still retaining excellent electrical insulation performance. Volcker and Koch (2001) are of the opinion that the reduction of SF6 and replacement with N2 gives a cost advantage if longer distances of kilometers length of GITL are covered. Salge et al. (2000) are of the opinion that SF6/ N2 (10:90) mixture can be strongly electronegative gas and is considered as a good combination for HV application. With this background and keeping the future needs of GIS technology, this study was initiated. The next chapter discusses the state of art and a review of literature is presented.

Electrical Breakdown in Air under AC and DC

The circuit diagram for experiments to determine the breakdown voltages (BDV) in air for different electrode configurations is shown in Fig. 4.1 for ac and Fig. 4.2 for dc. The ac source used is 50 kV (rms) and for ± dc, it is 75kV. An input voltage of 440 V ac is given to a step up transformer through a synchronous motor (for smooth variation). The secondary output of transformer is fed to the test object. The input voltage to the transformer can be in increased or decreased as per requirements of the experiments in steps of 1kV/sec. Required dc voltage can be obtained after passing the output voltage through a rectifier unit and a filter capacitor to reduce ripple. A water resistor is used to control the current in the circuit. There is provision for tripping of electrical circuit at the instant of breakdown. In addition, 100 kV ac and 100 kV dc breakdown equipments were used for experiments requiring higher voltages.

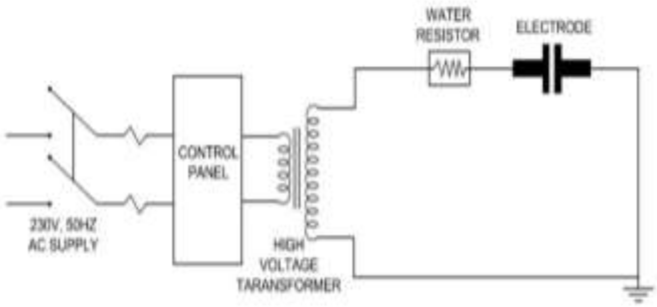


Figure 1: Circuit connections for the measurement of BDV under HVAC

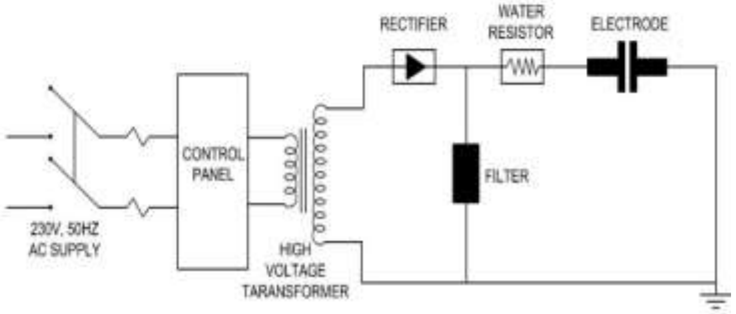


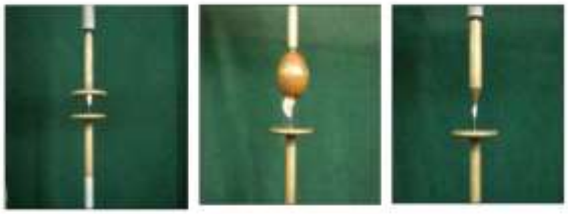
Figure 2: Circuit connections for the measurement of BDV under HVDC

(a) Plane-Plane Configuration (b) Sphere-Plane Configuration

(c) Rod-Plane Configuration (d) Point-Plane Configuration

Figure 3: Metallic particle placed horizontally (Center/Edge) on grounded plane electrode

Figure 4: Electrode configurations used for the experiment



(a) Plane-Plane (b) Sphere-Plane (c) Point-Plane

(d) Plane-Plane (e) Sphere-Plane (f) Point-Plane

Figure 5: Metallic particle placed vertically (Center/Edge) on grounded plane electrode showing discharges at breakdown from HV to ground electrode

Basic Studies

Air at atmospheric pressure is the most common gaseous insulation. The breakdown of air insulator is of considerable practical importance to the design engineers of power transmission lines and HV apparatus. The breakdown of insulation was noticed as early as 1912 by Rayners. With the help of a model circuit, the sudden nature of the discharges was demonstrated. A reasonably complete mechanism for the eventual breakdown was developed by Robinson (1935). Later, Austen and Whitehead (1941), proposed a capacitance analogue circuit to describe the discharge behavior of insulation. Meek and Crags (1978), Naidu and Kamaraju (1990), Khalifa (1990), Kuffel et al. (2000) have dealt in detail, the phenomenon of breakdown of air under different electrode configurations. Kobayashi (1997), Schumann et al. (2003) and Sato and Koyama (2003) have reported that the breakdown characteristics of air are highly dependent on the electrode surface conditions, electrode materials and other factors. Breakdown characteristics under non-uniform field conditions form an important part of study from utility and application point of view (Nandagopal 1976). Under vacuum, works of Leader (1953), Tarasova and Kalinin (1964), Rabinowitz and Donaldson (1965) and Latham and Braun (1970) indicate that in the range of small gap lengths of less than 1 mm, the breakdown voltage of non uniform gap system with the high voltage electrode as the anode, is much higher than that of a plane parallel gap or of uniform field electrode system at a corresponding gap length. Maglaras and Topalis (2009) have exclusively determined through simulation analysis on the prediction of corona and breakdown behavior of a given air Rod-

Plate gap to a given voltage and have deduced that the effect 34 of grounding also influences the corona current, depending upon the polarity of the applied voltage. In the larger air gaps, the corona current makes the field less in-homogeneous, increases the BDV proportionally and overlaps the effect of grounding in long enough air gaps. The influence depends on the polarity of the voltage and the length of the gap.

Compressed Gas Insulation

In spite of air being the best gaseous insulant for high stresses, other forms of insulation like oil, vacuum and compressed gases are used. The bigger advantage of compressed gases is that by increasing the pressure, it is possible to increase the breakdown strength without changing the overall dimensions of the HV system and apparatus. But pressure withstand capability and safety impose limitations on compressed gas insulation. However, the biggest advantage is the breakdown strength of SF6 gas as compared with air which is about 3 times under uniform field conditions. It will reduce depending on the local field conditions, pressure, moisture level and impurities in SF6. Hence, for pure SF6 and gas mixtures like SF6-N2, SF6-CO2 etc, behavior of insulation under metallic particles is very critical.

IV. ELECTRIC FIELD SIMULATION USING FEM

Finite Element Method (FEM), also known as finite element analysis is a numerical technique for finding approximate solutions of partial differential equations (PDE) as well as those of integral equations. The solution approach is based either on eliminating the differential equation completely (steady state problems), or rendering the PDE into an approximating system of ordinary differential equations, which are then numerically integrated using standard techniques such as Euler’s method, Runga-Kutta, etc. The development of FEM began in the middle to late 1950’s for airframe and structural analysis and in the 1960’s for use in civil engineering. The finite element method was provided with a rigorous mathematical foundation in 1973 and since then it 41 has been generalized into branch of applied mathematics for numerical modeling of physical system in a wide variety of engineering disciplines like electromagnetism. FEM is pre-eminent tool for the modeling of physical systems. FEM software provides a wide range of simulation options for controlling the complexity of both modeling and analysis of a system.

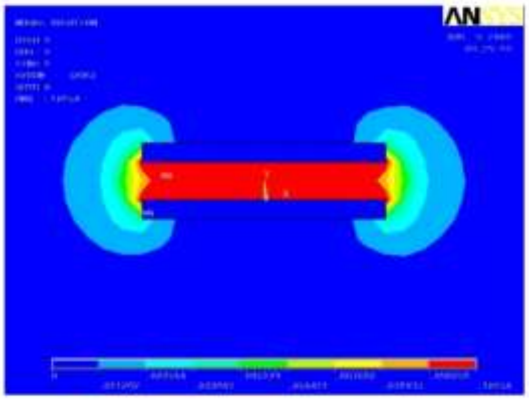


Figure 6: of 10 mm under Plane-Plane electrode configuration

Table 1: Metallic particles used for the experiment Electrical breakdown in air under ac and dc

Copper		Aluminum		Silver	
Size in mm	Len in mm	Size in mm	Len in mm	Size in mm	Len in mm
1.5	10	1.5	10	1.5	10
2.5	10	2.5	10	2.5	10
4	10	4	10	4	10

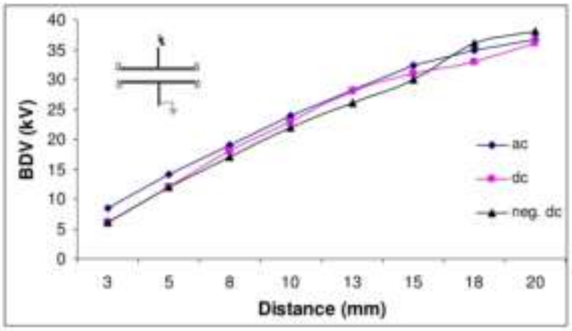


Figure 7: Variation of BDV under ac and ±dc in air across plane-plane electrode.

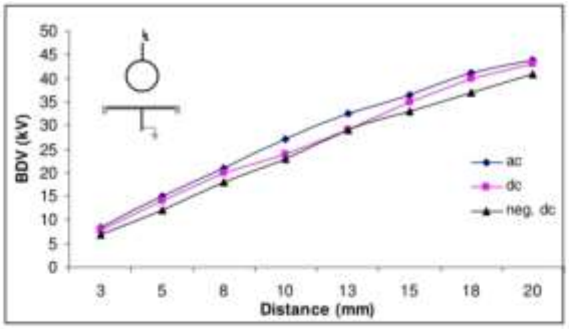


Figure 8: Variation of BDV under ac and ±dc in air across plane-sphere electrode.

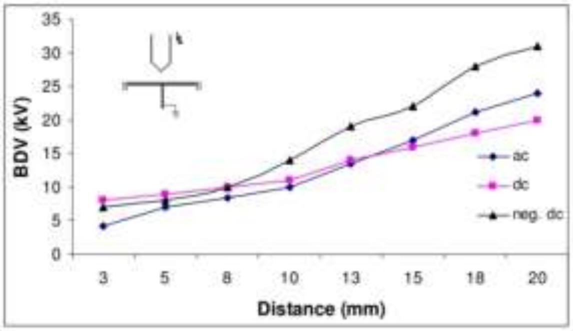


Figure 9: Variation of BDV under ac and ±dc in air across plane-point electrode.

V. CONCLUSION AND SCOPE FOR FUTURE WORK

Breakdown voltages of air and SF_6-N_2 (10:90) gas mixture have been investigated in this work. In addition, the effect of metallic particle contamination has been studied under uniform, non-uniform field configurations and in a co-axial geometry. Experimental results were also analyzed in case of breakdown across cylindrical spacers. The effect of dielectric covering of electrodes with polypropylene film, and presence of metallic particles trapped underneath it has also been studied. Further, studies have been carried out on the co-axial duct with and without particles and with polypropylene covering of the electrodes in SF_6-N_2 gas mixtures. The analysis of experimental results and its discussions in retrospect has revealed that the aims and objectives set forth for taking up the study have been met. In this chapter, section wise summary and conclusions of the study and scope for further work are highlighted.

Summary of Air Breakdown Studies

- Studies on breakdown of air under uniform field configuration shows that the electric field distortion is limited.
- The presence of contamination is evident at very long lengths of, relative to electrode diameter predominantly under negative dc.
- Under Plane-Plane electrode configuration, the effect of either vertically or horizontally fixed metallic particle on cylindrical of longer lengths, is almost same.

- Irrespective of the electrode configuration, the BDV of air gap having a long cylindrical spacer is not influenced by diameter of metallic particle, when it is in mid portion of the spacer.
- When the metallic particle is lifted to mid field region in a gas gap with spacer, it may adhere to the spacer. Under such conditions, BDV becomes independent of the mass of the particle. This is true for relatively short air gaps.
- In a clean air gap with dielectric covered electrode, the breakdown of air gap triggers the breakdown of dielectric. This is true for large air gap distances.
- In case of multi-layer dielectric covering of electrodes, the BDV of main gap triggers BDV of 1st layer of film, followed by second and so on. Thus, it is a combination of triggered and stepped breakdown. This is prominent under small air gaps.
- Under Rod-Plane configuration, the thickness of dielectric covering is not very effective in increasing the BDV and more so under positive dc.
- With particle of different material, size and at various locations in a co-axial.

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