Journal of Electrical Engineering & Technology Vol. 5, No. 4, pp. 631~636, 2010 631
DOI: 10.5370/JEET.2010.5.4.631

Effect of Metallic Particles on E-field Enhancement in Extra High Voltage Gas-insulated Transmission Lines

M. Mohana Rao†, S. Satyanarayana*, S. Vinay Kumar and H.S. Jain*****

Abstract – Gas-insulated transmission lines (GITL) are valued as technological solutions in hydro-power stations due to their enormous power handling capabilities. The performance of GITL is a function of the size of metallic particles inside the gas-insulated chamber. Electrostatic field (E-field) enhancement is a common phenomenon in gas-insulated lines due to these metallic particles. In this study, the E-field enhancement factor is calculated by considering metallic particles at various locations in the gas-insulated line/bus section, such as high-tension (HT) conductor, high-voltage shields, support insulator, and inner surface of grounded enclosure. For this purpose, a two-dimensional model based on finite element (FE) method is developed. The length of the metallic particle is in the range of 1 to 10 mm while the diameter is between 1 to 3 mm. E-field enhancement is also computed for various particle configurations of the gas-insulated system, with focus on dielectric coating made of epoxy on HT conductor and inner surface of grounded enclosure.

Keywords: Dielectric coating, Finite element (FE) method, Gas-insulated transmission lines (GITL), Metallic particles, Partial discharge (PD), Support insulator

1. Introduction

The development of compressed gas-insulated switchgear (GIS) and gas-insulated transmission line (GITL) equipment has rapidly progressed worldwide because of the excellent insulation properties of SF_6 gas. In such systems, gas breakdown voltage is reduced significantly by metallic particles [1]-[3]. Particle contamination results from debris left from manufacturing, assembly process, mechanical abrasion, movement of central conductor under load cycling, and vibration during shipment. Even with high levels of quality control, particle contamination is unavoidable. Under an applied electric field, a conducting particle acquires an electrical charge and lifts off from its resting position on the grounded enclosure when the electrostatic force from the electrostatic field (E-field) equalizes with gravitational force [2]. Particle movement plays a crucial role in determining the insulation behavior of gas-insulated systems. In practical systems, these particles exist in various shapes/sizes and densities. Numerous interrelated factors influence the degree to which particles reduce the dielectric withstanding capabilities of GIS. During service, the breakdown strength of SF_6 gas depends on a number of parameters, such as length and diameter of particles present, metallic or non-metallic type, quantity and nature of material, position of particles, type of particle movement, operating gas pressure, proportion of SF_6 gas quantity, and effectiveness of particle collection or trapping techniques [1]-[2].

Particle-initiated breakdown in a compressed gas-insulated system generally depends on the position of particles (i.e., in the gas gap, on the conductor surface, or on the insulator). For each position, a corresponding value of voltage is applied before a breakdown can occur. Conductors in gas-insulated systems can be coated with a dielectric material to restore some of the dielectric strength of the compressed gas, which in turn is lost due to surface roughness and the presence of metallic particles. Coating reduces the degree of surface roughness on conductors and decreases local electric field (E-field) enhancement. Coating impedes charge acquisition by a particle resting on the coating and markedly increases the particle lift-off field. This lift-off field is also increased by dielectric coating. However, once particles start moving due to any over-voltages during service, there a possibility of breakdown might occur, even with dielectric coating. From a manufacturer's point of view, it is important to control the cost of equipment by limiting the thickness of the coating. The effect of dielectric coatings on GIS insulation performance has been studied by several researchers under DC, AC, and impulse voltage contexts. Variations in coating thickness are conducted, and different coating materials, such as polymeric films, varnishes, epoxies, etc., have been evaluated for different types of voltage sources [4]-[6].

In this study, by using computational techniques, the performance of gas-insulated system is evaluated for metallic particles with different sizes. The variation of tangential E-field pattern on the insulator surface resulting from the

† Corresponding Author: Bharat Heavy Electricals Limited, Corporate R&D, Hyderabad-500093, India. (mmrao@bhelrnd.co.in)
* Bharat Heavy Electricals Limited, Corporate R&D, Hyderabad-500093, India. (ssatya@bhelrnd.co.in)
** Bharat Heavy Electricals Limited, Corporate R&D, Hyderabad-500093, India. (e-mail: svinay@bhelrnd.co.in)
*** Bharat Heavy Electricals Limited, Corporate R&D, Hyderabad-500093, India. (e-mail: jain@bhelrnd.co.in)
Received: February 2, 2010; Accepted: July 21, 2010

presence of differently sized particles in its vicinity is analyzed. The E-field enhancement factor at different locations of the gas-insulated bus duct model for various metallic particle contaminations is also analyzed and tabulated. The effect of dielectric coating on the inside surface of grounded enclosure and the outer surface of the central conductor at E-field levels is evaluated as well, in consideration of various particles in a gas-insulated bus duct.

2. Description of the GITL Model

GITL consists of a high voltage conductor placed in a grounded metallic enclosure and supported on either side with epoxy insulator. The length of the gas-insulated line is about 4 m. The outer diameter of the high-tension (HT) conductor and inner diameter of the enclosure are 120 and 550 mm, respectively. The relative permittivity (ε_r) of support insulator is 4.5. The insulators are of cone type. The following parameters are considered for the study:

1) The diameter of the particle is in the range of 1 to 3 mm.
2) The length of the particle is in the order of 1 to 10 mm.
3) The particle is represented by a cylinder hemi-spherically terminated at its tip.
4) The relative permittivity (ε_r) of the epoxy coating is 4.5.
5) Insulator height (d) is 150 mm.
6) Coating thickness is 100 to 2000 μm.

Fig. 1 shows the gas-insulated bus duct used for the study. Metallic particles are considered at different locations, such as on high voltage conductor/shields, support insulator, and grounded enclosure of the gas-insulated bus duct. Without any metallic particle, equi-potential lines are uniform and parallel. However, when within the range of a metallic particle, equi-potential lines might become distort and compress. Compression leads to increased amplitude of the E-field locally, as well as at critical locations like on HT conductor, tri-junction point, etc. In order to understand the effect on E-field levels, particles are assumed located in the following:

Fig. 1. Gas-insulated bus duct model under study.
1) HT conductor;
2) HT shield;
3) HT conductor in the vicinity of support insulator
4) Support insulator; and
5) Inside surface of LT enclosure

In actual GIS, a particle with length of 4-5 mm is most commonly observed during service. At initial stage of the manufacturing and assembly process, even for small particles 1-2 mm-long, can be controlled by different quality control practices. However, once GIS is in operation, particles of longer length are often generated due to the movement of switching contacts in different modules (i.e., circuit breaker, disconnector switch, and earthing switch). Particles of length up to 10 mm are considered in the study in order to understand their severity in GIS, which may be rare but is sometimes unavoidable. The most likely causes of such severe particle contamination are mechanical abrasion, movement of central conductor under load cycling, vibrations during shipment, etc. In a 420 kV GIS, a particle of length of 10 mm may cause a flashover with an applied voltage of 320-380 kV. This voltage is about 50% of power frequency withstand voltage (~680 kV) and may be inadequate to commission the equipment. Free-moving particles observed in service encounter low risks if their lengths are less than 3 mm [7].

The authors of this study simulated various types of defects in a gas-insulated bus duct, and the discharges are measured under varying voltages using an acoustic partial discharge (PD) detector. Figs. 2(a) and 2(b) show the PD

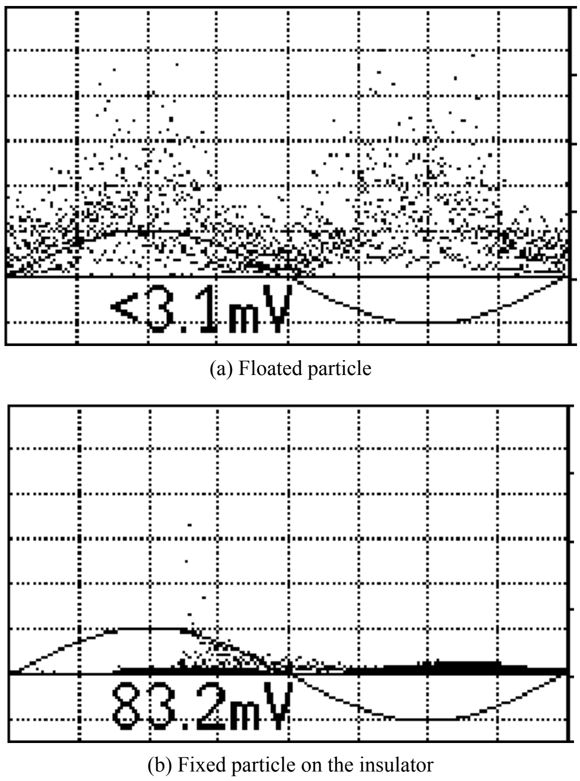


Fig. 2. PD due to metallic particle: (a) floated; (b) fixed on the support insulator in a GIS model.

pattern of a floating particle and a particle on the insulator surface, respectively. The length and diameter of each particle is 5 mm and 0.3 mm, respectively. In this study, 145 kV gas-insulated bus duct is considered. Excitation voltage is 117 kV (rms). The characteristics of the floating particles discharges connotes that sufficient voltage and time are required to excite the particles. The inception exhibits discharges appearing randomly throughout the AC cycle, unlike for the fixed particle on the insulator where discharges appear predominantly at or near voltage peaks. Once the floating particles are excited, the voltage needs to be reduced significantly to stop excitation. A defect in the insulator (i.e., crack) manifests as a symmetrical PD pattern. However, if the defect is near the high voltage conductor or grounded enclosure, the discharges become asymmetric at higher voltages. To check the discharge inception voltage, a conventional partial discharge detector is connected to the circuit as well. The experiment validates the measurement system for the various defects and discharge characteristics. This behavior is then coupled with an electrostatic field distribution across the insulation system; this can offer explanations on the severity of the particles and how particle size affects discharge inception, propagation, and final breakdown at service.

In view of above, the present paper aims to discover the effect of particle size on electrostatic field enhancement/field distribution around high-voltage parts of a gas-insulated equipment. Depending on the nature of defect/particle, a small difference in voltage between PD inception and flashover might exist. When only very little time is consumed between these voltages, it is difficult to identify defects during testing. This type of behavior can be well understood using the present analysis. Fig. 3 shows the bus duct with various configurations of the particles under study. The effect of metallic particle on E-field level due to dielectric coating of HT conductor/inner surface of the grounded enclosure is also analyzed.

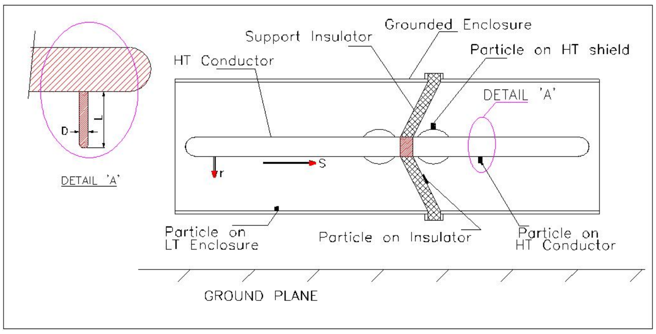
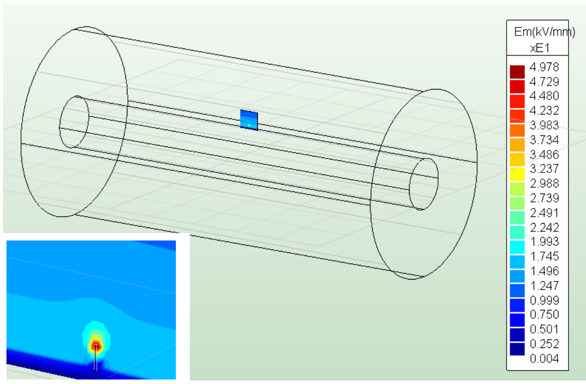


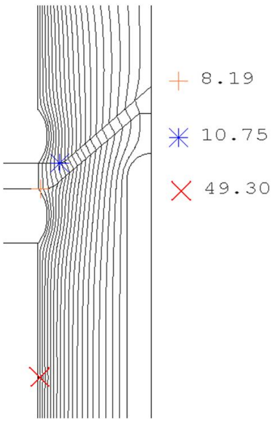
Fig. 3. Gas-insulated bus duct with various configurations of the particles.

3. Computation of Electrostatic Fields

E-field levels resulting from different particle dimensions under various configurations of bus duct are computed using a software based on a two-dimensional (2-D) finite element (FE) method. Prior to this estimation, the acceptability of the 2-D model is validated by calculating and comparing the E-fields of a particle on the HT conductor by using boundary element (BE) technique-based Coluomb-3D software. In this study, a particle length (L) of 5 mm and diameter (D) of 1 mm is considered. The FE method is a numerical technique for solving models in differential forms. For a given design, the FE model requires the entire design, including its surroundings, to be modeled with finite elements. A system of linear equations is generated to calculate the potential at the nodes of each element. The boundary element method (BEM) solves electrostatic field problems by focusing on an equivalent electrical charge. BEM uses elements with material interfaces or assigned boundary conditions, and provides perfectly smooth E-field solutions. Fig. 4 shows E-field levels calculated using the 2-D and 3-D models. The results are within 3% variation, which confirms that 2-D analysis is sufficient to understand the behavior of metallic particles present in GIS.



(a) 3-D model



(b) 2-D model

Fig. 4. Computation of E-fields.

4. Results and Discussion

In this paper, the effect of metallic particles on electrostatic field variations across the gas gap, as well as on the surface of the support insulator in the gas-insulated system, is investigated. The effect of dielectric coating on the HT conductor, as well as on the interior surface of grounded enclosure, that induce E-field enhancement in the presence of particles in extra high voltage (EHV) gas insulated lines is also explored.

4.1 HT Conductor and Grounded Enclosure without Dielectric Coating

Electrostatic field enhancement is calculated for the HT conductor, HT shield, insulator surface, and grounded enclosure (inner surface), which have resulted from the presence of metallic particles. In this study, dielectric coating is not considered for the high-voltage conductor and grounded enclosure. However, the particle is taken into account at the said locations. The effect of different parameters on E- field enhancement is analyzed.

4.1.1 Particle on the HT Conductor

When the particle is situated on HT conductor (i.e., normal to central axis), there is a significant increase in electrostatic field around the metallic particle. Table 1 shows the E-field level corresponding to the different dimensions of the particle. Field level enhancement rises with increase in particle length. The highest E-field level on the surface of the HT conductor without the particle is 17.43 kV/mm. The variation in E-field enhancement for a particular length of the particle is only marginal with increase in particle diameter/thickness. To explore the effect of particle position in the gas gap between HT conductor and grounded enclosure, the particle is assumed to be at different radial distances (r) from the center of the bus. The results are listed in Table 2. Enhancement is highest when the particle is at the vicinity of the HT conductor. This study focused on particle thickness/diameter of 1 mm and length of 5 mm.

Table 1. E-field enhancement vs. particle with various dimensions on the HT conductor

D, mm	E-field, kV/mm				
	L = 1	L = 3	L = 5	L = 7	L = 10
1.0	27.13	39.94	49.30	57.44	65.77
2.0	26.16	37.77	46.19	53.46	61.00
3.0	25.65	36.56	44.44	51.22	58.25

Table 2. E-field levels due to a particle at various radial distances (r) from HT conductor

S. No.	Distance (r) , mm	E-field, kV/mm
1	0 (HT conductor)	49.3
2	10	34.8
3	20	29.3
4	50	21.7
5	100	17.4
6	150	17.4
7	200 (Grounded enclosure)	17.4

4.1.2 Particle on the HT Shield

When the particle is placed on the HT shield (i.e., normal to central axis), significant increase in E-field levels around the particle is observed. Table 3 shows the E-field level for the particle with different dimensions.

Field level enhancement rises with increase in particle length. The E-field level without the particle on the HT shield is 21.95 kV/mm. In this study, the enhancement of E-field is almost in the same order as that of the particle on HT conductor.

Table 3. E-field enhancement vs. the particle on the HT shield.

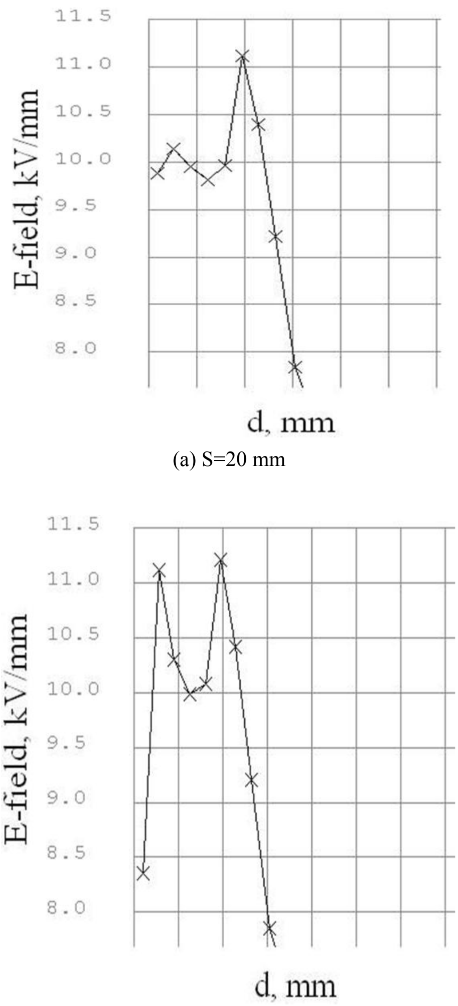
D, mm	E-field, kV/mm				
	L = 1	L = 3	L = 5	L = 7	L = 10
1.0	29.98	44.14	54.01	62.40	75.01
2.0	29.11	41.85	50.72	58.22	69.29
3.0	28.75	40.67	49.94	55.93	66.22

4.1.3 Particle on the HT Conductor in the Vicinity of Support Insulator

There is a significant increase in field levels due to the presence of the particle on the HT conductor. This might result in a worsened scenario if the particle sticks to the HT conductor in the vicinity of the support insulator. Fig. 5 shows the field enhancement resulting from the presence of the particle with 10 mm length and diameter of 1 mm at different distances (S) from the insulator. Although the change in E-field enhancement is significant, the variation in the field pattern at the tri-junction is only marginal. E-field level becomes somewhat uniform at the tri-junction point of the insulator as long as the particle is at a few-millimeter distance away from the insulator surface. Inasmuch as the particle is on the HT conductor and is far from the insulator surface, the change in tangential E-field on the surface is only marginal.

4.1.4 Particle on Support Insulator

When the particle is positioned at the middle of the concave side of the support insulator and in a direction tangential to the surface, significant change in tangential field pattern along the surface can be observed. The enhancement factor is significantly high although field level is lower than that observed on the HT conductor. Table 4 shows the E-field level (i.e., at the tip of particle) for different particle parameters. The highest tangential field appears around the particle tip on the insulator surface for particles of all sizes. Tangential field enhancement rises with increase in particle length. Nevertheless, for a specific particle length, the change in E-field enhancement with increase of particle diameter/thickness is only marginal. E-field enhancement is more significant, and in fact critical, for a particle located at insulator surface than on the HT conductor/HT shield. The highest E-field level without metallic particle on the insulator surface is 7.73 kV/mm.



(a) S=20 mm

(b) S = 2 mm

Fig. 5. Variations in E-field vs. particles with various distances (S) from the insulator.

4.1.5 Particle on the LT Enclosure

When the particle is positioned on the inside surface of the grounded enclosure in the direction normal to the HT conductor, a change in radial field pattern across the insulation gap exists. The enhancement factor for the E-field is lowest from among all other types of particle locations. Table 5 shows the E-field level for the different particle parameters. Due to particle presence on the grounded enclosure, the E-field level on the HT conductor does not significantly change; in contrast, on the LT enclosure, it changes considerably. For a specific particle length, the change in E-field enhancement with increase of particle thickness is only marginal. The E-field level without the particle on the grounded enclosure is 5.05 kV/mm.

4.2 Dielectric Coating of HT Conductor and Grounded Enclosure

Electrostatic field enhancement is calculated for the HT conductor, insulator surface, and grounded enclosure (inner surface), which resulted from the presence of metallic particles at various locations, as discussed above. Dielectric coating is considered on the high voltage conductor and on the interior surface of grounded enclosure.

Table 4. E-field enhancement vs. the particle on the support insulator

D, mm	E-field, kV/mm				
	L=1mm	L=3mm	L= 5mm	L=7 mm	L = 10 mm
1.0	10.56	17.38	23.27	28.58	35.82
2.0	10.64	17.17	22.80	27.87	34.80
3.0	10.75	17.09	22.55	27.47	34.17

Table 5. E-field enhancement vs. the particle on the LT enclosure

D, mm	E-field, kV/mm				
	L = 1	L = 3	L = 5	L = 7	L = 10
1.0	07.33	11.11	13.92	16.28	19.35
2.0	07.09	10.52	12.08	15.22	18.00
3.0	06.96	10.19	12.59	14.60	17.21

4.2.1 Dielectric Coating of HT Conductor

Electrostatic field enhancement is calculated for the HT conductor with 1000 μm-thick dielectric coating made of epoxy. Based on analysis and previous experience of researchers [2], [4], field enhancement is sufficiently high for inception of breakdown, although the difference of field enhancement is marginal, with and without dielectric coating. The decrease in E- field enhancement is only marginal with increase in coating thickness. At the same time, higher thickness for the dielectric coating helps increase the lift-off field for the particles. However, with such increase in coating thickness, even if reliability can be improved considerably, this approach may not be economical.

4.2.2 Dielectric Coating of the LT Enclosure

Electrostatic field enhancement is calculated on the inner surface of the grounded enclosure in consideration of dielectric coating at different thicknesses. Table 6 shows the field enhancement for dielectric coating of grounded enclosure due to the presence of a metallic particle. Based on

Table 6. E-field enhancement vs. the particle on the dielectrically coated grounded enclosure

S. No.	L, mm	Without dielectric coating, kV/mm	With dielectric coating, kV/mm
1	1.0	7.33	7.21
2	3.0	11.11	10.9
3	5.0	13.92	13.6
4	7.0	16.28	15.9
5	10.0	19.35	19.0

analysis, there is only marginal decrease in field enhancement on the LT enclosure because of the provision of dielectric coating.

5. Conclusions

An analytical model has been developed to estimate the E-field enhancement due to metallic particles at various locations in the gas-insulated bus section/transmission line. The study has confirmed that long particles with small diameters (cross section) are more critical from a discharge inception point-of-view. Particles on both the HT shield and the HT conductor provide higher field enhancement compared with other configurations. Particles on the inner surface of the grounded enclosure give lower enhancement in terms of electrical stresses. Field enhancement is reduced significantly as the metallic particle move away from the HT conductor and to the LT enclosure. Although the dielectric coatings on HT conductor and LT enclosure only marginally reduced E-field enhancement, they helped improve lift-off field for the metallic particles and hence, increased the discharge inception voltage.

References

[1] H. Anis and K.D. Srivastava, "Free conducting particles in compressed gas insulation", *IEEE Tran. Electrical Insulation,* Vol. EI-16, No. 4, pp. 327-338, 1981.

[2] H. Parekh, K.D. Srivastava, and R.G. Van Heeswijk, "Lifting field of free conducting particles in compressed SF_6 gas with dielectric coated electrodes", *IEEE Tran. Power Apparatus and Systems,* Vol. PAS-98, pp. 748-755, 1979.

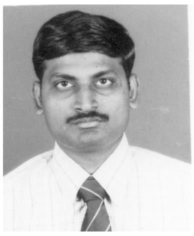
[3] J.D. Morgan and M. Abdellah, "Impulse breakdown of covered cylinders in SF6-gas mixtures", *IEEE Tran. Electrical Insulation*, Vol. EI-23, No. 3, pp. 467-472, 1988.

[4] D. Chee-Hing and K.D. Srivastava, "Insulation Performance of dielectric coated electrodes in sulphur hexafluoride gas", *IEEE Tran. Electrical Insulation,* Vol. EI-10, No. 4, pp. 119-124, 1975.

[5] K.S. Prakash, K.D. Srivastava, and M.M. Morcos, "Movement of particles in compressed SF6 gas with dielectric coated enclosure", *IEEE Tran. Dielectrics and Electrical Insulation,* Vol. DEI-4, No. 3, pp. 344-347, 1997.

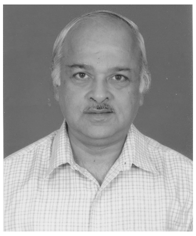
[6] M.M. Morcos, S. Zhang, K.D. Srivastava, and S.M. Gubanski, "Dynamics of metallic particle contaminants in GIS with dielectric coated electrodes", *IEEE Tran. Power Delivery*, Vol. PWRD-15, No. 2, pp. 455-460, 2000.

[7] Raymond Bell, Chris Charlson, Shaun Paul Halliday, Terry Irwin, Jose Lopez Roldan, and John Nixon, "High voltage Onsite commissioning Tests for Gas insulated substations using UHF Partial Discharge Detection", *IEEE Tran. Power Delivery*, Vol. PWRD-18, No. 4, pp. 1187-1191, 2003.



M. Mohana Rao received his Ph.D. degree from the Department of Electrical Engineering, Indian Institute of Science, Bangalore in 2006. At present, he is Manager of BHEL R&D. His research interest includes design and development of GIS, EMI/EMC studies in GIS, CFD analy-sis of CB arcs, and application of DSP techniques in power systems.

S. Satyanarayana received his M. Tech. degree from the Department of Electrical Engineering, Osmania University, Hyderabad in 1977. His research interest includes electrostatic field analysis for switchgear, transformer, bushing, and other power equipment. At present, he is an Additional General Manager of BHEL R&D.



S. Vinay Kumar received his M. Tech. (Instrumentation) degree from the Department of Electrical Engineering, Indian Institute of Technology, Kharagpur and joined BHEL R&D in 1974. He has been involved in research activities in vacuum, SF6 switchgear, and gas-insulated substations. Currently, he is an Additional General Manager of BHEL R&D.

H.S. Jain received his Ph. D. degree from the Department of Electrical Engineering, Indian Institute of Technology, Mumbai in 2001. He has been associated with Bharat Heavy Electrical Limited (BHEL) Corporate Research & Development Division at Hyderabad (India) since 1974 and specializes in vacuum/SF6 circuit breakers and gas-insulated power equipment. At present, he is a General Manager of BHEL R&D.