Executive Summary

Various kinds of insulation systems are widely used for high-voltage equipments in electric power transmission and distribution. For example, the gas insulated switchgears (GIS) and gas insulated lines (GIL) are the important components of power systems. Liquid and solid insulation systems are used for transformers, power cables and others. The advantages of the gas insulation systems are high reliability and infrequent requirement of maintenance due to their closed structure. However, it is known that the existence of small particles in a gas insulation system can significantly reduce the insulating capability of the system. Particles may appear in the insulation system in the process of manufacture, assembly or maintenance. On the other hands, solid and liquid dielectrics have high dielectric strength, in comparison with gaseous materials. The presence of cavities (voids) in a solid dielectric or bubbles in a liquid dielectric is critical to the insulating performance. The electric field in a void is higher than that in the enclosing medium because of the lower dielectric constant of the medium inside the void, usually gaseous one. When the electric field is excessively high, partial discharge (PD) initially takes place in the void. The PD activity involves chemical, mechanical, and thermal processes, which can cause deterioration in the surrounding dielectric. In critical cases, PDs may result in breakdown or insulation failure of the insulation systems.

This research studies the electrical and electromechanical behavior of particles in various kinds of profiles and configuartions. Note that a void or bubble can also be regarded as a form of particle which contaminates the main insulating (surrounding) medium. The studies have been done analytically and experimentally, and include the design of particle deactivation technique. The particle profiles considered in this research are oblate spheroidal, prolate spheroidal and spherical shapes. The overall objectives of the research are to make clear the electric field and electrostatic force on particles for a wide range of applications and to relate the fundamentals obtained from the research to the practical problems, such as the design of particle trap or the control of membrane potential.

The oblate spheroid is applied to the problems of air or gaseous voids in a solid dielectric, which are often the weak point for the partial discharge in high-voltage insulation systems. The study uses the method of multipole images in the oblate spheroidal coordinates. The electric potential is expressed as a sum of oblate spheroidal harmonics. The method utilizes the re-expansion and the image schemes of a dielectric oblate spheroid and a conducting plane to determine the solution of potential that satisfies all the boundary conditions involved. With the use of the oblate spheroidal coordinates, the void shape can be varied systematically to observe their effects on the electric field both in the interior and in the exterior. The analysis focuses on the variation of the electric field with the separation between the void and the electrode, the ratio of the major to minor axes of the void and the dielectric constant of the surrounding dielectric. Results from the study clarify the degree that electric field is intensified inside a void in comparison with the background electric field. The presence of an electrode near the void mitigates the electric field on the axis of symmetry of the void, as also specified in the existing literatures. However, we have found that higher field stress still

exists at the region away from the axis, and the field maximum is not significantly reduced by decreasing the separation, in particular when the void is very flat (in the direction of electric field). We also study the use of equivalent multipole moments to represent the influence of void on the electric field in the exterior. The study shows that higher order multipoles are needed for the field representation. In addition, the effects of the planar electrode on the equivalent multipole moments of the void are also discussed.

The prolate spheroid is applied to the problem of conducting particle contamination in gaseous insulation systems. The study is done by using an analytical method in both axisymmetric and three-dimentional configurations. We apply the method of images using multipoles to the electric field calculation. The calculation uses the multipole re-expansion formulae and the equivalent image charges of a prolate conducting spheroid. The induced charge, the electrostatic force and the electrostatic torques are determined either from the interaction between the field and the multipole images or from the numerical integral of the Maxwell stress. The axisymmetric configurations consist of a conducting spheroid which is in contact with or separated from a grounded plane. From the calculation results, we have found that the maximal field on the spheroid on the grounded plane increases nonlinearly with the major-to-minor axis ratio of the spheroid. We propose empirical formulae for approximating the maximal field, charge and force with the errors smaller than 2% for the axis ratio between 1 and 32. The propriety of the approximation of the electric field, charge and force based on a hemispheroidal model is examined in this research. For an uncharged spheroid separated from the grounded plane, we can clarify the relationship between the separation and the field intensification at the bottom pole of the spheroid. In addition, the position of the spheroid where the partial discharge takes place is estimated based on the critical field strength of the insulating medium.

For the three-dimensional (3D) electromechanical analysis, we treat a conducting prolate spheroid on a grounded plane under electric field. The 3D analysis focuses on the roles of tilt angle α between the particle and the plane on the electrostatic force and torque on the spheroid, which contribute to particle behavior in various applications. The results from this research show that the electric field is maximal at or near the higher pole of the spheroid if the tilt angle α is not equal to zero. The electrostatic force is minimal and maximal when the spheroid lies and stands on the plane, respectively. We present empirical formulae that approximate the minimal and maximal electrostatic force with error smaller than 1% for the spheroid having major-to-minor axis ratio between 1 and 10. For the electrostatic torque, we have found that the torque is always in the increasing α direction. The torque magnitude increases with α from 0° to about 45°, and then reduces to zero at α = 90°. The torque variation may be estimated by a quadratic relationship. Taking into account the gravitational force of the particle, we classify the electromechanical behavior of the prolate spheroid into three regimes, depending on the electric field and the tilt angle. Our results illustrate that the electrostatic torque promotes the lifting probability of the spheroid by the electric field.

In addition to the insulation systems, the oblate and prolate spheroidal profiles are used to analyze the electrostatic applications of biological cells. We apply the boundary element method, a numerical field calculation method, to calculate the direct-current and steady-state transmembrane potential of non-spherical biological cells. The objective is to determine the effects of cell profile and the conductivity of the extracellular medium on the characteristics of cell membrane voltage under dc electric field charging. The configuration of isolated cell and cell pair are considered, corresponding to the cells in the process of electroporation and electrofusion, respectively. The cell profiles are varied between oblate spheroidal, spherical, and prolate spheroidal ones, which have different ratios between the radii in different axial directions. From the results, we can clarify that a decrease in the conductivity affects both magnitude and distribution of transmembrane potential. We may approximate the cell membrane as a perfect dielectric when the extracellular conductivity is sufficiently high. For the same cell geometries, transmembrane potential is smaller for pairs of cells than for isolated cells, and this potential is more reduced at the contact poles than at the opposite poles. When the cell geometries are different, the shielding effect on the transmembrane potential is found. That is, either different axial lengths or different radii between the cells results in this disparity in transmembrane potential of the cell pair. However, if we decrease the extracellular conducitivity, we can obtain the same maximum potential of both cells at the contact poles.

The spherical profile is used for studying the particle manipulation in high-voltage insulation systems. The purpose of the study is to investigate the feasibility of particle manipulation by the dielectrophoretic (DEP) force for insulation systems. The study begins with the analysis of the electrostatic force by a numerical method. Experiments have been carried out to compare the particle motion under electric field with the numerical prediction. The experiment also clarify the particle behavior without the application of particle manipulating technique. The continuous motion of particles, which can lead to electrical discharge, is observed in the experiments. The experimental measurement of the particle displacement agrees well with the numerical results. For particle manipulation, the dielectric layers of silicone rubber (PDMS) and polyimide are placed on the grounded electrode to prevent a conducting particle from being charged. Numerical field calculation shows that with the dielectric layers, the DEP force attracts the particle to the region of higher field and immobilizes it at the termination of the dielectric layers. Experiments with stainless steel and aluminum particles of sub-millimeter sizes are carried out to verify the theoretical prediction.