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主　論　文　の　要　旨

論文題目　**Electric Field Grading by Functionally Graded Materials (FGM) for HVDC Gas Insulated Power Apparatus**
(直流高電圧ガス絶縁電力装置への傾斜機能材料(FGM)による電界制御に関する研究)

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論　文　内　容　の　要　旨

Nowadays, the world's electricity consumption is growing at a faster rate than the energy consumption. The increasing necessity over electricity combined with the Sustainable Development Goals for affordable and clean energy have encouraged the development of distributed generations which include on-site renewable energy sources, such as hydro energy, solar energy in desert areas, vast off-shore wind farms, etc. HVDC technology has been advantageous in serving this purpose since it has high-power capacity to transmit power over long distances from the energy sources to the load center. HVDC transmission system is also utilized as grid interconnection for AC systems, submarine power cables, and frequency converter that allow electricity trading among countries. More HVDC projects in the future require reliable infrastructure and compact apparatus. On the other hand, gas insulated equipment, such as gas-insulated switchgear (GIS) and gas-insulated transmission lines (GIL) have been favorable in the present power transmission system due to its compactness, high reliability, and ease of maintenance. Their applicability to AC system has been well proven, hence the research interests for DC application have grown in the last few decades. However, the problem rises when SF_6 gas which is used in GIS/GILs due to its excellent arc extinguishing and electrical insulation properties, is confirmed as extremely potent greenhouse gas with GWP values of 23,500. While the research of seeking SF_6 gas alternatives is still going, downsizing GIS/GILs is an effective means that may reduce not only SF_6 gas usage, but also cost, installation space, and manufacturing energy. Nevertheless, the consequence of downsizing the equipment is the enhancement of electric field stress in the insulation medium. Therefore, electric field control is necessary to maintain the high reliability of the apparatus.

Electric field grading by functionally graded material (FGM) application is proposed in this thesis as a novel technology to regulate electric field around solid insulators (spacers) in GIS/GILs. In FGM concept, the material properties (conductivity (σ) and/or permittivity (ε)) change spatially within the solid insulator bulk in order to control the surrounding resistive fields that occur under constant voltage stress and/or capacitive fields that occur under time-varying voltage stress. In the past research, a 245 kV-class AC GIS cone-type spacer with permittivity graded materials (ε-FGM) has been fabricated using Flexible Mixture Casting (FMC) method. The breakdown tests on ε-FGM spacer also show 28% improvement of flashover voltage under negative standard lightning impulse (LI) voltage at 0.6 MPa-abs SF_6 gas pressure compared to that of the conventional spacer, which leads to high possibility of downsizing the GIS.

This thesis investigates the feasibility of FGM application with graded permittivity and conductivity (ε/σ-FGM) for HVDC GIS/GIL spacers, with purpose to evaluate its effectiveness under various DC operating conditions in consideration of temperature distribution.

Chapter 2 discusses the concept of DC-FGM and material characteristics of the filled-epoxy composite for ε/σ-FGM spacer, i.e. ε and σ characteristics of epoxy composites containing semiconductive SiC filler particles and/or high permittivity $SrTiO_3$ filler particles. Three types of SiO_2-filled epoxy-based bulk samples are fabricated, each containing 0, 5, and 10 vol% SiC, where the total filler contents of SiC and SiO_2 is 50 vol% of the total epoxy-composite. Then, ε of each sample is measured through capacitance measurement, while σ is measured using double-ring electrode method at varying applied voltages (applied electric field strength E of 1 to 10 kV/mm) and at varying temperatures (T=303 K, 333 K, and 353 K). Afterwards, multivariate analysis is performed on the σ measurement data to obtain σ characteristics as a function of T, E, and SiC filler contents. On the other hand, the ε_r between 0 and 10 vol% SiC-filled epoxy composite show relatively small gap ($\Delta\varepsilon_r \sim 3$), which is expected as not sufficient for capacitive field grading. Therefore, it is necessary to combine the SiC-filled epoxy composite with another high ε_r composite in order to obtain the relaxation of both capacitive and resistive fields under various DC operating conditions.

In this case, the ε characteristics of $SrTiO_3$-filled epoxy composite which is used for AC GIS ε-FGM spacer is adopted.

Chapter 3 discusses the preliminary investigation results of electric field analysis on 320 kV HVDC GIS cone-type spacer models with and without ε/σ-FGM application, under various DC operation conditions: DC-steady state (DC-SS), DC-polarity reversal (DC-PR), DC-on, and superimposed positive and negative LI voltage on DC-SS (DC±LI). The effect of temperature distribution is also investigated with temperature difference ΔT between HV conductor and GND enclosure varies from 0 to 70 K. Several types of ε and σ distributions shapes are applied to ε/σ-FGM spacer, such as U-type and grading-to-higher conductivity (GHC)-type with ε_r range between 4 to 12 and σ range of 10^{-15} to 10^{-14} S/m (at T=300 K and E=1 kV/mm), in comparison to the Uniform spacer with constant ε_r of 4 and uniform σ distributions of 10^{-15} S/m. In this simulation, the σ characteristics are obtained from references values of typical epoxy resin. The results show that the effectiveness of FGM with graded σ for E relaxation under DC-SS is confirmed, where both σ(U)-FGM and ε(U)/σ(GHC)-FGM spacers can reduce E_{max} by 43% at ΔT=70 K, compared to the Uniform spacer. At DC-PR, ε(U)/σ(GHC)-FGM spacer has the largest E reduction effect at each ΔT among other type of spacers, with the largest ΔE_{max} of 30% compared to that of the Uniform spacer, which is obtained at ΔT=10 K. It is possible due to combination of graded ε and σ that reduces both capacitive and resistive fields that occur at DC-PR. ε(U)/σ(GHC)-FGM spacer is also effective in relaxing E distribution under DC-on, DC+LI, and DC-LI, with E_{max} reduction of at most 43%, 7%, and 20%, respectively.

In Chapter 4, toward future fabrication and experimental verification of ε/σ-FGM spacer, the actual measured σ characteristics of SiC-filled epoxy composite and ε characteristics of $SrTiO_3$-filled epoxy composite which are obtained in Chapter 2 are applied to a scaled model of DC GIS cone-type spacer. E analysis similar to those in Chapter 3 are then performed under various DC operating conditions and temperature distributions. Furthermore, heat conduction analysis is performed to ensure that thermal runaway does not occur. Finally, theoretical discharge inception voltage ($TDIV_{50}$) of ε/σ-FGM spacer is calculated under LI voltage at varying SF_6 gas pressures to estimate the breakdown probability. The E simulation results show that ε/σ-FGM spacer, made of 0–26.9 vol% $SrTiO_3$-filled epoxy composite and 5–10 vol% SiC-filled epoxy composite, and with GLP-type ε distribution (ε_r=12.7 to 4) and U-shaped σ distribution (σ~10^{-15} to 10^{-7} S/m) has higher E relaxation effect than the ε/σ-FGM models in those in Chapter 3, with maximum E_{max} reduction of 45%, 48%, 22%, and 36% compared to the Uniform spacer, under DC-SS, DC-PR, superimposed positive and negative LI on DC-SS, respectively. It is because higher σ level given by 5 to 10 vol% SiC-filled epoxy composite compared to the non-SiC-filled Uniform spacer reduces the resistive field components significantly. The SiC-filled epoxy composite also has lower *T*-dependency than that of typical epoxy resin, allowing almost constant *E* relaxation against increasing ΔT.

The heat conduction analysis which considers spacer's internal heating due to leakage current confirms that temperature rise does not occur within the designed ε/σ-FGM spacer composed of 5 to 10 vol% SiC-filled epoxy composite. Specification of ε/σ-FGM spacer is also given to obtain sufficient electric field relaxation and without causing thermal runaway. Finally, the $TDIV_{50}$ calculation results by Volume-Time theory under LI voltage show 19 to 26% improvement at SF_6 gas pressure of 0.1 to 0.5 MPa-abs, compared to the Uniform spacer. It is owing to the GLP-type ε distribution given by 0 to 26.9 vol% $SrTiO_3$-filled epoxy composite, which relax the capacitive field distribution around the spacer under LI applied voltages, hence $TDIV_{50}$ is improved.