

Homogenization Optimization of Electric Field in Nonlinear Nonuniform Dielectrics under Pulsed Excitations

Minyu Mao¹, Jiawei Wang¹, Jinghui Shao², and Youpeng Huangfu¹

¹State Key Laboratory of Electrical Insulation and Power Equipment, School of Electrical Engineering, Xi'an Jiaotong University, Xi'an, 710049, China

²TBEA Electrical Equipment Group Co., Ltd., Xi'an, 710068, China
youpeng.huangfu@xjtu.edu.cn

The application of dielectric functionally graded insulation (d-FGI) under pulsed excitations significantly homogenizes the electric field distribution, thereby effectively improving the insulation performance. Nevertheless, a critical issue in designing d-FGI lies in the optimal selection of the nonlinear and nonuniform behavior of the dielectric parameters (conductivity/permittivity). For this purpose, in this paper a needle-plate dielectric model under pulsed excitations is considered for the optimization of the construction of the d-FGI by using multi-objective genetic algorithm (GA). In specific, axisymmetric models in finite element analysis for a two-layer dielectric gradient and a multilayer dielectric gradient configuration are implemented. The nonlinear behaviors of the permittivity and the conductivity of the studied d-FGI are characterized by exponential functions of the electric field. The optimization results demonstrate the effectiveness of the proposed approach for the homogenization of the electric field in nonlinear nonuniform d-FGI under pulsed excitations.

Index Terms— Dielectric functionally graded insulation, genetic algorithms, optimization, pulsed excitation.

I. INTRODUCTION

The pulsed power devices toward the miniaturization and high voltage capabilities, leading to the issues of electrical insulation problems and surface flashover, primarily manifested in non-uniform electric field distribution [1]. To address this issue, many solutions have been proposed such as by increasing the curvature radius of electrodes and by altering the structural design of insulating components to enhance the insulation properties [2]. Nevertheless, common considerations of the structural optimization approaches arise due to the complication of the design of insulating components and the increase of the manufacturing difficulty. On the other hand, the dielectric functionally graded insulation (d-FGI) has been developed for the homogenization of the electric field while without altering the geometric structure of the insulators [3]. In this case, the nonlinear properties of the d-FGI are omitted which can be further applied for the purpose of better homogenization of the electric field.

Therefore, in this paper, the optimization work for a needle-plate dielectric model under pulse excitations is carried out by using multi-objective genetic algorithm (MOGA) to optimize objectives simultaneously. Specifically, the nonlinear behaviors of the permittivity and conductivity of the d-FGI are considered by using exponential functions of the electric field strength. The axisymmetric models for a two-layer dielectric gradient and a multi-layer dielectric gradient configuration are implemented by using finite element method (FEM). Furthermore, the influence of design parameters on the optimization results is analyzed. A significant reduction in the surface electric field strength can be observed, demonstrating the effectiveness of the proposed method.

II. PARAMETRIC OPTIMIZATION OF D-FGI

A. General Model for a Needle-plate Electrode

For illustration, a general needle-plate model consisting a cylindrical dielectric is present in Fig. 1. For simplicity, the material of the electrode is designated as copper and a silicone rubber is applied for the insulation purpose. The electrical parameters of the two materials are presented in TABLE I. A reference nanosecond pulse voltage with the amplitude of 20 kV, in accordance with the IEC61000-2-9 [4], is applied between the needle electrode and the plate electrode. The distribution of the electric field in the silicone rubber is further analyzed by using FEM. It is shown in Fig. 1 (b). Obviously, the electric field strength near the electrode-dielectric interface reaches a maximum of 13.122 kV/mm. Basically, it is significantly higher than the average field strength of 0.404 kV/mm, revealing a high degree of electric field non-uniformity within the insulation structure.

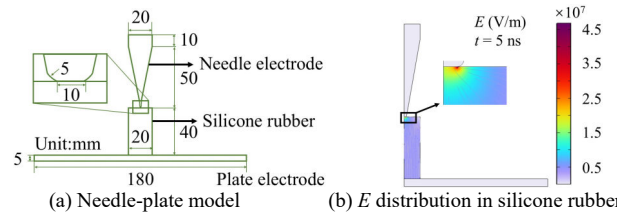


Fig. 1. (a) Sketch and (b) electric field distribution of a needle-plate electrode-cylindrical dielectric.

TABLE I. Material properties for the model in Fig. 1.

Components	Conductivity (S/m)	Relative permittivity
Electrode	5.80×10^6	1
Silicone rubber	$\sigma_0 = 1.00 \times 10^{-14}$	$\epsilon_r = 4$

B. Optimization of a Double-Layer D-FGI

To achieve a more manufacturable model of d-FGI, a double-layer dielectric gradient structure is designed [3], as illustrated in Fig. 2 (a). Can be noted, a layer of highly nonlinear material (σ_1 and ϵ_1) is internally embedded at the electrode-dielectric junction on the needle electrode side [1]. For simplicity, the nonlinear behavior of the adopted dielectric is characterized by

$$\begin{cases} \sigma_1 = \sigma_0 e^{\alpha_1 E} \\ \epsilon_1 = \epsilon_r e^{\beta_1 E} \end{cases} \quad (1)$$

where, σ_0 and ϵ_r are characterized by the conductivity and relative permittivity of the silicone, respectively; in addition, α_1 and β_1 takes 2×10^{-5} m/V and 2×10^{-7} m/V, respectively; moreover, E is the electric field strength.

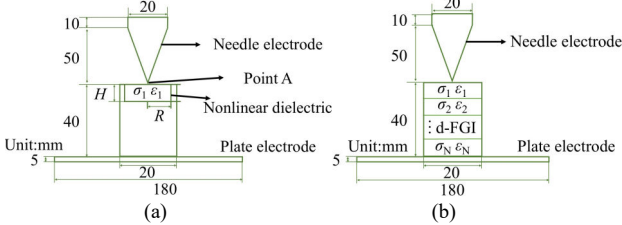


Fig. 2. (a) A double-layer d-FGI and (b) a multi-layer d-FGI.

Remark that the critical geometric parameters of the nonlinear dielectric are the depth H and the radius R , corresponding to the upper limits of the values 40 and 10, respectively. As a consequence, the multi-objective of the electric field optimization is to minimize both the electric field strength E_A at the junction point (Point A) and the electric field non-uniformity P of the cylindrical dielectric simultaneously (where $P = E_A/E_{av}$ and E_{av} denotes the average electric field strength within the dielectric). Consequently, this optimization problem can be formulated as a bi-variable, bi-objective multivariable optimization problem. It mathematically gives

$$\begin{aligned} \text{Min} : \{E_A, P\} &= f(H, R) \\ \text{s.t.} \quad &\begin{cases} H < 40 \text{ mm} \\ R < 10 \text{ mm} \end{cases} \end{aligned} \quad (2)$$

The optimization solution is $H = 2.834$ mm and $R = 1.538$ mm. The electric field distribution after the GA optimization is illustrated in Fig. 3. It is evident that, compared to the homogeneous dielectric structure, the maximum electric field strength (E_A) of the optimized gradient insulation structure has decreased from 13.122 kV/mm to 4.770 kV/mm, representing a reduction of 58.81%. Concurrently, the field non-uniformity factor P has decreased from 32.48 to 11.08. The peak electric field point has shifted from the junction along the surface to the apex of the non-linear inhomogeneous dielectric layer. Consequently, this transition has relocated the electric stress from the relatively weak needle electrode-dielectric interface to the more robust dielectric surface, achieving an optimized electric field distribution without adding extra volume.

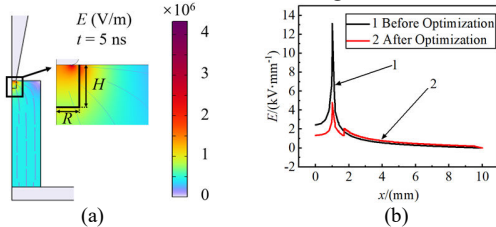


Fig. 3. The E distribution (a) after GA optimization for the double-layer d-FGI, (b) before and after optimization from the dielectric center to boundary.

TABLE II. Material properties for the model in Fig. 3.

States	$H, R(\text{mm}), \sigma, \beta(\text{m/V})$	P
Original	40, 10, 0, 0	32.48
Optimal	2.834, 1.538, 2×10^{-5} , 2×10^{-7}	11.08

C. Optimization of a Multi-Layer D-FGI

The schematic diagram of the multilayered functionally graded dielectric structure is presented in Fig. 2 (b). The nonlinear dielectric material is segmented into N layered regions in the columnar, with each layer of the same thickness and a uniform dielectric constant. As a consequence, in order to obtain an optimal distribution of the electric field, an optimization study by using GA is carried out. Mathematically, it is subjected to

$$\begin{aligned} \text{Min} : E = \{E_A, P\} &= f(N, \alpha_i, \beta_i) \\ \text{s.t.} \quad &\begin{cases} 0 < N < 100 \\ \alpha_{\min} \leq \alpha_i \leq \alpha_{\max} \\ \beta_{\min} \leq \beta_i \leq \beta_{\max} \end{cases} \end{aligned} \quad (3)$$

where α_i and β_i represent the coefficients of the nonlinear conductivity and relative permittivity in the i th layer, respectively; in this paper, the order of magnitude of α and β is set to 10^{-5} and 10^{-7} [1], respectively, suppose $\alpha_{\min} = 0.1 \times 10^{-5}$ m/V and $\alpha_{\max} = 5 \times 10^{-5}$ m/V; $\beta_{\min} = 0.1 \times 10^{-7}$ m/V and $\beta_{\max} = 5 \times 10^{-7}$ m/V.

The optimization results for the multi-layer d-FGI are presented in Fig. 4 with $N = 10$, $\alpha_{1-10} = \{0.683 \times 10^{-5}, 3.305 \times 10^{-5}, 2.408 \times 10^{-5}, 1.276 \times 10^{-5}, 0.260 \times 10^{-5}, 1.995 \times 10^{-5}, 1.041 \times 10^{-5}, 0.768 \times 10^{-5}, 3.949 \times 10^{-5}, 0.337 \times 10^{-5}\}$ m/V, $\beta_{1-10} = \{4.826 \times 10^{-7}, 2.318 \times 10^{-7}, 2.015 \times 10^{-7}, 0.428 \times 10^{-7}, 0.774 \times 10^{-7}, 0.369 \times 10^{-7}, 0.830 \times 10^{-7}, 1.367 \times 10^{-7}, 0.938 \times 10^{-7}, 0.979 \times 10^{-7}\}$ m/V. Clearly, compared to a homogeneous dielectric, the optimized multi-layer d-FGI demonstrates a significant reduction in the maximum electric field strength, decreasing from 13.122 kV/mm to 4.317 kV/mm, which corresponds to a reduction of 67.09%. Additionally, the P has decreased to 9.86. The uniformity of the electric field along the surface of the insulator has been markedly improved, and the local pulse electric field concentration phenomenon has been significantly mitigated. These results validate the efficacy of the GA optimization method and confirm the considerable potential of multi-layer d-FGI in electric field manipulation.

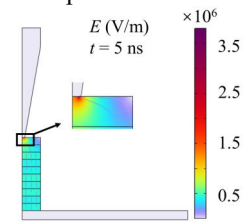


Fig. 4. The E distribution after GA optimization for the multi-layer d-FGI.

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