

# Functionally Graded Materials (FGM) for Spacers in Gas Insulated Systems: A Concise Review and Some Comments

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**Abstract-Functionally Graded Materials (FGMs) present a solution to control electrical stresses in high voltage applications. In this paper, a concise review is presented on the FGMs for spacers in gas-insulated systems. FGMs offer the possibility of a more even electric field distribution and thus a viable solution for industrial applications. FGMs are investigated here primarily as materials for permittivity control. Some aspects of FGMs are discussed as well as some thoughts on future challenges.**

**Keywords-functionally graded materials; gas insulated systems; dielectric constant; permittivity; triple junction point; dielectric strength; fillers; microfillers; nanofillers**

## I. INTRODUCTION

Electric stress control is a major challenge in high voltage engineering applications. Excessive electric stress may lead to the breakdown of insulation and definite deterioration of high voltage equipment [1]. Electric field stress control has been dealt with in some detail before, such as field distortions by conducting particles, field distortions by electrode asperities as well as field distortions due to multi-dielectric insulating arrangements [2]. Sandwiched multi-layer insulating systems can cause problems if the layers are of different dielectric constant. However, such insulating systems – if made up from very thin layers – can be of advantage since they usually present fewer defects than thicker insulation slabs [2, 3]. As has been pointed out, sharp edges, small radius elements and needle points must be avoided in insulation design [4, 5].

Elaborating further the question of multiple layer insulation, it was reported that the effect of multiple layers is particularly marked for materials where there is a wide spread in values of dielectric strength measured at different points on the surface. The main factor in this phenomenon is the loss of energy from the discharge at the interfaces. As has been mentioned some decades ago, a partial discharge having penetrated one layer cannot enter the next layer of the insulating material until the spot on the interface, which is centered on the discharge channel, has been charged to a potential which could produce a field comparable with that of the discharge channel at the level in question [6].

Interfaces play a most important role in high voltage engineering applications. In traditional insulating materials, interfaces must be avoided or they must be treated in a way that they do not cause additional problems to the insulating system. As has been pointed out before, irrespectively of the theory put forward to explain pre-breakdown and breakdown phenomena, either electrode imperfections or mismatch of dielectric materials in a composite insulating system result in electric field intensifications that may lead to ultimate failure. It goes without saying that interfaces are the root of a variety of problems regarding the insulating systems [7]. A way out of such problems is the better matching between dielectric materials (in case of an insulating system), or an alleviation of the applied electric field in the case of an insulating material in direct contact with an electrode [8, 9]. Another way is the use of Functionally Graded Materials (FGMs), which are materials characterized by gradual variation in composition and structure over volume, which may result in a more even distribution of the electric field. According to [10], FGMs are novel materials, the properties of which change gradually with respect to their dimensions. It is the advanced development of hitherto used composite materials, consisting of two or more materials, in order to achieve the desired properties according to the application where an FGM can be used. Expressed in a slightly different way, FGMs are very advanced engineering materials designed for a specific property or function, in which spatial gradations in the structure (and possibly in the composition) provide them with the desired characteristics [11]. The present paper aims to offer a concise review of the aforementioned materials with an emphasis on spacers in gas insulated systems.

## II. FUNCTIONALLY GRADED MATERIALS

In various high voltage applications, many electric field distortions may be observed. Such distortions are caused by the shape of electrodes and/or spacers and to the mismatch of the insulating materials. Distortions (or intensifications) of this kind may lower the electrical performance of insulating systems and of high voltage equipment. In other words, field intensifications may lead to Partial Discharges (PDs) and electrical treeing. If not detected, these phenomena may lead to complete failure of the insulating systems [12-15]. Thorough

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analyses of field distortions are described in [1, 2, 4, 16]. A possible remedy to field intensifications would be a smoothing out of problematic electrodes and the – as far as possible – better matching of the insulating materials in case of a composite insulating system.

An alternative to the above approaches is the application of FGMs, which with the well-controlled spatial distribution of dielectric constants inside would offer a more even electric field distribution [17, 18]. Although such materials were studied regarding their homogenization, heat transfer, stress, stability, and dynamic analysis and fracture [19], what is of interest for us is the application of such materials in high voltage engineering [20]. FGMs – as far as high voltage applications are concerned – consist of insulating materials with a certain filler concentration in order to vary one basic physical property, so that they can alleviate electric field intensifications [21]. In other words, FGMs replace the sharp transition of properties with smooth and gradually changing properties of the materials such as physical, chemical, mechanical or electrical [11].

FGMs do not encompass all possible high voltage applications. Among them, FGMs are applicable to spacers for gas-insulated power apparatus, cable joints, insulators and bushings, stator coils, and electrical insulation for power electronic modules [21, 22]. In the context of the present paper, a concise review will be given w.r.t. FGMs regarding the spacers in gas insulated systems. In other words, the review will be confined in the aforementioned application.

### III. FGMS FOR SPACERS AND GAS-INSULATED EQUIPMENT

Spacers are an indispensable part of gas-insulated switchgear [1, 23]. As was noted in [1], spacer flashover is the most probable breakdown mechanism in a compressed gas insulated system as any contamination of the space surface may produce flashover at a voltage (sometimes well) below the gas breakdown strength. Epoxy resin is primarily the insulating material used for spacers [8]. As is noted in [24], triple junctions present an important problem for spacers since at those points high electric field intensifications may be observed. By building FGMs with higher permittivities at both cathode and anode surfaces compared with other intermediate parts of the spacer, i.e. by having a U-distribution of permittivity, a relaxation of the electric field is obtained. According to [24], the maximum electric field was reduced by about 10% at the triple junction – in case of a foreign particle adhered to spacer - with the application of a U-shape FGM (in this case epoxy resin). Also in [24], it was reported that the electric field was relaxed by about 30% at both high voltage/spacer and ground/spacer interfaces by applying a U-shape FGM. Regarding the presence of foreign particles adhered to the spacer, an earlier study also indicated that their shape and location may influence the performance of FGM [25].

In [26], further discussions ensued w.r.t. the spacers with Graded Low FGM (GL-FGM), Graded High FGM (GH-FGM), and Graded U FGM (GU-FGM). This work was mainly a computer analysis of the various aforementioned FGMs in reference to a three-phase insulated gas bus duct. One of the

conclusions was that the GL-FGM results in rather high electric field stresses. Such conclusions are not at variance with earlier research which showed that GL-FGM gives a field relaxation in a rather narrow range of permittivities whereas GH-FGM offers a field relaxation in a much wider range of permittivities [27]. Authors in [28, 29] did not deviate from the main conclusions of [26], pointing out that the main problem in such structures is the triple point. In [26, 30], similar conclusions were reached regarding the GH-FGM, GU-FGM, and GL-FGM. The authors of [30] indicated that the highest percentage reduction of electric field stress is observed for GH-FGM and GU-FGM gradings. In the same paper, it was remarked that it is preferable to prepare FGMs by applying centrifugal forces, incorporating thus fillers of different diameters in order to obtain permittivity distribution for uniform field distribution rather than three dimensional (3D) printing, since it is the first method that is more efficient. Such views on the preparation method of FGMs are also shared by other researchers [31, 32]. The authors of [11] take a more cautious approach w.r.t. the aforementioned preparation techniques by pointing out that the controllability of the centrifugation method is not always the desired one and that one of the obstacles of the 3D printing technology, among others, is the limitation of printing materials (another preparation method, namely the flexible mixture casting method, has as main drawback the forming of many interfaces of the composing resins). The centrifugation method seems to be also preferred in [33], although the authors remarked that a more flexible fabrication method is urgently required. However, a different view regarding the 3D printing technology was offered in [34], where satisfactory flashover characteristics were obtained for insulators at both SF<sub>6</sub> and vacuum under DC voltages with the Fused Deposition Modeling (FDM) manufacturing process.

Further criticism of the above preparation methods was also put forward in [35], where another method was proposed, besides the aforementioned approaches with FGMs, namely to apply FGM to the spacer surface in order to form thickness (d) gradient surface layers of high permittivity (d-SFGM). This was done by the magnetron sputtering technique. The optimum layer thickness was found to be between 8 and 10 μm. The authors of [35], experimenting with d-SFGM, observed that electric field distribution is further homogenized, the maximum electric field strength at the HV triple junction is further reduced, and the AC flashover voltage was very satisfactory. Relevant to [35] is the work by the same research group with FGMs having spatial distribution of conductivity  $\sigma$  ( $\sigma$ -FGM) [36]. Such materials were fabricated with the surface fluorination of the insulating material. Such materials are more orientated to DC applications, where significant improvements were observed w.r.t. the flashover voltage as well as to the homogenization of electric field distribution. The authors of [37] approached the whole question of FGMs from another point of view, namely that of the behavior of FGM spacers in the presence of spherical conducting particles in gas-insulated systems. They also noticed the beneficial effect of the FGMs in this case, pointing out that the influence of the FGM spacer material may vary depending on the positioning and the size of the spherical particle w.r.t. the high voltage electrode and/or the ground electrode. FGM spacers seem to have a better overall

performance with adhering spherical particle than conventional materials.

Experimenting with  $\epsilon$ -grading to the lower permittivity by fabricating FGMs (GLP-FGM), it was found that the maximum electric field strength of a fabricated coaxial disc-type GLP-FGM spacer at the HV-electrode/spacer interface can be reduced by 12% in comparison with the one of a conventional spacer with uniform permittivity [38]. In contradistinction to the centrifugation method, the Flexible Mixture Casting (FMC) method [39], produced  $\epsilon$ -FGMs of a wide range of permittivities giving a relaxation of electric stress on the spacer surface by 64% in SF<sub>6</sub> gas and an improvement of discharge inception voltage by 70% in SF<sub>6</sub> gas at 0.4 MPa. A more unified approach to the question of spacers was dealt with in [40], where there was a simultaneous change of both electrode shape and insulating material for optimum electric field distribution. Thus, the cathode shape was modified by rounding the cathode radius near the triple junction. The maximum electric field was efficiently reduced through the application of the FGM spacer. When compared to the uniform permittivity spacer model, a 26.5% decrease in the maximum electric field was obtained with the optimal FGM spacer configuration. FGMs as solution for a more balanced distribution of electrical fields was also presented in [41], mentioning the research on post-type and truncated-cone-type solid insulators for gas-insulated switchgear, which were developed using the centrifugation technique to distribute the fillers and, therefore, permittivity. The authors of [41] present an example of a U-shape permittivity grading, which reduces the electric field stress between 10 to 20 times. Moreover, in the same paper, they propose the use of FGMs as a viable solution of great importance (along, among others, with polymer nanocomposites, high temperature materials, charging control dielectrics and nonlinear dielectrics).

Emphasis on the centrifugal method was given in [42]. This method was successful in obtaining the fabrication of  $\epsilon$ -FGM materials, for which both the packing fraction and size of the dispersed fillers were graded. According to the authors of [42], the fillers depending on their sizes play different roles in order to determine the profiles of the packing fraction and the resultant permittivity profiles in  $\epsilon$ -FGM materials. Among the small (with a diameter between 0.1 – 10  $\mu\text{m}$ ), medium (with a diameter between 10-100  $\mu\text{m}$ ), and larger fillers (with a diameter between 100  $\mu\text{m}$  - 1000  $\mu\text{m}$ ), the small and medium size fillers determine the gradient of permittivity in the dispersion layers whereas the larger fillers predominantly determine the permittivity in the fully packed area. The same group of researchers in an earlier paper rightly wrote that – w.r.t. the centrifugal method - the proper choice of the process parameters such that of operational time, of the angular velocity and the statistical distribution of the filler size may lead to the desired profile of permittivities [43]. The authors in [44] proposed a multi-layer FGM approach, according to which different kinds of grading processes are applied and, by so doing, the non-homogeneous dispersion of nanoparticles is achieved between each layer, which in turn creates a smooth grading action and improves the electrical properties of the samples. An improvement in dielectric strength was noted. A comprehensive theoretical analysis of multi-layered FGMs was

offered in [45], where computational estimates of permittivity and conductivity gave results much closer to the experimental data than well-known models (Maxwell-Garnett's model, Bruggeman's model, the coherent potential model, and Lichtenecker's model [46]). As was noted in [44], the theoretical estimates of permittivity and conductivity based on the models of [46] tend to deviate from the respective experimental values when filler loadings exceed the 10% of the volume, whereas this is not observed with the proposed computational model which is based on the Representative Volume Element (RVE) approach.

#### IV. PROPOSALS FOR FURTHER RESEARCH

FGMs contribute to the better distribution of electric fields in certain applications. A possibility for further research can be the exploration of these materials regarding their behavior in voltages at or just below the inception level. Previous work with conventional insulating materials has shown that deteriorating phenomena can be observed at voltage levels below the inception level. Past work compared the by-products emanating from deterioration above inception with the by-products produced below inception. The by-products on both occasions were very similar [47-49]. Moreover, charge injection and extraction may relate to a tree initiation mechanism that does not involve partial discharges [50, 51]. Work done with polymer nanocomposites [52], also tends to confirm the conclusions of [47-49, 53, 54]. It would be interesting to see whether with the FGMs one can get some experimental data at and below inception level, since charging phenomena below inception voltage seem to be important although not much attention has been paid to them. Furthermore, with the advent of recent research, another possibility would be the use of FGMs in high voltage applications having together micro-fillers as well as nano-fillers [55].

Another interesting possibility can be the application of such materials to high voltage applications requiring very thin layers. It is well known that considerable effort has been taken in order to improve the electrical performance of traditional high voltage insulators (glass/porcelain) with RTV coatings [56, 57]. It would be challenging from the fabrication point of view to find whether FGMs can be applied to small thicknesses, such as the thicknesses of the RTV coatings.

#### V. CONCLUSIONS

In this short review, an attempt was made to present some aspects of FGMs. These materials seem to be very promising in alleviating the electric field stress in spacers for gas insulated systems. FGMs – in the context of this short review – were approached primarily as materials for permittivity control. The experimental data show that there is an important diminution of electric stress in the triple junction point, which tends to be most crucial for spacers.

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