Study of electric field stress on the surface contour and at the triple junction in three phase GIS with FGM spacer under the depression defect

Abstract: Now days, the establishment of spacers is in wide usage in three-phase Gas Insulated Busduct (GIB) for providing mechanical support and better insulation to the conductors. The region of the intersection of SF6 gas, enclosure end and the spacer is one of the weakest links in GIB, so the major concentration is done on minimization of electric field stress at this junction by using Functionally Graded Material (FGM) technique. The other incidents of insulation failures are due to several defects like depression, delamination etc. reduces the dielectric strength of the spacers. In this paper, an FGM post type spacer has been designed for a three-phase GIB under depression and further electric field stress at Triple Junction (TJ) is reduced by introducing a metal insert (MI) nearer to the TJ. Several filler materials are used as doping materials for obtaining different permittivity values using FGM technique to achieve uniform electric field stress. Simulation is carried out for the designed spacer at various operating voltages with different types of FGM gradings. The effect of depression with different dimensions and positions is analyzed before and after inserting MI to the FGM post type spacer in three-phase GIB.

Keywords: depression; electric field stress; FGM; gas insulated busduct; metal insert; spacer.

1 Introduction

Presently, Gas Insulated Busduct (GIB) is in wide use, to meet the high electrical demand with low transmission losses and good efficiency. The GIB is more advantageous
than air-insulated substations and they are based on the
principle of enclosing all the conducting and energized
parts inside a metallic enclosure with zero potential insu-
lated with SF6 gas. Few authors [1, 2] has reviewed that
most of the electrical-breakdown in the GIB is due to
transient voltages which occurs during the switching
operation of disconnectors or circuit breakers by weak-
ening of the electric field inside the gas-insulated sub-
estations, affecting the performance of support insulators,
transmission lines, cables, current transformers, voltage
transformers, and high-voltage generators. Wenjia X. et al.
[3] has identified new calculation methods for induced
voltage and current for the hybrid transmission system in
Gas Insulated Lines which occurs due to several switching
operations of the switches under different conditions for
hybrid transmission system. Talaat M. [4] described mate-
rial spacer failures as the most challenges faced by GIB.
Such spacers lose their power due to many defects such as
void, delamination, etc. As a consequence of such faults,
an effective approach must be implemented to minimize
electrical field stress. This weakening of the electrical field
across the spacer contributes to disruption to the whole GIB
impacting the whole power system, resulting in a signif-
icant loss of resources. Few researchers [5–9] has observed
that Gas Insulated Substation leads very fast transient
overvoltage’s and their associated transient currents dur-
ing switching operations and analyzed parameters like
arching time, pre-arching time, secondary discharges, trapped
voltages, and level of contamination to design an
appropriate switch to prevent induced current from fault-
proof earthing switches. They also developed an analytical
model to calculate ground resistance, step and touch po-
tentials of the proposed GIS grounding system with proper
concrete foundations and designed current sensors to
measure the leakage current through the bushing insu-
lation and surge arrester blocks.

In the literature, few researchers [10, 11] studied func-
tional issues concerning the nature of cone type and
disk type spacers. The analysis of electric field stress in GIB,
where it was mainly observed that the efficiency of insu-
lation ability over spacers can be enhanced by different
techniques, such as shape regulation, the addition of
shield electrodes, embedded electrodes, etc. However,
these spacer design approaches have very limited influ-
ence over the distribution of electric field in the spacer and
as a consequence, a new methodology called Functionally
Graded Material (FGM) filled with specific permittivity
materials has been described by few authors [12–14] in
order to resolve the difficulties of the previous methods and
to make them more economical. Some researchers [15–17]
have stated that this is the latest technique of FGM design
of spacer, has certain difficulties in processing, construc-
tion, and so on. However, they have come up with a remedy
by producing an FGM spacer with three separate forms of
gradings, such as increasing, decreasing, and U form of
permitting ranges by utilizing centrifugal forces. Later
Naoki Hayakawa et al. [18] identified that ε-FGM with
spacial distribution is one of the effective methods for the
reduction of the electric field in along the length of the
spacer, despite several methods, Flexible Mixture Casting
(FMC) the method is chosen for the fabrication of ε-FGM
spacer. Muneaki K. et al. [19] reviewed that FEM analysis is
a mathematical tool used in the design of FGM spacer by
grading the plain epoxy spacer with different permittivity
values for the reduction of the electric field stress in the GIS.
Few authors [20, 21] have identified that electric field in-
tensity is very high at Triple Junction (TJ) due to high
electron emission and the reduction in the field stress has
been achieved by inserting metal inserts (MI) at this junc-
tion of the enclosure end and the conductor end of the cone
type spacer. C.M. Cooke et al. [22] investigated the surface
flashover on post-type support spacer for GIL and proved
that it can be reduced by placing MI, however, the concept
of MI and its effect on electric field at TJ is carried out for
cone type spacer in a single-phase GIS also the same can to
be analyzed in three-phase GIB. Some of the researchers
[23–25] have identified some defects like metal depression
will be produced inevitably due to irregularities of GIS
spacers during the installation and operation of GIS. These
metal depressions along with suspended particles can
cause distortion of the electric field over the spacer surface
and hence high electric field stress inside GIS, which leads
to Partial discharge and breakdown. Especially, with the
increase of operating voltage, even a small defect leads to
internal failures in compact GIS due to spacer failures.
Several authors [26, 27] observed that the failures of the
spacers are due to the presence of particles or defects like,
Free particles on the inner surface of the enclosure, Depress-
sion on the inner surface of the enclosure and narrow gaps
between the spacer and the electrode as they develop high
electric field stress at the contacts between the parts of the
HV conductor and low voltage (LV) conductor. Though SF6
exhibits very high dielectric strength within the GIS the
Electromagnetic wave is generated from the depression
and short gap discharge in gas-insulated substation due to
rise in partial discharge. It was observed by G. Ueta et al.
[28] that the rise and fall times of a defect in the spacer is
relatively longer than those of a defect in SF6 gas such as a
metallic particle, metallic depression on the conductor, or
floating electrode. Wensheng Gao et al. [29] have been
identified that partial discharge occurs due to four types of
typical defects like floating metal, depression, particle on the spacer, and void in solid insulation and analyzed their effects at different sizes of each defect for observing the consistency frequency spectrum characteristics. Qikun Feng et al. [30] has studied the effect of metal depression on concave sides of the basin-type insulator in GIS at different heights and radii of metal depression and observed that at high voltage conductor the electric field stress is higher than that of grounded enclosure. Feng-Chang Gu et al. [31] has identified four GIS models with typical defects where the models include internal conductor of porcelain bushing at load side like Type 1: Conductor of porcelain bushing containing oil grease, Type 2: Gas tank containing metal particles, Type 3: Operation handle containing welding depression, Type 4: Metal ring with an abrasion defect. Tao Wen et al. [32] has evaluated the effectiveness of on-site GIS equipment with insulation defects, based on the insulation characteristics of a coaxial cylinder structure SF6 gas gap with a conductive depression under the impulses of different dimensions resulted with 50% breakdown voltage in the voltage-time curve. Ladani M. et al. [33] has reviewed a new method for the reduction of the electric field at the spacer surface and at the TJ by geometry shape optimization by using Finite Element Method (FEM) and Nelder–Mead algorithm by optimizing the shape and size of the MI and the spacer.

Many researchers have been worked on the reduction of electric field stress due to several defects on the spacers like cone type, disc type etc. in a single-phase gas-insulated busduct at the TJ’s at HV and LV ends of the spacer by using several techniques like FGM rather than its shape control technique due to its complications. Whereas by considering dielectric failures of insulators as a challenge in a three-phase GIB the literature has been carried out on the defects like depression which on the solid materials. The main aim of this paper is to design a proper MI at the enclosure end for an FGM post type spacer for a three-phase GIB to study the electric field stress at the TJ’s due to defects like depression and analyze for the reduction of electric field stress after inserting MI. The FGM of the spacer is a new technique which is used for minimizing the electric field stress in the GIS by modulating the permittivity values of the spacer. By using this grading technique with appropriate permittivity distribution the field stress at the required position can be minimized. In this paper, FGM grading is done by applying centrifugal forces in three different types of gradings like GL-FGM, GH-FGM, and GU-FGM. Depression is one of the defects of the spacers which affects the electric field stress drastically, on its surface and protrusion is caused mostly due to scratches on the spacer surface because of insufficient care during assembly of GIB. The permittivity-grading of materials can be done in two methods, i.e., by applying centrifugal forces and three dimensional (3D) printing by incorporating fillers of different diameters in order to obtain the permittivity distribution for uniform field distribution [34]. Here a centrifugal the approach is used for the grading of permittivity values as it is found to be the most efficient method.

In this paper, the electric field stress due to normal FGM gradings was introduced and a MI was placed at the enclosure end of the proposed FGM post type spacer, which essentially decreases the electrical field stress at the TJ and obtains a uniform field along the spacer surface. The recessed MI at conductor B offered an appropriate shielding to minimize electric field stress at TJ due to depression of various radii. However, this method of introducing MI has been minimized the complexity and the cost of replacement of spacer. Simulation shall be carried out by designing a three-phase GIB by giving proper charge to the conductors and the enclosure. The electrical field stress was analyzed at the end of the enclosure near the TJ of the FGM spacer. The electric field distribution produced by depression of the FGM post type spacer on the spacer surface and the TJ is determined. The electric field stress on the spacer surface, the conductor and at the TJ at the enclosure end are analyzed. The same procedure is applied to three different ranges of permittivity values, three types of FGM grading techniques for conductor B at the enclosure end. The recessed MI is incorporated into the FGM spacer at the end of conductor B to provide better electrical field stress at the critical/weak junction of the spacer in order to maintain uniform field stress by considering an appropriate shape and size of the MIs to analyze the results.

2 Mathematical modeling of three phase GIB

Many researchers have calculated the electrical field by using Laplace and Poisson equations applied to a particular assumed domain. The three phase GIB’s are operating at HVs, so the analytical approach to Laplace’s equation and Poisson ‘s equation is very difficult. So to overcome this complexity numerical methods are used for the calculation of electric field. These methods are classified into Finite Difference Method (FDM), FEM, Charge Simulation Method (CSM), and the Boundary Element Method (BEM). Despite advantages and disadvantages of the above methods, FEM is observed as more suitable for solving the complex problems. The FEM is used in this paper to determine the
The electric field stress on the surface of the spacer, which is an efficient method for solving electrical field problems. When considering the presence of depression in GIB, a two dimensional (2D) simulation model was created and the governing equations are described as below

\[ \vec{E} = -\nabla \varphi \]  
\[ \nabla \cdot \vec{D} = \rho_v \]  
\[ \vec{D} = \varepsilon \vec{E} \]  

where \( \vec{D} \) is the electric flux density, \( E \) is the electric field intensity, \( \rho_v \) is the charge density, \( \varepsilon \) is permittivity, \( \varphi \) is the electric potential. Then by substituting Equations (1) and (3) in Equation (2),

\[ \nabla \cdot \varepsilon \vec{E} = \rho_v \]  

then

\[ \nabla \cdot (\varepsilon \nabla \varphi) = \rho_v \]  

The dielectrics under consideration are considered to be linear, isotropic and homogeneous, the \( 'e' \) can be taken from derivatives, then Equation (5) can be simplified by Equation (6) in Poisson’s equation.

\[ \nabla^2 \varphi = \frac{-\rho_v}{\varepsilon} \]  

The charge under consideration is distributed uniformly with zero volume charge density \( \rho_v \), and hence Equation (6) can be simplified to Laplace’s equation

\[ \nabla^2 \varphi = 0 \]  

Consider, \( \varphi_A, \varphi_B \) and \( \varphi_C \) are the voltage potentials of the three conductors A, B, C with respect to the zero potential end as shown in Figure 1. For a three phase balanced system, \( d_{AB}, d_{BC}, d_{CA} \) are distances between the three conductors with a radius of “r” mm and \( \rho_A, \rho_B, \rho_C \) are their line charge densities respectively.

\[ \varphi = \varphi_A + \varphi_B + \varphi_C \]  
\[ \nabla^2 \varphi_A + \nabla^2 \varphi_B + \nabla^2 \varphi_C = 0 \]  

\[ \varphi_A = \frac{\rho_A}{6\pi\varepsilon_0} \left( \ln \frac{d_{AB}d_{BC}}{r^3} \right) \]  
\[ \varphi_B = \frac{\rho_B}{6\pi\varepsilon_0} \left( \ln \frac{d_{BC}d_{CA}}{r^3} \right) \]  
\[ \varphi_C = \frac{\rho_C}{6\pi\varepsilon_0} \left( \ln \frac{d_{CA}d_{AB}}{r^3} \right) \]  

Substituting Equations (10)–(12) in Equation (9).

\[ \nabla^2 \varphi = \nabla^2 \left( [\rho_A + \rho_B + \rho_C] \ln \frac{d_{AB}d_{BC}d_{CA}}{r^3} \right) = 0 \]  

then Equation (13) can be simplified as,

\[ \varphi = \left( [\rho_A + \rho_B + \rho_C] \ln \frac{d_{AB}d_{BC}d_{CA}}{r^3} \right) \]  

From the concept of FEM analysis the electric field intensity for a 2D consideration for a three phase system is given by

\[ \vec{E} = -\frac{\partial \varphi(x, y)}{\partial x} \hat{x} - \frac{\partial \varphi(x, y)}{\partial y} \hat{y} \]  

But for a three-phase GIB, as all the conductors inside GIB are spaced at equidistant [25]. It is necessary to consider the symmetrical system, i.e., \( d_{AB} = d_{BC} = d_{CA} = d \) and Equations (14) and (16) can then be written as,

\[ \varphi = \left( [\rho_A + \rho_B + \rho_C] \ln \frac{d}{r} \right) \]  

\[ \vec{E} = -\frac{1}{2\pi \varepsilon_0} \left[ \frac{\partial}{\partial x} \left( \ln \frac{d}{r} [\rho_A + \rho_B + \rho_C] \right) \hat{x} + \frac{\partial}{\partial y} \left( \ln \frac{d}{r} [\rho_A + \rho_B + \rho_C] \right) \hat{y} \right] \]  

3 Electric field computation of three phase GIB by using finite element method

Finite Element Method has been commonly used to solve electrical field problems owing to its capacity to
understand the multiple constructions and dynamic forms of different domains electrodes. This approach relies on reducing the electrostatic energy function. Under steady state electrostatic fields within a dielectric material of constant dielectric strength, with the Cartesian coordinate system, and by using Laplace equation, the electrical energy “W” stored within the whole volume ‘v’ of the region considered as given below with Equation (19).

\[ W = \frac{1}{2} \iiint \varepsilon (\nabla^2 \phi) \, dv \]  

(19)

In 3D dimensions the electrostatic energy in terms of electrical potential is given as,

\[ W = \frac{1}{2} \iiint \left( \varepsilon_x \frac{\partial^2 \phi}{\partial x^2} + \varepsilon_y \frac{\partial^2 \phi}{\partial y^2} + \varepsilon_z \frac{\partial^2 \phi}{\partial z^2} \right) \, dv \]  

(20)

where \( \varepsilon_x, \varepsilon_y, \) and \( \varepsilon_z \) are the x, y, and z-components of the dielectric constant in the Cartesian coordinates. Thus the entire region being considered is subdivided into triangular components. Therefore the electrostatic energy for a small area of the 2D domain \((dxdy)\) is given by

\[ W' = \frac{1}{2} \iint \left( \varepsilon_x \frac{\partial^2 \phi}{\partial x^2} + \varepsilon_y \frac{\partial^2 \phi}{\partial y^2} \right) \, dxdy \]  

(21)

Since from Equations (7) and (19),

\[ dW = \frac{1}{2} \iint \varepsilon (\nabla^2 \phi) \, dxdy = 0 \]  

(22)

Therefore

\[ dW = 0 \]  

(23)

4 Functionally graded material post type spacer

Figure 2 represents the FGM technique applied to the design of the post type spacer in the proposed three-phase GIB to develop uniform field distribution throughout the spacer length. In this paper, multiple grading methods for FGM post type spacers, have used \( \varepsilon \)-FGM with three separate grading forms such as GL-FGM, GH-FGM, and GU-FGM using centrifugal forces. The fabrication of GL-FGM Post type spacer is done by the following Algorithm.

**Step-1.** Consider the filler materials like Al\(_2\)O\(_3\), TiO\(_2\), and SiO\(_2\) to combine with the Epoxy resin with hardener.

**Step-2.** Transfer the mixture of fillers and epoxy resin into a test cup.

**Step-3.** Evaporate the above sample to be free from air bubbles by Degassing.

**Step-4.** Apply centrifugal forces to the sample with the help of the centrifugal separator.

**Step-5.** Repeat the above procedure for the fabrication of GH-FGM and GU-FGM with the corresponding fillers.

In this paper, the three different ranges of permittivity are considered as given below for the three types of grading. The different types of FGM grading i.e., GL-FGM, GH-FGM and GU-FGM are designed with the permittivity values of different cases are as shown in Table 1. For the above table the variation of permittivity values for different FGM gradings with respect to the three cases are as described, the permittivity is in the range of 3.95–3.5 in case 1, 4.05–3.6 in case 2 and 4.15–3.7 in case 3 from conductor end to enclosure end for GL-FGM grading. For GH-FGM grading, it is observed that the permittivity is in the range of 3.5–3.95 in case 1, 3.6–4.05 in case 2 and 3.7–4.15 in case 3 from conductor end to enclosure end. Whereas for case 1 the filler concentration with high permittivity i.e., 3.95 at conductor end is considered, the filler permittivity is gradually decreased up to 3.5 and again increased in steps to 3.95 nearer to enclosure end. Similarly for case 2 and case 3 the permittivity is varied from 4.05 to 3.6 to 4.05 and 4.15 to 3.7 to 4.15 respectively as shown in Figure 3. The FGM spacer is designed with 10 equal height gradings for the three conductors of their respective lengths and widths. The grading is done with different ranges of permittivity in three different types of FGM technique. In the cases 1, 2, and 3 the permittivity ranges are chosen as 3.5–3.95, 3.6–4.05, and 3.7–4.15 respectively. The FGM spacer is analyzed for these three types of gradings GL-FGM, GH-FGM, GU-FGM gradings are achieved by adding centrifugal forces along with other materials to the mixture of...
epoxy content. For GL-FGM, permittivity is the function of the radius and the high permittivity at the end of the inner conductor shall be retained and slowly decreased by increasing the radius in the direction of the end of the enclosure. Likewise for GH-FGM grading high permittivity is at the end of the enclosure and for GU-FGM grading, permittivity distribution in U-shape.

5 Results and discussions

5.1 Simulation model of three phase GIB

The simple simulation model of a three-phase gas-insulated busduct with a radius of 225.5 mm of the typical enclosure busduct without depression. The three-phase GIB with a relative permittivity of 1.0015 is filled with SF6 gas. With a radius of 38.66 mm each, the three conductors A, B, and C are contained within the common enclosure and positioned at the corners of the equilateral triangle. The distance between the conductor A to that of the end of the enclosure is taken as 193.8 mm. Whereas the gap between the conductors B and C is taken as 43 and 193.8 mm respectively to that of the enclosure end and the width of each spacer is taken as 26 mm respectively. The three-phase GIB is simulated using the FEM concept. The proposed simulation model, positions of all three conductors A, B, and C within the common enclosed GIB are equidistant from each other. The conductor A is applied with the RMS voltages of VA equal to 72.5, 132, and 220 kV and the voltages of the conductor’s VB and VC are with a phase shift of −120° and +120° respectively. The outer electrode is grounded with zero voltage. Table 2 represents the corresponding maximum voltages of conductor A, B, C of the considered RMS voltages.

5.2 Effect of depression on FGM post type spacer

Depression is the most typical and frequently occurred defects on the spacer for its failure from the literature. Metal depressions are typically found on the spacers at the concave side and are often caused by scratches on the spacer surface due to inadequate care during assembly. Similar to the defects like metallic particles and delamination, depression occurs most commonly in GIB due to switching operations and lightning impulses. During high voltages, the shape of the depression tip can be either sharply angled and can also be modified to a round shape. Such two defects will affect the distribution of the electric field over the length of the spacer and thus the GIB operation. The rounded depression with several radii has been verified from the simulation of the designed FGM post type spacer for three-phase GIB as represented in Table 3. By

Table 1: Permittivity values of GL, GH, GU-FGM gradings.

| Grading type | Permittivity ranges |
|--------------|---------------------|
| GL-FGM      | Case 1: 3.95–3.5 | Case 2: 4.05–3.6 | Case 3: 4.15–3.7 |
| GH-FGM      | 3.5–3.95           | 3.6–4.05          | 3.7–4.15          |
| GU-FGM      | 3.95–3 to 3.95    | 4.05–3.6 to 4.15 | 4.15–3.7 to 4.15 |

Table 2: Maximum values of RMS voltages of conductor A, B, C.

| RMS voltage (kV) | V_A_max (kV) | V_B_max (kV) | V_C_max (kV) |
|------------------|--------------|--------------|--------------|
| V_1 = 72.5       | 102.515      | −51.258      | −51.258      |
| V_2 = 132        | 186.65       | −93.324      | −93.324      |
| V_3 = 220        | 311.08       | −155.54      | −155.54      |

Figure 3: Permittivity values of GL, GH, GU-FGM gradings at different cases.
comparing all the values of depression from Table 3, the field is highly affected due to depression at the 2nd grading segment with $D_d$ as the diameter of depression and radius 0.2 mm rather than the depression in 1st grading segment and the depression located at both the gradings at a time.

Figure 4 shows that the electric field increases with an increase in the operating voltage from 72.5 to 220 kV and also increases as the radius decreases from 2 to 0.2 mm. This is evident from Figure 5 that the electrical field rises with an increase in the operating voltage from 72.5 to 220 kV and is held almost constant when the radius is decreased from 2 to 0.2 mm. Through comparing Figures 4 and 5 it is clear that at the respective voltages the high electric field stress is obtained at 0.2 mm in grading-2 as opposed to grading-1. The above study, therefore, considers depression with a radius of 0.2 mm in the 2nd FGM grading section for further analysis in the three-phase gas isolated busduct as shown in Figure 6. Due to the defect depression, the electric field distribution at the spacer surface can be measured using the contact angle produced by this defect at the TJ. Figure 6 shows the design diagrams

| Radius (mm) | Grading 1 | Grading 2 |
|-------------|-----------|-----------|
|             | 72.5 kV   | 132 kV    | 220 kV    | 72.5 kV   | 132 kV    | 220 kV    |
| 2 0.055     | 0.1       | 0.173     | 0.102     | 0.1865    | 0.311     |
| 0.8 0.0631  | 0.115     | 0.1918    | 0.1095    | 0.199     | 0.332     |
| 0.6 0.082   | 0.1495    | 0.2487    | 0.11      | 0.201     | 0.335     |
| 0.2 0.1078  | 0.1963    | 0.3275    | 0.11105   | 0.2022    | 0.338     |

**Figure 4:** Variation of electric field stress at different radii of depression in grading-1.

**Figure 5:** Variation of electric field stress at different radii of depression in grading-2.

**Figure 6:** Representation of depression on conductor B.

**Figure 7:** Design of FGM post type spacer with depression and MI.
for three-phase GIB with the FGM post-type spacer defect depression without MI. To reduce this effect of depression, a recessed MI (the combination of rectangle and ellipse in the 2D approach) with dimensions of the rectangle as (22 × 1.5 mm) along the ellipse of the axis length as 12.5 mm and a b-axis of 1.5 mm has been identified with a maximum reduction of an electric field being designed at the end of the enclosure. As shown in Figure 7, this particular MI was designed to be introduced at conductor B.

5.3 Analysis of FGM post type spacer

An FGM post type spacer is designed to create a uniform distribution of electric fields, as shown in Figure 2. The various types of FGM gradations i.e., GL-FGM, GH-FGM, and GU-FGM are constructed with different case permittivity values. Figure 3 represents the variance of permittivity values for different FGM gradations with respect to the three cases. From Table 4, it has been found that GL-FGM grading has high electric field stress at the ends of the enclosure at TJ, for case 1 for conductors A and C and for case 3 for conductor B for all three applied voltages of $V_1$, $V_2$, $V_3$ compared to other situations. It is observed that the electrical field stress at conductor A is high since the applied voltage is comparatively maximum at conductor A, for $V_1 = 72$ kV as applied RMS voltage then the maximum voltages at A, B, C is $V_A = 102.515$ kV, $V_B = -51.257$ kV, and $V_C = -51.257$ kV respectively. From Figure 8 it is observed that for all three conductors the magnitude of electric field stress at the enclosure end is high. Figures 8–10 show the distribution of the electric field for conductors A, B and C at $V_1 = 72.5$ kV, $V_2 = 132$ kV, and $V_3 = 220$ kV respectively over GL-FGM post type spacer. Though there is a uniform distribution over the spacer surface, it is found that the three conductors with peak

### Table 4: Electric field stress of FGM post type spacer.

| Type  | Conductor | Permittivity values | $V_1 = 72.5$ kV | $V_2 = 132$ kV | $V_3 = 220$ kV |
|-------|-----------|---------------------|-----------------|----------------|----------------|
|       |           | Electric field stress at enclosure in kV/cm | Electric field stress at conductor in kV/cm | Electric field stress at enclosure in kV/cm | Electric field stress at conductor in kV/cm | Electric field stress at enclosure in kV/cm | Electric field stress at conductor in kV/cm |
| GL-FGM | A Case 1 | 0.00728 | 0.17245 | 0.01325 | 0.31397 | 0.0221 | 0.5233 |
|        | Case 2   | 0.00705 | 0.1718 | 0.01275 | 0.3128 | 0.0213 | 0.5214 |
|        | Case 3   | 0.00678 | 0.1714 | 0.01235 | 0.3121 | 0.0205 | 0.5205 |
|        | B Case 1 | 0.1102 | 0.1453 | 0.2023 | 0.26458 | 0.3372 | 0.441 |
|        | Case 2   | 0.11118 | 0.1454 | 0.2024 | 0.2647 | 0.3373 | 0.4414 |
|        | Case 3   | 0.11121 | 0.1455 | 0.2025 | 0.2648 | 0.3375 | 0.4415 |
|        | C Case 1 | 0.03595 | 0.1198 | 0.0655 | 0.2182 | 0.10915 | 0.3636 |
|        | Case 2   | 0.03593 | 0.1193 | 0.0654 | 0.2173 | 0.10898 | 0.3622 |
|        | Case 3   | 0.03585 | 0.1188 | 0.0653 | 0.2164 | 0.1088 | 0.3607 |
| GH-FGM | A Case 1 | 0.00075 | 0.1759 | 0.01285 | 0.3203 | 0.02143 | 0.53375 |
|        | Case 2   | 0.00685 | 0.1751 | 0.0124 | 0.3188 | 0.0208 | 0.5313 |
|        | Case 3   | 0.00666 | 0.1744 | 0.012 | 0.3175 | 0.02 | 0.529 |
|        | B Case 1 | 0.1007 | 0.1456 | 0.1833 | 0.26512 | 0.3055 | 0.44188 |
|        | Case 2   | 0.1009 | 0.14562 | 0.1838 | 0.26515 | 0.3064 | 0.4419 |
|        | Case 3   | 0.1013 | 0.1457 | 0.1842 | 0.2652 | 0.307 | 0.442 |
|        | C Case 1 | 0.03432 | 0.1222 | 0.06245 | 0.2225 | 0.1041 | 0.3709 |
|        | Case 2   | 0.03428 | 0.1215 | 0.0624 | 0.2214 | 0.104 | 0.3691 |
|        | Case 3   | 0.0342 | 0.121 | 0.06238 | 0.2204 | 0.1037 | 0.3675 |
| GU-FGM | A Case 1 | 0.007 | 0.1725 | 0.01278 | 0.3142 | 0.02128 | 0.5237 |
|        | Case 2   | 0.00687 | 0.172 | 0.0123 | 0.3135 | 0.0206 | 0.522 |
|        | Case 3   | 0.00655 | 0.1715 | 0.012 | 0.312 | 0.01998 | 0.52 |
|        | B Case 1 | 0.1019 | 0.1445 | 0.1855 | 0.2635 | 0.3094 | 0.4395 |
|        | Case 2   | 0.102 | 0.145 | 0.1864 | 0.2638 | 0.31 | 0.4398 |
|        | Case 3   | 0.1024 | 0.14504 | 0.1862 | 0.264 | 0.3105 | 0.44 |
|        | C Case 1 | 0.0345 | 0.12 | 0.0627 | 0.2198 | 0.1045 | 0.3635 |
|        | Case 2   | 0.0344 | 0.1193 | 0.0625 | 0.2173 | 0.1044 | 0.3621 |
|        | Case 3   | 0.03435 | 0.119 | 0.0622 | 0.2165 | 0.1042 | 0.361 |
values in the plots have high electric field stress at the conductor ends. It is found that there is a spike with a sudden increase in the magnitude of electric field stress of conductor B as compared to the other two conductors at TJ. Figure 11 is the surface plot of the designed FGM spacers with height. Because of its high potential, the red-colored rise in height represents high electric field stress at conductor A and the dark blue color indicates high electrical field stress that is observed at the ends of the enclosure.

5.4 Study of electric field stress FGM post type spacer with depression

The above designed FGM post type spacer with depression have been resulted with high electric field stress at TJ at the enclosure end of conductor B with 0.2 mm in grading 2 of the FGM spacer as shown in Figure 6. Accordingly, the simulation is carried for conductor B only and tabulated in Table 5. In order to develop a uniform distribution of electric fields over the spacer surface, an MI is incorporated in the conductor B enclosure as shown in Figure 7. It has been identified from Table 5 that case 3 of GL-FGM grading has high electric field stress at the ends of the enclosure at TJ for all three applied voltages of V1, V2, V3 compared to other cases and gradations. For GL-FGM grading of case 3 of conductor B, the electric field stress is measured as 0.11115 kV/cm and the field stress after inserting MI it is measured as 0.0086 kV/cm which is reduced by 92.26% at V1 = 72.5 kV, similarly at V2 = 132 kV, the field stress is reduced from 0.20235 to 0.0157 kV/cm with a reduction of 92.24% and at V3 = 220 kV, the field stress is reduced from 0.33725 to 0.02618 kV/cm with a reduction of 92.24%.

Figure 12 shows that the magnitude of electric field stress at the enclosure is high for all three operating voltages and also very high at the conductor end with the highest peak values and this high stress is further reduced by using MI at TJ’s and the results obtained are shown in Figure 14. Figures 13 and 15 clearly show the zoomed
electric field at the enclosure ends without and with MI. Figures 16 and 17 are the surface plots of the designed FGM spacers with depression at conductor B without and with MI’s respectively and from Figure 16, the arrows with greater dimension is observed at depression in grading 2, TJ at enclosure end of the FGM post type spacer which is representing high electric field stress. This field stress is reduced at the location of depression as well as at TJ, after introducing MI at enclosure end as shown in Figure 17. It is apparent from Figure 18 that the electrical field at TJ is measured very high with more electric field lines and further reduced by using MI with comparatively fewer field lines at TJ as shown in Figure 19. The above Figures 20 and 21 represent conductor B’s quiver plot for FGM post-type spacer with depression with high electric field stress and reduction of depression and MI in the electrical field stress. Likewise the electrical field stress in the designed FGM post type spacers can be seen from the mesh plot due to depression without and with MI. The mesh triangle’s thickness indicates that the field is high because of its curved shape. Mesh plot’s main purpose is to set the plot element quality, rather than a uniform color. Mesh plot uses various data sets for different plots and can be represented in a single plot group to achieve the most exciting results and the corresponding mesh plot of FGM post-type spacer with depression without and with MI is as shown in Figures 22 and 23.

### 6 Conclusion

In this paper, the effect of depression is analyzed which was developed due to aging, switching operations, and lightning impulses. This defect depression, affects the dielectric permittivity, insulation capacity and the electric field distribution of the FGM post type spacer. The 2D simulation model of FGM post type spacer for a three-phase GIB with GL-FGM, GH-FGM and GU-FGM gradings with different permittivity values are studied to analyze the effect of depression with several observations as listed below.

- The electric field stress at the conductor’s ends is more than that of the enclosure end for all the three conductors as the conductors are with high potential compared to the potential of enclosure end.
- High electric field stress is observed at the TJ of enclosure end of conductor B rather than conductors A and C, hence the defect depression is introduced at this conductor.
- The electric field stress has been increased drastically at TJ if the depression is located at grading 2,
which was also raised at 0.2 mm radius of the depression at different permittivity ranges of the spacer.

- The effect of depression on the electric field distribution increases as the relative permittivity of the spacer increases.

- For the above-mentioned location and the dimension of depression, it was observed that the highest electric field stress is obtained at case 3 of GL-FGM grading at the TJ of conductor B at all the operating voltages.

- The highest percentage reduction of electric field stress is observed in case 3 for GH-FGM and GU-FGM gradings.
Figure 18: Contour plot of FGM post type spacer with depression.

Figure 19: Contour plot of FGM post type spacer with depression and MI.

Figure 20: Quiver plot of FGM post type spacer with depression.

Figure 21: Quiver plot of FGM post type spacer with depression and MI.

Figure 22: Mesh plot of FGM post type spacer with depression.

Figure 23: Mesh plot of FGM post type spacer with depression and MI.
So this new technique of FGM insulation will provide a better solution to the distribution of electric field in GIB and with the insertion of the MI at the TJ, the electric field stress can be reduced even under the effect of severe defect like depression on an FGM post type spacer in three-phase GIB.

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