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Field Optimization and Electrostatic Stress Reduction of Proposed Conductor Scheme for Pliable Gas-Insulated Transmission Lines

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Featured Application: Flexible gas-insulated transmission lines (FGILs) are a potential candidate for the trenchless underground implementation of high-voltage transmission lines in metropolitan areas. This research highlights the necessity of field intensity minimization and field irregularity suppression for FGILs regarding stranded conductors and proposes a practicable scheme for the same. The proposed scheme will facilitate the achievement of analogous electrostatic and dielectric characteristics for FGILs as compared to conventional gas-insulated lines (GILs).

Abstract: The implementation of stranded conductors in flexible gas-insulated transmission lines (FGILs) requires field intensity minimization as well as field irregularity suppression in order to avoid dielectric breakdown. Moreover, the interdependence of enclosure and conductor sizes of FGILs regarding electrostatic aspects necessitate critical consideration of their dimensional specifications. In this research, geometric and electrostatic field optimization for FGILs regarding stranded conductors is performed. In addition, the effect of conductor irregularity on field dispersion is analyzed, and a semiconducting film (SCF)-coated stranded conductor is proposed as a potential candidate for FGILs. Considering the performed optimized design, an 11 kV scaled-down model of a 132-kV FGIL was also fabricated in order to practically analyze its electrostatic and dielectric performances regarding simple and SCF-coated stranded conductors. Simulation and experimental investigations revealed that the SCF-coated stranded conductor significantly minimized the field irregularity of the FGIL along with improving in its dielectric breakdown characteristics.

Keywords: dielectric strength; field grading; field utilization factor (FUF); gas-insulated transmission line; metropolitan; stranded conductor

1. Introduction

Escalating urbanization and industrialization has resulted in an increased load demand along with the necessity of higher system stability and reliability, which requires the upgrade and new installation of power transmission schemes (PTSs) [1–5]. Moreover, renewable energy integration [6,7], smart grid development [5,8], and the need of interruption-free operation in the case of faults [8,9] also require the implementation of PTSs within metropolitan areas [10,11]. Researchers have described that conventional PTSs include overhead lines (OHLs) [1,3,5,10,12], underground cables (UGCs) [7,13,14] and gas-insulated lines (GILs) [15–18]. Literature regarding the metropolitan application of PTSs mentioned



that OHLs and UGCs encounter hindrances such as right of way [2,3,19], spatial proximity [9,20,21], aesthetics [19,20], system failure due to prolonged fault clearance time [8,9], corrosion [2,22], trench requirements [14,23], and electromagnetic compatibility (EMC) concerns [2,4,21,24,25]. Further, studies mentioned that conventional GILs also face impediments regarding their implementation in urban vicinities due to their metallic profile, such as their structural rigidity [15,25,26], larger bending radius and lay length [15,16,27], jointing complexities [15,17,27], corrosion protection [16,24,28], requirement of acceleration dampers [17,24,29], and trench development [11,27,30]. Thus, protruding urbanization, despite being a potential load consumer, critically curtails the implementation of conventional PTSs in metropolitan vicinities.

References [11,31-34] reveal that flexible gas-insulated lines (FGILs) comprised of a reinforced thermoplastic enclosure, stranded conductor, and polyurethane (PU) post insulator are a potential candidate for curtailing the intricacies associated with the implementation of conventional PTSs in metropolitan areas. Further, researchers [35-37] have mentioned that flexible cables and enclosures like FGILs are practicable for horizontal directional drilling (HDD)-based underground laying schemes and do not require trench development, which is highly beneficial in urban vicinities. Thus, the simplification of several issues associated with conventional PTSs like right of way, EMC concerns, trench requirement, corrosion protection, and larger land area requirement makes FGILs an appropriate scheme for the subsurface metropolitan application of high-voltage lines. However, researchers have mentioned that the contour irregularity of stranded conductors [38] is a point of concern due to its irregular field distribution [39,40], which results in poor field utilization [17,24,41,42] and augments partial discharge activity [43–45] and streamers [43,45,46]. Moreover, references [17,24,41,42] mentioned that the interdependence of enclosure and conductor sizes apropos of field utilization necessitate critical consideration regarding the dimensional specifications of FGILs in case of any variation in their field utilization. Thus, field irregularity due to stranded conductors in FGILs along with its effect upon dimensional specification needs thoughtful consideration.

Researchers [47–56] mentioned that regarding GILs, irregular field distribution and partial discharge activity due to electrode irregularities could be curtailed by the implementation of a solid dielectric layer on the electrode. However, the implementation of a solid dielectric layer in an FGIL would result in its reduced structural flexibility, which is objectionable regarding their metropolitan applications. A probable solution for conductor irregularity suppression in FGILs could be the implementation of a flexible semiconducting film (SCF) over the stranded conductor. SCFs basically exhibit non-linear conducting characteristics and will facilitate the minimization of the field irregularity and field intensity of FGILs without compromising their structural flexibility. Thus, considering the field irregularity concerns of FGILs, in this research, Autodesk Inventor® was used to model the geometric variants of stranded conductors. These conductor models were then analyzed in COMSOL Multiphysics[®] regarding electrostatic and dielectric aspects along with the development of the geometrically and electrostatically optimized FGIL model. Considering the performed optimized design, an 11 kV scaled-down model of a 132 kV FGIL was also fabricated in order to practically investigate the electrostatic and dielectric stresses in the FGIL through a high-voltage experimental setup. Simulation and experimental investigations revealed that SCF-coated stranded conductor significantly minimized the field irregularity of the FGIL and improved its dielectric breakdown characteristics.

2. Stranded Conductor Geometric Variants

Stranded conductors are normally discriminated on the basis of strand geometry as well as the compactness technique used in the conductor development [57]. The geometric configuration of stranded conductors used in UGCs and OHLs are specified in Table 1, and Figure 1 represents circular and trapezoidal strand conductors [57].

Sr. No.	Conductor Type	Strand Geometry		
1.	Concentric strand	Circular		
2.	Compact strand	Circular		
3.	Compact strand	Trapezoidal		

Table 1. Stranded conductors used in conventional power transmission systems.



Figure 1. (a) Circular strand and (b) trapezoidal strand conductors used in conventional power transmission schemes.

Electric Field Dispersal Regarding Strand Geometry

The electric field dispersion in a region normally depends upon electrode geometry, surface irregularity, and gap distribution [58]. The field utilization factor (FUF) gives an idea of the effective utilization of field space and facilitates analysis of the electrostatic stresses imposed upon the dielectric material. In general, the FUF can be evaluated through Equation (1), where E_{avg} denotes the average electric field and E_{max} denotes the maximum electric field. Further, pertaining to its coaxial configuration, the FUF for an FGIL can be calculated through Equation (2), where *R* is the enclosure's radius in millimeters and *r* is the conductor's radius in millimeters [41].

$$\eta = \frac{E_{avg}}{E_{max}} \tag{1}$$

$$F = \frac{r \cdot \left(\ln \frac{R}{r}\right)}{R - r} \tag{2}$$

3. Design and Analysis

3.1. Dimensional Optimization of FGIL Enclosure Apropos of Stranded Conductor

The selection of a stranded conductor for an FGIL requires reconsideration regarding enclosure diameter because the FUF for GILs is normally kept in the range of 0.5 to 0.6 and is directly related with their dimensional specifications [24,41,42]. In a standard GIL, enclosure and conductor dimensions are normally selected to have approximately 1 as the solution of the logarithmic expression in Equation (2). That is, the enclosure diameter is approximately three times the conductor diameter [24,41,42]. However, in order to have an optimized enclosure size regarding the required FUF, Equation (2) was rearranged for enclosure dimension and expressed as Equation (3). Considering that Equation (3) appears as an implicit equation, its solution was performed through the Newton–Raphson iterative (NR) method in MATLAB[®] with the required accuracy up to four decimals and an initial estimate of 50 for the unknown parameter (i.e., enclosure radius). The estimated values and their errors showed a converging trend, and the enclosure radius finally converged in eleven iterations up to the required accuracy.

Dimensional appraisal of conductor and enclosure revealed that the enclosure was approximately three times the conductor size and resulted in the achievement of the desired FUF.

$$R = rexp\left(F \cdot \left(\left(\frac{R}{r}\right) - 1\right)\right) \tag{3}$$

3.2. Electrostatic Field Optimization of the FGIL

Electric field optimization is obligatory in electrical systems in order to eradicate the prospect of dielectric failure due to partial discharge or gap discharge [58]. Considering the stranded conductor as a potential candidate for pliable GILs and concerning its surface irregularity, detailed electrostatic appraisal is essentially required for the proposed scheme. Protrusions and surface irregularities in stranded conductors may lead to escalated electric fields on the conductor's surface contour, which may result in detrimental partial discharge activity followed by dielectric strength degradation due to streamers [43–45,58]. Thus, considering the importance of field dispersion in pliable GIL, COMSOL Multiphysics[®]-based electrostatic analysis was performed for the FGIL regarding the stranded conductor specimens given in Table 2 in comparison to existing GILs in order to achieve minimal electrostatic stresses as per the required standards for gas-insulated equipment. The stranded conductors used in the electrostatic examination were developed using Autodesk Inventor[®]. Dimensional and technical specifications like electrode gap, thickness, and diameter for the conventional and proposed schemes were based upon ASTM B 232, ASTM B 857, and 132 kV GIL standards along with the evaluations of Section 3.1 [59,60]. Table 2 presents the detailed specifications of different conductor specimens used in the electrostatic stress investigation [59,61,62].

Table 2. Conductor specimens used in the comparative appraisal.

Specimen No.	Category	Material	Structure	Strand Geometry	Profile	Diameter (mm)
1.	Conventional	Aluminum	Hollow		Smooth	89
2.	Proposed	Aluminum	Stranded	Circular	Irregular	44.79
3.	Proposed	Aluminum	Stranded	Trapezoidal	Irregular	44.70

3.2.1. Electrostatic Field Dispersion Apropos of Conventional and Stranded Conductors

Concerning the analysis of the field dispersion along with identification of regions of high electric fields in the proposed GIL scheme, COMSOL Multiphysics[®]-based models for conventional and pliable GILs were developed and compared regarding the different conductor configurations given in Table 2. Figure 2a,b demonstrates the electric potential and electric field dispersion in a conventional GIL. Figure 3a,b exhibits the electric potential and electrostatic field dispersal in the proposed GIL with a circular strand conductor. Figure 4a,b represents the electric potential and electrostatic field distribution in the proposed GIL with trapezoidal strand conductor. Field dispersion regarding conventional and proposed schemes revealed that stranded conductors resulted in regions of concentrated electric field on the conductor's surface contour. Figure 5a,b represents the enlarged view of such concentrated electric field regions in the FGIL scheme regarding specimen 2 and specimen 3 of Table 2. Critical perusal of Figures 2–5 regarding electric field dispersion reveals that due to protrusions and surface irregularities of the stranded conductors, high electric fields appeared on their surface contour as compared to the conventional scheme with a smooth solid conductor. However, the trapezoidal strand conductor had approximately 10% lower magnitude of maximum electric field stresses due to its relatively smoother profile in comparison to the circular strand conductor. Figure 6 compares the average and maximum electric fields for conventional and proposed GIL schemes regarding the different conductor specimens described in Table 2. Further, Figure 7 compares the FUF for conventional and proposed GIL schemes regarding the different conductor specimens described in Table 2. Detailed analysis of Figures 6 and 7 revealed that the surface irregularity of stranded conductors in the proposed pliable GIL resulted in objectionably high electric fields regarding specimen 2 and specimen 3 in

comparison to the conventional scheme regarding specimen 1. Further, the field utilization factor was also reduced by 31% and 23% respectively for specimens 2 and 3 regarding proposed pliable GIL in comparison to specimen 1 regarding the conventional scheme. A probable solution to the above stated problem could be to enlarge the enclosure's diameter or to suppress the conductor's irregularity [63–65]. COMSOL Multiphysics[®]-based simulations were performed for this purpose, which revealed that enclosure enlargement resulted in the minimization of the irregular field distribution and reduced the electrostatic stresses on the conductor's surface. However, the FUF was reduced in comparison to the standard allowable limit for GILs because as per GIL standards, the enclosure's diameter should be approximately three times the conductor's diameter in order to acquire an FUF in the permissible range of 0.5 to 0.6 [17,24,41,42]. The violation of the aforementioned constraint regarding enclosure diameter resulted in a poor field utilization factor for the proposed scheme, which is objectionable as per GIL standards. Thus, remedial measures regarding suppression of irregularities in the stranded conductor must be taken in order to achieve the required FUF and eradicate concentrated electric field regions.



Figure 2. (a) Potential difference and (b) field distribution apropos of a conventional gas-insulated transmission line (GIL) regarding specimen 1 of Table 2.



Figure 3. (**a**) Potential difference and (**b**) field distribution apropos of the proposed pliable GIL regarding specimen 2 of Table 2.



Figure 4. (**a**) Potential difference and (**b**) field distribution apropos of the proposed pliable GIL regarding specimen 3 of Table 2.



Figure 5. Location and magnitude of the maximum electric field for the proposed pliable GIL regarding (a) specimen 2 and (b) specimen 3 of Table 2.



Figure 6. Average and maximum electric field comparison regarding the different conductor specimens described in Table 2.



Figure 7. Field utilization factor comparison regarding the different conductor specimens described in Table 2.

3.2.2. Contour Irregularity Suppression of Stranded Conductor

Considering the objectionable deviations in the field utilization of the proposed FGIL due to stranded conductors, irregularity suppression essentially needs to be done in order to acquire the required FUF. A probable solution could be the implementation of a silicon carbide (SiC)-impregnated polyester-based SCF of 0.1–0.4 mm thickness on the stranded conductor in order to acquire a relatively smoother conductor profile [39,66,67]. The implementation of such film-coated stranded conductors in gas-insulated equipment necessitates detailed electrostatic and dielectric appraisal, as no published research regarding the implementation of field-graded stranded conductors in gas-insulated equipment exists to date.

3.2.3. Electrostatic Field Dispersion Apropos of Film-Coated Stranded Conductors

Concerning the effectivity of irregularity suppression for stranded conductors in terms of field utilization factor and electric field dispersion, SCF-coated stranded conductors were developed using Autodesk Inventor[®]. Dimensional specifications for the SCF-coated stranded conductors were based upon the ASTM B 232 and ASTM B 857 standards for stranded conductors, and the film thickness was based upon the standard film thickness for power cables [57,61,68]. Detailed specifications of the developed film-coated stranded conductors along with conventional GIL conductor are given in Table 3. Considering the conductor specimens given in Table 3, COMSOL Multiphysics[®]-based pliable GIL models were developed and analyzed in comparison to existing GIL schemes so as to achieve the desired electrostatic performance per the standards for GILs. Figure 8a,b demonstrates the electric potential and electrostatic field dispersion in the proposed pliable GIL scheme regarding specimen 2 of Table 3 respectively. Figure 9a,b exhibits the electric potential and electrostatic field distribution in the proposed pliable GIL scheme regarding specimen 3 of Table 3 respectively. Figure 10a,b shows the enlarged view of high electric field regions in the proposed FGIL scheme regarding specimens 2 and 3 of Table 3 respectively. Critical perusal of Figures 5 and 10 reveals that surface irregularity suppression resulted in substantial reduction in electrostatic stresses on the surface contour of the stranded conductor, and improved the field distribution for both stranded specimens of Table 3. However, specimen 3 had approximately 6% lower magnitude of maximum electrostatic stresses due to its nearly circular profile in comparison to specimen 2. Figure 11 compares the average and maximum electric fields for the conventional and proposed pliable GIL schemes regarding the respective conductor specimens of Table 3. Further, Figure 12 compares the field utilization factor of conventional and proposed GIL schemes regarding the respective conductor specimens of Table 3. Detailed analysis of

Figure 12 reveals that surface irregularity suppression resulted in achieving a relatively better FUF, with a trivial deviation of 7.5% and 1.8% regarding specimens 2 and 3 of Table 3 as compared to specimen 1 of the respective Table. In addition, a smoother conductor profile due to the SCF coating also resulted in substantial electrostatic stress reductions in the conductor contour up to 23% and 21% regarding specimens 2 and 3 of Table 3 in comparison to respective simple stranded conductors of Table 2. Further, in comparison to aluminum conductor steel reinforced (ACSR) and all aluminum alloy conductor steel supported (ACSS) category exhibit higher ampacity and thermal ratings within the same dimensional specifications [62]. Thus specimen 3 of Table 3 could serve as the optimal candidate regarding thermal, ampacity, and electrostatic requirements along with the desired flexibility for the proposed pliable GIL.

Specimen No.	Category	Material	Structure	Strand Geometry	Diameter (mm)	Film Material	Film Thickness (mm)
1.	Conventional	Aluminum	Hollow		89		
2.	Proposed	Aluminum	Stranded	Circular	44.79	SiC-impregnated polyester tape	0.2
3.	Proposed	Aluminum	Stranded	Trapezoidal	44.70	SiC-impregnated polyester tape	0.2

Table 3. Conductor specimens used in the comparative appraisal.



Figure 8. (a) Potential difference and (b) field distribution apropos of the proposed pliable GIL regarding specimen 2 of Table 3.



Figure 9. (a) Potential difference and (b) field distribution apropos of the proposed pliable GIL regarding specimen 3 of Table 3.



Figure 10. Location and magnitude of the maximum electric field for the proposed pliable GIL regarding (**a**) specimen 2 and (**b**) specimen 3 of Table 3.



Figure 11. Average and maximum electric field comparison regarding the different conductor specimens described in Table 3.



Figure 12. Field utilization factor comparison regarding the different conductor specimens described in Table 3.

3.3. Dielectric Appraisal of FGIL Apropos of the Stranded Conductor

In order to analyze the breakdown characteristics of the dielectric medium in the stranded-conductor-based FGIL model developed above, an analysis was performed regarding its minimum discharge voltage (i.e., breakdown voltage, BV). Existing methodologies for discharge voltage calculation can be categorized on the basis of the streamer breakdown theory as well as the critical field strength evaluations [58,69]. Both methodologies were incorporated in this research in order to ascertain the practicability of the suggested conductor scheme for a pliable GIL.

3.3.1. Breakdown Voltage of the Proposed Configuration Regarding Streamer Breakdown Theory

Per the streamer breakdown theory, a streamer may result in a partial discharge such as a corona or a complete gap discharge, and the associated potential level is considered as the breakdown voltage [58,69]. The minimum breakdown voltage in SF_6 insulated equipment can be evaluated by using Equation (4), where BV is the breakdown voltage in kV, P is the gas pressure in kPa, and d is the electrode gap in centimeters [58,69]. However, the effect of electrode surface irregularity should also be considered, as it significantly degrades the minimum breakdown voltage. Considering the conductor's surface irregularity in the model developed above, Equation (5) can be used for the evaluation of the minimum breakdown voltage, where BV is the breakdown voltage in kV, C is the curvature factor, d is the electrode gap in centimeters, F is the field utilization factor, P is the gas pressure in kPa, and S is the electrode roughness factor [58]. Further, considering the case when the dielectric medium comprises sulfur hexafluoride and nitrogen gases at a ratio of 20:80, its breakdown strength will be lesser in comparison to pure SF_6 gas, and will depend upon the percentage of SF_6 in the mixture. Thus, Equation (6) can be used for the evaluation of possible degradation in the minimum breakdown voltage of the gas mixture [69]. Figure 13 shows the electrode gap comparison between the 132-kV conventional and proposed GIL scheme which is further used in the evaluation of the minimum breakdown voltage for the proposed scheme. Reduction in electrode gap resulted due to the reduction of conductor diameter from 89 mm to 44.5 mm, as the proposed scheme comprises a stranded aluminum conductor whereas the conventional scheme comprises a hollow aluminum conductor. However, the ampacity of both conductors was kept approximately the same. Further, the diameter of the ground electrode was also reduced from 226 to 127.2 mm, as it is based on the dimensional evaluations performed in Section 3.1 regarding the standard field utilization factor as well as the standard dimensional specifications for GILs. Figure 14 represents the breakdown voltage for 100% SF₆ content and the respective reduction in this breakdown voltage due to surface irregularity of the stranded conductor using Equations (4) and (5). Moreover, it also highlights the reduction in breakdown voltage due to the reduced SF_6 content in the SF_6 and N_2 gas mixture through Equation (6). Critical analysis of Figures 13 and 14 shows that the BV for the given dimensional and operational specifications of the proposed 132 kV pliable GIL was well above the normal operating voltage and the standard basis insulation level (BIL) value of 132 kV. Thus, per the evaluated dimensional specifications, the proposed FGIL scheme exhibits good dielectric withstand capability.

$$BV = 1.321 \cdot (Pd)^{0.915} \tag{4}$$

$$BV = 0.8775 \cdot F \cdot S \cdot C \cdot P \cdot d \tag{5}$$

$$m = 38.03 \cdot n^{0.21} \tag{6}$$



Figure 13. Electrode gap comparison between conventional and proposed flexible GIL (FGIL) schemes.



Figure 14. Breakdown voltage (BV) appraisal for the proposed FGIL scheme.

3.3.2. Breakdown Field Strength of the Proposed Configuration Regarding Critical Field Intensity Theory

In the critical field intensity method, the breakdown voltage of a dielectric gas is associated with critical field, electrode gap, FUF, electrode surface irregularity, and gas pressure [69]. According to this theory, the operational and design magnitudes of the electric field should be well below its critical value in order to avoid dielectric breakdown through avalanche [58]. Further, in accordance with GIL standards, the typical allowable design criterion regarding electric field strength is approximately 20 kV/mm, and might be higher such that the influenced region is not substantially enormous [24]. Thus, concerning the practical viability of the proposed 132-kV FGIL scheme, its electrostatic field appraisal regarding operational, design, and critical field values is essentially required. The operational and design values of the electric field in the proposed pliable GIL could be evaluated through Equation (7) by considering the normal operating voltage and standard BIL voltages, respectively [41]. Further, Equation (7) can be rearranged by considering Equations (1), (5), and (6) for the evaluation of the critical electric field as shown in Equation (8) [41,58]. In Equation (8), *BV* is the breakdown voltage and *E*_C is the critical electric field as evaluated on the basis of Equations (5) and (6). Figure 15

shows the comparison regarding the operational, design, and critical electric fields for the proposed scheme. Critical perusal of Figure 15 shows that the operational and design values for the electric field were well within limits as specified by the standards for gas-insulated equipment, and both field magnitudes were much less than the critical field value. Thus, per the appraised dimensional specifications, the proposed 132-kV FGIL scheme exhibits good electrostatic stress withstand capability.

$$E_{max} = \frac{U_0}{r \cdot \ln\left(\frac{R}{r}\right)} \tag{7}$$

$$E_c = \frac{BV}{f \cdot (R-r)} \tag{8}$$



Figure 15. Electric field appraisal for the proposed FGIL scheme regarding operational, standard BIL, and breakdown voltages.

3.4. Field Stress Distribution in Bended Segment of FGIL

In order to analyze the practicability of the proposed scheme for bent segments, simulation regarding electrostatic stress distribution for FGIL in case of bend was performed in comparison to its equivalent straight model. For the said purpose, 20-m-long straight and bent FGIL models were developed using Autodesk Inventor[®], and further field distribution and FUF for the two models were analyzed using COMSOL Multiphysics[®]. Line bending was performed as per the permissible longitudinal minimum bending radius (LMBR) of reinforced polyvinyl chloride (RPVC), and field distribution as well as FUF analysis for the respective FGIL models was performed regarding axial and radial cross sections. Critical appraisal of bent and straight FGIL models regrading axial cross section revealed a trivial deviation of 0.7% and 0.8% in electric field intensity and FUF, respectively. Moreover, detailed comparison of two FGIL models regrading radial cross section showed a slight deviation of 0.4% and 0.5% in electric field intensity and FUF, respectively. Minimal deviation in the compared models was observed because longitudinal bending as per LMBR limits resulted in negligible circumferential deformation as well as gradual bending. Thus, field magnitude and stress distribution for the bent line segment were nearly the same as those for the straight line segment.

4. Fabrication of the Scaled FGIL Model

Regarding the practical viability of the proposed scheme, an 11-kV scaled-down model of the 132-kV FGIL was fabricated on the basis of electrostatic modeling by replicating the field distribution of a high-voltage GIL for a scaled down model [17,24,41,42]. Considering the standard FUF and allowable maximum electric field for the 132 kV GIL, dimensional specifications regarding enclosure

and conductor of the 11 kV scaled down model were evaluated per the technique described in Section 3.1. After finalizing the dimensional specifications, the scaled down model was first analyzed and compared with the actual 132 kV GIL model by using the technique described in Sections 3.2 and 3.3 regarding field distribution, field magnitude, FUF, and breakdown characteristics using COMSOL Multiphysics[®]. Then, a practical model was developed in order to conduct experimental investigations. RPVC was used as the enclosure material, and braided metallic mesh covered with aluminum foil was placed inside the enclosure as the ground terminal. A stranded aluminum conductor was placed inside the RPVC pipe, and threaded Teflon corks were used to prevent any gas leakage from pipe ends. Further, metallic clamps were placed on Teflon corks in order to avoid cork slippage and gas leakage at high gas pressures. Electrically pretested open cell rebond foam of 105 kg/m³ density was used to achieve concentric conductor alignment inside the enclosure [34]. A gas charging and discharging system was implemented to pressurize the flexible GIL model at different gas pressures, and to create vacuum. The material and thickness of SCF were selected per the scheme described in Sections 3.2.2 and 3.2.3. The specified FGIL model for high-voltage experimentation was developed for simple as well as SCF-wrapped stranded conductors. Figure 16a,b shows the simple and SCF-coated stranded conductors used in the development of the FGIL models respectively. Figure 17a shows the dimensional specifications of the designed flexible GIL model, and Figure 17b shows the fully developed model.



Figure 16. (**a**) Simple stranded conductor and (**b**) semiconducting film (SCF)-coated stranded conductor used in the development of FGIL models.



Figure 17. (**a**) Dimensional specifications of the scaled FGIL model and (**b**) the fully developed scaled FGIL model.

5. Experimental Setup Development

Pertaining to the practicability of the proposed scheme, an experimental setup was developed regarding lightning impulse and power frequency disruptive discharge tests for the proposed scheme, as per the IEC 60060-1:2010 standard [70]. FGIL models, fabricated respectively with simple and SCF-coated stranded conductors, were used in this experimental investigation. Concerning the lightning impulse discharge tests, U_{50} for different GIL specimens was determined by Up–Down method, where for power frequency discharge an average of ten disruptive discharges was considered. A compressor and a pressure control unit were incorporated in order to create a vacuum in the developed GIL model along with the injection of dielectric gas at the desired pressure. Gas-insulated equipment normally utilizes pure SF₆ or a mixture of SF₆ and N₂ at a ratio of 20:80, but the required gas pressure in the latter case was almost doubled as compared to the prior case. Considering the security concerns associated with the high-pressure containment of SF₆/N₂ mixture at the laboratory level, pure SF₆ gas was used, as it would result in a significant reduction of the required gas pressure without compromising the insulation characteristics. A block diagram of the experimental setup is shown in Figure 18. Figure 19a represents the different components used in the high-voltage experimentation, while Figure 19b represents the experimental setup placed in a high-voltage laboratory.



Figure 18. Experimental setup for the dielectric strength testing of the developed FGIL models.



Figure 19. (a) Different components used in the discharge tests and (b) the experimental setup for lightning impulse and disruptive discharge tests.

5.1. Dielectric Breakdown Analysis of the Fabricated FGIL Models

Experimental analysis apropos of the dielectric breakdown of the developed FGIL models was performed for SF_6 and air gases at different gas pressures in order to investigate the power frequency and impulse discharge characteristics of the FGILs.

5.1.1. Power Frequency Discharge Test

In order to appraise the dielectric characteristics of the FGILs regarding simple and film-coated stranded conductors, power frequency discharge tests using air and SF₆ were performed for the fabricated FGIL models. After creating vacuum in the FGIL models, moisture-free air was filled at different gas pressures from 1 to 2.5 bar, and the discharge voltage was noted for both GIL models. Followed by air, similar power frequency discharge tests were performed regarding SF₆ gas for both FGIL specimens at different gas pressures from 1 to 2.5 bar. Figure 20 shows the disruptive discharge test results of air- and SF₆-filled simple and film-coated stranded-conductor-based FGIL models under different gas pressures. Critical analysis of Figure 20 reveals that the discharge voltage increased with increasing gas pressure in all cases. However, the FGIL model with a film-coated stranded conductor had relatively higher discharge voltages in air as well as sulfur hexafluoride respectively in comparison to the FGIL model with a simple stranded conductor. Further, pertaining to their higher dielectric strength, SF₆-filled FGIL models achieved higher breakdown voltages at the respective gas pressures.



Figure 20. Power frequency disruptive discharge investigations regarding air and SF₆ for different FGIL models.

5.1.2. Lightning Impulse Discharge Test

Concerning the impulse withstand characteristics of the developed models, lightning impulse voltage tests were conducted for SF_6 - and air-filled FGIL models with simple and SCF-coated stranded conductors. After creating vacuum in the FGIL models, moisture-free air was injected at different gas pressures from 1 to 2.5 bar, and lightning impulse discharge voltage was noted for both GIL models. Followed by air, similar lightning impulse discharge tests were performed regarding SF_6 gas for both FGIL models at different gas pressures from 1 to 2.5 bar. Figure 21 represents the test results of SF_6 - and air-filled simple and film-coated stranded-conductor-based GIL models under different gas pressures. Critical analysis of Figure 21 reveals that the impulse discharge voltage increased with increasing gas pressure in all cases. However, the GIL model with a film-coated stranded conductor had relatively higher discharge voltages regarding air as well as sulfur hexafluoride respectively in comparison to the GIL model with a simple stranded conductor. Further, owing to its higher dielectric strength, SF_6 -filled GIL models achieved the required BIL value for 11 kV beyond 2 bar pressure. Figure 22 shows the

recorded waveforms of lightning impulse discharge tests regarding air and SF_6 gases at a pressure of 2.38 bar.



Figure 21. Lightning impulse discharge investigations regarding air and SF₆ for different FGIL models.



Figure 22. Measured lightning impulse discharge voltage regarding air and SF₆ in fabricated FGIL model at 2.38 bar.

5.2. Critical Field and Breakdown Field Analysis of Fabricated FGIL Models

Concerning the GIL, constraints regarding dielectric design require that the $(E/P)_{Breakdown}$ should be relatively lesser than the $(E/P)_{Critical}$ of the respective dielectric gas. The critical reduced field strength $(E/P)_{Critical}$ at $(\alpha - \eta) = 0$ regarding air and SF₆ per the computations using the BOLSIG+ tool were estimated as 30 kV/cm/bar and 89 kV/cm/bar [41]. Here, η represents the electron attachment rate and α is the coefficient of ionization. Regarding the developed experimental setup, the pressure normalized maximum field strength at U_{50} , $(E_{max}/P)_{Breakdown}$, could be evaluated by rewriting Equation (7) as Equation (9), where r represents the conductor's radius in mm, R represents the enclosure's radius in mm, and P is the gas pressure in kPa. Figure 23 shows the computations by Equation (9) regarding the experimental findings of lightning impulse discharge characteristics for air- and SF₆-insulated FGIL models with simple and SCF-coated stranded conductors. Critical analysis of Figure 23 reveals that the $(E/P)_{Breakdown}$ was lesser than the $(E/P)_{Critical}$ for all scenarios, and furthermore, the SCF coating over the stranded conductor enhanced the breakdown field level for both air- and SF₆-insulated FGIL models. Thus, the developed FGIL models fulfill the above-stated dielectric design requirements for GILs.



$$(E_{max}/P)_{Breakdown} = \frac{U_{50}}{r \cdot \ln(\frac{R}{r}) \cdot P}$$
(9)

Figure 23. Field strength comparison in fabricated FGIL models regarding air and SF₆ at different gas pressures.

6. Conclusions

Conventional GILs are comprised of a hollow conductor which, owing to its intrinsic rigidity, restricts several application perspectives of conventional GILs specifically in metropolitan areas. Thus, the incorporation of structural flexibility in GILs is essential in order to curtail the operational intricacies of conventional GILs. In this research, FGIL models based on flexible simple stranded and flexible field graded stranded conductors were developed and analyzed regarding electrostatic and dielectric aspects through simulation and experimental assay.

Simulation results revealed that the simple stranded conductors had regions of objectionably high electric fields which ultimately resulted in 31% and 23% degradation of the FUF regarding circular strand and trapezoidal strand conductors respectively in comparison to the conventional GIL. Thus, simple stranded conductors may result in dielectric breakdown due to their surface irregularity, and require contour stress minimization. Possible solutions regarding stress minimization include enclosure enlargement and the suppression of conductors' irregularity. However, enclosure enlargement significantly deviated the FUF of the FGIL from its allowable range, which is highly objectionable according to GIL standards. Thus, field-graded stranded-conductor-based FGIL models were developed and analyzed through simulation and experimental investigations.

Simulation results revealed that SiC-coated stranded conductors resulted in the achievement of analogous electrostatic characteristics compared to the conventional GIL, with a trivial deviation of 7.2% and 1.8% in the FUF for circular strand and trapezoidal strand conductors, respectively, which are quite acceptable per the allowable FUF range for GILs. Further, critical comparison regarding dielectric aspects revealed that the breakdown voltage for the proposed scheme was approximately 23% above the required standard BIL value for GILs. In addition, electric fields for the proposed scheme regarding standard BIL voltage were approximately 38% below the critical field value and were well within the standard allowable range for electric fields in GILs.

Additionally, experimental investigations of fabricated FGIL models revealed that in comparison to the simple stranded-conductor-based model, the field-graded stranded-conductor-based model

exhibited approximately 10–20% and 5–15% higher discharge voltages in power frequency and lightning impulse discharge tests. Moreover, the $(E/P)_{Breakdown}$ for the fabricated pliable models were observed to be relatively lesser than the $(E/P)_{Critical}$ at $(\alpha - \eta) = 0$ for the respective dielectric gases.

Consequently, simulation and experimental analysis revealed that the proposed conductor scheme could facilitate the achievement of the required dielectric and electrostatic characteristics for FGILs as described by GIL standards. However, the next step of this research is to perform similar high-voltage investigations on a full-scale 132-kV FGIL demonstrator.

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