

Theoretical Assessment of Breakdown Voltage in a Hybrid Insulation System Using Nitrogen/Oxygen Gas Mixture with 10% Oxygen

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Abstract

SF₆ is widely used in the insulation of high-voltage systems such as circuit breakers and switching devices, due to its exceptional insulating properties. However, this gas is recognized as one of the main greenhouse gases. To limit the use of this gas, a hybrid solution consisting of the nitrogen/oxygen (N₂/O₂) gas mixture with 10% oxygen (O₂) and solid dielectrics used as electrode coatings and a barrier between parts with a difference in electric potential is considered. The theoretical assessment of breakdown voltage in hybrid insulation system, based on streamer inception and propagation criteria, is carried out using COMSOL Multiphysics and MATLAB software. The results showed that the combination of solid dielectric coating and barrier leads to a substantial increase of the relative flashover voltage above 33% for all the gap distance evaluated.

Keywords

Breakdown Voltage, Dielectric Coatings, Eco-Friendly Electrical Insulation Gas, Hybrid Insulation Systems, Solid Dielectric Barrier

1. Introduction

Sulfur hexafluoride (SF₆) has been widely used as insulating gas in high voltage systems, especially in circuit breakers, due to its exceptional dielectric properties [1]. And, gas-insulated switchgear has been made more compact by using this gas [2]. However, SF₆ is known as a greenhouse gas with a long atmospheric

lifetime [3] [4]. To reduce the environmental impact of this gas the use of an environmentally friendly insulating gas with even better dielectric characteristics is needed.

However, it is well known that dielectric properties of environmentally friendly gases such as nitrogen (N_2), carbon dioxide (CO_2) and air are weaker than that of SF_6 [5]. To surmount this weakness, the flashover voltage of a hybrid insulation system designed as a combination of a dielectric gas and solid insulating elements is evaluated. The hybrid insulation concept for SF_6 replacement has already been implemented in extensive work [6]-[8]. F. Mauseth *et al.* [6] found that breakdown voltage of an air gaps can be increased significantly by covering one or both electrodes with a dielectric coating. Other works conducted by M. Sjöberg *et al.* [9] in 2003 showed the improvement of insulation performance of air gap by using a dielectric barrier between electrodes.

In 2019, T. Rokunohe *et al.* [10] showed that air presents the best dielectric performance among natural insulating gases because of electronegative properties of oxygen. Furthermore, the investigations of fundamental electrical insulation properties of N_2/O_2 gas mixtures with different oxygen fraction including synthetic air conducted by E.O. Ndong *et al.* [11] in a WI busbar-tank of Schneider Electric showed that gas mixture with 10% O_2 presented overall a better breakdown voltage. Assuming that dielectric performance of hybrid insulation using natural gas may increase when using a gas with a greater breakdown voltage, the present work aims to evaluate the flashover voltage of the hybrid insulation system composed by N_2/O_2 gas mixture with 10% O_2 content, noted MG10, and solid dielectric material. The solid dielectric material assimilated to Kapton [12] consists of a barrier between electrodes and a dielectric coating on the metal parts with a difference of electric potential. The evaluation of flashover voltage in the present work, is carried out using COMSOL Multiphysics software, for the calculation of electric field distribution in the inter-electrode gap spacing ranging from 1 to 10 cm, and MATLAB, for sparkover voltage assessment based on the streamer inception and propagation criteria [13].

2. Materials and Methods

Breakdown voltage evaluation of the hybrid electrical insulation using MG10 with dielectric barrier and coatings is carried out using a configuration of two spherical electrodes (**Figure 1**). Calculations being performed in non-uniform electric field condition, the characteristics of elements involved in the electrode configuration are given in **Table 1**.

It is considered that in gases with a pressure higher than or equal to 1 bar and for an inter-electrode gap distance larger than a few centimeters, sparkover voltage is mainly caused by the streamer mechanism [14]. The theoretical analysis of the present computational program uses an approach in which the streamer onset and the propagation criteria are calculated based on the distribution of the electrostatic field around the electrodes [14] [15].

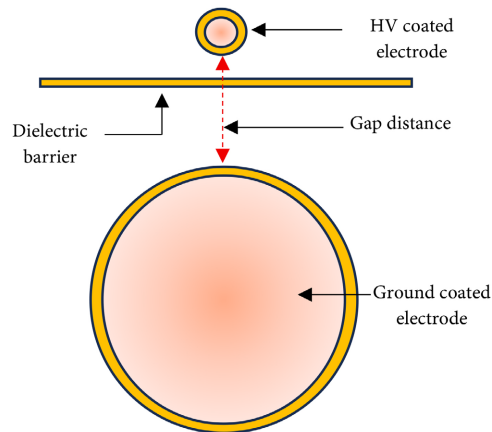


Figure 1. Model geometry simulated on COMSOL Multiphysics software.

Table 1. Geometric and dimensional characteristics of dielectric hybrid electrode configuration elements.

Element	Dimension
HV electrode	2 cm diameter
Ground electrode	20 cm diameter
Dielectric barrier	1 mm thickness and 20 cm diameter
Dielectric coating	0.5 to 1 mm thickness
Inter-electrode gap distance	1 to 10 cm inter-electrode gap distance

2.1. Streamer Inception and Propagation Criteria

The streamer inception criterion or Raether-Meek [14] condition states that the number of electrons in the active region of the electron avalanche must reach a critical value that would create a local electric field comparable to the applied external field. This condition is computed numerically by integrating the effective ionization coefficient $\alpha - \eta$ in the active region along the critical path, where the field strength is highest between electrodes and, therefore, where the strongest ionization of the gas takes place. The relation (1) gives a mathematical expression of streamer inception criterion [15].

$$\int_0^{x_c} [\alpha(E) - \beta(E)] dx = K \quad (1)$$

In relation (1) the coefficients α and η stand for ionization and attachment coefficients of the dielectric gas. These coefficients were taken as functions of electric field distributed along the critical path which the length is x_c in the inter-electrode gap distance. The constant K is the critical number of electrons in the tip of the avalanche [13]. In the present computational model, the effective ionization coefficient as a function of electric field is evaluated from BOLSIG+ [16] because of the difficulty to find reliable data in literature. The coefficient K of the integral is generally estimated between 9 and 18 [17]. Its value has been fixed at 9.15 as given in [13].

Figure 2 shows the behavior of the theoretical reduced effective ionization co-

efficient of different O₂ contents in N₂/O₂ gas mixture as a function of reduced electric field obtained from BOLSIG+ [16].

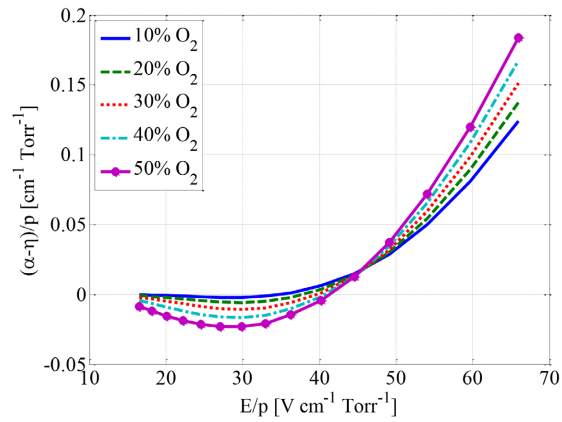


Figure 2. Reduced effective ionization coefficient as a function of reduced electric field for different fractions of O₂ in N₂/O₂ gas mixture calculated from BOLSIG+.

2.2. Breakdown Voltage Calculation

When the conditions of streamer inception and propagation are fulfilled at a certain magnitude of the applied voltage to the HV electrode, this voltage is considered as an estimate of the breakdown voltage. Therefore, evaluation of the breakdown voltage U_{BDV} can be given by the relation (2).

$$U_{BDV} = \int_0^{x_c} E(x) dx + E_p L_x \quad (2)$$

In the relation (2), the integral takes into account the voltage drop in the ionization region and the second term gives the voltage over the distance L_x defined as $L_x = d - x_c$, up to which the streamer propagates. The parameter d stands for the distance separating the electrodes in which sparkover appears during breakdown voltage process. E_p is the propagation field which the value has been fixed at 5 kV/cm for positive impulse breakdown voltage at 1 bar gas pressure [18].

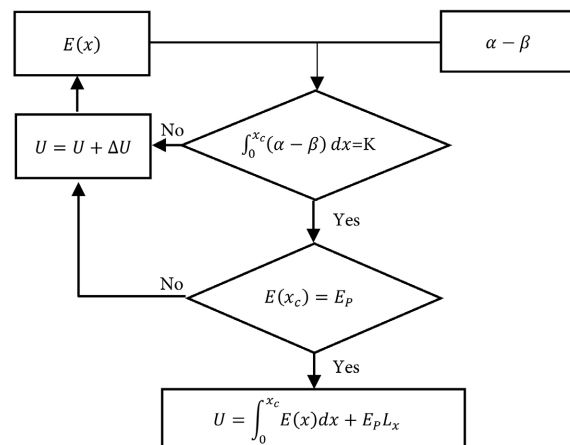


Figure 3. Computational flashover voltage flowchart implemented on Matlab software.

The algorithm used for positive sparkover voltage calculations (U_{BDV}) is implemented on MATLAB software according to the flowchart given in **Figure 3** [11].

2.3. Electric Field Calculation

The essential parameter at each stage of this study is the distribution of electric field $E(x)$ along the flashover path defined as the line where the field is stronger. For a configuration of spherical electrodes without solid dielectric barrier, the flashover path is taken as the shortest distance between these electrodes.

In presence of a solid dielectric barrier between electrodes, it becomes difficult to predict a breakdown path. However, as several authors in literature [19] [20], to assess breakdown voltage with a dielectric barrier, we considered the electric field distribution in two paths noticed path 2 and path 3 (**Figure 4**). Breakdown voltage calculated using these paths allows to determine a reasonable minimum and maximum theoretical values of breakdown voltage. The defined paths are drawn based on the fact that during breakdown process, streamer tends to skirt the solid dielectric barrier.

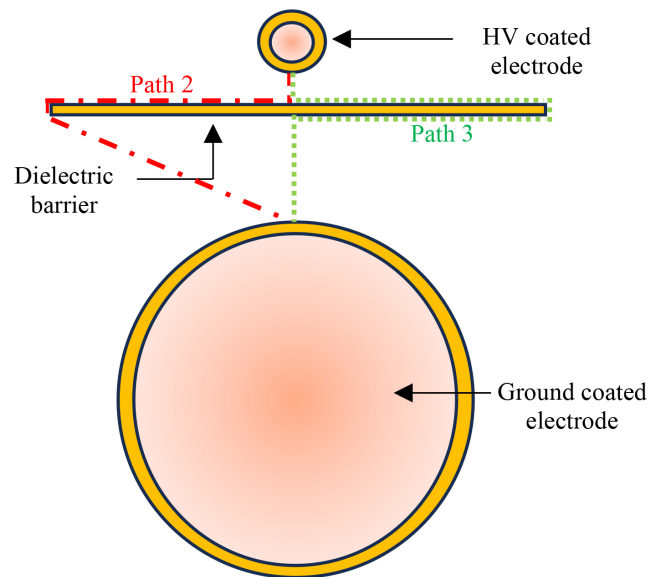


Figure 4. Path 2 and path 3 used for breakdown voltage calculation when considering solid dielectric in electrode configuration.

It is well known that breakdown voltage increases in presence of the barrier because this latter tends to lengthen the breakdown path. Path 2 and path 3 represent the longest and the shortest path for a streamer to reach the top of the grounded electrode. Therefore, the flashover voltage provides on these paths can be considered as a reasonable maximum and minimum breakdown voltage.

The electric field in the computational model is calculated for each distance separating the electrodes using finite elements based on COMSOL Multiphysics soft-

ware. The solid dielectric barrier and coating was assimilated to H-type Kapton [12]. A voltage of 1 V was applied to the 2 cm diameter copper sphere electrode while the 20 cm diameter sphere electrode in the same material was grounded. For meshing, the extremely fine mesh type was chosen in the numerical modelling.

3. Results and Discussion

3.1. Electric Field Distribution in Inter-Electrode Region

Figure 5 shows the electric field distribution in the sphere gap region when using a solid dielectric barrier and coatings. In this simulation, HV electrode has been supplied with an electric potential of 1 V and the other electrode was grounded for appreciating the field behavior. The environment of electrodes is considered as filled with 1 bar gas pressure (electric permittivity of 1) and the barrier was on electric floating potential. Thus, it is seen that electric field decreases logically from HV to grounded electrode (**Figure 5**).

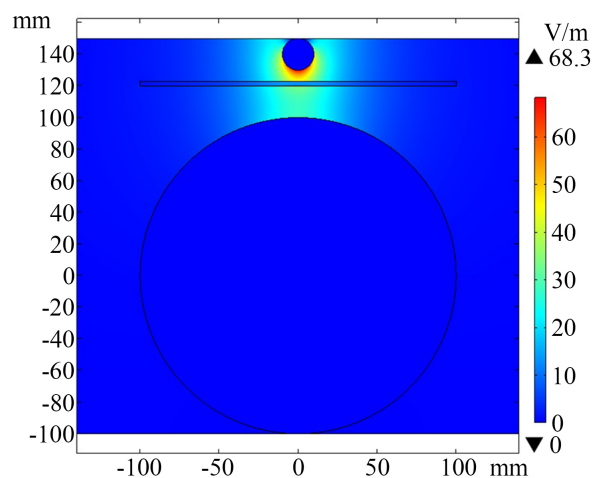
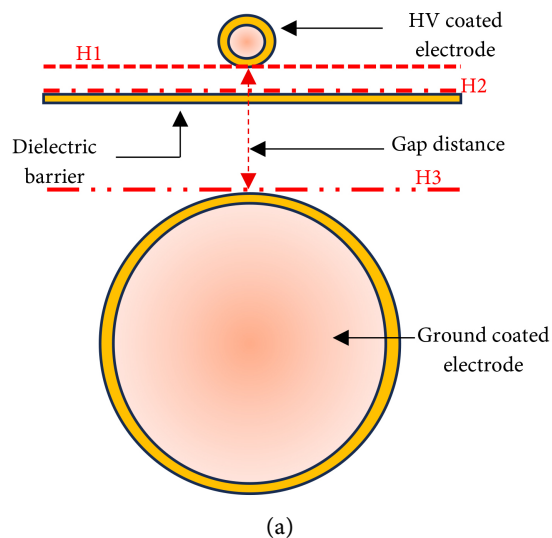


Figure 5. Electric field distribution in sphere gap region when using dielectric barrier between parts having a difference of electric potential and coating on electrode surfaces.



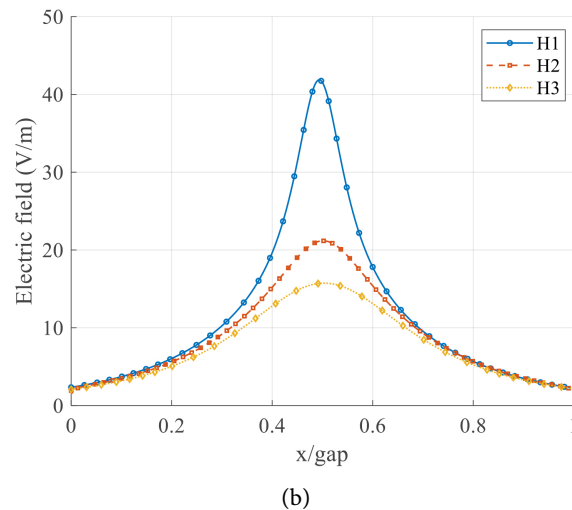


Figure 6. Determination of the critical path where electric field is strongest in the region located between electrodes. a) H1, H2 and H3 are the paths where electric fields have been evaluated, b) electric field distribution along the paths H1, H2 and H3 with the length noted gap. x stands as abscissa on length of these different paths.

The electric field behavior observed on the lines H1, H2 and H3 (**Figure 6(a)**) shows that, in the region located between electrodes, the field is strongest on the symmetric axis of electrodes (**Figure 6(b)**) and decreases when moving away from that axis. Therefore, without solid dielectric barrier the so-called critical path for streamer inception and propagation criteria is lied on the symmetric axis noticed path 1.

3.1.1. Electric Field Distribution on Path1 without Solid Dielectric

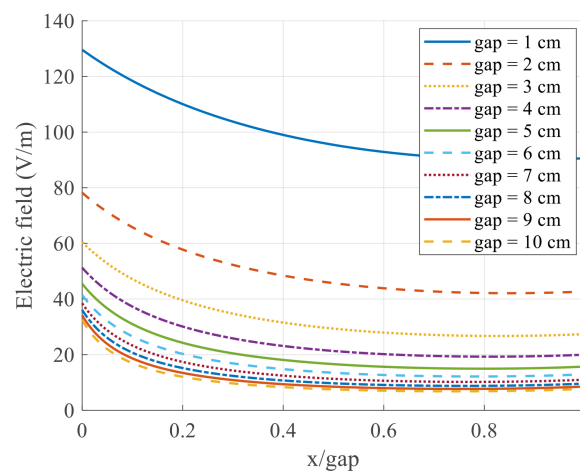


Figure 7. Electric field distribution in the critical path for different inter-electrode gap distances ranging from 1 to 10 cm. x stands as an abscissa in the critical path length.

Figure 7 highlights the electric field distribution on path 1 for different inter-electrode gap distances ranging from 1 to 10 cm without dielectric barrier and coatings. It is seen that electric field decreases logically from the HV electrode to the

ground electrode for all the inter-electrode distances. Simulation being carried out with an applied voltage of 1 V to the HV electrode, the decrease of the field observed by increasing of the gap distance stands to reason.

3.1.2. Electric Field Distribution on Critical Path with Dielectric Coating and Barrier

Figure 8 and **Figure 9** show the electric field distribution in path 1 for different inter-electrode gap distances ranging from 1 to 10 cm when considering the solid dielectric coating and barrier respectively.

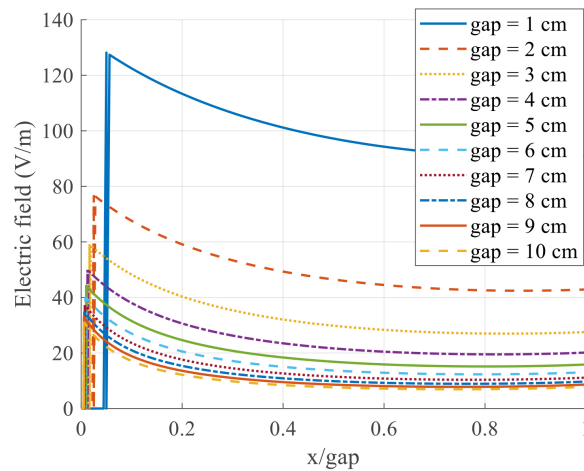


Figure 8. Electric field distribution in the critical path for different inter-electrode gap distances ranging from 1 to 10 cm with solid dielectric coating. x stands as an abscissa in the critical path.

The dielectric barrier is located near the HV electrode at a distance of a third of the inter-electrode distance. That location is known as the one which improves the breakdown voltage level of a hybrid insulated system constituting by dielectric gas and a solid dielectric barrier [20].

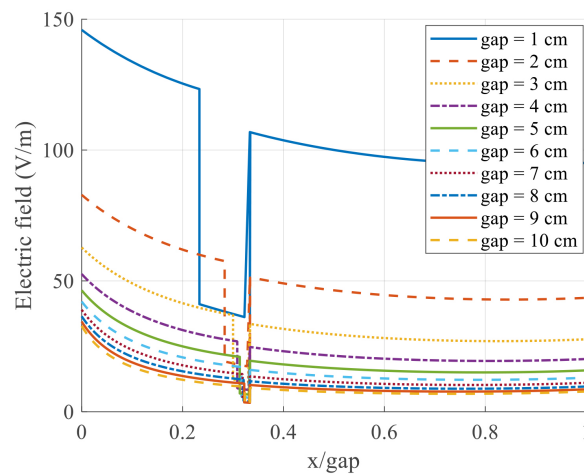


Figure 9. Electric field distribution in our electrode configuration with solid dielectric barrier regarding to the path 1.

In **Figure 8**, without dielectric barrier between electrodes, it is seen that the electric field behaves almost as that observed in **Figure 7**. However, the effect of solid dielectric coating on the surface of electrodes seems to shift the electric field near the electrode under voltage (HV electrode). In presence of a dielectric barrier between electrodes without a dielectric coating (**Figure 9**), a steep fall of the field appears at the level of the barrier due to the increase in the dielectric permittivity of the solid dielectric barrier.

In presence of barrier, flashover channel bypasses the barrier during breakdown process, therefore the field distributions in the paths 2 and 3 are also evaluated.

3.1.3. Electric Field Distribution on Path 2

Figure 10 shows the electric field distribution on the path 2 when a solid dielectric barrier is introduced in the electrode system without dielectric coating on the surface of electrodes. The electric field calculations are carried out with inter-electrode gap ranging from 1 to 10 cm.

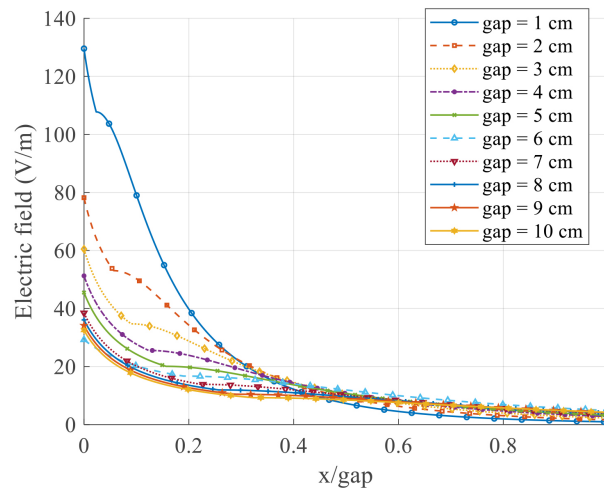


Figure 10. Electric field distribution in our electrode configuration with solid dielectric barrier regarding to the path 2.

It is seen in **Figure 10** that electric field decreases on the path 2 from the HV electrode to the ground electrode. This field decreases logically with the increase in the electrode gap distance up to a relative value of 0.4. Above this value, the field seems to be almost stable.

3.1.4. Electric Field Distribution on Path 3

The electric field change on the path 3 with different inter-electrode gap distances ranging from 1 to 10 cm is given on **Figure 11**.

It is observed that for all the gap distances, the electric field is more significant near electrodes in the case of path 3. **Figure 11** shows that the presence of the solid dielectric barrier leads to a strong increase of the field near the electrodes and its stabilization from the relative abscissa of 0.2 to 0.8.

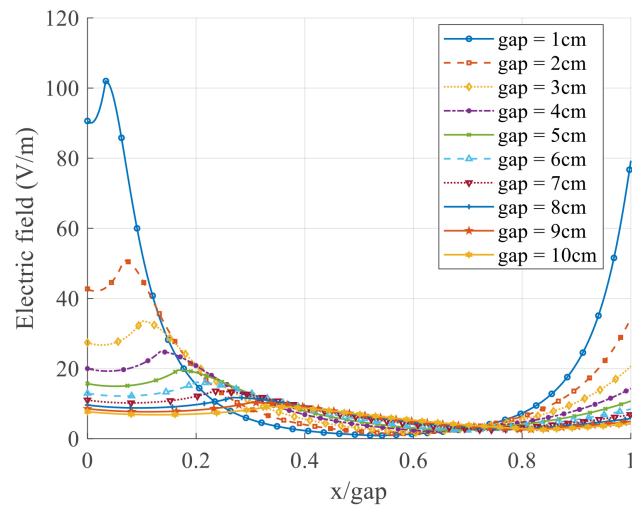


Figure 11. Electric field distribution on path 3 for different inter-electrode gap distances ranging from 1 to 10 cm without a solid dielectric coating. x stands as an abscissa on path 3.

3.2. Breakdown Voltage Assessment

The results of breakdown voltage calculations by using the electrode configuration without solid dielectric barrier are given in **Figure 12**. These calculations are carried out with MG10 for positive impulse polarity at 1 bar gas pressure. The influence of solid dielectric coating on electrode surfaces for different thicknesses of 0.5 and 1 mm is evaluated. Possible surface charges involved in breakdown process were not taken into account in this analysis. The inter-electrode gap distances were ranging from 1 to 10 cm.

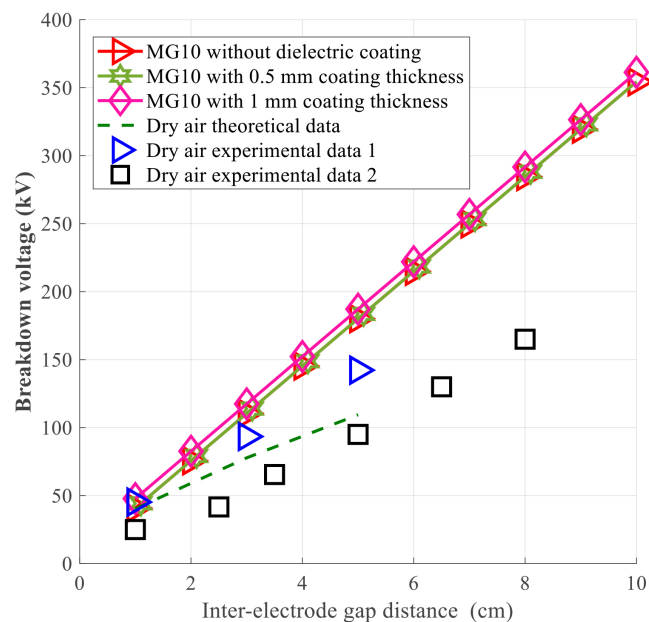


Figure 12. Theoretical breakdown voltage in MG10 calculated by using our electrode configuration without solid dielectric barrier.

It is seen that breakdown voltage in MG10 increases quasi-linearly with inter-electrode gap distance (**Figure 12**). This linear change in flashover voltage is also seen in dry air experimental average data (experimental data 1) measured with an approximate electrode configuration where the small and large sphere electrodes were 2 and 15 cm in diameter respectively. The breakdown voltage in MG10 is higher than that of dry air (theoretical data and experimental data 1) shown in **Figure 12** for comparison purpose [16]. The theoretical data are calculated using the present program with an appropriate effective ionization coefficient from BOLSIG+ software as given in [21]. A theoretical difference of 0.5 kV (1.2%) and 70.7 kV (64.5%) are seen respectively at 1 and 5 cm inter-electrode gap distances between the two dielectric gases.

The theoretical breakdown voltage of MG10 has also been compared to the experimental data obtained by P. N. Mikropoulos *et al.* [22] (experimental data 2) although the difference in electrode configuration. Indeed, the electrodes used by these authors were composed by a cylindrical rod of 2.3 cm diameter with a square cut end and a 15 cm diameter sphere. The quasi-linear behavior of flashover voltage against the inter-electrode gap distance is also seen in this case. The substantial gap with the theoretical sparkover voltage of MG10 (**Figure 12**) can be mainly understood because of the difference in the geometry of the small HV electrode, the field being stronger with sharp objects.

For the influence on breakdown voltage related to the solid dielectric coatings on the electrode surfaces, it has been observed that it is weak since the relative increase in breakdown voltage remains lower than 1% for the thicknesses considered in comparison with the MG10 breakdown voltage without coating (**Figure 12**). The influence of dielectric coating on the hybrid system with MG10 could be more significant by considering the surface charges influence on breakdown process [23].

Figure 13 shows the results of breakdown calculations performed with solid dielectric barrier and coating. These results are compared to those obtained in the same configuration of electrode without solid dielectric barrier and coating. The theoretical evaluation of breakdown voltage when considering a solid dielectric barrier is conducted following the paths 2 and 3 where breakdown is likely to occur [19] [20].

The results show a significant increase in breakdown voltage of MG10 gas when using a dielectric barrier between electrodes for both path 2 and path 3. It is noticed an increase of 325 kV (793%) and 116 kV (33%) for 1 cm and 10 cm inter-electrode gap distance respectively, between the reference breakdown (no barrier and coating) and the breakdown occurred with the path 2. The increase in flashover voltage with the path 3 is about 697 kV above the reference data for all the inter-electrode gap distance. The relative increase is seen to be about 1708% and 197% for 1 cm and 10 cm inter-electrode gap distance respectively.

The breakdown voltage assessed by using a solid dielectric barrier show logically higher values than those of the reference flashover voltage (without barrier and

coating) since the barrier lengthens the breakdown path. This explains also why the breakdown voltage calculated by using the path 3 is greater than that evaluated on the path 2.

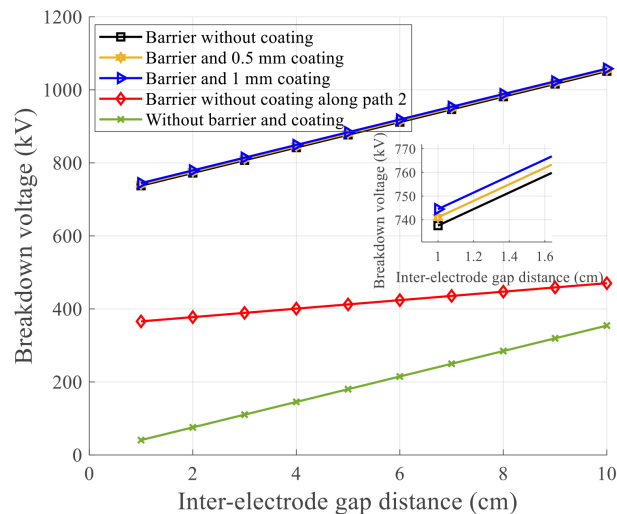


Figure 13. Calculated breakdown voltage as a function of inter-electrode gap distance when using solid dielectric coating and barrier in comparison with a reference breakdown voltage in which dielectric coating and barrier were not taken into account.

In presence of the barrier, the dielectric coating influence showed a relative increase, in comparison with the MG10 breakdown voltage calculated with the barrier and without coating, of 1% and 0.7% for 1 cm and 10 cm inter-electrode gap distance respectively for path 2. In path 3, the influence of coating with 1 mm thickness showed an increase of 0.9% and 0.6% respectively at 1 cm and 10 cm inter-electrode gap distance (Figure 11). As seen in literature [6] [9], the global influence of solid dielectric materials on flashover voltage obtained in the present work leads to an increase of the theoretical flashover voltage. As shown in [24], the influence of dielectric barrier being subjected to the size and the dielectric permittivity of the barrier material, the comparison with experimental measurements of the hybrid insulation using MG10 in the condition defined in this article could lead to a better understanding.

4. Conclusion

To find a substitute of a strong greenhouse dielectric gas such as SF_6 for high voltage engineering applications, given the weakness of insulating characteristics of environmentally friendly gases, a hybrid solution has been considered in the present work. This solution consisted of N_2/O_2 gas mixture with 10% O_2 and solid dielectrics used as electrode coatings and a barrier between parts with a difference in electric potential. The theoretical assessment of breakdown voltage in the hybrid insulation system, based on streamer inception and propagation criteria, was carried out using COMSOL Multiphysics and MATLAB software. The results

showed that the combination of solid dielectric coating and barrier leads to a substantial relative increase in breakdown voltage of 793% and 33% respectively for 1 cm and 10 cm inter-electrode gap distance when using the path 2. In the path 3 the relative increase in flashover voltage is seen to be about 1708% and 197% for 1 cm and 10 cm inter-electrode gap distance respectively. As in literature, the breakdown path related to the solid dielectric size, is logically relevant for the magnitude of flashover voltage in the dielectric hybrid used here. The theoretical evaluation of sparkover voltage in MG10 combined with solid dielectric material in inhomogeneous electric field conditions seems to show a significant increase in flashover voltage greater than 33%. Measurements should be performed for more appreciation of this hybrid system.

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Author Contributions

Elysée Obame Ndong and Adoum Traoré Ndama contributed to the conceptualization and design of the study. Simulations, data curation, and analysis were performed by Nathanaël Victoire Mouélé Nguélé and Jean Paul Yembi. The project was supervised by Elysée Obame Ndong and Jean Paul Yembi which also provided funding acquisition and project resources. Nathanaël Victoire Mouélé Nguélé wrote the first draft, while Elysée Obame Ndong, Adoum Traoré Ndama, and Jean Paul Yembi thoroughly reviewed and edited it. All authors read and approved the final manuscript.

Conflicts of Interest

The authors affirm that they have no known financial or interpersonal conflicts regarding the publication of this paper.

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