doi:10.14311/ppt.2026.1.31
Plasma Physics and Technology **13**(1):31–36, 2026

ASSESSMENT OF DIELECTRIC WITHSTAND OF G^3 AND CO_2/O_2 MIXTURES AFTER ARCING FOR HIGH-VOLTAGE CIRCUIT BREAKERS

V. Issartel[a,*], S. Gortschakow[b], R. De Holanda Sousa[a], M. Hadi[a], Ph. Robin-Jouan[a]

[a] *GE Vernova, 21 rue Cyprian - BP 1321 , Villeurbanne Cedex, 69611 France*
[b] *Leibniz Institute for Plasma Science and Technology, Felix-Hausdorff-Straße 2, 17489 Greifswald, Germany*
[*] vincent.issartel@gevernova.com

Abstract. Dielectric behaviour of g^3 or CO_2/O_2 mixtures after current interruption have been studied by numerical model. Arc properties during the arcing phase were determined from two-dimensional axisymmetric time-dependent magneto-hydrodynamic simulations. The probability of arc re-ignition (breakdown) after current interruption have been then estimated from evaluation of streamer criterion for the whole calculation domain. Corresponding input data - critical electric fields and effective ionisation coefficients - have been determined from the solution of kinetic Boltzmann equation for the electrons.

Keywords: high-voltage circuit breaker, dielectric withstand, breakdown, MHD simulations.

1. Introduction

Despite intensive research in the last decade, the substitution of SF_6 as a leading gas in switching applications remains a challenging task [1]. Alternatives have to fulfil a number of requirements, such as high switching performance, environmental compatible and secure operation and long lifetime. Promising candidates in the field of high-voltage applications is g^3 (green gas for grid), a balanced mixture of CO_2, O_2 with C_4F_7N [2] and CO_2/O_2 mixtures. Reliability of g^3 use for current interruption was proven by experiments and simulations [3]. However, one of the most important aspects after current interruption, is the prevention of arc re-ignition (electrical breakdown). The breakdown in gas medium occurs when applied electric field exceeds a critical value, known as critical electric field strength, which provides sufficient production of charge carries along a selected path between the electrodes. In order to predict the breakdown probability, the knowledge of general ionisation ability of switching gas is required. It admitted that the dielectric strength of g^3 is roughly 25% less than SF_6 under the same condition and pressure [2]. In case of g^3 or CO_2/O_2, the mixture composition is rather complex due to decomposition processes governed by temperature and plasma-chemical reactions [3]. In addition, original gas mixture is affected by PTFE (polytetrafluoroethylene, $((C_2F_4)_n)$ vapour which appears due to significant heat load on the nozzle during the arcing. A simple and reliable approach for determination of dielectric withstand of a gas mixture is a calculation of reduced effective ionization coefficient α_{eff}/N, where N is the total density of gas species. Evaluation of dielectric withstand of decomposed g^3 and CO_2/O_2 mixtures within a high-voltage circuit breaker is in the focus of current contribution. Additionally, an application case is presented, using this determined dielectric withstand in a criterion to predict arc re-ignition in high-voltage circuit breakers.

2. Simulation tools

Breakdown behaviour is physically complex and, in general, not compatible with realistic geometries of high-voltage circuit breakers in full scale arc simulations due to huge computational efforts. Therefore, the segregation of numerical models is often applied. The arc properties are determined from a multidimensional time-dependent magneto-hydrodynamic (MHD) model. Corresponding values serve then as an input for separate model which assesses the dielectric withstand or breakdown probability.

The electron component plays a leading role in the breakdown of partially ionized gases. After the arcing, the rest of the plasma might be away from equilibrium state due to relatively low temperature and steep pressure and density gradients. A possible re-ignition (breakdown) due to appearance of transient recovery voltage is, therefore, governed by the electrons, which are capable quickly gain the energy from the electric field. Dynamics of the electron density depends on the balance between electron gain and loss processes. In the presence of external electric field, those processes are ionization and detachment (gain) as well as attachment and recombination (loss). The corresponding reaction coefficients, namely ionisation coefficient α/N, attachment coefficient η/N, pooling ionisation coefficient β/N and recombination coefficient γ/N, can be calculated from appropriate integration of the electron velocity distribution function, which is determined from the solution of electron kinetic equation (Boltzmann equation). The reduced effective ionization coefficient arises from a sum of all those contributions according to

$$\frac{\alpha_{\mathrm{eff}}}{N} = \frac{\alpha - \eta + \beta - \gamma}{N}. \tag{1}$$

If the value of α_{eff}/N is negative, then no breakdown occurs. In the case of positive values, there is an increasing probability of the breakdown. The so-called critical electric field strength $(E/N)_{\mathrm{crit}}$ is usually determined as a field at which the effective ionisation coefficient is zero.

2.1. MHD model

The simulation of arcing flow interactions in circuit breakers has been integrated in a software package called MC^{3}Xms (Modelling and Computation of Circuit-Breaker Chamber eXtended Multi-Species) [4], developed at the École Polytechnique de Montréal in collaboration with GE Vernova. The tool is a two-dimensional axisymmetric time-dependant simulation software designed to model multiphysics and multi-species interactions, specifically targeting the coupled physical phenomena in high-voltage circuit breakers. The main software functionalities and hypothesis of the MHD model are :

- Unstructured, mobile and adaptive mesh based on the ALE (Arbitrary Lagrangian-Eulerian) approach (Figure 1).
- Compressible, supersonic and non-viscous fluid based on Euler's equations.
- Real gas model
- Electric arc is modeled as a hot, ionized gas generated and maintained by the Joule effect
- Electromagnetism : Maxwell's Equations
- Thermal radiation : P1 model
- Ablation is modeled as an addition of mass and energy by the sublimation of PTFE.

More details about the model can be found in [3] and references therein. As the main results, temporal evolution of conventional MHD properties (temperature, pressure, velocity fields, etc. as well as local gas properties in approach of local thermodynamic equilibrium (LTE), like e.g. composition and corresponding species densities are predicted.

Figure 2 illustrates a simulation result generated by MC^{3}Xms just after arc extinction.

2.2. Model for breakdown probability prediction

As explained before, one of the major risk is arc re-ignition in high-voltage circuit breakers. This occurs after the separation of contacts and restoration of Transient Recovery Voltage (TRV) on one of the arcing contacts when the alternating current is interrupt (Figure 3). The subsequent rapid increase in voltage can lead to a strong electric field that can exceeds the critical dielectric strength of gas and lead to arc re-ignition which would cause damage to the electric network and its equipment.

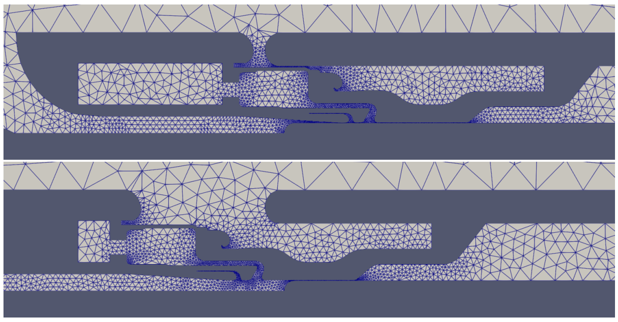

Figure 1. Example of meshing in the breaking chamber of a circuit breaker - before and after moving the pieces

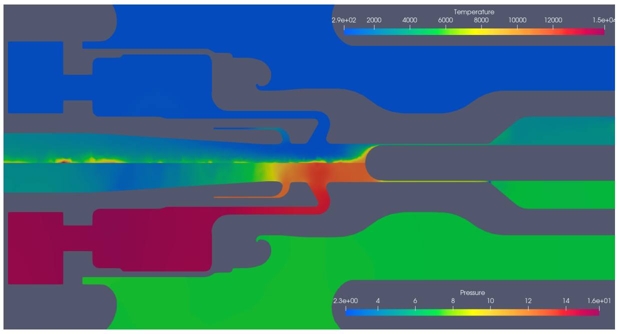

Figure 2. Exemple of a typical simulation result in MC^{3}Xms after arc extinction

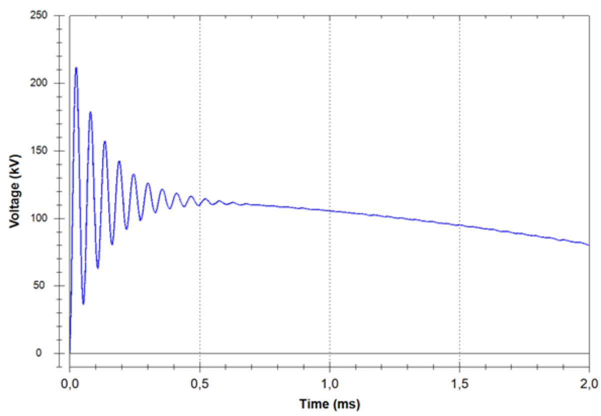

Figure 3. Exemple of a Transient Recovery Voltage

In order to estimate the breakdown probability and prevent this risk, a criterion based on the electric withstand is used :

$$\frac{1}{L} \int_0^L \frac{E/N}{(E/N)_{\mathrm{crit}}} \, \mathrm{d}l > 1 \tag{2}$$

This criterion involves comparing the reduced electric field with the critical reduced electric field. The values are averaged by integrating over a user-defined length along the electric field streamlines. If the criterion is less than one, the risk of dielectric restrike is weak, on the contrary if the criterion is greater than

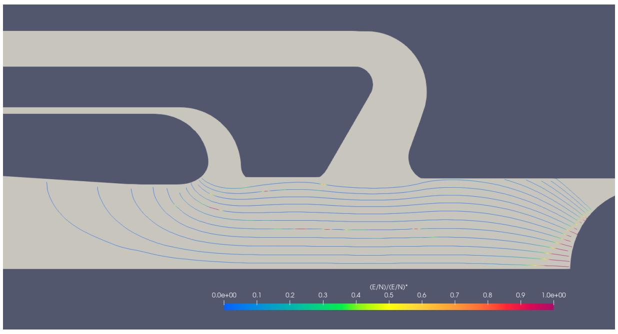

Figure 4. Example of use of criterion ParaView filter

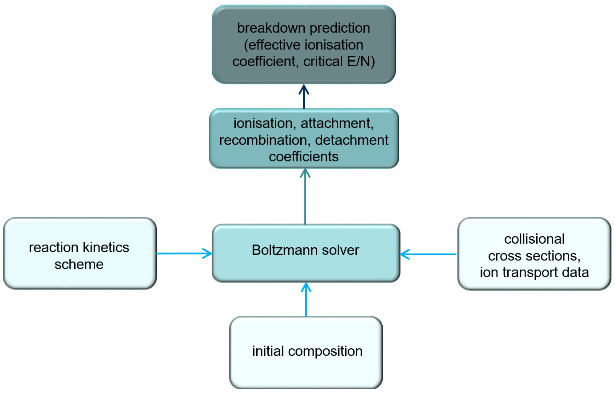

Figure 5. Flow chart of approach for determination of data necessary for prediction of dielectric withstand.

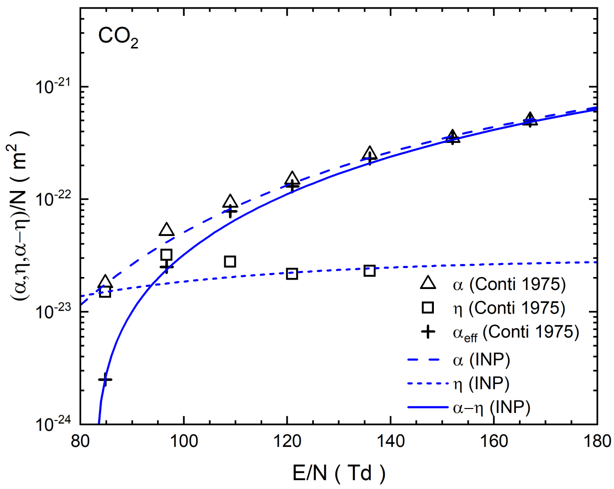

Figure 6. Reduced ionisation α/N, attachment η/N and effective ionisation $(\alpha-\eta)/N, \alpha_{\mathrm{eff}}$ coefficients for CO_2. Comparison between current data (INP) and literature [10].

one, the risk is important. Knowledge of the critical reduced electric field strength for g^3 and CO_2/O_2 mixtures is critical for the use of this criterion.

To automate the calculation of the criterion, a filter was developed within ParaView framework. ParaView is an open-source, cross-platform software for scientific data processing and visualization, built on the VTK library, which facilitates the analysis and visualization of large datasets [5]. Its capabilities can be enhanced through the development of plugins and filters. An example of the filter used for calculating the criterion value is shown in Figure 4.

2.3. Dielectric withstand database

Following initial parameters for the solution are necessary: densities of all plasma/gas species, plasma/gas temperature, reduced electric field strength (E/N), rate coefficients for reactions without direct participation of the electrons and transport parameters for ions.

The solution approach consists in calculation of effective ionization coefficient on the base of composition data and material data for all relevant atomic and molecular species in the mixtures of interest. Details of used approximations for the solution of the electron kinetic equation and the determination of ionization, attachment and recombination coefficients, as well as electron transport properties can be found in [6]. Figure 5 presents the flowchart diagram of used approach for determination of data which are necessary for prediction of dielectric withstand.

Following species have been considered in calculations: (i) neutral species: CO_2, C_2, C_3, C_4, C_5, C, F_2, F, N_2, N, O_2, O, O_3, CF, CF_2, CF_3, CF_4, C_2F, C_2F_2, C_2F_3, C_2F_4, C_2F_5, C_2F_6, CN, NCN, CNN, CO, C_2O, NF, NF_2, NF_3, FO, F_2O, NO, NO_2, NO_3, N_2O, N_2O_5, F_2CO, NCO, C_4F_7N, C_4N_2, CF_3CN, C_3F_6, C_3F_8, CFCN, C_3F_7; (ii) ions: CO_2^+, C_2^-, C_2^+, C^-, C^+, F_2^+, F_+, N_2^+, N^+, O_2^+, O^-, O^+, CF^+, CF_2^+, CF_3^+, $C_2F_2^+$, CN^+, CO^+, NO^+, NO_2^+, N_2O^+, $C_4N_2^+$, $C_4F_7N^+$, as well as electrons. Depending on mixture composition, up to 414 various plasma-chemical reactions have been taken into account.

The data for collision cross sections have been collected from the literature [7]. For the most critical species, which have significant density, 355 electron-heavy particle collision processes described by cross sections [7], 18 processes described by rate coefficients [8], as well as 42 electron-ion recombination processes described by corresponding formula from [9]. have been considered.

The values of effective ionisation coefficient have been calculated for temperature range 1000-4500 K, pressure range 0.01-150 bar at varying mixture composition with 5-10% of C_4F_7N, 10-30% O_2. 0-100% C_2F_4. Validation of calculated values has been performed by comparison with known literature data for pure substances. As an example, the results for CO_2 are shown in Figure 6. In general. a good agreement with known data was found.

The influence of PTFE vapour content on the critical electric field strength is presented in Figure 7 and Figure 8 for g^3 and CO_2/O_2 mixtures correspondingly. The data are shown for the case with 30% oxygen and 10% Novec4710. Percentage of PTFE was chosen in accordance with predictions of MHD model. The dependence is rather complex. In case when C_2F_4 is

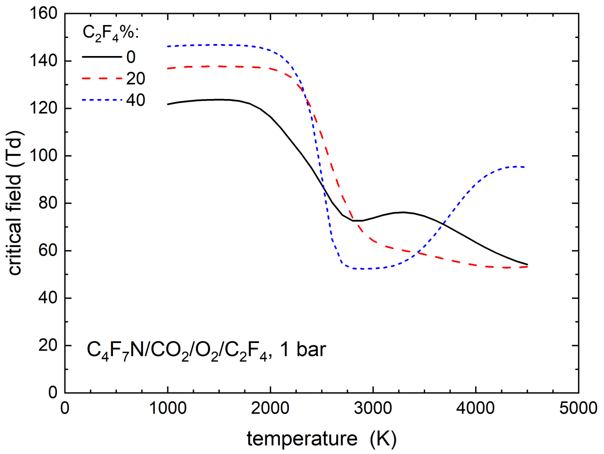

Figure 7. Reduced critical electric field strength $(E/N)_{\mathrm{crit}}$ for g^3/C_2F_4 mixtures with various PTFE content.

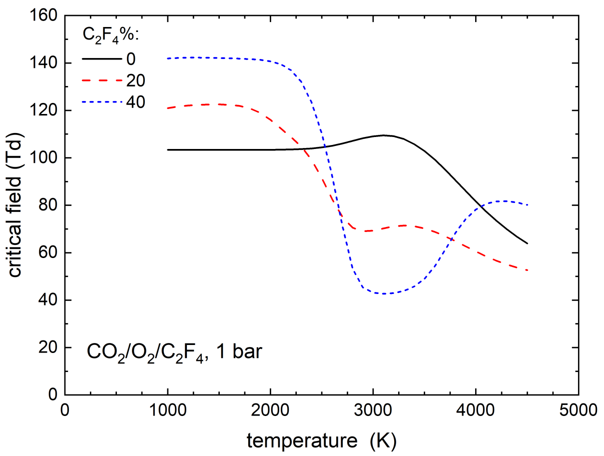

Figure 8. Reduced critical electric field strength $(E/N)_{\mathrm{crit}}$ for $CO_2/O_2/C_2F_4$ mixtures with various PTFE content.

present in the mixture, positive effects for $T < 2700\,\mathrm{K}$ occur. Analysis of main species densities responsible for electron attachment (Figure 9) has clarified that the reason is an enhanced production of F_2CO and CF_n molecules in this temperature range. For higher temperatures, however, this effect disappears due to the lack of molecular oxygen and carbon dioxide in PTFE containing mixtures. An increase of critical electric field strength for the mixtures with 40% PTFE content is related to higher density of CO molecules and atomic fluorine.

After calculations of effective ionisation coefficients and critical electric field strength for all relevant parameter combinations, those data were organised in a database in a form of look-up tables. The look-up tables were then used for determination of breakdown probability according to the approach described in section 2.2.

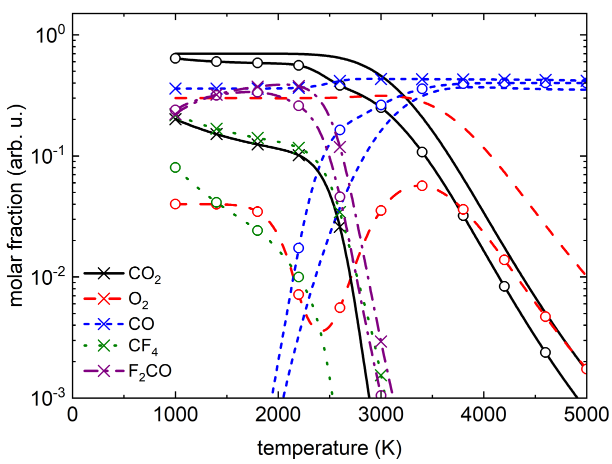

Figure 9. Molar fractions of main species densities responsible for electron attachment in the mixtures $CO_2/O_2/C_2F_4$ with various PTFE content. Percentage of C_2F_4: lines without symbols - 0%, lines with cycles - 20%, lines with crosses - 40%.

3. Experimental setup

A limited test campaign on a CO_2/O_2 gas mixture high-voltage circuit breaker project was conducted in CERDA Laboratory in Villeurbanne, France. The campaign included two specific tests aimed at assessing the risk of dielectric re-ignition. One test demonstrated a dielectric re-ignition, whereas the other did not. In the remainder of this paper, the test that experienced dielectric re-ignition will be referred as Test A, while the other test will be referred as Test B. The test setup enables the measurement of various parameters, including arc voltage, current, thermal volume pressure (using two sensors). The objective was to determine if the test outcomes could be reliably predicted using established criterion (2).

4. Correlation validation

A calibration step was conducted to guarantee that the simulation results are comparable with the test outcomes. To ensure a strong correlation, two primary parameters are typically utilized:

– Thermal volume pressure (Figures 10 and 11)

– Arc voltage (Figures 12 and 13)

Figures 10, 11 and 12, 13 respectively illustrate the thermal volume pressure and arc voltage as a function of time. At zero millisecond, the breaking occurs. To ensure confidentiality, values have been normalized and expressed as percentages.

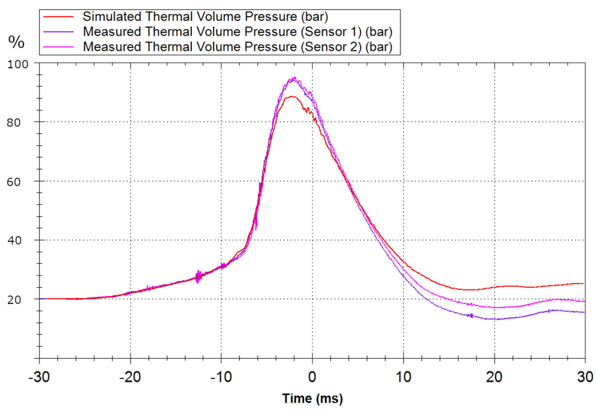

Figure 11. Thermal volume pressure for the test without re-ignition (Test B)

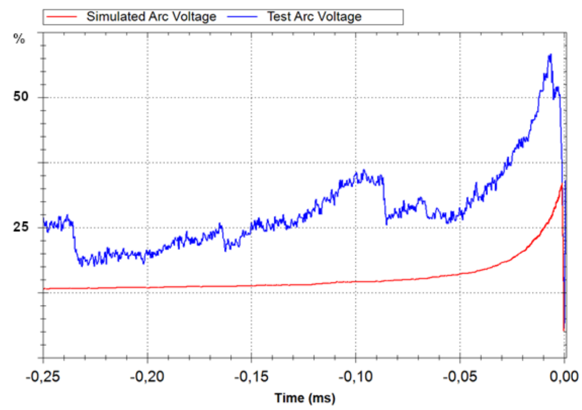

Figure 12. Arc voltage for the test with re-ignition (Test A)

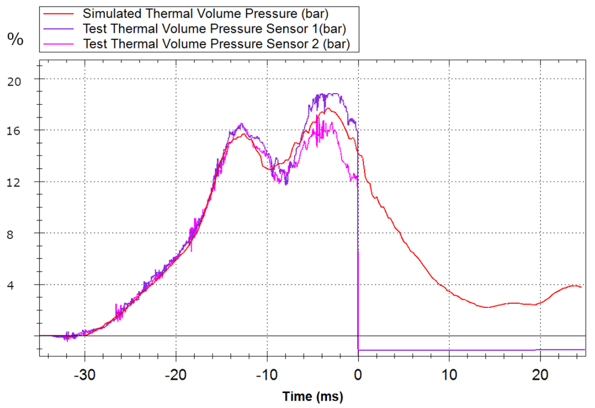

Figure 10. Thermal volume pressure for the test with re-ignition (Test A)

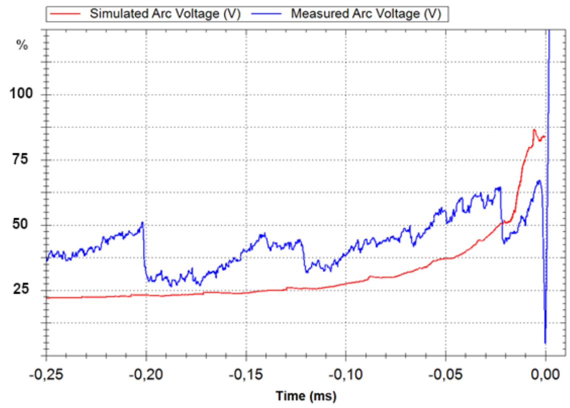

Figure 13. Arc voltage for the test without re-ignition (Test B)

Regarding, thermal volume pressure, the correlation between simulation and measurement is consistently robust across both tests. It is noteworthy that the thermal volume pressure sensors in test A experience errors after the current interruption, however, this absence of information is not significant since the crucial aspect is the maximum value, which occurs prior the current interruption.

In test A, the simulated thermal volume pressure aligns with the trend of the measured values, and its value is approximately the average of these measurements (Figure 10).

In test B, the correlation is weaker, specifically, the maximum thermal volume pressure is approximately 6% lower than the measured values. This discrepancy may affect the quality of the arc blowing. Although there is also a difference after the current interruption, but it is less significant. It was decided to maintain the current results as further improvement was not possible (Figure 11).

Ensuring a sufficient correlation for the arc voltage proved challenging, as illustrated in Figures 12 and 13. In most simulations, the arc voltage is frequently underestimated, although the trend is accurately followed. This difficulty primarily arises from insufficient mesh quality prior to extinction. The result is an underestimation of the arc energy and an overestimation of the breaking performance. Since improvement was not feasible, it was decided to maintain the current approach.

5. Results of simulations

Figure 14 depicts the evolution of the criterion value (2) over time for the two tests. Although the criterion can be calculated across multiple streamlines (as shown in Figure 4), only its value on the streamline where it is maximum is displayed. The test featuring dielectric re-ignition is displayed in red, while the test without dielectric re-ignition is shown in green. Measured percentage of PTFE inside the inter-contact area are less than 10%.

The streamlines with the maximum criterion value are consistently nearest to the axis of revolution, located at the center of the arc where the temperature peaks. This phenomenon can be attributed to the decrease in the critical reduced electric field strength as temperature rises (for percentage of PTFE less than 10%) (Figure 7), leading to an increase in the criterion. Furthermore, the criterion value is largely influenced by the rise of the Transient Recovery Voltage (TRV).

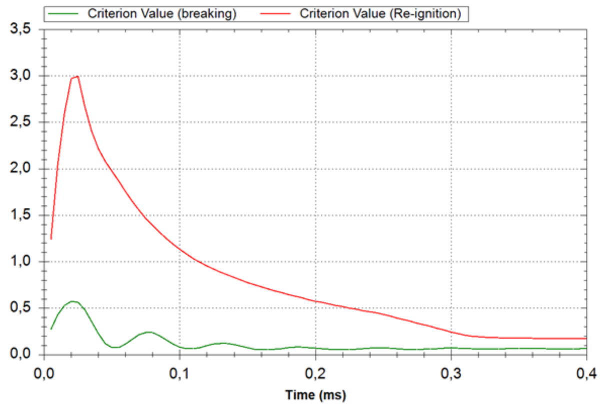

Figure 14. Criterion Results for Test A (red) and Test B (green)

As the TRV rises, the electric field strengthens, causing the criterion to grow. The maximum value of the criterion appears around the TRV peak.

A significant discrepancy is observed between the maximum values of the two criteria. The value for test A is considerably greater than one, whereas the value for test B is less than one. The criterion predictions align with the test results.

The disparity in criterion values primarily stems from the temperature observed in front of the pin and along the axis of revolution (Figure 2). This elevated temperature is largely attributed to a less effective arc blowing. Arc blowing is chiefly influenced by the thermal volume pressure, which is lower in test A and exhibits an atypical behavior with a double peak rather than a single one (Figure 10). This indicates premature blowing, resulting in the expulsion of significantly hotter gas in the second blowing just before the breaking time, which adversely affects dielectric strength and soar the risk of re-ignition, as illustrated in Figure 14.

6. Conclusions

The use of g^3 and CO_2/O_2 as a replacement for SF_6 required to know the dielectric properties of these gases in order to ensure new SF6-free high-voltage circuit breakers will maintain same performance despite lower dielectric strength.

A criterion has been developed in order to predict the risk of dielectric re-ignition requiring knowledge of the critical reduced electric field. This field was obtained by solving numerically the Boltzmann equation and by determination of the effective ionization coefficient. The results were validated for pure substances against existing literature. This critical reduced electric field is strongly influenced by the presence of C2F4 in the mixture, complicating its predictive behavior.

An application of the criterion was applied to the outcomes of a limited test campaign, where its predictions were compared with the test results. The findings appear promising, showing a strong alignment with the criterion's predictions. However, the limited number of case studies prevents a definitive conclusion regarding its reliability. These tests were carried out only for CO_2/O_2 mixtures, an extension of criterion study to g^3 mixtures is necessary. Further investigation will be conducted in the coming month to better estimate the quality and reliability of the criterion's prediction by evaluating its performance against other high-voltage circuit breaker test results.

Acknowledgements

The project was sponsored by EUROPEAN COMMISSION, Executive Agency for Small and Medium-Sized Enterprises, Grant Agreement number: LIFE18 CCM/FR/001096.

References

[1] M. Seeger, R. Smeets, J. D. Yan, et al. Recent development of alternative gases to SF_6 for switching applications. *CIGRE ELECTRA*, 291, 2017.

[2] Y. Kieffel, F. Biquez, and P. Ponchon. Alternative gas to SF_6 for use in high voltage switchgears: g^3. *Proceedings of the 23rd International Conference on Electricity Distribution*, 2015.

[3] S. Gortschakow, D. Uhrlandt, P. Kloc, et al. Study of switching behaviour of g^3 based gas mixtures. *J. Phys. D: Appl. Phys.*, 58:155205, 2025. doi:10.1088/1361-6463/adb858.

[4] S. Arabi and R. Trépanier, J.-Y.and Camarero. Transient simulation of nozzle geometry change during ablation in high-voltage circuit breakers. *J. Phys. D: Appl. Phys.*, 48:045501, 2015. doi:10.1088/0022-3727/48/4/045501.

[5] Kitware. Paraview. URL: https://www.paraview.org/.

[6] N. R. Pinhao, Z. Donko, D. Loffhagen, et al. Comparison of kinetic calculation techniques for the analysis of electron swarm transport at low to moderate e/n values. *Plasma Sources Sci. Technol.*, 13:719–728, 2004.

[7] I. Greifswald. Inp collection of cross section data.

[8] B. Eliasson and U. Kogelschatz. Basic data for modelling of electrical discharges in gases. *BBC Forschungsbericht*, 1986.

[9] Y. Raizer. *Gass discharge physics.* Springer, 1991.

[10] V. J. Conti and W. A. W. Ionization growth in carbon dioxide. *J. Phys. D: Appl. Phys.*, 8:2198, 1975.