Detailed Investigation of Breakdown Prediction Models for High Voltage Circuit Breakers

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Although studied for several decades, detailed knowledge on the leader mechanism conducting to a dielectric breakdown seems to be still insufficient. For this reason, based on home-made 2D-Euler CFD code, the present study handles the pressure and temperature as controlling parameters to consider for the efficient prediction of the dielectric breakdown. Moreover, it presents the limits of the suggested theoretical approach. This theoretical and numerical investigation is correlated with corresponding power test results on HV mock-ups.

Keywords: Numerical simulation, restrike mechanism, breakdown criterion, parametric analysis

1 INTRODUCTION

A careful Computational Fluid Dynamics (CFD) prediction of the dielectric breakdown behavior in the high voltage (HV) gas insulated circuit breakers is very precious for the manufacturers, because it allows calculating the breakdown limits and reducing tests number. For this purpose, different methods are proposed in the literature.

The first classical method is the analysis of the electric field *E*, applied on a given number of gas particles *N*. It influences directly the electron coefficients of ionization α and reattachment η. This *E/N* field considers the electron and ion kinetics as described in [1]; it could become critical (E_{cr}/N) for typical temperature and pressure values. Even if this method is adequate for insulating design of circuit-breaker chambers, it contains severe assumptions on the theoretical models and on the complex multi-physical phenomena related to the chambers.

The second method evaluates the probability of restrike between electrodes based on the comparison between the available and necessary energies, as proposed in [2]. The dielectric breakdown is investigated along a line with fixed length and radius.

However, these prediction methods seem to be inaccurate by applying them under high plasma temperature and unsteady gas flow conditions. For this reason, using a 2D axisymmetric home-made CFD code, we present a prediction method built on spatial integrations and on calculated E_{cr}/N tables.

2 ARC MODELING

Numerical simulations of the electric arc are as complex as the related plasma phenomena themselves. The software used in this study assumes the local thermodynamic equilibrium and deduces mass, momentum and energy. The viscous effects of SF_6 in presence of arc, i.e. at high temperature and high velocity, are negligible and permit to use the Euler's equations. Moreover, Joule and radiation effects are added in energy equation due to the electric arc. All the electromagnetic fields are calculated with simplified Maxwell's equations. The gas ionization which has a non-linear behavior is deduced in function of the temperature and the pressure.

The used CFD code is based on finite volume method (Roe's solver) and considers 2D axisymmetric resolution. The resolution uses an auto-adaptative, non-structured, triangular mesh [3]. The non-structured triangular mesh, adapt itself for each instant depending on calculated pressure, temperature, electric gradient, density and device movement.

3 THEORY

After the arc extinction and during the transient recovery voltage (TRV) application, an electron avalanche occurs in the highly electronegative gas. The critical electric field which decreases with temperature increase and pressure decrease, has to be close to the electric field in the gas. A streamer channel is created due to the electron avalanche, presenting a small radius, a low conductivity and a high electric field. The analysis of this streamer will give all necessary information to define the appropriate criterion.

The first step consists in the determination of the streamer length *L*. This length defines the necessary length required to get the same potential in the channel. This length is calculated by using the critical electric field E_{cr} [1] (cf. fig.1), and with the electric field E_0 issued from the TRV and calculated in respect with the local temperature and pressure, both located at the pin's tip. The streamer length *L* is calculated according to the following equation:

$$\int_0^L E_{cr}\, dl \quad = \int_0^L E_0\, dl \qquad (1)$$

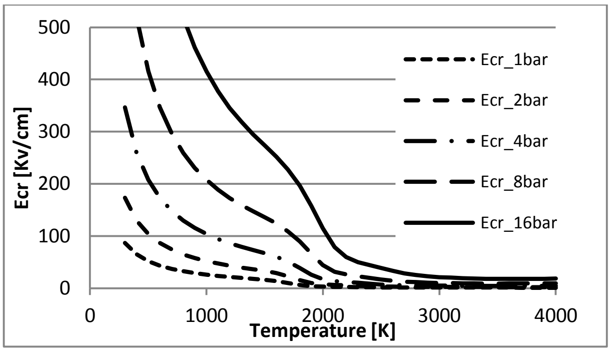

Fig.1: Evolution of the critical electric field for SF6 at several pressures

Since the electric field varies during the extinction phase, the streamer length will not be constant.

The second step is the calculation of the electric charges *Q* in the streamer channel (2) (based on M. Seeger's work [4]) with a dimensionless geometry factor *g*=0.5, a charge's split α=0.02, which is the theoretical value of the precursor mechanism discharge as described in [5], the vacuum permittivity ε_0, the streamer length *L* and the average critical field of the channel before heating $E_{cr,i}$.

$$Q = \alpha * g * \varepsilon_0 * E_{cr,i} * L^2 \quad (2)$$

The third and last step corresponds to the transformation of the streamer channel in a leader channel. When the charges Q pass through the streamer, it increases the local temperature and consequently reduces the critical electric field. This weaker potential difference in the channel will artificially transfer the potential to the tip of the pin. Therefore, it creates a stressed zone at the end of the channel, where the leader inception may occur until the creation of a new electric arc.

After all this calculation process, the expression of the criterion consists in the comparison between the applied electric potential U_0 and the potential in the leader channel U_c.

Consequently the breakdown criterion is:

$$\frac{U_c}{U_0} = \frac{\int_0^L E_{cr,f}\, dl}{\int_0^L E_0\, dl} < k \qquad (3)$$

$E_{cr,f}$ is the final critical electric field calculated by using the temperature increase caused by the leader inception as described in [4]. k is the breakdown limit taking into account the inhomogeneity of the electric field and supposed immediate propagation of the discharge. Thus, if the ratio U_c/U_0 is lower than *k*, the device is supposed to breakdown.

4 APPARATUS APLICATION

The criterion has been applied to real circuit-breaker geometries. The tested devices results presented are 2 circuit-breakers designed to withstand 245kV at 50Hz and filled with SF6. The tested currents in both cases were 18.9 kA (T30), the TRV peak is 500kV with a rate of 13kV/µs. One geometry has been tested twice, giving one success (case 1) and one failure results (case 2) for two different overlap distances. The arcing times are respectively 13ms and 19.8ms for case 1 and 2. The geometry is presented in fig. 2. A dielectric breakdown occurred in case 1, 35µs after current zero, under 500kV at the transient recovery voltage peak. The overlap distance, that is lower in case 1, creates a lower mechanical build up pressure in the compression volume in the phase before contact separation.

5 DISCUSSION

The analysis is made along the pin which presents the highest electric constraint. A longitudinal measure, normal to the surface is realized for several angles, starting from the pin tip as shown in fig.2. Five shots have been analyzed from 10° to 74°. As we can see on the result in fig.3, the shot with the highest probability of restrike is the one with the smallest angle. The lowest criterion result is the most critical. As a consequence, next studies will consider horizontal shots 2 mm above the axis. The spatial integration is essential to take into account possible recirculation of hot gases next to the pin, in particular for T30 cases.

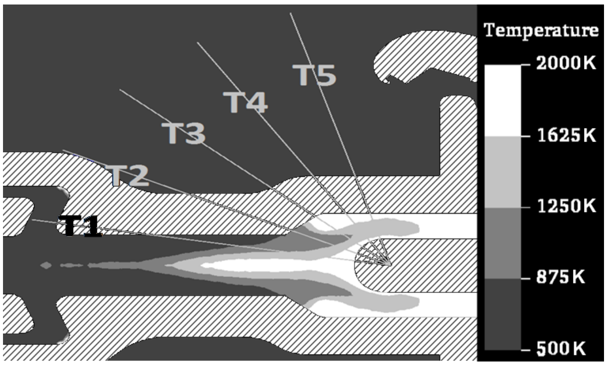

Fig.2 : Visualization of shots T1-10°/T2-26°/T3-42°/T4-58°/T5-74°

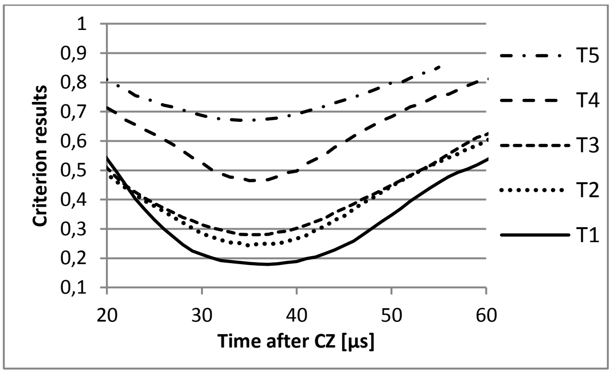

Fig.3: Criterion's time evolution for several angles – Case 1

At each time, the distance *L* is determined using relation (1). We consider that the streamer and leader channel lengths are equal and the streamer channel field is supposed to be at the critical field. Fig.4 shows the leader channel length over time for both cases. We observe that the length evolves with the TRV variations as normally expected.

These calculations allow us to estimate the voltage drop in the leader channel, as represented in fig.5. In this graph the voltage difference between the leader potential U_{cr} and the streamer potential U_0 is the highest around the TRV peak, when the criterion is the lowest.

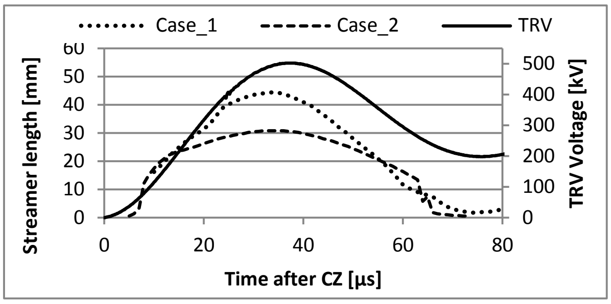

Fig.4: Evolution of streamer length for 245kV cases in parallel with the TRV evolution

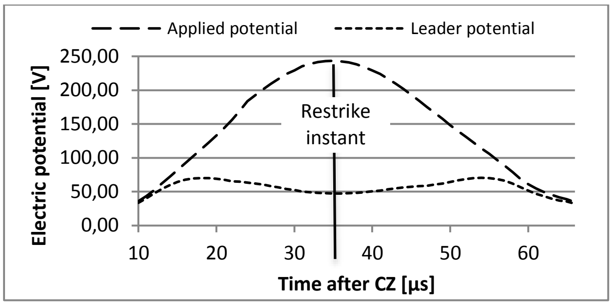

Fig.5: Comparison between criterion and potentials on streamer length – Case 1

Moreover it can be noticed, that for the first 10µs, case 2 is more critical, because of higher temperatures at current zero. Last but not least, at 35 µs, case 1, in agreement with the dielectric breakdown result, has a more critical result than case 2, though both are very close (fig. 6).

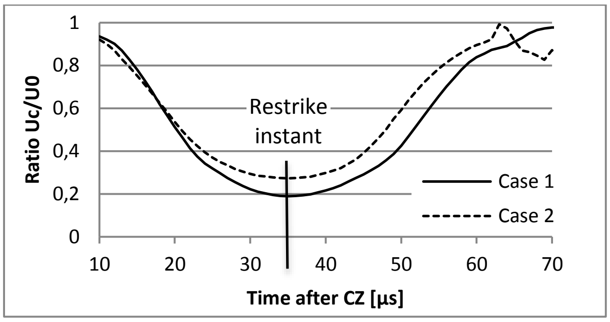

Fig.6: Criterion results in parallel with breakdown instant

The considered temperatures are higher than 1500K, which correspond to the temperature where the first charged species appear in SF6, and when insulating properties strongly decrease when the temperature increases (cf. fig.1). Therefore, studying the criterion response by temperature's variation will permit to determine its sensitivity range. As a consequence, a variation of the temperature should have an impact on the calculated gas density, the channel radius, and more significantly, on the length L of the leader channel due to a variation of the considered critical electric field. We apply a progressive correction of temperature between 75% and 125% with 5% steps. The results are presented in fig.7.

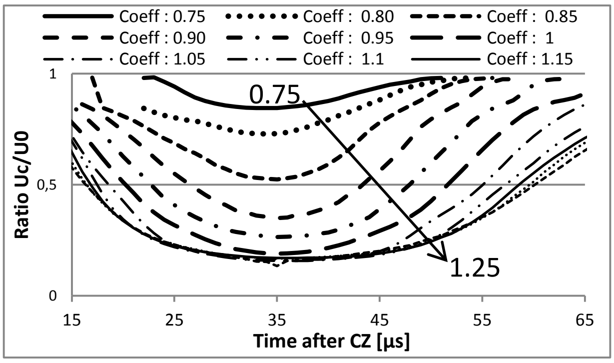

Fig.7: Criterion's evolution by applying coefficients on temperature data – Case 1

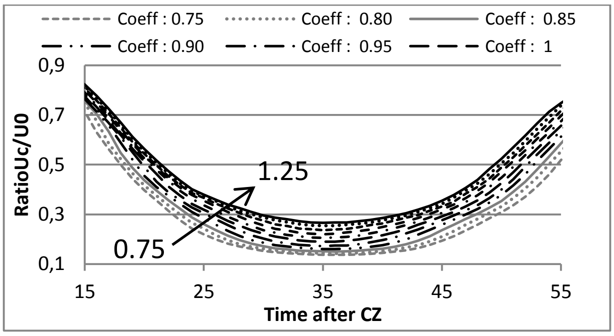

Fig.8: Criterion's evolution by applying coefficients on pressure data – Case 1

The temperature influence on the criterion is very sensitive, the criterion results vary significantly in a range of 20-25% as the temperature decreases, moreover there is a threshold effect when the considered temperature increases, confirming a diminution of the critical electric field variation with the temperature (fig.1).

The same study has been realized to characterize the criterion sensitivity with the pressure. As expected the impact on the criterion result is much less significant by varying the pressure (cf. fig.8). The criterion is directly linked to the critical electric field which presents greater variations by changing the temperature than the pressure (cf. fig.1).

6 CONCLUSION

This study shows the impact of several parameters on dielectric withstand. The full 2D spatial investigation for the dielectric criterion is important to consider all the detailed gas structured impact. It is particularly important for low energy gas flow like T30 or small arcing time configurations. The most critical parameter is the temperature which severely impacts the critical electric field and the criterion results. This suggests that any new CFD model would affect the criterion results for the dielectric phase. Typically, introducing any turbulence model, or any 2 temperature model or the 3D dimension would change greatly the analyzed results.

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