Comparison of the Breakdown Strength of N₂, CO₂ and SF₆ using the Extended Up-and-Down Method

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Abstract: Nowadays in Gas Insulated Systems (GIS), SF₆ is often used as insulating medium. Due to the fact that SF₆ is a greenhouse gas with a very high global warming potential (GWP), alternatives have been searched for over the last years. In particular, SF₆/N₂ gas mixtures have been extensively investigated for the use in Gas Insulated Lines (GIL) and is being used in several applications. However, in these cases SF₆ is still part of the insulating gas and the search for alternatives continues.

In this respect, nitrogen (N₂) and carbon dioxide (CO₂) are interesting alternatives. In this paper, investigations into the breakdown strength of these gases will be described. Both gases were investigated in a plane-plane configuration, with a distance of 10 mm between the planes. The gas pressure was varied in steps of 2 bar, from 7 to 11 bar.

To get to the 5% breakdown value under positive and negative lightning as well as switching impulses, the extended up-and-down method was applied and will be discussed in the paper. The results are compared to 3 and 4 bar SF₆ to get the required data that can be used for design purposes.

INTRODUCTION

It is well known that SF₆ is a green-house gas with a high global warming potential (GWP) of 23900. Therefore research into the application of other gases with lower GWP are being done at various locations. Two of the gases that might be of interest to replace SF₆ in future applications are carbon-dioxide (CO₂) and nitrogen (N₂). To compare the dielectric strength of both gases for design purposes, breakdown tests in homogeneous plane-plane configurations were performed. The breakdown voltage was determined using the extended up-and-down method and quantities such as the gas pressure, type of transient over voltage and gap distance were varied.

In this contribution, results are presented obtained during breakdown tests of CO₂ and N₂ gas. Comparison with 2 and 3 bar SF₆ are shown as well.

MEASURING SETUP

The experiments have been performed at three different gas pressures: 6, 8 and 10 bar (relative). The gases used during the experiments described in this report were CO₂ and N₂. The distance between the two plane electrodes with Rogowski-like profile was 10 mm. For comparison purposes, experiments in 2 and 3 bar (relative) SF₆ were performed as well.

A photo of the test setup is shown in figure 1.

Fig. 1. Experimental setup for breakdown tests in CO₂, N₂ and SF₆. Inset: electrode configuration.

The impulse voltages were generated by a 20 stage Marx impulse generator. The maximum voltage level is 4 MV, and can be seen in the background of figure 1. An example of the wave-shape of a positive lightning impulse imposed on the measuring setup is shown in figure 2. A 500 kV AC voltage transformer was used for the AC breakdown tests.

Fig. 2. Example of a positive lightning impulse imposed on the test setup.

MEASURING PROCEDURE

AC breakdown value

To determine the AC breakdown voltage, the test voltage is slowly increased until breakdown occurred. The average of 10 breakdowns have been used and represents $U_{50\%}$.

LI and SI breakdown value

To determine the breakdown voltage under lightning and switching impulses, the extended up-and-down method (EUD-method) was used [1]. The main difference of the EUD-method with the 'normal' up-and-down method is the fact that the equipment is tested with several shots of the same test level during one series. As a result, it is possible to determine the $U_{5\%}$ breakdown voltage, so the voltage level which has 5% probability of flashover.

If a flashover occurs during a series of shots, the test-voltage is decreased by one step. In no flashover occurs during the series, the test-voltage is increased by one step.

In fact, 11 series have been used and depending on the

Fig. 3. Flowchart of the measuring procedure.

number of shots during each series of equal test voltage, the breakdown voltage with certain probability is determined. In particular, when 7 shots are used during each series, $U_{10\%}^{(1)}$ value is determined; when 13 shots are used during each series, $U_{5\%}^{(1)}$ value is determined.

Between the shots, a stabilization time of 3 minutes has been taken into account. Figure 3 shows a flowchart of the followed measuring procedure.

THE EXTENDED UP-AND-DOWN METHOD

Theory

As described by Carrarra, using the extended up-and-down method with m shots in 11 series, the probability that a breakdown occurs during the series can be calculated using the following equation [1]:

$$P^{(m)} = 1 - (1 - P^{(1)}(u))^m \quad (1)$$

in which $P^{(1)}(u)$ is the 50% breakdown value coming from the normal up-and-down-method. For designing purposes, the $U_{5\%}$ -level is of importance. However, testing the gas using the EUD-method requires 11 series of maximal 13 shots with a waiting time of 3 minutes between the shots. This will lead to one full day testing per configuration.

Therefore, to speed up the process, series of only 7 shots (giving $U_{10\%}^{(1)}$) and of 3 shots (giving $U_{30\%}^{(1)}$) were performed as well. Based on equation (1), it can be deduced that the 5% breakdown voltage can be estimated using the following equations:

$$U_{5\%}^{(1)} = U_{31\%}^{(7)} = U_{50\%}^{(7)} - 0.5\sigma^{(7)} \quad (2)$$

$$U_{5\%}^{(1)} = U_{14\%}^{(3)} = U_{50\%}^{(3)} - 1.08\sigma^{(3)} \quad (3)$$

Example

In words, equation (2) states that in order to determine $U_{5\%}^{(1)}$ from the EUD-results with 7 shots and 11 series, we have to subtract half the standard deviation. To confirm this relation, two experiments have been performed using a gas pressure of 11 bar CO_2 with positive lightning impulse (LI+). During the first experiment, 13 shots have been performed during each series, during the second experiment 7 shots. The results are shown in table 1.

Table 1. Experimental data for determining the breakdown voltage of 11 bar CO_2 under positive lightning.

	m=13	m=7
	$U_{5\%}$	$U_{10\%}$
Number of shots	106	52
Average (kV)	234.1	235.7
Deviation (kV)	3.3	3.3

Table 2. Measuring data as obtained using the extended up-and-down method for CO₂ gas at different gas pressures.

		AC	LI+	LI-	SI+	SI-
10 bar CO ₂	Value [kVp]	239.1	235.7	233.6	234.1	234.3
	Deviation [kV]	2.5	3.3	5.5	4.6	6.9
	Pressure [barR]	10.0	9.9	9.9	10.0	9.9
	U/p [kw/barA]	21.7	21.6	21.5	21.3	21.4
8 bar CO ₂	Value [kVp]	197.6	195.0	196.5	196.6	195.1
	Deviation [kV]	1.2	3.5	2.7	4.0	3.8
	Pressure [barR]	8.0	8.0	8.0	8.1	8.1
	U/p [kw/barA]	21.9	21.7	21.7	21.6	21.6
6 bar CO ₂	Value [kVp]	156.9	160.4	158.8	157.4	154.9
	Deviation [kV]	1.0	3.2	4.3	3.4	3.2
	Pressure [barR]	6.0	6.1	6.0	6.0	6.0
	U/p [kw/barA]	22.4	22.6	22.6	22.4	22.1

According to equation (2) in order to estimate the $U^{(1)}_{5\%}$ from the results obtained using $m=7$ shots, we have to subtract 0.5σ , resulting in a value of $U^{(1)}_{5\%}=235.7-1/2 \cdot 3.3=234.1$ kV. In this example the results fit remarkably well, however the differences in other cases showed to be minimal as well. Based on these results it was decided to perform the experiments using 7 shots and 11 series to determine the $U^{(1)}_{10\%}$ and then estimate the $U^{(1)}_{5\%}$ using equation (2).

MEASURING RESULTS

CO₂ experiments

The experimental results as obtained in carbon-dioxide are shown in table 2. Because the gas pressure varied slightly during the different experiments, the ratio of the voltage and actual gas pressure (U/p) was taken and plotted as well, see figure 3.

It can be concluded from figure 4 that the breakdown voltage decreases slightly with increasing gas pressure, however only a deviation of about 3% is observed. Moreover, no significant difference in the results obtained under different voltage waves can be concluded. It can be stated that LI+>LI->SI+>SI-, but the difference again is very small and about 2%.

Fig.4. U/p for CO₂ as function of the gas pressure.

N₂ experiments

During the experiments performed in nitrogen, a large scatter in the breakdown values was observed. In particular, after the first breakdown in some cases, there was immediate breakdown again, and the voltage had to be reduced by 20-25% before the gas withstood the impulse voltage, even after a delay time of more than 5 minutes. In other cases however, after the first flashover, the voltage had to be increased by 20-25% before the second flashover occurred. This unpredictable behavior is of course unwanted in practical applications of such a gas. Similar results have been observed [2]. In designing components with gaseous insulation, a stable and predictable performance is required.

Table 3. Measuring data as obtained using the extended up-and-down method for N₂ gas at different gas pressures.

		SI+
10 bar N ₂	Value [kVp]	172.4
	Deviation [kV]	20.9
	Pressure [barR]	10.0
	U/p [kw/barA]	15.7
8 bar N ₂	Value [kVp]	187.1
	Deviation [kV]	5.7
	Pressure [barR]	8.0
	U/p [kw/barA]	20.8
6 bar N ₂	Value [kVp]	160.2
	Deviation [kV]	8.6
	Pressure [barR]	6.2
	U/p [kw/barA]	22.2

Therefore, only for comparison reasons, it was decided to perform 11 series consisting of 3 shots each instead of 7 shots. As shown in equation (3) the 5% breakdown voltage can then be estimated from these 3-shots-series as well. Moreover, only positive switching impulse tests were performed for three gas pressures. The results are given in table 3. From the table can be concluded that especially at the higher gas pressures, the results show a large scatter. In any case it is 2-4 times the scatter observed in the CO₂ results. Moreover, the $U^{(1)}_{5\%}$ at 10 bar is lower than the $U^{(1)}_{5\%}$ of N₂ at 8 bar.

SF₆ experiments

To evaluate the results of the CO₂ and N₂ experiments it has to be compared to SF₆ gas. Therefore, experiments have been conducted in SF₆ as well. Again, for comparison purposes, only positive lightning impulse testing was performed at gas pressures of 2 and 3 bar. The results are given in the table 4.

Table 4. Measuring data as obtained using the extended up-and-down method for SF₆ gas at different gas pressures.

		LI+
3 bar SF ₆	Value [kVp]	300.0
	Deviation [kV]	7.0
	Pressure [barR]	3.0
	U/p [kw/barA]	75.2
2 bar SF ₆	Value [kVp]	248.5
	Deviation [kV]	5.3
	Pressure [barR]	2.0
	U/p [kw/barA]	82.4

Comparison of experiments

Figure 4 compares the $U^{(1)}_{5\%}$ values for the performed investigations. As expected, SF₆ is superior to CO₂ and N₂. The difference in the breakdown voltage of CO₂ and N₂ is very small up to 8 bar. At higher gas pressures, the breakdown voltage of N₂ drops and is roughly 30% lower than CO₂ [3]. Moreover, the spread in the experimental results is shown as well. It is clear that N₂ has quite a large scatter in the results. As stated before, this is an influencing effect during the design process and should be taken into account.

Table 5 compares the average breakdown values in kV per distance and gas pressure. Compared to the intrinsic values, it can be expected that the practical values are lower. Again, it shows that the scatter for the N₂ experiments is quite large: 15%. In case of CO₂ the scatter is below 5% and in SF₆ is about 7%.

Fig. 4. U/p for CO₂ as function of the gas pressure.

Although the breakdown values are not so different for both investigated alternative gases, it can be concluded that CO₂ is more stable and has less scatter in the

Table 5. Breakdown values for different gas pressures.

Gas	Intrinsic breakdown [kV/mmbar]	Experimental breakdown [kV/mmbar]
N ₂	3.29	2.0 ± 0.3
CO ₂	3.01	2.2 ± 0.1
SF ₆	8.90	7.9 ± 0.5

results.

CONCLUSIONS

Based on the experiments described in this contributions, the following conclusions can be drawn:

- 1) Although the breakdown values are not so different for both investigated gases, it can be concluded that CO₂ is more stable and has less scatter in the results than N₂;
- 2) It is theoretically and experimentally proven that the $U_{5\%}$ breakdown value can be estimated from the $U_{10\%}$ breakdown value;
- 3) Within 5% accuracy, there is a linear relation between the gas pressure and the breakdown voltage of CO₂;
- 4) There is only 2% difference between the breakdown values obtained with LI and SI for CO₂;
- 5) The spread in the results obtained in N₂ is very large.

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