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Lightning Impulse Testing in Short Air-Gaps and Memory Effect of Previous Discharges

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***Abstract*—This paper reports on an observed phenomenon of increasing breakdown voltage while performing standard up and down lightning impulse (LI) testing in short air-gaps with weakly non-uniform field in an enclosed volume. The phenomenon could occur due to accumulation of space charges in the gap, changes in the chemical composition of the insulation gas, and/or changes in electrode surface due to discharges. To investigate the effect of these factors, LI tests are carried out in a 10 mm rod-plane air gap using four different methods: 1) ion flushing by DC voltage application in between LI shots, 2) with opposite polarity LI intertwined, 3) using forced air flow by a fan during the test, and 4) a reference test without any fan or voltage application. Results indicate that the phenomenon is more likely to be caused by formation of electronegative byproducts, e.g., ozone. Ozone was also experimentally detected near the test gap followed by consecutive LI breakdowns. It was found that air circulation rapidly reduces ozone concentration, which may explain why the increasing trend is not observed when a fan is used. Calculation of electron transport coefficients indicates that lack of primary electrons might be the prime reason of the increased impulse breakdown voltage of the air gap in presence of ozone.**

***Index Terms*—Lightning impulse testing, air gap, up and down test, medium voltage switchgear, ozone.**

I. INTRODUCTION

AIR is a frequently used insulation medium in switchgear applications. Since the recent trend is to shift from SF_6 towards more environmentally friendly alternatives, the use of air in gas-insulated switchgears (GIS) has increased lately besides other alternative gases [1]. Depending on the electric field, the filling pressure, and the type of the voltage stress, the dielectric performance of air is around 30-40% of SF_6. To make a compact switchgear using pressurized air instead of SF_6, the design of each part must be optimized to avoid flashovers. One of the most frequently occurring voltage stresses on power systems is induced by lightning strokes [2], and it is essential to perform laboratory tests under standard lightning impulse (LI) voltages during the design and development phase of new switchgear components.

A recommended method for impulse testing of insulation gaps is the up and down method, which involves sequential application of shots at equally spaced impulse voltage levels. This method is widely used by the industry as it requires fewer number of shots to evaluate the dielectric performance of the insulation medium [2]. An up and down test series is considered trustworthy only if the consecutive impulses or shots are statistically independent with no increasing or decreasing trend in the test voltages followed by the first breakdown in the series [3]. However, previous studies have shown that the insulation performance of some test objects might be influenced by the previous shots of the test series, i.e., there can be a memory effect of preceding discharges despite providing a waiting time up to several minutes in between shots [4]–[6]. Such memory effect can lead to an artificial increase or decrease in the impulse breakdown voltage, thereby limiting the reliability of the test results.

Possible mechanisms that can modify the LI breakdown voltage could be an increase in the number of ions or space charges in the gap between the electrodes, changes in the chemical composition of the insulation medium, and/or electrode surface change followed by a discharge. The memory effect would also depend on the electrode geometry and the gap distance, which directly influence the electric field and particle distribution. However, there is a lack of research on the effect of different factors on the impulse test results. The effects are not adequately discussed in the standard for impulse testing either. This paper probes the relevance of these factors during LI testing in short air-gaps with weakly non-uniform field. In this regard, up and down LI tests are conducted using four different methods: 1) ion flushing by DC voltage application in between LI shots, 2) with opposite polarity LI intertwined, 3) using forced air flow by a fan during the test, and 4) a reference test without any fan or voltage application between the LI shots. Calculations of electron transport coefficients are carried out to explain the experimental results. Findings from this study can serve as guidelines for ensuring statistical independence during impulse testing, especially during the research and development phase.

The work of this paper is part of the "KSP - New gases for GIS" project, mainly financed by The Norwegian Research Council (ref 319930).

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Manuscript received Month DD, YYYY; revised Month DD, YYYY.

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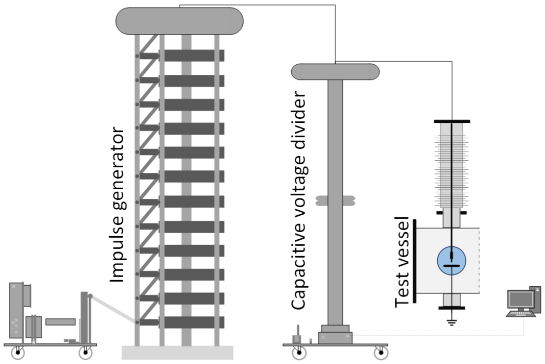

Fig. 1. Schematic diagram of the lightning impulse testing system.

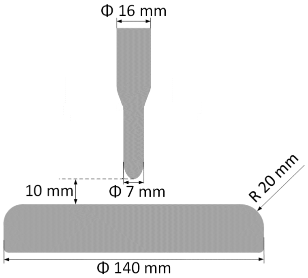

Fig. 2. Electrode configuration used in experiments.

II. EXPERIMENTAL SETUP AND TEST PROCEDURE

A. Experimental Setup and Circuit

The setup for the lightning impulse testing is schematically illustrated in Fig. 1. The tests were conducted in a 130 L cylindrical stainless steel pressure vessel. A HighVolt 12 stage Marx multiplier type impulse generator was used to generate the impulses. The impulse generator can be charged up to 100 kV per stage and the stage energy is 5 kJ. In this study, 4 stages of the generator were used. Front and tail resistors of the generator were adjusted such that the resulting waveform is a $1.35/47.7\,\mu s$ impulse which is within the tolerance limit of a standard LI [7].

B. Electrode Configuration

A rod-plane electrode arrangement, see Fig. 2, housed inside the test vessel, was used to conduct the LI withstand tests. The impulse voltage was applied to the rod electrode through the vertical bushing of the test vessel and the plane electrode was connected to earth potential, as shown in Fig. 1. The gap distance between the electrodes was 10 mm. The electrode arrangement was suggested by CIGRE working group D1.67 and results in a weakly non-uniform electric field [3]. The degree of homogeneity, i.e., the ratio of the average electric field to the maximum electric field for this electrode arrangement is around 0.3. The electrodes were cleaned with 99.5% isopropanol before the experiments to get rid of impurities. To limit surface erosion from consecutive breakdowns, the electrodes were made of chromium-nickel (CrNi) steel.

C. LI Test Procedure

The LI tests were conducted according to the up and down approach described in IEC 60060-1 with 76 shots [7]. The up and down test series starts at a voltage below the expected mean breakdown voltage. The peak voltage of each lightning impulse is then increased stepwise by a magnitude ΔU until the first breakdown occurs. Following each breakdown, the next prospective peak voltage is reduced by ΔU and for each withstand, the next voltage is increased by ΔU.

Four test methods were explored to investigate if the breakdown voltage in consecutive LI shots changes due to space charge accumulation or by air byproduct formation from the previous discharges. Both positive (LI+) and negative polarity (LI-) withstand tests were performed in each of these methods. Measurements of pressure, humidity, and temperature were taken within the vessel before and after each LI test using a WIKA GDHT-20 sensor. Table I presents an overview of all test methods. The tests were performed on dry air (80% N_2, 20% O_2) at 1.3 bar absolute pressure, and in ambient air at 1 bar. Before filling with dry air at 1.3 bar, the pressure vessel was cleaned thoroughly with isopropanol and evacuated down to < 1 mbar with one round of flushing (by dry air up to 1 bar). To regulate humidity, a desiccant (Zeolite 5Å) was placed inside the vessel during the experiments with dry air (similar to those found in switchgear).

In method 1, a DC voltage of 2 kV was applied across the test electrodes for at least 30 seconds to flush away any space charges that might accumulate in the air gap after each impulse application. To drift away the space charges, method 2 was also explored where both positive and negative polarity shots were intertwined in the same test series. Here, each positive LI shot was followed by a negative LI shot before proceeding to the next positive LI shot and vice versa. The starting voltages of the up and down tests for both polarities were independent of each other and the subsequent shots for one polarity follow the standard up and down procedure for the respective polarity. In method 3, a small fan (12 V, 0.8 W) was installed inside the test vessel which continuously circulated the air inside. The aim was to minimize changes in the chemical composition of air, which might have occurred locally in the rod-plane gap due to consecutive discharges, Finally, reference LI tests were conducted on both mediums without any fan or flushing voltage in between the shots (method 4), which is typically how standard LI testing is performed.

D. Detection of Ozone in Test Gap

As mentioned earlier, the increasing trend in the breakdown voltage could occur due to changes in the chemical composition of the air gap. In particular, ozone (O_3) can be formed during electrical discharges through air [8]–[10]. To experimentally determine if and how much ozone is produced during the test series, some additional tests were conducted in ambient air at 1 bar without forced air flow. For positive LI, a total of four tests were conducted. At first, 50 shots were consecutively applied with a prospective peak of 100 kV. Afterwards, two mobile ozone meters, Dräger X-am 5600 multi-gas detector and TROTEC OZ-ONE ozone analyzer,

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TABLE I
OVERVIEW OF TEST METHODS.

No.	Method	Flushing voltage	Fan	Waiting time [minutes]	Insulation medium	Absolute pressure [bar]	Dessicant (Zeolite 5Å)
1	Ion flushing by DC voltage application in between LI shots	2 kV DC for 30 s	no	3	Dry air	1.3	yes
2	Opposite polarity LI intertwined	LI- or LI+	no	3	Dry air	1.3	yes
3	Forced air flow by fan during LI test	no	yes	1	Dry air Ambient air	1.3 1	yes no
4	Reference test	no	no	1	Dry air Ambient air	1.3 1	yes no

TABLE II
TECHNICAL SPECIFICATIONS OF THE OZONE SENSORS.

	Measuring range	Resolution	Accuracy
Dräger (O_3)	0 - 10 ppm	0.01 ppm	20%
TROTEC (O_3)	0 - 1 ppm	0.01 ppm	±0.02 ppm
TROTEC (RH)	0 - 99.9%	0.1%	±3%

were held near the test gap (within around $2-4$ cm) to measure ozone concentration. The ozone meter by TROTEC also provided relative humidity (RH) measurements. Table II shows technical specifications of these instruments at test conditions [11], [12]. To investigate the rate of decay of ozone concentration with respect to time, readings by the Dräger ozone meter were taken at 1, 10, and 20 minutes after the impulse applications, and those by the TROTEC sensor were taken after 5, 15 and 25 minutes. The test was repeated while varying the prospective peak voltage (40 kV or 100 kV) and the number of shots (10 or 50). Similar tests were also carried out with negative LI with a prospective peak of -75 kV and the number of shots were varied between 10, 30, and 50.

Finally, to investigate if there is any impact of air circulation on ozone concentration, one final test was carried out with 30 shots of positive LI at a prospective peak of 45 kV. The vessel was kept fully open on both sides (i.e., with both lids off), thus allowing cross-ventilation during the test.

III. RESULTS

A. LI Test Results

The up and down test results were evaluated following the procedure suggested by the CIGRE working group D1.67 [3]. In the case of withstand or breakdown occurring in the falling edge of the impulse, the measured peak voltage is considered. If breakdown takes place in the rising edge, the actual breakdown voltage is taken. The shot immediately before the first change from hold to fail and all the subsequent shots are considered to evaluate the minimum breakdown (lowest fail) and the maximum withstand (highest hold) voltage. The mean breakdown voltage is determined from the breakdown voltages between the lowest fail and the highest hold.

Fig. 3 shows the results for both positive and negative LI in 1.3 bar dry air for the four test methods outlined in Table I. The highest hold, lowest fail, and mean breakdown voltages of the corresponding series are represented by error bars of same colour. The up and down test results are also summarized in Table III, where U_{start} denotes the starting voltage of the series and ΔU is the voltage step by which the prospective peak was varied from shot to shot. The mean breakdown voltage, the highest hold, and the lowest fail are denoted by U_{mean}, U_{max}, and U_{min}, respectively.

It is apparent that, the test series conducted according to method 1, 2, and 4 had a number of hold sequences, resulting in an overall increase in the mean breakdown voltage. In contrast, the series with forced air flow (method 3) did not manifest the increasing trend and the holds and fails were evenly distributed at both polarities. Compared to the LI+ series conducted according to method 3, U_{mean} was found to be increased by around 28-40% in method 1, 2 or 4. In the case of the LI- series, U_{mean} was found to be increased by around 22-73% in method 1, 2 or 4 compared to that in method 3, and the average field between the electrodes even exceeded the breakdown strength of air at 1.3 bar. In comparison to method 1, 2 or 4, the scatter between the highest hold and the lowest fail in the test series carried out using method 3 was also significantly lower at both polarities. Such up and down test series with no increasing or decreasing trend and a low scatter are usually considered trustworthy [3].

During the negative LI test series, breakdowns mostly took place in the rising edge of the impulses and the actual breakdown voltage was often significantly lower than the prospective peak of the applied shot. This led to significantly lower value of the minimum breakdown voltage (U_{min}) compared to the peak voltage (U_{max}) of the shot at which the highest hold occurred. In contrast, during the positive LI test series, all the breakdowns occurred in the falling edge and the peak voltages were then considered for the calculation of both U_{min} and U_{max}. Therefore, the error bars between U_{min} and U_{max} were in general lower in the positive LI test series compared to those in the negative polarity.

It can be further observed that, for same polarity LI, the first change from hold to fail occurred in the same range for different test methods except for the reference LI- series. In that case, the first breakdown occurred at a significantly higher voltage level compared to the other LI- series, although the starting voltages were the same. The reference LI- series was actually conducted right after two reference LI+ series, whereas all other series were started several hours after the previous LI test.

In order to confirm if method 3 consistently results in stable LI up and down test series without any increasing or

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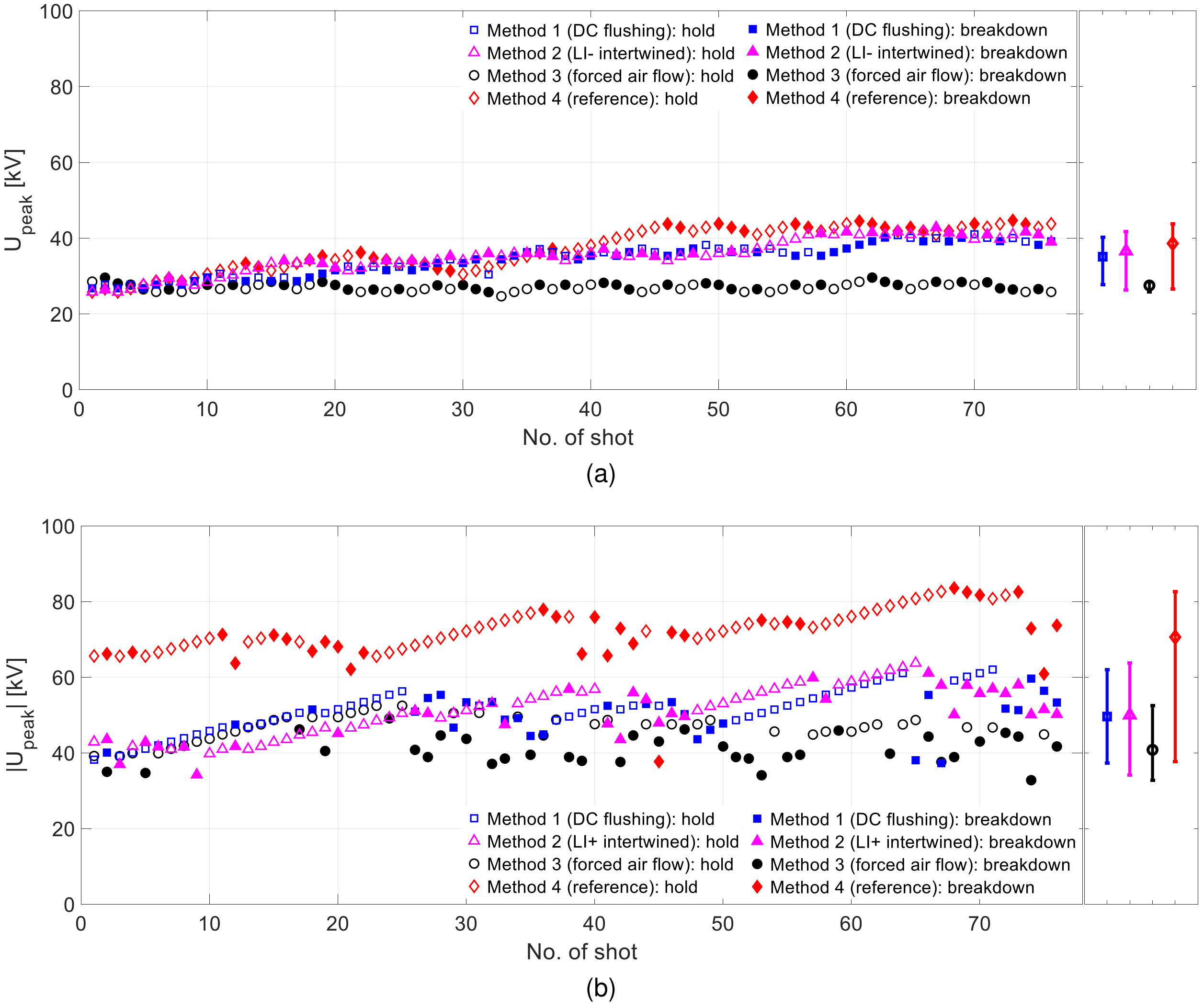

Fig. 3. Up and down test results in 1.3 bar dry air. (a) Positive LI. (b) Negative LI. In the case of withstand or breakdown in the falling edge of the impulse, the measured peak voltage is shown. For breakdown in the rising edge, the actual breakdown voltage is shown. The error bars in the right side represent the mean, the highest hold (upper whisker), and the lowest fail (lower whisker) voltages.

TABLE III
UP AND DOWN TEST RESULTS FOR POSITIVE AND NEGATIVE LI

		Dry air 1.3 bar					Ambient air 1 bar				
Polarity	Method	U_{start} [kV]	ΔU [kV]	U_{mean} [kV]	$U_{\max}$ [kV]	$U_{\min}$ [kV]	U_{start} [kV]	ΔU [kV]	U_{mean} [kV]	$U_{\max}$ [kV]	$U_{\min}$ [kV]
+	1	25	1	35.1	40.2	27.7					
+	2	25	1	36.6	41.7	26.4					
+	3	25	1	27.5	28.5	25.8	20	2	20.5	19.1	18.9
+	4	25	1	38.6	43.8	26.6	20	2	36.5	42.0	20.9
-	1	38	1	49.6	62.0	37.3					
-	2	38	1	50.0	63.7	34.2					
-	3	38	1	40.8	52.5	32.8	25	2	32.2	40.0	27.9
-	4	38	1	70.6	82.7	37.7	25	2	53.0	64.7	39.9

decreasing trend, additional tests were performed in ambient air at 1 bar for both positive and negative LI using methods 3 and 4, and the results are presented in Fig. 4 and also in Table III. As for 1.3 bar dry air, the series conducted using forced air flow had breakdowns at a consistent voltage level. In contrast, the reference series exhibited sequences of consecutive holds leading to an increased value of the mean breakdown voltage and a significantly larger scatter. Compared to the series using forced air flow, the mean breakdown voltage increased by about 78% and 65% in the reference series for positive and negative polarity, respectively. During the positive LI series, breakdowns in general occurred in the falling edge of the applied impulses, whereas breakdowns in the rising edge were more frequent for negative polarity. This further led to larger error bars between the maximum withstand and the minimum breakdown voltage in the negative LI test series. For both polarities, the mean breakdown voltages were around 1.3 times lower than those in 1.3 bar dry air when the fan was

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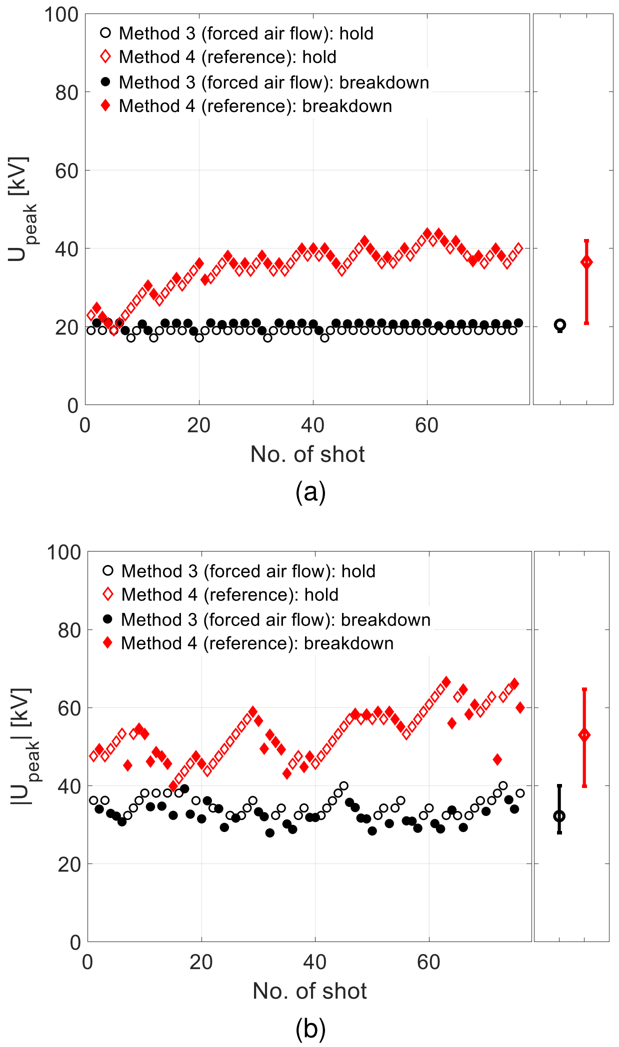

Fig. 4. Up and down test results in 1 bar ambient air. (a) Positive LI. (b) Negative LI. In the case of withstand or breakdown in the falling edge, the measured peak voltage is shown. For breakdown in the rising edge, the actual breakdown voltage is shown. The error bars in the right side represent the mean, the highest hold (upper whisker), and the lowest fail (lower whisker) voltages.

on, which is in agreement with the pressure-scaling of the breakdown voltage [2]. However, such dependence was not observed in case of the reference test with positive polarity, implying that the method fails to produce the true U_{mean} at least in this particular case.

In both 1.3 bar dry air and 1 bar ambient air, the negative LI breakdown voltage was around 1.4-1.8 times higher than the positive LI counterpart. This can be due to the well-known field distortion effect of space charges depending on the polarity of the applied voltage in non-uniform fields [2]. Other explanations could be differences in critical volume (the volume where the electric field is sufficiently high to support streamer inception) and/or the source of the first electron to initiate an electron avalanche and breakdown streamer depending on the polarity [13]. For instance, electron detachment from negative ions could be the main source of primary electrons and the applied electric field might push these ions away for the negative polarity before the growing critical volume catches up with them. This will reduce or eliminate the source of the first electron. The larger scatter between the maximum withstand and the minimum breakdown voltage in case of negative polarity might also be explained by this lack of initial electrons within the critical volume.

After each test series, the electrodes were visually inspected for breakdown traces. In the test series that did not use forced air flow (methods 1, 2, and 4), breakdown traces were observed away from the center of the plane electrode and higher up on the rod electrode. In contrast, for method 3, which used forced air flow, the breakdown traces were consistently confined close to the center of the plane electrode and the rod tip.

No significant surface erosion was found on the electrodes after any of the LI tests. The mean surface roughness of the high voltage electrode remained at around 50 µm, and that of the ground electrode was around 1 µm before and after the test series. The surface roughness levels are within the range recommended by the CIGRE working group D1.67 [3].

Furthermore, no noticeable change was observed in pressure, temperature, and humidity as measured by the WIKA sensor during the LI tests. The pressure was more or less consistent at 1.3 bar in case of dry air and at 1 bar in case of ambient air. Humidity was ∼50-60 ppmv and ∼4800-4900 ppmv in dry and ambient air, respectively. The temperature was ∼19-20 °C for all test series.

B. Measurement of Ozone in Test Gap

Fig. 5 shows the results of the ozone measurement tests, where concentrations of ozone as measured with the ozone meters by Dräger and TROTEC are plotted as a function of time after application of the LI shots in 1 bar ambient air. All applied shots in each of these tests resulted in breakdowns. Both ozone meters showed zero concentration of ozone (O_3 ppm = 0) near the air gap before each test. However, followed by the impulse breakdowns, ozone was detected by both meters. In general, the ozone analyzer by TROTEC gave higher reading of ozone concentration compared to the Dräger ozone meter. This can be due to the specified risk of cross-sensitivity of the TROTEC sensor to other components such as, nitrogen dioxide, nitric oxide, carbon dioxide, water vapour and so on [12]. Nonetheless, readings from both the sensors indicated an increase in the ozone concentration with discharge energy as a higher concentration of ozone was measured by both sensors followed by greater number of breakdowns or a higher applied voltage level, as can be seen from Fig. 5. The highest concentration of ozone (0.06 ppm by Dräger, 0.12 ppm by TROTEC) was measured after the test with 50 LI- shots at a prospective peak of 75 kV.

Furthermore, ozone being a relatively unstable compound, its concentration steadily decayed over time as indicated by both the sensors. While the ozone concentration measured by the Dräger sensor dropped down to 0 ppm within 20 minutes after most of the tests, the TROTEC sensor was still detecting ozone after 25 minutes. In case of the first test, i.e., that with 50 LI+ shots applied at 100 kV prospective peak, the TROTEC ozone meter was showing 0.03 ppm of ozone even 90 minutes after the test. The ozone concentration finally came down to

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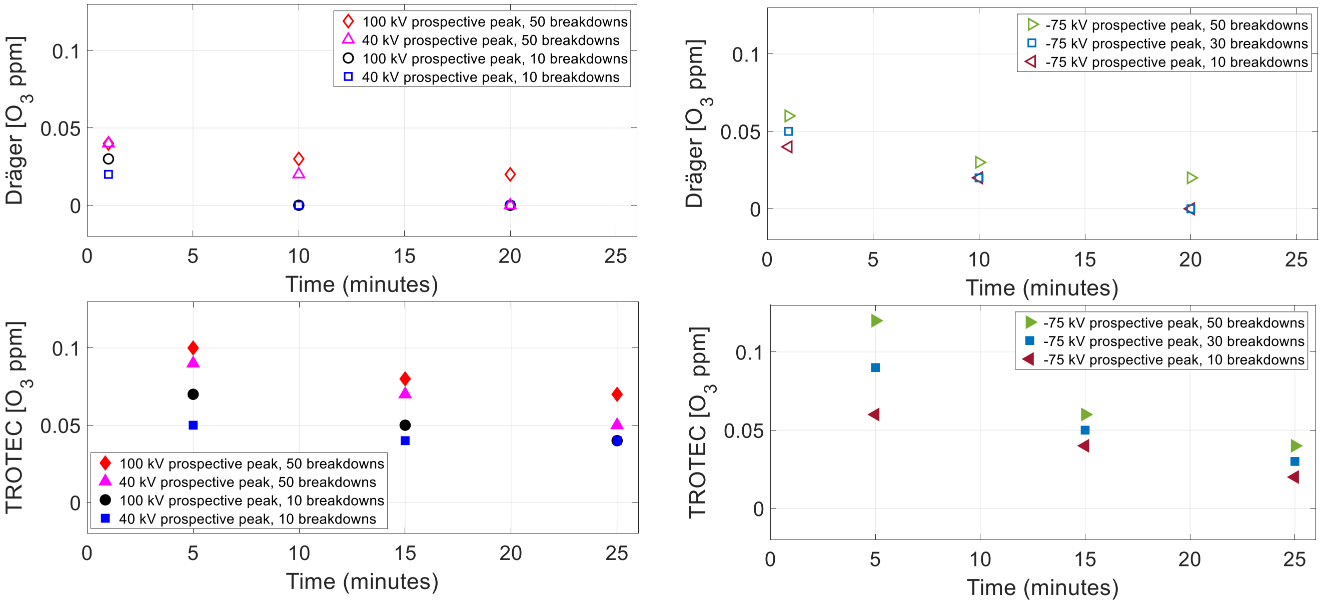

(a) (b)

Fig. 5. Measured concentration of ozone with respect to time after application of (a) positive LI shots, and (b) negative LI shots, in 1 bar ambient air. All shots in each test resulted in breakdowns. O_3 ppm = 0 before each test.

zero when the fan in the vessel was turned on for several seconds with the lids wide open. For rest of the tests, the fan was switched on after 30 minutes to get rid of any residual ozone within the gap before proceeding to the next test. During the experiment, it was also observed that the humidity near the test gap as measured by the TROTEC sensor also increased slightly after each test, as shown in Table IV. The increase was, however, not more than 7% RH in any of the tests.

It should be emphasized that, the readings of the ozone meters should not be considered as accurate, given the accuracy limitations of the sensors in Table II. Moreover, because of the large dimensions of the sensors compared to the electrode arrangement, the sensors could not be placed directly in the gap between the rod-plane electrodes, where ozone concentration or humidity might have been locally higher. Additionally, both sensors being handheld, their placement probably varied somewhat while taking measurements. Nevertheless, findings from these tests give a general indication that impulse breakdowns through an air gap lead to ozone formation. The concentration of ozone near the test gap increases with discharge energy, which gradually decreases over time on the order of tens of minutes. Furthermore, no ozone was detected near the gap when the fan was turned on after the ozone measurement tests. The impact of air circulation was further verified by the test that had provision for cross-ventilation with the lids of the vessel open. All 30 LI+ shots at 45 kV prospective peak in that test resulted in breakdowns. However, none of the ozone sensors could detect any ozone within the test gap right afterwards. In contrast, when the vessel was closed, ozone was detected by both sensors (0.02 ppm by Dräger, 0.05 ppm by TROTEC) even after the test with only 10 LI+ breakdowns at 40 kV prospective peak, as can be seen from Fig. 5 (a).

TABLE IV

RELATIVE HUMIDITY MEASUREMENTS BY TROTEC OZ-ONE OZONE ANALYZER BEFORE AND AFTER IMPULSE BREAKDOWNS.

Polarity	U_{peak} [kV]	No. of shots	%RH (before)	%RH (after)
+	100	50	33.0	37.7
+	40	50	36.6	41.5
+	100	10	31.9	38.8
+	40	10	37.9	45.3
-	75	50	32.8	35.3
-	75	30	34.4	39.8
-	75	10	33.4	39.6

IV. DISCUSSION

The experiments indicate that the observed increase in breakdown voltage is more likely to be caused by changes in the chemical composition of the air gap (e.g., formation of ozone), rather than accumulation of space charges or electrode surface erosion. The LI tests with a flushing voltage showed the same increasing trend with frequent continuous hold sequences as in the reference LI tests. If space charges were solely responsible, application of a flushing voltage should have nullified the effect. In particular, the DC flushing voltage was applied for 30 seconds, which should be sufficiently long to drift the residual charges away.

No remarkable change was observed in the electrode surface profiles followed by the LI tests. Therefore, the increasing trend cannot be explained by conditioning of the electrodes either. Moreover, if the trend was due to electrode conditioning effect, using forced air flow by a fan should have little or no effect on the up and down test results.

However, the chemical constitution of the air between the electrodes can be altered over consecutive discharges in the LI tests, which might change the breakdown voltage of the gap especially if there is no provision for air circulation within the vessel. In a previous study by Ryzko, the impulse breakdown voltage was found to be increased by up to 40% when a closed volume of air was exposed to spark discharges [14]. Chrzan et al. also reported on a substantial increase in the impulse withstand voltage of air exposed to arcing [15]. Formation of highly electronegative substances such as ozone was stated as the reason behind such increase. An increase in the electrical strength was reported in another study for a mixture comprising ozone in ambient air [16].

Electrical discharges through air result in an intense plasma with a substantially complex chemistry [17], and there are multiple pathways towards ozone formation, many of which involve either atomic oxygen or meta-stables of molecular oxygen. For example, oxygen atoms can be formed through the dissociation process [9], [10],

$$\mathrm{e}^{-} + \mathrm{O_2} \longrightarrow \mathrm{O} + \mathrm{O} + \mathrm{e}^{-}, \tag{1}$$

$$\mathrm{e}^{-} + \mathrm{O_2} \longrightarrow \mathrm{O} + \mathrm{O}^{-}, \tag{2}$$

and ozone can then be produced as a result of the three-body reaction

$$\mathrm{O} + \mathrm{O_2} + \mathrm{M} \longrightarrow \mathrm{O_3} + \mathrm{M}, \tag{3}$$

where, M is a placeholder for either molecular oxygen or molecular nitrogen. All the reactions above are substantially faster than the waiting time in the LI tests performed in this study. For example, the rate of the electron impact dissociation in reaction (1) is in the order of around $2.5 \times 10^{9}\ \mathrm{s^{-1}}$ at relevant electron energies. Likewise, reaction (3) occurs in less than $10\,\mu\mathrm{s}$, the third-body M being molecular oxygen [17].

In addition to O_3, oxides of N_2 such as, nitric oxide (NO), nitrous oxide (N_2O), and nitrogen dioxide (NO_2) can be formed due to spark discharges through air [18]. Among these, NO and NO_2, are presumed to have little influence on increasing the breakdown voltage of air as their peak attachment coefficients are considerably lower. In case of NO, the breakdown voltage may even get reduced due to its lower ionization potential [14]. Ozone and N_2O, on the other hand, are reported to have very large electron attachment cross-sections at electron energies in the range of $0 - 4\,\mathrm{eV}$ [18]. However, N_2O is less likely to be responsible for the large increase in breakdown voltage as it is a stable compound with a long atmospheric lifetime of around 150 years [19]. In this study, it was observed that the increased value of impulse breakdown voltage of air lowered down to the initial level within several hours after the test. This could be due to slow drift of the electron attaching compounds away from the discharge gap in the course of time. However, in an enclosed volume without any air circulation, it seems more likely that the enhanced breakdown performance is caused by a short-lived compound like ozone, which is expected to decay in the absence of any discharges [15].

In order to evaluate how the ionization and attachment coefficients change if air is mixed with ozone of varying concentrations ($0 - 10^{4}$ ppm), the ionization and attachment coefficients of N_2-O_2-O_3 mixtures were calculated using BOLSIG+, based on the cross-sections in the Biagi database (for N_2/O_2 collisions) [20] and the Morgan database (for O_3) [21]. However, only attachment and ionization cross-section data were available for the latter, so the roles of elastic and inelastic collisions with O_3 were not included. Fig. 6 shows plots of the reduced ionization (α/N) and attachment coefficients (η/N) as a function of the reduced electric field (E/N) for pure air and air mixed with 10^{4} ppm of O_3 at 1 bar and 300 K, with the neutral density N being around $2.45 \times 10^{25}\ \mathrm{m^{-3}}$. As can be seen, no significant difference was found in the computed transport coefficients even after including an artificially high concentration of O_3 in the calculations. At lower concentrations of O_3 (1 ppm, 10 ppm, 10^{2} ppm, and 10^{3} ppm), the transport coefficients of the N_2-O_2-O_3 mixture were virtually identical to those in pure air. The calculations show that the breakdown field at the experimentally measured ozone concentrations does not change.

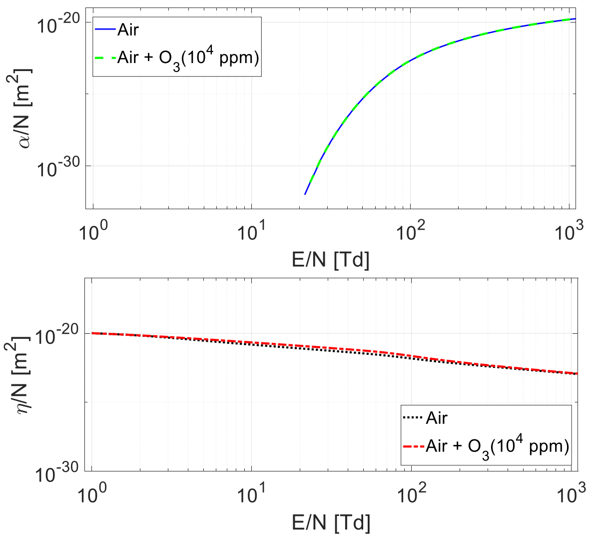

Fig. 6. Transport coefficients computed with BOLSIG+ as a function of reduced electric field in air and air with 10^{4} ppm O_3 at 1 bar.

However, in case of pure air, the free electrons available in the gas (created by, for example, background ionization, e.g., cosmic rays or radon decay) rapidly attach to molecular oxygen through the three-body attachment

$$\mathrm{e}^{-} + \mathrm{O_2} + \mathrm{O_2} \longrightarrow \mathrm{O_2^{-}} + \mathrm{O_2}. \tag{4}$$

Depending on the electron energy, reaction (4) typically occurs in an order of around 100 ns at 1 bar pressure [17]. The O_2^{-} ions generated in this process can act as a potent source of primary electrons for repeatedly pulsed discharges due to its fast electron detachment in an electric field [22]. However, accumulation of O_3 in air may lead to a significant decrease in the primary electron availability through charge transfer from O_2^{-} to O_3 [17], [23]:

$$\mathrm{O_2^{-}} + \mathrm{O_3} \longrightarrow \mathrm{O_2} + \mathrm{O_3^{-}}. \tag{5}$$

The rate of reaction (5) is $kN_{\mathrm{O_3}}$, where $N_{\mathrm{O_3}}$ is the neutral density of ozone and $k = 4 \times 10^{-16}\ \mathrm{m^3 s^{-1}}$ [17]. If an ozone concentration ($N_{\mathrm{O_3}}/N$) of around 0.1 ppm is considered based on the measurements in the ozone detection tests, the neutral density of ozone, $N_{\mathrm{O_3}}$, becomes approximately $2.45 \times 10^{18}\ \mathrm{m^{-3}}$

at atmospheric pressure. This is much higher than the background ionization, which is typically on the order of 10^{10} m^{-3}. The lifetime of O_2^- at this concentration of O_3 is $\left(kN_{O_3}\right)^{-1} \approx 1\,\mathrm{ms}$, and virtually all O_2^- ions rapidly shed their electrons in charge exchange collisions with O_3, and the dominant primary electron source would therefore be O_3^- rather than O_2^-. Since ozone has a significantly higher electron binding energy than O_2, electron detachment would be less probable [22], [23]. Consequently, the probability of streamer inception would also be reduced, specially in the case of LIs where the first electron must appear in the critical volume within a narrow time window of a few microseconds.

It should be noted that the application of a flushing voltage after a discharge will necessarily reduce the concentration of both O_2^- and O_3^- ions, but it does not affect the concentration of O_3. Between discharges, and regardless of whether or not flushing is applied, primary electrons may again become available due to background ionization in the gas. The O_3 molecules would then transform into O_3^- ions again through reactions (4) and (5), which eventually leads to reduced availability of free electrons as discussed above.

Due to this lack of primary electrons in regions where O_3 is formed followed by a breakdown, a substantial overvoltage might be required to initiate streamer discharge further up along the electrode where the concentration of O_3 is lower. In this case, the subsequent breakdowns may occur through the air surrounding previous spark channels which contain ozone. This could explain why traces of breakdowns were found further towards the edge of the plane electrode and higher up on the rod electrode in case of the LI test series that did not employ forced air circulation. Accumulation of ozone might therefore be responsible for the increased breakdown voltage during those test series. This also indicates that the memory effect would only be relevant in non-uniform fields. In uniform fields like that in a plane-plane electrode arrangement, the circumvention of previous ozone-containing spark channels would not entail a longer distance. The memory effect would essentially depend on the electrode geometry and the gap distance, which directly influence the electric field and particle distribution. Moreover, the memory effect would not be present under DC or power frequency AC voltage stresses since the starting electron would then be a virtual guarantee. The effect would also be less significant under switching impulse voltages as the required time window for the appearance of the first electron is much wider in this case compared to LIs.

For the LI test series conducted using forced air flow by a fan, the increasing trend was not observed even with a waiting time of only 1 minute. Essentially, a fan may help in two ways to keep the breakdown voltage consistent throughout the tests. Firstly, it transports ozone away from the discharge gap. Secondly, a forced air flow may reduce ozone concentration within the vessel as the half lifetime of ozone decreases exponentially with air velocity [24]. This could explain why no ozone was detected near the test gap during the ozone measurement tests in presence of air circulation. However, in an enclosed volume, the half lifetime of ozone can be up to several hours if there is no provision for forced air flow [24]. In that case, the waiting time between consecutive shots should also be chosen accordingly during impulse testing in short air-gaps especially if the electric field is non-uniform.

In the reference LI- series in 1.3 bar dry air, the high value of the first breakdown voltage could be explained with the residual ozone from the reference LI+ series conducted immediately before that LI- series. Since the LI+ series had been conducted without fan, a considerable amount of ozone might have been accumulated between the electrodes.

Another aspect that might be important to consider with regards to the increasing trend of the LI breakdown voltage is the effect of humidity. Previous studies suggest that the impulse breakdown voltage of rod-plane air gaps may increase with humidity [25], which is consistent with the humidity measurements taken during the ozone detection tests on ambient air in this study. The residual space charges in the insulation gap followed by a breakdown may attract polar water molecules [26], thereby increasing the humidity within the gap. Apart from ozone formation, increase in humidity might be another reason behind the increasing trend of the up and down test voltages in ambient air. However, similar increasing trend was found while performing up and down tests in dry air, even after using desiccant to regulate humidity. If humidity was the prime reason behind the increasing trend, the effect should have been lower in case of dry air.

Moreover, due to the measurement uncertainties associated with the TROTEC sensor as discussed earlier, it cannot be said for sure if humidity had increased significantly within the test gap in ambient air either. Moreover, the WIKA sensor did not indicate any remarkable change in humidity within the vessel while performing the up and down tests in dry or ambient air. Nonetheless, this sensor was placed some distance away from the electrodes and the measurements are not indicative if humidity increases locally within the test gap. To conclusively determine the effect of humidity (if any) on the increasing trend of the LI test voltages, more investigation is needed. Moreover, to experimentally verify if the increasing trend is due to lack of first electrons in presence of ozone, further experiments should be carried out with an ultraviolet lamp or a radioactive source for generating more starting electrons.

V. CONCLUSIONS

This paper investigates possible causes for an observed phenomenon of increasing breakdown voltage while performing LI tests (both positive and negative) in short air-gaps with weakly non-uniform electric field using the standard up and down procedure. The relevant findings are:

- It is more likely that the phenomenon occurs due to formation of electronegative air byproducts, such as ozone, rather than accumulation of space charges or changes in the electrode surface.
- Consecutive LI discharges in air lead to ozone formation, and the concentration of ozone increases with the discharge energy.
- The ionization and the attachment coefficients do not change if ozone is accumulated in air, i.e., formation of ozone would not affect the critical field or streamer-to-spark transition. It may, however, reduce the probability

of the first electron significantly, thereby leading to an increase in the impulse breakdown voltage.

- As air circulation helps in reducing ozone concentration, the memory effect was not present when a fan blew near the test gap, even with a waiting time of only 1 minute. In contrast, several hours of waiting time might be needed to get rid of the effect of ozone in absence of a forced air flow.
- The mean LI breakdown voltage without fan increased by up to 78% compared to that with fan on. It is therefore recommended to ensure air flow during LI up and down tests in short air-gaps with a non-uniform field in an enclosed volume to prevent the observed memory effect. Further investigations should be made for a clear understanding of the effect of air byproducts and the standard impulse testing techniques should be revised accordingly.

ACKNOWLEDGMENTS

This work is supported by the Norwegian Research Council project no. 319930. The authors are grateful to Hans Kristian Meyer, Fahim Abid, Fanny Skirbekk, Fredrik Iversen, Dag Kjelstrup Myrvang, and Morten Flå for their contributions.

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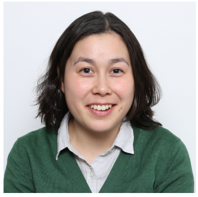

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This article has been accepted for publication in IEEE Transactions on Dielectrics and Electrical Insulation. This is the author's version which has not been fully edited and content may change prior to final publication. Citation information: DOI 10.1109/TDEI.2024.3374276

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