Comparison of superimposed voltage tests with spark gap and coupling capacitor at a gas-insulated model arrangement

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Abstract: **Superimposed voltage tests are widespread to qualify HVDC equipment. Two possible test circuits are used, which result in different voltage shapes: superimposition by a coupling capacitor or by a spark gap. So far, there is no data available, which compares the resulting breakdown voltages of both methods with each other. This paper closes this gap by determination of the breakdown voltage at a model arrangement using both methods. The investigation was focused on gas-insulated systems, which are a typical application in HVDC. The model arrangement was built such that it represents a typical gas-solid interface in a coaxial GIL assembly. HVDC effects were included by heating of the earthed electrode. The determination of reproducible data was challenging, but could be achieved by adaptions inside the test circuit, as well as a suitable test procedure. The collected data with the built test arrangement is presented and discussed further in this paper. Based on the results a first conclusion is given, whether the different voltage shapes resulting from the use of a coupling capacitor and a spark gap, respectively, also result in different breakdown voltages.**

I. Introduction

Gas-insulated HVDC technology is generally of high interest for future grid expansion. So far, first recommendations to qualify such equipment are given in CIGRE TB 842 [1] from JWG D1/B3.57. Based on that, TC17 WG5 is working on a new standard IEC 62271-5.

Superimposed voltage tests (SIMP) play an important role during qualification of gas-insulated HVDC equipment [2]. In such tests an impulse voltage is superimposed while the DC voltage is still applied to the device under test (DUT). Fig. 1 shows the basic circuit for SIMP tests. The DC voltage U_{DC} is applied through a blocking resistor R_{d} to the DUT C_{DUT}. R_{d} blocks the applied impulse voltage and protects the DC source

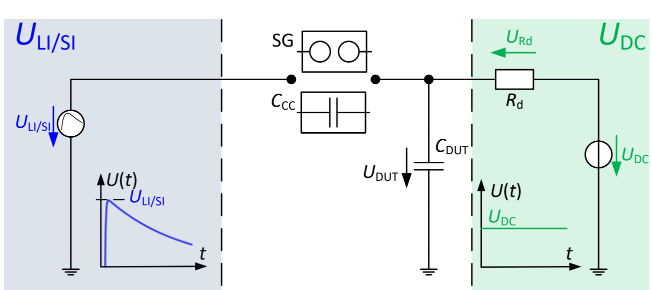

Fig. 1. General SIMP test circuit.

from damage. Two possible coupling elements are known to superimpose the impulse voltage $U_{\mathrm{LI/SI}}$ to the direct voltage U_{DC}: spark gaps (SG) and coupling capacitors (CC) [3][4]. Both methods are commonly accepted for testing [1]. However, the literature reports significantly different voltage wave shapes for both methods [1][3][4][5][6][7]. Up to now, it is uncertain if these different voltage shapes may also result in different flashover voltages at the DUT. Therefore, CIGRE TB 842 [1] recommends for SG test circuits that the voltage shape should not be distorted within a certain time interval. But so far, there is no laboratory data, which proves the sufficiency or necessity of such specifications. The question arises if the current specification is sufficient or may even be neglected.

Literature [7] discusses, weather further impulse front time specifications are required for superimposed voltage tests, because of the different voltage shapes at SG and CC testing. CIGRE TB 842 [1] recommends to set the time parameters without DC voltage and with short circuited blocking element. Again, the question arises, if this recommendation is sufficient or has to be extended.

II. Voltage Shapes

In total, the reported differences during superimposed SG and CC testing can be classified according to Table I [1][3][4][5][6][7].

TABLE I:

Differences in voltage shape by use of SG and CC for LI and SI voltage

		LI	SI
D1	Different tails because of the superposition principle	x	x
D2	Discharging to 0 kV and recharging to DC level	x	x
D3	Continuity of impulse front	x	x
D4	Harmonics in the voltage	x	x
D5	Holding of the impulse peak value		x
D6	Repetitive re-ignition of the coupling element on the tail		x

Differences D1 and D2 are shown in Fig. 2. They result from the different working principles of SG and CC. The SG directly applies the impulse voltage at the DUT, while the CC adds the impulse voltage to the test object, which leads to the difference D1. Since the SG stays conductive until its current goes to zero, it does not extinguish until the 0 kV level is reached. Afterwards the DUT will be recharged by the DC voltage source

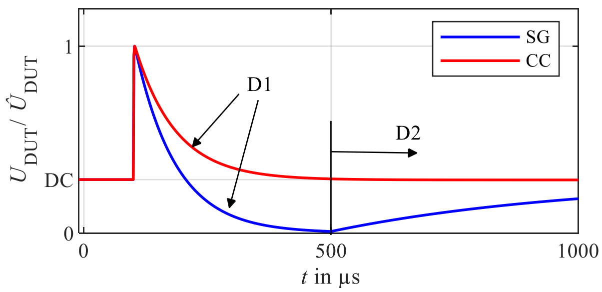

Fig. 2. D1 and D2 for a unipolar superimposed LI with SG and CC (theoretical shapes).

approximately with the time constant $R_d \cdot C_{DUT}$. For CC testing, the voltage reaches the DC voltage level directly after the impulse. These differences result in the different shapes at D2 (Fig. 2).

Fig. 3 shows the differences D3 to D6, based on different literature data of SIMP LI tests [1][3][4][7]. The effects D3 to D6 are characteristic at SG testing. At the impulse front, literature describes a rapid voltage increase of U_{DUT} after spark gap ignition, which results in a non-continuous impulse front (D3). The spark gap ignition also causes visible harmonics of the test voltage (D4). Especially during SI tests the SG tends to extinguish at the impulse peak, which results in the voltage shape according to D5. Such extinguishing may also re-occur during the impulse tail repetitively, resulting in a non-continuous voltage shape (D6).

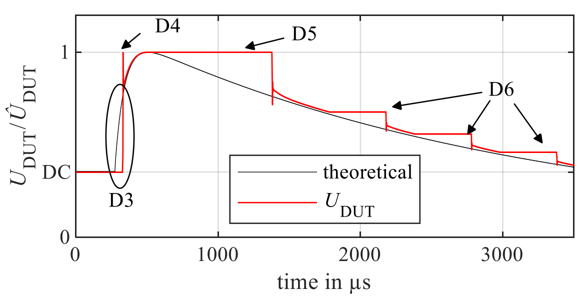

Fig. 3. D3 to D6 for a unipolar superimposed SI with SG based on literature (dashed = theoretical SG shape).

The differences D3 to D6 may be avoided by use of an optimized SG. D3 and D4 are avoided by triggering both spheres of the SG [2][6]. D5 and D6 are avoided by increasing the SG current e.g. by additional capacitors in parallel to C_{DUT} [2].

III. Test Arrangement

The investigation was performed with the test circuit shown in Fig. 4. The test arrangement was designed for 300 kV DC and LI voltages in the range of 1.2 MV.

The applied DC voltage U_{DC} and impulse voltage U_{LI} were measured at the sources and combined to get the superimposed voltage shape. Therefore, the voltage drop across the coupling and blocking element need to be examined [1]. The examination of the DC voltage drop across R_d for SG as well as CC was performed with a temporarily installed resistive voltage divider.

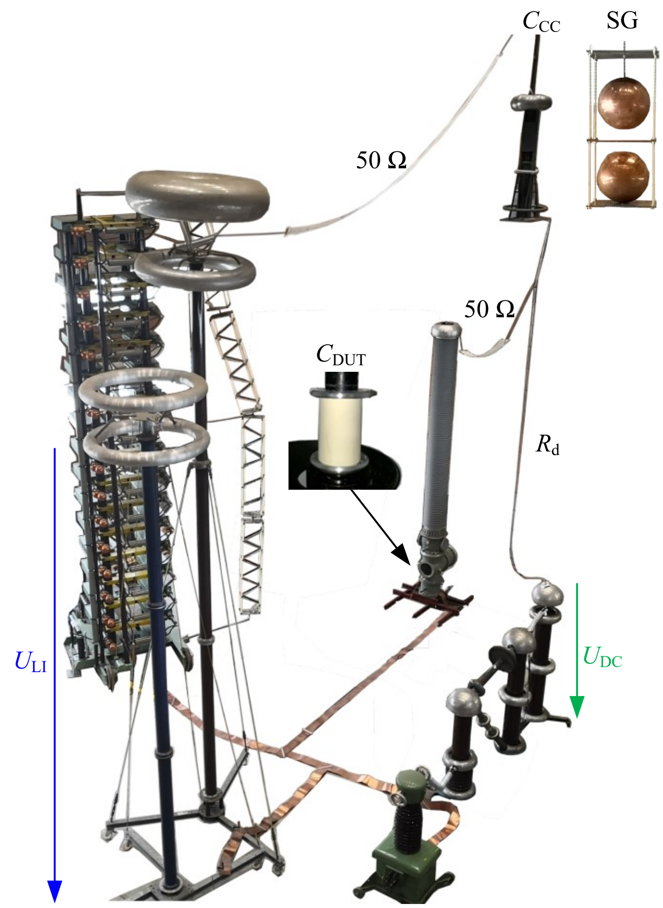

Fig. 4. SIMP laboratory arrangement for 300 kV DC / 1.2 MV LI.

Its value was periodically checked to determine possible changes due to resistivity changes of the water blocking resistor R_d. The impulse voltage drop across the SG is negligible according to literature [1], because the impulse voltage is directly applied to the test object. The SG was built with two 50 cm diameter spheres. The gap distance was in the range of 20 cm. The impulse voltage drop across the CC was examined on the basis of IEC 60052 [8] by use of standard gaps. Instead of an air gap in parallel to the test object, the gas vessel was equipped with a gas gap to examine the voltage drop for the installed coupling element. As expected the voltage drop was rather small, since C_{CC} was in the range of 15 nF and the test object capacitance in the range of only a few pF.

A. *Gas-insulated model arrangement*

Generally, a gas-insulated system consists of a gas gap and the gas-solid interface. For most technical applications, the gas-solid interface is more critical with respect to design and breakdown voltage. Therefore, a gas-solid model arrangement was built first by use of a straight cylindrical support insulator based on a commercial HVDC epoxy material (refer Fig. 4) [9][10]. Such insulator types can be used e.g. to support the inner conductor in a DC GIL arrangement. The model arrangement is installed in a gas vessel, which is filled with a SF_6/N_2 mixture at 0.7 MPa, which is in the range of typical GIL installations [10].

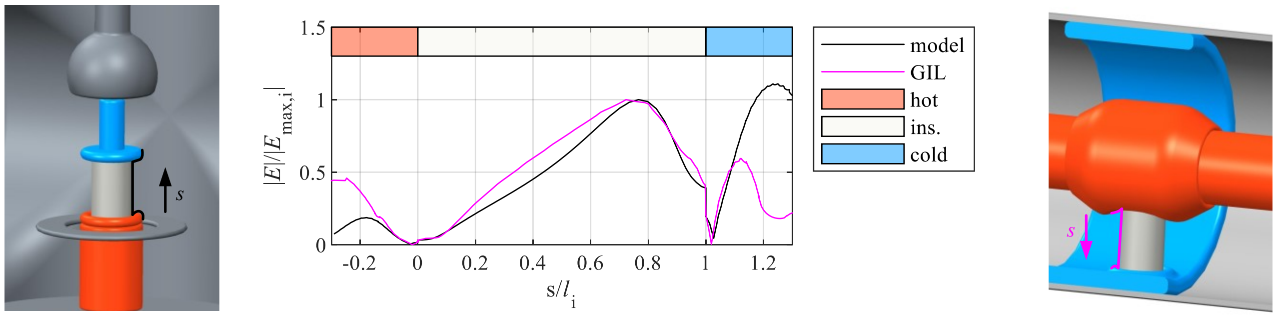

Fig. 5. Comparison of the model and a GIL arrangement. Orange = heated electrode, blue = cold electrode. Direction of s is in both cases from hot to cold. The x-axis is normalized to the insulator length l_i. The y-axis shows the absolute value of the electric field strength normalized to the maximum field strength on the insulator at each arrangement. The simulation uses the measured values of the temperature dependent conductivity of the insulator material.

The model arrangement is shown in detail in Fig. 5 left. At the bottom a heater was installed to simulate the heated conductor in practical arrangements. The heater was calibrated such that a temperature gradient of 30 K developed across the insulator, which is in the range of nominal values at gas-insulated HVDC systems [1]. At the top and bottom of the insulator two shielding electrodes are placed to simulate the insulator installation inside a commercial coaxial GIL [11].

The resulting electrical field strength $|E|$ along the shielding and insulator surface route s is shown in Fig. 5 as well. The direction of s goes from the heated (orange) to the cold (blue) electrode. The simulation uses a temperature dependent conductivity of the insulator according to [9] as well as parameters from [11][12] and simulates thereby all major DC phenomena. A simulation of the electric field distribution of the same insulator installed in a coaxial GIL arrangement is added to Fig. 5 (right) in order to transfer the results from the model arrangement to typical technical installations. Overall, the electric field distributions along the insulator surface are very similar for a GIL and the model arrangement. It is thereby assumed, that the measured breakdown voltages at the model arrangement adequately represent the breakdown behavior in practical insulator arrangements.

The electrical field strengths at the shielding electrodes show higher deviations between the model and the GIL arrangement. This results from the practical limits of the model arrangement. Since the model arrangement is placed in an earthed enclosure and heated at earth potential, the resulting field at the high voltage electrode will always be much higher than at the earth electrode. However, the electrode with the highest electrical field in the model and the GIL arrangement and thereby the start of a flashover is the colder electrode. Since the model arrangement has a higher electric field strength at this electrode, flashovers are assumed to be typically triggered much earlier compared to the GIL arrangement. The electric field at the earth electrode is estimated to have low impact on the breakdown in both arrangements. Summarized, the model arrangement is assumed to be suitable to simulate the breakdown behavior of gas-solid interfaces in general and to be representative for a practical coaxial GIL arrangement.

To transform the polarity dependent breakdown voltages from the model to a GIL arrangement, the opposite polarities in both arrangements have to be considered (refer Fig. 5). E.g. results for –DC and positive impulse in the model arrangement are comparable to results with +DC and negative impulse in the GIL arrangement.

B. Test procedure

In particular, an insulator arrangement is problematic with regard to the reproducibility of the breakdown voltage. Flashover traces on the insulator surface as well as protrusions on the shielding electrodes might lead to degradation of the arrangement and result in different breakdown voltages. An important addition to the test arrangement was the two low-inductive 50 Ω resistors, which are connected from the voltage divider to the coupling element and from the coupling element to the DUT (see Fig. 4). These resistors damp the impulse current in case of the breakdown of the model arrangement and need therefore proper insulation distances (Fig. 4). Thus the energy fed into the flashover and thereby the traces on the model arrangement were minimized and enabled a reproducible measurement. Besides that, damages at the CC occurred without installed damping resistors. It is assumed, that these damages occurred because of the high voltage drop and impulse current at the CC in case of breakdown at the model arrangement. Higher resistance values turned out to be problematic, since they flashed over during breakdown of the model arrangement.

The chosen epoxy material was especially robust to flashover traces and was able to withstand a certain amount of energy and impulses without changing too much its breakdown characteristic. However, the test procedure still requires to check for degradation during the experiment. That is why the used procedure according to Fig. 6 starts and ends with an impulse voltage measurement without DC voltage and a comparison of both voltages with each other. Thereby also possible differences between the individual measuring series due to gas handling etc. can be tracked, since all measurements have a reference measurement at 0 kV DC voltage. Each breakdown voltage is determined by the up-and-down-method with 25 impulses. The breakdown voltages in this paper are therefore the $U_{d,50}$ values of the model arrangement.

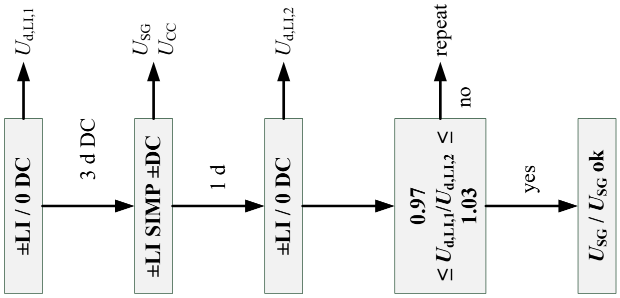

Fig. 6. Test procedure to investigate the breakdown voltage for SIMP tests.

The actual superimposed voltage measurement is initiated with a three days DC pre-charge to transform the initial capacitive field distribution to the final resistive one. The time of three days was chosen based on findings from previous charge measurements with the used epoxy material [13]. After the SIMP test, a waiting period of one day was sufficient to be able to check the degradation. The measurement was only considered valid if the impulse voltage measurements before and after the SIMP tests were within ±3 %.

C. *Pre-Investigations*

In order to perform statistical evaluations, it has furthermore to be ensured that a flashover will not affect the breakdown voltage of the next SIMP impulse voltage test. It would be conceivable that the charge flow during the breakdown could significantly change the insulator surface charge distribution and thereby the electric field distribution [1], e.g. due to earthing of the insulator at the time instant of the breakdown. Performed up-and-down tests were therefore checked for the breakdown voltages of the SIMP tests having a trend up- or downwards in direction to U_d at 0 kV DC. Since there was not any indication of such trend, it is assumed that such effect is negligible, which is plausible from a physical point of view. A flashover in the model arrangement lasts for a relative short time period compared to the recharging time of at least 60 seconds up to the next impulse. Therefore, possible changes due to a flashover are assumed to be compensated until the next impulse is applied.

Fig. 6 shows that unipolar and bipolar tests are performed within one sequence. It was checked in pre-investigations if the breakdown voltage is changed due to the order of unipolar and bipolar tests. The pre-investigation did not show significant differences in the breakdown voltage, for which reason no effects based on the sequence were considered. This result seems plausible as well, because the charge distribution mainly results from the constantly applied DC voltage and not from the short impulse.

Literature [14] describes, that the breakdown voltage of heated electrodes is reduced. This effect should play a minor role in the regarded comparison of CC and SG, since a possible reduction will happen equally in both methods and will therefore not change the result. However, it was investigated by impulse voltage tests, which resulted in differences in the range of 1.5 %. This makes the effect negligible indeed.

The model arrangement has therefore been qualified to be used to collect reproducible breakdown voltages. Since all DC effects are strongly depending on the applied material, such pre-investigations should be reconsidered when investigating different materials.

IV. Results

The results were gained by use of the test procedure shown in Fig. 6. Some sequences had to be repeated, because of degradation effects due to the amounts of breakdowns. Typically, degradation showed through a slight reduction of the breakdown voltage, which was hardly noticeable during the up-and-down sequence. In the end, the degradation process led to a flashover trace from high-voltage to earth potential. This trace dramatically reduced the breakdown voltage of the model arrangement, so that the insulator had to be grinded and cleaned or replaced to properly restore the dielectric behavior and breakdown voltage of the model arrangement.

Repetition of sequences was also required because of outages of the heater installed at the earth electrode (see Fig. 5) due to the high impulse current through its housing in case of a breakdown of the model arrangement. The outages were handled by use of surge arresters at all terminals as well as an insulating transformer to feed the heater isolated from earth potential.

A. *LI voltage*

The measurement was performed for 0 kV, +300 kV and -300 kV DC voltage with installed CC and SG. The LI breakdown voltages of the model arrangement were in the range of (900…1200) kV. The resulting LI voltage shape was similar to Fig. 2 and Fig. 3 and included the effects D1 to D4 (Table I). Examples of real oscillograms of unipolar LI tests are shown in Fig. 7. The time parameters were derived from the 0 kV DC voltage oscillogram.

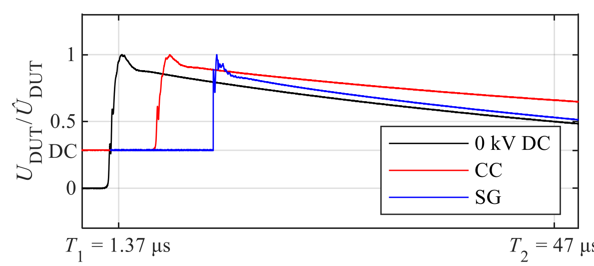

Fig. 7. Unipolar LI voltage shape – separate impulse and DC voltage measurement combined

The ratios between the collected 50 % breakdown voltages for installed SG U_{SG} and for installed CC U_{CC} are shown in Table II.

TABLE II:
RATIO OF $U_{D,50}$ WITH THE SG AND THE CC CIRCUIT FOR A 1.2/50 LI VOLTAGE

	$(U_{SG}/U_{CC}-1)\cdot 100\ \%$	
DC in kV	**+LI**	**-LI**
+300	+4.2	0.7
-300	-2.3	2.6
0	-0.9	2.9

Table II shows that the maximum difference between both superposition principles is approximately 4 %. More important than the maximum difference is the difference for the lowest breakdown voltages, since these are the most critical stresses during testing. For instance, a tested object is stressed with all polarity combinations, but typically with the same withstand voltages levels [15]. The highest probability for flashovers during the test is at the most critical stresses. The lowest breakdown voltages at the model arrangement were measured at the combination of -LI and -300 kV DC. Table II shows a difference between SG and CC of approximately 3 %. The deviations at 0 kV DC could be assumed to indicate the measuring uncertainty of the testing method. The differences for +300 kV and -300 kV only differ low from the 0 kV DC differences. Overall, the data does not show any sign of a higher breakdown voltage of one of the methods in principle, because both positive and negative ratios were determined over all polarity combinations.

The time to crest T_C was evaluated for all impulses. It is defined as the time from the impulse that triggers the impulse voltage generator up to the breakdown. In average, T_C for SG was 5.16 µs and for CC 7.48 µs. This means that the breakdown tends to appear earlier in SG circuits.

B. *SI voltage*

The investigation was focused on LI voltage, because LI is typically more critical with respect to design and type testing of gas-insulated systems, especially when a much higher LI than SI withstand voltage is tested [1][16]. Some SI voltage tests in the range of 800 kV SI were performed with CC only during an analysis of different effects and with a comparable insulator model arrangement, which will be presented in detail in future publications. However, some general results of this measurement can be used to evaluate possible differences of CC and SG circuits as well.

Fig. 8 shows the used SI voltage shape and all measured breakdowns for 0 kV, +DC and -DC voltage. In total, the data of 50 flashovers was collected. Fig. 8 clearly shows that independent from the polarity combination, most flashovers occurred before or near the peak. In average time to breakdown results in $T_C = 213$ µs, which means that the breakdown typically occurs before the nominal time to peak of 250 µs.

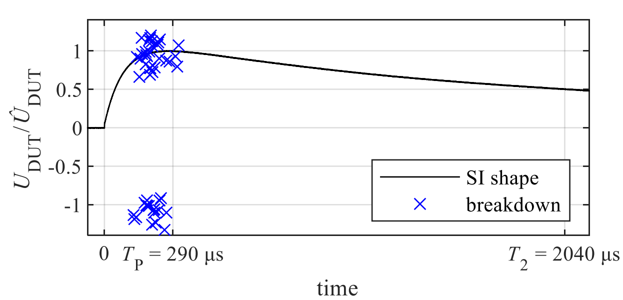

Fig. 8. Measured SI time to breakdown and magnitude.

V. Discussion

The SI and LI voltage test results show that the breakdown mainly occurs around the peak voltage. Based on this result, it becomes obvious that differences in the impulse tail (D1, D2, D6 – Table I) seem negligible with regard to the breakdown voltage. Especially the repetitive re-ignition effect D6 (Fig. 3) typically occurs at the end of the impulse shape and can thus be neglected.

CIGRE TB 842 [1] generally neglects the effect D2 for all impulse voltage shapes. TB 842 [1] considers effects regarding the discharging and recharging of the test object. The difference D2 is neglected, because the recharging time will be too short to significantly influence the charge distribution along the gas-solid interface.

A. *LI voltage*

Overall, the LI results show an only small difference between both test methods. The difference D1 (Fig. 2) resulting from the different superposition principles was observed to have no impact on the LI breakdown results. Considering the measuring uncertainty of the used dividers and equipment, which is given as 3 %, no significant difference of the breakdown voltage can be observed. SG and CC arrangements are therefore assumed to result in similar LI breakdown voltages at the gas-insulated model arrangement even due to all the typical LI differences D1 to D4 listed in Table I. Transferring this result to practical gas-insulated arrangements, SG and CC can be considered as equivalent for LI testing. Besides insulator arrangements, LI breakdown voltages with different tail times and 0 kV DC were investigated in literature at gas gaps [17]. Here, also no significant differences in breakdown voltages were observed especially for large tail times, which is in line to the observations collected at the insulator model arrangement.

B. *SI voltage*

Breakdowns under SI stress were observed to develop in a rather short time and will therefore, as expected, occur near to the peak voltage level. The difference D1 (Fig. 2) influencing the tail and resulting from the different superposition principle should therefore be neglectable at all. Generally, a SI has also a rather flat peak, which means, that e.g. the used SI according to Fig. 8 stays above 95 % of its peak value in a time interval of 450 µs, which is more than the maximum measured time to crest of approximately 330 µs. This means a spark gap ignition at 95 % of the peak value would still offer sufficient time for a breakdown to develop, if the dielectric stress to the system is too high. Evaluating the peak holding effect D5 (Table I), it has to be considered that it would only poorly be visible in a breakdown voltage oscillogram because of the flat SI voltage shape and the short time to breakdown. The breakdown voltage of a SG circuit is therefore assumed to be independent from the occurrence of the effect D5.

The remaining differences in the impulse front D3 and D4 (Table I) for SG testing cannot be evaluated with the collected SI data. The LI data indicate a rather low impact of these effects. However, further investigations would be required to evaluate their influence on superimposed SI voltages.

VI. Conclusion

The differences between superimposed voltage tests with spark gaps (SG) and coupling capacitor (CC) were determined on a gas-insulated model arrangement. This was built such that HVDC charging effects are covered. The model arrangement was installed in a gas vessel, where superimposed voltages with CC and SG with their typical differences were applied. The test setup was particularly defined to minimize any degradation effects of the model arrangement. The reproducibility of the data was pre-investigated and checked by the presented test procedure. The investigation was focused on superimposed LI testing, because this is known to be the more critical dielectric stress for gas-insulated systems. With the built arrangement, first results were collected for gas-insulated systems:

- No significant differences in the breakdown voltage of superimposed LI testing with CC and SG could be determined on the used model arrangement.
- Both methods, therefore, seem to behave equally for superimposed LI testing of gas-insulated systems. Differences in the impulse voltage shape can be assumed to be neglectable.
- Any requirements on allowed distortions during SIMP LI testing do not seem necessary.
- The determination of the impulse time parameters with short circuited blocking element and without applied DC voltage seems to be sufficient.
- The breakdowns were observed to happen mostly during or near to the impulse front both for LI and SI voltages.
- All typical effects influencing the SI tail during superimposed testing with SG are obviously negligible.

Future research should consider the following aspects and should try to integrate the following optimizations in the test circuit:

- The presented procedure may be used to collect data of CC and SG breakdown voltages for SI or different insulator materials.
- Further data about the impact of the front time differences during superimposed SI testing would be beneficial.
- The electrical field distribution of an insulator model arrangement could be achieved in line to practical arrangements by heating the high voltage electrode rather than the earth electrode.
- The effects could be investigated at a model arrangement, which simulates the gas gap in order to complete the data for gas-insulated systems
- The measuring uncertainty could be reduced by use of a universal divider in parallel to the test object.

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