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Type testing a 420 kV, 63 kA, 50 and 60 Hz circuit-breaker based on C4-FN/CO_2/O_2 mixture technology

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SUMMARY

The first eco-efficient 420 kV circuit breaker, which is based on a 3.5 mol% C4-FN, 10 mol% O_2, and 86.5 mol% CO_2 gas mixture, was recently presented [1] at CIGRE (Paris, 2022).

The breaker covers the 420 kV / 63 kA ratings (50 and 60 Hz) for both gas-insulated switchgear (GIS) and dead tank breaker (DTB) applications. It adopts two breaking chambers connected in series, one drive per phase and a robust kinematic chain for movement transmission. Two standard grading capacitors, connected in parallel to each one of the breaking chambers, evenly distribute the voltage between the two interrupters.

This breaker showed excellent performance throughout the development test campaign in accordance with the IEC and IEEE standards. In previous work we showed that the breaker could successfully pass the SLF75 and SLF90 test duties with a 100 ns time delay and very low post-arc currents [1].

The design of the circuit-breaker is robust also in terms of mechanical stability and switching and dielectric performance. The breaker recently underwent a complete type test campaign.

In this contribution, the most relevant results of this campaign will be described, including terminal fault, short line fault, high voltage, and capacitive and inductive switching tests.

KEYWORDS

HV Circuit Breakers, eco-efficient switchgear, SF_6 alternatives, SF_6-free circuit breakers, C4-FN mixtures.

1 Introduction

The development of eco-efficient circuit breakers represents a very important step towards the reduction of the CO_2 footprint of power grids, electrical installations, and transmission systems. After a successful campaign of development tests, the world's first SF_6-free 420 kV circuit breaker, which is based on a 3.5 mol% C4-FN, 10 mol% O_2, and 86.5 mol% CO_2 gas mixture, was recently presented at CIGRE [1]. Its performance is now fully confirmed by type tests, of which this paper presents the key results and the strategies used to perform them correctly and efficiently.

The circuit breaker is based on reliable and well-proven gas circuit breaker technology utilizing the puffer principle, adapted, and optimized for the chosen gas mixture. It adopts two breaking chambers connected in series, one drive (spring-hydraulic mechanism) and a robust kinematic chain for movement transmission between the chambers. Two standard grading capacitors, installed in parallel to each of the breaking chambers, distribute the voltage between them. The design covers both 50 and 60 Hz and both gas-insulated switchgear (GIS) and dead tank breaker (DTB) applications with the same interrupter, the DTB variant differing in the absence of partition insulators and in having a direct connection to the bushings. The main ratings are reported in Table 1.

Table 1. Main ratings of the 420 kV breaker that uses a C4-FN mixture.

Rated voltage	U_r	420 kV
Rated lightning impulse withstand voltage	U_p	1425 kV
Rated switching impulse withstand voltage	U_s	1050 kV
Rated power frequency withstand voltage	U_d	650 kV
Rated continuous current	I_r	5000 A
Rated short-circuit breaking current	I_{sc}	63 kA
Rated short-time withstand current (3s)	I_k	63 kA
Rated peak withstand current	I_p	171 kA
Rated first–pole-to-clear factor	k_{pp}	1.3 / 1.5
Capacitive load switching	class	C2
Capacitive voltage factor	k_c	1.4
Rated capacitive currents	I_l, I_c	400 A
Shunt reactor current switching		Acc. to IEC 62271-110 and IEEE C37.015
Rated frequency	f_r	50 Hz / 60 Hz
Mechanical endurance	class	M2
Rated operating sequence		O-0.3s-CO-1min-CO
Operating temperature		-30 °C … +40 °C

To achieve maximum flexibility for application of the breaker in different countries, the test campaign[1] needed to cover both 50 and 60 Hz requirements and both the IEEE (420 kV and in some cases 362 kV[2]) and IEC (420 kV) standards. This required a large number of type tests; therefore, the test campaign was devised to cover at the same time the greatest number of ratings within the same test shift, also minimizing the number of the test objects needed.

More in details, the test campaign combined:

1. Different type tests in a single test shift using the same test object. This was possible due to the excellent breaker design and performance also in worn conditions. The test combinations listed below were selected to optimize the test program for the circuit breaker, including reducing the effort and time needed to change the test circuit in the laboratory. These choices are therefore not indicative of the performance limits of the circuit breaker in terms of electrical wear.
    a. terminal faults T10-T30-T60,
    b. shunt reactor current switching tests and a short line fault (SLF75),
    c. out of phase (OP2) and terminal fault T60,
    d. terminal fault T100s, double earth fault (DEF) and service capability.

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[1] All type tests were performed at accredited laboratories, which are members of the Short-Circuit Testing Liaison (STL).

[2] In IEEE standard C37.04 [2], 420 kV rating exists only for GIS (see Table 7 of [2]).

2. Different frequencies[3]. Both IEEE and IEC standards allow some type test to be performed only at one frequency and still be valid for the other frequency:
    a. LC (line charging) and CC (cable charging) – 60 Hz test covers 50 Hz since it is more severe.
    b. Shunt reactor current switching tests – tests at 60 Hz are valid for 50 Hz, tests at 50 Hz are valid for 60 Hz, provided that no re-ignitions occur for arcing times between 8.3 and 10 ms
    c. T10 and T30 – tests at 60 Hz are valid for 50 Hz and vice versa[4].
    d. OP2 – tests at 60 Hz are valid for 50 Hz and vice versa.
3. Requirements related to different standards (IEEE and IEC), in some cases covered by simply adding a resistance measurement before and after a test and by performing mechanical operations with minimum coil voltages specified in the IEEE standard.

With this efficient strategy, an overall minimization of time and costs was achieved. A more detailed summary, also showing the test-specific additional IEEE [2] requirements is given in Table 2.

Table 2. Summary of the type test campaign with details on the additional requirements related to the IEEE standard [2]. Rows having the same shading represent the usage of the same test object for those type tests.

<table>
<tr><th>50 Hz</th><th>60 Hz</th><th>Additional requirements for IEEE validity</th></tr>
<tr><td colspan="2">T10</td><td>Application of the more severe TRV specified by the IEEE standard, mechanical operations with IEEE minimum coil voltage, resistance measurement before and after tests.</td></tr>
<tr><td colspan="2">T30</td><td>Application of the more severe TRV specified by the IEEE standard, mechanical operations with IEEE minimum coil voltage, resistance measurement before and after tests.</td></tr>
<tr><td></td><td>T60</td><td>Mechanical operations with IEEE minimum coil voltage, resistance measurement before and after tests.</td></tr>
<tr><td colspan="2">OP2</td><td>Mechanical operations with IEEE minimum coil voltage, resistance measurement before and after tests.</td></tr>
<tr><td>T60</td><td></td><td>Mechanical operations with IEEE minimum coil voltage, resistance measurement before and after tests.</td></tr>
<tr><td>T100s</td><td></td><td>Mechanical operations with IEEE minimum coil voltage, resistance measurement before and after tests. One making and one breaking operation with IEEE minimum coil voltage.</td></tr>
<tr><td></td><td>T100s + DEF + service capability</td><td>Mechanical operations with IEEE minimum coil voltage, resistance measurement before and after tests. One making and one breaking operation with IEEE minimum coil voltage. Service capability (required only by the IEEE standard) can be performed as an extension of the DEF and T100s tests.</td></tr>
<tr><td>T100a</td><td></td><td>Mechanical operations with IEEE minimum coil voltage, resistance measurement before and after tests.</td></tr>
<tr><td></td><td>T100a</td><td>Mechanical operations with IEEE minimum coil voltage, resistance measurement before and after tests.</td></tr>
<tr><td colspan="2">LC/CC</td><td>Mechanical operations with IEEE minimum coil voltage, resistance measurement before and after tests.</td></tr>
<tr><td colspan="2">Shunt reactor current switching tests</td><td>Mechanical operations with IEEE minimum coil voltage, resistance measurement before and after tests. Test report must contain some additional measurements and provide chopping number of the breaker.</td></tr>
<tr><td>SLF75</td><td></td><td>Mechanical operations with IEEE minimum coil voltage, resistance measurement before and after tests.</td></tr>
<tr><td></td><td>SLF75</td><td>Mechanical operations with IEEE minimum coil voltage, resistance measurement before and after tests.</td></tr>
<tr><td>SLF90</td><td></td><td>Mechanical operations with IEEE minimum coil voltage, resistance measurement before and after tests.</td></tr>
<tr><td></td><td>SLF90</td><td>Mechanical operations with IEEE minimum coil voltage, resistance measurement before and after tests.</td></tr>
<tr><td colspan="2">HV GIS</td><td><i>Not required by IEEE, but by some US utilities:</i> higher lightning impulse peak voltage (1430 kV instead of 1425 kV), HV power frequency during 72 s.</td></tr>
<tr><td colspan="2">Low and high temperature / continuous current test</td><td>Maximum allowed temperature rise for contacts is 65 K for IEEE, 75 K for IEC. Waiting time after temperature equilibrium is longer according to IEEE to confirm equilibrium. In most cases IEEE covers IEC (except for parts that cannot be touched by hand). Mechanical functional tests with IEEE minimum coil voltage.</td></tr>
<tr><td colspan="2">Short time currents (STC)</td><td>None</td></tr>
<tr><td colspan="2">M2</td><td>Mechanical operations at minimum coil voltage performed at the IEEE minimum coil voltage (lower than IEC, therefore also covering the IEC requirement). A total of 10’000 accumulated mechanical operations covers the requirements for both IEEE and IEC.</td></tr>
<tr><td colspan="2">HV DTB</td><td>Chopped wave withstand voltage test and wet switching impulse are required only by IEEE.</td></tr>
<tr><td></td><td>TLF1 and 2</td><td>Transformer Limited Faults are required only by IEEE.</td></tr>
</table>

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[3] SLF75 had to be performed for both 60 Hz and 50 Hz. Nevertheless, it is the opinion of the authors that for this breaker technology (puffer breaker) with a valid test at 60 Hz, the SLF75 at 50 Hz poses no challenges and could be omitted.

[4] With conditions on arcing times / current slope at current zero, see Chapter 12 of [3].

The paper is organized as follows. Section 2 describes the challenges, the test program, and the results of the high voltage testing campaign. Section 3 presents the results of the capacitive and inductive load switching test, with some comparisons to SF_6 technology and some insight into the advantages of C4-FN mixtures with respect to pure CO_2.

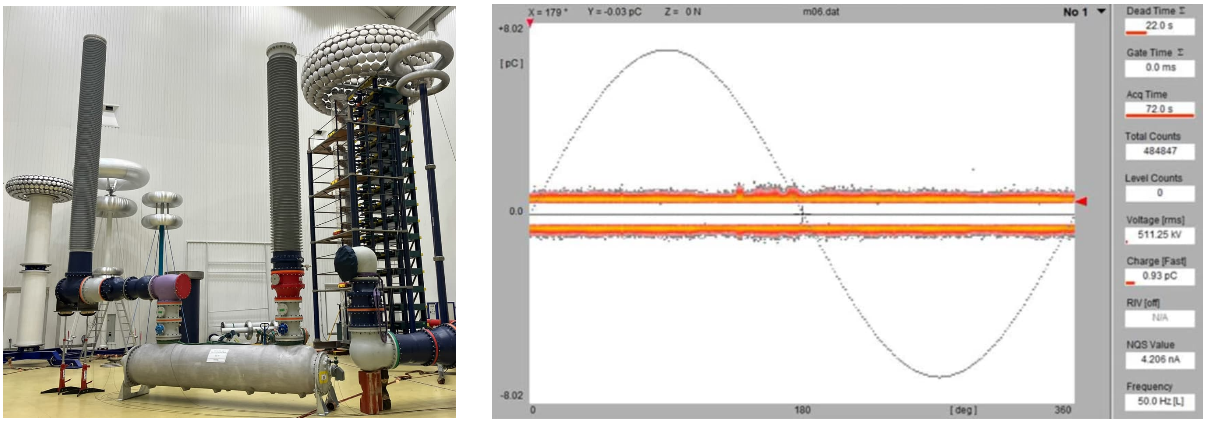
Section 4 introduces the terminal faults and gives details on the test parameters and methods which allowed the combination of IEEE and IEC standard. Section 5 presents some examples of the short line faults tests performed by the breaker, with comparisons between SLF75 and SLF90 and, finally, in Section 6 some conclusions are drawn.

2 Dielectric tests

The SF_6 dielectric design process involves optimization of the various breaker parts in order to fulfil internally developed and widely verified guideline limits. During this process, the electric field (E-field) at each different breaker location is compared to the correct limiting value. The same well-established tools and processes were applied to the new SF_6-free double-unit circuit-breaker, by proper adaptation of the limits to the C4-FN mixture. The internal knowledge built over several years during the study of this and other alternative gases was the key to easily extend the design methodology to cover also C4-FN mixtures [4][5].

As mentioned in the introduction, the SF_6-free 420 kV circuit-breaker adopts a double chamber solution with grading capacitors. Such solution requires proper shielding of active parts. The shield design of the two-unit concept was one of the key elements of the dielectric design, and it was accomplished with the help of both 2D and 3D simulations and optimizations. The arcing region was also dielectrically designed and verified using 2D and 3D E-field simulations.

Following this process, the first design was achieved extremely efficiently and fast, and already fulfilled the requirements for both lightning impulse (LI) and chopped wave (CW) tests, the latter being more severe than the former for inside withstand[5]. As a consequence, the type test of the GIS variant was passed without any issues, both for LI and switching impulse (SI) (Table 3), as well as for power frequency voltage (Table 4).



Dead Time Σ: 22.0 s
Gate Time Σ: 0.0 ms
Acq Time: 72.0 s
Total Counts: 484847
Level Counts: 0
Voltage [rms]: 511.25 kV
Charge [Fast]: 0.93 pC
RIV [off]: N/A
NQS Value: 4.206 nA
Frequency: 50.0 Hz [L]

(a) (b)

Figure 1: The novel 420 kV breaker (GIS variant) during HV lightning impulse (with BIAS) voltage tests (a) and partial discharge signal pattern of closed breaker at 504 kV_{rms} (b) showing a PD level below 2 pC for 72 s acquisition time.

Figure 1 (a) shows the test setup in the high voltage laboratory (Zurich test facility, Switzerland). For what concerns the AC tests phase to ground, the signal of the partial discharge measurement was always below 2 pC at 504 kV_{rms} as required for systems without effectively earthed neutral (see Table 6 in [6]). The PD signal pattern observed during this test is reported in Figure 1 (b).

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[5] According to IEEE HV requirements [2], CW (362 kV) requires 1680 kV peak voltage, whereas LI (420 kV) requires 1425 kV peak. LI bias requires a similar peak voltage withstand as CW, but only across breaker, and not on each breaker side (with opposite side on ground) as the CW requirement.

In conclusion, the SF_6-free 420 kV circuit breaker showed a very good performance under HV testing, for all impulse and AC test duties including partial discharge measurements, where no partial discharge signal above the noise level could be recorded at all required voltage levels.

Table 3: Overview of the performed lightning and switching impulse voltage tests on the GIS variant. Lightning impulse voltage 1430 kV instead of 1425 kV, all other ratings according to [6]. All the listed voltage applications were withstood.

Test duty	Impulse voltage applied to drive side	Impulse voltage applied to exit side
Lightning impulse 1430 kV open	15 voltage applications (pos. and neg.)	15 voltage applications (pos. and neg.)
Lightning impulse 1430 kV closed	--	15 voltage applications (pos. and neg.)
Lightning impulse BIAS (1430+240) kV	15 voltage applications (pos. and neg.)	15 voltage applications (pos. and neg.)
Switching impulse 1050 kV open	15 voltage applications (pos. and neg.)	15 voltage applications (pos. and neg.)
Switching impulse 1050 kV closed	--	15 voltage applications (pos. and neg.)
Switching impulse BIAS (900+345) kV	15 voltage applications (pos. and neg.)	15 voltage applications (pos. and neg.)

Table 4: Overview of the performed power frequency tests, all ratings according to [6].

Test duty	AC current applied to drive side	AC current applied to exit side
Open – phase opposition	408 kV_{rms} for 72 s withstood	408 kV_{rms} for 72 withstood
Open – phase to ground	650 kV_{rms} for 72 s withstood, exit side grounded	650 kV_{rms} for 72 s withstood, drive side grounded
Closed – phase to ground	--	650 kV rms for 72 s withstood

3 Capacitive and shunt reactor current switching tests

The switching of capacitive loads, such as open transmission lines or cables or capacitor banks used to improve power quality in the high voltage transmission network, is an important function of high voltage circuit breakers. The 420 kV SF_6-free circuit breaker successfully cleared the line and cable charging switching type tests at 60 Hz, with a capacitive voltage factor $k_c = 1.4$ corresponding to not solidly grounded networks. These tests automatically cover the requirements for solidly grounded networks and 50 Hz. During development, the performance of the circuit breaker was first assessed using a simplified testing approach that is ideal for assessing limits and does not require a short-circuit current generator. This approach, commonly used in SF_6 breaker development and described in detail in [7] and [8], was successfully adapted for the tests performed on the 420 kV SF_6-free circuit breaker during development. The circuit breaker showed large margin compared to a full capacitive switching test performed according to the IEC or IEEE standard ([9] and [2]), which require use of a short-circuit current generator. The capacitive switching (LC and CC) type tests at 60 Hz, cleared with a capacitive voltage factor $k_c = 1.4$ and performed according to the IEC standard (and covering the requirements of the IEEE standard), confirm the results obtained during development. An example of a capacitive switching operation, performed with a synthetic test circuit (applying an AC voltage with a DC offset on both sides of the circuit breaker) at 60 Hz is shown in Figure 2. A synthetic test approach was selected due to limitations of the test laboratory, which could not perform a direct capacitive switching test at this voltage level. Because synthetic testing was performed, additional voltage applications had to be performed. In particular, the required load side DC voltage had to be applied for each polarity on each side for 0.3 s, and this was successfully tested after TD1 and TD2.

The strong capacitive switching performance of the 420 kV SF_6-free circuit breaker can be attributed in large part to the contribution of the C4-FN molecules in the gas mixture to the overall dielectric strength. Previous studies, reviewed in Section 2.3.6 of [10], have clearly demonstrated the important contribution of C4-FN to the dielectric performance for even higher currents than are typically tested for capacitive switching.

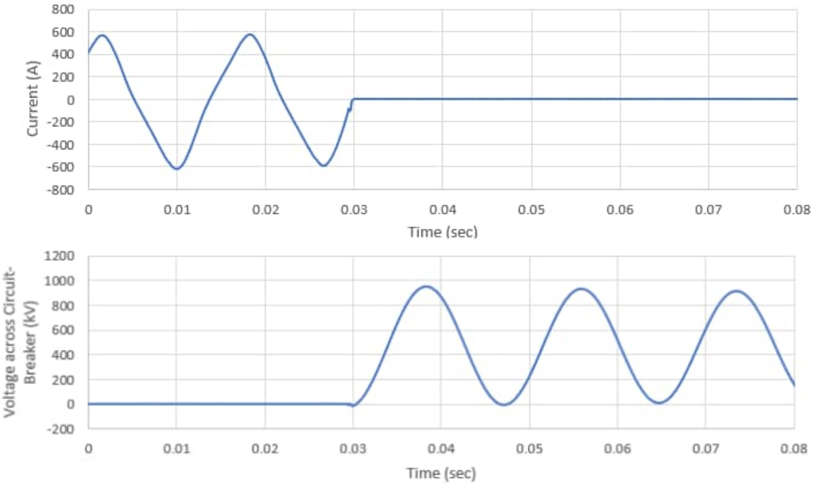

Figure 2. Example of capacitive switching (CC) operation (60 Hz test) at minimum arcing time (acc. to IEC, synthetic test approach). Capacitive current through the breaker (top) and voltage across the breaker after capacitive current interruption (bottom).

The capability to reliably switch inductive loads, needed for the application of the breaker to shunt reactor current switching, was also demonstrated by the SF_6-free breaker; it fully satisfies the requirements of [11] and [12]. Since some applications require very frequent switching operations[6], the IEC standard sequence – 78 operations in four test duties [11] – was extended by 55 additional operations (limit given by time constrains). The breaker had an extremely large reignition free window at 60 Hz (from 2.4 ms to 8.3 ms) even larger than the already excellent one of existing 420 kV SF_6 breakers. Results and comparisons at 60 Hz are shown in Figure 3. The chopping numbers of the SF_6 breaker and the SF_6-free breaker are similar within the scatter.

The 420 kV SF_6-free circuit breaker, with its large reignition-free window and very low likelihood of multiple reignitions occurring during a single power-frequency current-zero crossing, stands in contrast to vacuum circuit breakers. High voltage vacuum circuit breakers are currently not available for transmission voltage levels, but a comparison with vacuum circuit breaker technology can be done by extrapolating based on observations of lower voltage circuit breakers. During shunt-reactor switching by a vacuum circuit breaker a large number of multiple high-frequency reignitions typically occurs during many of the switching operations, as described in [10]. This large number of reignitions and the associated over-voltages (large voltage escalations at multiple high-frequency reignitions, see 16.4.3 of [3]) increase the risk of damage to the shunt reactor and other components of the grid during shunt-reactor switching operations. In fact, for these and other reasons [13] states that “gas circuit breakers are the present solution to cover high-voltage applications for these inductive loads.” The addition of filter circuit elements, proposed as a work-around by [13], adds complexity, cost, and the need to properly select and dimension the filter circuit elements; the approach will only work “as long as the parameters of the RC suppressor are tuned to the specific system transient behavior” [13]. The 420 kV SF_6-free circuit breaker presents a simple, effective, and reliable solution that relies on well proven gas circuit breaker technology. This circuit breaker is also ideal for the application of controlled switching, since it has a very large re-ignition free window (much larger than that of a typical vacuum circuit breaker [10]).

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[6] Thousands of operations are reached in certain cases, e.g. shunt reactor, throughout the life-time of a breaker.

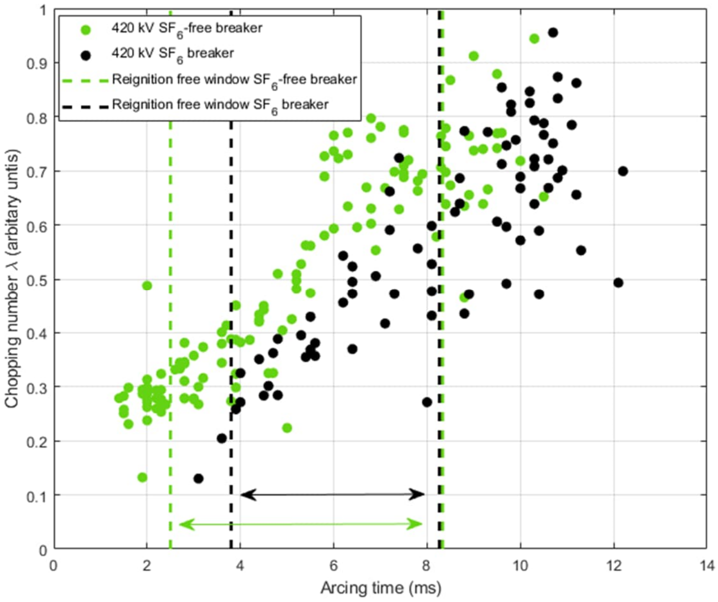

Figure 3. Chopping number comparison between SF$_6$ and C4-FN technologies (all results are from shunt reactor current switching tests at 60 Hz). Green circles show the results for the 420 kV SF$_6$-free breaker (133 operations); black circles refer to a 420 kV SF$_6$-puffer breaker (78 operations). The chopping numbers of the two breakers are comparable, the SF$_6$ breaker having a slightly narrower reignition free window and a larger number of operations with reignition than the SF$_6$-free one.

4 Terminal faults

The SF$_6$-free 420 kV circuit breaker successfully passed all the terminal fault tests for 63 kA (T10, T30, T60, T100s, and T100a) defined by the IEC and IEEE standards. The tests were performed in a manner that permitted the requirements of both the IEC and the IEEE standards to be covered, as noted in Table 2. The most relevant differences are related to the operating sequence and the transient recovery voltage (TRV) applied. The IEC requires a more complex sequence of test operations to be performed, including an open-close-open (O-CO) operation followed within three minutes (if not prevented by the limitations of the test laboratory) by a close-open (CO) operation. The IEEE standard, on the other hand, requires higher TRV peak values than the IEC standard for the T10 and T30 test duties. Specifically, for the T10 test, the IEC standard specifies a TRV peak of 787 kV for the first pole to clear, while the IEEE standard requires 844 kV. Similarly, for the T30 test the IEC standard specified 792 kV for k_{pp}=1.5, while the IEEE standard requires 813 kV. Since the IEC standard considers a test with higher voltage than specified to be valid, a test with the IEEE TRV also covers the requirements of the IEC standard. The TRV requirements for the T60, T100s, and T100a tests are the same in both the IEC and IEEE standards.

The minimum arcing time of the circuit breaker were found in all terminal faults to be rather low (comparable or lower than SF$_6$)—illustrating the strong performance of the circuit breaker. Given the short minimum arcing times and opening times provided by the fast drive, interruption can be achieved within two power frequency cycles.

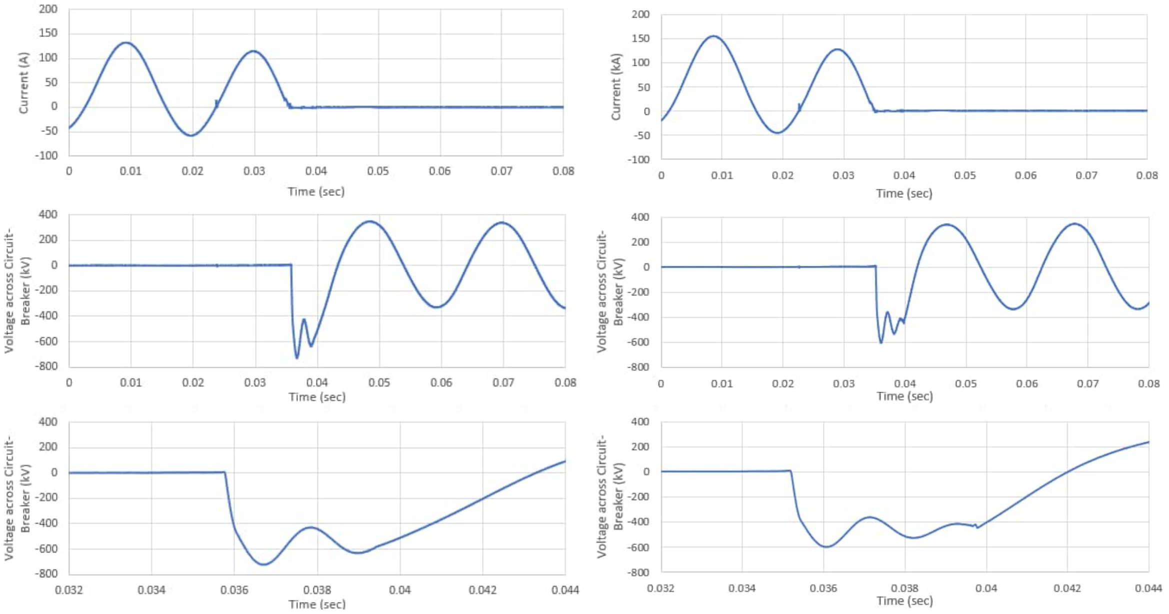

Figure 4. Example of T100a test shots at 50 Hz. Left-hand plots correspond to first-pole-to-clear, major loop, intermediate asymmetry and right-hand plots to second-pole-to-clear, major loop, rated asymmetry. The top panel illustrates the applied short-circuit current, including the synthetic current injected before the final zero-crossing. The middle and bottom panel show the TRV across the breaker (the recovery voltage phase and a close-up view).

During the T100s and T100a tests the maximum short-circuit current must be interrupted by the circuit breaker. As mentioned above, both test duties were successfully passed, for both 50 and 60 Hz. Concerning T100s, part (a) consists of making tests and the breaker demonstrated successfully asymmetrical making with peak factor 3.1, corresponding to a 195 kA.

The 420 kV SF_6-free circuit breaker has low post-arc currents, less than about 1 A and with a duration of only 10-20 µs, as discussed in [1]. These post-arc currents were measured during the L90 test duty, i.e., the worst case, since the steep rise of the line-side voltage after current-zero leads to even higher post-arc currents than during T100s and T100a tests. Recently, it has been shown that vacuum circuit breakers struggle under such conditions [14]: Even after T100s current interruption, higher post-arc currents (of order 10 A) are measured. These high post-arc currents lead to problems with the voltage distribution between chambers connected in series (even when appropriate grading capacitors are used), specifically when there is only a slight time delay between opening of the chambers. According to [14], more than two-thirds of the voltage may be distributed across only one of the vacuum chambers, resulting in failure to clear the fault. It should be noted that in vacuum circuit breakers the dielectric withstand voltage does not scale linearly with increasing contact distance. Instead, the dielectric withstand saturates (or increases only very slowly) with increasing gap distance [15]. Therefore, employing multiple interrupting chambers for higher ratings (above 145 kV) becomes a necessity, rather than an option. Figure 4 shows two examples of successful T100a interruptions of the major loop current at rated (134 kA peak, corresponding to a DC time constant of 75 ms) and at intermediate asymmetry during the type tests performed at 50 Hz.

5 Short line faults

The breaker successfully cleared the SLF75 and SLF90 test duties for 63 kA covering IEEE and IEC standards and the ITRV (Initial Transient Recovery Voltage) requirements (with less than 100 ns time delay). From the type tests, since all were successful, it would not be possible to say which test among the SLF75 and SLF90 has the larger margin. From development tests, though, where margins were actively determined by increasing the current derivative at current zero (di/dt) and performing several additional breaking operations, it was determined that SLF75 has a larger margin than SLF90. It has been speculated—based on a comparison to air-blast circuit breakers—that the SLF75 test duty may be more severe than the SLF90 test duty for CO_2-based circuit breakers [10]. However, in the case of the 420 kV ratings, SF_6-free puffer technology, this is contradicted by the obtained results. This is similar to SF_6 and in line with expectations, since the 420 kV SF_6-free circuit breaker design is based on the reliable puffer SF_6 technology and current interruption physics. During type tests, shorter minimum arcing times and higher extinction peaks (see examples at 50 Hz in Figure 5) have been obtained for the SLF75 with respect to SLF90, for both 50 and 60 Hz. This is an indication of the better performance of the former.

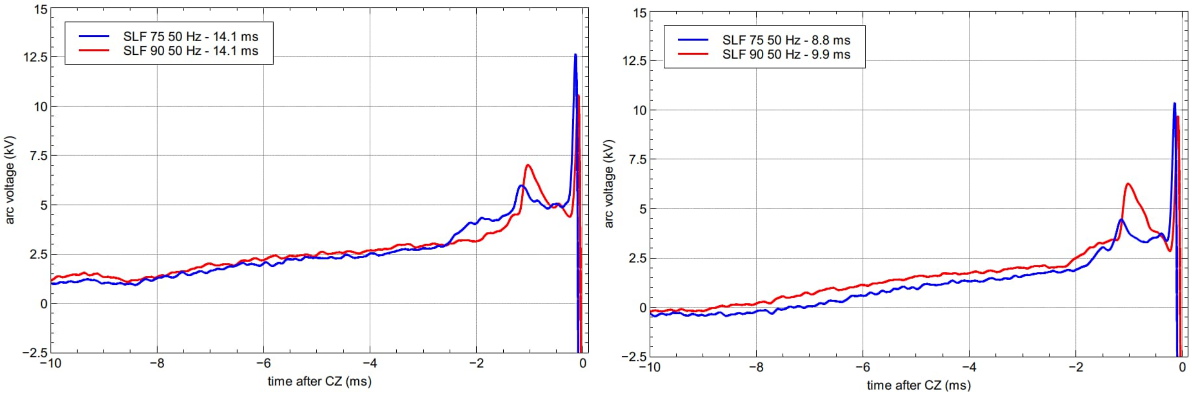

Figure 5. Arc voltages during similar operations in SLF90 and SLF75 at 50 Hz, the latter having larger extinction peaks.

The main challenge during these type tests was therefore not the thermal interruption capability, but for the testing facility to cope with the high arc voltages and extinction peaks and the need to ensure valid shots (test values within tolerances). The high arc voltages (some examples are shown in Figure 5) are mainly due to the double chamber design.

Specifically, it becomes challenging for the laboratory to compensate for the strong reduction of the current during the last half-wave before current zero. In these cases, especially at long arcing times, aiming for the nominal last current half-wave peak (I_{lhwp}, e.g., 80.2 kA for SLF90, as the standard prescribes), might result in invalid breaking operations, i.e., with I_{lhwp} below the tolerance. Proper compensation is needed, and the information on the amount of reduction needs to be known e.g., by performing development tests.

During all type tests, the breaker showed consistently very short minimum arcing times. This is mostly due to the good puffer technology adopted and is an important indication of the breaker performance and clearing capability. A short minimum arcing time allows having shorter medium and maximum arcing times, with less energy input, less ablation, and finally less wear of the breaker at the end of the tests. This allows a high number of short-circuit switching operations, as also demonstrated by the service capability test.

6 Conclusions

The type test results of the first eco-efficient 420 kV gas circuit breaker based on a 3.5 mol% C4-FN, 10 mol% O2, and 86.5 mol% CO2 gas mixture have been presented. The breaker was developed in order to cover both 50 Hz and 60 Hz and type tested according to both IEEE and IEC standard, covering the more severe requirements for both. The breaker is based on a reliable gas circuit breaker technology utilizing the puffer principle. It has demonstrated excellent performance in all type tests, particularly LC/CC (60 Hz), dielectric tests, shunt reactor current switching tests (very large reignition free window), terminal faults (with 75 ms time constant for T100a at 50 Hz, making peak factor of 3.1 in T100s making test, and the higher IEEE TRV requirements for T10 and T30), and short line faults (with excellent performance for both SLF90 and SLF75).

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