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Presentation of SF6-free Dead-Tank Circuit Breaker rated 145kV,63kA

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SUMMARY

Design and verification testing performed during the development of a mixed gas-insulated AC HV dead-tank power circuit breaker rated 145 kV, 63 kA, 4000 A, 60 Hz are described. The circuit breaker utilizes a mixture consisting of carbon dioxide (CO_2), oxygen (O_2) and fluoronitrile (C4-FN) gases. The development of this breaker required the adaptation of existing gas-insulated technology to the interrupting and insulating characteristics of this gas mixture. The gas mass in the circuit breaker is 40% of that of an SF_6-insulated breaker and the GWP of the gas mixture is 1.3% of SF_6 GWP.

Breaking tests were performed under terminal, transformer limited, short-line, and out-of-phase fault conditions. Breaking service capability was also demonstrated. Capacitive switching tests were performed for a C2 Class with voltage factor of 1.7.

Dielectric tests included power frequency withstand, BIL, chopped wave and AC withstand at atmospheric pressure. Mechanical endurance tests achieved M2 class with 10,000 operations. Current carrying capability tests were performed at 3000 and 4000 A.

The circuit breaker main current path resistance in new condition and after reaching the electrical endurance was stable. This technology demonstrated similar performance to SF_6 with nearly the same material content, dimensional characteristics, and without requiring excessive operating pressure.

KEYWORDS

Circuit breaker, dead tank, breaking tests, SF_6-free, alternative gases.

1 Introduction

Dead-Tank circuit breakers constitute the predominant outdoor High-Voltage (HV) switching technology in the UK power grid at 145kV. Requirements imposed on circuit breakers by renewable generation are challenging for the existing SF_6 technology and should be addressed for any alternative technology. Regulatory initiatives have been enacted or are under consideration with the purpose of limiting the use of SF_6 as well as reducing emissions of SF_6 insulated equipment.

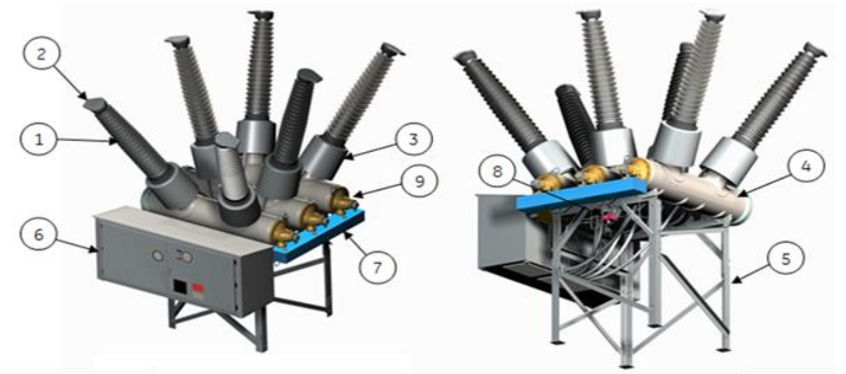
The UK network requirements for this equipment is covered by testing according to IEC standards [1, 2], like switching duties related to widespread use of outdoor air-insulated substations and overhead transmission lines leading to fast voltage transients, lightning and switching surge exposure, high asymmetry, and magnitude of short-circuit currents, practices of outdoor maintenance and assembly.

The aim of this paper is to describe a high voltage circuit breaker covering 63kA 60Hz & 40kA 50/60Hz performance with an SF_6 free solution which is completing its full type tests campaign before summer 2023

2 Development of a dead tank circuit breaker rated 145 kV, 63 kA, 60Hz & 40kA 50/60Hz

1.1 Circuit Breaker and Interrupter Description

The circuit breaker (Figure 1) is rated 145 kV, 63 kA, 4000 A, 60 Hz, 3 cycles. The three-phase circuit breaker is mounted on a common structure and is ganged-operated with an FK 3-4 spring operating mechanism. The center pole is mounted vertically, and the side poles are inclined 30 degrees to maintain external insulation coordination while minimizing the structure footprint. The cabinet is located on the left side and contains the mechanism, controls, auxiliaries, and terminals. The output shaft motion of the mechanism is transferred to the front and across the poles by means of the linkage.



1	Bushing (Porcelain or Composite)	2	Center Conductor/ Top Cap
3	Current Transformers	4	Tank
5	Support Structure	6	Control Cabinet and Operating Mechanism(s)
7	Linkage	8	Density Monitor
9	Pressure Relief Device (PRD)		

Figure 1. Dead Tank 145kV g^3 layout and main components.

Each pole consists of a common gas volume comprised of a single-piece tank with a bell-crank on the front, a rear cover, two bushings and CT housings. The Dead tank 145kV g^3 interrupting chamber is based on its SF_6 counterpart with improvements and changes implemented in order to adapt to the nature and behavior of the gas mixture. More than 70% of parts are common between the SF6 existing product and new one with alternative gas. Circuit breaker has a two-volume chamber with a combination of compression and self-blast actions. The interrupter has double motion. Adaptations that were necessary included:

- Optimization and improvement of mixing in the thermal volume.
- Increase in compression action and exhaust volume.
- Extension of the interrupting action duration.

The mixture composition used was 3.5% C4-FN /13% O_2/ 83.5% CO_2 , which will be also referred to in this document as the "gas mixture". The pressure scale has lockout pressure at 7.5 bar relative and the rated pressure is 8.5 bar relative. This composition and pressure scale is suitable for a rating of -30°C. The gas mass in the circuit breaker is 40% of that of an SF_6-insulated breaker and the GWP of the gas mixture is 1.3% of SF_6 GWP.

1.2 Footprint comparison

Thanks to the dielectric properties of C4FN mixtures [3], the circuit breaker has the same mass and dimensions as its SF_6 (figure 2). Table 1 purpose a comparison of footprint between a dead tank circuit breaker using dry air [4] as insulating gas versus C4FN mixture which offer the possibility to replace existing SF6 product by alternative without change of foundation.

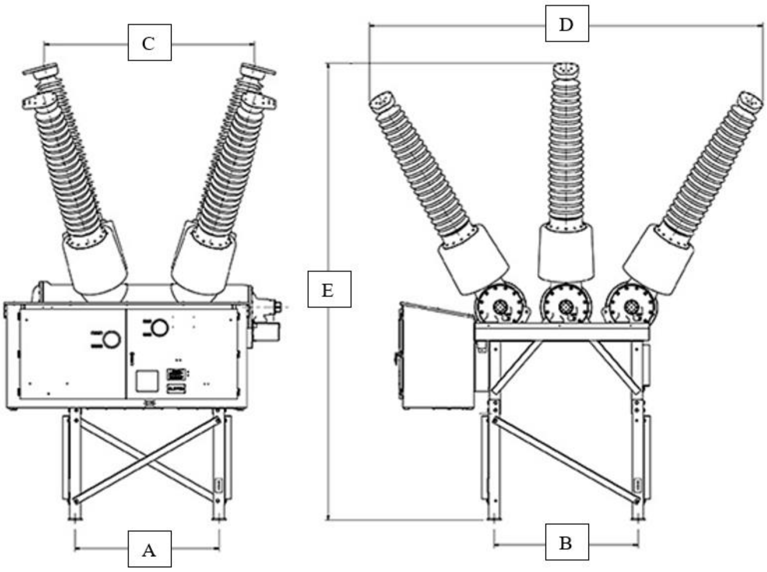


Figure 2. Dead tank 145g^3 footprint

Dimensions	A	B	C	D	E
C4F7N	1317mm	1317mm	1922mm	3596mm	4179mm
Dry air	2100mm (+60%)	2450mm (+86%)	1922mm	4030mm (+12%)	4587mm +(10%)

Table 1. Footprint comparison of Dead tank 145kV C4F7N mixture vs dry air solution.

1.3 Breaking test results

Standard fault and load breaking test duties have been successfully tested on the Dead Tank 145kV g^3 for a 145 kV, 63 kA, 4000 A, 60 Hz, 3 cycle rating. The circuit breaker during the power tests performed at CERDA Laboratory in Villeurbanne, France is shown in Figure 3. Tests combined the maximum TRV requirement prescribed by IEEE standards [5, 6] with a first pole-to-clear factor of 1.5 with arcing windows to cover grounded and ungrounded networks. Terminal fault tests included symmetrical and asymmetrical tests at 100% rated short circuit current (T100a, T100s), 60, 30 and 10% (T60, T30 and T10) of 63 kA. Transformer-limited fault TLF1 and TLF2 [7] tests were performed at 10% and 30% of 63 kA. Short-line fault L75 and L90 were completed. Out-of-phase switching tests OP2 were at the maximum factor of 2.5. Service capability tests included six interruptions of T100s to demonstrate electrical endurance. Capacitive switching for line and cable switching LC/CC were performed at a current of 30 A/300 A to demonstrate C2 Class (very low restrike probability) with 1.7 voltage factor, covering grounded, ungrounded conditions and switching in the presence of a fault. Inductive load switching tests have been performed for a current of 100 A. The test list is included in Table 2.

Figure 3. Dead tank 145g^3 during power breaking tests at CERDA.

	OP2(a+b)	TLF1	TLF2	T10	T30	T60	T100s	T100a	L75	L90	LC-CC	Service capability
Tripolar	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓	✓

Table 2. List of breaking tests performed on the Dead tank 145g^3 circuit breaker.

In addition of 63kA 60Hz performance, this circuit breaker also completed 40kA 60/50Hz power test in accordance with IEC standards. The 63kA rating allows to guarantee large DC component at 40kA without delayer which are more and more required especially in region like the UK where large renewable generation is being connected to the grid.

1.4 Dielectric tests

Dielectric withstand tests were performed on a three-phase Dead Tank 145kV g^3 circuit breaker filled with the gas mixture at lockout pressure of 7.5 bar relative. Tests included one-minute power frequency withstand, basic impulse level with a 15-shot sequence and chopped wave impulse with a 3x9 sequence. The circuit breaker was tested in the closed and open position with voltage application to both sides of each pole (Figure 4). Tested values were the following.

- Power frequency	315 kV
- Lightning impulse	650 kV, 15 pass/0 failures, all positions
- Chopped wave (2 μs)	838 kV, 3 pass/0 failures, all positions

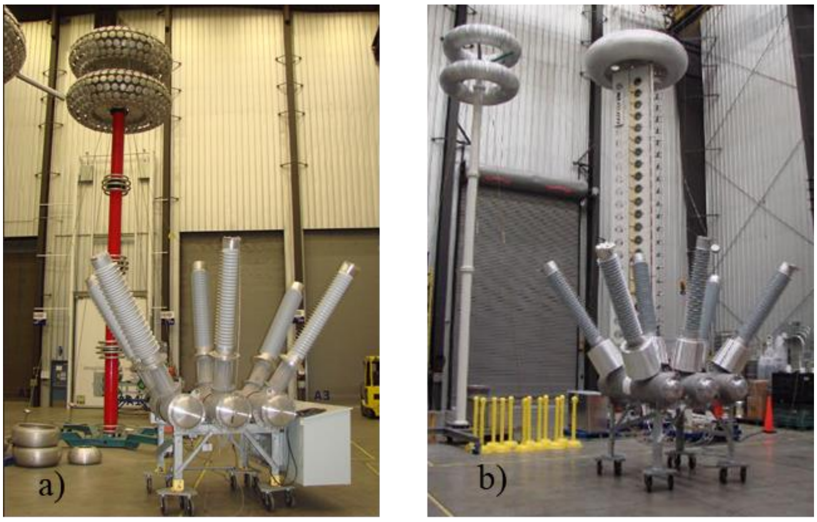


Figure 4. Dead Tank 145g^3 circuit breaker during a) AC withstand, b) BIL and chopped wave dielectric tests.

Comfortable insulation margin was obtained with no breakdown in any of the tests. Such results demonstrate the scalability this gas mixture for internal insulation in compact switchgear architectures and the ability to reach the expected performance.

1.4.1 Zero relative pressure dielectric tests

Although no standardized values exist for power frequency withstand at zero relative pressure inside the pole, utilities specify this requirement to mitigate the risk of rapid insulating gas pressure loss. Values from 1.2 to 1.5 $Un/\sqrt{3}$ are common in existing SF_6 designs. At atmospheric pressure, the C4FN/ O_2/CO_2/ gas mixture has 70% of the withstand of SF_6 and can still withstand a voltage above line to earth (1.2 pu). Therefore, it is possible to maintain the same internal pole dimensions. Technical air has 56% of the withstand of SF_6, requiring increased tank and insulator radial dimensions to achieve performance at or above 1.0 pu. Consequently, vacuum/air designs cannot comply with this requirement while maintaining cost-effective dimensions.

	SF_6	**C4FN/O_2/CO_2**	**Technical air**
Relative dielectric withstand (pu)	1.0	0.7	0.40
Zero relative pressure performance	1.4	1.2	0.56

Table 3. Comparison of capability at zero relative pressure for SF_6, C4FN/ O_2/CO_2/and technical air.

1.4.2 Dielectric check after service capability

A. Service capability requirement

The IEEE circuit breaker testing standard [5] defines the service capability short circuit test duty as the base for electrical endurance demonstration. It consists of a series terminal fault breaking operations equivalent to six T100s tests on a same pole followed by a voltage condition check. This test is carried out at lockout gas pressure and minimum functional gas composition.

B. Test sequence and results

The service capability test for a circuit breaker rated 145 kV corresponds to a cumulative breaking energy of 3.20 MJ associated with six breaking operations a full rated short circuit current of 63 kA. The test was performed at minimum filling pressure of 7.5 bar relative. The test sequency consisted three interruptions of 30% transformer-fed fault TLF2 at 20 kA followed by five T100s breaking operations at 64 to 65 kA, refer to Table 4. The resulting accumulated energy was 3.50 MJ. The circuit breaker successfully interrupted all of these breaking operations. The test is completed with voltage condition check. For circuit breakers rated 145 kV there are two options:

- Apply a BIL test with peak voltage equal to 80% of the rated basic impulse level: 650 kV x 0.8 = 520 kV, or
- Apply a 10% terminal fault (T10) TRV with the peak voltage equal to 60% of the rated BIL. T10 TRV shape being very similar to a switching impulse, the severity is comparable to perform this voltage condition check with a switching impulse in a dielectric laboratory: for a 145kV rated circuit breaker: 390kV.

Test n°	Test duty	I (kA)	operation	Arcing time (ms)	Results	Accumulated wear (MJ)
10837-1	TLF2	20.2	Os	13	OK	0.09
10837-2	TLF2	20.1	Os	20	OK	0.26
10837-3	TLF2	20.2	Os	16.6	OK	0.39
10837-4	T100s	64	Os	12.4	OK	0.7
10837-5	T100s	64	Os	12	OK	1.1
10837-6	T100s	64	OCOs	12 & 19.5	OK	2.2
10837-7	T100s	65	COs	18.1	OK	2.9
10837-8	T100s	64	COs	16.4	OK	3.5

Table 4. Complete service capability test sequence on a Dead tank 145g^3.

Both dielectric tests were applied to the Dead Tank 145kV g^3 after 3.5 MJ accumulated wear. Lightning and T10 TRV/switching impulse withstand voltages exceeded the requirements in the IEEE standard as shown in Table 5.

	Voltage condition check requirement (kV$_p$)	Withstand limit result during test (kV$_p$)	Margin
BIL	520	690	32%
T10 TRV / SIL	390	520	33%

Table 5. Voltage condition check test values demonstrated

1.5 Mechanical endurance tests

Mechanical endurance tests were performed on the Dead Tank 145kV g^3 for an M2 class qualification consisting of 10,000 operations [1]. This test consisted on 2500 operation each at minimum, rated and maximum control voltage and 2500 trip-free operations (Figure 5). After completing the operations, the circuit breaker passed a one-minute power frequency withstand test in open and closed position at 315 kV. An additional 2 pu, 30-minute AC dielectric test at 167 kV was performed across the open circuit breaker to demonstrate its withstand capability after mechanical wear.

Figure 5: Dead tank 145g^3 during mechanical endurance test.

1.6 Temperature rise tests

Temperature rise experiments were carried out on the Dead Tank 145kV g^3 at nominal currents between 3000 A and 4000 A (Figure 6). The pole had composite bushings and was instrumented with temperature sensors along the main current path including contacts, castings, bolted connexions, bushing conductor, tank and terminals. Tests were performed with the same equipment filled with the gas mixture and with SF_6 gas to provide a comparison.

Figure 6: Dead tank 145g^3 during temperature rise test at 3000 and 4000 A.

Temperature rise measurements on the interrupter (Figure 7) were 12.6 to 15.6% higher with the breaker filled with the gas mixture compared to SF_6 (Figure 8). All values were below maximum allowed by the IEEE & IEC standard.

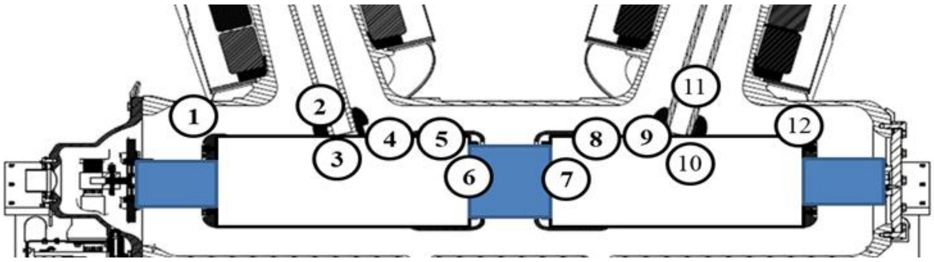


Figure 7: Illustration of dead tank interrupter with temperature probes.

The temperature profiles for the interrupting chamber at 3000 A and 4000 A, were nearly parallel. Thus, the temperature elevation between SF_6 and mixed gas cases is nearly constant regardless of the interrupter component material, its finish or the kind of connections (inserted, bolted or pressed). For the bushing conductor temperature measurements at 3000 A and 4000 A, the hottest point is localized on the middle of the central conductor. Profiles are parallel in the lower part of the bushing and are nearly equal at the high-voltage terminal. The temperature rise remained below the glue glass-transition temperature in the composite insulator top flange glue joint at 3000 A and 4000 A [12].

Calculated overload coefficients were 1.82 for a 10% overload from 3000 A and 1.72 from 3500 to 4000 A. IEEE and IEC standards consider a coefficient of 1.8, which is still valid for the gas mixture [12].

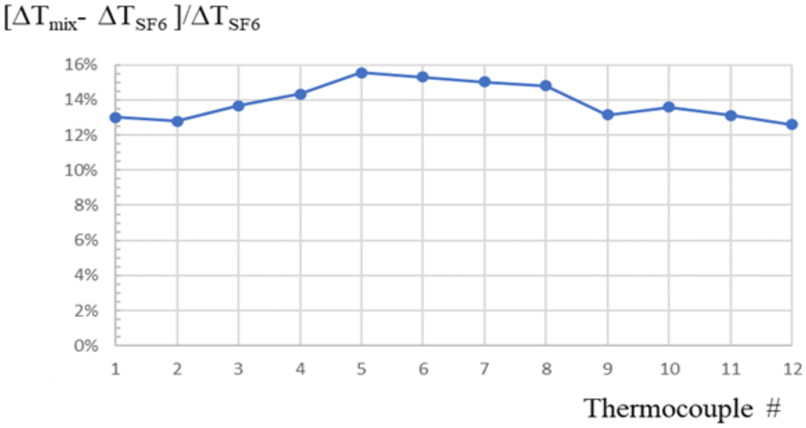


Figure 8. Differences in temperature rise between mixed gas and SF_6.

1.7 Variation of contact resistance with electrical wear in mixed gas Dead tank 145g^3

During power test campaign according of the Dead Tank 145kV g^3, the main circuit contact resistance was measured before and after the tests. The chart in Figure 9 includes the results obtained with a DC current of 200 A circulating between high-voltage terminals. The difference obtained was 10% after 338 kA^{2}s and 15% after 448 kA^{2}s accumulated interruptions, depicted in yellow bars.

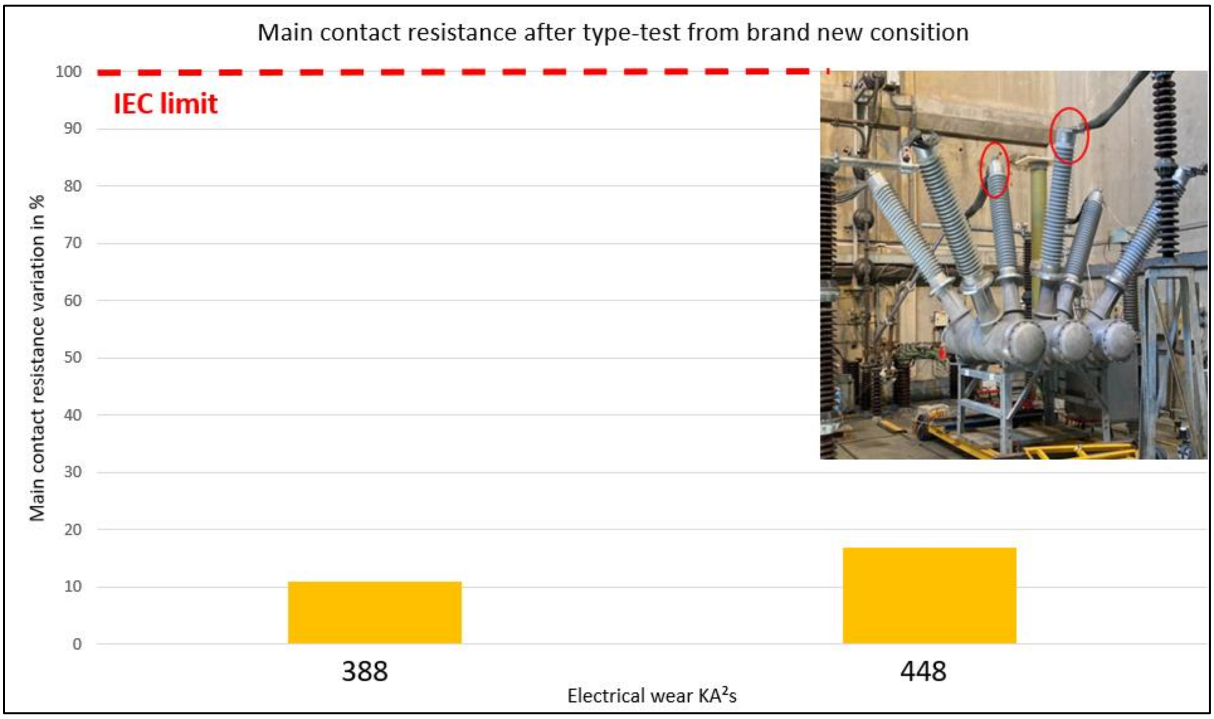


Figure 9. Main contact resistance variation after type test from brand new condition

According to the applicable IEC standard [1] the resistance condition check is considered satisfactory if the resistance increase for each phase is not greater than 100% (250% for IEEE standard). This limit is depicted in the chart in Figure 13 by the blue bar.

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