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Dead-Tank SF_6-Free Circuit Breaker for Networks Rated 145 kV, 63 kA

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SUMMARY

Dead-tank, SF_6 gas-insulated circuit breakers constitute the predominant outdoor high-voltage switching technology in the US power grid. In recent years, SF_6-free circuit breakers have been developed and installed in an effort to reduce the US electrical network carbon footprint and emissions. In addition, regulatory initiatives are under consideration or have been enacted with the purpose of limiting the use of SF_6. This is occurring as the transition to renewable generation is introducing more stringent and challenging duties for the existing switching technology. This document describes the design and verification testing performed during the development of a mixed gas-insulated DT circuit breaker rated 145 kV, 63 kA, 4000 A, 60 Hz. This 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 A 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. Material content has significant implications for the equipment's climate change impact, compensating for the favorable emission impact of competing technologies using technical air insulation with zero GWP.

KEYWORDS

Circuit breaker, dead tank, breaking tests SF_6-free, alternative gases, fluoronitrile, LCA, life cycle assessment.

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1 INTRODUCTION

Dead-Tank (DT) circuit breakers constitute the predominant outdoor High-Voltage (HV) switching technology in the US power grid. The US network has specific requirements for this equipment which include: design & testing according to IEEE standards [1, 2], switching duties related to widespread use of outdoor air-insulated substations and overhead transmission lines leading to special fast voltage transients [3], increased lightning and switching surge exposure, high asymmetry and magnitude of short-circuit currents, practices of outdoor maintenance and assembly, emergency rated voltage withstand while operating without internal overpressure, among others. In addition, this equipment should be validated for operation at extreme ambient temperatures worsened by climate change.

Requirements imposed on circuit breakers by renewable generation are challenging for the existing SF_6 technology and should be addressed for any alternative technology. These include: operation over the maximum rated voltage (110% operating voltage), long periods of time energized in the open position during synchronizing or in bus-tie applications, and high continuous current in densely interconnected networks and/or in proximity to power generating facilities as well as frequent operation of reactive power compensation elements (shunt reactors and capacitors) due to the variations in generation output and loads.

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. In the US, the California Air Resources Board (CARB) adopted a new Subarticle 3.1, Regulation for Reducing Sulfur Hexafluoride Emissions from Gas Insulated Switchgear sections 95350 to 95359, title 17, California Code of Regulations in 2011. Effective January 1, 2022, the regulation was amended as Regulation for Reducing Greenhouse Gas Emissions from Gas-Insulated Equipment. A key feature of the amendment limits installation of new SF_6 gas-insulated equipment to further reduce the risk of greenhouse gas emissions [4]. It includes a schedule dependent on rated voltage and short-circuit current. to progressively phase-out the acquisition of new SF_6 gas insulated equipment in the state beginning January 1 2025 for 38 kV < $V_{rated} \leq$ 145 kV and extending to January 1, 2033 for V_{rated} > 245 kV, with allowance for technical or feasibility exceptions. Nationally, the US Environmental Protection Agency (EPA) 40 CFR 98 Subpart DD requires utilities to track and report SF_6 emissions beginning in 2011 and proposed revisions to greenhouse gas reporting requirement have been proposed. Similarly, the European Union has set mandatory targets for reducing emissions through its EU F-gas regulation.

SF_6-free DT HV circuit breakers are being developed and installed an effort to reduce the US electrical network carbon footprint and emissions. There are two leading groups of alternatives to SF_6 HV switchgear DT circuit breakers:

- The use of CO_2-based gas mixtures in which pressurized gas provides the interrupting action and insulation functions. This technology is similar to existing SF_6-insulated HV switchgear [6].
- A combination of vacuum interrupters with pressurized technical air (80% nitrogen, 20% oxygen) for insulation [7].

As a result of regulatory changes as well as corporate initiatives to reduce greenhouse gas emissions, the high voltage industry has increasingly demonstrated a desire to implement SF_6-free solutions. Key market technical performance drivers include:

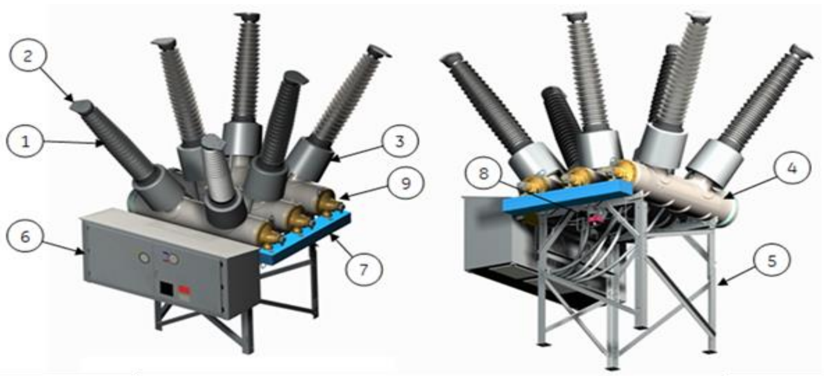
- Meet, as much as possible, equivalent SF_6 equipment ratings, dimensions, mass, and cost. Including direct replacement of existing circuit breakers without the need for substation modifications or changes in ratings.
- Special duty applications including shunt capacitors, shunt reactors, high system X/R ratio, very low probability of restrike/reignition and special TRV.
- Safety, maintenance, and cost of ownership.
- Lifetime environmental performance.
- Universal solution for all system ratings and applications.

The availability of SF_6-free high voltage DT circuit breakers has thus far been limited to 72.5 kV, 31.5 kA and 40 kA ratings. A recent announcement was issued of a new 123 kV/145 kV, 40 kA DT which currently has limited in-service experience. Users may need to adapt specifications and applications to accommodate some of the new technologies. Industry adoption in expected to increase the availability of SF_6-free solutions, especially as manufacturers launch common solutions and introduce higher performance products. As users become accustomed to SF_6-free solutions volume will increase and manufacturers will adapt production capacity to accommodate the transition.

2 DEVELOPMENT OF A DEAD TANK CIRCUIT BREAKER RATED 145 kV, 63 kA, 60Hz

2.1 Circuit Breaker and Interrupter Description

The circuit breaker is named DT1-145g-63-F1 (Figure 1), 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 (Figure 2). 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. DT1-145g layout and main components.

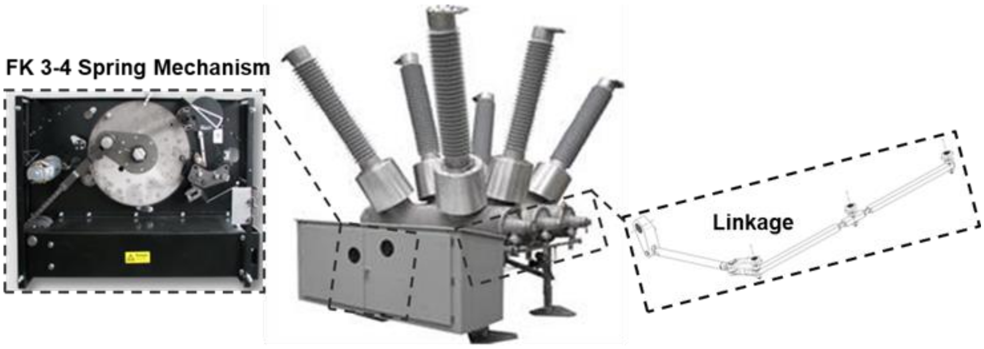


Figure 2. DT1-145g drive and linkage

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 circuit breaker has similar mass and dimensions as its SF_6 counterpart. The DT1-145g interrupting chamber is based on the SF_6 equipment with improvements and changes implemented in order to adapt to the nature and behavior of the gas mixture. It has a two-volume chamber with a combination of compression and self-blast actions. The interrupter has non-linear double motion. Initially and during the compression phase, only one side moves. Later in the stoke, after contact part, both sides are in placed in 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 83.5% CO_2/13% O_2/3.5% C4-FN, 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.

2.2 Breaking test results

Standard fault and load breaking test duties have been successfully tested on the DT1-145g 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 [1, 2] 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 [3] 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 [2]. Inductive load switching tests have been performed for a current of 100 A. The test list is included in Table 1.

Figure 3. DT1-145g during power breaking tests at CERDA.

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

Table 1. List of breaking tests performed on the DT1-145g circuit breaker.

2.3 Dielectric tests

Dielectric withstand tests were performed on a three-phase DT1-145g 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

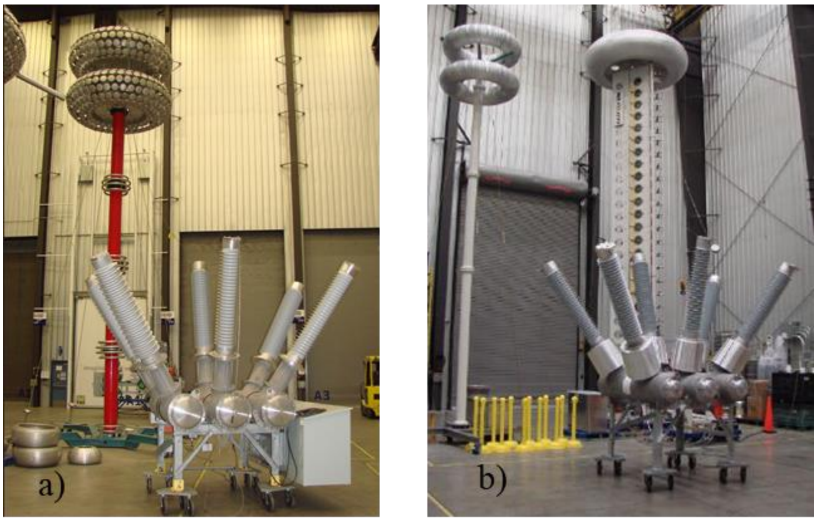


Figure 4. DT1-145g circuit breaker during a) AC withstand, b) BIL and chopped wave dielectric tests.

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.

2.3.1 Zero relative pressure dielectric tests

Although there are no standardized values for power frequency withstand at zero relative pressure inside the poles, utilities specify this requirement to mitigate the risk of rapid insulating gas pressure loss. Values from 1.2 to 1.5 Un/√3 are common in existing SF_6 designs. At atmospheric pressure, the CO_2/O_2/C4-FN 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	**$CO_2/O_2/C_4$-FN**	**Technical air**
Relative dielectric withstand (pu)	1.0	0.7	0.40
Zero relative pressure performance	1.4	1.2	0.56

Table 2. Comparison of capability at zero relative pressure for SF_6, CO_2/O_2/C4-FN and technical air.

2.3.2 Dielectric check after service capability

A. Service capability requirement

The IEEE circuit breaker testing standard [2] 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 about 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 of 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 3. 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	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 3. Complete service capability test sequence on a DT1-145g.

Both dielectric tests were applied to the DT1-145g 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 4.

	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 4. Voltage condition check test values demonstrated on DT1-145g.

2.4 Mechanical endurance tests

Mechanical endurance tests were performed on the DT1-145g for an M2 class qualification consisting of 10,000 operations [2]. This test consisted of 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: DT1-145g during mechanical endurance test.

2.5 Temperature rise tests

Temperature rise experiments were carried out on the DT1-145g 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: DT1-145g 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 standard [1].

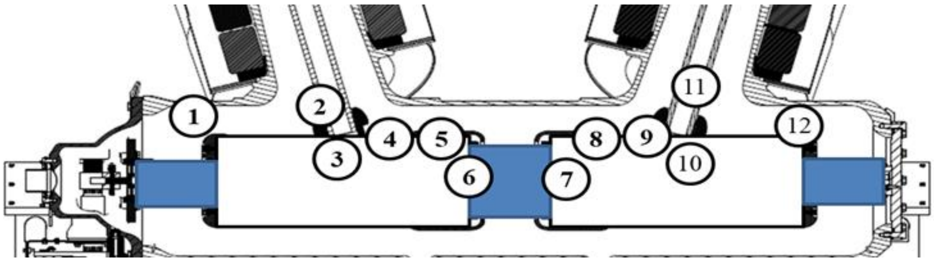


Figure 7: Illustration of dead tank interrupter with temperature probes.

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 [11].

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].

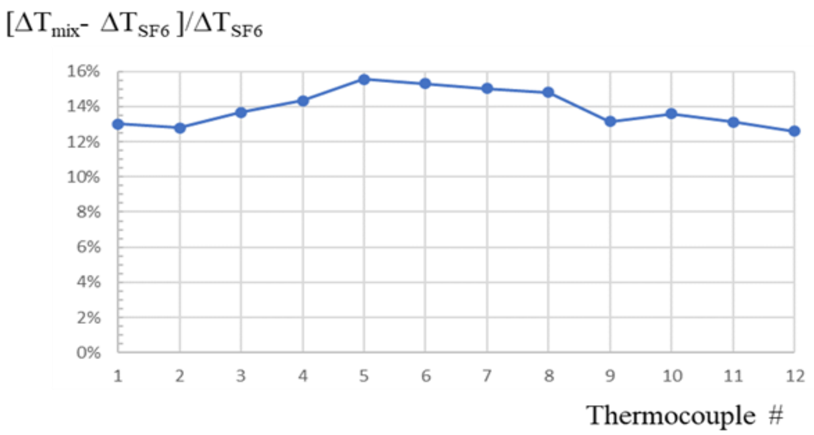


Figure 8. Differences in temperature rise between mixed gas and SF_6.

2.6 Variation of contact resistance with electrical wear in mixed gas DT1-145g

During power test campaign according of the DT1-145g, 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.

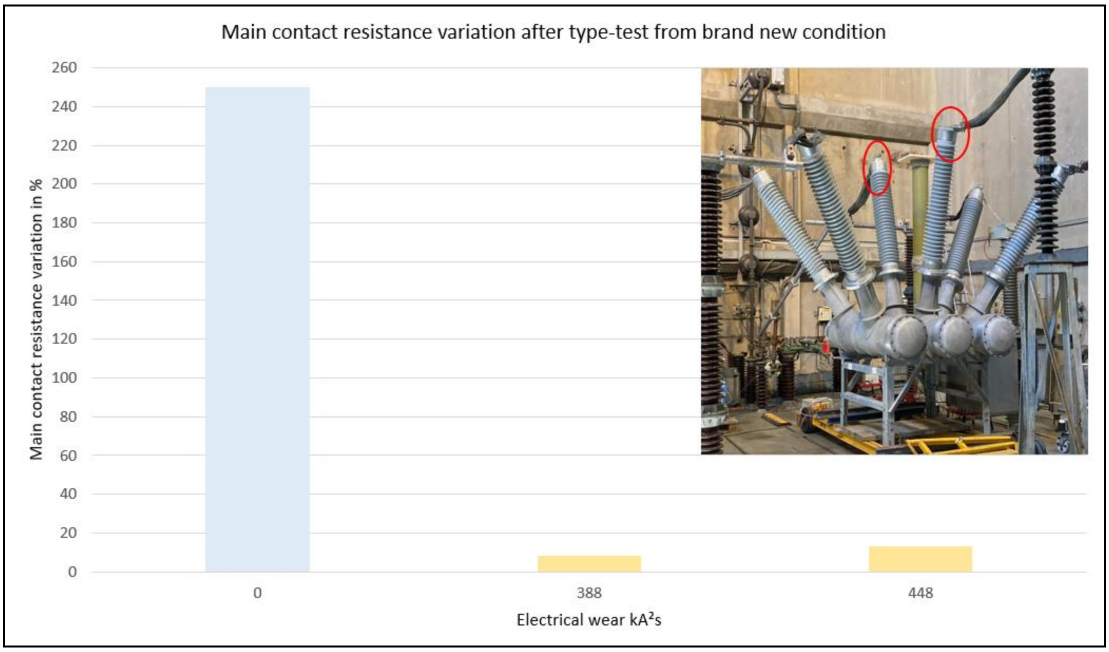


Figure 9. Main contact resistance variation after type test from brand new condition

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

3 DISCUSSION

3.1 Scalability

Due to the similarities of CO_2/O_2/C4-FN gas-insulated circuit breakers with the existing SF_6-insulated equipment, scalability of this technology is likely to be achieved throughout the HV and EHV range. In Europe, GIS circuit breakers are currently in the final stage of development up to 420 kV [8, 9]. Recently, an US DoE Advanced Research Projects Agency - Energy (ARPA-E) three-year funded project has been initiated with the purpose of demonstrating the feasibility of this mixed gas technology for dead-tank circuit breakers rated 245 and 550 kV.

3.2 Climate change impact considerations

A complete climate change assessment of various competing circuit breaker technologies must consider the full life cycle of the equipment. The following generalized description is based on the contents of Figure 10. The initial climate change impact (in CO_2 equivalent, CO_2e), as the equipment is placed in service, is associated with the circuit breaker material content (including the insulating gas), manufacturing, transportation and installation. The dead-tank circuit breaker technology with the lowest material content is the existing SF_6 equipment, which can be used as a reference with 100% material content. CO_2/O_2/C4-FN gas-insulated DT circuit breakers will have approximately 105 to 120% material content and technical air-insulated/vacuum DT circuit braker will have approximately 120 to 160% material content, with this difference increasing with the maximum voltage rating. It is estimated that an air/vacuum DT circuit breaker with about 145% material content would have the same initial climate change impact as an equivalent SF_6 circuit breaker. The initial climate change impact for a CO_2/O_2/C4-FN gas-insulated DT circuit breaker is 65 to 70% of an equivalent SF_6 circuit breaker.

After installation, the climate change impact increase is associated with emissions and resistive losses for SF_6 and CO_2/O_2/C4-FN circuit breakers and resistive losses for air/vacuum circuit breakers. If a curve is drawn representing the climate change impact with respect to time in service, the emissions impact is proportional to GWP and leakage rate. For example, an air/vacuum circuit breaker with a material content of 160% and higher initial CO_2e than an existing SF_6 circuit breaker would catch-up to the same CO_2e after seven years if SF_6 gas leaks occur at a rate of 0.5% per year. An air-vacuum circuit breaker with material content of 130% would still have a greater CO_2e impact after 40 years than a CO_2/O_2/C4-FN circuit breaker with a leak rate of 0.5% per year.

Resistive or joule losses are associated with the resistance between circuit breaker terminals, the current flowing through the main circuit, anti-condensation heaters to reduce humidity level in cabinets, heaters used to maintain the temperature for controls and auxiliary elements in cold conditions and tank heaters needed for operation of SF_6 and CO_2/O_2/C4-FN DT circuit breakers at ambient temperatures below -30^{o}C. The CO_2e impact of these losses depends on the particular generation mix of the network. Fault interruption will increase the resistive losses associated with the main current path. It is reported that the impact of fault interruption leads to greater resistance increase for air/vacuum compared to both SF_6 and CO_2/O_2/C4-FN DT circuit breakers [10]. In contrast, air/vacuum circuit breakers do not require tank heaters for applications below -30^{o}C. All circuit breakers require cabinet heaters.

The maintenance intervals of existing SF_6 circuit breakers have been increased to periods of 10 to 15 years. Gas losses during maintenance intervals involving gas handling and refilling that contribute to the climate impact of SF_6-insulated circuit breaker. This impact is negligible for CO_2/O_2/C4-FN and null for air/vacuum circuit breakers.

At the end of life of the equipment, some of the climate change impact is reduced through material recycling. For SF_6 circuit breakers, the insulating gas should be reconditioned and reused in order to minimize this impact.

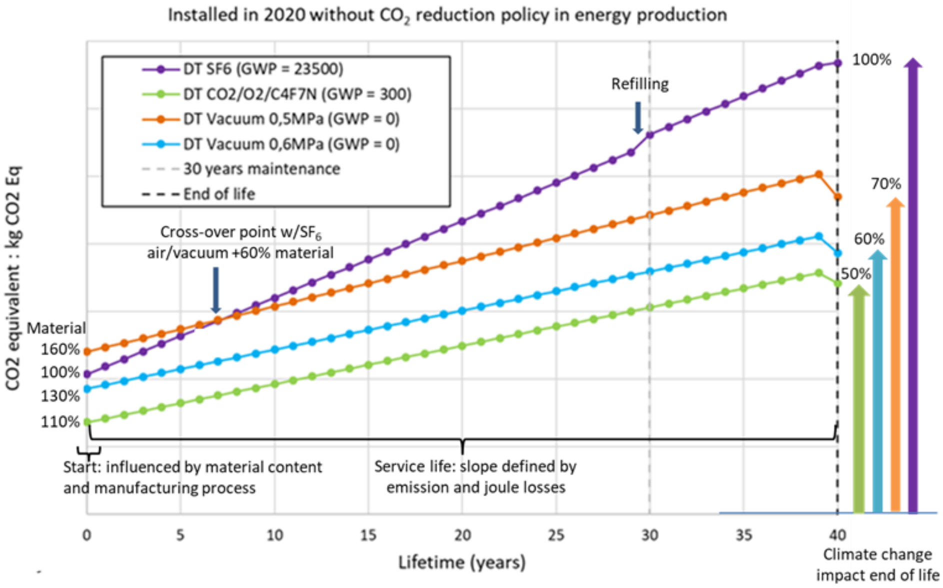


Figure 10. Climate change indicator (CO_2e) for SF_6, two air/vacuum and CO_2/O_2/C4-FN gas mixture dead-tank circuit breakers installed in 2020 over a 40-year period [5].

A life-cycle assessment over a period of 40 years in service [5], shows that circuit breakers with alternative insulating gases offer a reduction in climate change impact in the range of 50 to 70%. Due to higher material content, human toxicity, particulate matter, ionizing radiation, ozone formation, acidification, eutrophication, fresh-water ecotoxicity, water consumption, land usage and resource depletion are higher for air/vacuum circuit breakers compared to SF_6 and CO_2/O_2/C4-FN gas-insulated DT circuit breakers. Ozone depletion is equal for SF_6 and CO_2/O_2/C4-FN gas mixture and lower for air/vacuum.

4 CONCLUSIONS

The DT1-145g 145 kV, 63 kA CO_2/O_2/C4-FN gas-insulated, dead-tank circuit breaker has been tested to cover applicable IEEE standards [1, 2, 3] which reflect the requirements of the US power network. Fault current breaking tests have been performed to the highest TRV factors in these standards. To address voltage operation at 110%, terminal fault duties up to 60% were tested with a voltage of 152 kV. Transformer-fed fault tests have been performed at 30 an 10% of the rated short circuit current. Capacitive switching has been demonstrated for Class C2 with very low restrike probability up to 1.7 voltage factor, covering lines, cables and shunt capacitor banks for grounded, ungrounded and breaking under fault conditions. Inductive current switching test have been performed at 100 A. This circuit breaker has passed all dielectric tests with margin both in new condition and with electrical wear after breaking tests with a voltage condition check. It is capable of withstanding 1.2 pu AC withstand with zero overpressure of the gas insulation. Mechanical endurance is 10,000 operations Class M2, including a voltage check at full 1-minute power frequency withstand and a 2.0 pu 30-minute withstand in the open position. Temperature rise tests were performed for 3000 and 4000 A rating. The 3000 A test included an overload test at 3300 A (10% overload). The resistance of the circuit breaker main current path has demonstrated stability after breaking tests. Lastly, electrical endurance has been demonstrated up to 3.50 MJ of accumulated fault interruptions.

Proposed regulations focus entirely on emissions reduction, ignoring other aspects that have significant climate change impact such as the equipment's material content and joule losses. A comparative life-cycle assessment favors the proposed CO_2/O_2/C4-FN mixed gas-insulated dead-tank circuit breaker over vacuum/technical air technology for climate change impact and all other environmental impact aspects in an LCA study, except ozone depletion.

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BIBLIOGRAPHY

[1] IEEE Std C37.04-2018, "IEEE Standard for Ratings and Requirements for AC High-Voltage Circuit Breakers with Rated Maximum Voltage Above 1000 V", IEEE, New York, NY, 2018.

[2] IEEE Std C37.09-2018, "IEEE Standard Test Procedure for AC High-Voltage Circuit Breakers Rated on a Symmetrical Current Basis", IEEE, New York, NY, 2018.

[3] IEEE Std. C37.06.1-2017, IEEE Recommended Practice for Preferred Ratings for High-Voltage (>1000 volts) AC Circuit Breakers Designated Definite Purpose for Fast Transient Recovery Voltage Rise Times" IEEE, New York, NY, 2017.

[4] https://ww2.arb.ca.gov/our-work/programs/elec-tandd/regulation
https://www.epa.gov/ghgreporting/subpart-dd-use-electric-transmission-and-distribution-equipment

[5] Hermosillo, V., E. Laruelle, L. Darles, C. Gregoire, Y. Kieffel, "Environmental Performance of Dead-Tank Circuit Breakers with SF_6 and Alternative Gases", CIGRE Paris Centennial Session, paper A3-102, France, 2021.

[6] Nechmi, H., A. Beroual, A. Girodet and P. Vinson, "Fluoronitrile/CO_2 gas mixture as promising substitute to SF_6 for insulation in high voltage applications", IEEE Transactions on Dielectrics & Electrical Insulation, Vol. 23, No. 5.

[7] Kueschel, M., et al., "First 145 kV/40 kA gas-insulated switchgear with climate-neutral insulating gas & vacuum interrupter as an alternative to SF_6 - design, manufacturing, qualification & operational experience", CIGRE, paper B3-107, Paris, France, 2020.

[8] Gregoire, C., et al, "Switchgear scalability demonstration using environment friendly C4-FN/O_2/CO_2 gas mixture in 420 kV GIS Substations", CIGRE, paper A3-ID10848, Paris, France, 2022.

[9] Ozil, J, et al., "Return of experience of the SF_6-free solution by the use of Fluoronitrile gas mixture and progress on coverage of full range of transmission equipment", CIGRE Centennial Session, paper A3-117, Paris, France, 2021.

[10] Dullni, E., et al., "Resistive increase of vacuum interrupters due to high-current interruptions", IEEE Trans. Dielectrics & Electrical Insulation, Vol. 23, No. 1; 2016.

[11] Hermosillo, V. et al, "Comparative Continuous and Overload Current Performance of High Voltage Switchgear with SF_6 and Alternative Gases", CIGRE, A3-ID10126, Paris, France, 2022.

[12] IEC TR 62271-306: High-voltage switchgear and controlgear – Part 306: Guide to IEC 62271-100, IEC 62271-1 and other IEC standards related to alternating current circuit-breakers.